AGMET

June 20, 2013

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Via E-Mail

Michelle Braun
Rules Coordinator
Ohio EPA
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Re: Comments on Draft Conceptual Beneficial Use Program Language

Dear Ms. Braun,

Agmet, LLC appreciates the opportunity to comment on Ohio EPA's May 24, 2013 draft conceptual rule language. Ohio EPA's facilitation of an early stakeholder outreach is important to the regulated community.

Agmet is a leading recycler of metal-bearing industrial products in North America based in Oakwood Village, Ohio. Agmet has two plants in the Midwest (Oakwood Village, Ohio and Maple Heights, Ohio), offices in California and Florida, and a network of affiliated companies located throughout North America. We acquire, repurpose and sell industrial byproducts as valuable metals (nickel, cobalt, copper and tin) to other companies. All metals that we acquire are recycled, sold and reused as part of our unique Recycle 100 philosophy that results in virtually no by-product or waste.

Agmet is focused on developing innovative, custom solutions to keep metal by-products out of landfills by recycling, reducing, re-using, reclaiming and reselling them as valuable raw materials used in various industries. In addition to the beneficial aspect of keeping by-products out of landfills, Agmet's business reduces the need for raw material demands to be met with virgin ores, the mining of which requires vast amounts of energy, water and chemicals. These goals are environmentally significant.

In 2013, Agmet adopted our Recycle 100 philosophy which ensures virtually no by-product wastes from the products we receive. Utilizing a proprietary process, we purchase and repurpose thousands of tons of metal-bearing materials from industrial processes each year including:

- Metal Hydroxide Filtercakes and Sludges, including qualified F006 hazardous wastes allowable under the terms and conditions of Agmet's 2005 Variance from Ohio EPA
- Spent Plating Solutions
- Spent Catalysts
- Metallic Grindings and Dusts

Agmet recovers and resells these metal units into concentrated product that has value to refiners. This prevents metal waste from being deposited in landfills where it can negatively impact the earth.

Agmet is generally supportive of an administrative rule structure that recognizes that evolving technological advances are changing the way we think about materials management. Indeed, technology is changing the way we define waste – meaning those end materials that have no purpose, value or destination other than a landfill. An innovation shift has occurred and it is not appropriate to label as wastes those materials that are byproducts of one industrial process, useful inputs for another, and bought and sold at fair prices.

Ohio EPA's June 2012 stakeholder outreach materials state that it is seeking input on "an approach to promote responsible and beneficial use of industrial byproducts ... [to] [m]ake byproducts resources instead of waste." Ohio EPA explained that:

> In general terms, beneficial use is considered the use of industrial byproducts to replace or supplement a raw material or competing product. Industrial byproducts generally refer to residual materials that could meet the regulatory definition of solid waste or industrial waste or the definition of waste in different regulatory programs. The beneficial use program would not change or replace existing beneficial use programs established in waste-specific reuse rules such as hazardous waste, scrap tires, compost, sewage sludge and clean hard fill.

Agmet encourages Ohio EPA to act consistently with this original programmatic vision and to compose a program that meets Ohio EPA's objectives to ensure reuse is legitimate, without regulating materials that are not in fact wastes. To that end, Agmet offers the following comments for consideration:

1. **Materials excluded from the definition of waste under Ohio EPA's hazardous waste rules must be excluded from regulation under the proposed beneficial use rules.**

   Agmet purchases and repurposes certain materials that could be regulated as hazardous wastes *but for* the application of exclusions from the definition of waste found at Ohio Administrative Code ("O.A.C.") 3745-51-02(E), promulgated pursuant to Revised Code ("R.C.") Chapter 3734. This section excludes from the definition of waste materials that are recycled by being a) used or reused as ingredients in an industrial process to make a product, provided the materials are not being reclaimed; or b) used or reused as effective substitutes for commercial products. When Agmet recycles materials in accordance with these provisions, the materials are not wastes within the hazardous waste rules.

   The May 24, 2013 conceptual draft rules provide a general exclusion for "[h]azardous wastes regulated pursuant to Chapter 3734 of the Revised Code and rules adopted thereunder." Draft 3745-599-05(E).

   The stakeholder outreach materials referenced above state that Ohio EPA's intention is that **"[t]he beneficial use program would not change or replace existing beneficial use programs established in waste-specific reuse rules such as hazardous waste ..."**

   Ohio EPA must make clear in any subsequent draft that, because the hazardous waste rules already address these materials and already govern the use/reuse of these materials under an existing recycling exemption, that Ohio EPA will not regulate these materials under the proposed draft beneficial use rule.

During the June 12, 2013 stakeholder meeting when the question was raised, Ohio EPA expressed uncertainty as to how it would handle hazardous waste exclusions and stated that it might consider materials governed by that exclusion to still be regulated solid wastes and therefore regulated under this proposed beneficial use program.

That result would be entirely inconsistent with the way that Ohio EPA has regulated Agmet's materials in the past, and inconsistent with R.C. 3734.01(E), which defines solid waste to specifically exclude any material that is a hazardous waste. Such an interpretation would overlap regulatory programs that the statute expressly intended to be separate, and needlessly duplicate regulation of the same materials under two use/reuse regulatory schemes. This would render the exclusion from the definition of waste under O.A.C. 3745-51-02(E) meaningless. It would also result in an overly burdensome and unreasonable scheme as Ohio EPA would be proposing a solid waste reuse program an order of magnitude more stringent than the hazardous waste program it adopted in accordance with federal RCRA mandates. Additionally, it would be inconsistent with Ohio EPA's stated intentions for the program.

Agmet suggests that Ohio EPA revise Draft 3745-599-05(E) to insert the underlined text to clarify that the chapter is not applicable to "[h]azardous waste regulated <u>or excluded from the definition of waste under use/reuse provisions</u> pursuant to Chapter 3734 of the Revised Code and the rules adopted thereunder."

2. **<u>Byproduct materials that are purchased at fair market value for reuse should be excluded from the definition of select wastes.</u>**

Ohio EPA has linked the definition of select waste under Draft 3745-599-02(S)(1) with the definition of solid waste under Draft 3745-599-02(S)(3). The draft says that solid waste has the same meaning as R.C. Chapter 3734, meaning primarily that the materials are unwanted. In the draft, Ohio EPA has defined unwanted to mean:

> [A] material that is discarded by the generator or is used in a manner that shows the generator no longer reasonably needs or desires the select waste. Unwanted does not include a select waste that has been beneficially used in accordance with this chapter.

Draft 3745-599-02(S)(3). When Agmet pays fair market value for its feedstock materials, those materials are not discarded, unwanted, unneeded or undesired – not by Agmet or the generator/seller. The generator/seller may not itself have need of the byproduct, but that does not render the material a solid waste. If it did, every sale of commercial goods would meet the definition because, in order to have a sale, one party must be willing to part with the item. Willingness to part with a byproduct in exchange for a fair market value does not make a solid waste.

Agmet appreciates that under the conceptual draft a material that *has been* beneficially used in accordance with the rules is not unwanted, and therefore not a solid waste. However, Agmet questions whether Ohio EPA has jurisdiction under R.C. Chapter 3734 of byproduct materials that *will be* beneficially reused and are not unwanted. To reach Ohio EPA's conclusion that it does, you must assume that a material does not become wanted until the moment it is

beneficially reused. According to the definition of beneficial use in Draft 3745-599-02(B)(1), a byproduct will not lose its waste stigma until the point that it is used as an ingredient or product or in a manner that contributes to a manufacturing process or product. This is inconsistent with the definition of solid waste as there is no point when these materials are unwanted. Agmet encourages Ohio EPA to reconsider these concepts.

Even if Ohio EPA proceeds to regulate these materials as solid wastes, Agmet urges Ohio EPA to revise Draft 3745-599-02(S)(3) to insert the underlined text to clarify that "[u]nwanted does not include a select waste that has been purchased at fair market value for beneficial reuse in accordance with this chapter."

3. **General permit coverage should not be required for every entity along the byproduct supply chain.**

In the June 12, 2013 stakeholder meeting, Ohio EPA expressed its opinion that every entity along the supply chain would be required to obtain coverage under a general permit. This would include generators, brokers, receivers, preparers, processors, distributors and, potentially, end users. Ohio EPA reasoned that it needs to ensure the party with the greatest knowledge of the byproduct (origins, characteristics, etc.) had permit coverage.

Requiring every entity along the supply chain to submit a Notice of Intent for coverage would be unduly burdensome. Agmet competes with companies in other states for contracts to purchase metal byproducts, and for contracts to sell its processed metal units. If Agmet had to require its byproduct customers, its byproduct customers' customers going all the way back to the generator, its processed metal unit customers, and its processed metal unit customers' customers extending all the way out to the last user to obtain permit coverage in Ohio as a precondition of doing business with Agmet, it would be unduly burdensome, unreasonable, and a serious disincentive to doing business with Agmet in Ohio.

Why do business with an Ohio company when it requires becoming a permitted entity? This would encourage entities to continue landfilling rather than taking on the regulatory burden of reuse. If Ohio EPA stays true to its stated objectives, there is no reason why beneficial reuse should require more permits than landfilling.

Permitting schemes frequently require the permit holder to take on the responsibility of providing the agency with materials information, and permit holders frequently obtain that information from other non-permitted entities in order to comply. Requiring a permit for the entity with the most knowledge about the byproduct makes sense; requiring every entity that touches the material to have a permit does not.

Agmet encourages Ohio EPA to reconsider. This requirement would dramatically increase the number of entities both inside and outside the state of Ohio that would need to become permitted entities in order to do business in Ohio.

Agmet reserves its ability to comment further as new issues are identified on the May 24, 2013 draft conceptual rule, or as subsequent drafts evolve.

We appreciate the opportunity to be involved in this early stakeholder process. If you have any questions, please feel free to contact me.

Sincerely,

Dana J. Cassidy
President & CEO

association of ohio metropolitan wastewater agencies

Dax J. Blake, P.E.
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June 21, 2013

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Re: Comments in response to Ohio EPA's May 2013 Early Stakeholder Outreach (ESO) Request Concerning Development of a Beneficial Use Regulatory Program

Dear Ms. Braun:

The Association of Ohio Metropolitan Wastewater Agencies ("AOMWA") appreciates the opportunity to provide input on Ohio EPA's development of a "beneficial use" regulatory program in response to the agency's May 2013 Early Stakeholder Outreach notice ("ESO"). AOMWA is a non-profit organization that represents the interests of Ohio's public wastewater treatment agencies. As evidenced by AOMWA's comments on Ohio EPA's June 2012 ESO notice, our members have a great interest in the development of a regulatory program that would recognize the beneficial use of waste materials, including sewage sludge incinerator ash, and reduce disposal costs for municipalities with limited budgets. As a preliminary matter, we want to commend Ohio EPA for the significant outreach that it has conducted as part of the development of this proposed program. The program's design presents complex issues for byproduct management and AOMWA members appreciate Ohio EPA's efforts to obtain input on the key concepts of this program from the regulated community through both the ESO comment process and the various stakeholder meetings that it has conducted. We hope that such input will help craft a scientifically sound regulatory program that is workable in application and practice.

With respect to the program's design, AOMWA would note that it is generally supportive of the tiered permitting categories being advanced by Ohio EPA. However, while supportive, we do have comments and questions regarding specifics of the program and raise those issues for your consideration below:

1. AOMWA agrees with concerns raised by others with the proposed use of the term "select waste" in the context of this program. While AOMWA agrees with Ohio EPA's plan to expand the program beyond industrial by-products (discussed in more detail below), AOMWA believes that the term "select waste" does not appropriately reflect the intent of the program which is to encourage reuse. AOMWA might suggest instead use

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of the term "select material" or "beneficial use material." (For purposes of our comments, we continue to use the term "select waste" as it is currently used in the draft rules).

2. Given existing regulatory programs, AOMWA agrees that land application of sewer sludge and composting should remain excluded from the proposed beneficial use program as the agency has proposed in draft OAC 3756-599-05. We also believe that lime sludge from water treatment plants for agricultural uses should be expressly excluded where the Ohio Department of Agriculture has exercised its jurisdiction over this material and its application.

3. AOMWA supports the construction material exclusions articulated in draft OAC 3745-599-10. As discussed at the June 12th meeting, this approach was proposed to reflect the fact that agency jurisdiction ceases if the resulting product poses no potential for releases to surface water and soils. To the extent that incinerator ash is incorporated into one of the listed construction materials, we agree that it should be excluded from regulation as well.

4. We further support an exclusion for earth and contaminated soils in draft OAC 3745-599-15. At the June 12th meeting, the agency discussed the need for alternative use of dredged soils from Lake Erie, given the shallow depths of the lake and reduced federal involvement. We would also note that many stormwater control structures will need cleaning and having an outlet for deposited sediments will greatly assist communities and private entities in properly maintaining these structures.

5. AOMWA believes that beneficial uses of sewage sludge incinerator ash not otherwise qualifying for the exclusions or pre-approval should nonetheless be authorized by general permit. Sewage sludge incinerator ash is an inert, non-toxic material that is currently being beneficially reused in a number of states as a soil amendment, in the making of bricks, as daily and final landfill covers, in the manufacture of Portland cement, and as fill material. Based upon existing data that has been submitted to Ohio EPA by our members, characterization and use specifications can be developed specific to sewage sludge incinerator ash and included in a general permit. AOMWA would encourage that in the development of general permit terms for incinerator ash the focus should be on standards for the end use and not on the by-product material before such use.

6. Additionally, while we support use of a general permit for incinerator ash uses (not otherwise incorporated into excluded construction materials or subject to pre-approval), AOMWA members have concerns about the characterization plans that may be required under a general permit, including the test methodologies that will be required with respect to incinerator ash, the number of tests and how characterization and use plans will be evaluated by Ohio EPA and under what standard. Ohio EPA has suggested that many of these issues will be addressed not in draft rules, but in draft general permits. However, without such draft permits available to review, it is difficult to assess these issues. Accordingly, once draft general permits are prepared by Ohio EPA for certain categories of materials, which we understand will be forthcoming in the near future, AOMWA would request the opportunity to meet and confer with Ohio EPA regarding the development of a similar draft general permit for incinerator ash. We hope many of our

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questions and comments can be addressed through the cooperative development of such a permit.

7. With regard to the draft rules, AOMWA is concerned that the applicability of the "general requirements" in Draft OAC 3745-599-30 is overly broad. Sections (A), (B), (D) and (E) apply to "any person" beneficially using a select waste. The term "person" is broadly defined under the draft rules and thus would arguably include not just any "generator" or "distributor", but could also include any "end-user" or other individual that ultimately uses a product in which a select waste is incorporated. To require an end-user or individual that simply purchases a product to be subject to the requirements of the program appears overly broad and unnecessarily duplicative, particularly the permitting requirements of this program.

   Further, because of the broadness of these sections, they are also vague. It is not clear who has to comply and what requirements they must comply with. This is a problem we see in other sections of the draft rules as well. Indeed, in our view, it is not clear under the program requirements when a distributor or end-user could be required to apply for a permit or maintain compliance with the other requirements of the rules in addition to a generator. If the intent of the rules is to require persons other than the generator to apply for an individual or general permit, then the rules must provide more clarity on this point and expressly define what their obligations are. (For example, we would note that the term "applicant" is not defined in the draft rules.)

8. Additionally, draft OAC 3745-599-30(C) also states that the Director can require any permittee approved under a general permit to apply for an individual use permit. We would request clarifications on when and under what circumstances this provision might be imposed. We think it would be prudent to include a standard into the rules on this issue.

9. AOMWA is also concerned that some of the requirements in OAC 3745-599-40 are vague and/or unnecessary and duplicative. OAC 3745-599-40 describes the notice and information necessary for distribution of select waste. Section (A) requires this notice go to "the person" receiving the material. Again, there could be a long line between the generator and the end user or individual that uses a product in which select waste is incorporated. At its broadest, this section would require everyone in that line to be provided with such notice. Again, this seems overly broad, unduly burdensome and impossible to ensure in cases where an end product is developed for sale.

   Further, Subsection (A)(4) provides that the notice to a person receiving the select waste or a product that contains the select waste is to include a summary of results from any characterization required in accordance with OAC 3745-599-50. However, Subsection (B)(2) states that such information is *only* required if specified in the beneficial use general permit or the individual permit or upon request by a person receiving the select waste. These two sections are at odds. As such, the language of Subsection (A)(4) requiring submittal of the characterization information in all instances should be removed since Subsection (B)(2) provides that the general permit controls whether such information is required.

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10. In draft OAC 3745-599-45(A)(2) and (3), a generator would be required to annually submit a copy of its waste characterization and analysis plan as well as all laboratory results of its waste characterization. This requirement seems unnecessary as it would require multiple submissions of the same information over the course of several years. We would suggest instead that submittal of a waste characterization and analysis plan or laboratory results only need be provided following an initial submittal if there has been a change in characteristics of the select waste or an update to the sampling plan. Same comment for Section (B)(3) of this same section.

11. We are concerned that draft OAC 3745-599-50(A) and (C) are contradictory. Section (A) states that a permit applicant "shall" develop a select waste characterization and analysis plan for every select waste it wants to beneficially use. However, Section (C) states that a select waste characterization and analysis plan may not be required if so specified in a general use permit. When reading the two subsections together, it is our understanding that the general permit will control whether and what to submit with respect to a waste characterization and analysis plan. Accordingly, the Sections should be clarified to expressly provide that a waste characterization plan must be prepared for an individual permit and may be required in a general permit, but that the terms of the general permit control in that situation.

    Further, the requirements of the waste characterization and analysis plan for a general permit should be set forth in the general permit. Thus, if a general permit contains such requirements, an applicant applying under that general permit should be exempted from the requirements in draft OAC 3745-599-50(D). Otherwise, each general permit NOI will be more akin to an application for an individual permit.

12. Section (D)(4) of draft OAC 3745-599-50 also provides that select waste that will be placed on the land shall be analyzed for toxicity using the aquatic organisms (*P.promelas* and *C.dubia*) in accordance with the methods specified in OAC 3745-1-03 (A)(1) to (A)(3), which include whole effluent toxicity testing. As described on the USEPA web-site at http://water.epa.gov/scitech/methods/cwa/wet/, whole effluent toxicity testing measures the aggregate toxic effect to aquatic organisms from all pollutants contained in a facility's wastewater effluent. We question the necessity or appropriateness of this test as applied to materials that are to be beneficially reused and seek an understanding as to the scientific rationale or basis for use of this test in connection with beneficial use materials.

13. AOMWA believes that the annual sampling requirement in draft OAC 3745-599-55 is unduly burdensome. Sampling should be required only if there is a change in characteristics of the select waste.

14. OAC 3745-599-210 describes the information to be submitted to the Director as part of the notice of intent to obtain coverage under a general permit. At the June 12th meeting, discussion centered on whether there was a need to have both the generator and the distributor submit NOIs for general permit coverage. There may be situations where this is considered necessary by the agency and other situations where such dual coverage is not needed. These situations should be clarified so that it is clearly understood by the regulated community when these obligations would apply and what the obligations are.

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One way to do this would be to have the rule provide that the general permit will prescribe whether the generator and distributor or both would be required to obtain general permit coverage depending upon such factors as whether the material is beneficially used without further modifications, whether the material is incorporated into a final product, the characteristics of the product, and the situations in which the material or the product containing the material is used. Indeed, depending upon the final commodity or product, the agency may have no interest, or authority for that matter, to need or retain oversight of a product containing a select waste. The general permit for each beneficial use material should be the mechanism for determining the extent of permit coverage.

Additionally, we think there needs to be clarification in the event that both are required to submit NOI's for coverage under a general permit what their relative liability will be for compliance and enforcement under such a permit.

15. Ohio EPA has advised that it has not yet developed draft language regarding its fee structure. However, the proposed fee structure will be important part of the program. We are interested in the agency's plan on both application and allocation (generator v. distributor v. end-user) as it can greatly impact reuse and management decisions. The agency should provide more detail about its planned fees and the fee structure so that this aspect can be considered and commented on by the regulated community.

16. Finally, Ohio EPA requested information on the costs and benefits of a beneficial use program. While developing such a program may be daunting given the various waste streams that may be eligible for coverage, the variety of potential uses, and the intersection of various laws and rules that may apply, we believe such effort to be well worth the time and trouble.

    In particular, for our members, we will see substantial cost savings by being able to beneficially use incinerator ash as opposed to landfilling such material. For example, based on pricing information from 2010, the City of Columbus determined that the unit cost of disposing of incinerator ash in a landfill was $66.12 per wet ton and $132.24 per dry ton. In prior years, the City has disposed of upward of 15,000 wet tons of ash in landfills. Given such costs and tonnage, Columbus would save approximately $1 million in disposal costs if allowed to beneficially reuse such ash. Other members would see similar savings.

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Again, AOMWA appreciates your attention and consideration of our comments on this important program and looks forward to further discussions with Ohio EPA. Should you have any questions regarding our comments, please contact, Jessica DeMonte, Squire Sanders (US) LLP, at (614) 365-2809, or Andrew Etter, Squire Sanders (US) LLP, at (614) 365-2765.

Sincerely,

Dan Hanket, per email authorization / JED

Dan Hanket
Residual Committee Chair, AOMWA

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June 28, 2013

VIA ELECTRONIC MAIL

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Re: Comments of ArcelorMittal Cleveland LLC and The Stein Companies With Respect to Ohio EPA's Conceptual Draft Rules to Implement a Program to Regulate the Beneficial Use of Solid, Industrial or Other Wastes

Dear Ms. Braun:

The following are the comments of ArcelorMittal Cleveland LLC ("ArcelorMittal") and The Stein Companies ("Stein") with regard to Ohio EPA's conceptual draft rules to implement a program to regulate the beneficial use of solid, industrial and other wastes. ArcelorMittal is the world's largest steel company. A core value of the company is its commitment to sustainability, which includes use of the co-products and byproducts generated by the steelmaking process. Stein provides slag processing and steel mill services, including steel and blast furnace slag removal, reclamation of its metallic content and slag sales and marketing. Stein is headquartered in Broadview Heights, Ohio. ArcelorMittal and Stein hereby incorporate the comments filed by the Ohio Steel Group, but submit these further comments to underscore their concerns regarding Ohio EPA's plan to include slag within the purview of the program.

I. INTRODUCTION

The conceptual draft rules would generally prohibit the "beneficial use" of a "select waste" without the approval of Ohio EPA. The term "beneficial use" is defined at draft OAC 3745-599-02(B)(1) as "the legitimate use of a select waste as an ingredient or product in a manner that contributes to a manufacturing process or product, that does not constitute disposal or cause pollution of any waters of the state." The term "select waste" is defined at draft OAC 3745-599-02(S)(1) as "a solid waste, industrial waste or other waste specifically identified for properties necessary or preferred for beneficial use." Although slag is specifically exempt from the definition of solid waste at R.C. §3734.01(E) and has never been managed by the steel

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industry and its steel processors as a waste, Ohio EPA has advised that its intent is that the beneficial use of slag will fall within the conceptual program.

The conceptual draft rules contemplate that the approval for the beneficial use of slag take the form of compliance with either a general permit issued pursuant to draft OAC 3745-599-200 or an individual permit issued pursuant to draft OAC 3745-599-300. Beneficial use would be subject to a host of general requirements outlined in draft OAC 3745-599-30, including certain "legitimacy" criteria outlined in draft OAC 3745-599-35, certain notice and information requirements for downstream users in accordance with OAC 3745-599-40, recordkeeping and reporting requirements in accordance with draft OAC 3745-599-45, extensive waste characterization and analysis in accordance with draft OAC 3745-599-50 and annual sampling to confirm constituent characterization in accordance with draft OAC 3745-599-53.

The Division announced a comment deadline on the conceptual draft rules of June 21, 2013. John Schierberl, Division of Materials & Waste Management, has advised that a brief extension of time to **June 28, 2013** in which to file comments would be acceptable. As a result, these comments are timely filed.

II. COMMENTS

Slag is a co-product that is produced as a result of processes that occur in either the blast furnace, the basic oxygen furnace, or the electric arc furnace. Slag has a variety of recognized uses, including use as an aggregate in bituminous mixes, a concrete aggregate or ingredient in cement, as an agricultural soil amendment, landfill daily cover material and as environmental remediation material. Virtually all of the slag generated in the state of Ohio is sold for the foregoing uses. Slag competes with crushed stone, sand and gravel, limestone and other natural aggregates and, as a result, the concern is that the cost of additional regulation will act as a disincentive to the choice of slag as the preferred material. Specific comments include the following:

- Ohio EPA offers no technical justification, other than anecdotal, for regulation of slag as a waste. Slag has been successfully used for over 100 years in construction applications throughout Ohio and the nation. For roadway application (which is the primary use of slag), materials specifications published by the Ohio Department of Transportation outline quality control, sampling, testing and acceptance levels in roadway applications. *See e.g. Ohio Department of Transportation Specification 703 and Supplemental Specifications 1027 and 1034.*

- While Ohio EPA has included a limited exemption for select waste incorporated into construction material at draft OAC 3745-599-10, that exemption is not sufficiently expansive to include the co-products and byproducts being used by the Ohio steel industry. Draft OAC 3745-599-10 excludes a select waste from regulation under the program if that waste is incorporated into one of a number of construction materials meeting engineering construction specifications and placed on land as part of a construction project. However, the language "meeting construction specifications and placed on land as part of a construction

project" is vague and standardless and the identification of the construction materials subject to the exemption do not include many established uses for the materials generated by the Ohio steel industry.

- The conceptual draft rules will not achieve Ohio EPA's own objectives for the program, those being, "to reduce disposal costs for generators, provide sources of raw materials for end users, extend the capacity of landfills and conserve resources, and make byproducts resources instead of wastes." *See Fact Sheet: Early Stakeholder Outreach Beneficial Use Regulatory Program Development* (June 2012), http://epa.ohio.gov/dmwm/dmwmnonhazrules.aspx. In fact, the overly proscriptive nature of the requirements outlined in the conceptual draft rules virtually guarantees a reduced market for these materials. For example, draft OAC 3745-599-35 requires that the select waste be "adequately contained" and that the select waste not be "accumulated speculatively", which includes, *inter alia*, a demonstration that approximately 75% of a select waste being accumulated is used over a calendar year. This provision does not recognize the realities of many construction projects and the manner in which these materials are used. In addition, draft OAC 3745-599-40 requires that permittees provide a host of information to downstream users regarding the material, including a statement that the material is a select waste and a summary of the results of the characterization of the material in accordance with draft OAC 3745-599-50, as well as continued updates regarding that information. In comments in response to Ohio EPA's Early Stakeholder Outreach in June of last year, the Ohio Department of Transportation questioned the workability of what it termed the "cradle to grave" tracking under discussion. *See Early Stakeholder Outreach / Beneficial Use Regulatory Program Development / Ohio Department of Transportation Comments, July 30, 2012.*

- Other states have provided greater incentives to promote use of slag, which is significant to companies competing regionally, nationally and globally. For example:

    - **Indiana**. The Indiana Code specifically precludes the adoption of solid waste management rules regulating the production, transportation, storage, processing or legitimate use of slag generated by the production of iron or steel under Bureau of the Census Standard Industrial Classification 3312. See IC 13-19-3-8-(1)(5).

    - **Michigan**. Michigan's definition of "solid waste" does not include "[s]lag or slag products directed to a slag processor or to a reuser of slag or slag products." Mich. Comp Laws. §324.11506(1)(f). Slag is defined to mean "the nonmetallic product resulting from melting or smelting operations for iron or steel." Mich. Compo Laws. §325.11505(8).

- **West Virginia**. "Solid waste" in West Virginia does not include "[m]aterials which are recycled by being used or reused in an additional process to make a product, as effective substitutes for commercial products, or are returned to the original process as substitutes for raw material feedstock." W. Va. Code §33-1-2.119g.

- **Illinois**. Illinois' solid waste disposal regulations do not apply to "the not otherwise prohibited use of iron and steelmaking slags, including the use as a base for road building, but not including use for land reclamation except as allowed under subsection (e)." 35 Ill. Admin. Code §817.101(c). The solid waste disposal regulations also do not apply "to the use or reuse of iron and steelmaking slags…as ingredients in an industrial process to make a product." 35 Ill. Admin. Code §817.101(f). Steel industry wastes that are not exempt from solid waste definitions may be used as a substitute for commercially available materials if they meet maximum allowable leaching concentrations. See 35 Ill. Admin. Code §§817.201, 817.202(a) and 817.106.

III. CONCLUSION

The continued vitality of the market for slag is critical to ArcelorMittal and Stein. Lost sales associated with the large volume of slag currently sold in the state of Ohio annually, coupled with the cost of landfilling this material, could result in a significant economic impact to Ohio's steel industry. In addition, the conceptual program could force the use of additional raw aggregates, the mining of which can have a bigger environmental impact than the use of slag. We urge you to reconsider including the co-products and byproducts generated by the steel industry, particularly slag, within the scope of this rulemaking.

Thank you for the opportunity to comment on the conceptual draft rules. Given the significance of these issues to ArcelorMittal and Stein, we would appreciate meeting with you to discuss this rulemaking initiative in further detail.

Very truly yours,

Karen A. Winters

KAW/jaw

CARMEUSE

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RECEIVED
JUN 21 2013
Ohio EPA - DMWM

June 18, 2013

By overnight delivery

Michelle Braun
Ohio EPA Division of Materials and Waste Management
P.O. Box 1049
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michelle.braun@epa.state.oh.us

Re: Comments on Ohio EPA's BURP Concept Papers

Dear Ms. Braun:

Ohio EPA has asked for comments on its Division of Materials and Waste Management's Beneficial Use Regulatory Program. Carmeuse Lime & Stone (hereinafter, "Carmeuse") provides the following initial comments on Ohio EPA's Regional concept paper.

Carmeuse operates multiple quarries and kiln operations in the state of Ohio which produce high quality lime products and lime byproducts. The byproducts which are legally defined as "lime mining wastes," have considerable value when beneficially used in manufacturing activities, agricultural applications, construction projects, oil and gas industry, environmental remediation, and biosolids treatment. Currently, the bulk of Carmeuse's beneficial use activities are regulated under DMRM's jurisdiction, pursuant to R.C. 1514. Carmeuse also works with third-party brokers which have a long history of using lime mining wastes for various beneficial uses (including construction, oil and gas, agriculture, environmental remediation, and treatment of biosolids) which the new rule program would impact. Consequently, Carmeuse addresses its comments towards those applications which, while not directly operated by Carmeuse, would affect Carmeuse's beneficial use of lime mining wastes.

The proposed program is unworkable and would severely reduce, if not completely eliminate, a large number of currently environmentally sound beneficial uses for lime mining wastes handled by third-party brokers. The Agency's proposal to require incredibly detailed waste characterization's on a repeated basis along with multiple levels of review and authorizations would essentially overburden the beneficial use process to the point that it would be financially unfeasible. Most third-party brokers would simply abandon Ohio as a market. Ohio EPA has proposed far too few exclusions to allow the beneficial use of any material in construction projects regardless of the context. Further, while the concept of a general permit is usually considered a flexible and reasonable approach, the large amount of testing, retesting, certification, and paperwork required by the rules as now written would make any application of a general permit unlikely.

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To have any hope of making these rules useful to the regulated community, Ohio EPA must make two significant changes in its philosophical approach to the program. First, the Agency should develop an exclusion for any beneficial use which is done pursuant to another state or federal agency's specifications and oversight. For example, Ohio's Department of Transportation conducts hundreds of projects every year in the building and maintenance of Ohio's roadways. ODOT has preapproved specifications for the use of a wide variety of building materials both virgin and byproducts, including lime mining waste. If ODOT is overseeing a road project and has a specification for these lime mining wastes in its construction specifications, Ohio EPA should not regulate another government agency's activities in this manner. The fact that ODOT has set a specification for the use of lime mining wastes in its road construction specifications should by itself constitute prior approval and Ohio EPA should recognize this. Otherwise, not only will Ohio EPA significantly harm the regulated community's ability to beneficially use materials, but it will also potentially impact ODOT's ability to conduct construction projects while minimizing costs by beneficially using byproducts. Another example, would be Ohio EPA and the Great Lakes Legacy Act Program (part of the US EPA) use of lime mining wastes on a successful project cleaning up the Ottawa River contaminated sediments in Toledo, Ohio. The use of the lime mining wastes not only satisfied the requirement of the project but also saved the federal government and state of Ohio a significant amount of money.

The second significant change Ohio EPA should consider is recognizing that large volume material byproducts do not need constant testing, retesting, or review. Lime mining wastes are highly consistent. The natural chemical and physical composition of Carmeuse's materials has not changed dramatically over decades. It would be impractical for Carmeuse or its third-party brokers to meet the Agency requirements to submit all existing sampling data (which may go back decades) and, as such, it is unreasonable for the Agency to demand that new sampling be done on any of the frequencies proposed in these rules. Likewise, many of the reviews and certifications laid out in the rule program are equally repetitive and unnecessary and would do nothing to actually increase environmental benefit, but only drive up the burden and cost of beneficial use of the materials.

If Ohio EPA is unwilling to consider the beneficial uses, the development of the program will accomplish nothing but ending most current environmentally sound beneficial use projects in the state of Ohio. The Agency needs to make a fundamental change in its approach to beneficial use or simply drop the rules and continue with the informal system now in place.

Yours truly,

Kevin J. Whyte
Vice President and General Counsel

COLUMBUS CASTINGS

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June 17, 2013

Ms. Michelle Braun
OEPA, DMWM
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RE: Comments on Beneficial Use Conceptual Draft
Issued May 24, 2013

Dear Ms. Braun,

Columbus Castings is pleased to be able to provide comments on the Conceptual Draft regulations for beneficial use of certain materials. Participating in the rule-making process has been very educational and we hope it will result in a fair and balanced regulation.

Overall, Columbus Castings is encouraged by the concept of three levels of permits: Authorization by rule, general and individual. Depending on what the authorization by rule and general permits look like, they have the potential to streamline operations and facilitate the use of these valuable materials. Following are our comments on the draft rules by regulatory section.

599-02: Beneficial use definitions: The term "Select waste" is definitely a problem as many companies will not even consider taking something called "waste" to use in a product. The definition provided in the draft rules say "Select waste means a solid waste…" It is not until you get to the definition of solid waste that select waste is excluded, when properly managed. These definitions need to be simplified for the untrained business person to understand.

I did not hear a good alternative term for Select Waste during the meeting on June 12th, but we would like to offer a definition for the new term: industrial by-products, dredged materials and other, specified soils that have identified properties necessary, or preferred, for beneficial use. Ensuring that the word "waste" is kept out of the term describing these products and associated definitions is paramount to our ability to find uses for our materials.

I also have a question regarding applicability of this rule. We are in the early stages of buying a thermal sand reclamation unit. This unit would take used foundry sand, heat it to drive off most of the binder, and return it to our sand system as "new" sand. Once the sand has gone through all of the stages of this reclamation unit, it has essentially identical properties to new, purchased sand. One of our plans is to sell this processed material to a sand distributor to sell to other foundries or similar companies. I don't believe that this processed sand should fall under this rule at all, because it has been "regenerated" into "new" sand – hence it is no longer a by-

product. I would like to see something added to this rule clearly stating the re-processing any by-product prior to it leaving the site is exempt from this regulation. For the sand that stays on site, we are simply engaging in on-site recycling of our sand, which is already a common practice and not subject to any regulations.

Given the amount of discussion on the phrase "placed on land" and the fact that it does include placing materials in the ground, it may be a good idea to add a definition for "placed on land." This would clarify that land includes any in ground use such as piping, foundations, etc.

599-20: Prohibitions: Paragraph (B) of this section states that select waste may not be placed where it will result in a discharge to waters of the state. We generally agree that nothing should contaminate our waters, however, where does a process like soil blending fit into this prohibition? For example, if used foundry sand is mixed with soil and then sold to homeowners for land application, it is very reasonable to assume that the mixed soil is going to come into contact with storm water and that some amount of the foundry sand could be washed into a water of the state. There is no expectation that the low levels of materials washed away in this example would contribute to degradation of the waterway, however, it would technically be in violation of this regulation. Adding something to paragraph (B) stating that once a select waste has been sent for reuse it is no longer subject to this restriction, could help resolve this potential conflict.

Paragraph (E) of this section also poses some question. Will the Authorization by Rule and General Permit specify how material can be used? If so, and we only send our material for these approved uses, then this rule seems okay. Our concern is that we would need to get pre-approval for each use, otherwise we could think it was proper use and then find out later it wasn't and be penalized for it. As long as the Authorization by Rule and General Permits are either very specific in their approvals, or broad enough to cover many operations and provide protection from this catch-all regulation, we are okay.

599-30: General Requirements: Paragraph (F) of this section is a little confusing, especially without the Authorization by Rule or General Permits available. It requires us to have a waste characterization and analysis plan "unless otherwise specified in the permit." What permit is this referring to? We will certainly do enough testing to understand what is in our foundry sand, but that could be a different level of effort compared to the list of requirements in 599-50. We are trying to do something good with our material, anything that adds a lot of cost makes reuse more difficult.

599-35 Legitimacy Criteria: This rule is also hard to judge without seeing the Authorization by Rule or General Permits. It is very possible for us to keep foundry sand on site for over a year and then have a large project use it over a fairly short period. Once additional permits are available for rule, we may have additional comments on this section.

599-45 Recordkeeping and Reporting: I understand submitting an annual report, but I don't see any value in submitting an additional report 30 days after a permit expires. Many regulations require you to submit a report on your annual due date, even if you quit being subject to the permit months earlier. For example, when I closed a plant a few years ago in June, I still had to

submit the annual air emission report on April 15, the annual Tier II report on March 1, and the biennial hazardous waste report on March 1. A permit ending should not trigger an immediate reporting requirement.

This is especially true if you renew the expiring permit. Then the report due April 1st would still cover the previous calendar year, but you would reference both permits you were operating under. We do this a lot with air permits and water permits, it is not that difficult. Remembering to submit a report in the middle of the year because a permit expired and rolled to the next one, is setting us up for failure.

599-50 Characterization and Analysis Plan: Paragraph (A) of this section states that applicant shall develop a characterization and analysis plan. However, in the June 12 meeting, it was stated that this would only apply to individual permits. The agency planned to develop characterizations for most Authorizations by Rule and General permits. This paragraph needs to reflect that only individual permits would be required to develop their own plan.

I do agree that occasional testing should be done to ensure the waste is not hazardous. That is just good waste management, but how do we demonstrate this during the application process? Can generator knowledge be considered sufficient for all wastes, or will testing be required? Used foundry sand, for example, comes into contact with many of the metals listed as toxic characteristic wastes (D-listed wastes). Without doing testing, how do we demonstrate to the agency that the sand will pass the TCLP test? Past data certainly indicates that there is very little metal in the sand, is that enough for a general permit and not require us to submit annual sampling proving we pass the TCLP test? This type of testing could get very expensive and discourage beneficial reuse.

Putting together the information and testing required in Paragraphs (D)(6-8) is a substantial amount of work. Given the different areas where we generate sand, it would be far easier and cheaper for us to landfill the sand than go through this much work. If all of this only applies to very unique materials that have to get an individual permit, you may be able to justify this, but for common materials, this is extremely excessive.

599-55 Annual Sampling: As stated above, annual sampling seems somewhat excessive for something as routine as foundry sand (and other by-products). Depending on how the general permit reads, this may be fine.

599-210 Notice of Intent for General Permit: Paragraph (A)(1)(d) states that we must provide information for every intended distributor of the select waste. This makes it unnecessarily complicated for something like soil blending or road construction using foundry sand. We are always looking for more companies to take our used sand and having to modify our NOI application, 60 days in advance, seems excessive. These are common, approved uses of sand and should not need that much work.

Additionally, it is going to be very difficult to get construction companies to obtain a special permit to use our foundry sand in their road base instead of buying “new” sand that doesn’t

require a permit. Requiring them to obtain a special waste permit essentially eliminates that outlet as an option for beneficial use.

The general permit may address some of these issues, but if the base regulation states that all NOI applications must contain this data "at a minimum" (Paragraph (A)(1)) then the general permit can't require different information. Rule 210 may need to be simplified to state that all information on the NOI must be completed. That way the agency has the flexibility to determine what information they really need for each general permit.

599-220 Coverage under General Permit: Paragraph (A)(2) states that we may not start operating under the conditions of the general permit until approval is granted by the agency. Under general permits for air and water, coverage is immediate upon submittal of the NOI. Why is that not the case for these permits? How long will it take for the agency to issue the new permits? The whole point of these simplified, general permits was that they would take affect right away.

Under the other programs, the general permit lists the requirements the applicant must be, any applicable limits, and record keeping and reporting requirements. The general permits for beneficial use will probably have these items also, so it is the generators responsibility to ensure that our materials meet the specifications listed in the permit and to comply with all of the other requirements. The burden of proof of compliance is on the generator, as it always is. We should not have to wait months for the agency to review and approve these basic permits.

599-300 Individual Permit: Paragraphs (C)(2) and (3) are a little confusing as written. It is common for permits to continue as long as a timely and complete renewal application has been submitted. Instead of separating this one idea, these two statements could be combined to read: "Permittees shall cease beneficial use of a select waste when the permit expires, unless a renewal application has been submitted in accordance with 3745-599-340 of the Administrative Code."

Thank you very much for the opportunity to participate in the rule making process and to provide comments on the conceptual draft. If you have any questions regarding my comments, please contact me at 614-445-2059 or via e-mail at LDenison@columbuscastings.com.

Sincerely,

Linda J. Denison, CHMM
Environmental Manager

June 21, 2013

VIA E-MAIL (Michelle.Braun@epa.ohio.gov
& REGULAR U.S. MAIL

Ms. Michelle Braun
Ohio EPA
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Columbus, OH 43216-1049

Re: Comments to Ohio EPA's *Conceptual Draft Rule Language for Beneficial Use*

Dear Ms. Braun:

Emerald Environmental, Inc. ("Emerald") respectfully submits the following comments to Ohio EPA's *Conceptual Draft Rule Language for Beneficial Uses* (the "Draft Beneficial Use Rules"). As you may recall, on July 31, 2012 Emerald submitted written comments to Ohio EPA's *Beneficial Use Rules Development Concepts*. A copy of Emerald's July 31, 2012 letter is enclosed for your convenience and is incorporated herein by reference.

Emerald commends Ohio EPA for its continued efforts to develop a beneficial use regulatory program, and Emerald appreciates the opportunity to provide its comments to the Draft Beneficial Use Rules. As explained in Emerald's July 31, 2012 letter, Emerald has considerable expertise and experience in dealing with the beneficial use of conditioned alum residuals. Emerald recognizes that there are legitimate concerns with the beneficial use of unconditioned alum residuals. Specifically, unconditioned alum residuals contain raw water turbidity, unreacted alum coagulants and/or alum polymer coagulants, and reactive hydroxide compounds, which interfere with the beneficial use of the unconditioned material. However, conditioned alum residuals can be beneficially used in a manner that eliminates these concerns. Emerald has previously provided Ohio EPA with relevant documentation regarding conditioned alum residuals, including but not limited to studies and data demonstrating the beneficial uses for this material.

While Emerald supports Ohio EPA's development of a beneficial use regulatory program, Emerald recommends the following revisions to the Draft Beneficial Use Rules:

1. The definition of "Beneficial use" as set forth in O.A.C. 3745-599-02(B)(1) could be interpreted in a manner that would prohibit the beneficial use of materials such as conditioned alum residuals as a soil amendment or for agronomic benefit. Therefore, to avoid any such misinterpretation, it is recommended that the definition be revised as follows:

   > "Beneficial use" means the legitimate use of a select waste as an ingredient or product or in a manner that contributes to a manufacturing process or product *or is an agricultural additive or provides an agronomic benefit,* that does not constitute disposal or cause pollution of any waters of the state.

   In addition, the following definition should be added to the rules:

   > "*Agronomic benefit" has the same meaning as in section 6111.01 of the Revised Code.*

2. The definitions of "beneficial use" and "disposal" set forth in O.A.C. 3745-599-02 each refer to the other term and could result in a circular interpretation. To avoid such a result, the following sentence should be added to the end of the definition of the term "disposal":

   Disposal does not include the placement of a select waste onto the ground that is an agricultural additive or has an agronomic benefit.

3. O.A.C. 3745-599-05 of the Draft Beneficial Use Rules provides a number of general exclusions. Paragraph (M) of that draft rule provides an exclusion for the following:

   > Sewage, sewage sludge, and sewage sludge materials including a select waste commingled with sewage, sewage sludge, and sewage sludge materials regulated pursuant to Chapter 6111. of the Revised Code and rules adopted thereunder.

As written, it appears that if an entity desired to comingle a select waste with sewage, sewage sludge or a sewage sludge material and beneficially use the commingled material, authorization would be needed under the sewage sludge regulations adopted under R.C. Chapter 6111, opposed to the beneficial use program. It would be appreciated if Ohio EPA would confirm that this is the intent of this this exclusion, and that there is a mechanism under the sewage sludge regulatory program to obtain such an approval. If this is not the case, then the exclusion should be revised to allow an entity to request such an authorization under the beneficial use program.

In addition to the above, paragraph (M) should be revised to avoid confusion that could arise over the interpretation of the terms used in that paragraph. The terms "sewage" and "sewage sludge" are defined terms under R.C. Chapter 6111. While the term "sludge material" is also defined term in R.C. Chapter 6111, the term "sewage sludge material" is not a defined in R.C. Chapter 6111 or in O.A.C. Chapter 3745-40. Importantly, the term "sewage sludge", as defined in R.C. §6111.01(U) (which incorporates the definition in R.C. §3745(Y)) expressly does not include certain materials, such as ash generated during the firing of sewage sludge. To avoid the confusion that could result from the use of the term "sewage sludge materials", Emerald recommends that the phrase "excluding those materials that are excluded from the definition of sewage sludge in R.C. 3745.11(Y)," be inserted after the term "sewage sludge materials" in the first line of paragraph (M).

4. The expiration provision set forth in O.A.C. 3745-599-300(C)(2) is in direct conflict with the statutory requirements set forth in R.C. §119.06. Specifically, R.C. §119.06 provides, as follows:

> When periodic registration of licenses or renewal of licenses is required by law, a licensee who has filed an application for registration or renewal within the time and in the manner provided by statute or rule of the agency shall not be required to discontinue a licensed business or profession merely because of the failure of the agency to act on the licensee's application.

To comply with the statutory mandate in R.C. §119.06, it is recommended that Ohio EPA add the following phrase at the end of O.A.C. 3745-599-300(C)(2): "unless a permittee has timely filed a renewal application in accordance with O.A.C. 3745-599-340."

5. While there is a definition of the term "permittee", the rules do not adequately describe the type of entity that is responsible for obtaining coverage under an individual or general permit. To avoid any confusion, it is recommended that Ohio EPA insert the following requirement in O.A.C. 3745-599-300:

> Except as otherwise provided for in this chapter, the person that intends to beneficially use a select waste and the person that intends to market a select waste for beneficial use shall be responsible for obtaining coverage under a general or individual beneficial use permit prior to engaging in the beneficial use or marketing of the select waste.

Thank you for your consideration of the foregoing comments. To the extent that you have any questions or need any further information, please do not hesitate to contact me directly.

Sincerely,

Scott Hershberger

Enclosure

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HULL

June 20, 2013

Ms. Michelle Braun
Rules Coordinator
Ohio EPA
P.O. Box 1049
Columbus, Ohio 43216-1049

RE: Stakeholder Input on Beneficial Use Draft Conceptual Rule Language; 3000.100.1633

Dear Ms. Braun:

Hull & Associates, Inc. (Hull) is an engineering and science firm with four offices in Ohio (Cincinnati, Cleveland, Columbus, and Toledo [and soon an additional location in St. Clairesville]), one office in Pittsburgh, Pennsylvania, and one office in Indianapolis, Indiana. We have assisted public and private industry clients with the implementation of safe and responsible waste management programs for over 30 years. Consequently, we are very familiar with the evolution of state and federal environmental regulations that have led to our work with clients in more than 10 states at over 150 waste management facilities that include landfills, transfer stations, composting operations, and material management and recycling facilities. Hull has been involved in the beneficial use rule development since the inception of modern waste and material management regulations, and we advocate for any and all rules to be based upon sound engineering, science and economic principles.

We are generally pleased with the progress being made by Ohio EPA and stakeholders regarding conceptual language for developing proposed beneficial use rules, but much work remains. Hull believes that the implementation of a new set of beneficial use rules is past-due and advancing them should be considered "urgent." A significant volume of materials (e.g., by-products, excluded wastes, and relatively inert waste like drill cuttings and other wastes from shale oil and gas exploration and production) are being managed within landfills that could be suitable for beneficial use applications. This is counter to Ohio's recycling and conservation goals, and costs industry significant resources to manage under the current regulatory programs. Therefore, we suggest that Ohio EPA and stakeholders work at a more aggressive pace and possibly develop work groups to resolve significant issues in a timely manner. If this cannot be achieved, some of the major issues identified herein could be addressed in the ongoing House Bill 592 review of solid waste rules, specifically within the definitions section.

Paramount in the conceptual beneficial use rule language is the clarification of "unwanted material" in the definition of a solid waste. Hull strongly supports this approach, which should break the *waste is a waste is always a waste convention* in Ohio, and allow a waste to be recognized as a material or product if it possess desirable characteristics. Hull believes this development is laudable and addresses our recycling and conservation goals, while supporting the three core concepts of sustainability (e.g., environmental, social and economic).

Equally important to the clarification of the solid waste definition is establishing a term that encompasses multiple types of waste AND materials. We respect the fact that Ohio EPA presented the term "select waste" to broaden the scope of waste and materials that are eligible for inclusion in the beneficial use program, although we suggest assigning a different term that does not use the term "waste." Our first reason is that some of the materials currently eligible

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for the beneficial use are excluded waste (some people use the term exempted) and the inclusion of these materials under the definition of a select waste leads to confusion. Secondly, the promotion of the beneficial use of waste and materials may be impeded by the perception of the term "waste" – if a by-product, material or waste meets the specified characteristics for an end use or product, and it meets criteria established by Ohio EPA for protection of human health, safety and the environment, then it should not be stigmatized with the "waste" label. A term suggested during the stakeholder meeting was "by-product material," which may be acceptable or an alternate may be proposed. Hull uses the term "by-product material" throughout our comments in lieu of the "select waste" term.

Other specific issues that Hull suggests for consideration are presented below:

1. Applicability

   Clarification needs to be provided on what waste and/or materials are included in the proposed beneficial use rules. Ohio EPA addressed this issue during our recent stakeholder meeting, and presented a diagram that included the following: 3734 excluded, liquid waste, soils/earthen material, preapproved vs. excluded, etc. This implies that Ohio EPA is working to expand the waste and/or materials to which the proposed beneficial use rules would be applicable - we recommend changes to the applicability section of the proposed rule to provide clarification.

2. Definitions

   The definitions section of the proposed rules will need to be inclusive of all terms and concepts to which they apply. For example, the words fill, flowable fill, and structural fill are not included in the definitions, but clarification for these terms may prove to be important to the final rule in that some (if not many) of the end uses for the waste or materials may fall under these end uses. While it is not possible to define all terms at this time, we note that careful attention will be needed in the designation of definitions in the final rule package.

   Additionally, an understanding of the consistency and compatibility of definitions as they relate between Ohio EPA's 6111, 3745 and other relevant programs need to be established. An example is "industrial waste," which is defined differently in Ohio EPA's 6111 and 3745 regulations. We recommend that Ohio EPA and stakeholders identify definitions of interest for further discussion.

   Further, Ohio EPA and stakeholders should revisit definitions that need to be included (or excluded) after some of the more significant issues in the proposed rules are established. For example, the definition of groundwater may need to be revisited after proposed rule language is reviewed regarding the concept of "risk" relative to waste and/or material characterization, compliance limits and end uses. The current definition for groundwater is consistent with the definition in Ohio EPA's 6111 and 3745 rules. However, the definition and categorization of groundwater in Ohio EPA's Voluntary Action Program may need to be

considered as it incorporates risk-based decision making criteria and is more specific.

3. General exclusions

We understand and appreciate the need to address exclusions in the proposed beneficial use rules, and understand that many of the waste and/or materials that are listed in the exclusions are included because Ohio EPA does not want to duplicate approaches that are clearly defined in existing regulations. There are two items listed that relate to the shale oil and gas exploration and production industry that require clarification. The inclusion of radioactive waste and waste from oil and gas exploration operations requires the need for further evaluation and clarification.

4. Exclusion of by-product material in certain construction materials

We understand that Ohio EPA is in the process of identifying certain by-product materials that may be authorized for beneficial use in construction materials. Many of these by-product materials have been widely used in construction materials such as roadways and building materials. A wealth of characterization data are available and the by-product materials have proven to work well within the specified end uses without causing impacts to human health, safety and the environment. Hull strongly supports the use of these by-product materials in beneficial use applications. With this said, we believe that the list of excluded by-product materials needs to be expanded and it would be useful for Ohio EPA to facilitate an open discussion with stakeholders regarding characterization, compliance limits and other issues that need to be vetted as we move forward.

Additionally, we believe that it will be difficult at this time to identify all materials that should be listed within the exclusion of by-product materials for incorporation into construction materials. Technological advances and new materials will arise, and the proposed rules should allow some degree of flexibility for inclusion of by-product materials that can be demonstrated to meet specifications of a proposed end use.

5. Exclusion of earthen and contaminated soil

We support the exclusion of earthen and contaminated soil in the proposed rules, and believe that the concept of unified standards should apply (as appropriate) across the spectrum of media, waste, materials, other by-products, etc. We understand that the agency is interested in finding beneficial uses for contaminated earth including dredging sediments, possibly drill cuttings from shale oil and gas exploration and production, and other contaminated soils in remediation and economic development projects. While no specific language

was proposed on earthen and contaminated soil (or flowable fill), we look forward to an open discussion on this issue with Ohio EPA and other stakeholders.

6. Prohibitions

We understand that some prohibitions may be necessary, but such prohibitions should not be overreaching or biased against the use of products or materials that are approved for use under the proposed beneficial use rules. As a rule, a product or material developed using raw materials, or waste or materials under the beneficial use program, should be regulated the same way independent of the origin of the raw material source. Subjecting by-product materials that have been approved for use under the beneficial use program to additional prohibitions is unfair, and would be counterproductive to meeting recycling and conservation goals.

7. General Requirements

We agree that general requirements will need to be developed to apply to by-product materials in beneficial use applications. We support the multi-tier approach that provides for the issuance of either a general or individual permit. We are not clear on what Best Management Practice (BMP) guidance will be applied or incorporated by reference into the proposed rules, and applying BMPs to a material containing a by-product material approved under the proposed beneficial use rules may be overreaching. The same concern applies to providing notification and necessary information as is also referenced in the proposed beneficial use rules.

Another issue is the requirement for a waste characterization and analysis plan. If an acceptable amount of data is already available, then a characterization and analysis plan should not be required. If data is not available, Ohio EPA and stakeholders will need to work together to establish expectations on what exactly needs to be included in the plan, including sample frequencies, parameter lists, test methods, number of samples, data evaluation requirements, and other criteria – this could likely take a significant amount of time and effort that may require the formation of working groups to establish approaches for characterization and sampling requirements for specific by-product materials and end uses.

A final issue with the proposed rule on general requirements is the self-reporting requirement for non-compliance within twenty-four hours after discovering non-compliance with the characterization and analysis plan, or the general or individual permit. The inclusion of this requirement is confusing as it relates to a characterization and sampling plan. Also, the twenty-four hour requirement for reporting if non-compliance is discovered is arbitrary and needs justified. Again, if a by-product material is approved for use under a beneficial use permit, then it

should be considered as a product or a material and not subjected to additional reporting criteria.

8. Legitimacy criteria

A clear definition of legitimacy criteria is required to assure compliance with applicable rules and regulatory authority. A requirement in the proposed rule is to ensure that the material is managed and stored as a valuable commodity. A definition of valuable commodity will need to be included in the proposed rules. The issue of speculative accumulation will require further discussion, as the proposed rule includes an arbitrary criterion that requires the use of 75% by weight or volume of the material within the calendar year. This is a very rigid standard. The proposed rule provides flexibility in that the permit can include an alternate schedule for use. Further discussion on the issue is warranted.

9. Notice and information for distribution

The proposed language regarding the notice and information requirements is not warranted in most cases. As stated earlier, if the by-product material is approved for use by Ohio EPA, it should be treated as a product and no further notice or information should be required – it should be treated just like any other product on the market. We appreciate that there may be special cases or exceptions to the rule, so if Ohio EPA does require that notice and information be distributed, then this should be a special condition agreed upon by the parties in the permit. This is also the case for recordkeeping and reporting.

10. Waste characterization and analysis plan

The requirement for a waste characterization and sampling plan should be further discussed with Ohio EPA and stakeholders. We understand that some by-product materials have been used extensively over many decades and significant characterization data are already available – for these materials, we do not believe waste characterization and analysis plans should be required. For other materials, we understand that the plans may be required. The issue with this is not whether a plan is required or not, but what is in the plan. Significant time must be set aside for a work group of Ohio EPA and stakeholders to work through the required contents in the plan. Information regarding numbers of representative samples, lab methods (and data validation), parameter lists, data analysis requirements, frequencies, etc. must be discussed. Questions that need to be answered include: 1) does the by-product material need to be characterized before and/or after it is incorporated into an end use, 2) how will data from the characterization be used in technical demonstrations and risk evaluations to support end uses both for encapsulated or non-encapsulated applications, 3) how will compliance limits be established for various end uses, and 4) will the proposed rules include or incorporate by reference a risk-based approach to establishing compliance limits? If so, what will the risk goal be?

There are many questions to be addressed, so the development of an understanding between Ohio EPA and stakeholders on this subject should be established as soon as possible.

11. Pre-approved beneficial use

No proposed pre-approved beneficial uses were included in the proposed rules, but Hull supports the concept. Ohio EPA will need to work with stakeholders to establish an inclusive list of pre-approved uses, and this should also allow for the addition of new by-product materials over time and as emerging technologies and data become available.

12. General permit and notice of intent for general permit

We support the development of a general permit program, and that the categories should be inclusive of the many types of by-product materials currently available on the market. Additional categories should have the ability to be added over time, or special requests for Ohio EPA's consideration for inclusion in the general permit program. Our earlier comments on recordkeeping and reporting also apply to this subject.

We support the Notice of Intent (NOI) concept. Concerning the proposed requirement that the applicant list each location of the beneficial use project, we do not support this requirement. Again, if by-product material meets compliance criteria established for beneficial use by Ohio EPA, then the material should be treated as a product. We understand that if the material does not meet specific criteria, then the applicant may be required to demonstrate how the material will be used (and stabilized/treated/etc. or incorporated into a project) if it meets risk-based end use criteria and the applicant provides appropriate notification, recordkeeping and reporting, including end use locations.

The proposed rules include general permit coverage limitations, which we do not agree with, such as use in a drinking water source protection area, setbacks from potable drinking water wells or livestock, etc. Again, if the by-product material is approved for use by Ohio EPA, it should be treated as a product and no further notice or information should be required – it should be treated just like any other product on the market.

Hull appreciates that Ohio EPA has committed to releasing examples of general permits for specific by-product materials. Examples mentioned during stakeholder meetings have included, but are not limited to, lime sludge and spent foundry sand. We anticipate that stakeholders who produce large volumes of relatively inert by-product material that exhibit physical and/or chemical characteristics suitable for inclusion in products and/or end use applications will work directly with Ohio EPA to advocate for inclusion in the general permit program.

13. Individual permit application, issuance, changes, and renewal

We understand the purpose of the individual permit program and support having a category for materials that do not fall within the pre-approved or general permit categories. Similar to previous comments, specific issues will need to be resolved regarding BMPs; end use; characterization and analysis plan; restrictions and setbacks; and denial, suspension and revocation criteria. Ohio EPA and stakeholders should establish work groups to identify and resolve these overriding issues.

Additionally, we support Ohio EPA's comment in earlier stakeholder meetings that by-product materials that are managed under individual permits may petition for inclusion in the general permit program over time and as additional data on the physical and chemical characteristics of the by-product material becomes available.

14. Liability

Ohio EPA should be clear in the proposed rules where and with whom management liability starts and ends, and whether this is with the generator, distributor, or end user, which could all be separate entities. The conceptual language indicates a notice of information for distribution, but is not clear on management responsibilities thereafter.

The above comments are the more significant points that Hull feels require further consideration. We will be contacting you to schedule a time to meet directly to discuss additional thoughts and details of the beneficial use conceptual language included in the proposed rules. Thank you for dedicating significant time and energy to this effort. We look forward to continuing to work with you on this most important issue.

Sincerely,

William G. Petruzzi, P.G.
Principal

WGP/jab

ct: John H. Hull, P.E., BCEE
Craig A. Kasper, P.E.

There needs to be an enforcement mechanism.

I have read the rules and at first sight they seem reasonable. But there should be an enforcement mechanism which makes non-compliance significantly more costly than non- compliance. Only such an enforcement mechanism will deter individuals and companies from taking the risk of non-compliance.

Johannes Kicken

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June 21, 2013

Michelle Braun
Ohio Environmental Protection Agency
Division of Solid and Infectious Waste Management
P.O. Box 1049
Columbus, Ohio 43216 – 5373

RE: Interested Party Review
Beneficial Use Rules Development Concepts
http://epa.ohio.gov/portals/34/document/draftrule/Gray_May%202013%20Updated%20ESO%20BU%20Rules%20Outline.pdf
Beneficial Use Conceptual Draft Rule Proposal
http://www.epa.ohio.gov/portals/34/document/draftrule/599_draft_5.24.13.pdf
Dated: May 24, 2013

Dear Ms. Braun,

Listed below are interested party comments submitted on behalf of the Mahoning County District Board of Health concerning the Beneficial Use Conceptual Draft dated May 24, 2013. The opportunity to comment is appreciated. Please consider the comments and/or recommendations:

GENERAL COMMENTS RULE DEVELOPMENT CONCEPTS

The development concepts use the term "select waste to replace industrial byproduct." Although it is meant to be more inclusive, please incorporate references and language that encompasses industrial solid waste and residual solid waste as defined in Ohio Administrative Code (OAC) 3745-29 and 30 respectively.

Under the basis of the beneficial rules, beneficial use should be further expanded to include materials that can used beneficial as stand-alone fill material and may not be an ingredient or part of a manufacturing process. Please note that several of these items are included in the proposed 2006 Beneficial use rule package and it is not apparent why they were removed.

GENERAL COMMENTS DRAFT RULE PROPOSAL

Please note this rule package fails to stipulate or further define the numerical standards that will be or should be used in evaluating any beneficial use requests, especially for non-toxic fly ash and foundry and/or waste characterizations. The Division of Surface Water guidance document was rescinded for illegal rule-making but the Division of Material and Waste Management continue to utilize those standards for waste characterizations to define 'non-toxic fly ash and foundry'. Please clarify what constitutes a 'non-toxic' material as used in Ohio Revised Code (ORC) 3734 and/or 6111. For consistency, specify the standards used to characterize and evaluate other select wastes as stated in Section 3745-599-50 and 200.

ORC 3734.125 Solid and Hazardous Wastes (as proposed in House Bill 59)
House Bill 59 proposes new language which requires rule making for beneficial use of gas and oil well industry wastes. See lines 55924 – 55929 which creates a new rule section that allows OEPA to develop rules for the beneficial use of material from a horizontal well that has come in contact with a refined oil-based substance but is not considered technically enhanced radioactive material (TENORM). Please incorporate these requirements into the draft rule package.

Since these rules are incorporating both 3734 and 6111, please clarify which division is responsible for implementation of these rules. However, please be aware that the approved local health department does not and should not have any responsibility for review, approval, or oversight of these rules because the material is no longer a solid waste.

OAC 3745-599-02 Definitions

Section (B)(1) defines beneficial use.
The proposed definition only allows beneficial use if the "select waste is an ingredient or product or in a manner that contributes to a manufacturing process or product...". Please clarify whether fly ash and foundry sand that are not exempt in the definition solid waste as 'non-toxic' are allowed to be beneficially used as fill materials, for example as base for foundations and driveways.

Section (I) defines industrial waste.
Please reference industrial solid waste (a type of solid waste) as defined in Ohio Revised Code (ORC) 3734 and Ohio Administrative Code (OAC) 3745-29-01. Please note the beneficial use rules should address 'non-toxic' fly ash and foundry sand.

Section (O)(4) Other Waste.
Please include language referencing other waste as defined in 3734 of the Ohio Revised Code (reference comments for industrial and residual solid wastes).

Section (R) does not define residual waste.
Please incorporate reference to residual waste (a type of solid waste) as defined in ORC 3734 and OAC 3745-30-01. Please note that the beneficial use rules should address placement and use of lime sludge.

OAC 3745-599-15 Beneficial use-exclusion for earth and contaminated soil

It is noted that this section is reserved. Please note the Agency is remiss in not addressing this issue now. Both the regulated community and local health departments have expressed concerns over the management of soils, especially: 1) petroleum contaminated soils and 2) soils potentially contaminated from approved gas & oil (brine) applications.

OAC 3745-599-35 Beneficial use – legitimacy criteria

Section (C)(2) appears to allow speculative accumulation if a generator or operator believes, "the select waste has a feasible means of being beneficially used...". Speculative accumulation can lead to open dumping. What timeframe will be used to determine storage for a feasible purpose?

OAC 3745-599-50 Select waste characterizations and analysis plan.
As previously stated, it is unclear what numerical values or industry standards will be used or are considered "appropriate" for waste characterizations or when evaluating and issuing beneficial use applications.

Section (B) allows for characterization through generator knowledge. This leads to inconsistency for similar waste streams. Require sampling and waste characterization. For consistency purpose, define the numerical standards.

OAC 3745-599-200 Beneficial use – general permit.

Section (B) indicates that "the director may issue a general use general permit without application." It is unclear as to how the rest of section 200 is implemented if there is no application?

OAC 3745-599-210 Notice of Intent to obtain coverage under a beneficial use general permit

Section (A)(2) references OAC 3745-599-400. There is no section 400 proposed. Please clarify the reference.

SUMMARY

In conclusion, there are item in the 2006 draft rule package that could be reincorporated into the 2013 proposals, such as:

- OAC 3745-525-805 Initial characterizations
- OAC 3745-525-806 Beneficial use – pollutant limits for the pre-approval uses of industrial byproducts
- OAC 3745-525-807 Beneficial use – pre-approved uses of industrial byproducts

Should you have any questions, concerns or desire clarification of any comment listed above, please feel free to contact me the letterhead address, by phone at (330) 270 – 2855 ext. 134, or by email at mhsmith@mahoninghealth.org .

Respectfully,

Mary Helen Smith, MPH, RS, REHS
Director of Environmental Health

David Fetchko, RS
Solid & Infectious Waste Program

cc: Solid Waste Beneficial Rule Package File

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June 21, 2013

Ms. Michelle Braun
Rules Coordinator
Ohio EPA
P. O. Box 1049
Columbus, OH 43216-1049

Dear Ms. Braun:

On behalf of the officers, trustees, and members of the Ohio Cast Metals Association (OCMA), I am submitting the attached comments regarding the Updated Conceptual Draft for a Beneficial Use Regulatory Program published on May 24, 2013.

OCMA was proud to help Ohio EPA develop Ohio EPA Policy 400.007 back in 1994 when the policy was considered groundbreaking in its approach to the issue. Significantly, since the development of those rules, research concerning the environmental viability of foundry sand has taken place that has overwhelmingly concluded that most foundry sands are actually cleaner than native soil. Unfortunately, despite these developments, the Ohio EPA has not chosen to expand the opportunities for beneficial use of these byproducts. We are hopeful that this process will rectify that situation.

Specifically, Ohio EPA needs to make significant changes in the Conceptual Draft to reduce the time and expense for those companies seeking to beneficially reuse their environmentally friendly byproducts. As written, the proposed rules are much too complex, burdensome, and costly. If the Agency is serious about promoting beneficial reuse of industrial byproducts it would do well to seriously consider the attached OCMA comments.

The OCMA represents the interests of more than 150 metal casting companies in Ohio, the number one metal casting state in the nation. Sadly, this number is approximately half of what it was in 1994. Although we do have several large corporate members such as GM Powertrain-Defiance, Columbus Castings, and Honda of America Mfg., Inc., they are the exceptions. Most of our members are small or medium-sized businesses, often family-owned with less than 100 employees.

We appreciate the opportunity to provide comments on the Updated Conceptual Draft for a Beneficial Use Regulatory Program Development Document. If we can provide any additional information about these comments, please do not hesitate to call or email. We look forward to continuing to work with you on this important issue.

Sincerely,

Russ Murray
Executive Director

Cc: OCMA Environmental Affairs Committee
John Kurtz, OCMA Secretary

The Ohio Cast Metals Association (OCMA) Comments Regarding

the May 24, 2013 Conceptual Draft of a

Beneficial Use Regulatory Program

General Comment

Recently the Ohio Cast Metals Association (OCMA) has been working with the Ohio EPA to help develop new regulations governing the beneficial use of byproducts in the state of Ohio. While we recognize the fact that regulations are a necessary tool that regulatory agencies use for administration of a given regulatory program, we are concerned that these regulations are too focused on the "command and control" of the beneficial use program in Ohio. They appear to be aimed at preventing the inappropriate use of byproducts, as opposed to encouraging the wise reuse of byproducts so as to conserve our energy resources and help sustain our valuable natural resources in the State of Ohio. The comments that follow although specific to individual paragraphs of the conceptual draft of the regulation have been offered in an effort to strike a better balance.

OCMA also commented at the stakeholders meeting held on Wednesday, June 12, 2013, that it was difficult to provide meaningful comments on the conceptual draft rules because we were not told which byproducts would be covered under a General Permit, nor were we given a conceptual draft of a General Permit so that we could have the proper context for reviewing the presented language and for making informed comments. It is our assumption that most, if not all of the byproducts generated by the foundry industry would be covered under one or more general permits. Ohio EPA has access to a significant amount of existing file information about these materials and it has access to published literature and research on foundry byproducts. OCMA reserves its right to make additional comments on these conceptual draft rules once we are given General Permit language that is specific to foundry byproduct(s).

3745-599-03 - The Use of the Term "Select Waste"

The Conceptual Draft substitutes the term "select waste" for "industrial byproduct". Ohio EPA has suggested that select waste is a broader term and the beneficial use program will regulate materials that are not necessarily from industrial processes. This change is a terrible idea! A major goal of all individuals and organizations attempting to broaden the acceptance of the beneficial reuse of byproducts whether they be from industrial processes or other processes has been to remove the connotation that these materials are "wastes". The use of the term "waste", in and of itself, presents an unnecessary barrier to beneficial reuse that foundries must overcome in their attempts to find environmentally sound and economically viable beneficial reuse opportunities. The OCMA strongly urges Ohio EPA to change all references of "select waste" to a more favorable term such as "recyclable byproduct", "beneficial material", or "recyclable material". It has been the experience of many of our members that potential beneficial reuse customers of our materials are somewhat hesitant because

previous OEPA Policy 400.007 referred to these materials as "waste". This reference leads to concerns on the part of these potential customers that the material, though non-toxic, may be regulated under the various environmental rules, including those dealing with proper handling and disposal of solid waste and hazardous waste (RCRA) and may give the impression of potential Superfund liability.

3745-599-10 The exclusion of flowable fill from list of construction materials

Under this rule, Ohio EPA has proposed to eliminate industrial byproducts that may be used as ingredients in certain construction products and are placed on the land. This decision is acceptable to OCMA however; the omission of flowable fill from the proposed list is unacceptable. Foundry sand has been used in flowable fill for more than twenty years. In that time, no instances of environmental harm have been brought to our attention. In fact academic studies have recommended the use of foundry sand in flowable fill because of its inert nature and under certain circumstances the foundry sand is actually superior in its engineering characteristics to the alternative general fill that would be used by contractors. Included in these comments is an attachment of a study performed at Penn State University under a U.S. Department of Energy grant. This study, "Excess Foundry Sand Characterization and Experimental Investigation in Controlled Low-Strength Material and Hot-Mixing Asphalt", concluded that foundry sand was both environmentally benign and acceptable as a key ingredient in flowable fill. Flowable fill using foundry sand should be included in the list of excluded construction materials in the beneficial reuse proposal.

3745-599-30 General Requirements

This entire rule should be eliminated. Why is it necessary to include language clarifying that beneficial uses of a select waste comply with applicable laws? Is there really any question that use of these materials must comply with applicable laws? Why would the Agency find it necessary to create additional language outlining the obvious?

Paragraph (C) suggests that the director has the authority to compel a company with a general permit to obtain an individual permit. We cannot surmise any circumstances where this authority would be necessary and this paragraph should be eliminated.

Paragraphs (D) & (E) require that any person using a select waste shall ensure that the beneficial use…conforms to applicable engineering standards and agronomic practices … best management practices. In what other arena in the marketplace, is the provider of a product responsible for how the product is used by the person or company purchasing the product? As stated numerous times in these comments, if the Agency is truly interested in increasing the opportunities for beneficial use of industrial byproducts it must provide minimal direction to producers and users of the industrial byproduct once that byproduct has been proven to meet environmental standards of acceptability. For example, spent foundry sand has been found through numerous studies to be as clean as or cleaner than native soils. It makes little sense to place numerous barriers to the beneficial use of spent foundry sand once the sampling process has demonstrated that the spent foundry sand meets the environmental standards set forth. We believe that the language in this paragraph is a good example of the lack of "balance" presented in these rules.

Very few foundries in Ohio employ more than 100 employees. It is highly unusual for an operating foundry to have an individual on staff whose responsibilities are solely environmental. In many cases that same individual will be responsible for HR activities, workers compensation, and often safety and industrial hygiene as well. To expect that an individual in this situation would know, or have the time to learn, the best management practices, accepted engineering standards, or agronomic practices is unreasonable. It is highly likely that the users of the spent, foundry sand will be the experts in accepted engineering standards and/or agronomic practices. The Agency should be less concerned about these matters and more concerned about setting environmental standards that are sensible and practical.

While we are not going to identify all typographical errors in a conceptual draft, the word "application" should be changed to "applicant" in paragraph (F).

Paragraph (G) requires notification within twenty-four hours after discovering non-compliance. This is an inappropriate period of time and should the requirement remain it should be changed to two business days.

The remainder of this paragraph appears to be just the reiteration of other paragraphs of the proposed conceptual draft and therefore, is unnecessary and should be removed.

3745-599-35 Beneficial use – legitimacy criteria

In paragraph (B) the terms "valuable commodity" and "adequately contained" are undefined and ambiguous, therefore the phrase "as a valuable commodity and is adequately contained" should be removed from the sentence.

Paragraph (C) (3) contains a requirement that a generator must beneficially use or transfer to a different site "at least seventy-five per cent by weight or volume of the amount of select waste accumulated at the beginning of the calendar year". Under certain circumstances foundry sand can be used for construction projects that call for large volumes of foundry sand. It may be that storing of the foundry sand for these projects may entail holding the foundry sand for more than one year to prepare for use in the construction project. This proposed language may preclude the use of large volumes of foundry sand for no apparent reason and it should be removed.

<u>3745-599-40 Beneficial use – notice and information for distribution</u>

This rule outlines the responsibilities of the beneficial reuse permittee to provide information to the recipient of the recycled byproduct. There is no reasonable explanation for the mandate that the recipient receive all of the stipulated information. This transaction should not be subject to any more or less information sharing than any other transaction taking place in our economy every day. Once the recycled byproduct meets the beneficial use criteria then by definition the recycled byproduct cannot be harmful to human health or the environment. What is the reason for mandating that the generator of the recycled byproduct take the time and expense of providing an excessive amount of information to the recipient of the byproduct? If the recipient of the byproduct is interested in obtaining this

information, he/she may request it from the generator. There is no reason why Ohio EPA should be mandating this transfer of information.

3745-500-45 Beneficial use – record keeping and reporting

This rule calls for the generator of the recyclable byproduct to submit an annual report to the Ohio EPA. The report would contain an excessive amount of information that is likely to collect dust somewhere in the bowels of state government. The information mandated has already been supplied to Ohio EPA with the submittal of the general or individual permit. Why would Ohio EPA wish to burden generators of the recyclable byproduct unnecessarily? Some information outlined in the rule would not be revealed during the application process however; generally this information is too burdensome and costly to collect and in some cases would be impossible to collect. For example, the language calls for "a list of all persons that (sic) received the select waste from the generator and the quantity of select waste distributed annually to each person expressed in dry tons or in volume". Can this be serious? This material has been determined to be environmentally safe so why would a generator be forced to expend the necessary manpower and cost of collecting this data and reporting it to Ohio EPA. If the agency were truly serious about developing a beneficial use program and expanding opportunities for the beneficial use of recyclable byproducts, it would not propose such an outlandish requirement pertaining to record keeping and reporting.

3745-599-50 – Select waste characterization and analysis plan

As set forth in the conceptual draft this rule is very generic, incredibly complex, burdensome, and would preclude any type of beneficial reuse of recyclable byproducts in the State of Ohio with the possible exception of extremely high volume byproducts with significant end user demand. The conceptual draft takes more than two pages to set forth requirements that go well beyond what is necessary to determine whether an industrial byproduct would cause environmental harm. As written, any company that was interested in beneficially reusing an industrial byproduct would be forced to hire an environmental consultant to perform the outlined tasks and the cost of performing those tasks would be so expensive that most companies would not spend the money.

The conceptual draft calls for the development of a unique select waste characterization and analysis plan from each applicant for approval of a beneficial reuse project. As outlined above this proposal is too expensive, too burdensome, and unworkable. Rather Ohio EPA should set forth a consistent approach within the rule that can be applied to all materials subject to regulation. OEPA Policy 400.007 set forth material testing requirements in a number of paragraphs pertaining to sampling methods, toxicity testing and analysis, and number of samples. That policy served our industry well from 1994 until it was rescinded. Furthermore, for the materials most likely to be beneficially reused in Ohio in the near future such as foundry sand, fly ash, and steel slag, Ohio EPA already has a significant amount of information and experience with characterization of these byproducts. It makes no sense to force companies in these industries to develop new select waste characterization and analysis plans when information about their use is so readily available. States such as Wisconsin and Pennsylvania have established very reasonable testing programs for foundry byproducts that can be implemented without

having to hire outside technical expertise and without jeopardizing the economics of the potential end use. We should be able to develop something that builds on what has already been done in other states. In the case of new or exotic proposed beneficial reuses, the Director could have the discretion to require a unique select waste characterization and analysis plan from these applicants. In addition, we find the term "waste characterization and analysis plan" to be somewhat problematic. As stated before in our comments, we believe the agency should avoid the term "waste" in these rules. The term "materials characterization and analysis" would seem to get around this issue. Finally, the term "plan" is somewhat problematic. Typically a plan would outline what the generator intends to do. However, within these rules it appears that that the plan is also intended to provide the analytical **results** from the material characterization. Typically the **results** would not be included in the plan. Perhaps this could be clarified by using the title of **Material Characterization and Analysis** for this rule

3745-599-55 Annual sampling confirmation characterization

The rule provides for confirmatory sampling for both general and individual permits. OCMA recommends that this rule be removed. Any requirements for additional characterization should be included in the general or individual permit.

3745-500-210 Notice of intent to obtain coverage under a beneficial use general permit

Paragraph (A) (1)indicates that an application for a general permit must be submitted not later than 60 days prior to the anticipated date of the beneficial use. A thirty-day period would be a more acceptable time frame. In many situations, the beneficial reuse has a very small window of opportunity. If the Agency could turn around a general permit within thirty days of receiving a completed application it would facilitate more beneficial reuse.

Paragraphs (A) (1) (g) & (A) (1) (h) state that the general permit must include each location of the proposed beneficial use as well as the estimated volume use on an annual basis. These subparagraphs should be removed. It is impossible to know when applying for the general permit where and how much of the material will be used. The important factor to be determined is whether the material proposed for a general permit meets environmental standards. If so, the Ohio EPA does not need to know where the material is being used or how much is being used. Again, the Agency is attempting to place an undue burden on industry attempting to beneficially reuse an industrial byproduct that is cleaner than dirt.

Paragraph (A) (2) refers to 3745-599-400 of the Administrative Code. Are there additional paragraphs that are going to be added to these rules or is this a typographical error. Should the reference be 3745-599-50?

3745-599-220 Coverage under a beneficial use general permit

Paragraph (C) indicates that the permittee shall notify the director when there is a change in the generating process or in the feedstock etc. The language needs to be tightened up to only apply to those changes that would have a material impact on the production of the industrial byproduct. In the

manufacturing process, changes are made all the time and it would be ridiculous for the permittee to advise the director of any change as outlined in the proposed language. If a change is considered that would have a material impact on the industrial byproduct that was going to be beneficially reused, then a notification may be warranted.

Paragraph (D) applies to denial of coverage under a beneficial use general permit. Under (D) (4) the proposed language suggests that the director may deny coverage when there are any unresolved enforcement actions against the applicant…. Is it normal practice for the Agency to deny a permit when there are unresolved enforcement actions against a generator of an industrial byproduct? This provision is so ambiguous that it can only be expected to result in arbitrary and capricious judgments concerning what "unresolved" means. It should be removed.

EXCESS FOUNDRY SAND CHARACTERIZATION AND EXPERIMENTAL INVESTIGATION IN CONTROLLED LOW-STRENGTH MATERIAL AND HOT-MIXING ASPHALT

Prepared for

U.S. Department of Energy
Contract No. DE-FC36-01ID13974

FINAL REPORT

October 2004

By P. J. Tikalsky, H. U. Bahia, A. Deng and T. Snyder

PENNSTATE

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Technical Report Documentation Page

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7. Author(s) Paul J. Tikalsky, Hussain U. Bahia, An Deng and Thomas Snyder		8. Performing Organization Report No. 2005-01
9. Performing Organization Name and Address The Pennsylvania Transportation Institute Transportation Research Building The Pennsylvania State University University Park, PA 16802-4710		10. Work Unit No. (TRAIS) **11. Contract or Grant No.** DE-FC36-01ID13974
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15. Supplementary Notes
COTR: Debo Aichbhaumik, (303) 275-4763

16. Abstract

This report provides technical data regarding the reuse of excess foundry sand. The report addresses three topics: a statistically sound evaluation of the characterization of foundry sand, a laboratory investigation to qualify excess foundry sand as a major component in controlled low-strength material (CLSM), and the identification of the best methods for using foundry sand as a replacement for natural aggregates for construction purposes, specifically in asphalt paving materials. The survival analysis statistical technique was used to characterize foundry sand over a full spectrum of general chemical parameters, metallic elements, and organic compounds regarding bulk analysis and leachate characterization. Not limited to characterization and environmental impact, foundry sand was evaluated by factor analyses, which contributes to proper selection of factor and maximization of the reuse marketplace for foundry sand. Regarding the integration of foundry sand into CLSM, excavatable CLSM and structural CLSM containing different types of excess foundry sands were investigated through laboratory experiments. Foundry sand was approved to constitute a major component in CLSM. Regarding the integration of foundry sand into asphalt paving materials, the optimum asphalt content was determined for each mixture, as well as the bulk density, maximum density, asphalt absorption, and air voids at N_{ini}, N_{des}, and N_{max}. It was found that foundry sands can be used as an aggregate in hot-mix asphalt production, but each sand should be evaluated individually. Foundry sands tend to lower the strength of mixtures and also may make them more susceptible to moisture damage. Finally, traditional anti-stripping additives may decrease the moisture sensitivity of a mixture containing foundry sand, but not to the level allowed by most highway agencies.

17. Key Words Foundry sand, hot-mix asphalt, controlled low-strength material, aggregate, asphalt paving materials, leachate characterization, survival analysis, moisture damage, bulk density, optimum asphalt content		18. Distribution Statement No restrictions. This document is available from the National Technical Information Service, Springfield, VA 22161	
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EXCESS FOUNDRY SAND CHARACTERIZATION AND EXPERIMENTAL INVESTIGATION IN CONTROLLED LOW-STRENGTH MATERIAL AND HOT-MIXING ASPHALT

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Chapter 1

INTRODUCTION

This report is organized in 10 chapters. The first chapter includes the problem statement, research objective, and work plan of the study. Chapter 2 presents the literature review. Chapters 3 through 5 are concentrated on the characterization of foundry sand. Chapter 6 describes the characteristics of the materials and the test methods used in the laboratory studies. Chapters 7 and 8 are dedicated to the experimental investigation, results, and discussion. Chapter 9 presents conclusions based on the previous chapters, and Chapter 10 details recommendations for future studies.

1.1 Problem Statement

One of the most pressing problems facing the metal casting industry today is the disposal of foundry byproducts. The annual generation of foundry by-product was reported to range from 9 to 13.6 million tons in 1999 [Bol'shakov and Winkler 2001, DOE 1999]. An estimated 6-10 million tons of excess foundry sand is disposed of annually in the United States. These byproducts are generated by metal casting foundries during the production of cast metal components. The disposal of foundry byproducts represents a significant cost for the foundry industry, whether disposal occurs in company-owned facilities or in municipal or privately owned landfills. Most of the excess foundry sands are potentially available for various reuse applications [Regan et al.

1993]. Diversion of byproduct materials into beneficial reuse will have a substantial positive impact on foundries' bottom lines. Given the national average tipping fee of foundry byproducts to landfills ($15-75 per ton) [Winkler et al. 1999], including costs to store the sand, transportation, labor, and other directly related costs, there is a potential average annual savings of around $180 million in disposal expenses with a 50% reutilization of excess foundry sand.

In the mid- to late-1980s, the era of environmental awareness and corporate liability of the foundry industry started. The binder and heavy metal residuals in foundry byproducts have attracted attention for their environmental impact, government regulations, and long-term liability. These issues compel manufacturers to make processing changes to comply with the Resource Conservation and Recovery Act (RCRA, Section 2.2.1). In addition, large numbers of landfills began to close, with the total number declining from 20,000 in the 1970s to only 2,500 after 1997 [Foundry Management & Technology 1996]. With the decrease in available landfill sites, landfill disposal costs are escalating due to the surcharges for transportation and landfill operation. Although the disposal of excess foundry sand can be reduced by reclamation of a greater percentage of the sand before disposal, new sands are required to supplement for shake-out loss, and sand that has degraded beyond quality standard. Degraded sand should be removed from the casting process to keep a good binding system and ensure casting quality. An ultimate solution to this issue is to beneficially reuse foundry byproducts.

Controlled Low-Strength Material (CLSM) and Hot-Mix-Asphalt (HMA) are two growing markets that meet the basic economic and technical qualifications to address a beneficial reuse program. There are a variety of technical, economic, and environmental arguments that need to be addressed before foundry byproducts can focus on these applications.

CLSM in its simplest form is a premixed flowing soil-cement that hardens to form a strong, cohesive geotechnical product. It can be designed for nearly any strength (0.3 - 8.3 MPa), hydraulic conductivity (10^{-2} - 10^{-6} cm/sec), rheological property (100 - 275 mm slump), or setting time (2 - 24 hours). In addition, it can be mixed, pumped, and placed with standard concrete equipment.

Excess foundry sand is basically a fine mineral aggregate. More than 80% of the particles by mass are concentrated by size between 0.15 – 0.70 mm, compared to 0.30 – 4.75 mm for conventional fine aggregate. The AFS Grain Fineness Number (AFS GFN), a foundry industry parameter indicating the average grain size (bigger, finer), ranges between 40 – 90 for most of the excess foundry sands, compared to around 40 for conventional fine aggregate. In addition, foundry sand is a uniform equidimentional-subangular aggregate. These basic physical properties enhance the flow consistency of CLSM when excess foundry sand is incorporated into CLSM mixtures.

The reuse of foundry sand offers substantial environmental and economic benefits. The cost and environmental impact of mining and dredging virgin sand for

CLSM, asphalt and concrete are gradually rising. These rising costs of transportation, environmental regulation, fuel and energy in mining and dredging, and the developmental cost of virgin sources of aggregate are driving the need for the reuse of natural resources. The use of CLSM and HMA containing foundry sand reduces the need for mining or dredging virgin granular aggregate. There are no costs of disposing foundry byproducts to landfills, only the shipping to local contractors. Both natural mineral resources and the urban environment are protected.

The lack of technical performance data and specifications puts use of foundry sand in the CLSM and HMA at a competitive disadvantage, not only against conventional granular materials but also against other recycled materials such as fly ash, steel mill slag, and recycled glass. The critical qualifications include the characterization of foundry sand, the engineering specifications, and technical performance standards for its CLSM and HMA applications.

The characteristics of excess foundry sands are not universally documented, particularly in regard to chemical and environmental characteristics. As a result of a wide variety of binding processes, sources of metal feed, and differences in state regulations, up to 48 inorganic elements and 43 organic elements may be evaluated by chemical extraction and testing procedures prior to its disposal or reuse. The widespread collection of the results of these characterizations is not centrally located. Systematic characterization of foundry sand needs to be addressed to ensure environmental compliance.

The performance of CLSM and HMA containing foundry sand is not documented by highway and building standards or specifications. Detailed technical data need to be collected from CLSM and HMA containing foundry sand to validate its performance. Use guidelines pertaining to the construction and performance of CLSM and HMA need to be set up and standardized.

1.2 Research Objective

Overcoming technical barriers to reuse excess foundry sand in CLSM and HMA is the primary goal of this research. The research will result in substantial energy and cost savings for both foundries and user industries, as well as provide an environmental benefit at the local and national level.

A universally acceptable and open database was to be developed to address the characterization of excess foundry sand. Large numbers of datasets addressing the environmental, chemical, and physical properties of excess foundry sands were pooled from industrial partners and input into this unit for initial evaluation purposes. Follow-up datasets were added from various resources to make the data resource more robust and abundant.

Data mining research covered chemical, environmental, and physical aspects of excess foundry sand, and intended to define the variations of foundry sand characteristics,

and how it performs as a component of CLSM and HMA. Major topics included in the research are concentration level and distribution models of individual elements, factors influencing the elements and engineering parameters. Most of the research is carried out using statistical methodology and corresponding software. The inference from this part is statistically confident and supported by nationwide data resources. It deserves to be a valuable reference for the state's characterization of excess foundry sand.

Documenting material and performance specifications of CLSM and HMA with excess foundry sand opens the door to beneficially reusing sand. The generation of materials standards (American Society for Testing and Materials [ASTM], American Association of State Highway and Transportation Officials [AASHTO]) and construction specifications is essential in order for legal entities to adopt provisions for materials that contain CLSM and HMA. Most other competitive industry byproducts, such as fly ash and slag, are documented by various technical standards for multiple engineering applications. The research eliminates the gap between excess foundry sand and other byproducts after successfully developing CLSM and HMA containing excess foundry sand.

The development of user guidelines for CLSM and HMA mixture designs finalizes the research objective. Developing educational and professional guidelines creates a standard of practice that contractors and engineers can be expected to meet. This development is essential for the specification and implementation of CLSM and HMA containing excess foundry sand.

Broad dissemination of the dataset, guidelines, standards, and specifications will be the cornerstone of the implementation of the proposed work.

1.3 Research Methodology

The scope of the research includes three parts: characterization of excess foundry sand, technical qualifications of CLSM using excess foundry sand, and technical qualifications of HMA containing excess foundry sand. The first part concentrates on the chemical and environmental issues of excess foundry sand through data processing techniques, such as the toxicity level of excess foundry sand and factors influencing its toxicity. The latter two parts are experimental research in a laboratory environment that mixes CLSM and HMA samples using excess foundry sand and qualifies its performance in comparison to standard CLSM and HMA specifications.

The research was performed in stages as follows:

Stage 1 — Collection of Datasets

Datasets addressing bulk chemical analysis, extraction chemical analysis, and physical analysis of excess foundry sand were collected from regulatory independent commercial laboratories. These datasets were input into a database coded with MS-Access for convenient management.

Stage 2 — Evaluation of Datasets

Confident statistical methodologies were developed to characterize excess foundry sand from chemical, environmental, and physical standpoints. First, a data plotting technique was applied. Data plotting is a basic and straightforward technique that presents the real characterization without any assumption or data transformation. Furthermore, an innovative approach, survival analysis, was developed to address environmental monitoring data containing censored data.

Stage 3 — Scouting of CLSM

Representative excess foundry sands from nationwide foundry facilities were collected to evaluated CLSM characteristics. The selection spans two significant factors differentiating individual excess foundry sand, including metals cast and binding systems.

Prior to the initiation of the massive investigation of CLSM performance, small trial batches were conducted to probe the formulations of excavated CLSM and structural CLSM. Controlling parameters of CLSM were addressed in this stage, such as flowability consistency, bleeding, shrinkage, and strength development. The formulations were approved or improved depending on how close their performance complied with CLSM specifications.

Stage 4 — Massive Excavatable CLSM

Using the recommended formulations from Stage 3 for each excess foundry sand, massive excavatable CLSMs were mixed and tested. Sufficient numbers of samples were

prepared for performance investigation purposes, such as strength development, hydraulic conductivity, density development, and setting time. Most of the mixtures of CLSM in this stage complied with major provisions of standard CLSM specifications. In cases where some excess foundry sands did not qualify, mixes with improved formulations were prepared and investigated.

Stage 5 — Massive Structural CLSM

The formulations of structural CLSM were inferred from the formulations of scouting CLSM, formulations of excavatable CLSM, and highway specification for CLSM. Investigation procedures are identical to those for excavatable CLSM.

Stage 6 — Evaluation of CLSM

Factors influencing CLSM performance were discussed in this stage. Technical problems, such as the control of strength development, bleeding reduction, flow consistency improvement, and acceleration of setting time were resolved.

Stage 7 — Collection of HMA Data

The engineering properties were determined for the control sand and each of the 17 foundry sands chosen, and the aggregate mixes in which they were incorporated. These properties included gradation by mass, angularity, asphalt absorption, maximum and bulk density, clay content, and organic material content. In many cases, non-traditional methods were used to test the sands' properties because standard methods could not be applied for some foundry sands. For the maximum density, the CoreLok™

(InstroTek, 2001) device, built by InstroTek, was used instead of the traditional vacuum pump method. The bulk density was determined using a modified version of a testing method developed by InstroTek. It involves finding the density of an aggregate that is submerged in water but has air trapped in its surface pores. The clay content was determined by saturating the foundry sands with methylene blue dye and measuring the concentration of unabsorbed methylene blue with a spectrophotometer.

Stage 8 — Collection of Performance Data of HMA

The performance data collected can be broken down into the following categories: HMA volumetric data, energy indices derived from gyratory compaction testing, indirect tensile stress and strain measurements, and moisture sensitivity testing. The performance measures are standard methods used by the asphalt pavement industry.

Stage 9 — Development of Guidelines for HMA

Based on the engineering properties of the foundry sands and the performance data collected, guidelines were developed. These guidelines describe the responsibilities of each of the foundries and the aggregate suppliers in the preparation and shipment of the sands. There are also specifications limiting the amount of foundry sand used based on its methylene blue content and binder system used. The guidelines also include specific steps that asphalt contractors should follow to produce mixtures with foundry sands of acceptable quality.

1.4 Potential Impact to Society

Results from the research will aid the foundry industry in reducing costs and decrease potential energy consumption and environmental impacts. The lack of technical data is eliminated through this project, mitigating a critical barrier that makes it costly and time consuming for large foundries to develop reuse alternatives and financially infeasible for small foundries. The competitive advantage of beneficial reuse is strengthened by this research.

The energy industry is a large potential beneficiary of the research. National energy savings on the order of magnitude of 50 million MBtu will result from reducing energy otherwise expended by foundries in handling and reclaiming foundry byproducts [Tikalsky 2000]. Energy savings will also accrue from greenhouse gas emissions reductions; from avoidance of energy requirements of transportation, disposal, and construction of landfill capacity to dispose of foundry byproducts; and from substitution of foundry byproducts for construction sand and gravel as an alternative to virgin mineral extraction activities.

This research provides an environmental benefit at the local and national level. Increased beneficial reuse of excess foundry sand is an effective way to reduce emissions to the environment, conserve increasingly limited capacity, increase the amount of material that is recycled in the industry, and reduce the amount of virgin sand being mined or dredged. All of these factors result in substantial environmental benefits.

The construction industry benefits by the introduction of CLSM and HMA containing excess foundry sand. Cost savings arise with decrease in material cost, sufficient material supplies and matched construction quality; designers are free to incorporate excess foundry sand into CLSM and HMA supported by technical documents; and constructors benefit from the less labor-intensive technique and its rapid construction.

Chapter 2

LITERATURE REVIEW

The first part of chapter 2 gives an overview of the foundry process and explains several key concepts used in the foundry industry. This includes the difference between a mold and a core, different types of base sands, different types of binder systems, and the different kinds of fillers used. The second part of chapter 2 focuses on past studies regarding the characterization of foundry sand. The last part of chapter 2 is an overview of past studies about incorporating recycled foundry sand into CLSM and HMA.

2.1 Introduction to Metal Casting Industry

The scope of the metal casting industry encompasses a major segment of the U.S. economy. Its sales reached $18.3 billion in 2001 (see Figure 2-1) and its shipments reached 12.2 million tons in 2001 (see Figure 2-2), [U.S. Census Bureau 2002]. It employs, directly and indirectly, 225,000 people. The industry's product, castings, enters into every field in which metals serve man, including but not limited to automotive, military, construction, agriculture, power generator, aerospace and atomic energy applications.

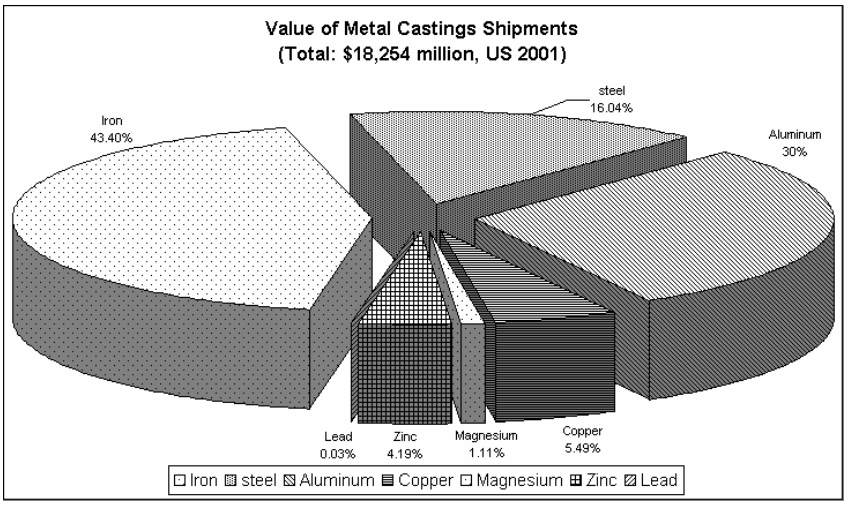

Figure **2-1**: Value of metal casting shipments

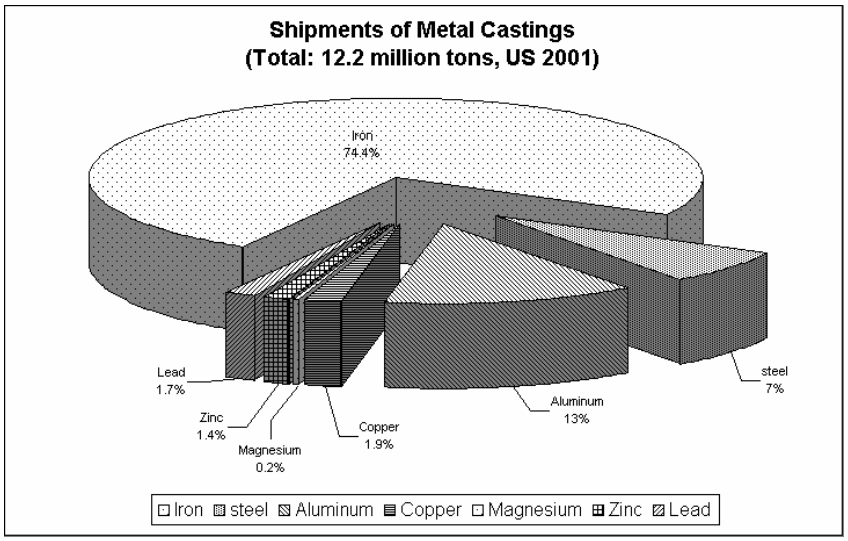

Figure **2-2**: Producers' shipments of metal castings

A metal casting foundry is a commercial establishment for producing metal castings. A metal casting is a shape obtained by pouring liquid metal into a mold or cavity and allowing it to freeze and thus to take the form of the mold. In a typical foundry facility system, five fundamental steps are followed to fulfill the casting: patternmaking,

core making, molding, melting and pouring, cleaning and reclaiming. The sequence of elements in such a system is shown in Figure 2-3.

The types of molding and core making processes generally include a sand casting process, permanent-mold process, die-casting process, centrifugal process, shell-mold process, investment process, lost foam process, plaster process, and graphite process. The sand casting process is the most popular casting process, with low cost, high efficiency, and reuse cycles. Of the total tonnage of castings produced each year, the greatest percentage is produced by sand casting [Ammen 2000]. The process consists of making molds with sand aggregate, then pouring a molten metal or alloy into them and allowing it to solidify.

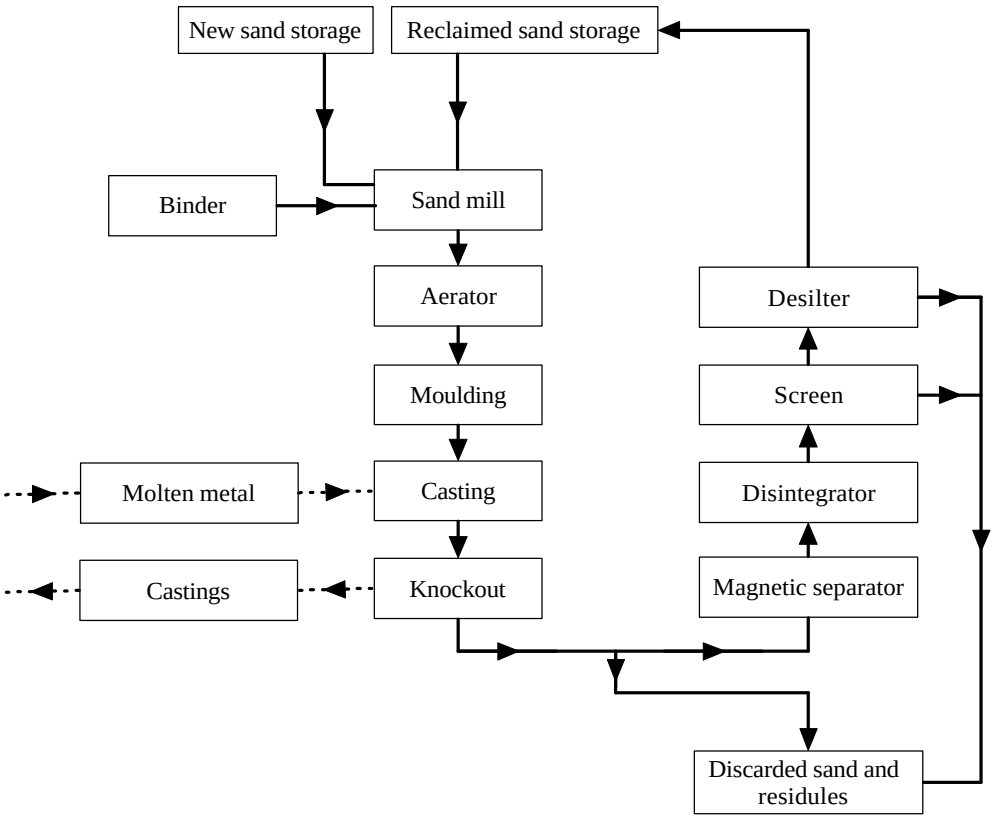

Figure **2-3**: Flow diagram for typical molding sand system [Beeley 2001]

2.1.1 Molds and Cores

In the sand casting process, molds and cores are prepared prior to pouring melting metals. The mold is made by packing molding aggregate around a pattern, Figure 2-4. When the pattern is withdrawn, its imprint provides the mold cavity, which is ultimately filled with metal to become the casting. In general, sand molds are shaken off and reclaimed to new molds. Molds are made by various bonding systems, including green sand, organic bonding systems, and inorganic bonding systems, addressed in Section 2.1.4.1 and Section 2.1.4.2.

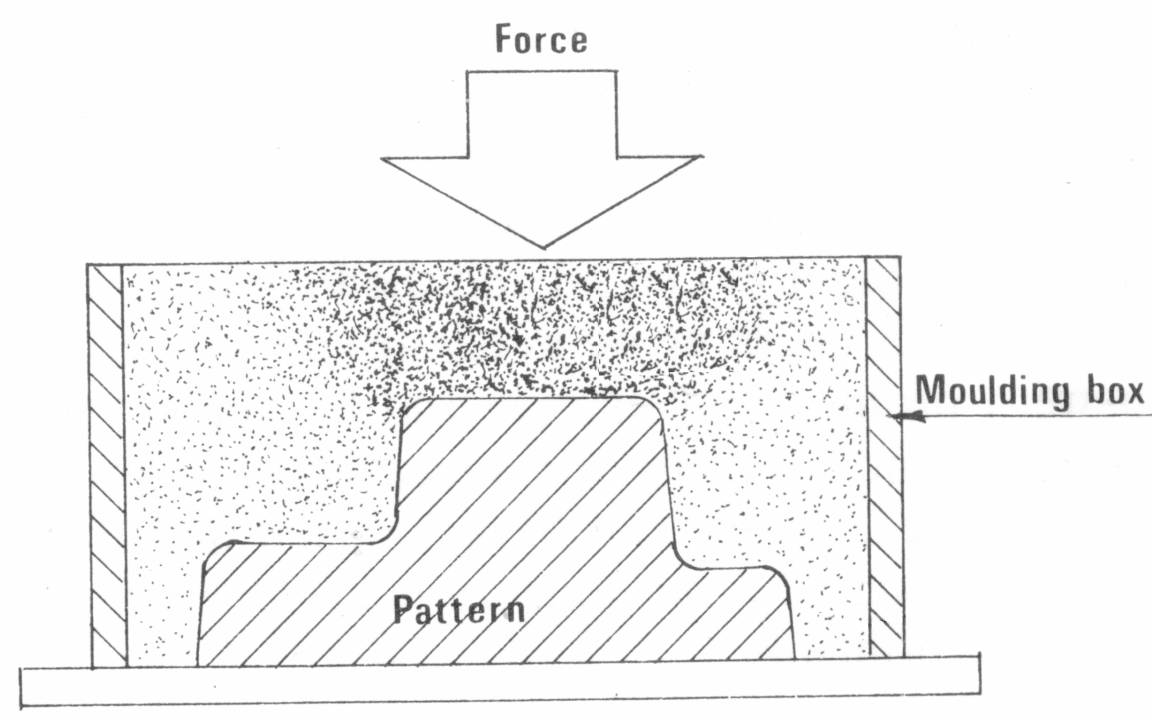

Figure **2-4**: Compaction characteristics of a green sand [Webster 1980]

Cores are forms, usually made of sand, which are placed into a mold cavity to form the interior surface of a casting. The void space between the core and mold-cavity surface is what eventually becomes the casting. Cores are made by core boxes, which are filled with core sand, rammed, and struck off. The immediate example is a simple round cylinder form needed to core a hole through the hub of a wheel or bushing. Its external shape becomes the internal shape of the casting. The cores are usually made of organic and inorganic bonding systems, addressed in Section 2.1.4.2.

2.1.2 Virgin Foundry Sands and Excess Foundry Sands

The most widely used aggregate for molds and cores is sand because it has the ability to absorb and transmit heat as it allows gases evolved during binder breakdown to pass between the grains; the ability of grains holding together and giving strength; and the ability to withstand high heat with moderate breaking down or fusing [Ekey 1958]. As shown in Table 2-1, there are many types of sand utilized by the foundry industry. However, because of its wide availability and relatively low cost, silica sand is the one used in most of the metal casting [Carey 1994]. Quartz and other silica minerals are the main components of silica sand. It is essentially SiO_2. Silica sand is found in nature on the bottoms and banks of river, lakes, on seashores, in dry river deposits, and in substrata layers of the earth. Many of these deposits are mined and used without alteration.

The cost of new, clean, dry, clay-free sand in conjunction with enhanced environmental requirements, transport, and tipping charges has meant that greater urgency has been given to possible recovery and reuse of sands used in the molding and coremaking systems. The principal methods of sand recovery are dry scrubbing (pneumatic, mechanical, or shot blast) for clay, organic and inorganic binders, calcination (thermal) for organic binders, and wet washing for clay and silicate binder [Granlund 1984].

Table **2-1**: Comparison of foundry base sands [Webster 1980]

	Silica	Olivine	Chromite	Zircon	Zircon/Aluminum Silicate	Staurolite	Carbon Sand
Composition	Varying connection of SiO_4^{4-} tetrahedron	SiO_4^{4-} tetrahedron bonded together by Mg^{2+} and Fe^{2+}	---	$ZrSiO_4$	---	---	Petroleum, C
Origin	USA	USA (WA, NC) Norway	S. Africa	USA, Australia	USA (FL)	USA (FL)	Man-made
Color	White-Light Brown	Greenish Gray	Black	White-Brown	Salt & Pepper	Dark Brown	---
Hardness	6.0 – 7.0	6.5-7.0	5.5-7.0	7.0-7.5	6.5-7.0	6.5-7.0	---
Dry Bulk Density (lb/ft^3)	85-100	100-125	155-165	160-185	155-168	143-146	64
Specific Gravity	2.2-2.6	3.2-3.6	4.3-4.5	4.4-4.7	3.2-4.0	3.1-3.8	---
Grain Shape	Angular/Rounded	Angular	Angular	Rounded/ Angular	Rounded	Rounded	Rounded
Thermal Expan. 1,600° (in./in.)	0.018	0.0083	0.005	0.003	0.005	0.007	---
Appar. Heat Transfer	Average	Low	Very High	High	High	High	
Fusion Point (°F)	2,600-3,200	2,800-3,200	3,200-3,600	3,700-4,000	3,300-3,600	2,500-2,800	>4,532
High Temp. Reaction	Acid	basic	basic	Acid	Slightly Acid	Slightly Acid	---
Wettability with Molten Metal	Easily	Not Generally	Resistant	Resistant	Resistant	Resistant	---
Chemical Reaction	Acid-Neutral	Basic	Basic-Neutral	Acid-Neutral	Neutral	Neutral	---
Grain Dist. (# Screens)	2-5	3-4	4-5	2-3	3	3-4	---
AFS GFN	25-180	40-160	50-90	95-160	Approx. 80	Approx. 70	---
Cost: 1 cheapest; 4 most expensive	1	2	3	4	---	---	Expensive
Density: 1 lightest; 4 heaviest	1	2	3	4	---	---	lightweight
Composition	> 95% SiO_2	SiO_2 (42%), MgO (50%), Fe_2O_3 (7%)	SiO_2 (2%), MgO (10%), Fe_2O_3 (25%), Cr_2O_3 (50%), Al_2O_3 (15%)	SiO_2 (32%), ZrO_2 (65%)	---	---	---

Sand employed in a mechanical sand preparation and handling system is called system sand. After several cycles of reclamation, sand is removed from the system and becomes excess foundry sand. Reclamation units allow foundries to reuse mold sand and thereby generate less excess sand product. Grain cracking, core sand additions, and free clay content limit the amount of reclamation to approximately 75-90%; even foundries using reclaim units send sand out as a waste stream. A considerable amount of excess foundry sand, around 6-10 million tons, is discarded from facilities annually as continuous reuse of sands is followed by deterioration of its quality and workability. For example, in a closed sand system, if a 97% yield is obtained after reclamation but the molding sand mixture can only be made with 80% reclaimed sand and 20% new sand, the excess 17% reclaimed sand must be discarded or recycled to another application.

The steady worsening of the sand mass can be physical. Reclamation causes physical changes to occur to the sand, since it smoothes and rounds the surface of the grains. Breakdown of quartz grains and accumulation of fusible fines reduce both permeability and refractoriness [Beeley 2001]. The shakeout may be a mixture of mold and core sand with different gradation which is not feasibly reclaimed due to low yields. Inorganic residuals in the pores of grains may not be removed, which results in incompatibility [Carey 1994].

The degradation can also be of a chemical nature. The surface chemistry of reclaimed sand is drastically altered by the resin, catalyst, and additives. Even if the coating is almost completely removed during every reclamation cycle, the chemistry of

the reclaimed sand may vary somewhat with each cycle [Carey and Sturtz 1996]. The clay at or near the casting surface becomes heated and destructed to “dead.” After this has occurred, milling and additions of water will not bring back the bond. Too much “dead” clay results in brittle sand, poor strip, and bad lifts. [Webster 1980].

2.1.3 Sand Binders

A binder is a “material added to the sand or provided by nature with the sand that imparts cohesiveness” [Ekey 1958]. Its typical mass percentage varies from 0.5% to 15% based on the base sand, binder and bonding system. Binders are categorized into three groups: clay-type binders, organic-type binders, and inorganic-type binders. The last two groups are frequently called chemical binders.

Clay-type binder, in the amount of 4-10% by weight of base sand [Bol'shakov and Winkler 2001], is used for making small, medium, and large molds. It is relatively inexpensive and of low strength. Chemical binder is usually used for small to medium-size molds and cores and is relatively stronger with good erosion resistance. The major subdivisions of the clay family are montmorillonites (bentonites mostly used in foundry), kaolinites, and illite.

Organic binders include two major groups, resin and oil-based binders. They are combustible and are destroyed by heat [Heine 1967]. The resin is made by mixing various proportions of phenolic, furfuryl alcohol (furan), urethane and formaldehydes,

ranging from 1.5 to 8% based on base sand [Sylvia 1972]. They are liquids or gums, natural or synthetic, where the individual molecules have the capacity to polymerize or fuse together to form very long chains. This polymerizing reaction can be triggered by certain chemical reagents or heat. The resulting chain hardens to form a powerful bond with other materials [Burns 1986].

The oils in the amount of 0.5-3% can be either natural oils, such as linseed, perilla, tung and dehydrated castor oils, or processed oils, such as unsaturated mineral oils, synthetic oil, and alkyd resin. Their mechanism of hardening is similar to resin, polymerization with or without heat.

Inorganic-type binders include sodium silicate and portland cement, which are incombustible. They are environmentally benign compared to organic binders and have low cost, low sand sensitivity, and low gas evolution. The sodium silicate, generally called water glass, refers to a three-ingredient system: silica, sodium oxide, and water. The cement-based bonding system is a mixture of sand, 8-12% high-early-strength hydraulic cement, and 4-6% water. Inorganic-type binders develop great hardness and strength by the setting action of sodium silicate or portland cement. However, they present slow cure characteristics, and once used, they are poor to break down or reuse [Sylvia 1972, Webster 1980], which offsets their environmental advantage.

In most processes, one or multiple additives are added to the sand for improving some special bonding or casting features, or catalyzing the binders. Examples are sea coal, wood flour, and silica flour.

Sea Coal

Sea coal is nothing more than ground bituminous coal. It helps to improve the surface finish of the molded part. During the pouring process, the sea coal swells and fills the voids between sand grains [American Foundry Society 2000]. It also helps to remove the part from the mold sand during the shakeout process. Lastly, it helps prevent the mold sand from drying out, by retaining water.

Iron Oxide

Red Oxide in the form of Fe_2O_3 is the most commonly used iron oxide [American Foundry Society 2000]. During the pouring process, the iron oxide fuses together with the silica sand and forms a plastic glaze [American Foundry Society 2000]. This helps to decrease certain casting defects like veining and metal penetration. It also helps to fill in the gaps between sand grains and increase the finish of the cast part.

Soda Ash

Sodium carbonate, a.k.a. soda ash, is usually added in very small quantities, 0.0025-0.005% of the batch weight [American Foundry Society 2000]. It is used to free up additives and inert fines so they are not clumped. It also is used to increase the pH of

the molding sand as it is returned and reused through the mold system. The fermentation of cereals can decrease the pH.

Cellulose

Cellulose, in the actual sense, is the material plants create to give their cell walls structural support, and essentially to give the whole plant structural support. Cellulose, for foundries, is any material that has been derived from plants or a plant by-product [American Foundry Society 2000]. It usually is made from corn cobs, oat hulls, wood, nut shells and rice hulls. They are processed and sized to make them suitable for foundry usage. Cellulose is more commonly used for bentonite bound mold sand, and acts like a cushioning material in much the same way as cereals and starch [American Foundry Society 2000]. As metal is poured in the mold, the silica sand grains expand due to the heat. Simultaneously, the cellulose burns up, giving the expanding sand grains the needed room to expand. Cellulose also helps to retain water and improves shakeout and flowability.

Cereals & Starches

The foundry industry classifies cereals and starches as natural organic carbohydrates, and are produced from different grains that all behave in a similar manner when used in foundry sand [American Foundry Society 2000]. Common types of cereals and starches include corn, milo (sorghum), wheat, bran, rye, and oat flour, dextrin and corn sugar. Like cellulose, cereals and starches are used to compensate for the thermal expansion of the silica sand grains, by burning up during metal pouring. They also help

with moisture retention and control, to increase the range of acceptable moisture levels. Finally, they allow the mold sand to be more moldable to accommodate more complicated patterns [American Foundry Society 2000].

2.1.4 Sand Bonding Processes

Binders need to be exposed to the appropriate process to activate cohesion between the refractory grains in the green or hardened state. Generally the processes are divided into green sand, chemical bonding process, and unbonded sand system. Combinations of binder and its bonding systems are presented in Table 2-2.

2.1.4.1 Green Sand Process

Green sand is the most widely used bonding process in the world because it is low in cost, high in performance, and environmentally benign, and the materials are reusable. It is composed of uniform high-quality refractory quartz sand (85-95%), cohesive bentonite clay (4-10%) as the binder, a volatile carbonaceous sea-coal additive (2-10%) as filler to improve casting surface finish, iron oxide (0.5-5%) for strength, and water to activate clay (2-5%) [Bol'shakov and Winkler 2001]. It is referred to as “green” because of the moisture present and is thus distinguished from dry sand.

Table **2-2**: Conventional binders and bonding systems [Bol'shakov and Winkler 2001]

	Thermosetting Processes	Self-Setting Processes	Gas-Cured Processes
Organic Binders	**1.** Shell process: Novolac ("shell") resin + Phenol Formaldehyde **2**. Hot Box processes: Urea Formaldehyde Phenol Formaldehyde a. Novolac b. Resole Furan Modified a. UF + FA b. PF + FA c. PF + UF **3.** Warm Box process: Furan a. free formaldehyde b. UF or PF c. sulfonic acids or copper salts **4.** Core Oil process: Oils water activated cereal	**1.** Acid No-Bake processes: Furan no-bake a. H_3PO_4 b. TSA c. BSA Phenol Formaldehyde a. TSA b. BSA c. xelenesulfonic acid **2.** Ester Cured processes: Phenolic Resole a. free phenol b. free formaldehyde **3.** Urethane No-Bake (Amine Cured) processes: Alkyd Urethane a. vegetable oil b. polyisocyanate Phenolic Urethane a. pyridine derivative b. polyphenyl PIC Polyol Urethane	**1.** Free Radical Curing: Vinyl Urethane Oligomer a. $N_2 + SO_2$ b. epoxy / hydroperoxyde **2.** Cold Box processes: Phenolic Urethane Polymeric Isocyanate a. TEA vapor + air b. DMEA vapor + air Furan + SO_2 a. methyl alcohol b. MEK peroxide Acrylic/Epoxy + SO_2 a. hydroperoxide Phenolic Resole + Ester a. glycol ethers b. methylformate vapor
Inorganic Binders	**1.** Clay Based processes: Bentonites Fire Clays Kaolinite	**1.** Ester Cured processes: Sodium Silicate a. glycerol diacetate b. EGDA c. glycerol triacetate Ethyl Silicate **2.** Cement Bonding process: Hydraulic Cements **3.** Oxide Cured process: Phosphates a.aluminum phosphate b.magnesium oxide	**1.** CO2 Silicate process: Sodium Silicate (SiO_2:Na_2O) + CO_2

Notes: FA = furfuryl alcohol; UF = urea formaldehyde; PF = phenol formaldehyde; TEA = triethylamine; DMEA = dimethylethylamine; PIC = polyisocyanate; TSA = toluenesulfonic acid; BSA = benzenesulfonic acid; MEK = methyl ethyl ketone; EGDA = ethylene glycol diacetate

Clays used in foundries include hydrous alumina silicates, known as “bentonites,” addressed in Section 2.1.3. Their properties provide cohesion and plasticity in the green state and also high strength when dried. In most of the cases, two types of bentonite,

sodium bentonite (western-type) and calcium bentonite (southern-type), are blended to produce strong molding sands with low moisture content.

The principal properties of green sand are governed by the clay-water-silica relationship. Because of lack of electrical neutrality of montmorillonite and an unequal balance of charge at the fractured quartz surface, polarized water molecules are attracted either between the clay plates or to the quartz surface. As a result, a linkage, quartz-water-clay-water-quartz (or clay), is therefore set up throughout the molding sand [Flinn 1963, Blistan 1974]. Besides the electrostatic bonding, surface tension forces and interparticle friction bond also build the clay bonding system [Sylvia 1972, Blistan 1974].

2.1.4.2 Chemical Bonding Process

Chemical binders, addressed in Section 2.1.3, need to be exposed to the appropriate chemical bonding process to exhibit their cohesion feature. The chemical bonding process is normally classified into three groups, defined by the respective approaches to hardening, hot curing, cold setting, and gas or vapor hardening [Beeley 2001], providing a cold and hot tensile strength ranging from 50 psi to 150 psi depending on the bonding system. The most widely used bonding processes include cold box, no-bake, hot box, and warm box.

Cold box core and mold making describes any binder process that uses a gas or vaporized catalyst to cure resin-coated sand while the sand is in contact with a room-

temperature pattern. The no-bake core and mold making process is designed around a continuous mixer that blends the binder with the catalysts or coreactants as it coats the sand and dispenses the coated sand into the tooling. In the hot box coremaking process, after the sand has been coated, it is blown into a heated corebox pattern at a temperature of 450 to 550 ºF. It starts to harden and form a shell-like skin. Warm box coremaking uses the same sand processing system as hot box. They differentiate in the temperature of hot pattern. The typical temperature for the warm box pattern ranges from 350 to 450 ºF. The most employed combinations of binder types and bonding process are listed chronologically in Table 2-3.

2.1.4.3 Unbonded Systems

Unbonded sand systems make the mold and core without the addition of binders to hold refractory aggregates into shapes. Frozen molds, in which the main bonding action is derived from the water content of the sand, enable block molds of high strength to be produced with the aid of liquid nitrogen or carbon dioxide sprays. Another innovative unbonded process is magnetic molding, in which a magnetic granular material is held in form by a strong magnetic field. The most effective and widely adopted systems have been those in which unbonded sand is held in shape by the application of vacuum suction to the sand mass within the mold container [Beeley 2001].

Table **2-3**: Chemical bonding series [Carey and Sturtz 1995]

Approx. commercial intro.	System	Major resin, catalyst and mass percentage based on base sand
1950	Core oil	Oil (up to 20 ingredients), cereal, water, less release agent, 2-3%
1950	Shell; liquid and flake	Phenolic novolak flake resin, hexamethylenetetramine
1952	Silicate/CO_2	Sodium silicate, water, CO_2, 3-5%
1953	Airset oils	---
1958	Phenolic acid catalyzed no bake	---
1958	Furan acid catalyzed no bake	---
1960	Furan no bake	Furfuryl alcohol (from corn husks, rice hulls), 0.9-2.0%
1962	Phenolic/furfuryl alcohol hot box	Phenol, furfuryl alcohol, urea, formaldehyde, ammonium chloride, ammonium nitrate, 1.5-2.0%
1965	Oil urethane no bake	Oil resin, polymeric isocyanate, amine and metallic compounds, 1-2%
1967	Phenolic CO_2 cold box	---
1968	Phenolic/urethane/amine cold box	Phenolic resin, polymeric isocyanate, amine, 0.8-1.5%
1968	Silicate ester catalyzed no bake	Sodium silicate, ester catalyst, 2-4%
1970	Phenolic urethane no bake	Phenolic polyol, isocyanate, amine, 0.8-1.75%
1977	Furan SO_2	Phenolic modified furan, silane, organic peroxide reacted with SO_2
1978	Polyol urethane no bake	Polyol resin, isocyanate, amine
1978	(Furan) warm box	20% less resin than that of hot box, copper salts of toluene sulfonic acid, copper chloride
1980	CO_2 cured alkaline phenolic cold box	Alkaline phenolic resin, around 2.0-3.5%
1982	Free radical curing SO_2	Acrylic resin, SO_2, 0.5-2%
1983	Epoxy SO_2	Epoxy, SO_2, 0.5-2%
1984	Phenolic ester no bake	Phenolic resole resin, 1.0-1.5%, ester (organic, alcohol)
1985	Phenolic ester cold box	Water soluble, ester (methyl formate)
1992	Alumina phosphate	---

2.1.4.4 Environmental Improvements

Critical concerns pertinent to binders are their environmental and health impacts inside the workshop and at the disposal site, as some resin binder potentially poses harmful threats on the human body. Most foundry binder systems are available in a lead-free version. Foundry resin manufacturers replace lead with other dryers. The elimination of lead not only benefits workers, but has also made excess foundry sand safer and easier to reuse, reclaim and dispose. Exposure to formaldehyde has been a concern. Binder suppliers have endeavored to reduce formaldehyde content and to reduce the emission of formaldehyde during binder curing. Techniques include more efficient manufacturing processes, the use of formaldehyde scavengers, and reduction in level by improving catalyst technology [Carey and Sturtz 1996].

2.1.5 Casting Metals

The most common alloys used in metalcasting are shown in Table 2-4. Metals are most commonly categorized as ferrous or nonferrous.

The metalcasting industry is the "original recycler." Rather than use new or "virgin" materials as melt stock, nearly all foundries reuse scrap metals as their primary melting material. Annually, foundries consume 15-20 million tons of recycled scrap metal, giving new life to products that would otherwise go to landfills. The properties of casting metals can be improved with respect to fluidity, melting point, strength, and

hardness by the addition of alloying elements [Ammen 2000, Sylvia 1972]. Typical metals for casting and their melting points are listed in Figure 2-5.

Table **2-4**: Classification of foundry alloys

Ferrous castings		Nonferrous castings
Cast Steel	Cast iron	
Plain carbon steel Low-alloy steel High-alloy steel	Gray cast iron (high-carbon) Ductile or nodular cast iron (spheroidal-graphite) White cast iron (medium-carbon) Malleable iron (annealed white iron with graphite)	Aluminum-base Copper-base Lead-base Magnesium-base Nickel-base Tin-base Zinc-base Miscellaneous

The charge materials for typical iron casting consist of pig iron, iron and steel scrap, foundry returns, lime and iron ore. Typical melting stock for steel casting includes pig iron, steel, cast iron and alloying additions. The alloying elements commonly employed for the purpose of securing steel hardenability include manganese, chromium, molybdenum, nickel, silicon, copper, vanadium, totally up to 87% by mass.

The normal metal charge of aluminum-based facility consists of clean foundry scrap (remelt), prealloyed aluminum pig and scrap of heterogeneous origin. Alloying elements, such as copper, silicon, zinc, nickel, chromium, titanium, manganese, are added as rich alloys or hardeners [Heine 1967].

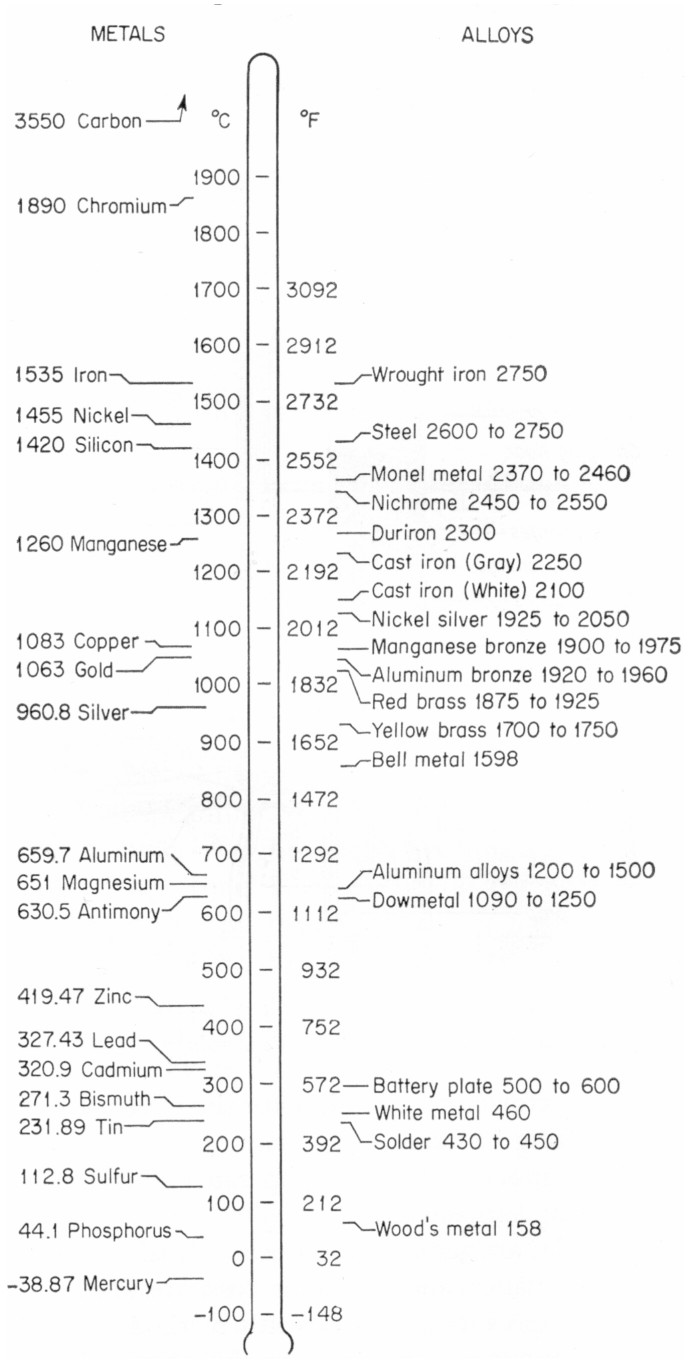

Figure **2-5**: Melting of metals for casting [Ekey 1958]

The normal metal charge for copper-based facility consists of clean foundry scrap (remelt) and pig or ingot of the desired analysis. Additions, such as zinc, tin and lead, are

made to achieve the desired analysis. Many copper-alloy castings require excellent surface finish as cast. Fines aggregate has been found to give a more desirable finish. Facing materials such as cereal, flour, plumbago, and sea coal are dusted on the mold-cavity face to improve surface finish [Heine 1967].

2.1.6 Pouring

When metal is poured into a mold, the following events occur: (1) Free moisture is driven off the sand beginning at the mold-metal interface and either condenses in the cooler parts of the mold or evolves as steam into the atmosphere. (2) Volatile matter is driven from organic materials such as sea coal and from the residual binder on the surfaces of core sand that has entered into the system by the shakeout route. (3) As the sand heats up, the clay bonding materials are deactivated and "killed." At temperatures above 600 ºC (1,100 ºF), combined water is driven out of the clay bond. All clays lose their combined water in parts of the molds as they reach 1,470 ºF and become ineffective. (4) The sand heats up as the casting solidifies and expands. (5) When the sand is heated up to temperatures over 820 ºC (1500 ºF), the possibility of chemical reaction between metal and sand, fusion of the sand, increases. [Heine 1967, Carey 2002].

2.1.7 Waste Streams

A typically foundry can generate from 8 to 40 individual waste streams, including excess molding sand, core sand, copula slag, scrubber sludge, baghouse dusts, shotblast

fines, buffling wastes, and others [Winkler 2000]. Typically, they are classified into four waste streams depending on the nature of the waste streams: sand, dust, slag, and sludge, as listed in Table 2-5. Mold and core sands are the main ingredients of excess foundry sand and occupy up to 80% of the total waste streams. Further, their behavior is more stable than other waste streams, and environmental characteristics are gentler. Sands can often be beneficially reused in construction applications. Furthermore, the disposal expense of large quantities of excess foundry sands is a big burden on foundries. Hence, excess foundry sands are selected for beneficial reuse purposes. Dust is mainly the fine particles collected by various collectors installed in a foundry facility. The formation of slags used in metal melting and refining processes can be summarized as protection of the melt from contaminations from the furnace atmosphere and combustion products, insulation of the melt to maintain the heat in it, and an acceptor of unwanted materials as refining media to the melt [Webster 1980].

Table **2-5**: Conventional description for foundry waste streams

Waste Streams	Descriptions
Sand	Sand, green sand, mold, shell core, oil sand, furfural alcohol, recyclable sand, isocure, tank, tail, pulley, sand dropout
Dust	Dust, shot blast, shakeout (sand), muller, grinding, wheelabrators, collector, cleanroom, blast, fume, pretreater and desulfurization, cutoff, fines, finish, pagborn, carter day collector, large wet collector, sand reclaimer, tailing, baghouse
Slag	Slag, furnace refractory, iron, ductile, melt, copula, popcorn, ladle relining, crucibles/ brick
Sludge	Sludge, copula, furnace, pugmill, cake

2.2 Chemical and Environmental Characterization of Excess Foundry Sands

Chemical and environmental characterization of excess foundry sand is a critical issue that needs to be addressed prior to wider acceptance of beneficial reuse programs. It is essential to understanding the potential for the development of beneficial applications. Each stream of material has unique characteristics that assist engineers in making a decision between beneficial reuse, reclamation or waste disposal. Chemical and environmental concerns of excess foundry sands dominate the issue of reusing them. They may contain elements or compounds that pose impacts to environments and threats to human health. The thresholds of these elements or compounds are regulated by environmental regulations. Their measurements are covered by extraction procedures and chemical analytical techniques.

2.2.1 Act and Regulations

The act regulating excess foundry sand as a solid waste is the Resource Conservation and Recovery Act (RCRA). RCRA was enacted in 1976 with the intent to "protect human health and the environment from the improper handling of solid waste and to encourage the conservation of natural resources." The Office of Solid Waste (OSW) of the U.S. Environmental Protection Agency (EPA) administers the RCRA program.

The Code of Federal Regulations (CFR) is a codification of the rules published in the *Federal Register* by executive departments and agencies of the federal government.

The CFR is divided into 50 titles that represent broad areas subject to federal regulation, with environmental regulations contained mainly in CFR Title 40. CFR Title 40 contains the rules that EPA uses to implement the requirements of the RCRA.

The parts closely relating to the characterization of excess foundry sands in CFR Title 40 are Part 261, "Identification and Listing of Hazardous Waste," Part 141 "National Primary Drinking Water Regulations," Part 143, "National Secondary Drinking Water Regulations," and Part 264, "Standards for Owners and Operators of Hazardous Waste Treatment, Storage, and Disposal Facilities." Part 264 provides the maximum concentration of constituents that the uppermost aquifer underlying the waste management area meets for groundwater protection purposes. The thresholds corresponding to individual regulation are listed in Table C-1, Table C-2 and Table C-3 in Appendices C.1 and C.2.

A groundwater transport model is used to set regulatory levels against which concentrations in the leachate by the Toxicity Characteristics Leaching Procedure (TCLP, addressed in Section 2.2.2.1) are compared. Regulatory levels represent a back-calculation from an acceptable chronic exposure level in a receptor well, through the unsaturated and saturated zones, back to the sources, the bottom of the landfill, accounting for dilution and attenuation that is predicted to occur between bottom of the landfill and receptor well, through a groundwater transport model, as demonstrated in Figure 2-6. EPA assumes that water wells were situated 150 m (500 ft) down gradient from the landfill on which EPA based its determination of dilution and attenuation factor

(DAF) of 100 for all of the listed toxic constituents based on the availability of chronic toxicity reference levels [EPA 1995]. The available references include Standards of National Drinking Water and Groundwater. For instance, the limit for mercury in drinking water and groundwater is 0.002 ppm. Considering the dilution and attenuation occurring to mercury when transported 150 m from the initial landfill leaching site to water wells or sources, the maximum allowable concentration for mercury in initial leachate ("A" in Figure 2-6) is 0.2 ppm.

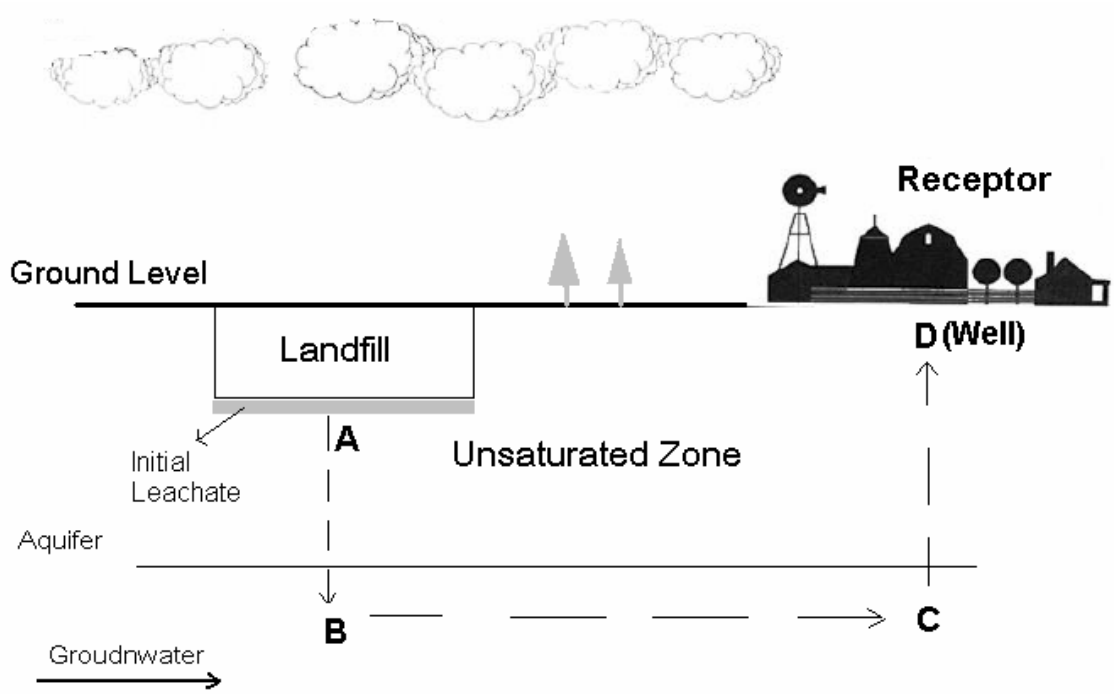

Figure **2-6**: Demonstration of leachate transport model [Kimmell 1999]

Although thresholds are only specified for leachates by the Toxicity Characteristics Leaching Procedure based on the dilution and attenuation model, leaching protocol is essentially independent of the threshold values. The thresholds are determined by a transport model of leachate and available standards for groundwater and drinking water. Thresholds are basically set for any initial leachate below landfills ("A" in

Figure 2-6). That is, a leachate from Synthetic Penetration Leaching Procedure (SPLP, Section 2.2.2.2) should transport according to the dilution and attention model as well. Thresholds for that leachate similarly comply with DAF 100. Hence, thresholds for TCLP are applicable to an initial leachate extracted by any leaching protocol. In essence, the difference among various leaching protocols is not their thresholds, but the field conditions they simulate, such as actively decomposing municipal solid waste landfills simulated by TCLP (Section 2.2.2.1) and industrial waste monofills by SPLP (Section 2.2.2.2).

2.2.2 Chemical Analytical Techniques

The ability to accurately detect and quantify an element or compound present in a sample, even at extremely low concentrations, is critically important in terms of assessing a waste stream for potential contamination. For example, when monitoring a disposed foundry sand, the toxicity violation of a single volatile organic compound in its leachate is often taken as evidence that the foundry sand has a direct impact on the environmental quality, while the absence of volatile organic compounds leads to a neutral assessment. The assessment as out-of-compliance could be extremely costly to the facility, and may prevent the beneficial reuse of future material.

Chemical analytical techniques are used to prepare, identify and quantify elements or compounds contained in excess foundry sand. The tasks are mainly classified into two parts: bulk chemical analysis and leachate chemical analysis. Bulk chemical

analysis determines the compound mass percentage of solid wastes in dry or as-received condition without any extraction. Leachate chemical analysis evaluates the compound concentration level in the leachate extracted from dry or as-received solid waste samples by appropriate leaching protocols. The latter is generally selected to determine whether the disposed solid wastes are hazardous or not. The most used protocols include Toxicity Characteristics Leaching Procedure, Synthetic Precipitation Leaching Procedure, and Shake Extraction of Solid Waste With Water (ASTM D 3987). Both bulk chemical analyses and leachate concentration analyses require selecting appropriate chemical procedures to measure an element or compound. The most used procedure manuals include: "Test Methods for Evaluating Solid Waste, Physical/Chemical Methods" [EPA SW-846 2000] and "Methods for the Determination of Metals in Environmental Samples" [EPA 1991].

2.2.2.1 Toxicity Characteristics Leaching Procedure

TCLP is a leaching protocol published by EPA as Method 1311 [EPA SW-846 2000]. This leaching protocol is meant to model the leaching behavior of a material disposed in an actively decomposing municipal solid waste landfill in which carboxylic acids are formed from microbial processes, which is a particular worst-case scenario under the RCRA specification of a mismanagement scenario of wastes. If disposal conditions are different from the municipal landfill conditions, another test may better predict the actual leaching of a waste and provide better numerical estimates of leaching. In TCLP, solid samples are extracted with an acetate buffer solution. The extraction fluid

employed is a function of the alkalinity of the solid phase of the waste. A liquid-to-solid ratio of 20:1 by weight is used for an extraction period of 18 ± 2 hours. After extraction the solids are filtered through a 0.6 to 0.8 µm filter from the liquid extract, and analyses are conducted on the leachate to determine the elements' concentrations.

2.2.2.2 Synthetic Precipitation Leaching Procedure

SPLP is a leaching protocol published by EPA as Method 1312 [EPA SW-846 2000]. This leaching protocol was developed to simulate leaching through an industrial waste monofill under acid rain conditions. The procedure is similar to the TCLP; however, the amount of acidity used in the test is significantly less. Furthermore, an aqueous solution of nitric/sulfuric acid mixture is used in the SPLP as an extraction fluid, rather than a more aggressive buffered acetic acid in the TCLP. This procedure more closely simulates the field conditions for beneficial use in the general construction industry.

2.2.2.3 Shake Extraction of Solid Waste with Water (ASTM D 3987)

ASTM D 3987 is a neutral leaching protocol published by ASTM [ASTM D 3987 1985]. This procedure is a useful indicator in considering the potential environmental impact of foundry sand waste and its beneficial use practices. The intent of this test method is that the water extraction simulates conditions where the solid waste is the dominant factor in determining the pH of the extract. It uses Type IV reagent water as the

extraction solution, which differentiates it from the acidic medium leaching protocols TCLP and SPLP.

2.2.3 Research on Characterization of Excess Foundry Sands

A literature review indicated that characterization of excess foundry sand can be divided into two parts, qualitative characterization and quantitive characterization. Qualitative characterization represents those evaluations concentrating on summary statistics of excess foundry sand characterization. The frequent topics are as follows:

- Is the sand hazardous in the context of toxicity regulation [Orkas 2002, Ji et al. 2001, Ham et al. 1993]?
- What is the maximum extraction level of some compounds?
- Is there any correlation between field leaching level and laboratory extraction level [Ham 1984, Kendall 2003], among compounds [Boyle 1984], or with other external factors [Ham and Boyle 1981]?
- Which waste stream leaches worse [Ham 1984, Boyle 1984]?
- What is the distribution of compounds after arbitrary assumption [Kauffman and Voigt 1999]?
- What are the chemical characteristics of spent sand across the foundries [Regan et al. 1994]?

Quantitive characterization concentrates on deeper characteristics of excess foundry sand. Supported by abundant data resources, it employs a professional statistical methodology to look further into the data and make data more meaningful. The topics include censored data processing, estimation of mean and its confidence interval, and factorial design and analysis. Peer disciplines such as water resources, medical and biological studies, chemical studies, and soil and earth studies have conducted research on censored data. However, little work has been done to study excess foundry sand characterization at the quantitative level.

2.2.4 Chemical Characteristics from Past Studies

An overview of publicly available results on leachability of metals from foundry sand waste is collected and summarized in Tables 2-6 through 2-9. Random scattering around mean values is significant. The standard deviations are usually greater than the respective mean concentrations. Average, median, or maximum values are occasionally reported. Only a few projects were completed with a comprehensive statistical analysis that included the determination of a roster of statistical parameters to characterize a vast pool of analytical data [Winkler 2000].

One vital conclusion drawn from Table 2-6 is that excess foundry sand disposed of in a foundry monofill or used in highway construction leaches regulated metals well below the characteristic toxicity levels. This is usually because the constituents are either present in forms that are not soluble or are unavailable to the leaching media. Even when

the presence of the constituents in a bulk waste stream can be traced, this does not always imply that they could readily be leached. A comparison to a mixed-waste municipal landfill indicates that the foundry sand waste leaches one to two orders of magnitude less than the typical waste in a municipal landfill [Winkler 2000].

Table **2-6**: Leachability of metals from foundry sand waste [Winkler 2000]

Research Description	Leaching Method	Primary Contaminants (mg/l)							Secondary Contaminants (mg/l)					**
		As	Ba	Cd	Cr	Hg	Pb	Se	Ag	Cu	Fe	Mn	Zn	Ni
Drinking Water Maximum Contaminant Level	Total Elem	0.05	2.0	0.005	0.01	0.002	0.015*	0.05	0.1	1.0	0.3	0.05	5.0	
Toxicity Characteristic Level	TCLP	5.0	100	1.0	5.0	0.2	5.0	1.0	5.0					
Highway embankment constructed with Indiana ferrous foundry waste sand. Maximum measured values.	Field Leachate			0.054	–		–			–			0.85	0.0
Median Wisconsin field leachate values, averaged over six ferrous foundry mixed waste landfills.	Field Leachate	<.005	<0.46	<.001	<0.02	<.005	<0.02	<0.13	<.002	0.02	0.54	0.27	0.15	
Typical Wisconsin mixed municipal solid waste landfill. Maximum values.	Field Leachate			0.07	1		1.1			0.3			54	1.7
Spent molding sands. Average over 52 Pennsylvania foundries.	TCLP	0.06	0.4	0.03	0.1	0.005	0.3	0.08	<.049	0.25	70	0.9	2.2	0.2
Spent sand waste. Average over a cluster of 28 out of 33 Pennsylvania ferrous and non-ferrous foundries.	TCLP, ASTM D346	0.006	0.33	0.03	0.1	.0005	0.25	0.03	0.06	0.2	28	0.35	0.4	0.1
Mixed molding waste (sand, binder, dust, sludge). Gostyn foundry, Poland.	TCLP EP			– 0.1	– –		0.25 –			1 0.2	13 31	1.6 2.2	1.4 0.9	7 –
Wisconsin brass foundry sands + dusts. Average value.	TCLP+EP						**11**							
Wisconsin brass foundry sands + dusts, chemically treated to convert metals into non-leaching forms.	TCLP+EP	–	–	0.018	–	–	0.18	–	–					
Wisconsin ferrous foundry waste sand. Average of two.	EP										0.04	1.1		
Wisconsin typical ferrous foundry mixed waste landfill.	EP	<.005	<0.46	<.001	<.003		<0.01	<0.13	<.002	<.002	66	2.9	0.4	
Molding sand (6% western bentonite, 7% sea-coal) subjected to process temperature. Maximum values.	3 Leaching Cycles, H_2O		<0.75		<1.1					1.1	15	<0.75	1.2	
Brown-black furan-bonded sand waste + dust (1:1), air dried. Dessau foundry, Germany.	DIN 38414 S4 H_2O pH=7.5	0.01		<0.1	0.07	<.001	0.6			0.25			0.5	0.3
Black-brown silicate waterglass-bonded fine sand waste, air dried. Magdeburg foundry, Germany.	DIN 38414 S4 H_2O, pH=10.1	0.13		<0.1	0.08	<.001	0.6			0.5			1.1	0.6
Brown-black furan-bonded sand waste + dust (1:1), air dried. Dessau foundry, Germany.	DIN 38414 S7 Aqua Regia	0.45		0.3	69	0.02	11			27			33	6
Black-brown silicate waterglass-bonded fine sand waste, air dried. Magdeburg foundry, Germany.	DIN 38414 S7 Aqua Regia	0.67		0.3	79	<.002	4.6			8.5			17	16

Note: See notes under Table 2-7.

Table **2-7**: Bulk content of metals in foundry sand waste, sands and soils [Winkler 2000]

Research Description	Method	Primary Contaminants (mg/kg)							Secondary Contaminants (mg/kg)					**
		As	Ba	Cd	Cr	Hg	Pb	Se	Ag	Cu	Fe	Mn	Zn	Ni
Drinking Water Maximum Contaminant Level	Total Elem	0.05	2.0	0.005	0.01	0.002	0.015*	0.05	0.1	1.0	0.3	0.05	5.0	
Toxicity Characteristic Level, mg/l	TCLP	5.0	100	1.0	5.0	0.2	5.0	1.0	5.0					
Brown-black furan-bonded sand waste + dust (1:1), air dried. Dessau foundry, Germany.	Total Elem X-ray fluo	<2		<2	284	<2	14			27			33	5
Black-brown silicate waterglass-bonded fine sand waste, air dried. Magdeburg foundry, Germany.	Total Elem X-ray fluo	<2		<2	5870	<2	7			7			32	21
Spent molding sands. Average over 52 Pennsylvania foundries.	Total Elem	2.3	24	2.2	29	1.5	49	2.2	<1.9	308	1.5%	108	246	
Spent sand waste. Average over a cluster of 30 out of 33 Pennsylvania ferrous and non-ferrous foundries.	Total Elem	1.1	13	1.9	8.9	0.06	24	1.2	2.4	117	3.9%	72	26	29
Molding waste (sand, binder, dust, sludge). Median values derived from 14 samples. Gostyn foundry, Poland	Total Elem			3	101		45			15	15%	291	112	32
Black spent sand piles. Samples averaged over two New England iron casting foundries.	Total Elem EPA 6010	2	30	<0.2	2.8	0.02	7.5	<5	<0.5					
Black spent sand + dust. Massachusetts iron foundry. Average of 4 samples collected within 6 months.	Total Elem EPA 6010	4.5	35	0.2	3.4	0.01	9	<5	<0.5					
Florida natural soil: Candler fine sand (96.7% sand, 2.5% clay, 0.8% silt, 0.8% organics, pH=6.5).	8 Leaching Cycles, H_2O									0.23	0.20	0.44	0.08	
Unprocessed sand for molding. Median values obtained with 5 samples. Gostyn foundry, Poland.	Total Elem			1	–		6			0.4	970	–	21	–
U.S. sandy soils, lithosols on sandstones. Vegetation safe	Total Elem	5.1	400		40	0.08	17	0.5		14	1-3%	345	40	175
U.S. non-contaminated soils. Maximum values.	Total Elem	60	3000	0.7	1000	0.3	200	2	5	100	5%	3000	300	300

Note: A cell is blank if a parameter was not measured.

< Below detection limit.

– Below unspecified detection limit.

* Action level which triggers treatment of water system if exceeded in more than 10% tap water samples.

** Ni is mandatory for monitoring along with other contaminants tabulated by the National Primary Drinking Water Regulations, but no maximum contaminant level is currently specified by EPA. MA DEP defines Ni 0.1mg/l as the concentration in drinking water at or below which adverse, non-cancer health effects are unlikely to occur after chronic (lifetime) exposure. MA DEP only indicates a potential need for further legislative action to be decided.

Table **2-8**: Typical TCLP and SPLP results from smelting operation sludge [Winkler 2000]

Metal Leaching	TCLP (mg/L)	SPLP (mg/L)
Pb	570	1.5
Cd	1.9	0.13
Cr	5.1	0.9

Table **2-9**: Lead leachability versus total element analysis of red brass foundry sand samples and synthesized mixtures [Winkler 2000]

Sample	EP Toxicity [a] Pb, mg/L	Total [b] Pb mg/kg	Ratio EP Tox/Total
Spent molding sand, Leaded brass foundry A	70	1900	0.04
Spent molding sand, Leaded brass foundry B	111	1100	0.10
Spent molding sand, Leaded brass foundry C	35		
Clean virgin sand + Pb fine particles (0.1%)	673	1000	0.67
Clean virgin sand + PbO (1%)	6380	10000	0.64
Clean virgin sand + $PbSiO_3$ (0.1%)	318	1000	0.32

[a] 100g sample, 2000 mL acetic acid solution (0.5N), pH=5.0, agitation 24 hours.
[b] 1g random sub-sample, total acid digestion (HNO_3 + HCl).

2.3 Controlled Low-Strength Material (CLSM)

2.3.1 Introduction

CLSM, also referred to as flowable fill, is a self-compacted, self-set, marginally cementitious material used primarily as a backfill in lieu of compacted backfill. It has the following features listed by American Concrete Institute (ACI) Committee 229 [ACI Committee 229 1994]:

- Self-leveling, liquid-like materials, and self-compacting to 95-100% of the maximum unit weight with minimal effort and no vibration or tamping.
- Maximum compressive strength[1] of 8 MPa (1200 psi) at 28 days.

Most CLSM applications require unconfined compressive strengths of 1,400 kPa (200 psi) or less to allow for future excavation using hand tools or light digging equipment.

CLSM necessarily contains cement and water. It may also contain fly ash, aggregate, or chemical admixtures in proportions such that the final product meets the strength and flow consistency requirements.

The main construction advantages of CLSM can be summarized as: limited labor, equipment and inspection, accelerated construction, ready placement at inaccessible locations, improved safety, and the possibility of manual excavation in the future [Abichou et al. 1999]. CLSM may be an economical alternative to placing and compacting soil in trenches and around, pipes, vaults, sewers, and manholes. There could be considerable savings of time and labor over conventional backfill methods. CLSM can be delivered in ready-mixed concrete trucks and placed by chute directly into the area to be filled or into a pump for final placement. It eliminates the need for vibrating compaction machinery on a job site, increases the speed of construction, and reduces the liability exposure for backfilling deep trenches.

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[1] In this report, compressive strength represents unconfined compressive strength.

The geotechnical advantages of CLSM include: improved flow properties, improved strength control, limited subsidence, uniform density and load, negligible impact from volume changes due to moisture levels, and low hydraulic conductivity.

The main applications of CLSM can be summarized as follows, depending on the strength control. Excavatable CLSM is used widely as backfill for utility cuts, trenches, pipes, vaults, abandoned underground pipes, culverts, tanks, mines, sewers, voids under roadways, foundations, and retaining walls. Structural filling is used widely as load support for pipe bedding, road base, bridge approaches, paving subbase, floor slab subbase, liner base, cover mats, and replacement of poor-quality soil [Adaska and Krell 1992, Naik et al. 1990, Naik and Singh 1997, Larsen 1990, Wilson 1999].

Limitations and cautions do exist for CLSM, despite its numerous advantages. CLSM is a heavy fluid material and during placement will exert high fluid pressures against any form, embankment, or walls. Placing CLSM in multiple layers may be required to control movement or shifting and prevent floating of pipes or vaults.

2.3.2 Specification of CLSM Containing Excess Foundry Sands

The use of CLSM on construction projects is gaining popularity, and most states have developed or are developing specifications or regulations for CLSM [Abichou et al. 1999, Regan et al. 1998, Regan et al. 1997, Regan and Voigt 1996, Kauffman et al. 1996, Van Tassel 1999]. Pennsylvania Department of Transportation (PennDOT) has

developed extensive specifications for flowable backfills. The specifications were developed for four types of CLSM [PennDOT 1995]. Type A and Type B are CLSM where future excavation is desirable. They are typically used as backfill for utility trenches, pipe trenches and bridge abutments, and around box or arch culverts. Type C CLSM is used when future excavation is not anticipated. It is typically used to replace unsuitable soils below foundations and to fill abandoned conduits, tunnels, and mines. Type D CLSM is used for construction on areas requiring low-density backfill such as abutments over soft soils, backfill for sensitive retaining walls, vault filling, and backfill on top of buried structures. Type A and Type D CLSM contain only fly ash and cement and therefore are not considered for beneficial reuse of foundry sands. PennDOT specifications for these four CLSM are summarized in Table 2-10.

Table **2-10**: PennDOT specifications for CLSM [PennDOT 1995]

Component	Type A	Type B	Type C	Type D
Cement (Kg/m^3)	60	30	89-119	178-415
Fly ash (Kg/m^3)	1187	178	178	60-237
Bottom ash (Kg/m^3)	0	1543	1543	---
Spread (cm)	15-23	15-23	15-23	15-23
Strength, 3 day (kPa)	> 172	> 172	> 2069	> 276
Strength, 28 day (kPa)	345-862	345-862	> 5516	621-2758

The flowable fill specification developed by the Iowa Department of Transportation allows the use of fine aggregate, fly ash and cement. Fine aggregate is defined as natural sand consisting of mineral aggregate particles or foundry sand from the castings of ferrous material. The basic proportioning for flowable fill mortar is presented in Table 2-11.

Table **2-11**: Iowa DOT specifications for CLSM [Iowa DOT 2004]

Quantities of Dry Materials Per Cubic Yard (Cubic Meter)	
Cement	100 pounds (60 kg)
Fly Ash	300 pounds (180 kg)
Fine Aggregate	2,600 pounds (1545 kg)

The specifications of Ohio Department of Transportation refer to CLSM as low-strength mortar backfills. They recommend the mixture design presented in Table 2-12. The Ohio specifications specifically mention the possibility of using foundry sands and require the development of alternative mixtures to meet the strength and flowability criteria. These specifications also provide detailed information about mixing and placement of flowable fills.

Table **2-12**: Ohio DOT specifications for flowable fill [ODOT 1997]

	Type 1*		Type 2		Type 3	
Cement	kg/m^3	lbs/yd^3	kg/m^3	lbs/yd^3	kg/m^3	lbs/yd^3
Fly Ash, Class F	30	50	59	100	0	0
Fly Ash, Class C ****	148	250	**	**	890	1500
Sand ***	0	0	0	0	297	500
Water (Target)	1726	2910	1436	2420	0	0
	297	500	125-178	210-300	504	850

* An air-entraining agent specifically designed for use in the low-strength mortar mixture may be added to this mix.

** Entrained air is substituted for fly ash in this mix.

*** Saturated surface dry.

****Class C fly ash may be substituted for Class F fly ash in Type 1 mixes with an approved mix design meeting the alternate mix design criteria of this specification.

Other states require mixture designs similar to the above specifications. However, they do not specifically refer to the potential beneficial reuse of foundry sand as a portion

or a full replacement of the fine aggregate in flowable fills. In addition, it was recommend that design mixtures be developed to satisfy local and state strength and flow requirements. The mix presented in Table 2-13 could be used as a starting mixture. Cement quantity is adjusted to meet strength criteria [Abichou et al. 1999].

Table **2-13**: Starting mixtures of CLSM [Abichou et al. 1999]

Components	Mix I	Mix II (IDOT)
Cement (kg/m^3, lbs/yd^3)	30/50	59/100
Fly Ash (kg/m^3, lbs/yd^3)	148/250	0
Sand (kg/m^3, lbs/yd^3)	1726/2910	1436/2420
Water (kg/m^3, lbs/yd^3)	Adjusted to meet flowability criteria	

2.3.3 Research of CLSM Containing Excess Foundry Sands

The introduction of excess foundry sand to CLSM is a recent innovation. The early research can be traced back to the demonstration projects on flowable fill that were initiated by the Ohio Cast Metals Association (OCMA) et al. in 1993.

CLSM is typically a mixture of sand, fly ash, cement, and water. Since sand is the major component of CLSM, replacing the natural sand with foundry sand is an attractive beneficial reuse application. Research includes laboratory experiments and field construction and investigation. The main topics concentrate on the percentage of excess foundry sand substituted for fly ash or fine aggregate, monitoring performance and environmental impacts in highway construction, and developing mixture formulations. Most of the research used one to three excess foundry sands as the raw feed. The critical

performance parameters, as proposed by this research, include flowability/work consistency, unconfined compression strength development, hydraulic conductivity, and environmental impacts.

Javed and Lovell prepared flowable fill mixtures using Class F fly ash, Type I cement, and a foundry sand [Mast 1997]. Mixture designs were tested for spread (flowability), set time, and compressive strength. It was concluded that foundry sand mixtures perform better than conventional flowable fill mixture [Joved and Lovell 1994B]. Investigations regarding the economy of foundry sand reuse, flow characteristics, hardening patterns, 28-day compressive strength, long-term strength, pore size distribution, hydraulic conductivity, pH of the pore water, and stress-strain characteristics were conducted, and it was concluded that flowable fill, containing up to 55.5% foundry sand, is an economic alternative to conventional compacted fills [Bhat and Lovell 1996]. In the same investigation, a step-by-step procedure for flowable mix design was developed. The CLSMs containing Class F fly ash and foundry sand from ferrous castings are environmentally benign [Joved and Lovell 1994B, Bhat and Lovell 1996, Bhat and Lovell 1997].

Naik and Singh [Naik and Singh 1997B] concluded that foundry sand can be used in flowable fills to replace up to 85% of the fly ash used in the reference mixture, and that the permeability of the flowable mixtures was affected by an increase in either the water to cementitious materials ratio or the foundry sand content. The other aspect of the study dealt with hydraulic conductivity [Naik and Singh 1997]. The hydraulic conductivity is

important because more permeable fills have greater leachability potential. Results of the test program showed that a minimum hydraulic conductivity occurs when 30% of the fly ash is replaced with foundry sand. Flowable fills having 70% of the fly ash replaced with foundry sand do not have significantly different hydraulic conductivities. However, when 85% of the fly ash is replaced with foundry sand, the hydraulic conductivity increases dramatically. Low hydraulic conductivity is also correlated to water to cementitious material ratios ranging from 0.4 to 0.6. Three green sands from ferrous foundries and two Class F fly ashes were used. The flow behavior, hardening characteristics, ultimate strength behavior, and permeability characteristics of flowable fill were investigated. The penetration resistance necessary to sustain workability as the fresh flowable fill hardens was determined. The pH of pore solution of hardened flowable fill indicated that the potential for corrosivity was low.

Additional research studies have been performed to enhance or qualify excess foundry sand applied to CLSM. The chemical characteristics of a wide spectrum of spent molding sands from Pennsylvania foundries were established, from which environmental impacts might be determined, and statistical protocols were used, including clustering and factorial analyses to address the chemical characteristics [Regan et al. 1993]. A database addressing the projects on the beneficial reuse of excess foundry sand was developed [Abichou et al. 1999]. In this database, 98 nationwide projects were categorized into applications of flowable fill, embankment and subgrade, portland cement concrete, asphalt concrete, portland cement manufacturing, landfill cover and linear system, and soil amendments. The section of flowable fill reviewed the laboratory

research and field study on the beneficial reuse of excess foundry sand to flowable fill. Laboratory tests were performed to characterize physical and mechanical properties of foundry sands [Hiltunen et al. 1992]. The leaching of chemicals from all major foundry waste streams and leachability of materials that include the beneficially used foundry by-products as aggregates were studied [Winkler 2000, Bol'shakov and Winkler 2001].

Research studies have been performed to demonstrate the beneficial reuse of excess foundry sand, which are not limited to CLSM. The addition of non-hazardous excess foundry sands to soil amendments for the greenhouse and nursery industries has been investigated as an environmentally sound, beneficial use option of these foundry residuals [Dunkelberger and Regan 1997]. The potential reuse of selected foundry wastes for highway construction, such as for bridge approach embankments, was performed [Lovejoy et al. 1996].

2.4 Hot-Mixing Asphalt (HMA)

2.4.1 Findings From Previous Studies at UW - Madison

The first study from the University of Wisconsin–Madison Asphalt Research Group that dealt with incorporating foundry sand into HMA was led by Ms. Edna Miller and was entitled, “Utilization of Foundry Sand in Hot Mix Asphalt” [Miller et al. 1998]. In this study, 17 foundry sands from around Wisconsin were tested for their gradation, angularity, absorption and sand equivalent value. They were also individually

incorporated into a mix design to see how they would affect the volumetric properties of HMA. The JMF of each mix was held moderately constant to the control JMF.

It was found that foundry sands can contain between 1.0% and 16.5% of material passing the 75 µm (#200) sieve, depending on the type of binder system used. Generally, if a sand contains bentonite, there will be a larger amount of fines. The angularity of the sands ranged between 39% and 48%. The high angularities were attributed to rough surface texture and irregular rounded shapes. This was partly due to burnt additives adhering to the silica sand surface, as when iron oxide adheres to silica sand when used with the sodium silicate binder. The clay content was measured using the sand equivalent test, varied between 6% and 97%. Finally, the percent absorption ranged between 0.3% to 6.2%.

The second study completed by the University of Wisconsin – Madison Asphalt Research Group was led by Mr. Kenneth Delage [Delage et al. 2001]. This project focused more on the performance testing of the compacted samples, and not as much on the physical properties of the foundry sands, or on how they affect the volumetric properties of HMA. Five of the sands from Miller's study were used. The main performance tests used were the GLPA, the Hamburg Wheel for rutting and moisture damage, and the Superpave Shear Tester.

Delage concluded that it was difficult to measure the sand equivalency of foundry sands and suggested this could be overcome by mixing foundry sands with regular

natural sands. It was also concluded that foundry sands cause HMA to become less sensitive to moisture damage as compared to the control. Lastly, it was concluded that foundry sands do not necessarily increase or decrease a mixture's rutting potential, but do improve fatigue performance.

The most recent study completed by the UW Asphalt Research Group was one led by Mr. Andrew Braham entitled, "The Use of Blended Recycled Foundry Sand in Hot Mix Asphalt" [Braham 2002]. In this study, five sands from Indiana and three sands from Wisconsin were used. Each sand was tested for its absorption, angularity, and percent of material passing the 75 µm sieve. The sands were then mixed together to vary the levels of absorption, angularity and P-75µm to see how it would affect the volumetric properties of the mixes, energy indices, and moisture sensitivity.

It was concluded that varying the levels of the absorption, angularity and fines did not affect the performance of the HMA. Secondly, the absorption test used for aggregates does not work well for foundry sands, because of the high amount of clay found in most foundry sands. Also, the sand equivalent test could not be used for foundry sands due to the additives "clouding up" the test. Last, it appeared that foundry sands decreased the tensile strength ratio of HMA mixes, but because the 95% confidence interval was so large, the TSR values could have been negative, or exceeded 100%.

2.4.2 Overcoming Problems Faced in Previous Studies

Based on these three studies, it was decided that in order to be able to accurately determine the effects of foundry sand on HMA performance, a better way to measure the clay content, absorption, and moisture sensitivity would have to be developed. For the clay content, a method used by the foundry industry involving the methylene blue cation was modified and used. For absorption, a method developed by a company called Instrotek® was modified and used. For the TSR, stricter sieving procedures were used, as well as the help of an automated saturation device. The following sections give background for each of the methods used.

2.4.2.1 Methylene Blue

The methylene blue molecule has the following chemical composition [Pike 1992]:

$$C_{16}H_{18}N_3S.Cl.xH_2O$$

The methylene blue cation is readily absorbed by clays. Worrall [1968] stated that methylene blue was absorbed in three different stages. In the first stage, the methylene blue cations create a monolayer around the clay molecules. After this, they begin to replace all the other cations that are on the clay surface (for example, sodium cations on western bentonite and calcium ions on southern bentonite). Eventually the methylene blue cations are physically absorbed by the clay surface, but because of the large size of the MB cation, the absorption is only minor. Hang and Brindley [1970] surface area of the molecule to be about 130 ? ^{2} with dimensions of 17.0 x 7.6 x 3.25 ? .

The foundry industry has taken advantage of clay's ability to absorb the methylene blue cation and has developed several standards to measure the clay content of foundry sands. As mentioned earlier in this chapter, due to the intense heat of the foundry process, clay can break down and lose its ability to adhere to silica sand particles. When this happens, it also loses its ability to attract methylene blue cations. By monitoring how much methylene blue a foundry sand can absorb, a foundry can determine the level of active clay left in the foundry sand. The two most common methods used are the AFS 2210-00-SS "Methylene Blue Clay Test, Ultrasonic Method, Molding Sand," and 2211-00-S, "Methylene Blue Clay Test, Boiling Method, Molding Sand" [American Foundry Society 2001].

Originally for this project, it was decided that AFS 2210-00-SS would be used to determine the methylene blue values of the foundry sands. The boiling method was more dangerous and left more room for error. The AFS 2210-00-SS method uses an ultrasonic cleaner to remove any clay from the silica sand particles and put them into solution. The solution is then stirred using a magnetic stir rod, and methylene blue dye is added by use of a burette. To check the titration point, material is removed using a glass stirring rod and dropped onto filter paper. Once a light blue halo appears, the titration point has been found, and the clay particles are assumed to be saturated.

The most difficult problem with this method is determining when the blue halo appears. Through personal contacts with Mr. Mark Nagel of the Cast Metals Institute, it

was apparent that there is no definite blue halo, but its presence is subject to the opinion of the person running the test. Since the graduate and undergraduate students working on this project lacked the experience to determine where the blue halo occurs, a procedure was developed using a spectrophotometer. The wavelength was set at 670 nm. It was shown by Gessner, Schmitt, and Neumann that methylene blue dye absorbs this wavelength of light most readily.

The second obstacle to overcome was to determine the level of absorbance (absorbance of 670 nm light) at which the sample has reached its titration point. Figure 2-7 shows a plot of volume of methylene blue dye solution verses absorbance. From this figure it seems that at an absorbance of about 0.2 the slope of the data changes. The point at which the slope changes was considered to be the titration point. It was assumed that the clay is no longer absorbing the methylene blue cation, but is instead going into solution.

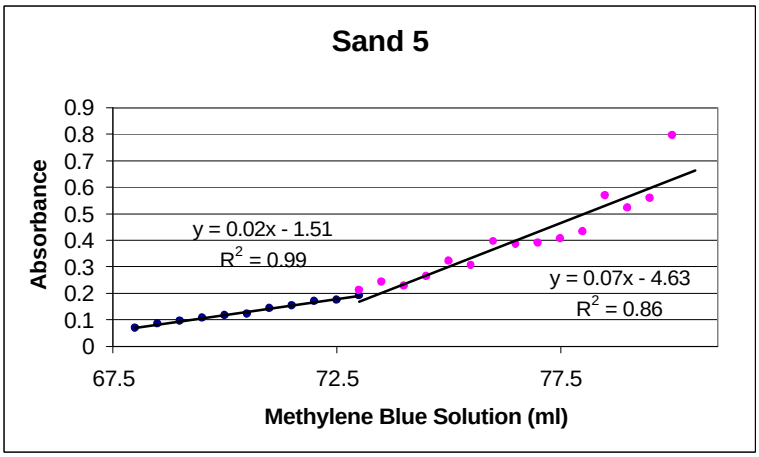

Figure **2-7**: Titration point of Sand 5

2.4.2.2 Absorption

The main purpose of the absorption test is to determine the bulk and effective density of an aggregate. The method commonly used to determine the bulk density is ASTM C127. In this method, the fine aggregates are soaked in water for 24 hours. This soaking is supposed to encourage water to penetrate the macro and micro pores of the aggregate. If the aggregate is then weighed in water, the apparent density can be determined. This method is straightforward and leaves less room for debate than finding the bulk density. The bulk density is defined as the mass of aggregate per volume of aggregate plus its micro pores. The main question then arises, "What is the defining line between a micro pore and a macro pore?" (see Figure 2-8).

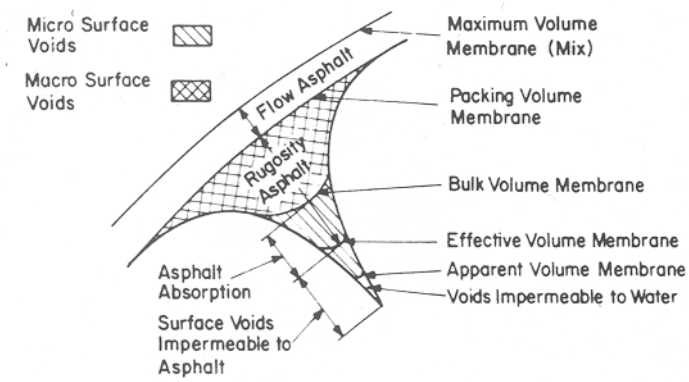

Figure **2-8**: Apparent, effective and bulk densities [Ishai and Ton 1977]

According to ASTM C127, after the aggregates have been totally saturated with water, they have to become Saturated Surface Dried (SSD). SSD is when the macro pores are free of water, but the micro pores are still filled with water. To reach the saturated surface dried condition, the aggregates are very slowly dried using a fan. This process can

take up to 6 hours. As the aggregates become drier, they are placed in a cone and tapped 25 times. Once the aggregates slump, the water is assumed to have left the macro pores, and has reached a saturated surface dry condition. Most contractors and researchers do not like this test, because it is time consuming and is not based on scientific reasoning. As Braham pointed out in his thesis [Braham 2002], the clay particles made it difficult to reach the SSD condition, because clay likes to bind silica sand particles together. So, even if the sand had reached the SSD condition, it may not have slumped due to the adhesive nature of the clay.

The InstroTek® Company developed another method to determine the dividing line between macro and micro pores. Instead of saturating the sample with water and then slowly drying the aggregates, their method first saturates the macro and micro pores with air, and fills the macro pores with water, while leaving the micro pores filled with air. This is done by placing the aggregates in water, and then quickly, but gently stirring the aggregates, so that air is removed from the packing and macro pores, but left in the micro pores (Figure 2-9). The aggregates are then weighed in water and the bulk density is determined. This method is much easier to use because it takes only a fraction of the time as ASTM C127, so it can be repeated more rapidly. Also, there is no cone and tapping hammer, which can lead to human errors. Last, and most important to this research project, the clay's adhesive properties do not cause error in determining the bulk density. Even though clay is adhesive, it should not prevent water from penetrating the packing and macro pores.

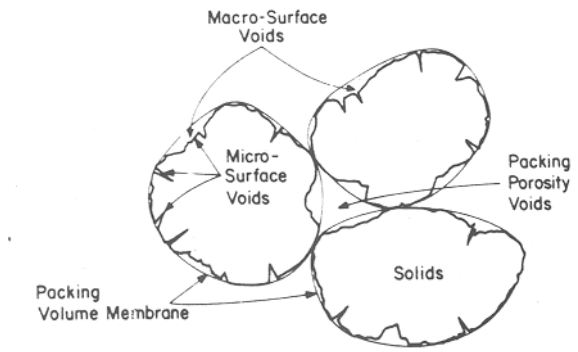

Figure **2-9**: Difference between packing, macro and micro voids [Ishai and Ton 1977]

2.4.2.3 Tensile Strength Ratio

One of the important findings reported by Braham in his study report is that the error associated with the indirect tension test rendered most of the results to be invaluable, even though specifications were followed [Braham 2002]. Khosla, Birdsall, and Kawaguchi [2000] showed that the level of air voids and saturation greatly influenced the indirect tension values. They showed that as the percent air voids increased from 6% to 8%, and as the level of saturation increased from 55% to 80%, the TSR value decreased from 74.5% to 48.6% with Asheboro aggregates, 79.6% to 58.2% with Fountain aggregates, and 88.8% to 61.7% with Castle Hayne aggregates. So although the same aggregate, gradation, and asphalt content were used, and ASTM D4867 was followed properly, the variation associated with the TSR caused the results to be inconclusive as to whether or not an HMA mixture was susceptible to moisture damage.

The first step that was taken to narrow the error in this study was to do a more thorough job of sieving aggregates. It was assumed that as aggregates are more carefully sieved, and sieved to more fine components, better quality control can be achieved. Typically, aggregates are only sieved down to the 2.36 mm (#8) sieve size. All material passing the 2.36 mm sieve is considered as one size material and is sieved no further. In this study, all the fine aggregates were sieved down to the 75 µm (#200) level. Also, the dust correction factor was taken for each aggregate size to take into account dust that was statically attached to the larger aggregates. This sieving procedure allowed a more consistent air void content to be achieved. To create a more consistent level of saturation, the Corelok™ device was used instead of the rice pump. Since the Corelok™ device is automated, it can very consistently draw a partial (and programmable) vacuum on the compacted asphalt sample, so that a certain level of air voids become saturated.

Chapter 3

CHARACTERIZATION DATA

In this chapter, the datasets addressing the characterization of excess foundry sand and other foundry by-products, including dust, slag, and sludge, that were collected nationwide were analyzed through charts of scatterplots. Charts of plots are more informative than lists of tables. It is an inductive procedure in which data are summarized rather than tested. Results through plotting provide patterns and support theories of how the data systems behave and provide guidance for the selection of appropriate deductive hypothesis testing procedures [Hesel and Hirsch 1992].

3.1 Excess Foundry Sand Characterization System

According to RCRA and federal regulations, excess foundry sand needs to be exposed to toxicity evaluation preceding its disposal or reutilization. The mandatory evaluation is on the leachate extracted by approved leaching protocols. Some samples are pre-exposed to bulk chemical analysis to evaluate whether the samples require leaching evaluation.

The leaching protocols extensively used by commercial chemical laboratories include TCLP (Section 2.2.2.1), SPLP (Section 2.2.2.2), and ASTM D 3987 (Section 2.2.2.3). The selection of leaching protocols depends on state regulations and laboratory

facilities. The significant difference among three leaching protocols is the extraction environments they simulate, which leads to operation variation. TCLP intends to simulate an actively decomposing municipal solid waste landfill in which carboxylic acids are formed from microbial processes. SPLP intends to simulate an acid rain condition similar to an industrial waste monofill. ASTM D 3987 intends to simulate a condition where the solid waste is the dominant factor in determining the pH of the extract.

Not all leaching protocols have corresponding toxicity thresholds for TCLP, which forms a barrier to assess the toxic characterization of samples extracted by SPLP and ASTM D 3987. However, TCLP thresholds are reasonably applicable to evaluation of SPLP and ASTM D 3987 leachates (Section 2.2.1).

3.2 Data Sources

The data were collected from 180 foundries throughout the United States from the years of 1997-2001 using tests performed by independent commercial laboratories for regulatory compliance. The datasets are partitioned by waste streams, leaching protocols and metals cast in Table 3-1. In each dataset, up to 27 general chemical parameters, 24 metallic elements, and 55 organic compounds are addressed. They are managed by a database coded with Microsoft Access, which was released as a CD disk. In this study, excess foundry sand was exclusively characterized.

Table **3-1**: Partition of datasets

	Bulk analysis			Leachate composition		
Sand	314	192	61%	650	343	53%
Dust		58	18%		173	27%
Slag		57	18%		111	17%
Sludge		7	2%		23	4%
TCLP	N/A			1163	543	47%
SPLP					345	30%
ASTM D 3987					275	24%
Iron-based facility	263	187	71%	607	457	75%
Steel-based facility		30	11%		64	11%
Aluminum-based facility		31	12%		61	10%
Copper-based facility		15	6%		25	4%

3.3 Bulk Chemical Analysis

Bulk chemical analysis is the characterization of foundry sand without any extraction. Elements covered in bulk chemical analysis include those regulated by TCLP thresholds and heavily involved in the metal casting process. They are normally divided into three groups: general chemical parameters, metallic elements and organic compounds. Most of them are measured at trace level in parts per million, except for several parameters in their own standard units, such as pH, conductivity, and moisture, etc.

3.3.1 Major Oxides

Major oxides are analyzed by x-ray fluorescence analysis. The American Foundry Society (AFS) conducted an investigation of oxides in excess foundry sands, with results

presented in Table 3-2. It is indicated that silica occupies on average 88% by mass of the excess foundry sand.

Table **3-2**: Foundry sand sample chemical oxide composition [AFS 1991]

Oxides	Percentage by mass (%)
SiO_2	87.91
Al_2O_3	4.70
Fe_2O_3	0.94
CaO	0.14
MgO	0.30
SO_3	0.09
Na_2O	0.19
K_2O	0.25
TiO_2	0.15
P_2O_5	0.00
Mn_2O_3	0.02
SrO	0.03
TOTAL	94.72

Silica is not a regulated toxic element and is environmentally benign regardless of its concentration, except for its respirable hazard at a defined particle size. It mainly comes from the sand aggregates that are the refractory materials of casting molds and cores. Its variation in concentration spans from 36% to 99.7% as shown in Figure 3-1.

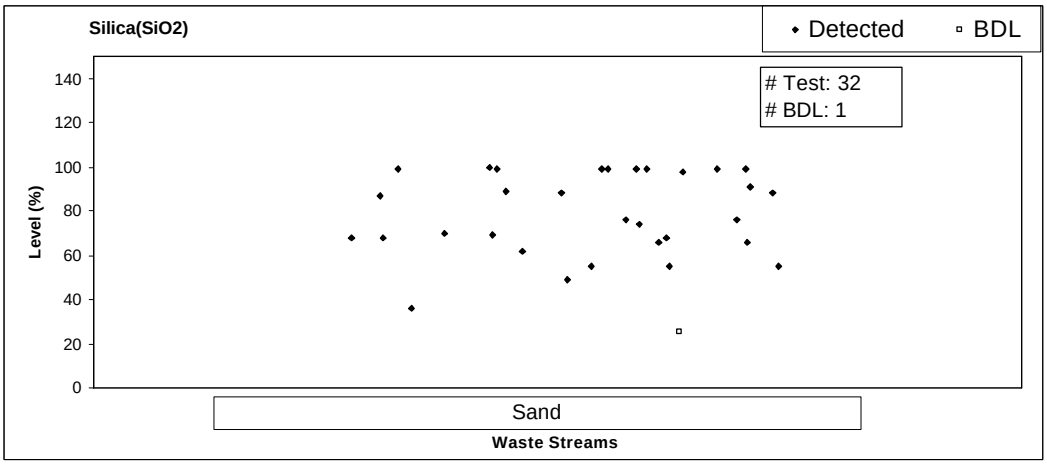

Figure **3-1**: Silica content by mass in waste streams

3.3.2 Metallic Elements

The term "trace element" is rather loosely used in the scientific literature to designate a number of elements that occur in natural systems in small concentrations. As defined in many dictionaries, trace elements are those chemical elements, especially metals, used by organisms in minute quantities but believed essential to their physiology. However, the term is and has been used to designate elements with no known physiological function which, when present in sufficient concentrations, may be toxic to living systems [Bradford et al. 1996].

Trace level metallic elements listed in Table 3-3 are the mostly monitored elements. They cover a wide spectrum of heavy metals that may come from various scrap feed or alloy additions, and common light metals that are also hazardous to human health if digested or inhaled in enough amounts. The compositions of these elements for collected samples are plotted in Figure D-1 in Appendix D.1.

Table **3-3**: Metallic elements in bulk chemical analyses

Aluminum	Antimony	Arsenic	Barium	Beryllium
Boron	Cadmium	Calcium	Chromium	Cobalt
Copper	Iron	Lead	Magnesium	Manganese
Mercury	Molybdenum	Nickel	Selenium	Silicon
Silver	Thallium	Zinc	---	---

It is indicated that the distribution of most metallic elements is consistent with the dilution theory and simulation model of environmental data, “a concentration resulting from a series of independent random dilutions tends to be lognormally distributed” [Ott 1990]. As illustrated in Figure D-1, the dominating tendency of distribution is that

observations heavily cluster to a low level, even zero, and occurrence frequency varies inversely against concentration. Therefore, the estimated frequency curve is right skewed. However, each assumption for the distribution model of each metallic element, in spite of lognormal or normal distribution, needs to be statistically tested to make results defensible.

3.3.3 Chemical Parameters

General chemical parameters listed in Table 3-4 represent typical inorganic elements and chemical properties identified in general chemical characterization reports. Most of them are inorganic and nonmetallic elements. Parts of them address characteristics regulated by environmental regulations, such as reactive cyanide and reactive sulfide for reactivity, pH for corrosivity, and ignitable point for ignitability. The detailed distributions for these parameters are plotted in Figure D-2 in Appendix D.2.

Table **3-4**: General chemical parameters in bulk chemical analyses

Chloride	Reactive cyanide	Total cyanide	Fluoride
Formaldehyde	Ignitable point	Hexavalent chromium	Total phenols
Total moisture	Total petroleum hydrocarbons	Extractable organic halides (EOX)	Total organic halogens (TOX)
pH	Total volatile solids	Oil and grease	Reactive sulfide
Sulfide	Total volatile residue	Loss on ignition (LOI)	---

The reactivity characteristic is to identify wastes that, because of their extreme instability and tendency to react violently or explode, pose a problem at all stages of the waste management process [EPA SW-846 2000]. One evaluating method is the concentration of reactive cyanide and reactive sulfide.

For reactivity, the concentrations of reactive cyanide for foundry sands are well below the threshold of environmental regulation. The concentrations of reactive sulfide for foundry sands are well below the threshold of environmental regulation, except for one sample: sand from an aluminum-based facility. The observation is 2,075 ppm against a reactivity threshold of 500 ppm.

The corrosivity characteristic is designed to identify wastes that might pose a hazard to human health or the environment due to their ability to mobilize toxic metals if discharged into a landfill environment, to corrode handling, storage, transportation, and management equipment, or to destroy human or animal tissue in the event of inadvertent contact [EPA SW-846 2000]. From the pH tests, it is presented that foundry sands are non-corrosive. All observations are within threshold intervals of 2-12.5. And foundry sands tend to be alkali.

The objective of the ignitability characteristic is to identify wastes that either present fire hazards under routine storage, disposal, and transportation or are capable of severely exacerbating a fire once started [EPA SW-846 2000]. Foundry sands have a flash point greater than 60 ºC, which is the regulated minimum of ignitability. Thus, foundry sands are non-ignitable.

3.3.4 Organic Compounds

Trace-level organic elements listed in Table 3-5 represent most compounds used or potentially produced by decomposition in metal casting bonding processes. The bulk distributions of these compounds for collected foundry sand samples are plotted in Figure D-3 in Appendix D.3.

Table **3-5**: Organic compounds in bulk chemical analyses

Aroclor-1016	Aroclor-1221	Aroclor-1232	Aroclor-1242
Aroclor-1248	Aroclor-1254	Aroclor-1260	Total-PCBs
Acenaphthylene	Anthracene	Benzene	Benzo(a)anthracene
Benzo(b)fluornathene	Benzo(k)fluornathene	Chrysene	o-Cresol
m_p-Cresol	2,4-Dimethylphenol	Ethylbenzene	Fluoranthene
Fluorene	1-Methyl naphthalene	2-Methyl naphthalene	4-chloto-3-methyl Phenol
Naphthalene	Phenanthene	Pyrene	Styrene
Toluene	Xylene	---	---

Censored observations, those values below detection limits (BDL), occupy a great portion of observations for bulk organic compounds in foundry sands. Compounds with 100% censoring include Aroclor-1016, Aroclor-1221, Aroclor-1232, Aroclor-1242, Aroclor-1248, Aroclor-1254, Aroclor-1260, and Total-PCBs. The other organic compounds have censoring fraction mostly above 50%. The principal reason for a high censoring fraction is that most of the organic compounds are significantly burned out during high-temperature melting. Even if minimum organic residuals are attached to by-product grains, they cannot be quantified by bulk chemical analyses. Due to high censoring, there is no information to infer but that these organic compounds are below reporting limits.

3.4 Leachate Concentration

The criteria to determine whether a waste stream is hazardous or not depends on the characteristics of leachate extracted from waste streams using acceptable leaching protocols [40 CFR Part 261 1986]. Currently the federal regulation accepts TCLP as a leaching procedure and provides a toxicity threshold for toxicity assessment purposes. Some regulatory agencies and commercial laboratories use SPLP and ASTM D 3987 leaching procedures, as mentioned in Section 2.2.2. The leachate characterization is divided into three groups: metallic elements, general chemical parameters, and organic compounds. Most of them are measured at trace level using unit ppm or ppb.

3.4.1 Metallic Elements

The leachate concentrations of metallic elements listed in Table 3-6 are plotted in Figure E-1 in Appendix E.1. The X-axis represents leaching protocols; the Y-axis represents concentrations of elements. Each point (solid or hollow) corresponds to an observation. The count of total observations and count of censored observations are listed in each chart associated with corresponding leaching protocols. The dashed line in the top of the chart indicates the toxicity threshold.

Table **3-6**: Metallic elements in leachate analyses

Aluminum	Antimony	Arsenic	Barium	Beryllium
Boron	Cadmium	Chromium	Cobalt	Copper
Iron	Lead	Magnesium	Manganese	Mercury
Molybdenum	Nickel	Selenium	Silver	Sodium
Thallium	Vanadium	Zinc	---	---

The EPA toxicity thresholds, presented in Table C-1 in Appendix C.1, are the standards by which foundry sands are assessed. If the TCLP leachate concentration of any metallic element, including arsenic, barium, cadmium, chromium, lead, mercury, selenium, and silver is above the corresponding toxicity threshold, the foundry sand yielding the leachate is considered hazardous [40 CFR Part 261 1986].

Although metallic elements do exist in the leachate as presented in Figure E-1 in Appendix E.1, excess foundry sand has been found to be largely environmentally benign through toxicity assessment. The concentrations of RCRA eight metallic elements, including arsenic, barium, cadmium, chromium, lead, mercury, selenium, and silver, are well below corresponding thresholds. It is suggested that excess foundry sand can be beneficially reused, posing very low environmental or human health risk.

Two observations for selenium exceeded TCLP toxicity limits. The description of the samples is “recyclable.” Further classification from the metal casting facilities and chemical lab would be required to determine the nature of the observed samples.

Leaching protocol is a significant factor. TCLP tends to yield more metallic elements, particularly RCRA eight metallic elements, than SPLP and ASTM D 3987 protocols. This is because the toxicity tests are designed to simulate the worst-case conditions in a municipal landfill. The other two protocols more closely simulate beneficial reuse conditions of foundry sand, such as embankments and flowable fill. A further quantitive investigation is performed in Section 5.6.

The distributions of metallic element concentrations in the leachate are closer to the lognormal model than normal model, which means that denser frequency is close to zero. This is consistent with the distribution tendency indicated by bulk analysis in Section 3.3.2. However, the distribution assumption requires further diagnosis.

3.4.2 Chemical Parameters

The leachate concentrations of general chemical parameters listed in Table 3-7 are plotted in Figure E-2 in Appendix E.2.

Table **3-7**: General chemical parameters in leachate analyses

Cyanide	Formaldehyde	Phenols	Initial pH
Final pH	Fluoride	Ammonia	Hexavalent chromium
Chloride	Nitrate	Nitrite	Oil and grease
Sulfate	Acidity	Alkalinity	Conductivity
Total dissoluble solid (TDS)	Total organic halide (TOH)	Total petroleum hydrocarbon	Chemical oxygen demand (COD)
Total sulfide	---	---	---

3.4.3 Organic Compounds

The leachate concentrations of organic compounds listed in Table 3-8 are plotted in Figure E-3 in Appendix E.3. According to RCRA, 34 organic compounds are regulated regarding the toxicity of solid waste by federal regulations [40 CFR Part 261 1986], as presented in Tables C-2 and C-3 in Appendix C.2. As with metallic elements, a violation of any organic compound results in the assessment that samples are hazardous and cannot

be disposed to traditional landfills or reused in construction. In this investigation of foundry sands, 23 out of 37 organic compounds are regulated as presented in Figure E-3. All observations are well below toxicity thresholds and foundry sands are non-hazardous based on regulated organic compounds.

Table **3-8**: Organic compound in leachate analyses

Compounds with 100% censoring		
Cresol_para	Pentachlorophenol	Methylene chloride
Cresol_total	Pyridine	1_1_1-Trichloroethane
Dinitrotoluene (2_4)_total	Trichlorophenol (2_4_5)	Vinyl chloride
Hexachloro-1_3-butadienel	Trichlorophenol (2_4_6)	m_p Xylene
Hexachlorobenzene	Carbon tetrachloride, total	Chlorobenzene
Hexachloroethane	Fluoranthene	Chloroform
Nitrobenzene	Methyl ethyl ketone	Dichlorobenzene (1,4 total)
1_2-Dichloroethane	1_1-Dichloroethylene	
Compounds with censored and uncensored data (censoring percentage)		
Acetone (0%)	**Phenanthrene (75%)**	Benzene (96%)
Toluene (55%)	**Ethyl benzene (75%)**	Tetrachloroethylene (96%)
Styrene (69%)	2_4-Dimethylphenol (84%)	Cresol_ortho (85%)
Naphthalene (71%)	Xylene_total (85%)	Methyl isobutkl ketone (88%)
Trichloroethylene (73%)	Cresol_meta (92%)	

It is presented in Figure E-3 that censored observations, which are marked by hollow squares, occupy a great portion of the observations. In Table 3-8, 23 out of 37 typical organic compounds are 100% below detection limits in sand leachate. Seven out of the remaining 14 compounds are more than 80% censored; these are cresol_m, cresol_o, benzene, 2_4-Dimethylphenol, tetrachloroethylene, xylene_total and methyl isobutkl ketone. Compounds with a censoring fraction less than 80% include acetone, ethyl benzene, naphthalene, phenanthrene, styrene, toluene, and trichloroethylene. Those

23 organic compounds with 100% censoring are suggested to be eliminated from regulatory requirements, as inappropriate testing keeps foundry sand from beneficial reuse.

The phenomenon of high censoring for organic compounds is consistent with the high censoring that observed in the bulk analysis of organic compounds. The same reasoning can be used to explain that most of the organic compounds are significantly burned out during high-temperature melting, and even if minimum organic residuals are attached to by-product grains, they are difficult to dissolve or extracted and quantified in the leachate analyses. Due to high censoring, there is no information to infer but that these organic compounds are below reporting limits.

Chapter 4

METHODOLOGY ADDRESSING CENSORED DATA

This chapter addresses a statistical methodology to evaluate characterization data that are highly nested with incomplete observations. Starting with survival analysis, this method estimates summary statistics and hypothesis testing with sound confidence.

4.1 Censored Data

More often than not, environmental monitoring data consist of a mixture of results that can and cannot be quantified precisely. The portion of nonquantifiable observations, reported as below limits or "not detected," is referred to as "censored data" for statistical purposes.

In chemical analyses, the instrument detector provides the electronic signals to register the mass to determine the concentration. The lower the concentration is, the more difficult it is to clearly distinguish the signals from other electronic background noise. Conceptually there has to be some limit, below which it is not possible to determine if there is detection or not. In that concept, some numerical standard is brought in to specify the limitation of the instrument.

One important standard is called the “Method Detection Limit” (MDL), which is approved by the U.S. EPA. MDL is defined as the minimum concentration of a substance that can be measured and reported with 99% confidence, where the analyte concentration is greater than zero and is determined from analysis of a sample in a given matrix containing the analyte [40 CFR Part 136 Appendix B 1986]. The derived terms of detection limits that may exist in chemical reports include “Quantity Detection Limit” (QDL) and “Low Detection Limit” (LDL).

In the database of this research program, datasets may contain observations censored at multiple reporting limits for a parameter. This occurs frequently as limits are lowered over time at a single laboratory or when data having different censoring limits are pooled from multiple laboratories [Hesel 1990]. Environmental monitoring data usually are right skewed, and sometimes very highly skewed. This is especially true for data close to zero that include censored data, because the lower bound of zero ensures a right skew [Hesel 1990].

4.2 Current Methods

In general, if the data were not censored, they could be used to determine the parameters of a Probability Density Function (PDF) and Cumulative Distribution Function (CDF) to diagnose the best-fit distribution model of uncensored data, and then PDF and distribution models could be used to predict any characteristics of waste streams. Data on environmental chemicals are often modeled with the lognormal PDF

[Ott 1990]. Lognormal PDF eliminates the risk of estimating negative concentrations and predicts mostly low concentrations except for a long tail to the right, simulating contaminated situations [Science Advisory Board 1995]. Weibull PDF is another option that has the same feature with the additional advantage that it can be integrated analytically to produce a CDF that enables convenient estimates of the occurrence of specific concentrations [Mackay and Paterson 1984].

However, the nature of frequently censored environmental data impedes the application of conventional statistical procedures. The data of interest are not complete. Censored observations represent ranges rather than a number. Censoring ranges from 0 to 1 depending on the composition of samples and quantitive level of instruments. It is not applicable to run conventional statistical programs on data containing quantified and nonquantifiable data, and it is not suitable to substitute arbitrarily for nonquantifiable data. Multiple censoring limits in a data pool further complicate the issue.

A flag system is recommended to annotate those censored data to facilitate data processing [Mikel 2001]. EPA has recommended that laboratories be asked to provide uncensored data on all water samples with measurements near or below the limit of detection [EPA 1991]. However, for those censored data in the research reported herein, there are no quantitative values provided but the reporting limits. A methodology needs to be developed to address censored data. In 2001, a literature search was conducted for EPA to identify articles that discuss detection and quantitative limit approaches

[DynCorp 2001]. A total of 181 publications were identified in this search. The main approaches are discussed in the followed sections.

4.2.1 Substitution

EPA has traditionally substituted zero or one-half the reporting limits for censored data and computed the average concentration in the usual way. Its assumption of equal precision or zero fill-ins is demonstrably false, but the method is computationally simple and often adequate for most practical purposes if the quantifiable frequency is 80% or more [Gibbons and Coleman 2001, Hesel 1990]. With the advent of convenient software, there appears to be no reason to use simple substitutions.

4.2.2 Regression on Order Statistics (ROS)

Hashumoto and Trussell were the first to suggest normal regression for the problem of estimation of censored water quality data [Hashimoto and Trussell 1983]. A straight line is fit to the normal scores of the order statistics for the uncensored observations and then to fill in values extrapolated from the straight line for the observations below the detection limit. Distribution parameters of mean and standard deviation were determined by Gilliom and Hesel [Gilliom and Hesel 1986]. First, the mean and standard deviation are computed by using the half detection limits, then the censored data are replaced by random variates selected from a right-truncated normal distribution with derived mean and standard deviation. The mean and standard deviation

are recomputed as the estimated parameters for total population. This method is modified by more robust approaches, which combine uncensored data with censored data extrapolated, assuming a distributional shape fitted by maximum likelihood estimation (MLE) or probability plot procedures, in order to compute estimates of summary statistics [Hesel and Cohn 1988]. In a similar way, censored data are replaced by the expected value of the normal order statistics with the mean and standard deviation estimated from the noncensored data. The process is repeated until there is no significant change in the mean and standard deviation in the total data set [Gleit 1985].

4.2.3 Maximum Likelihood Estimation

Maximum likelihood estimation uses both uncensored and censored observations to compute statistics for the entire data set. It calculates the estimated mean and standard deviation by adjusting downward the statistics of the uncensored observations as a function of the amount of censoring in the data set.

The earliest and most used method was published in two papers by Cohen [Cohen 1959, Cohen 1961]. This method gives the following maximum likelihood estimators for censored data, Equation 4.1 and Equation 4.2, in terms of a tabulated function of two arguments:

$$m_{ML} = m^* - (m^* - x_0)\, f(g,h) \qquad \text{Equation } \mathbf{4.1}$$

$$s_{ML}^2 = s^{*2} + (m^* - x_0)^2\, f(g,h) \qquad \text{Equation } \mathbf{4.2}$$

Where: m_{ML} = estimated value of the population mean by maximum likelihood

s_{ML}^2 = estimated value of the population variance by maximum likelihood

m^* = sample mean for uncensored values

s^* = sample standard deviation for uncensored values

x_0 = detection limit

$$g = \frac{s^{*2}}{(m^* - x_0)^2}$$

h = fraction of censored data

f = Refer to tables developed by Cohen

Persson and Rootzen [1977] developed two sets of estimators that are somewhat simpler to compute, called restricted maximum likelihood estimators. However, these methods are limited to single censoring data, which are not popular in environmental monitoring data.

4.2.4 Nonparametric Methods (NP)

ROS and MLE are parametric methods, because their validity depends on knowing the population distribution function, and any hypothesis test or confidence interval estimation is based on the assumption that the population distribution function is known, or known except for some unknown parameters. Nonparametric methods do not assume a particular population probability distribution, and are therefore valid for data from any population with any probability distribution, which can remain unknown. These

methods use ranks that may be considered preferable to the actual data. If the numbers assigned to the observations have no meaning by themselves but attain meaning only in an ordinal comparison with the other observations, the numbers contain no more information than the ranks contain [Conover 1999].

A number of studies have been published comparing these methods and showing alternative algorithms for solving the censoring problem [Gleit 1985, Gilliom and Hesel 1986, Kroll and Stedinger 1996, Gibbons and Coleman 2001]. These studies have consistently found the ROS and MLE procedures superior to simple substitution methods. ROS and MLE perform about equally well under low to moderate censoring, while MLE has some advantage when the censoring fraction is high (up to 80%). As expected, the efficiency of the estimators decreases with the degree of censoring and the effect is more pronounced on the estimate of the variance versus the mean.

Even with an agreed-upon censoring point, there is considerable controversy regarding the appropriate method or methods for incorporating the censored data in computing summary statistics, resting hypothesis, and computing interval estimates. This is not at all surprising, since the correct choice of method depends on both the degree of censoring (e.g., 20% versus 80% nondetects) and the type of application (e.g., computing the mean versus computing a prediction limit from data that are a mixture of quantifiable and nonquantifiable observations), as well as ease of use. Additionally, the controversy can be fueled by an inclination toward a particular favorable outcome [Gibbons and Coleman 2001].

Although various methods for processing censored data are available, none of them will perform better than the analogous method for uncensored data, and the method for censored data will probably be more complicated [Porter, Ward and Bell 1988].

When censoring is low (i.e., less than 50%) these methods are sufficiently robust to estimate the parameters [Gibbons and Coleman 2001]. When censoring is higher than 50%, none of the methods discussed above works well, and due to the validity of assumptions taken by most methods, an alternative strategy must be employed.

4.2.5 Methods Discussion

Ignoring censored data is the worst procedure because it loses the left tail information, which occupies much in the case of left-censored data. Replacing those censored data with any arbitrary number, such as zero, a tenth of the reporting limits, half of the reporting limits, and the report limits, is theoretically unsupportable and results in unpredictable significant bias. Competitive substitutions may include the mean or median of those uncensored data below the reporting limits. However, it is difficult to qualify this substitution, too. Essentially the mean or median of the uncensored data below a reporting limit is not the unbiased estimate of the reporting limit. Methods using any kind of substitution should be avoided.

An assumption of many current methods is that the measurements are continuous and normally distributed, or can be suitably transformed to approximate a normal

distribution. In the context of foundry sand characterization applications there are two special problems. First, measurements are nested within laboratory and sand background. The data from a laboratory on a sample may be normally distributed; however, each sampling location may have a different mean and variance, offsetting the measurements from one location to another. A test of normality for the composite will generally yield a rejection of the hypothesis that the data are normally distributed.

Second, the presence of censored observations will generally produce rejection of the normality hypothesis regardless of whether or not the quantifiable observations are normally distributed. One solution is simply to ignore the censored data and test the assumption of normality on uncensored data. When detection frequency is high (say 90% or more), this may produce reasonable results. If the censoring is high, ignoring the nondetects can be misleading because it eliminates the lower tail of the distribution and can be therefore falsely reject the hypothesis of normality. On the other hand, including the nonquantifiable observations at the detection limit introduces a spike in the distribution that can also, incorrectly, cause the rejection of normality [Gibbons and Coleman 2001].

Both MLE and ROS assume that the true concentrations in all samples come from a common population that is lognormally distributed. Violation of this assumption can lead to invalid applications of a statistical technique. The decisions and conclusions derived from incorrectly used statistics can be expensive. For example, incorrect use of a statistical limit may lead to excessively conservative or unsafe conclusions, such as

remediation of a clean part of the site, or no remediation at a contaminated part of the site. The first conservative conclusion will result in an unnecessary cleanup, whereas the second unsafe conclusion may cause a threat to human health and the environment. It is likely that the availability of new and improved statistical software has also increased the misuse of statistical techniques [Singh et al. 1997].

When a statistical method is based on assumptions that appear to be invalid or impossible to verify, nonparametric methods have been become essential tools in the statistical analysis workshop. It does not depend on any distribution assumption and making more efficient use of the data, when parametric methods are inappropriately applied. The immediate application to censoring data is survival analysis.

4.3 Survival Analysis

In this section, survival analysis is discussed and applied to process environmental censored data. The main topics include estimated mean and its confidence interval, the hypothesis tests, and distribution model analysis.

4.3.1 Introduction

Survival analysis addresses the right-censored observations, namely the time to "death." The time may be observable, say "death," or unobservable, say "loss." The Kaplan-Meier Estimator (KME) [Conover 1999] is a widely used method in this field. It

uses the fact that if "death" occurs after time x, then "death" also occurs after all time prior to x. For example, 3 of 10 timing belts survive 85,000 miles, and the other 7 timing belts break prior to 85,000 miles. The probability of surviving 85,000 miles $P(X >$ 85,000) = 3/10 = 0.3. If a timing belt survives 85,000 miles, it definitely survived 80,000 miles. The joint probability of surviving both 85,000 miles and 80,000 miles is $P(X >$ 85,000, $X >$ 80,000) = 3/10 = 0.3. Hence, the probability of timing belts surviving 85,000 miles is equal to the probability of timing belt surviving both 85,000 miles and 80,000 miles. Equations 4.3 and 4.4 provide general reasoning.

Call $x_0 < x_1 < x_2$,

then $P(X > x_1) = P(X > x_1,\ X > x_0) = P(X > x_1 | X > x_0) \cdot P(X > x_0)$ Equation **4.3**

$P(X > x_2) = P(X > x_2,\ X > x_1) = P(X > x_2 | X > x_1) \cdot P(X > x_1)$ Equation **4.4**

Where: $P(X > x_1)$ = the probability of variable X greater than observation x_1

$P(X > x_1,\ X > x_0)$ = joint probability of variable X greater than observation x_1 and x_0

$P(X > x_1 | X > x_0)$ = the probability of variable X greater than observation x_1 given variable X greater than observation x_0, a conditional probability

In real censored data, $P(X > x_0)$ can be determined, and $P(X > x_i)$ and $P(X > x_{i-1})$ are frequently correlated. However, $P(X > x_i | X > x_{i-1})$ needs to be

estimated because the probability of survival of x_i is a future event that has not yet been reached.

4.3.2 Cumulative Probability and Survival Probability

In environmental data, data are generally left-censored, rather than right-censored data in survival analysis. This means that data are reported below reporting limits or quantifiable values. Two examples help differentiate right-censored and left-censored data.

Example 1 (right-censored data)

Eight fanbelts are tested on cars. The mileages are recorded. At the conclusion of testing, four have broken with mileages (in thousands of miles) of 77, 47, 81, and 56. The other four are unbroken with mileages of 62, 60, 43, and 71. The latter four data are censored. They present nothing but the information that their mileages are larger than 62, 60, 43, and 71, respectively.

Example 2 (left-censored data)

The concentrations of arsenic in 8 solutions are tested by 8 chemical labs. Four have detected values (in ppm) of 0.1, 0.03, 0.25, and 0.07. The other four are reported below method limits of 0.2, 0.04, 0.1 and 0.01. The latter four data are censored. They present nothing but the information that their arsenic concentrations are less than 0.2, 0.04, 0.1, and 0.01, respectively.

The fact used for probability reasoning for left-censored data is similar but in reverse to that for right-censored data. If the concentration of a sample is below x, then the concentration is also below all limits or values above x. Here is the detailed reasoning:

Call n observations in descending order, $x_0 > x_1 > x_2 > \ldots\ldots > x_{(n-1)}$, then

$$P(X < x_0) = 1 \qquad \text{Equation } \mathbf{4.5}$$

$$P(X < x_1) = P(X < x_0,\ X < x_1) = P(X < x_1 \mid X < x_0) \cdot P(X < x_0) \qquad \text{Equation } \mathbf{4.6}$$

$$P(X < x_2) = P(X < x_1,\ X < x_2) = P(X < x_2 \mid X < x_1) \cdot P(X < x_1) \qquad \text{Equation } \mathbf{4.7}$$

$$\ldots\ldots$$

$$P(X < x_{(n-1)}) = P(X < x_{(n-2)},\ X < x_{(n-1)}) = P(X < x_{(n-1)} \mid X < x_{(n-2)}) \cdot P(X < x_{(n-2)}) \qquad \text{Equation } \mathbf{4.8}$$

In these equations, $P(X < x_i \mid X < x_{(i-1)})$ is a conditional probability, which represents the probability of X less than x_i given that X is less than $x_{(i-1)}$. It is estimated using Equation 4.9. $P(X < x_i)$ is estimated using Equation 4.10, which is obtained by repetitive replacements of the above equations.

$$\hat{P}_i = (\text{Number of samples below } x_i) \,/\, (\text{Number of samples below } x_{(i-1)}) \qquad \text{Equation } \mathbf{4.9}$$

$$\hat{P}(x_i) = \hat{P}(X < x_i) = \hat{P}_1 \cdot \hat{P}_2 \cdot \hat{P}_3 \cdot \cdots \cdot \hat{P}_i = \prod_{0 < j \le i} \hat{P}_j \qquad \text{Equation } \mathbf{4.10}$$

So, the cumulative distribution function $P(x) = P(X < x)$ is estimated by Equations 4.11 through 4.14, which are similar to the KME. It is an increasing step function that takes steps at observed data. It is demonstrated in Figure 4-1. The function estimates the probability less than a value. For instance, a cumulative probability for the concentration of arsenic is $\hat{P}(0.3) = \hat{P}(X < 0.3) = 0.49$ in Figure 4-1. It indicates that the population probability of the arsenic concentration less than 0.3 is estimated as 49%, or equally, that the 49% quantile of population concentration is estimated as 0.3.

$$\hat{P}(x) = \hat{P}(X < x) = 1 \qquad \text{for } x > x_0, \qquad \text{Equation } \mathbf{4.11}$$

$$\hat{P}(x) = \hat{P}(X < x) = \prod_{x(i) \geq x} \hat{P}_i \qquad \text{for } x_{(n-1)} \leq x \leq x_0, \qquad \text{Equation } \mathbf{4.12}$$

$$\hat{P}(x) = \hat{P}(X < x) = 0, \qquad \text{for } x < x_{(n-1)},\ x_{(n-1)} \text{ is uncensored} \qquad \text{Equation } \mathbf{4.13}$$

$$\hat{P}(x) = \hat{P}(X < x) \in [0,\ \hat{P}(x_{(n-1)})], \text{ for } x < x_{(n-1)},\ x_{(n-1)} \text{ is censored} \qquad \text{Equation } \mathbf{4.14}$$

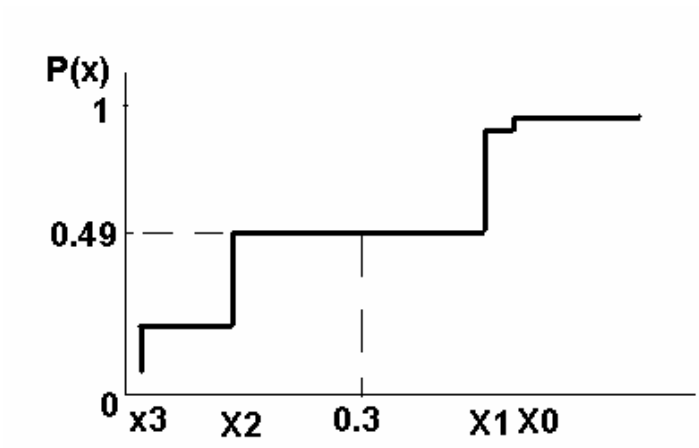

Figure **4-1**: Demonstration of cumulative distribution function

The facts used for the reasoning above are the following: if the concentration of a sample is below x, then the concentration is also below all limits or values above x. It is inappropriate to use the fact that if the concentration of a sample is above x, then the concentration is also above all limits or values less than x, which is applicable to right-

censored data. The main reason for rejecting the second fact is the nature of left censoring.

Call n observations in descending order, $x_0 > x_1 > x_2 > \ldots\ldots > x_{(n-1)}$, and parts of them are left-censored. At first, $P(X > x_{(n-1)})$ cannot be estimated as 1, for there are chances that parts of the left-censored data have real values less than $x_{(n-1)}$. Secondly, Equation 4.15 is inferred; however, its conditional probability $P(X > x_{(i+1)} \mid X > x_i)$ cannot be estimated. The number of observations known to be greater than x_i and $x_{(i+1)}$ is uncountable. Some observations are censored at limits greater than x_i and $x_{(i+1)}$; however, their real values are not meant to be greater than x_i or $x_{(i+1)}$. Counting these observations produces bias to an extent that depends on the nature behind these censored observations.

$$P(X > x_i) = P(X > x_{(i+1)},\ X > x_i) = P(X > x_{(i+1)} \mid X > x_i) \cdot P(X > x_i) \qquad \text{Equation } \mathbf{4.15}$$

Here is an example to further support the rejection. Consider an assumed arsenic concentration in leachates, Table 4-1. To estimate cumulative probability $P(X < 0.01)$, it is known that $P(X < 0.01) \geq 10\%$. Ninety percent of observations place censors at 0.5, and the uncensored data are well below 0.5. These uncensored data may indicate by their own weight that the real values of those 0.5-censored observations are well below 0.5 or within the range 0-0.01. Hence, the probability of observations less than 0.01 is increased more than 10%. If using the rejected fact, it is seriously biased to estimate $P(X > 0.01)$ as 90% or (1-10%), for those 90 censored observations may actually be partly or wholly

less than 0.01 according to their censoring nature and 10 quantified observations. This possibility results in a decrease of $P(X > 0.01)$.

Table **4-1**: Demonstration data of arsenic in leachates

Concentrations	Observations	Left censoring
0 – 0.01	10	No
0.5	90	Yes

The arithmetic to calculate the CDF of left-censored data can be executed using a Microsoft-Excel spreadsheet, discussed in Section 4.3.3. However, relying on Excel to process left-censored data is time consuming and yields relatively sparse statistical information. Important statistical parameters, including standard error, confidence interval etc., are not provided. And sometimes it is more important to know the percentage of variable exceeding a limit in environmental assessment. For instance, given a pool of datasets and a corresponding threshold, the probability of the data exceeding the threshold is investigated. A professional statistical software package called Mini Tab can handle this concern with ease. Its program for left-censored data outputs survival probability $S(X)$ rather than cumulative probability $P(X)$.

Survival probability $S(X)$ represents the probability that a variable exceeds a limit, $S(x_0) = P(X > x_0)$ in Section 4.3.1. The relation between the factors of cumulative probability $P(X)$ and survival probability $S(X)$ is presented by Equation 4.16. Hence, the probability determination is simple. The survival function is a decreasing step function, as demonstrated in Figure 4-2. It only decreases at quantified observations. It is

indicated that the probability of the variable greater than 0.3 is estimated as 32%, or equally, that the 32% quantile of population concentration is estimated as 0.3.

$$P(X) + S(X) + p(X) = 1 \qquad \text{Equation } \mathbf{4.16}$$

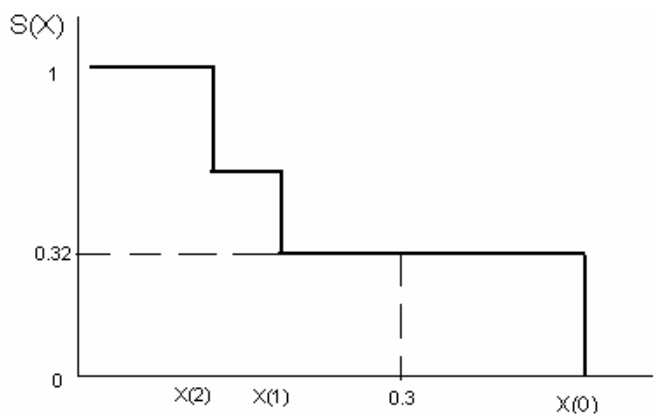

Figure **4-2**: Demonstration of survival function

4.3.3 Demonstration

An actual example to demonstrate survival analysis is presented in this section. Two datasets addressing the concentrations of barium in the leachate extracted from aluminum-based excess foundry sands by TCLP and ASTM D 3987 protocols are illustrated. Raw data are presented in Table 4-2. The raw data were fed into the spreadsheet of MS-Excel and coded arithmetically according to the survival analysis discussed in Section 4.3.2. Results are presented in Table 4-3. Regarding the cumulative distribution of barium in the TCLP leachate, it is estimated that 100% of concentrations are below 10 ppm, 94.4% of concentrations are below 1.8 ppm, the percentile corresponding to 1 ppm is 88.9%, and so on.

Table **4-2**: Barium in leachate by TCLP and ASTM D 3987

TCLP		ASTM D 3987	
Test Result (ppm)	Censoring	Test Result (ppm)	Censoring
10	Yes	0.47	No
10	Yes	0.33	No
1.8	No	0.31	No
1.62	No	0.18	No
1	Yes	0.17	No
0.7	No	0.14	No
0.54	No	0.126	No
0.39	No	0.089	No
0.36	No	0.04	No
0.33	No	0.033	No
0.32	No	0.01	Yes
0.31	No	0.01	Yes
0.3	Yes	0.01	Yes
0.2	Yes		
0.2	Yes		
0.2	Yes		
0.185	No		
0.115	No		
0.0783	No		
0.0251	No		

Table **4-3**: Estimated cumulative function of barium in leachate by TCLP

Observations (ppm)	Censoring	Numerator	Denominator	P_i	$P(X)$
10	Yes	20	20	1	1
10	Yes	19	19	1	1
1.8	No	17	18	0.944	0.944
1.62	No	16	17	0.941	0.889
1	Yes	16	16	1.000	0.889
0.7	No	14	15	0.933	0.830
0.54	No	13	14	0.929	0.770
0.39	No	12	13	0.923	0.711
0.36	No	11	12	0.917	0.652
0.33	No	10	11	0.909	0.593
0.32	No	9	10	0.900	0.533
0.31	No	8	9	0.889	0.474
0.3	Yes	8	8	1.000	0.474
0.2	Yes	7	7	1.000	0.474
0.2	Yes	6	6	1.000	0.474
0.2	Yes	5	5	1.000	0.474
0.185	No	3	4	0.750	0.356
0.115	No	2	3	0.667	0.237
0.0783	No	1	2	0.500	0.119
0.0251	No	0	1	0.000	0.000

MiniTab was used to evaluate the data in the calculation of survival function. The survival function for barium concentration in sand TCLP leachate is presented in Figure 4-3. From the survival function, it is interpreted that the maximum quantified observation is 1.8 ppm. Its minimum observation is close to zero, say 0+. Ninety percent of actual concentrations are between 0 and 0.7 ppm. The median is around 0.3 ppm. In addition, any quantile corresponding to a concerned probability and any percentile corresponding to a concerned value are estimated by interpreting the X-axis or Y-axis of crossed point in the survival function. For instance, the probability of concentration above 1 ppm is around 0.11. The quantile for a survival probability of 5% is around 1.8

ppm. The probability of concentration less than or equal to 0.54 ppm is estimated to be 0.8296, which is obtained by subtracting 0.1704 from 1.

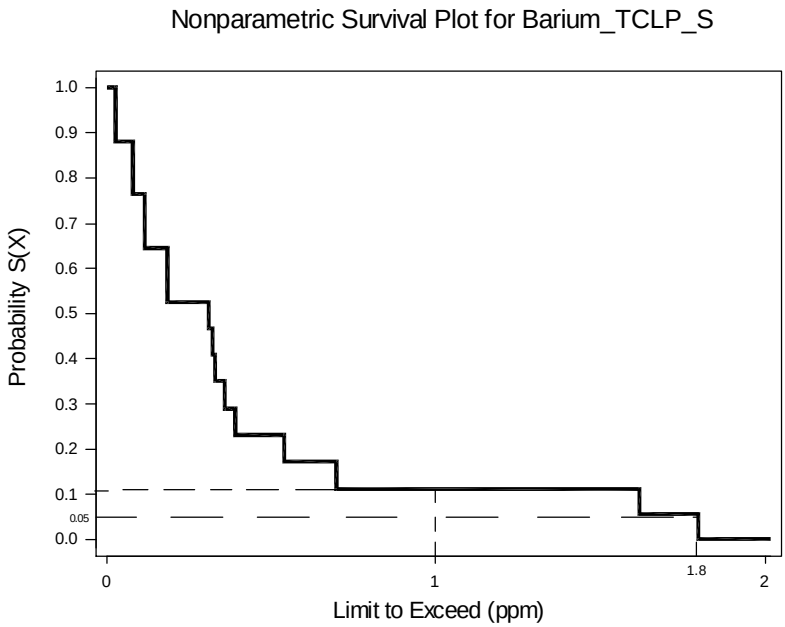

Figure **4-3**: Survival function for barium in TCLP

Equation 4.16 is verified through the combination of survival function $S(X)$ in Figure 4-3 and cumulative function $P(X)$ in Table 4-3. For example, when x = 0.31 ppm, $P(x < 0.31)$ is equal to 0.474; $p(x = 0.31)$ = $P(x < 0.32)$ - $P(x < 0.31)$ = 0.0593; and $S(x > 0.31)$ is equal to 0.4667. The sum of three factors is 1.

Using the same procedure as for TCLP, the survival function for barium in ASTM D 3987 is presented in Figure 4-4.

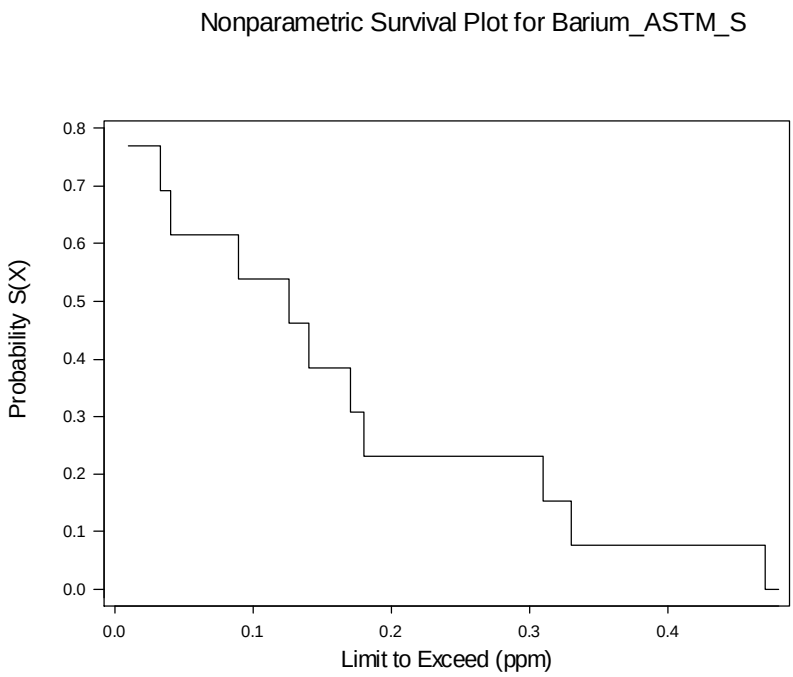

Figure **4-4**: Survival function for barium in ASTM D 3987

4.3.4 Mean Estimation

The mean of a nonnegative random variable is equal to the area under the corresponding survival function [Kaplan and Meier 1958], which is proven in Appendix J.1. The survival functions of barium in TCLP and ASTM D 3987 leachate are presented in the same chart in Figure 4-5. It is indicated that the estimated mean of barium concentration in TCLP leachate is greater than the estimated mean of barium concentration in ASTM D 3987 leachate by the comparison of their areas under individual survival function.

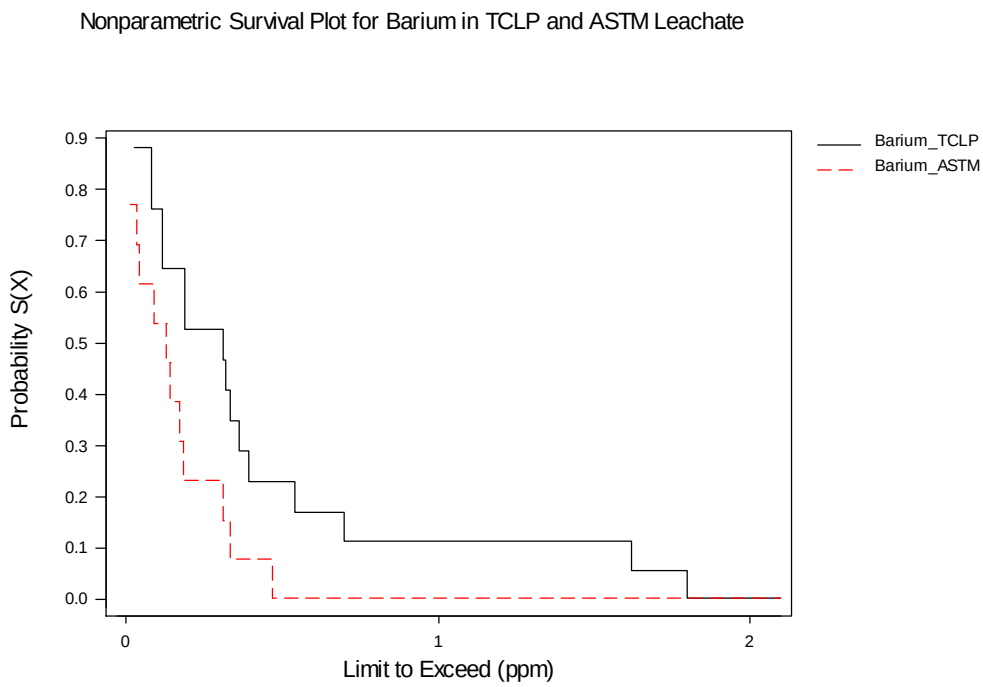

Figure **4-5**: Comparison of survival functions for barium

The CDF is not determined at every value, as indicated in Equation 4.14. When X is less than the minimum observation $x_{(n-1)}$ and $x_{(n-1)}$ is censored, its cumulative probability $\hat{P}(x)$ is expressed as $\hat{P}(X < x) \in$ [0, $\hat{P}(x_{(n-1)})$]. Kaplan and Meier regarded the results as unbiased if $\hat{P}(x)$ is "completed" by following $x <$ $x(n-1)$ to $x(n-1)$ [Kaplan and Meier 1958]. Then, survival function is "completed" similarly. Hence, the estimated mean for left-censored is calculable.

By summing the area of partitioned rectangular slices, the estimated mean for barium concentration in TCLP leachate is:

$$\hat{m} = (0.025-0)(1)+(0.0783-0.025)(0.88)+\ldots+(1.62-0.7)(0.111)+(1.8-1.62)(0.056)$$
$$= 0.410 \text{ ppm}$$

The estimated mean for barium concentration in ASTM D 3987 leachate is:

$$\hat{m} = (0.033-0)(0.77)+(0.04-0.033)(0.69)+...+(0.33-0.31)(0.15)+(0.47-0.33)(0.077)$$
$$= 0.145 \text{ ppm}$$

The confidence interval for estimated mean is determined by calculating the area under survival functions of 95% confidence level.

4.3.5 Estimation of Censored Data

Censored data impede the application of most conventional statistical methodologies such as regression analysis, analysis of variance (ANOVA), and multi-variate analysis of variance (MAVOVA) because the data for these methods need to be complete, quantified or categorized. This issue can be resolved by estimating censored data using survival analysis. Furthermore, estimating censored data helps discover the nature of foundry waste streams, which is hidden by censoring. In this section, a simple method is presented to estimate the censored data.

In Figure 4-6, 30 observations (solid diamonds) are quantified and 10 observations (hollow squares) are censored at 5. It is intended to estimate the mean of those 10 censored observations based on the other 30 quantified observations. First, estimate the mean m of the whole 40 observations using survival analysis (Section 4.3.4). Second, calculate arithmetically the summary s of those 30 quantified observations. Finally, treat the estimated mean for those 10 censored observations as unknown variable $\bar{x}$, and $\bar{x}$ is arithmetically determined by Equation 4.17. In this case,

m is estimated as 1.371 using survival analysis, and s is equal to 43.750. Thus, $\bar{x}$ is equal to 1.109. It is discovered that $\bar{x}$ is equal to the estimated mean of quantified observations less than censoring limit 5. Hence, the mean estimation of censored data is uniquely determined by those quantified data less than its censoring limit.

$$\frac{10\bar{x}+s}{40}=m \qquad \text{Equation } \mathbf{4.17}$$

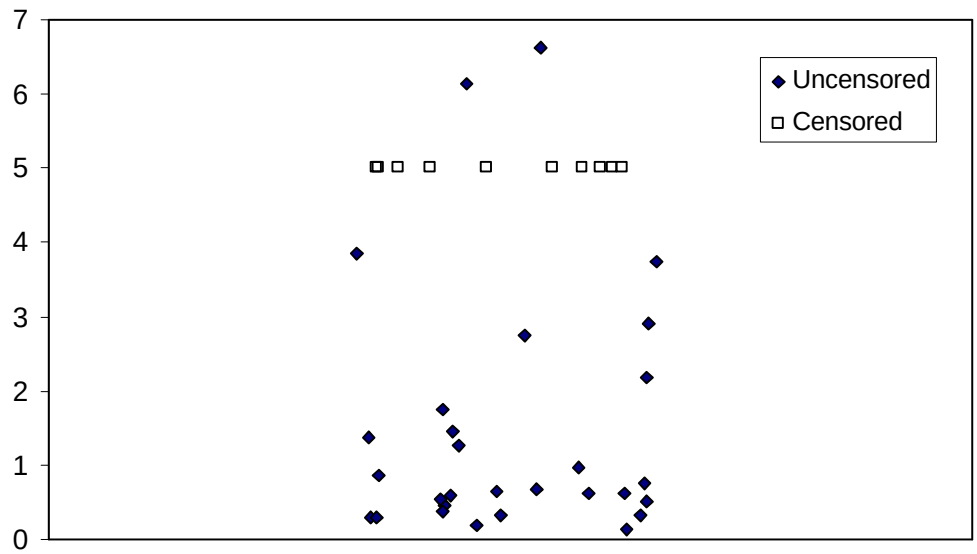

Figure **4-6**: Demonstration of censored data and uncensored data

The finding that estimation of censored data is determined by quantified observations below its censoring is demonstrated in Figure 4-7. Figure 4-7 presents observations on 15 samples by three labs. Instruments of these three labs have different reporting limits, which results in different censoring fractions on observations. Lab1 has the greatest censoring fraction. Its results only present 3 quantified observations and 12 censored observations. Lab2 lowers its instrument reporting limit and presents 11

quantified observations and 4 censored observations. Instrument of Lab3 has the capacity of quantifying every sample. In the estimation of censored observations from Lab2, quantified observations from Lab3 are referred to. Four censored observations from Lab2 are estimated by four quantified observations below Lab2's reporting limit.

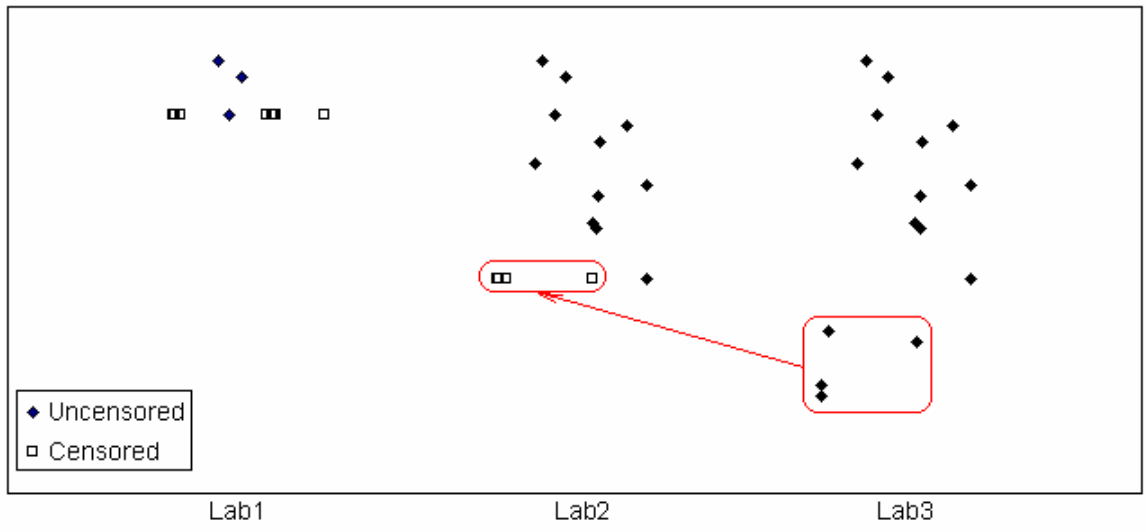

Figure **4-7**: Demonstration of estimation of censored data

4.3.6 Goodness-of-Fit Test (GOF)

There are numerous distribution diagnosis methods available, but the methods applied to censored data are limited. Ignoring the nonquantifiable data can be misleading because it eliminates the lower tail of the distribution and can therefore falsely reject the hypothesis of normality or any distribution assumption. A method testing normality in censored samples is reviewed by Gibbons and Coleman [Gibbons and Coleman 2001]. The chi-square goodness-of fit (GOF) can test any distribution based on cumulative function and binned data only if the sample size is large enough [Conover 1999]. The

Kolmogorov-Smirnov (KS) test is a nonparametric test that can be used to evaluate the fit of any hypothesized distribution [Conover 1999]. One of its limitations is that the parameters of the hypothesized distribution are assumed to be known, but actually partly unavailable. And the KS test is not valid if the parameters of the hypothesized distribution are estimated from the dataset [Gilbert 1987]. It is a method based on CDF. Another approach based on CDF is the Anderson-Darling (AD) test, which is modified from the KS test and focuses on the weight of tails [Stephens 1974]. It tests the distribution assumptions of normal, lognormal, extreme-value, Weibull, etc. This is done using probability plots for those distributions. Using the AD test, conventional distribution models can be compared to infer which distribution is the most appropriate.

Probability plots are based on a scheme that plots the quantified observations (or a transformation of the quantified observations) on the x-axis versus the estimated cumulative probabilities P on the y-axis. Transformations of both the x and y data are needed to ensure that the plotted y values are a linear function of the plotted x values. To help assess the linearity of the plotted data, a fitted line is also drawn on the probability plots. The probability plots for concentration of barium in TCLP leachate are presented in Figure 4-8. Four mostly used and approximated distribution models, including Weibull, lognormal, normal, and logistic, are fitted and compared. It is indicated that the lognormal-based distribution fits the data pool better than distributions of normal, Weibull, and logistic ($1.052<1.099<1.883<2.150$). Its probability plot is closest to a straight line. However, MiniTab does not provide P-value for the GOF test. Hence, it is

unknown whether the lognormal model fits the concentration of barium in TCLP leachate with confidence or not.

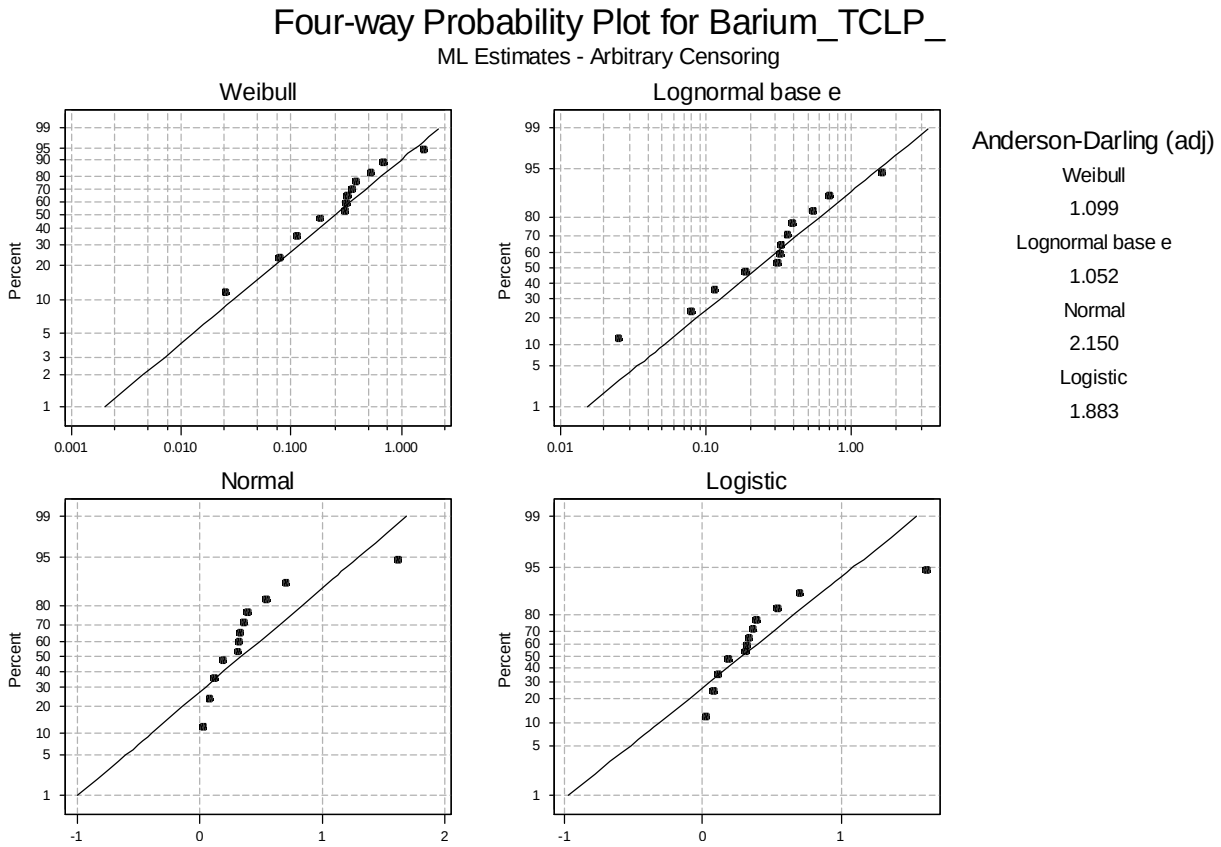

Figure **4-8**: Comparison of fitness for barium in TCLP leachate

The same fitting procedures are conducted for concentration of barium in ASTM D 3987 leachate. The probability plots are presented in Figure 4-9. It is discovered that Weibull distribution most closely fits the data (1.668<1.803<1.854<1.873). Hence, the best fitting model is not always lognormal for environmental monitoring data. It is changeable, which depends essentially on the distribution nature of the data pool. In practice, the distributions of environmental data are rarely if ever known [Hesel and

Hirsch 1992]. To assume any distribution model without diagnosing its fitness may result in less sound conclusions.

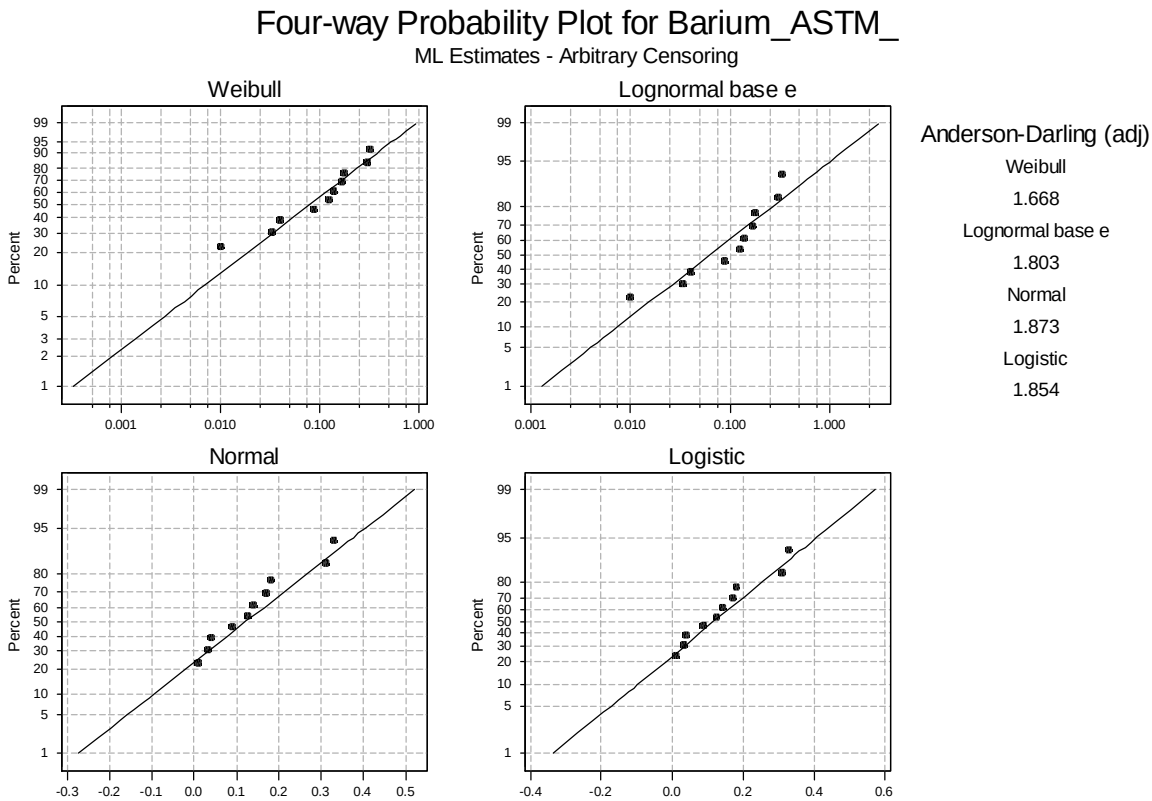

Figure **4-9**: Comparison of fitness for barium in ASTM D 3987 leachate

4.3.7 Factor Effect

Although the comparisons of critical points, including estimated means or median, of two independent sample groups are different, it is not determinate to conclude that two groups are significantly different. A further statistical procedure is performed to test whether these two sample groups are from two different populations; whether the two

distribution functions associated with two populations are identical; or whether the factor effect between the two groups of data is significant.

The two-sample hypotheses can be tested using KS test and Cramer-von Mises (CM) test based on the survival function [Conover 1999]. But they are not figured out for censored data. And there is no commercial statistical software package handling a two-sample test of censored data. Alternatively, the testing procedures can be fulfilled by Microsoft Excel spreadsheet coding using the methodology of the KS or CM test.

In this research, the KS test is employed to compare data pools and to evaluate factor effect, for KS is more related to CDF and survival function. In the applications of KS test, two CDFs of two data groups are presented in a chart. The maximum vertical distance between two CDFs is regarded as the test statistic for the two-sided test. Although the KS test was developed for CDF, the maximum vertical distance between two survival functions is identical to the maximum vertical distance between corresponding CDFs. Hence, the KS test is applied directly to survival functions. Generally, test confidence level a is selected as 0.05. If the test statistic is greater than the 1-a quantile for a two-sided test, this goes against the hypothesis that two data groups tend to present identical results or that the factor is not significant at a level. If the test statistic is less than the 1-a quantile for a two-sided test, it is concluded that there is no significant evidence against the hypothesis, and that hypothesis is accepted. Another test used is a one-sided test that employs the maximum one-way vertical

distance as the test statistic. Its testing criteria are identical to the two-sided test. However, this test evaluates whether one data pool is greater than another.

The test procedure on two data groups is demonstrated. One data group is the concentration of barium in TCLP leachate, and the other data group is the concentration of barium in ASTM D 3987 leachate, presented in Table 4-3. Their survival functions are presented in Figure 4-5. The spreadsheet calculation indicates that the maximum vertical distance between two survival functions is 0.3128. Referring to "Table of Quantiles of the Smirnov Test Statistic for Two Samples of Different Size" [Conover 1999], the 95% quantile for the two-sided test is 7/15, which is greater than the test statistic 0.3128. By interpolation, the p value is estimated to be larger than 0.20. A p value close to zero signals that null hypothesis is false, and typically that a difference is very likely to exist. Large p values closer to 1 imply that there is no detectable difference for the sample groups. A p value of 0.05 is a typical threshold used in industry to evaluate the null hypothesis. Therefore, hypothesis H_0 that two data groups have an identical distribution function or concentration is accepted at the 0.05 level. Leaching protocols of TCLP and ASTM D 3987 are not significant factors differentiating concentrations of barium in leachates.

Chapter 5

CHARACTERIZATION ANALYSES AND CONCLUSIONS

This chapter concentrates on the characterization of foundry sand through both bulk analysis and leaching analysis. The main technique is the survival function, which is discussed in Chapter 4. Major topics includes survival mean estimation, sample group comparison, and environmental impact assessment.

5.1 Plan of Analyses

Using the survival function for left-censored data (discussed in Section 4.3.2, demonstrated in Section 4.3.3) and mean estimation for left-censored data (discussed in Section 4.3.4), the survival probability function and estimated mean for general chemical parameters, inorganic elements, and organic compounds are presented in Sections F.1 through F.4 in Appendix F. The main factors considered in the factorial design include leaching protocol and metal cast. The effect of factors, or statistical comparison of the cumulative distribution of elements using survival technique, is evaluated using the methodology discussed in Section 4.3.7. Parameters to be analyzed include all chemicals in bulk chemical analysis and leachate characterizing analysis. It covers up to 27 general chemical parameters, up to 24 metallic elements and up to 55 organic compounds.

By the presentation of survival probability plot and estimated mean, the characterization of foundry sand is delineated. First, the presentation addresses all elements and compounds regarding the chemical and environmental characteristics of foundry sands. These parameters not only cover those parameters specified by federal and state regulation; they also span the environmental concerns encountered in any beneficial reuse application of foundry by-product. Second, the barrier to looking into the distribution of each parameter is eliminated. The censoring issue regarding almost all parameters is addressed by the introduction of survival theory. The characterization of excess foundry sand is addressed with statistical confidence. Distribution for an individual parameter is more easily interpreted and located, including minimum, maximum, mean, and any percentile. A reliable and hands-on methodology addressing the censored data is set up. Finally, the factors of leaching protocol and metal cast are considered. Two to four survival plots with one factor effect are presented in a chart. Statistical tests are performed to evaluate the significance of the factor. For instance, it is estimated whether TCLP leaches out more arsenic from sand than SPLP or ASTM D 3987. This kind of hypothesis test is a more general form of location alternative than the statement that samples differ only by a critical point (mean or median) [Conover 1999]. It can be solved by the KS test.

The factor tests are diverse. In evaluation of leaching characterization, two factors are considered, leaching protocol (3 treatments) and metal cast (4 treatments), and up to 12 ($3\times4 = 12$) treatments exist. Their pairwise combination is up to $C_{12}^{2} = 66$. Thus, up to 66 comparisons are targeted to be evaluated on up to 76 variables. Not all 66 comparisons

are required in this research. Comparison interest is focused on comparisons of leaching protocols and metals cast. The list of hypothesis tests for selected pairwise factors is presented in Tables 5-1, 5-2, and 5-3.

Table **5-1**: List of hypothesis tests per metal cast for as-received foundry sand

		As-Received Sand			
		Iron	Steel	Aluminum	Copper
As-received Sand	Iron		x		
	Steel	x		x	
	Aluminum		x		x
	Copper			x	

Note: “x” indicates tests conducted.

Table **5-2**: List of hypothesis tests per leaching protocol for sand leachates

		Sand Leachate		
		TCLP	SPLP	ASTM D3987
Sand Leachate	TCLP	A	x	
	SPLP	x		x
	ASTM D3987		x	

Note: “x” indicates tests conducted. “A” is detailed in Table 5-3.

Table **5-3**: List of hypothesis tests per metal cast for TCLP sand leachate

		TCLP Sand Leachate			
		Iron	Steel	Aluminum	Copper
TCLP Sand Leachate	Iron		x		
	Steel	x		X	
	Aluminum		x		x
	Copper			X	

Note: “x” indicates tests conducted.

5.2 Estimated Mean for As-Received Sand

The estimated means for the bulk chemical analysis of sand are presented in Table 5-4 (general chemical parameters), Table 5-5 (metallic elements) and Table 5-6 (organic compounds). Further characterization in distribution shape and percentile for individual parameter scan be referred to corresponding charts grouped in Figure F-1 (general chemical parameters) in Appendix F.1.1, Figure F-2 (metallic elements) in Appendix F.1.2, and Figure F-3 (organic compounds) in Appendix F.1.3.

Table **5-4**: Estimated mean for bulk chemical analysis of as-received sand (general chemical parameters)

Parameters	Estimated Mean (Unit: ppm, expect LOI, moisture, pH)
Silica	77.2
LOI, %	2.54
Moisture, %	1.27
Oil and grease	1744
Total petroleum hydrocarbon	223.52
Formalhyde	9.21
Phenol	21.45
pH	8.11
Total reactive sulfide	37.02
Total volatile residual	20995
Total volatile solid	1.90

Table **5-5**: Estimated mean for bulk chemical analysis of as-received sand (metallic elements)

Parameters	Estimated Mean (ppm)
Aluminum	3326
Antimony	4.34
Arsenic	0.86
Barium	14.95
Beryllium	0.08
Boron	38.53
Cadmium	0.22
Calcium	3309
Chromium	114.03
Hexavalent chromium	0.08
Copper	103.60
Iron	10911
Lead	15.72
Magnesium	1881
Manganese	257
Mercury	0.04
Molybdenum	38.84
Nickel	107.94
Selenium	0.64
Silicon	1772
Silver	0.47
Thallium	0.43
Zinc	102.48

Table **5-6**: Estimated mean for bulk chemical analysis of as-received sand (organic compounds)

Parameter	Acenaphthylene	Anthracene	Benzene	Benzo-(a)anthracene
Estimated Mean (ppm)	0.10	0.37	0.12	0.01
Parameter	Benzo-(b)fluornathene	Benzo-(k)fluornathene	Chrysene	o-Cresol
Estimated Mean (ppm)	0.01	0.002	0.027	2.722
Parameter	m_p-Cresol	2,4-Dimethylphenol	Ethylbenzene	Fluoranthene
Estimated Mean (ppm)	1.119	1.194	0.046	0.306
Parameter	Fluorene	1-Methyl naphthalene	2-Methyl naphthalene	Naphthalene
Estimated Mean (ppm)	0.037	0.328	0.406	0.435
Parameter	Phenanthene	Pyrene	Styrene	Toluene
Estimated Mean (ppm)	1.604	0.047	7.796	0.045
Parameter	Xylene	---	---	---
Estimated Mean (ppm)	0.061	---	---	---

5.3 Factor of Metal Cast for As-received Sand

The estimated mean and factor effect of metal cast for metallic elements from as-received sand are presented in Table 5-7. Major considered comparisons include "concentrations of elements in sand from iron-based facility versus concentrations of elements in sand from steel-based facility"; "concentrations of elements in sand from a steel-based facility versus concentrations of elements in sand from an aluminum-based facility"; and "concentrations of elements in sand from an aluminum-based facility versus concentrations of elements in sand from a copper-based facility." Further comparison and

characterization in distribution shape and percentile for individual parameters can be referred to corresponding charts grouped in Figure F-4 in Appendix F.2.1.

Based on the statistical comparison of the cumulative distribution of elements using survival technique presented in Table 5-7, there is no significant evidence against the hypotheses that sand from iron-based facilities and sand from steel-based facilities tend to present similar amounts of aluminum, arsenic, barium, boron, calcium, chromium, copper, iron, lead, manganese, and nickel. Sand from iron-based facilities tends to present more zinc than sand from steel-based facilities. There is no significant evidence against the hypotheses that sand from steel-based facilities and sand from aluminum-based facilities tend to present similar amounts of aluminum, arsenic, barium, calcium, chromium, and copper. Sand from steel-based facilities tends to present more iron, manganese, and nickel and less zinc than sand from aluminum-based facilities. There is no significant evidence against the hypotheses that sand from aluminum-based facilities and sand from copper-based facilities tend to present similar amounts of aluminum, arsenic, barium, calcium, chromium, iron, and manganese. Sand from aluminum-based facilities tends to present less copper, lead, nickel, and zinc than sand from copper-based facilities. Sands from iron-based facilities and steel-based facilities tend to present less copper and zinc than sand from copper-based facilities. Sand from iron-based facilities tends to present less lead than sand from copper-based facilities. There is no significant evidence against the hypotheses that sand from steel-based facilities and sand from copper-based facilities tend to present similar amounts of lead.

Table **5-7**: Estimated mean and factor effect for as-received sand (metallic elements)

Parameter	Iron-based	Steel-based	Aluminum-based	Copper-based	Statistical comparison of the cumulative distribution of elements using survival technique
	Unit: ppm				
Aluminum	1327	1576	12931	1190	“Iron=Steel”, p >0.20; “Steel=Aluminum”, p >0.20; “Aluminum=Copper”, p >0.15;
Arsenic	0.76	6	0.34	0.39	“Iron=Steel”, p >0.20; “Steel=Aluminum”, p >0.20; “Aluminum=Copper”, p >0.20;
Barium	24.31	7.77	6.53	3.97	“Iron=Steel”, p =0.17; “Steel=Aluminum”, p =0.2+; “Aluminum=Copper”, p =0.14;
Boron	9.86	276.2			“Iron=Steel”, p >0.20;
Calcium	4842	1366	927	2481	“Iron=Steel”, p >0.20; “Steel=Aluminum”, p >0.20; “Aluminum=Copper”, p >0.20;
Chromium	16.23	1664.1	4.63	3.21	“Iron=Steel”, p >0.20; “Steel=Aluminum”, p =0.2+; “Aluminum=Copper”, p >0.20;
Copper	30.32	404.73	17.68	653.2	“Iron=Steel”, p >0.20; “Steel=Aluminum”, p =0.20; “Aluminum<Copper”, p =0.008; “Iron<Copper”, p =0.005; “Steel<Copper”, p =0.01+;
Iron	11163	60819	1898	1986	“Iron=Steel”, p >0.20; “Steel>Aluminum”, p =0.02; “Aluminum=Copper”, p >0.20;
Lead	19.81	8.42	3.62	88.6	“Iron=Steel”, p >0.20; “Steel=Aluminum”, p =0.20; “Aluminum<Copper”, p =0.008; “Iron<Copper”, p =0.008; “Steel=Copper”, p >0.20;
Manganese	483	523	26.66	14.33	“Iron=Steel”, p >0.20; “Steel>Aluminum”, p =0.02; “Aluminum=Copper”, p =0.2+;
Nickel	6.85	1664.6	44.17	9.86	“Iron=Steel”, p =0.20; “Steel>Aluminum”, p =0.04; “Aluminum<Copper”, p =0.04;
Zinc	131	64.1	31.6	691.2	“Iron>Steel”, p <0.05; “Steel<Aluminum”, p =0.04; “Aluminum<Copper”, p =0.008; “Iron<Copper”, p <0.005; “Steel<Copper”, p =0.01+;

Note: A p value close to zero, or $p < 0.05$, signals a significant factor effect.

It is inferred that metal cast in the facilities is not a significant factor regarding most metallic elements in as-received excess foundry sand. The exceptions are lead, copper, and zinc, which are frequently of greater composition in as-received sand from copper-based facilities than from other alloy facilities. The greater composition for these three metallic elements is possibly caused by the relatively substantial addition of lead, copper, and zinc (up to 30%) as alloys in copper-based facilities.

5.4 Estimated Mean for Sand Leachate per Leaching Protocol

The estimated mean for parameters in sand leachate is presented in Table 5-8 (general chemical parameters), Table 5-9 (metallic elements), and Table 5-10 (organic compounds). Hypothesis tests in regard to leaching protocol on metallic elements are presented in Table 5-9. Further characterization in distribution shape and percentile for individual parameters can be referred to corresponding charts grouped in Figure F-5 (general chemical parameters) in Appendix F.3.1, Figure F-6 (metallic elements) in Appendix F.3.2, and Figure F-7 (organic compounds) in Appendix F.3.3.

The estimated mean and leaching protocol effect for metallic elements in sand leachates are presented in Table 5-9. Considered comparisons include “concentrations of elements in TCLP leachate versus concentrations of elements in SPLP leachate”; “concentrations of elements in SPLP leachate versus concentrations of elements in ASTM D 3987 leachate”; and “concentrations of elements in TCLP leachate versus concentrations of elements in ASTM D 3987 leachate.”

Table **5-8**: Estimated mean for sand leachate per leaching protocol (general chemical parameters)

Parameter	TCLP	ASTM
	Unit: ppm	
Acidity		11.8
Alkalinity		50
Ammonia		4.511
Chemical oxygen demand		439
Chloride		8.003
Cyanide		0.003
Fluoride		0.734
Formalhyde	0.332	
Nitrate		1.266
Nitrite		0.021
Oil and grease		14.700
Phenol	0.154	0.992
Sulfate		56.596
Total dissolved solid		347
Total oxygen halogen		6.221
Total petroleum hydrocarbon		2.047

Table **5-9**: Estimated mean and factor effect for sand leachate per leaching protocol (metallic elements)

Parameter	TCLP	SPLP	ASTM D 3987	Statistical comparison of the cumulative distribution of elements using survival technique
	Unit: ppm			
Aluminum	1.785	2.698	2.094	“TCLP ≠ SPLP”, p <0.01; “SPLP=ASTM”, p =0.1-;
Antimony		0.083		
Arsenic	0.031	0.001	0.003	“TCLP>SPLP”, p =0.025; “SPLP<ASTM”, p <0.005;
Barium	0.639	0.388	0.173	“TCLP>SPLP”, p <0.005; “SPLP>ASTM”, p <0.005;
Boron		0.236		
Cadmium	0.004	---	0.0003	“TCLP=ASTM”, p >0.20;
Chromium	0.042	0.002	0.007	“TCLP=SPLP”, p >0.20; “SPLP=ASTM”, p >0.20;
Hexavalent chromium			0.008	
Copper	0.521	0.061	0.087	“TCLP=SPLP”, p >0.20; “SPLP=ASTM”, p >0.20;
Iron	61.78	6.095	1.245	“TCLP>SPLP”, p <0.025; “SPLP>ASTM”, p <0.005;
Lead	0.222	0.009	0.008	“TCLP>SPLP”, p =0.01; “SPLP=ASTM”, p >0.20;
Manganese	1.009	0.215	0.061	“TCLP>SPLP”, p <0.005; “SPLP=ASTM”, p >0.20;
Mercury	0.0002	---	0.0002	“TCLP<ASTM”, p =0.005;
Molybdenum		0.233		
Nickel	0.183	0.029	0.006	“TCLP>SPLP”, p <0.005; “SPLP=ASTM”, p >0.20;
Selenium	0.041	---	0.002	“TCLP>ASTM”, p =0.02;
Silver	0.004			
Sodium			15.043	
Vanadium			0.003	
Zinc	1.006	0.264	0.177	“TCLP>SPLP”, p <0.005; “SPLP>ASTM”, p <0.025;

Note: A p value close to zero, or $p < 0.05$, signals a significant factor effect.

Table **5-10**: Estimated mean for TCLP sand leachate (organic compounds)

Parameter	Cresol_m	Cresol_O	Acetone	Benzene
Estimated Mean (ppm)	22.33	46.40	265.5	1.46
Parameter	2_4-Dimethylphenol	Ethyl benzene	Naphthalene	Phenanthrene1
Estimated Mean (ppm)	30.59	5.78	71.69	6.99
Parameter	Styrene	Toluene	Trichloro-ethylene	Xylene_total
Estimated Mean (ppm)	57.30	51.92	7.23	3.73
Parameter	Methyl isobutkl ketone	---	---	---
Estimated Mean (ppm)	50.5	---	---	---

Based on the statistical comparison of the cumulative distribution of elements using survival technique presented in Table 5-9, TCLP sand leachate tends to present more arsenic, barium, iron, lead, manganese, nickel, and zinc than SPLP sand leachate. TCLP sand leachate tends to present less phenol and mercury, and more selenium than ASTM D 3987 sand leachate. TCLP sand leachate tends to present a different amount of aluminum from SPLP sand leachate. There is no significant evidence against the hypotheses that TCLP sand leachate and SPLP sand leachate tend to present similar amounts of chromium and copper. There is no significant evidence against the hypotheses that TCLP sand leachate and ASTM D 3987 sand leachate tend to present similar amounts of cadmium. SPLP sand leachate tends to present less arsenic and more barium, iron, and zinc than ASTM D 3987 sand leachate. There is no significant evidence against the hypotheses that SPLP sand leachate and ASTM D 3987 sand leachate tend to

present similar amounts of aluminum, chromium, copper, lead, manganese, and nickel. It is inferred that TCLP is more aggressive on sand than SPLP and ASTM D 3987.

5.5 Factor of Metal Cast in TCLP Sand Leachate

The estimated mean and factor effect of metal cast for metallic elements in TCLP sand leachate are presented in Table 5-11. Major considered comparisons include "concentrations of elements in TCLP sand leachate from an iron-based facility versus concentrations of elements in TCLP sand leachate from a steel-based facility"; "concentrations of elements in TCLP sand leachate from a steel-based facility versus concentrations of elements in TCLP sand leachate from an aluminum-based facility"; and "concentrations of elements in TCLP sand leachate from an aluminum-based facility versus concentrations of elements in TCLP sand leachate from a copper-based facility." Further comparison in distribution, shape, and percentile for individual parameters can be referred to corresponding charts grouped in Figure F-8 in Appendix F.4.1.

Table **5-11**: Estimated mean and factor effect for TCLP sand leachate (metallic elements)

Parameter	Iron-based	Steel-based	Aluminum-based	Copper-based	Statistical comparison of the cumulative distribution of elements using survival technique
	Unit: ppm				
Aluminum	1.793	4.239	0.816	1.393	"Iron=Steel", p =0.15; "Steel<Aluminum", p <0.017; "Aluminum=Copper", p >0.20;
Barium	0.672	0.582	0.413	0.589	"Iron=Steel", p >0.20; "Steel=Aluminum", p >0.20; "Aluminum=Copper", p >0.20;
Cadmium	0.003	0.009	---	---	"Iron=Steel", p >0.20;
Chromium	0.044	0.063	---	---	"Iron=Steel", p =0.05+;
Iron	106.7	23.8	3.44		"Iron=Steel", p =0.2+; "Steel=Aluminum", p >0.20;
Lead	0.123	0.023	0.174	0.73	"Iron=Steel", p =0.15; "Steel=Aluminum", p >0.20; "Aluminum<Copper", p =0.035; "Iron<Copper", p =0.005; "Steel<Copper", p =0.008;
Manganese	1.409	1.307	0.447	---	"Iron=Steel", p >0.20; "Steel=Aluminum", p >0.20;
Mercury	0.0004	0.0006	0.0005	---	"Iron=Steel", p >0.20; "Steel=Aluminum", p >0.20;
Nickel	0.198	0.455	0.071	---	"Iron=Steel", p =0.15; "Steel>Aluminum", p >0.035;
Selenium	0.042	0.021	---	---	"Iron=Steel", p =0.20;
Zinc	0.785	0.318	0.715	---	"Iron=Steel", p >0.20; "Steel=Aluminum", p >0.20;

Note: A p value close to zero, or $p < 0.05$, signals a significant factor effect.

Based on the statistical comparison of the cumulative distribution of elements using survival technique presented in Table 5-11, there is no significant evidence against the hypotheses that TCLP sand leachate from iron-based facilities and TCLP sand leachate from steel-based facilities tend to present similar amounts of aluminum, barium, cadmium, chromium, iron, lead, manganese, mercury, nickel, selenium, and zinc. There is no significant evidence against the hypotheses that TCLP sand leachate from steel-based facilities and TCLP sand leachate from aluminum-based facilities tend to present similar amounts of barium, iron, lead, manganese, mercury, and zinc. TCLP sand leachate from steel-based facilities tends to present less aluminum and more nickel than TCLP sand leachate from aluminum-based facilities. There is no significant evidence against the hypotheses that TCLP sand leachate from aluminum-based facilities and TCLP sand leachate from copper-based facilities tend to present similar amounts of aluminum and barium. TCLP sand leachate from aluminum-based facilities tends to present less lead than TCLP sand leachate from copper-based facilities.

It is inferred that metal cast in the facilities is not a significant factor regarding most metallic elements in TCLP sand leachate. One of the exceptions is lead, which is frequently of greater concentration in TCLP sand leachate from copper-based facilities than in TCLP sand leachate from other alloy facilities. This finding is consistent with the finding mentioned in Section 5.3 that lead is frequently of greater composition in as-received sand from copper-based facilities than from other alloy facilities.

5.6 Impacts of Metallic Elements in Foundry Sand

When environmental problems related to trace elements in soils or groundwater are discovered, there has been a tendency for the public to identify the most visible industry first without proper technical assessment of other possible environmental or natural causes [Letey et al. 1986]. To defeat the arbitrary judgment, a comparison of background concentrations of trace metallic elements in soils of a U.S. state [Bradford et al. 1996] to characterization of foundry sand and sand leachates is presented in Table 5-13 through Table 5-16.

The comparison between background concentration of soil and average bulk analysis of foundry sand suggests the degree of environmental impact waste streams may pose. The comparison is summarized in Table 5-12, supported by data in Tables 5-13 through 5-16. While excess foundry sands contain higher levels of metallic elements (aluminum, copper, and iron), the concentrations of most regulated metallic elements are less than or in the same level as those of soil. This illustrates that excess foundry sands do not pose greater threats to the environment than soil.

Table **5-12**: Metallic elements comparison between soil and excess foundry sand

Foundry sand > Soil	aluminum, antimony, copper, iron, molybdenum, and silicon, selenium
Foundry sand = Soil	boron, cadmium, chromium, magnesium, nickel, lead, silver, thallium, zinc
Foundry sand < Soil	arsenic, barium, beryllium, calcium, mercury, manganese

Listed in Tables 5-13 through 5-16, TCLP leachate threshold [40 CFR Part 261 1986] is the only available federal regulation evaluating hazardous characteristics of solid wastes. Full thresholds cover toxicity, reactivity, ignitability, and corrosivity (Section 3.3.3) [EPA SW-846 2000]. A typical question in the reuse of excess foundry sand is the impact of metallic elements in the sand to the environment. To assess its toxicity, excess foundry sand is exposed to the TCLP leaching procedure, and its leachate, which may seep into the surrounding environment and potentially pose a threat to human beings, is chemically analyzed. The results are compared against corresponding toxicity thresholds. If all metallic elements are within corresponding TCLP thresholds, excess foundry sand is nonhazardous and has the potential to be reused. A violation of any metallic element leads to the judgment that excess foundry sand is hazardous and should be disposed of in a special landfill.

Characterization data for any metallic elements are dispersed. Hence, only comparisons of estimated means and associated distributions to thresholds are convincible. There may exist significant tail exceeding thresholds. To prove statistically that foundry sand is well below thresholds, the 95th percentile is presented for each metallic element. If sand has its 95th percentile below thresholds, it is statistically sound to infer that the sand is nonhazardous.

Tables 5-13 through 5-16 present worst-case comparisons between TCLP thresholds and 95th percentiles of TCLP sand leachate to assess the toxicity and impact of foundry sand on the condition of an actively decomposing municipal solid- waste landfill.

Alternative comparisons were conducted between TCLP thresholds and SPLP or ASTM D 3987 leachate level, approved in Section 2.2.1. The comparison between TCLP thresholds and 95th percentiles of SPLP sand leachate is to assess the toxicity and impact of excess foundry sand in condition of industrial waste monofills, and the comparison between TCLP thresholds and 95th percentiles of ASTM D 3987 sand leachate is to assess the toxicity and impact of excess foundry sand in the condition of neutral extraction. It is indicated that the sand leachate from any leaching protocol has its 95th percentiles of metallic element concentrations well less than thresholds. Thus, excess foundry sand is generally not hazardous.

In Tables 5-13 through 5-16, additional comparison between TCLP thresholds and 95th percentiles of bulk analyses of as-received sand contributes to saving of toxicity evaluation, because if bulk analyses of waste streams are within thresholds there is no requirement for further leaching evaluation. Comparisons indicate that sand has its 95th percentiles of metallic element compositions well less than thresholds, except for lead and chromium. It is suggested that the full spectrum of metallic elements need not be exposed to leaching analysis. The selection relies on observed concentration of metallic elements.

Table **5-13**: Comparison of means and 95th percentiles among soil, foundry sand and sand leachates

		Silver (Ag)	Aluminum (Al)	Arsenic (As)	Boron (B)	Barium (Ba)	Beryllium (Be)
Soil	Mean	0.8	73000	3.5	19	509	1.28
	Standard deviation	1.43	17000	2.5	15	210	0.52
TCLP leachate threshold		5	---	5	---	100	---
As-received foundry by-products (mean / 95th percentile)	Sand	0.47 / 0.21	3326 / 4300	0.86 / 1.6	38.53 / 88.9	14.95 / 28	0.08 / 0.229
As-received excess foundry sand (mean / 95th percentile)	Iron-based facilities	---	1327 / 3800	0.76 / 1.8	9.86 / 39	24.31 / 52	---
	Steel-based facilities	---	1576 / 1200	**6 / 0.56**	276.2 / 29	7.77 / 18	---
	Aluminum-based facilities	---	12931 / 15000	0.34 / 0.67	---	6.53 / 12	---
	Copper-based facilities	---	1190 / 480	0.39 / 0.49	---	3.97 / 4.51	---
TCLP leachate (mean / 95th percentile)	Sand	0.004 / 0.008	1.785 / 4.51	0.031 / 0.07	---	0.639 / 2.4	---
SPLP leachate (mean / 95th percentile)	Sand	---	2.698 / 12	0.001 / 0.002	0.236 / 0.89	0.388 / 1.9	---
ASTM D 3987 leachate (mean / 95th percentile)	Sand	---	2.094 / 6.6	0.003 / 0.005	---	0.173 / 0.6	---
TCLP leachate sand (mean / 95th percentile)	Iron-based facilities	---	1.793 / 11	---	---	0.672 / 2.4	---
	Steel-based facilities	---	4.239 / 21	---	---	0.582 / 1.48	---
	Aluminum-based facilities	---	0.816 / 3.5	---	---	0.413 / 1.62	---
	Copper-based facilities	---	1.393 / 2.7	---	---	0.589 / 1.68	---

Table **5-14**: Comparison of means and 95th percentiles among soil, foundry sand and sand leachates (Cont.)

		Calcium (Ca)	Cadmium (Cd)	Chromium (Cr)	Copper (Cu)	Iron (Fe)	Mercury (Hg)
Soil	Mean	14466	0.36	122	28.7	37000	0.26
	Standard deviation	10703	0.31	223	19.3	16000	0.21
TCLP leachate threshold		---	1	5	---	---	0.2
As-received foundry by-products (mean / 95th percentile)	Sand	3309 / 11000	0.22 / 0.25	114.03 / 65	103.6 / 350	10911 / 25000	0.04 / 0.06
As-received excess foundry sand (mean / 95th percentile)	Iron-based facilities	4842 / 12200	---	16.23 / 67	30.32 / 154	11163 / 25000	---
	Steel-based facilities	1366 / 3600	---	**1664.1 / 5.6**	404.73 / 7.4	60819 / 340000	---
	Aluminum-based facilities	927 / 2100	---	4.63 / 19.3	17.68 / 64.3	1898 / 4600	---
	Copper-based facilities	2481 / 278	---	3.21 / 4.82	653.2 / 1860	1986 / 5750	---
TCLP leachate (mean / 95th percentile)	Sand	---	0.004 / 0.018	0.042 / 0.11	0.521 / 0.4	61.78 / 285	0.0002 / 0.00004
SPLP leachate (mean / 95th percentile)	Sand	---	---	0.002 / 0.003	0.061 / 0.18	6.095 / 30	---
ASTM D 3987 leachate (mean / 95th percentile)	Sand	---	0.0003 / 0.0004	0.007 / 0.018	0.087 / 0.033	1.245 / 5.02	0.0002 / 0.0003
TCLP leachate sand (mean / 95th percentile)	Iron-based facilities	---	0.003 / 0.012	0.044 / 0.11	---	106.7 / 285	0.0004 / 0.002
	Steel-based facilities	---	0.009 / 0.06	0.063 / 0.39	---	23.8 / 72.2	0.0006 / 0.004
	Aluminum-based facilities	---	---	---	---	3.44 / 4.23	0.0005 / 0.001
	Copper-based facilities	---	---	---	---	---	---

Table **5-15**: Comparison of means and 95th percentiles among soil, foundry sand and sand leachates (Cont.)

		Magnesium (Mg)	Manganese (Mn)	Molybdenum (Mo)	Sodium (Na)	Nickel (Ni)	Lead (P
Soil	Mean	9923	646	1.3	15838	57	23.9
	Standard deviation	5356	285	1.5	9309	80	13.8
TCLP leachate threshold		---	---	---	---	---	5
As-received foundry by-products (mean / 95th percentile)	Sand	1881 / 5240	257 / 480	---	---	107.94 / 58	15.72 /
As-received excess foundry sand (mean / 95th percentile)	Iron-based facilities	---	483 / 548	---	---	6.85 / 29	19.81 /
	Steel-based facilities	---	523 / 2800	---	---	**1664.6 / 12.3**	8.42 / 3
	Aluminum-based facilities	---	26.66 / 109	---	---	44.17 / 3	3.62 / 1
	Copper-based facilities	---	14.33 / 33	---	---	9.86 / 17.8	88.6 / 6
TCLP leachate (mean / 95th percentile)	Sand	---	1.009 / 5.72	---	---	0.183 / 0.875	0.222 /
SPLP leachate (mean / 95th percentile)	Sand	---	0.215 / 0.928	0.233 / 0.1	---	0.029 / 0.06	0.009 /
ASTM D 3987 leachate (mean / 95th percentile)	Sand	---	0.061 / 0.19	---	15.043 / 56.3	0.006 / 0.026	0.008 /
TCLP leachate sand (mean / 95th percentile)	Iron-based facilities	---	1.409 / 7.03	---	---	0.198 / 0.875	0.123 /
	Steel-based facilities	---	1.307 / 4.31	---	---	0.455 / 1.28	0.023 /
	Aluminum-based facilities	---	0.447 / 2.04	---	---	0.071 / 0.439	0.14 / 0
	Copper-based facilities	---	---	---	---	---	0.73 / 2

Table **5-16**: Comparison of means and 95th percentiles among soil, foundry sand and sand leachates (Cont.)

		Antimony (Sb)	Selenium (Se)	Silicon (Si)	Vanadium (V)	Zinc (Zn)
Soil	Mean	0.6	0.058	29.4	112	149
	Standard deviation	0.39	0.084	4.6	53	32
TCLP leachate threshold		---	1	---	---	---
As-received foundry by-products (mean / 95th percentile)	Sand	4.34 / 31	0.64 / 0.49	1772 / 1410	---	102.48 / 216
As-received excess foundry sand (mean / 95th percentile)	Iron-based facilities	---	---	---	---	131 / 42
	Steel-based facilities	---	---	---	---	64.1 / 7.4
	Aluminum-based facilities	---	---	---	---	31.6 / 99
	Copper-based facilities	---	---	---	---	691.2 / 620
TCLP leachate (mean / 95th percentile)	Sand	---	0.041 / 0.1	---	---	1.006 / 5.29
SPLP leachate (mean / 95th percentile)	Sand	0.083 / 0.46	---	---	---	0.264 / 0.84
ASTM D 3987 leachate (mean / 95th percentile)	Sand	---	0.002 / 0.0026	---	0.003 / 0.0043	0.177 / 0.41
TCLP leachate sand (mean / 95th percentile)	Iron-based facilities	---	0.042 / 0.191	---	---	0.785 / 2.54
	Steel-based facilities	---	0.021 / 0.07	---	---	0.318 / 0.52
	Aluminum-based facilities	---	---	---	---	0.715 / 0.65
	Copper-based facilities	---	---	---	---	---

5.7 Conclusions

Based on the statistical comparison of the cumulative distribution of elements using survival technique rather than a location (such as mean, maximum, or any quantile) comparison, the following conclusions are summarized for the characterization of foundry sands. Further comparisons in shape and scale of survival function for individual elements/compounds/parameters can be referred to corresponding charts in Appendices F.1 through F.4.

TCLP is more aggressive on sand than SPLP and ASTM D 3987. SPLP is most reprehensive for fill applications.

For as-received foundry sand, metal cast in the facilities is not a significant factor regarding most metallic elements. The exceptions are lead, copper, and zinc, which are frequently of greater composition in sand from copper-based facilities than from other alloy facilities.

For TCLP sand leachate, metal cast in the facilities is not a significant factor regarding most metallic elements. The exception is lead, which is frequently of greater concentration in TCLP sand leachate from copper-based facilities than in TCLP sand leachate from other alloy facilities.

In comparison with soil, excess foundry sands from copper-based casting facilities contain more copper and excess foundry sands from steel-based facilities contain more iron. However, neither of these metals is a regulated RCRA metal. In summary, the compositions of most regulated metallic elements in excess foundry sand are less than or in the same level as those of soil, with the exception of copper-based facility excess foundry sand. These have higher concentrations of lead and copper. Hence, excess foundry sands do not typically pose more threats to environment than soil.

Sand leachate has its 95th percentiles of metallic element concentrations well less than TCLP thresholds. Thus, foundry sands are generally not hazardous.

Comparisons indicate that foundry sand has its 95th percentiles of metallic element bulk analyses well less than TCLP thresholds, except for lead and chromium. Hence, it is not necessary to expose sand to a leaching protocol and measure the full spectrum of metallic elements.

Chapter 6

EXPERIMENTAL MATERIALS

In this chapter, materials used in CLSM and HMA programs are introduced. Materials include cement, fly ash, aggregate, water, and excess foundry sand.

In the CLSM program, materials selected include Type I portland cement, Class F fly ash, excess foundry sand, and water. The selection was inferred from the specification of CLSM containing cement, fly ash, and bottom ash/coarse aggregate/fine aggregate developed by Pennsylvania Department of Transportation (PennDOT) [PennDOT 1995], and previous studies on this topic.

In the HMA program, aggregates from a local asphalt pavement contractor were used. They can be classified as a crushed limestone. The natural sand (lake sand) used was supplied by a local aggregate supplier. The control gradation used for this research project was designed by the same contractor.

Seventeen different foundry sands were used in this study. The sands came from 11 different states in the United States: Illinois, Indiana, Massachusetts, Michigan, North Carolina, Ohio, Pennsylvania, Texas, Virginia, West Virginia, and Wisconsin. Variables in excess foundry sand include metal cast, binder, and binding process. No other

variables, such as additives of silica fume and slag, were considered for the purpose of focusing on variation of excess foundry sands.

6.1 Materials

6.1.1 Cement

The cement used in this research conforms to AASHTO M 85, “Standard Specification for Portland Cement,” for Type I/II designation and was manufactured by ESSROC. The chemical composition of the cement is shown in Table 6-1. Cement was kept the same throughout experimental investigation.

6.1.2 Fly Ash

The fly ash used in this research originated from Mineral Solutions, Inc., which is a provider approved for transportation material sources. It is a Class F fly ash, and its bulk chemical analysis is presented in Table 6-1. Fly ash was kept the same throughout the experimental investigation.

Table **6-1**: Bulk chemical composition of Type I cement and Class F fly ash

Component (Oxide)	Capitol Cement	Min. Solutions Fly Ash
	Percentage by Mass	
Al	5.04	20.40
B	<0.005	0.06
Ba	0.06	0.05
Ca	64.00	2.66
Co	0.01	0.01
Cr	0.01	0.01
Fe	3.00	12.70
K	1.04	1.67
Mg	3.25	0.39
Mn	0.04	0.02
Mo	<0.005	<0.005
Na	0.40	0.68
Ni	<0.005	<0.005
Si	19.50	57.00
Sr	0.13	0.06
Ti	0.21	0.32
V	<0.005	0.02
Zn	0.01	0.01
F	<0.005	<0.005
Cl	0.01	<0.005
NO_2	<0.005	<0.005
NO_3	<0.005	<0.005
PO_4	<0.005	<0.005
SO_4	2.26	0.99
Total	100.14	98.69
Moist.	0.04	0.08
LOI (1000)	1.17	1.64

6.1.3 Excess Foundry Sand

In the database, information from 180 foundry facilities was collected, which spans a wide variety of backgrounds identified by metals cast, binders, and binding systems. Using statistical sampling, 17 facilities were randomly selected as sources of

excess foundry sands. Their backgrounds are presented in Table 6-2. Their physical properties and chemical compositions are listed in Sections 6.2 and 6.3. As indicated in Table 6-2, iron-based facilities using bentonite and green sand are the most used combination in the foundry industry.

6.1.4 Water

External water is required to produce CLSM mixtures. Potable tap water at approximate room temperature (23 ºC) was used for mixing.

6.2 Characteristics of Excess Foundry Sands

The physical characteristics of foundry sands, such as particle size distribution, grain fineness number, and grain surface characteristics, are important determinants of flowability, compacted density, and strength in reuse applications [Carey and Sturtz 1995]. Excess foundry sands are not as pure as virgin silica sand after repetitive exposures to inorganic or organic bonding processes, high-temperature contact, and mechanical reclamations, which is demonstrated by the characteristics of green sand presented in Table 6-3 [Winkler et al. 1999]. Investigations of physical characteristics of excess foundry sand not only affect its reuse, but recognize the difference among waste streams as well.

Table **6-2**: Backgrounds of excess foundry sands

SN	Sand origin	Metal Cast	Binder	Fillers	Binding System
FS01	Lake sand	Ductile iron	Bentonite (Mold) + Phenolic Urethane (Core)	Sea Coal, Starch, Peanut Hulls, etc. (Mold) + Iron Oxide (Core)	Green Sand
FS02	Silica sand	Gray and ductile iron	Furfurl Alcohol (Mold)	None	---
FS03	Silica sand	Gray and ductile iron	Bentonite (Mold) + Phenolic Urethane (Core)	Sea Coal (Mold) +None (Core)	Green Sand + Cold Box/Shell
FS04	Silica sand	Gray and ductile iron	Bentonite (Mold) + + Phenolic Urethane	Sea Coal	Green Sand
FS05	Silica sand	Grey iron	Bentonite (Mold) + Phenolic Urethane (Core)	Sea Coal (Mold) + None (Core)	Green Sand (Mold) + Shell/Cold Box/No-Bake (Core)
FS06	Sand	Gray iron	Bentonite (Mold) + Sodium Silicate (Core)	Sea Coal, Cereal, Soda Ash (Molding) + None (Core)	Green Sand + Sodium Silicate
FS07	Lake sand, Silica	Gray iron	Bentonite (Mold)	Sea Coal, Flocarb	Green Sand
FS08	Lake sand	Gray and ductile iron	Bentonite (Mold) + Phenolic Urethane Cold Box + Phenol Formaldehyde Hot Box	Sea Coal, Klean Kast, Carbonate	Green Sand
FS09	Silica sand	Iron	Bentonite + Phenolic Urethane Cold Box + Phenol Formaldehyde Hot Box	Sea Coal + Fuse Silica	Green Sand
FS10	Lake sand	Aluminum	Sodium Silicate	Corn Flour	---
FS11	Lake sand	Aluminum	Bentonite (Mold) + Phenolic Urethane (Core)	None (Mold, Core)	Green Sand (Mold)+ Isocure (Core)
FS12	Silica sand	Aluminum	Phenolic Urethane	None	No-Bake
FS13	Silica sand	Gray and ductile iron	Bentonite (Mold)+ Phenolic Urethane (Cold Box)	Sea Coal, Corn Flour	Green Sand
FS14	Silica sand	Brass/Bronze/Aluminum	Bentonite (Mold) + Phenolic Urethane Cold Box	Sea Coal, Cellulose, Soda Ash, Gilsonite	Green Sand
FS15	Sand	Gray and ductile iron	Bentonite (Mold)+Furan+Oil	Sea Coal	Green Sand+Shell
FS16	Silica sand	Steel	Bentonite (Mold)+ Phenolic Urethane	Corn Flour	Green Sand
FS17	Silica sand	Steel	Sodium Silicate (Mold + Core)	None	No-bake

Table **6-3**: Typical characteristics of excess green sand

Components	Property Range
Sand	70-80%
Water	2-4%
Clay	5-15%
Additives	2-5%
Moisture	0-4%
Carbon Loss on Ignition	0.2-8%
pH	3-12
AFS-Grain Fineness No.	40-150
% Fines (Passes 200 Mesh Sieve)	1-12% (higher for brass)
Density	1.0-1.6 g/cm3 (zircon: 2.6 g/cm3)

6.2.1 Bulk Density, Compaction and Void

Bulk density is necessary for use in selecting proportions of mixture, and it is used for determining mass/volume relationship for conversions in purchase agreements [ASTM C 29 1997]. Void represents the space between particles in foundry sand mass not occupied by solid particles. It estimates the space that should be filled by other materials when mixing together. The testing specification for this investigation is ASTM C29/C29M-97, “Standard Test Method for Bulk Density (Unit Weight) and Voids in Aggregate.” In the investigation, the compaction was conducted by rodding procedure, in which compaction is fulfilled with 25 strokes of the tamping rod by 3 layers. Testing results are presented in Table 6-4. It is indicated that the distribution for variables is normal, and corresponding distribution parameters are provided.

Table **6-4**: Physical evaluation of excess foundry sand

FS ID	Loose Bulk Density as Received (kg/m^3)	Loose Bulk Density as Oven-dry (kg/m^3)	Compact Bulk Density as Oven-dry by Rodding (kg/m^3)	Void for Loose Sand as Oven-dry, %	Void for Compact Sand as Oven-dry, %	Bulk Specific Gravity	Specific Gravity (SSD)	Absorption (%)	Moisture Content as Received (%)
	ASTM C 29 / C 29M					ASTM C 128			ASTM C 566
FS01	1458	1289.17	1432.08	48.39	42.66	2.503	2.579	3.029	1.73
FS02	1666.39	1381.67	1576.25	49.13	41.97	2.722	2.732	0.381	0.29
FS03	1383	1285.00	1412.50	46.91	41.64	2.425	2.481	2.312	3.17
FS04	1466.9	1422.92	1530.42	39.99	35.46	2.376	2.446	2.944	1.42
FS05	1415	1369.58	1519.58	43.01	36.76	2.408	2.449	1.688	1.96
FS06	1314	1095.00	1238.33	56.90	51.26	2.546	2.592	1.807	1.70
FS07	1518	1303.33	1435.83	48.73	43.52	2.547	2.587	1.564	0.00
FS08	1378.1	1288.75	1393.33	45.86	41.47	2.385	2.465	3.348	2.03
FS09	1518	1429.17	1545.42	44.66	40.16	2.588	2.616	1.092	1.62
FS10	1491	1447.92	1606.25	44.87	38.84	2.632	2.645	0.523	3.50
FS11	1606	1328.75	1441.67	48.68	44.32	2.594	2.617	0.860	4.08
FS12	1650	1505.00	1651.67	44.01	38.55	2.693	2.714	0.787	0.64
FS13	1580	1522.08	1670.83	42.19	36.54	2.638	2.635	0.718	0.00
FS14	1544	1389.58	1557.08	43.86	37.10	2.480	2.583	**4.148**	0.14
FS15	1103	1052.08	1201.25	55.68	49.40	2.379	2.470	3.834	4.08
FS16	1478	1162.50	1312.08	53.83	47.88	2.523	2.601	3.093	1.02
FS17	1572	1553.75	1715.00	40.94	34.81	2.636	2.667	1.171	4.85
Min	*1103*	*1052*	*1201*	*39.99*	*34.81*	*2.38*	*2.45*	*0.38*	*0.00*
Max	*1666*	*1554*	*1715*	*56.90*	*51.26*	*2.72*	*2.73*	*4.15*	*4.85*
Average	*1479*	*1343*	*1484*	*46.92*	*41.31*	*2.53*	*2.58*	*1.96*	*1.90*
Standard Deviation (SD)	*137*	*142*	*146*	*4.92*	*4.85*	*0.11*	*0.09*	*1.23*	*1.54*
Normality	*Yes, p=0.35*	*Yes, p=0.48*	*Yes, p=0.79*	*Yes, p=0.44*	*Yes, p=0.45*	*Yes, p=0.5*	*Yes, p=0.13*	*Yes, p=0.17*	*Yes, p=0.21*

6.2.2 Specific Gravity and Absorption

Bulk specific gravity (saturated surface dry, SSD) is the ratio of the mass of a volume of a material—including the mass of water within the pores in the material (but excluding the voids between particles)—at a stated temperature, to the mass of an equal volume of distilled water at a stated temperature. Absorption values are used to calculate change in the weight of an aggregate due to water absorbed in the pore spaces within the constituent particles, compared to the dry condition, when it is deemed that the aggregate has been in contact with water long enough to satisfy most of the absorption potential [ASTM C 128 1993]. Specific gravity is an aggregate characteristic generally used for calculation of the volume occupied by the foundry sand aggregate in CLSM that is proportioned or analyzed on an absolute volume basis. It is also used in the computation of voids in aggregate and the determination of moisture in aggregate by displacement in water [ASTM C 70 1994].

The testing specification for specific gravity and absorption is ASTM C128 "Standard Test Method for Density, Relative Density (Specific Gravity), and Absorption of Fine Aggregate." The results are presented in Table 6-4. The variation in specific gravity of excess foundry sands has been attributed to the variability in fines and additive contents in different samples. Reported values of absorption are found to vary widely, which can be attributed to the presence of binders and additives [Joved and Lovell 1994].

The variation of both variables are verified to be normal distributed, Table 6-4. Corresponding parameters are presented in Table 6-4.

6.2.3 Moisture Content

Most binder systems need water as solvent or catalyst to activate various inorganic and organic binder raw materials. Although the melting temperature is high, it decreases significantly along the dimensions of molding. After the refractory process, a low water content is retained in the excess foundry sand. Ignoring this part of water leads to the inaccuracy of CLSM formulation. The water content is treated as a source of water in this research and is considered when CLSM formulations are made. The testing specification for water content is ASTM C566-97, "Standard Test Method for Total Evaporable Moisture Content of Aggregate by Drying." In this investigation, samples are kept in a ventilated oven at a temperature of 110 °C until each sample's weight is constant [ASTM C 566 1997].

The results of the water content investigation are presented in Table 6-4. They ranged from 0 to 4.85%, which may depend on the bonding process and stocking methods. Water contents of excess foundry sands are normally distributed, as indicated in Table 6-4.

6.2.4 Gradation

Gradation has an important effect upon flowable consistency, compaction and strength. Particularly in the application of CLSM, compaction is its pronounced feature. It is shown that the true sphere of a given size when perfectly packed occupies 74% of the total volume. Greater compaction can be obtained by filling the remaining voids with particles of decreasing size order [Webster 1980]. Evaluating the gradation of excess foundry sand is an essential step toward integrating excess foundry sands into CLSM.

Gradation was investigated by sieve analysis and visualized by the gradation curve. The testing specification for sieve analysis is AFS 1105-00 "Sieve Analysis (Particle Size Determination of Sand)." It was conducted by separating the grains into 10 segments by letting a representative sample pass through a series of screens with openings that get increasingly smaller; plotting individual weight of the fraction to form an x/y graph of particle size versus individual weight will give a bell-shaped curve that represents the grain distribution (by size) for that sand [AFS 1105 2000].

The quantified results of sieve analysis are presented in Tables G-1 and G-2 in Appendix G.1. Corresponding gradation curves are plotted in Figure 6-1. The gradation curves show distributions of particle sizes. It is indicated that gradation of excess foundry sand is dominated by a common shape. Although grain sizes span from 3.5 mm down to zero, the size is highly concentrated, with 90% in the narrow range of 0.15 mm (5% quantile) to 0.80 mm (95% quantile). And in this range, particles are

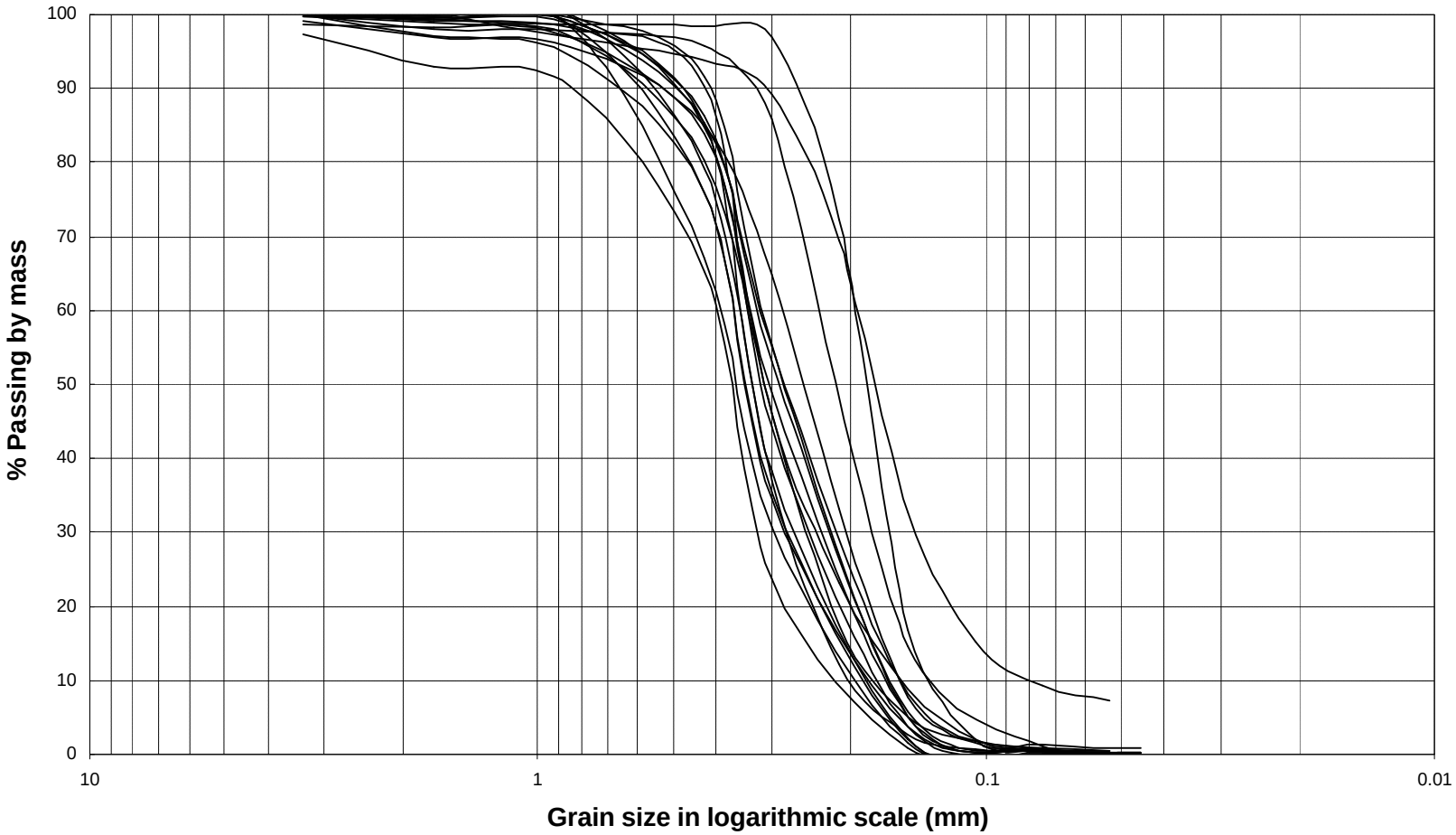

Figure **6-1**: Gradation curve of excess foundry sands

distributed by size. Ninety percent by mass of foundry sands are uniformly distributed along size 0.15-0.80 mm. The remaining 10% of the particles are extended two-way. The grain size distribution of excess foundry sand is more uniform and finer than conventional CLSM fine sand. While the fineness of spent foundry sand contributes to limited segregation of flowable fill, there is a need to investigate the impact of alternative gradations to permit wider use of excess foundry sand for this application.

Table 6-5 presents parameters describing the gradation characteristics of sand. D_{10}, D_{30}, D_{50}, D_{60} represents the particle sizes corresponding to 10%, 30%, 50%, and 60% finer in the gradation curve. Uniformity coefficient C_u, D_{60} divided by D_{10}, and coefficient of gradation C_z, square of D_{30} divided by product of D_{60} and D_{10}, are used to characterize gradation. By these two terms, foundry sands are classified as very uniform (C_u <5) and well graded (1<C_z <3) aggregates. The long-established AFS Grain Fineness Number (AFS GFN), a measure of average grain size, is based on the number of openings per inch of a sieve that would just pass the average size calculated from the sieving analysis [Beeley 2001].

Steel castings typically use a very coarse sand grain size with a low grain fineness number, such as 45-55 AFS GFN, because they have a lot of gas to get rid of in a hurry. Iron castings use a slightly finer sand, 55-70 AFS GFN. Nonferrous castings are even finer, 65-90 AFS GFN. The AFS GFN investigated on the 17 foundry sands according to AFS 1106-00-S, “Grain Fineness Number, AFS GFN, Calculation,” are presented in Table 6-5. It is consistent with the variation of foundry background.

Table **6-5**: Gradation evaluation of excess foundry sand

FS ID	D_{50} (mm)	D_{10} (mm)	D_{30} (mm)	D_{60} (mm)	Size 200 (0.075 mm) passing percentage by weight (%)	C_u	C_z	AFS GFN
	Quantiles of Gradation				ASTM C117	$\frac{D_{60}}{D_{10}}$	$\frac{D_{30}^2}{D_{60} \times D_{10}}$	AFS 1106
FS01	0.347	0.180	0.278	0.377	0.482	2.094	1.136	50.19
FS02	0.345	0.186	0.276	0.376	0.078	2.021	1.089	49.45
FS03	0.331	0.182	0.265	0.358	0.172	1.966	1.081	51.69
FS04	0.225	0.124	0.182	0.246	1.186	1.980	1.091	76.92
FS05	0.284	0.156	0.220	0.320	0.493	2.051	0.968	61.26
FS06	0.379	0.209	0.319	0.409	0.000	1.953	1.186	41.97
FS07	0.284	0.165	0.224	0.316	0.655	1.917	0.967	60.28
FS08	0.304	0.167	0.236	0.340	0.502	2.035	0.978	56.28
FS09	0.290	0.164	0.227	0.326	0.522	1.996	0.966	59.18
FS10	0.316	0.173	0.247	0.343	1.345	1.979	1.030	56.68
FS11	0.366	0.193	0.296	0.401	0.077	2.076	1.132	46.92
FS12	0.187	0.130	0.165	0.198	0.369	1.526	1.054	69.99
FS13	0.313	0.155	0.238	0.249	0.515	1.601	**1.467**	51.62
FS14	0.179	**0.079**	0.143	0.196	**9.209**	**2.479**	**1.318**	**90.36**
FS15	0.338	0.198	0.275	0.368	0.414	1.861	1.040	45.66
FS16	0.259	0.156	0.204	0.287	0.726	1.843	0.936	54.71
FS17	0.315	0.175	0.251	0.351	0.928	2.006	1.024	48.68
min	*0.1791*	*0.079*	*0.143*	*0.196*	*0.0000*	*1.526*	*0.936*	*41.974*
max	*0.3789*	*0.209*	*0.319*	*0.409*	*9.2088*	*2.479*	*1.467*	*90.363*
average	*0.2978*	*0.164*	*0.238*	*0.321*	*1.0396*	*1.964*	*1.086*	*57.166*
SD	*0.0576*	*0.0311*	*0.0465*	*0.0654*	*2.1372*	*0.2039*	*0.1370*	*12.2559*
Normality	*Yes, p=0.19*	*Yes, p=0.14*	*Yes, p=0.89*	*Yes, p=0.53*	*No, p=0+ or Yes without FS14, p=0.23*	*No, p=0.007*	*No, p=0.02*	*No, p=0.03, or Yes without FS14, p=0.32*

Aggregates finer than 0.075 mm sieve can be separated from larger particles much more efficiently and completely by wet sieving than through the use of dry sieving [ASTM C 117 1995]. Therefore, this wet sieving approach of ASTM C 117, "Standard Test Method for Materials Finer than 75-µm (No. 200) Sieve in Mineral Aggregates by Washing," was selected to determine the concentration of particles finer than 0.075 mm. The results are shown in Table 6-5. In general, less than 1.345% by mass of foundry sands passes 0.075 mm, except for sand from copper-based facilities, which use finer aggregate for finer finishing.

The normality tests for each variable are presented in Table 6-5. It is assumed that quantiles for gradations of sands are normally distributed, which include D_{10}, D_{30}, D_{50}, and D_{60}. This assumption is verified by gradation curves presented in Figure 6-1, in which horizontal lines are plotted across the cluster of curves, and the x values of these crossed points are normally distributed. However, the rest of the variables are not normalized very well. Mass percentage passing size 200 and AFS GFN would be normalized only if data of sand FS14 were eliminated. Sand FS14 is from a copper-based facility that uses finer particles than the other facilities. Gradation coefficients C_u and C_z are not normally distributed.

6.2.5 Grain Shape

Grain shape of virgin sand is determined by its geological origin [Beeley 2001]. Four different basic shapes are recognizable for foundry sand: round, sub-angular,

angular, and compound or composite [AFS 1107 2000]. The characteristics may be readily observed under a microscope. Grain shape is important with respect to flowability and strength. Round sands give superior flowability to angular sands. And angular sands yield higher strength than round sands do. However, round grain has the lowest surface area and requires the least amount of cementitious material. Most lake sands are in this shape. Angular sands have grains with edges that form acute angles (less than 90 degrees). They are poor for making a good working consistency, for angular particles lock up and neither slide nor compact as well as round ones do. They are made from crushed rock. Compound sands have grains that are stacked together. They look like popcorn balls. They do not flow well, and when they do break apart, there are a lot of fines.

Sand was screened into 10 segments as a result of sieve analysis in Section 6.2.4. The shape of each segment was investigated according to Standard AFS 1107, "Grain Shape Classification." The shape observation for each segment is mingled with corresponding gradation results and presented in Figure G-1 in Appendix G.2.

In sands with sizes covering 90% excess foundry sands, 0.15-0.80 mm (Section 6.2.4), subangular and round grains occupy more than 50% by mass. It was discovered that as the size increases, the shape tends to be compound or round. If the size decreases, the shape tends to be angular or jagged. It was observed that the compound grains were composed of subangular and round grains once they were crushed under a microscope. Therefore, subangular and round dominate the shape of sands. The spherical shape of

excess foundry sand particles contributes to superior flowable characteristics of flowable fill. However, increased particle fineness and sphericity result in lower strength-bearing capacity of the hardened flowable fill [Larsen 1990].

6.2.6 Organic Content and Methylene Blue Value

The organic content was determined using AASHTO Standard Procedure T 267-86, with one modification. Instead of being burned for 6 hours, the samples were burned for 24 hours to ensure thorough combustion of the organic components.

The following procedure originated from AFS 2210-00-S standard, "Methylene Blue Clay Test, Ultrasonic Method, Molding Sand" [American Foundry Society 2001]. Instead of using the spot test on filter paper to determine the titration point, a spectrophotometer was used. For our study, a Milton Roy Spectronic 301, Item: 335401 was used to measure the "% absorbed" to determine the level of blueness. The titration equipment, HM-58, was purchased from the Gilson Company, along with the methylene blue dye, HMA-78. The methylene blue test was run a total of three times. The first two times were to get a general idea of where the methylene blue titration point was, the last time was to get a more exact value.

Each sand was tested for its organic content, and methylene blue value (MBV). The organic content is the amount of material burned off at 455C for a period of 24

hours. The 95% confidence interval is also shown for the organic content. The confidence intervals were calculated by Equation 6.1.

$$95\% C.I. = \frac{t \times S.D.}{\sqrt{n}} \qquad \text{Equation } \mathbf{6.1}$$

S.D. = Standard deviation of the measurements

t = Student's t distribution = 3.18

n = Number of measurements per sand = 4

All of the confidence intervals were very tight for the organic contents. The organic material mostly comes from sea coal, but can also come from carbohydrates that are added to the sand, or from organic-based binder systems. Since all of the organic contents are under 5%, and since the mix is only made up of 10% foundry sand, the organic content does not seem to be a significant contributor to the performance of the mix.

The methylene blue value is an indicator of the amount of clay that is in a foundry sand or aggregate. It is the ratio of the milligrams of methylene blue dye that a gram of foundry sand can absorb. It is measured using a spectrophotometer. The 95% C.I. is also shown for the control and three sands in Table 6-6. For these, the student's t-distribution is 4.30 since the number of measurements was limited to 3 per sand. The confidence interval seems to vary more widely for the MBV as compared to the organic content, since it ranges from 0.3 to 5.3. The MBV was also recorded for the foundry sands after they were tested for their organic contents.

Table **6-6**: Organic Contents and Methylene Blue Values

Sand No.	% O.C.	M.B.V. (mg M.B./gram F.S.)	M.B.V. After LOI @ 455 EC
Control (P0.60)	N.R.	1.9±0.3	N.R.
FS01	2.5±0.1	31.4±5.3	30.5
FS02	4.7±0.1	0.8	0.8
FS03	3.8±0.1	27.3	28.1
FS04	2.9±0.1	22.8	23.2
FS05	4.7±0.1	28.1	29.6
FS06	1.3±0.1	1.3	0.8
FS07	2.5±0.1	22.4	23.8
FS08	3.3±0.1	27.5±0.4	23.5
FS09	1.3±0.1	10.1	8.9
FS10	0.2±0.1	0.8	0.6
FS11	0.7±0.1	21.0	19.6
FS12	1.2±0.1	0.4	0.8
FS13	1.2±0.1	0.8	0.6
FS14	1.6±0.1	3.2±1.8	2.5
FS15	2.1±0.1	30.2	28.2
FS16	1.6±0.1	36.3	34.1
FS17	0.2±0.1	1.4	0.8

According to the Green Sand Additives [American Foundry Society 2000] handbook, the temperature of destruction for southern bentonite ranges between 315-390 EC, and for western bentonite, ranges between 650-815 EC. Since the LOI test was run at 455 EC, it was believed all the southern bentonite would be destroyed, thus allowing a measure of the western bentonite. But from the values shown in Table 6-6, it appears the MBV hardly changes. It is possible that during the foundry process the southern bentonite was already destroyed, or the values given in the AFS handbook are not completely accurate. The other possibility is that the level of southern bentonite in the sand is lower than the accuracy of the test. Either way, measuring the MBV of the foundry sand after it has been tested for LOI does not seem to be a good method to use to determine the southern bentonite content.

The methylene blue value was also determined for pure southern and western bentonite. They were very high compared to the foundry sands, with southern bentonite showing a MBV of 391 mg/g and western bentonite showing a MBV of 385 mg/g. Sand FS16 has the highest MBV of 36.3 mg/g. If clay has a typical MBV of about 388 mg/g, this means the clay content of sand FS16 would lay at around 9.4%. Figure 6-2 shows the comparison between the fines content and the methylene blue value of each of the foundry sands. There is a general correlation between the two, which shows that as the fines content increases, so does the MBV. Since clay is a fine material, this seems intuitive. Figure 6-3 shows a comparison between the fines content and MBV for foundry sands that contain bentonite. The higher R^2 value further verifies that the clay content is related to the fines content.

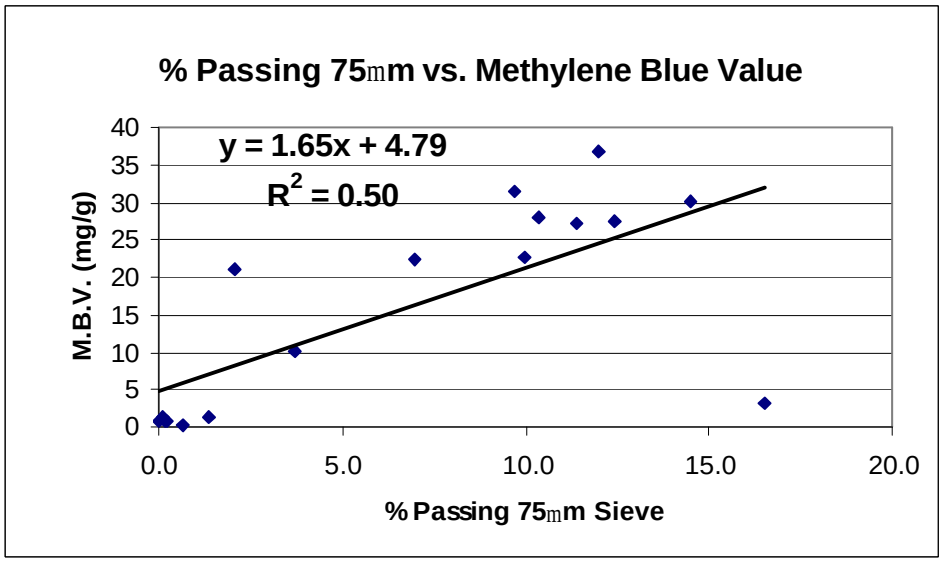

Figure **6-2**: Comparison of fines content to M.B.V.

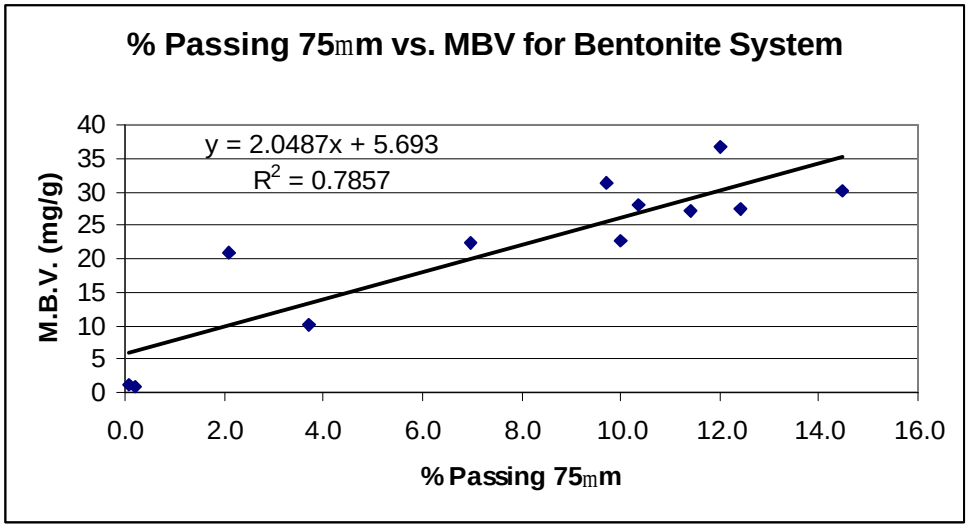

Figure **6-3**: Comparison of fines content to M.B.V. for bentonite system

6.3 Bulk Chemical Analysis of Excess Foundry Sands

Bulk chemical analysis was conducted on 17 sands to evaluate the concentrations of elements that are regulated. The toxicity evaluation is avoided if the bulk chemical analysis is within the toxicity threshold.

EXYGEN, a commercial analytical chemical laboratory, performed the bulk chemical analysis according to EPA testing methods and X-ray fluorescence methods. The elements investigated include oxides and organic compounds. Results are presented in Table H-1 for organic compounds in Appendix H.1 and Table H-2 for oxides in Appendix H.2. For the organic compounds, the frequent quantified compounds include o-cresol, m,p-cresol, cresol-total, 2,4-dimethylphenol, phenanthrene, and acetone. Two observations for naphthalene and one observation for methyl ethyl ketone were reported

much greater than observations of the other samples. Further investigation is desired regarding these unusual observations. For the oxides, FS14 is identified as containing more CaO and MgO and less SiO_2 than the other excess foundry sands. FS10 is identified as containing more SO_3, MgO, and CaO than the other sands.

Chapter 7

EXPERIMENTS QUALIFYING CLSM USING EXCESS FOUNDRY SAND

In this chapter, an experimental program was conducted to characterize the performance of CLSM containing excess foundry sands, and to provide technical data qualifying CLSM using excess foundry sands.

7.1 Experimental Design of CLSM

7.1.1 Executive Summary

Flowable fill mixtures are usually designed on the basis of compressive strength, generally after 28 days of ambient temperature curing, but sometimes on the basis of longer-term (90 days or more) strength. They are designed to have high flowability during placement and to develop limited strength, typically between 340 kPa (50 psi) and 1,400 kPa (200 psi) at 28 days, which is sufficient to support traffic without settling, yet can be readily excavated and gain limited strength after that [PCA 1990].

Fist of all, scouting mixtures were conducted to produce limited excavatable CLSM samples. The behavior of the CLSM was tested and observed, and the formulations were improved for excavatable CLSM. Using the modified formulations, an initial batch of excavatable CLSM was mixed using all 17 sands. Their construction behavior and geotechnical performance were tested and observed. If the parameters of

CLSM attain the specified requirements of CLSM by ACI 229, no further excavatable CLSM is needed. Otherwise, mixtures were redesigned and tested until critical performances were attained. The design of structural CLSM was based on the design of excavatable CLSM and PennDOT specification for Type C CLSM. Identical experimental mixing and testing were performed. For this research, water was added until the desired flowability was achieved according to the flowability test of ASTM D 6103-97, "Standard Test Method for Flow Consistency of Controlled Low Strength Material (CLSM)."

7.1.2 Critical Parameters

The integration of excess foundry sand to CLSM is mainly qualified by its competitive performance against general CLSM containing fine aggregates. The performances are compared using construction and geotechnical properties. A summary of the critical parameters is listed in Table 7-1. Corresponding experimental programs, including sampling and testing procedures, are listed as well.

Flow consistency testing determines the fluidity and monitors the CLSM capacity in self-leveling, self-compaction, and workability in the fresh condition. Flowability is a critical parameter in flowable fill design because it ensures that all void space in the designed cavity is filled by the flowable fill material [Mast 1997]. Bleed tests were used to measure the relative quantity of mixing water that will bleed from freshly mixed CLSM. Bleeding is the discharges of CLSM to surrounding environments, which

possibly will pose environmental concerns. Its volume influences the assessment of environmental impact resulting from CLSM.

Table **7-1**: Parameters qualifying CLSM using excess foundry sand

	Parameters	Samples or Containers	Standard
Fresh CLSM	Fresh Density	1 - ƒ 15.24 x 12.7 cm steel measurement	ASTM D 6023
	Flow Consistency	1 - ƒ 7.6 x 15.2 cm open-ended cylinder	ASTM D 6103
	Bleeding	1 - ƒ 10.2 x 20.4 cm cylinder	ASTM C 232
	Settlement	4 - ƒ 10.2 x 20.4 cm cylinders	ASTM C 827
	Setting Time and Penetration Resistance	1 - 23.5 x 23.5 x 8.7 cm or 30.5 x 30.5 x 8.7 cm container	ASTM C 403
	Toxicity of Bleeding	Up to 1,500 ml bleeding	EPA SW-486
Hardened CLSM	Density (3, 7, 14, 28, 90, and 180 day)	4 - ƒ 10.2 x 20.4 cm cylinders	------
	Oven-Dry Density (180 day)	1 or 2 - ƒ 10.2 x 20.4 cm cylinders	ASTM C 567
	Hydraulic Conductivity (28 day)	1 - ƒ 10.2 x 10.2 cm metal proctor mold	ASTM D 2434
	Compressive Strength (3, 7, 14, 28, 90, and 180 day)	18 - ƒ 10.2 x 20.4 cm cylinders	ASTM D 4832
	Toxicity of CLSM (28 day)	1 - ƒ 10.2 x 20.4 cm cylinder	EPA SW-486
	Resistivity	1 - 23.5 x 9 x 8.7 cm container	ASTM G57

Settlement testing determines the change in height of a cylindrical specimen from the time of placement until its final set. It provides a means for comparing the relative settlement or expansion of cementitious mixtures. It is particularly applicable to grouting, patching, and form-filling operations where the objective is to completely fill a cavity or other defined space with a freshly mixed cementitious mixture that will continue to fill the same space at the time of hardening. Generally, CLSM presents settlement to an extent that depends on the water bleed, particle gradation and hydration of cementitious materials.

Since the setting of CLSM is a gradual process, any definition of time of setting must necessarily be arbitrary. The times required for the CLSM to reach specified values of resistance to penetration are used to define times of setting. It provides a measure of the effects of variables, such as foundry sand variation, grain gradation and shape, and water-cement ratio upon the hardening properties of CLSM.

Hydraulic conductivity determines the coefficient of permeability by a constant-head method using tap water through hardened CLSM. It establishes representative values of coefficient of permeability of CLSM placed as embankments or backfills. This parameter is useful in the evaluation of environmental impact and corrosivity of CLSM. Less hydraulic conductivity helps mitigate leaching and stagnate ion movement.

CLSM is typically used as a backfill material around structures, particularly in confined or limited spaces. Compressive strength testing is performed to assist in the design of the mixture and to serve as a control technique during construction. Mixture design is typically based on 28-day strengths and construction control tests performed 3, 7, 14, 90, and 180 days after placement.

Bleeding and leachate from CLSM are the two discharges of CLSM that pose potential environmental impact. In this research program, they are collected and analyzed for toxicity evaluation of CLSM.

7.1.3 Formulations of Scouting CLSM

The formulations presented in Section 7.1.3, 7.1.4, and 7.1.5 are calculated by mass and by volume on solid materials at oven-dry condition. They were worked out through a back-calculation procedure based on measurements. These measurements include mass and specific gravity of raw materials, water content of foundry sands, and fresh density of CLSM. Simple substitution of foundry sand for standard fine aggregate in current CLSM specifications produces errors due to significant difference in gradation and specific gravity of the two materials.

Scouting experiments included two parts: scouting experiment I tending to probe the lower bound of formulations, and scouting experiment II tending to probe the upper bound of formulations. Eleven sands were used in the scouting experiments. The formulations by mass and by volume for scouting experiment I are summarized in Table 7-2 and Table 7-3, respectively. Corresponding formulations for scouting experiment II are summarized in Table 7-4 and Table 7-5. Water addition in the mixing proportion complies with normal distribution, N (405, 65) for scouting experiment I and N (406, 61) for scouting experiment II, which indicates the water addition amount. The fresh densities of two scouting experiments are normally distributed as well, N (1920, 138) and N (1930, 136), respectively.

Table **7-2**: Formulation by mass as oven-dry in scouting experiment I

FS ID	Bulk Proportion* (Unit: kg/m^3)					Percentage by Weight, %			
	Cement	Fly Ash	Sand	Water	Total	Cement	Fly Ash	Sand	Water
FS01	29	263	862	543	1697	2	16	51	32
FS02	45	401	1332	339	2116	2	19	63	16
FS03	38	338	907	481	1764	2	19	51	27
FS04	38	343	991	436	1808	2	19	55	24
FS05	40	362	1005	428	1835	2	20	55	23
FS06	49	440	1137	365	1991	2	22	57	18
FS07	41	372	1130	397	1940	2	19	58	20
FS08	43	383	1036	402	1863	2	21	56	22
FS09	44	400	1196	367	2007	2	20	60	18
FS10	49	444	1303	315	2111	2	21	62	15
FS11	43	383	1176	383	1984	2	19	59	19
Min.	*29*	*263*	*862*	*315*	*1697*	*2*	*16*	*51*	*15*
Max.	*49*	*444*	*1332*	*543*	*2116*	*2*	*22*	*63*	*32*
Avg.	*42*	*375*	*1098*	*405*	*1920*	*2*	*19*	*57*	*21*
SD	*5.64*	*50.53*	*152.03*	*65.09*	*137.51*	*0.00*	*1.57*	*3.95*	*5.04*

* Mass of raw material per unit of fresh CLSM

Table **7-3**: Formulation by volume as oven-dry in scouting experiment I

FS ID	Bulk Volume as Oven-dry, m^3/m^3 *			Percentage by Bulk Volume as Oven-dry, %					Percentage by Absolute Volume in CLSM, %			
	Cement	Fly Ash	Sand	Water	Cement	Fly Ash	Sand	Water	Cement	Fly Ash	Sand	Water
FS01	0.03	0.20	0.67	0.54	1.8	13.9	46.5	37.8	0.9	10.3	34.4	54.3
FS02	0.04	0.30	0.96	0.34	2.4	18.4	58.6	20.6	1.4	15.7	49.0	33.9
FS03	0.03	0.26	0.71	0.48	2.3	17.3	47.8	32.6	1.2	13.3	37.4	48.1
FS04	0.03	0.26	0.70	0.44	2.4	18.2	48.9	30.6	1.2	13.5	41.7	43.6
FS05	0.04	0.27	0.73	0.43	2.4	18.6	49.9	29.1	1.3	14.2	41.8	42.8
FS06	0.04	0.33	**1.04**	0.36	2.4	18.7	58.4	20.5	1.6	17.3	44.7	36.5
FS07	0.04	0.28	0.87	0.40	2.3	17.8	54.8	25.1	1.3	14.6	44.4	39.7
FS08	0.04	0.29	0.80	0.40	2.5	18.9	52.4	26.2	1.4	15.1	43.4	40.2
FS09	0.04	0.30	0.84	0.37	2.5	19.6	54.1	23.7	1.4	15.7	46.2	36.7
FS10	0.04	0.34	0.90	0.31	2.7	21.1	56.4	19.7	1.6	17.4	49.5	31.5
FS11	0.04	0.29	0.89	0.38	2.4	18.2	55.5	24.0	1.4	15.0	45.3	38.3
Min.	*0.03*	*0.20*	*0.67*	*0.31*	*1.8*	*13.9*	*46.5*	*19.7*	*0.9*	*10.3*	*34.4*	*31.5*
Max.	*0.04*	*0.34*	*1.04*	*0.54*	*2.7*	*21.1*	*58.6*	*37.8*	*1.6*	*17.4*	*49.5*	*54.3*
Avg.	*0.04*	*0.28*	*0.83*	*0.41*	*2.4*	*18.3*	*53.0*	*26.4*	*1.3*	*14.7*	*43.4*	*40.5*
SD	*0.005*	*0.038*	*0.118*	*0.065*	*0.220*	*1.753*	*4.229*	*5.669*	*0.196*	*1.983*	*4.529*	*6.509*

* Bulk volume of raw material per unit of fresh CLSM.

Table **7-4**: Formulation by mass as oven-dry in scouting experiment II

FS ID	Bulk Proportion* (unit: kg/m^3)					Percentage by Weight, %			
	Cement	Fly Ash	Sand	Water	Total	Cement	Fly Ash	Sand	Water
FS01	66	299	947	483	1795	4	17	53	27
FS02	88	395	1268	351	2102	4	19	60	17
FS03	74	334	859	491	1758	4	19	49	28
FS03	73	242	915	505	1735	4	14	53	29
FS04	81	363	1012	406	1862	4	20	54	22
FS05	77	346	922	457	1802	4	19	51	25
FS06	**144**	433	1025	381	1984	7	22	52	19
FS06	**192**	431	973	388	1984	10	22	49	20
FS07	81	362	1060	416	1919	4	19	55	22
FS08	82	369	956	428	1835	4	20	52	23
FS09	91	409	1178	355	2034	4	20	58	17
FS10	**147**	440	1198	325	2110	7	21	57	15
FS10	**199**	447	1168	318	2131	9	21	55	15
FS11	86	386	1149	379	1999	4	19	57	19
Min.	*66*	*242*	*859*	*318*	*1735*	*4*	*14*	*49*	*15*
Max.	*199*	*447*	*1268*	*505*	*2131*	*10*	*22*	*60*	*29*
Avg.	*106*	*375*	*1045*	*406*	*1932*	*5*	*19*	*54*	*21*
SD	*45.15*	*58.12*	*126.44*	*60.61*	*135.79*	*2.12*	*2.07*	*3.29*	*4.67*

* Mass of raw material per unit of fresh CLSM.

Table **7-5**: Formulation by volume as oven-dry in scouting experiment II

FS ID	Bulk Volume as Oven-dry, m^3/m^3 *				Percentage by Bulk Volume as Oven-dry, %				Percentage by Absolute Volume in CLSM, %			
	Cement	Fly Ash	Sand	Water	Cement	Fly Ash	Sand	Water	Cement	Fly Ash	Sand	Water
FS01	0.06	0.23	0.73	0.48	3.9	15.1	48.9	32.2	2.1	11.7	37.8	48.3
FS02	0.08	0.30	0.92	0.35	4.7	18.2	55.8	21.4	2.8	15.5	46.6	35.1
FS03	0.07	0.25	0.67	0.49	4.4	17.1	45.2	33.2	2.4	13.1	35.4	49.1
FS03	0.06	0.18	0.71	0.50	4.4	12.5	48.7	34.5	2.3	9.5	37.7	50.5
FS04	0.07	0.28	0.71	0.41	4.9	18.8	48.6	27.7	2.6	14.3	42.6	40.6
FS05	0.07	0.26	0.67	0.46	4.7	17.9	46.1	31.3	2.4	13.6	38.3	45.7
FS06	0.13	0.33	**0.94**	0.38	7.2	18.5	52.8	21.5	4.6	17.0	40.3	38.1
FS06	0.17	0.33	**0.89**	0.39	9.6	18.4	50.2	21.9	6.1	16.9	38.2	38.8
FS07	0.07	0.27	0.81	0.42	4.5	17.4	51.7	26.4	2.6	14.2	41.6	41.6
FS08	0.07	0.28	0.74	0.43	4.8	18.4	48.8	28.1	2.6	14.5	40.1	42.8
FS09	0.08	0.31	0.82	0.36	5.1	19.7	52.5	22.6	2.9	16.1	45.5	35.5
FS10	0.13	0.33	0.83	0.33	8.0	20.6	51.2	20.1	4.7	17.3	45.5	32.5
FS10	0.18	0.34	**0.81**	0.32	10.7	20.7	49.2	19.4	6.3	17.6	44.4	31.8
FS11	0.08	0.29	0.86	0.38	4.7	18.1	53.7	23.5	2.7	15.1	44.3	37.9
Min.	*0.06*	*0.18*	*0.67*	*0.32*	*3.9*	*12.5*	*45.2*	*19.4*	*2.1*	*9.5*	*35.4*	*31.8*
Max.	*0.18*	*0.34*	*0.94*	*0.50*	*10.7*	*20.7*	*55.8*	*34.5*	*6.3*	*17.6*	*46.6*	*50.5*
Avg.	*0.09*	*0.28*	*0.79*	*0.41*	*5.8*	*18.0*	*50.2*	*26.0*	*3.4*	*14.7*	*41.3*	*40.6*
SD	*0.041*	*0.045*	*0.090*	*0.059*	*2.155*	*2.112*	*2.911*	*5.207*	*1.434*	*2.292*	*3.561*	*6.061*

* Bulk volume of raw material per unit of fresh CLSM.

7.1.4 Formulations of Excavatable CLSM

Investigation of the formulation of excavatable CLSM took a multi-phase procedure. Due to the number of selected foundry sands and the variations in individual properties, each CLSM formulation was continuously redesigned to comply with standardized performances. The formulations by mass and by volume for phase I are summarized in Table 7-6 and Table 7-7, respectively. Corresponding formulations for phase II are summarized in Table 7-8 and Table 7-9. The water addition in the mixture proportions is normally distributed, N (412, 55) for phase I and N (378, 56) for phase II, which indicates water addition amount. The fresh densities are normally distributed as well, N (1919, 93) and N (1947, 80), respectively. All the parameters correlate soundly with corresponding parameters in the scouting experiments.

In summary of two phases of excavatable experiments, formulations by mass and by volume of final excavatable CLSM are presented in Table 7-10 and Table 7-11, respectively. Cement, which significantly influences the strength of CLSM, varies its proportion due to the variation of foundry sand. In fresh CLSM, both water and sand occupy more than a third by absolute volume (water averaged 40%, and sand averaged 43%).

Table **7-6**: Formulation by mass as oven-dry in excavatable CLSM experiment phase I

FS ID	Bulk Proportion* (unit: kg/m^3)					Percentage by Weight, %			
	Cement	Fly Ash	Sand	Water	Total	Cement	Fly Ash	Sand	Water
FS01	66	355	970	448	1839	3.6	19.3	52.8	24.4
FS02	73	394	1264	343	2074	3.5	19.0	61.0	16.5
FS03	63	340	876	504	1784	3.5	19.1	49.1	28.3
FS04	70	379	1055	405	1910	3.7	19.9	55.3	21.2
FS05	69	371	988	445	1872	3.7	19.8	52.8	23.8
FS06	83	448	1059	364	1954	4.2	22.9	54.2	18.6
FS07	65	352	1031	428	1876	3.5	18.8	55.0	22.8
FS08	67	360	934	460	1822	3.7	19.8	51.3	25.3
FS09	74	400	1151	355	1979	3.7	20.2	58.1	17.9
FS10	81	436	1180	345	2042	4.0	21.4	57.8	16.9
FS11	66	358	1066	440	1931	3.4	18.5	55.2	22.8
FS12	65	353	1156	359	1933	3.4	18.3	59.8	18.6
FS13	75	405	1218	349	2048	3.7	19.8	59.5	17.1
FS14	72	389	1154	392	2006	3.6	19.4	57.5	19.5
FS15	74	400	818	489	1782	4.2	22.5	45.9	27.5
FS16	64	345	975	464	1849	3.5	18.7	52.8	25.1
Min.	*63*	*340*	*818*	*343*	*1782*	*3.4*	*18.3*	*45.9*	*16.5*
Max.	*83*	*448*	*1264*	*504*	*2074*	*4.2*	*22.9*	*61.0*	*28.3*
Avg.	*70*	*380*	*1056*	*412*	*1919*	*3.7*	*19.8*	*54.9*	*21.6*
SD	*5.97*	*32.03*	*125.63*	*54.68*	*93.23*	*0.25*	*1.35*	*4.08*	*3.88*

* Mass of raw material per unit of fresh CLSM.

Table **7-7**: Formulation by volume as oven-dry in excavatable CLSM experiment phase I

FS ID	Bulk Volume as Oven-dry, m^3/m^3 *				Percentage by Bulk Volume as Oven-dry, %				Percentage by Absolute Volume, %			
	Cement	Fly Ash	Sand	Water	Cement	Fly Ash	Sand	Water	Cement	Fly Ash	Sand	Water
FS01	0.06	0.27	0.75	0.45	3.8	17.6	49.3	29.3	2.1	14.0	38.9	45.0
FS02	0.06	0.30	0.92	0.34	4.0	18.4	56.5	21.2	2.4	15.7	47.2	34.8
FS03	0.06	0.26	0.68	0.50	3.7	17.2	45.5	33.7	2.0	13.1	35.4	49.5
FS04	0.06	0.29	0.74	0.41	4.1	19.2	49.6	27.1	2.2	14.6	43.5	39.7
FS05	0.06	0.28	0.72	0.45	4.0	18.6	47.8	29.5	2.1	14.2	40.1	43.5
FS06	0.07	0.34	0.97	0.36	4.2	19.4	55.5	20.9	2.7	17.9	42.4	37.1
FS07	0.06	0.27	0.79	0.43	3.7	17.3	51.3	27.7	2.1	14.0	40.8	43.1
FS08	0.06	0.27	0.73	0.46	3.9	18.0	47.8	30.4	2.1	14.0	38.6	45.4
FS09	0.07	0.30	0.81	0.36	4.3	19.8	52.7	23.2	2.4	16.0	45.4	36.2
FS10	0.07	0.33	0.82	0.35	4.6	21.1	52.2	22.1	2.6	17.3	45.3	34.9
FS11	0.06	0.27	0.80	0.44	3.7	17.2	51.0	28.0	2.1	13.9	40.6	43.5
FS12	0.06	0.27	0.77	0.36	4.0	18.4	52.9	24.7	2.2	14.6	45.3	37.9
FS13	0.07	0.31	0.81	0.33	4.4	20.2	53.5	21.9	2.4	16.2	47.6	33.8
FS14	0.06	0.29	0.83	0.39	4.0	18.6	52.6	24.8	2.2	14.8	45.1	37.9
FS15	0.07	0.30	0.78	0.49	4.0	18.5	47.5	29.9	2.3	15.5	33.9	48.3
FS16	0.06	0.26	0.84	0.46	3.5	16.1	51.8	28.6	2.0	13.5	38.4	46.1
Min.	*0.06*	*0.26*	*0.68*	*0.33*	*3.5*	*16.1*	*45.5*	*20.9*	*2.0*	*13.1*	*33.9*	*33.8*
Max.	*0.07*	*0.34*	*0.97*	*0.50*	*4.6*	*21.1*	*56.5*	*33.6*	*2.7*	*17.9*	*47.6*	*49.5*
Avg.	*0.06*	*0.29*	*0.80*	*0.41*	*4.0*	*18.5*	*51.1*	*26.4*	*2.2*	*14.9*	*41.8*	*41.0*
SD	*0.005*	*0.024*	*0.073*	*0.056*	*0.286*	*1.273*	*3.007*	*3.837*	*0.206*	*1.364*	*4.109*	*5.102*

* Bulk volume of raw material per unit of fresh CLSM.

Table **7-8**: Formulation by mass as oven-dry in excavatable CLSM experiment phase II

FS ID	Bulk Proportion* (unit: kg/m^3)					Percentage by Weight, %			
	Cement	Fly Ash	Sand	Water	Total	Cement	Fly Ash	Sand	Water
FS05	37	334	972	474	1817	2.0	18.4	53.5	26.1
FS06	64	429	1094	378	1965	3.2	21.8	55.7	19.3
FS08	41	370	998	395	1803	2.3	20.5	55.4	21.9
FS09	45	404	1207	320	1976	2.3	20.4	61.1	16.2
FS10	32	463	1212	329	2036	1.6	22.8	59.5	16.2
FS13	37	394	1242	348	2020	1.8	19.5	61.5	17.2
FS14	15	398	1182	394	1990	0.8	20.0	59.4	19.8
FS16	94	361	1020	426	1901	4.9	19.0	53.7	22.4
FS17	43	387	1118	423	1972	2.2	19.6	56.7	21.5
FS17	25	444	1225	291	1984	1.2	22.4	61.7	14.7
Min.	*15*	*334*	*972*	*291*	*1803*	*0.8*	*18.4*	*53.5*	*14.7*
Max.	*94*	*463*	*1242*	*474*	*2036*	*4.9*	*22.8*	*61.7*	*26.1*
Avg.	*43*	*398*	*1127*	*378*	*1947*	*2.2*	*20.5*	*57.8*	*19.5*
SD	*21.99*	*39.05*	*101.52*	*56.10*	*80.28*	*1.15*	*1.46*	*3.20*	*3.53*

* Mass of raw material per unit of fresh CLSM.

Table **7-9**: Formulation by volume as oven-dry in excavatable CLSM experiment phase II

FS ID	Bulk Volume as Oven-dry, m^3/m^3 *				Percentage by Bulk Volume as Oven-dry, %				Percentage by Absolute Volume, %			
	Cement	Fly Ash	Sand	Water	Cement	Fly Ash	Sand	Water	Cement	Fly Ash	Sand	Water
FS05	0.03	0.25	0.71	0.47	2.2	17.2	48.3	32.3	1.2	12.9	39.5	46.4
FS06	0.06	0.32	1.00	0.38	3.2	18.5	56.8	21.5	2.0	16.9	43.1	38.0
FS08	0.04	0.28	0.77	0.39	2.4	18.8	52.2	26.6	1.3	14.9	43.1	40.6
FS09	0.04	0.31	0.84	0.32	2.6	20.2	55.9	21.2	1.5	16.5	48.6	33.4
FS10	0.03	0.35	0.84	0.33	1.8	22.7	54.2	21.3	1.0	18.3	47.7	33.0
FS13	0.03	0.30	0.82	0.35	2.2	20.0	54.6	23.3	1.2	15.7	48.0	35.2
FS14	0.01	0.30	0.85	0.39	0.9	19.3	54.5	25.3	0.5	15.2	46.2	38.2
FS16	0.08	0.27	0.88	0.43	5.0	16.5	52.9	25.7	3.0	14.2	40.4	42.5
FS17	0.04	0.29	0.72	0.42	2.6	19.9	48.8	28.7	1.4	15.0	41.9	41.8
FS17	0.02	0.34	0.79	0.29	1.5	23.4	54.9	20.3	0.8	18.6	49.6	31.0
Min.	*0.01*	*0.25*	*0.71*	*0.29*	*0.9*	*16.5*	*48.3*	*20.3*	*0.5*	*12.9*	*39.5*	*31.0*
Max.	*0.08*	*0.35*	*1.00*	*0.47*	*5.0*	*23.4*	*56.8*	*32.3*	*3.0*	*18.6*	*49.6*	*46.4*
Avg.	*0.04*	*0.30*	*0.82*	*0.38*	*2.4*	*19.7*	*53.3*	*24.6*	*1.4*	*15.8*	*44.8*	*38.0*
SD	*0.020*	*0.031*	*0.084*	*0.055*	*1.104*	*2.159*	*2.831*	*3.859*	*0.695*	*1.782*	*3.647*	*4.888*

* Bulk volume of raw material per unit of fresh CLSM.

Table **7-10**: Final formulation by mass as oven-dry for excavatable CLSM

FS ID	Bulk Proportion* (unit: kg/m^3)					Percentage by Weight, %			
	Cement	Fly Ash	Sand	Water	Total	Cement	Fly Ash	Sand	Water
FS01	66	355	970	448	1839	3.6	19.3	52.8	24.4
FS02	73	394	1264	343	2074	3.5	19.0	61.0	16.5
FS03	63	340	876	504	1784	3.5	19.1	49.1	28.3
FS04	70	379	1055	405	1910	3.7	19.9	55.3	21.2
FS05	37	334	972	474	1817	2.0	18.4	53.5	26.1
FS06	64	429	1094	378	1965	3.2	21.8	55.7	19.3
FS07	65	352	1031	428	1876	3.5	18.8	55.0	22.8
FS08	41	370	998	395	1803	2.3	20.5	55.4	21.9
FS09	45	404	1207	320	1976	2.3	20.4	61.1	16.2
FS10	32	463	1212	329	2036	1.6	22.8	59.5	16.2
FS11	66	358	1066	440	1931	3.4	18.5	55.2	22.8
FS12	65	353	1156	359	1933	3.4	18.3	59.8	18.6
FS13	37	394	1242	348	2020	1.8	19.5	61.5	17.2
FS15	74	400	818	489	1782	4.2	22.5	45.9	27.5
FS16	94	361	1020	426	1901	4.9	19.0	53.7	22.4
FS17	25	444	1225	291	1984	1.2	22.4	61.7	14.7
Min.	*25*	*334*	*818*	*291*	*1782*	*1.2*	*18.3*	*45.9*	*14.7*
Max.	*94*	*463*	*1264*	*504*	*2074*	*4.9*	*22.8*	*61.7*	*28.3*
Avg.	*57.3*	*383.1*	*1075.4*	*398.6*	*1914.4*	*3.0*	*20.0*	*56.0*	*21.0*
SD	*18.81*	*37.77*	*133.64*	*63.79*	*92.02*	*1.02*	*1.55*	*4.58*	*4.25*

* Mass of raw material per unit of fresh CLSM.

Table **7-11**: Final formulation by volume as oven-dry for excavatable CLSM

FS ID	Bulk Volume as Oven-dry, m^3/m^3 *				Percentage by Bulk Volume as Oven-dry, %				Percentage by Absolute Volume, %			
	Cement	Fly Ash	Sand	Water	Cement	Fly Ash	Sand	Water	Cement	Fly Ash	Sand	Water
FS01	0.06	0.27	0.75	0.45	3.8	17.6	49.3	29.3	2.1	14.0	38.9	45.0
FS02	0.06	0.30	0.92	0.34	4.0	18.4	56.5	21.2	2.4	15.7	47.2	34.8
FS03	0.06	0.26	0.68	0.50	3.7	17.2	45.5	33.7	2.0	13.1	35.4	49.5
FS04	0.06	0.29	0.74	0.41	4.1	19.2	49.6	27.1	2.2	14.6	43.5	39.7
FS05	0.03	0.25	0.71	0.47	2.2	17.2	48.3	32.3	1.2	12.9	39.5	46.4
FS06	0.06	0.32	1.00	0.38	3.2	18.5	56.8	21.5	2.0	16.9	43.1	38.0
FS07	0.06	0.27	0.79	0.43	3.7	17.3	51.3	27.7	2.1	14.0	40.8	43.1
FS08	0.04	0.28	0.77	0.39	2.4	18.8	52.2	26.6	1.3	14.9	43.1	40.6
FS09	0.04	0.31	0.84	0.32	2.6	20.2	55.9	21.2	1.5	16.5	48.6	33.4
FS10	0.03	0.35	0.84	0.33	1.8	22.7	54.2	21.3	1.0	18.3	47.7	33.0
FS11	0.06	0.27	0.80	0.44	3.7	17.2	51.0	28.0	2.1	13.9	40.6	43.5
FS12	0.06	0.27	0.77	0.36	4.0	18.4	52.9	24.7	2.2	14.6	45.3	37.9
FS13	0.03	0.30	0.82	0.35	2.2	20.0	54.6	23.3	1.2	15.7	48.0	35.2
FS15	0.07	0.30	0.78	0.49	4.0	18.5	47.5	29.9	2.3	15.5	33.9	48.3
FS16	0.08	0.27	0.88	0.43	5.0	16.5	52.9	25.7	3.0	14.2	40.4	42.5
FS17	0.02	0.34	0.79	0.29	1.5	23.4	54.9	20.3	0.8	18.6	49.6	31.0
Min.	*0.02*	*0.25*	*0.68*	*0.29*	*1.5*	*16.5*	*45.5*	*20.3*	*0.8*	*12.9*	*33.9*	*31*
Max.	*0.08*	*0.35*	*1*	*0.5*	*5*	*23.4*	*56.8*	*33.7*	*3*	*18.6*	*49.6*	*49.5*
Avg.	*0.051*	*0.291*	*0.805*	*0.399*	*3.244*	*18.819*	*52.088*	*25.863*	*1.838*	*15.213*	*42.850*	*40.119*
SD	*0.017*	*0.029*	*0.080*	*0.064*	*0.997*	*1.951*	*3.374*	*4.189*	*0.600*	*1.682*	*4.703*	*5.689*

* Bulk volume of raw material per unit of fresh CLSM.

7.1.5 Formulations of Structural CLSM

Formulations of structural CLSM were based on the formulations in scouting experiments (Section 7.1.3), formulations of excavatable CLSM experiments (Section 7.1.4), and specifications for PennDOT Type C flowable fill (Table 2-10). The formulations of structural CLSM are summarized in Table 7-12 and Table 7-13. Water addition is normally distributed, N (405, 67), which is close to the distribution of water addition for excavatable CLSM, N (399, 64). Thus, water addition is not significantly correlated with type of CLSM. It may be determined exclusively by cement content, or sand gradation and shape. Fresh density of structural CLSM is normally distributed, N (1922, 109), which is close to the distribution of excavatable CLSM, N (1914, 92). This is primarily true because the major difference between excavatable CLSM and structural CLSM is the proportion of cement, and the percentage by mass of cement is relatively low, 3% and 12%, respectively.

Table **7-12**: Formulation by mass as oven-dry in structural CLSM experiment

FS ID	Bulk Proportion* (unit: kg/m^3)					Percentage by Weight, %			
	Cement	Fly Ash	Sand	Water	Total	Cement	Fly Ash	Sand	Water
FS01	215	291	779	488	1773	12	16	44	28
FS02	257	347	1113	338	2055	13	17	54	16
FS03	227	306	763	491	1787	13	17	43	27
FS04	235	318	873	447	1874	13	17	47	24
FS05	214	321	914	396	1845	12	17	50	21
FS06	231	389	974	401	1995	12	20	49	20
FS07	230	310	909	428	1877	12	17	48	23
FS08	135	303	802	504	1744	8	17	46	29
FS09	168	378	1104	311	1960	9	19	56	16
FS10	124	450	1175	320	2068	6	22	57	15
FS11	257	347	992	371	1967	13	18	50	19
FS12	247	333	1085	348	2013	12	17	54	17
FS13	206	371	1164	329	2071	10	18	56	16
FS15	277	374	732	471	1854	15	20	39	25
FS16	435	284	790	433	1941	22	15	41	22
Min.	*124*	*284*	*732*	*311*	*1744*	*6*	*15*	*39*	*15*
Max.	*435*	*450*	*1175*	*504*	*2071*	*22*	*22*	*57*	*29*
Avg.	*230.5*	*341.5*	*944.6*	*405.1*	*1921.6*	*12.1*	*17.8*	*48.9*	*21.2*
SD	*71.30*	*44.71*	*154.68*	*66.73*	*108.77*	*3.56*	*1.78*	*5.69*	*4.71*

* Mass of raw material per unit of fresh CLSM.

Table **7-13**: Formulation by volume as oven-dry in structural CLSM experiment

FS ID	Bulk vVlume as Oven-dry, m^3/m^3 *				Percentage by Bulk Volume as Oven-dry, %				Percentage by Absolute Volume, %			
	Cement	Fly Ash	Sand	Water	Cement	Fly Ash	Sand	Water	Cement	Fly Ash	Sand	Water
FS01	0.19	0.22	0.61	0.49	13	15	40	32	7	12	32	50
FS02	0.23	0.26	0.81	0.34	14	16	49	21	8	14	42	35
FS03	0.20	0.23	0.59	0.49	13	15	39	32	7	12	32	49
FS04	0.21	0.24	0.61	0.45	14	16	41	30	7	12	36	44
FS05	0.19	0.24	0.67	0.40	13	16	45	26	7	13	39	41
FS06	0.20	0.29	0.89	0.40	11	16	50	22	7	15	38	40
FS07	0.20	0.24	0.70	0.43	13	15	45	27	7	12	36	44
FS08	0.12	0.23	0.62	0.50	8	16	42	34	4	12	34	50
FS09	0.15	0.29	0.77	0.31	10	19	51	21	6	16	45	33
FS10	0.11	0.34	0.81	0.32	7	22	51	20	4	18	45	33
FS11	0.23	0.26	0.75	0.37	14	16	46	23	8	14	39	38
FS12	0.22	0.25	0.72	0.35	14	16	47	23	8	14	42	36
FS13	0.18	0.28	0.77	0.33	12	18	49	21	7	15	45	33
FS15	0.25	0.28	0.70	0.47	14	17	41	28	9	14	30	46
FS16	0.38	0.22	0.68	0.43	22	13	40	25	14	11	31	44
Min.	*0.11*	*0.22*	*0.59*	*0.31*	*7*	*13*	*39*	*20*	*4*	*11*	*30*	*33*
Max.	*0.38*	*0.34*	*0.89*	*0.5*	*22*	*22*	*51*	*34*	*14*	*18*	*45*	*50*
Avg.	*0.2*	*0.3*	*0.7*	*0.4*	*12.8*	*16.4*	*45.1*	*25.7*	*7.3*	*13.6*	*37.7*	*41.1*
SD	*0.06*	*0.03*	*0.09*	*0.07*	*3.38*	*2.06*	*4.32*	*4.64*	*2.29*	*1.88*	*5.27*	*6.22*

* Mass of raw material per unit of fresh CLSM.

7.2 CLSM Mixing Procedure and Sample Preparation

After a mixture formulation was established, mixing and sample preparation were performed using the following procedures:

Step 1: Proportioning and blending dry materials.

The dry materials (cement, fly ash, foundry sands) were weighed according to formulations presented in Sections 7.1.3, 7.1.4, and 7.1.5. They were added into a 0.057 m^3 steel concrete mixer by sequences of 1/3 foundry sand, 1/2 fly ash, 1/2 cement, 1/3 foundry sand, 1/2 fly ash, 1/2 cement, and 1/3 foundry sand. The blending of these dry materials lasted 10-15 minutes prior to the addition of water.

Step 2: Measuring and adding water.

After proportioning and blending of the dry materials, water was weighed and prepared according to the corresponding formulation of the individual batch. It was divided into four equal parts. Initially, two parts were added to the dry mixture. The blending of moist materials lasted 5-10 minutes. The remaining water was added in small increments followed by additional flow consistency measurements until a flow greater than 20.3 cm was achieved [ASTM D 6103 1997]. Once this point was reached, any remaining water or supplemented water was weighed and subtracted or added to the original formulation.

Step 3: Filling molds and performing fresh CLSM tests.

After thorough mixing, all cylinders or containers were filled with fresh CLSM and its fresh properties were tested for parameters listed in Table 7-1. Samples in cylinders were made in accordance with ASTM C 192 except that the samples were not rodded or vibrated.

Step 4: Curing samples.

After placement, cylinder samples for strength tests were placed in an open area with air contact and temperature at 23 ºC for one day. After that period, the forms were removed and the CLSM cylinders were placed into a curing chamber (23 ºC, 100% RH) until the date of testing. The steel proctor mold containing CLSM for hydraulic conductivity testing was placed into curing chamber immediately after it was cast.

7.3 CLSM Testing Procedure and Results

To characterize the behavior of CLSM both in fresh and hardened condition, critical parameters listed in Table 7-1 were selected to investigate. The performances on these parameters determine whether foundry sands are qualified as a major component integrated into CLSM matrix. The investigation was divided into two parts, performances of fresh CLSM and performances of hardened CLSM.

7.3.1 Fresh CLSM

7.3.1.1 Flow Consistency

The workability of the CLSM was determined by its flow consistency in accordance with ASTM D 6103, "Standard Test Method for Flow Consistency of Controlled Low Strength Material." This procedure involves a bottomless, plastic, cylindrical mold resting on a smooth, non-absorbent, metal surface. The mold was filled with fresh CLSM and vertically removed over a 10-second interval. The diameter of the resulting spread of fresh CLSM was measured to determine the flow consistency [ASTM D 6103 1997, Van Tassel 1999]. In this experiment, water was added to each mixture until the spread diameter was greater than 20.3 cm to ensure that the fresh CLSM was self-leveling and self-compacting.

7.3.1.2 Bleeding and Settlement

The volume of water collected on the surface of the fresh CLSM cylinders (*f* 10.2 x 20.4 cm) was taken as a measurement of bleeding until the bleeding stops. The settlement was determined by measuring the change in height from fresh CLSM cylinders (*f* 10.2 x 20.4 cm) to hardened CLSM cylinders. Both measurements were performed on those cylinder samples for strength measurements. The results of bleeding and settlement of excavatable CLSM phase I and II, and structural CLSM based on *f* 10.2 x 20.4 cm cylinders, are summarized in Table 7-14, Table 7-15, and Table 7-16, respectively.

Table **7-14**: Bleeding and settlement of excavatable CLSM phase I

FS ID	Bleed Water (ml/100ml*)	Bleeding per Unit CLSM Surface Area, ml/cm^2	Bleeding as Percentage of Water Content, %	Bleeding Period (hrs)	Settlement, %
FS01	3.23	0.617	7.21	Not Tested	Not Tested
FS02	2.56	0.494	7.47	Not Tested	Not Tested
FS03	0.65	0.123	1.28	Not Tested	Not Tested
FS04	3.05	0.58	7.53	3.9	Not Tested
FS05	2.60	0.494	5.85	0.5	Not Tested
FS06	2.81	0.543	7.71	3.17	Not Tested
FS07	0.22	0.043	0.51	4.08	2.07
FS08	0.22	0.043	0.48	3.05	2.79
FS09	2.53	0.485	7.11	3.5	3.29
FS10	5.34	1.024	15.45	4.9	6.74
FS11	0.97	0.185	2.21	4	2.11
FS12	8.73	1.678	24.34	5.33	4.56
FS13	4.57	0.864	13.08	5.08	7.14
FS14	4.43	0.852	11.31	5.75	7.63
FS15	0.86	0.16	1.75	2.72	3.5
FS16	< 0.326	< 0.062	< 0.702	Not Tested	1.86
Min.	*0.22*	*0.0425*	*0.48*	*0.5*	*1.8628*
Max.	*8.73*	*1.6784*	*24.34*	*5.75*	*7.6302*
Avg.	*2.69*	*0.5154*	*7.12*	*3.8319*	*4.1703*
SD	*5.26*	*0.1937*	*42.49*	*2.0223*	*0.0005*

* 100ml represents volume of fresh CLSM.

Table **7-15**: Bleeding and settlement of excavatable CLSM phase II

FS ID	Bleed Water (ml/100ml*)	Bleeding per Unit CLSM Surface Area, ml/cm^2	Bleeding as Percentage of Water Content, %	Bleeding Period (hrs)	Settlement, %
FS05	0.326	0.062	0.689	4.00	2.07
FS06	3.874	0.753	10.237	3.38	8.19
FS08	0.225	0.043	0.572	2.87	3.48
FS09	2.449	0.469	7.644	3.12	3.69
FS10	2.900	0.555	2.900	5.67	4.16
FS13	5.754	1.086	16.553	3.55	9.42
FS14	5.078	0.963	5.078	6.77	Not Tested
FS16	0.000	0.000	0.000	0	0.08
FS17	3.965	0.740	9.367	2.75	6.19
FS17	6.146	1.148	20.947	3.00	6.14
Min.	*0*	*0*	*0*	*0*	*0.08*
Max.	*6.146*	*1.148*	*20.947*	*6.77*	*9.42*
Avg.	*3.1*	*0.6*	*7.4*	*3.5*	*4.8*
SD	*2.30*	*0.43*	*7.08*	*1.80*	*2.95*

* 100ml represents volume of fresh CLSM.

Table **7-16**: Bleeding and settlement of structural CLSM

FS ID	Bleed Water (ml/100ml*)	Bleeding per Unit CLSM Surface Area, ml/cm^2	Bleeding as Percentage of Water Content, %	Bleeding Period (hrs)	Settlement, %
FS01	0.260	0.049	0.533	2.62	2.88
FS02	2.049	0.395	6.160	2.95	1.59
FS03	0.712	0.136	1.465	2.50	3.38
FS04	0.519	0.099	1.150	2.42	2.11
FS05	2.734	0.518	6.719	3.82	5.03
FS06	0.000	0.000	0.000	0	2.02
FS07	0.692	0.136	1.661	3.13	1.29
FS08	0.128	0.025	0.255	1.33	3.00
FS09	0.964	0.185	3.171	2.18	1.67
FS10	4.308	0.827	13.633	4.17	4.38
FS11	0.778	0.148	2.088	2.57	2.29
FS12	2.569	0.494	7.456	3.43	1.24
FS13	4.245	0.802	13.035	3.73	4.24
FS15	1.387	0.259	2.887	2.75	3.60
FS16	1.043	0.197	2.476	7.67	-2.65
FS17	0.940	0.173	2.776	3.25	2.66
Min.	*0*	*0*	*0*	*1.33*	*-2.65*
Max.	*4.308*	*0.827*	*13.633*	*7.67*	*5.03*
Avg.	*1.458*	*0.277688*	*4.091563*	*3.234667*	*2.420625*
SD	*1.356676*	*0.258653*	*4.240767*	*1.420849*	*1.766056*

* 100ml represents volume of fresh CLSM.

The investigation indicates that the bleed volume ranges between 0 and 8.73% based on the volume of fresh CLSM. It generally lasts 0-7 hours after first contact with water. As a result of bleeding, settlement resulting from fresh CLSM to solid CLSM ranged from 0.08% to 9.42%. Furthermore, two-tailed correlation testing indicates that bleeding and settlement are fairly positive-correlated for excavatable ($r = 0.728$) and the correlation is significant ($p = 0.001$). Fifty-three percent of the variation in settlement is related to bleeding. The rest of the variation may involve the gradation of sand particles. For structural CLSM, bleeding and settlement are not correlated ($r = 0.396$, $p = 0.129$). Bleeding is moderately positive-correlated with bleeding period ($r = 0.469$, $p = 0.028$) for excavatable CLSM. That is, more bleeding tends to last longer. However for structural CLSM, bleeding and bleeding period are not correlated ($r = 0.324$, $p = 0.239$). It was discovered that moderate bleeding for FS16 takes the longest period to drain. If FS16 were eliminated, bleeding and bleeding period would heavily correlate for the remaining structural CLSM ($r = 0.827$, $p = 0+$).

7.3.1.3 Setting Time and Penetration Resistance

The setting time, also referred to as hardening time, was evaluated according to ASTM C 403, “Standard Test Method for Time of Setting of Concrete Mixtures by Penetration Resistance” [ASTM C 403 1999]. In this experiment, a rectangular, wood water-tight mold was filled with fresh CLSM. The drainage was allowed only through the top surface of the materials. Any free bleeding water was removed before each measurement of penetration resistance. The container was tilted slightly to aid the

collection of the bleeding by a pipette. After at least 2 hours had elapsed from the first addition of water, the CLSM penetration resistance was measured using a 19.35 cm^2, 6.45 cm^2, 3.23 cm^2, or 1.61 cm^2 steel penetration needle, depending on the resistance development. From that point onward, the penetration resistance was measured at 1 to 4 hour intervals until penetration resistance was over 344 kN/m^2 (50 psi), which is defined as the initial set penetration resistance.

The presentations of setting time versus penetration resistance of excavatable CLSM phase I and II are summarized in Figure I-1 and Figure I-2 in Appendix I.1. Corresponding presentations for structural CLSM are summarized in Figure I-3 in Appendix I.2. All test results are summarized in Figure 7-1, Figure 7-2, and Figure 7-3. The horizontal dashed lines represent 344 kPa (50 psi), 689 kPa (100 psi), 1,379 (200 psi), and 2,758 kPa (400 psi), respectively, which are thresholds for critical loads, such as human body loads or vehicle loads. This indicates that the penetration resistance starts to develop after 3-5 hours following water addition. The resistance development is not uniform for CLSM with varying foundry sands. Structural CLSM develops penetration resistance more quickly than excavatable CLSM.

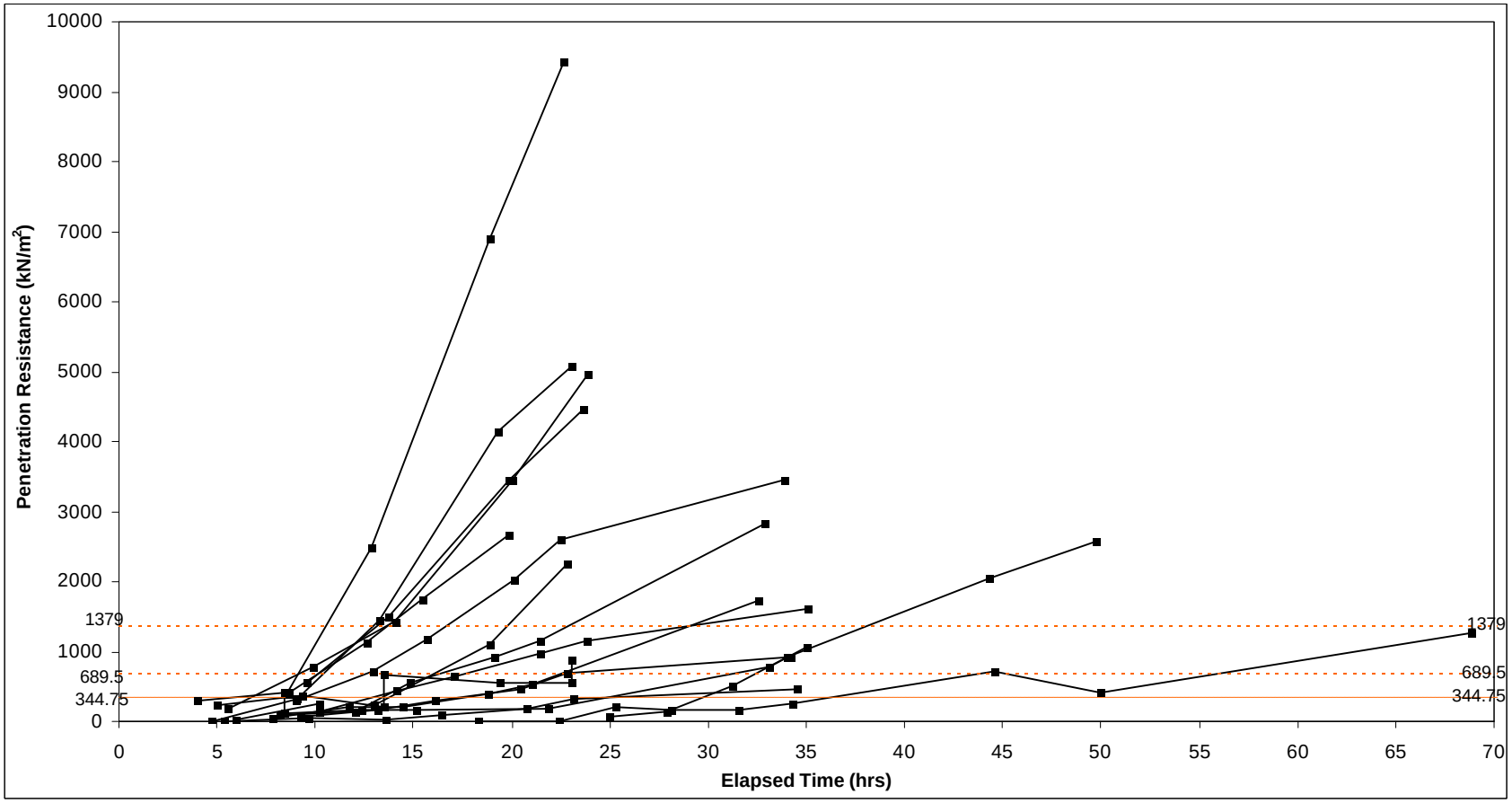

Figure **7-1**: Setting time of excavatable CLSM phase I

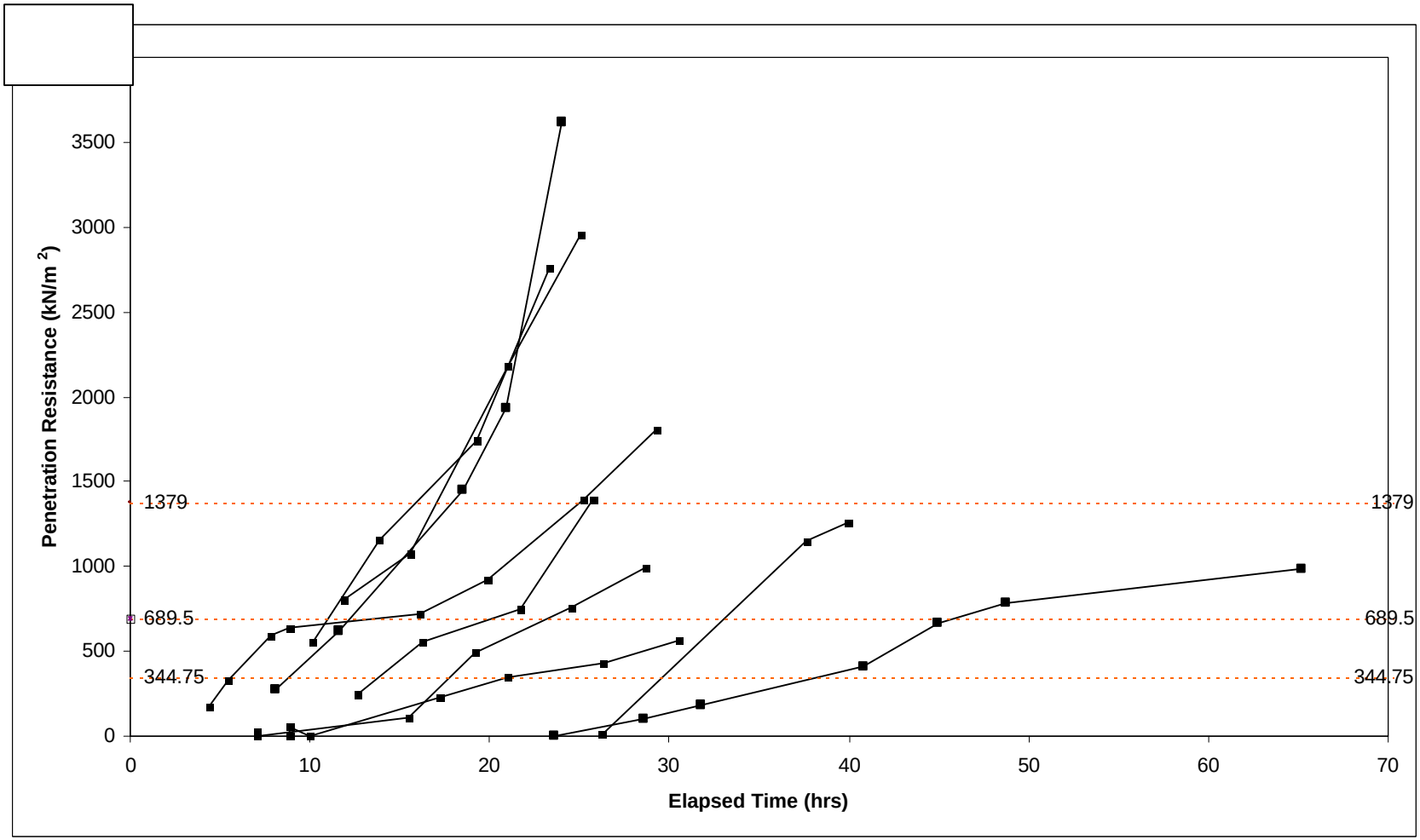

Figure **7-2**: Setting time of excavatable CLSM phase II

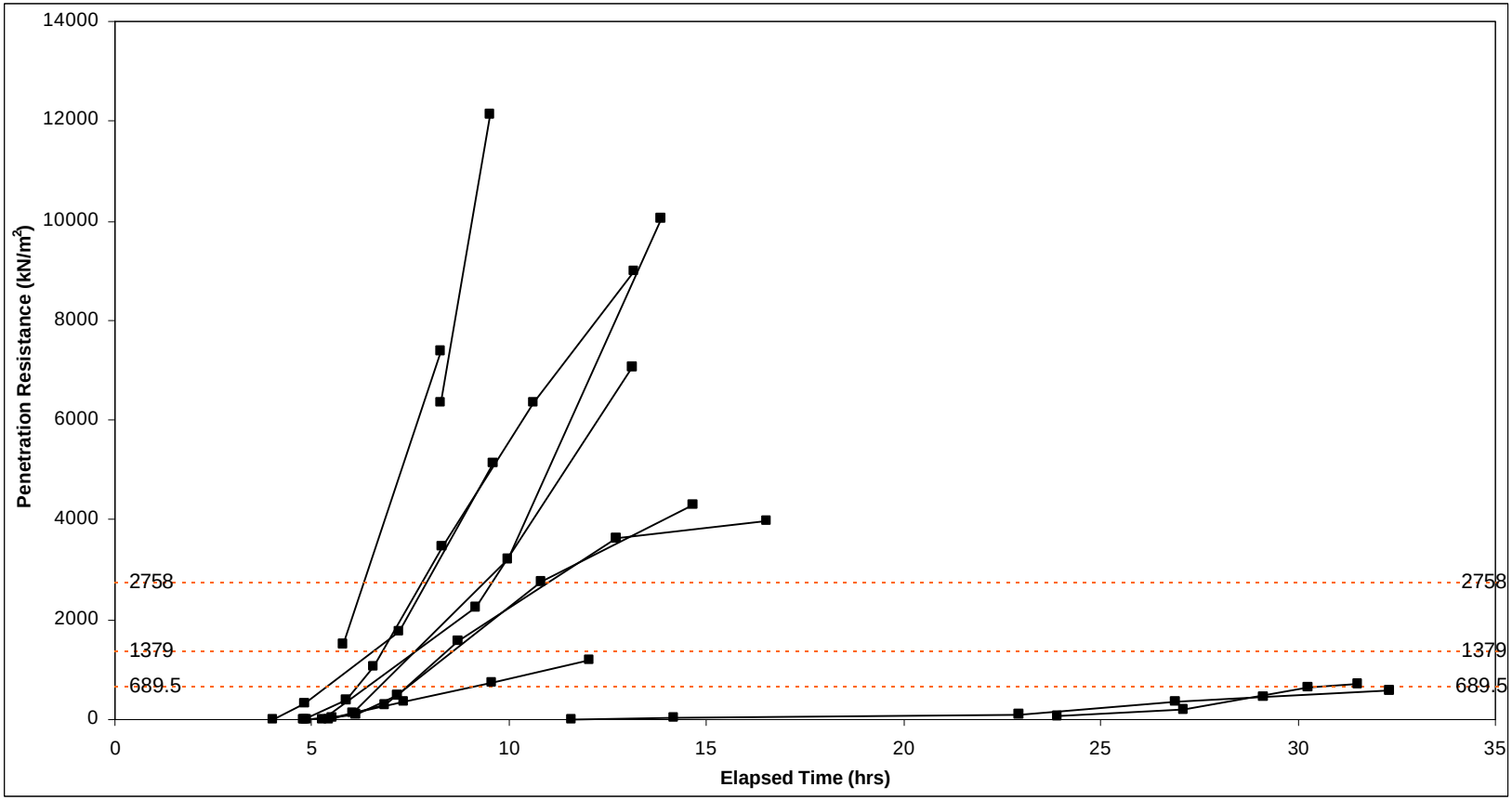

Figure **7-3**: Setting time of structural CLSM

Interpolation was used to estimate the elapsed time corresponding to critical penetration resistances of 344 kPa (50psi) and 689 (100psi) and penetration resistances corresponding to elapsed time of 6, 12, 18, and 24 hours. The results are presented in Table 7-17, Table 7-18, and Table 7-19. It is indicated that the time to attain 344 kPa, which is defined as the initial set penetration resistance or bearing capacity for human body loads, ranges from 6.73 to 36.23 hours for excavatable CLSM phase I, 5.65 to 38.06 hours for excavatable CLSM phase II, and 4.89 to 28.19 hours for structural CLSM.

7.3.1.4 Fresh Density

Fresh CLSM was placed into a calibrated volume container to compute the fresh density. The results are presented in Table 7-20 and Table 7-21 for excavatable CLSM, and Table 7-22 for structural CLSM to compare its corresponding hardened density.

Table **7-17**: Critical setting time and penetration resistance for excavatable CLSM phase I

FS ID	Elapsed Time (hrs)		Penetration Resistances (kN/m^2)			
	Attaining 344 kN/m^2 (50 psi)	Attaining 689 kN/m^2 (100 psi)	6 hrs elapse	12 hrs elapse	18 hrs elapse	24 hrs elapse
FS01	13.1	17.8	21	267	704	1158
FS02	6.7	9.2	186	1104	2764	4964
FS03	25.0	---	0	60	121	334
FS04	8.7	10.2	---	1094	2857	4468
FS05	17.1	23.1	---	136	377	708
FS06	8.4	14.7	272	558	766	905
FS07	9.4	12.8	---	610	1611	2707
FS08	8.3	10.2	---	1024	2278	3533
FS09	9.3	10.4	96	1108	3558	5297
FS10	24.9	31.5	---	156	170	297
FS11	13.4	16.5	---	145	814	1536
FS12	13.7	16.1	---	89	975	2596
FS13	8.5	9.2	---	2085	6265	10353
FS14	36.2	44.3	0	0	0	110
FS15	17.8	22.6	0	208	353	831
FS16	29.8	32.5	0	0	0	76
Min.	*6.7*	*9.2*	*0*	*0*	*0*	*76*
Max.	*36.2*	*44.3*	*272*	*2085*	*6265*	*10353*
Avg.	*15.6*	*18.7*	*72*	*540*	*1476*	*2492*
SD	*8.9*	*10.4*	*105*	*591*	*1706*	*2744*

Note: 1 kN/m^2 = 0.145 psi.

Table **7-18**: Critical setting time and penetration resistance for excavatable CLSM phase II

FS ID	Elapsed Time (hrs)		Penetration Resistances (kN/m^2)			
	Attaining 344 kN/m^2 (50 psi)	Attaining 689 kN/m^2 (100 psi)	6 hrs elapse	12 hrs elapse	18 hrs elapse	24 hrs elapse
FS05	21.0	34.4	0	63	251	391
FS06	5.7	13.7	386	670	821	1282
FS08	17.8	23.2	0	74	369	731
FS09	13.8	20.1	---	197	613	1112
FS13	---	10.4	---	800	1575	2752
FS14	38.1	45.8	0	0	0	7
FS16	29.6	33.0	0	0	0	7
FS17	8.9	11.0	---	858	1604	2915
FS17	8.8	12.2	75	661	1387	3613
Min.	*5.6*	*10.4*	*0*	*0*	*0*	*7*
Max.	*38.1*	*45.8*	*386*	*858*	*1604*	*3613*
Avg.	*17.9*	*22.6*	*77*	*369*	*735*	*1424*
SD	*11.2*	*12.6*	*154*	*368*	*648*	*1344*

Note: 1 kN/m^2 = 0.145 psi.

Table **7-19**: Critical setting time and penetration resistance for structural CLSM

FS ID	Elapsed Time (hrs)		Penetration Resistances (kN/m^2)			
	Attaining 344 kN/m^2 (50 psi)	Attaining 689 kN/m^2 (100 psi)	6 hrs elapse	12 hrs elapse	18 hrs elapse	24 hrs elapse
FS01	6.8	7.5	110	3277	---	---
FS03	6.9	7.5	121	3235	---	---
FS04	6.3	6.8	138	6779	---	---
FS05	5.9	6.5	419	5695	---	---
FS06	26.7	35.9	0	7	62	162
FS07	5.8	6.2	501	7781	---	---
FS08	7.2	9.2	128	1186	---	---
FS09	4.9	5.5	1027	8542	---	---
FS10	28.2	31.5	0	0	0	48
FS11	---	5.4	2026	16125	---	---
FS12	---	---	0	23642	---	---
Min.	*4.9*	*5.4*	*0*	*0*	*0*	*48*
Max.	*28.2*	*35.9*	*2026*	*23642*	*62*	*162*
Avg.	*11.0*	*12.2*	*447*	*6933*	*31*	*105*
SD	*9.4*	*11.4*	*637*	*7243*	*44*	*80*

Note: 1 kN/m^2 = 0.145 psi.

Table **7-20**: Density development of excavatable CLSM phase I

FS ID	Fresh Density (kg/m^3)	Hardened Density (kg/m^3)					
	0 day	3 day	7 day	14 day	28 day	90 day	180 day
FS01	1838.8	1833.1	1834.6	1823.9	1814.1	---	1862.6
FS02	2073.6	2037.2	2041.5	2036.7	2029.7	---	2093.2
FS03	1783.6	1769.5	1775.6	1775.8	1774.1	---	1795.4
FS04	1909.9	1923.7	1924.6	1925.3	1917.1	1895.5	1946.2
FS05	1872.5	1881.9	1879.3	1879.1	1882.3	1891.6	1891.2
FS06	1954.0	2016.3	2022.9	2034.0	2039.4	2055.7	2045.4
FS07	1876.1	1890.0	1889.2	1892.4	1901.4	1912.3	1919.6
FS08	1821.7	1846.5	1850.0	1854.6	1857.9	1862.1	1869.0
FS09	1979.5	2001.4	2013.1	2022.1	2025.7	2032.7	2044.2
FS10	2042.3	2097.2	2098.5	2107.2	2119.6	2129.4	2162.5
FS11	1931.1	1939.4	1936.8	1942.8	1948.1	1955.7	1961.0
FS12	1933.0	1940.4	1934.7	1952.7	1968.7	1996.2	2010.0
FS13	2048.4	2124.2	2132.1	2134.0	2140.0	2149.1	2158.7
FS14	2006.2	2054.0	2055.0	2063.3	2071.3	2080.6	2082.8
FS15	1781.6	1805.4	1807.8	1811.4	1816.7	1820.5	1822.0
FS16	1848.7	1818.9	1818.9	1835.5	1844.6	1857.1	1865.8
Min.	*1781.6*	*1769.5*	*1775.6*	*1775.8*	*1774.1*	*1820.5*	*1795.4*
Max.	*2073.6*	*2124.2*	*2132.1*	*2134.0*	*2140.0*	*2149.1*	*2162.5*
Avg.	*1918.8*	*1936.2*	*1938.4*	*1943.2*	*1946.9*	*1972.2*	*1970.6*
SD	*93.4*	*109.1*	*110.4*	*111.7*	*113.9*	*109.4*	*117.7*

Note: 1 kg/m^3 = 1.685 lb/yd^3.

Table **7-21**: Density development of excavatable CLSM phase II

FS ID	Fresh Density (kg/m^3)	Hardened Density (kg/m^3)						Oven-dry Density (kg/m^3)	Void
	0 day	3 day	7 day	14 day	28 day	90 day	180 day	180 day	31%
SFS05	1817.3	1829.0	1830.7	1833.3	1835.0	1836.4	1837.0	1398.3	18%
SFS06	1965.5	2038.9	2039.6	2040.0	2041.7	2052.1	2060.0	1748.1	32%
SFS08	1803.0	1843.3	1845.7	1848.0	1849.8	1852.9	1853.5	1407.3	19%
SFS09	1976.0	2016.4	2018.3	2021.1	2022.9	2027.0	2028.1	1701.6	17%
SFS10	2036.4	---	2044.6	2055.4	2064.5	2080.9	2086.0	1787.6	14%
SFS13	2020.1	2118.6	2120.7	2125.1	2128.1	2135.5	2143.9	1874.2	20%
SFS14	1990.3	---	---	---	2076.8	2099.5	2113.4	1756.5	27%
SFS16	1900.6	1852.9	1860.4	1878.5	1892.0	1911.5	1915.8	1503.0	17%
SFS17	1971.6	2039.3	2046.0	2060.7	2068.1	2075.7	2083.7	1787.7	31%
SFS17	1984.3	2062.0	2063.7	2071.0	2074.9	2082.1	2074.3	---	---
Min.	*1803.0*	*1829.0*	*1830.7*	*1833.3*	*1835.0*	*1836.4*	*1795.4*	*1398.3*	*14%*
Max.	*2036.4*	*2118.6*	*2120.7*	*2125.1*	*2128.1*	*2135.5*	*2143.9*	*1874.2*	*32%*
Avg.	*1946.5*	*1975.0*	*1985.5*	*1992.6*	*2005.4*	*2004.5*	*1992.4*	*1662.7*	*22%*
SD	*80.3*	*114.4*	*108.8*	*108.8*	*105.5*	*107.8*	*110.2*	*178.3*	*0.067*

Note: 1 kg/m^3 = 1.685 lb/yd^3.

Table **7-22**: Density development of structural CLSM

FS ID	Fresh Density (kg/m^3)	Hardened Density (kg/m^3)						Oven-dry Density (kg/m^3)	Void
	0 day	3 day	7 day	14 day	28 day	90 day	180 day	180 day	
FS01	1773.4	1801.7	1805.7	1825.1	1837.6	1852.5	1859.3	1406.1	32%
FS02	2055.1	2071.0	2075.0	2089.6	2098.5	2112.1	2118.0	---	---
FS03	1787.3	1833.4	1853.7	1858.8	1863.5	1876.0	1883.1	1450.6	30%
FS04	1873.9	1889.6	1892.6	1910.3	1919.8	1933.6	1942.6	1571.4	24%
FS05	1844.8	1919.8	1927.1	1933.8	1938.4	1947.4	1952.4	1596.0	22%
FS06	1994.5	2019.5	2024.2	2025.9	2026.9	2037.8	2057.4	---	---
FS07	1877.3	1896.5	1901.4	1904.5	1910.6	1922.3	1928.1	1533.7	26%
FS08	1744.2	1795.7	1800.7	1804.3	1809.6	1814.7	1817.9	1340.2	36%
FS09	1960.4	1990.9	1994.1	1997.3	2003.0	2011.0	2014.8	---	---
FS10	2068.4	2126.1	2133.0	2136.9	2140.7	2143.7	2133.4	---	---
FS11	1966.9	2001.7	2009.2	2012.9	2016.8	2024.9	2030.1	1712.9	19%
FS12	2013.4	2023.7	2032.9	2042.7	2047.3	2062.6	2068.8	1776.5	16%
FS13	2070.7	2135.3	2138.8	2147.0	2151.9	2156.6	---	---	---
FS15	1854.3	1899.7	1901.2	1926.2	1940.0	1949.2	1952.4	1549.2	26%
FS16	1941.3	1851.7	1856.9	1871.3	1881.3	1890.7	1890.3	---	---
FS17	2042.9	2091.5	2100.1	2103.7	2111.3	2121.7	2105.0	---	---
Min.	*1744.2*	*1795.7*	*1800.7*	*1804.3*	*1809.6*	*1814.7*	*1817.9*	*1340.2*	*16%*
Max.	*2070.7*	*2135.3*	*2138.8*	*2147.0*	*2151.9*	*2156.6*	*2133.4*	*1776.5*	*36%*
Avg.	*1929.3*	*1959.2*	*1965.4*	*1974.4*	*1981.1*	*1991.1*	*1983.6*	*1548.5*	*26%*
SD	*109.3*	*113.2*	*112.8*	*110.7*	*109.4*	*108.5*	*99.8*	*139.3*	*0.062*

Note: 1 kg/m^3 = 1.685 lb/yd^3.

7.3.2 Hardened CLSM

7.3.2.1 Wet Density, Oven-Dry Density and Water Content

At the time of testing, four solid CLSM cylinders were weighed and their density was calculated. On the 180th day, 1-2 solid cylinders were oven-dried at a temperature of 105 °C until there was no mass decrease. Oven-dry density was calculated based on these cylinders. Water content measures the ratio of water by mass in hardened CLSM. It is based on the difference between the wet density and the oven-dry density. The results of density and water content for excavatable CLSM phases I and II and structural CLSM are summarized in Table 7-20, Table 7-21, and Table 7-22, respectively.

It is indicated that the density of solid CLSM increases slightly with time if cured under moist conditions, which means external water is absorbed into the CLSM matrix if available. The density is normally distributed regarding various foundry sands, except for the density measured in excavatable CLSM phase II experiments. There is no more than one-third mass occupied by water in CLSM after 180 days of moisture curing. The difference in water content between excavatable CLSM and structural CLSM is not significant, 22% for excavatable CLSM versus 26% for structural CLSM. Both of them are normally distributed.

7.3.2.2 Hydraulic Conductivity

The hydraulic conductivity tests were carried out in accordance with ASTM D 2434, “Standard Test Method for Permeability of Granular Soils (Constant Head)” on cylindrical samples (*f* 10.2 x 10.2 cm) at a curing time of 28 days. The hydraulic gradient was kept around 15 m/m. In general, water seepage lasted 24 hours. Results of hydraulic conductivity of excavatable CLSM phases I and II are presented in Figure 7-4 and Figure 7-5, respectively. It is indicated that the hydraulic conductivity of excavatable CLSM is typically in the range of 3×10^{-6} to 4×10^{-7} cm/sec, which is comparable to the hydraulic conductivity of sandy to silty clay.

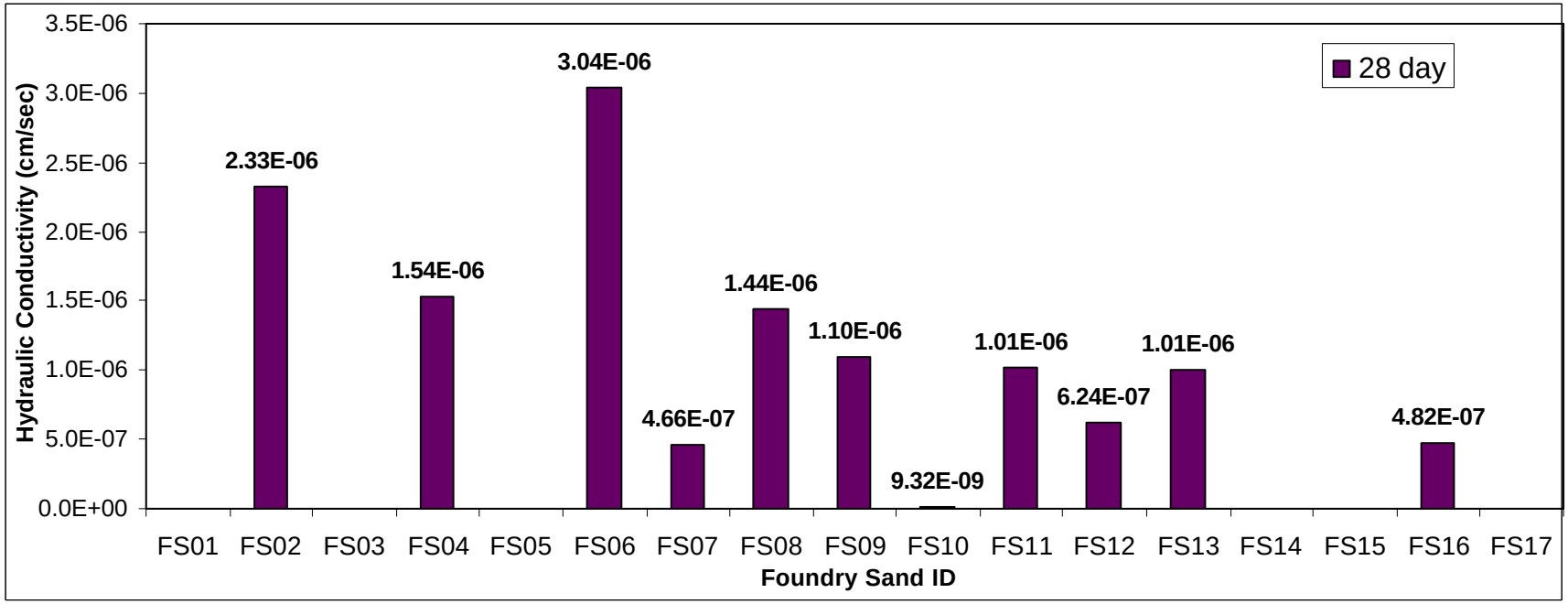

Figure **7-4**: Hydraulic conductivity of excavatable CLSM phase I

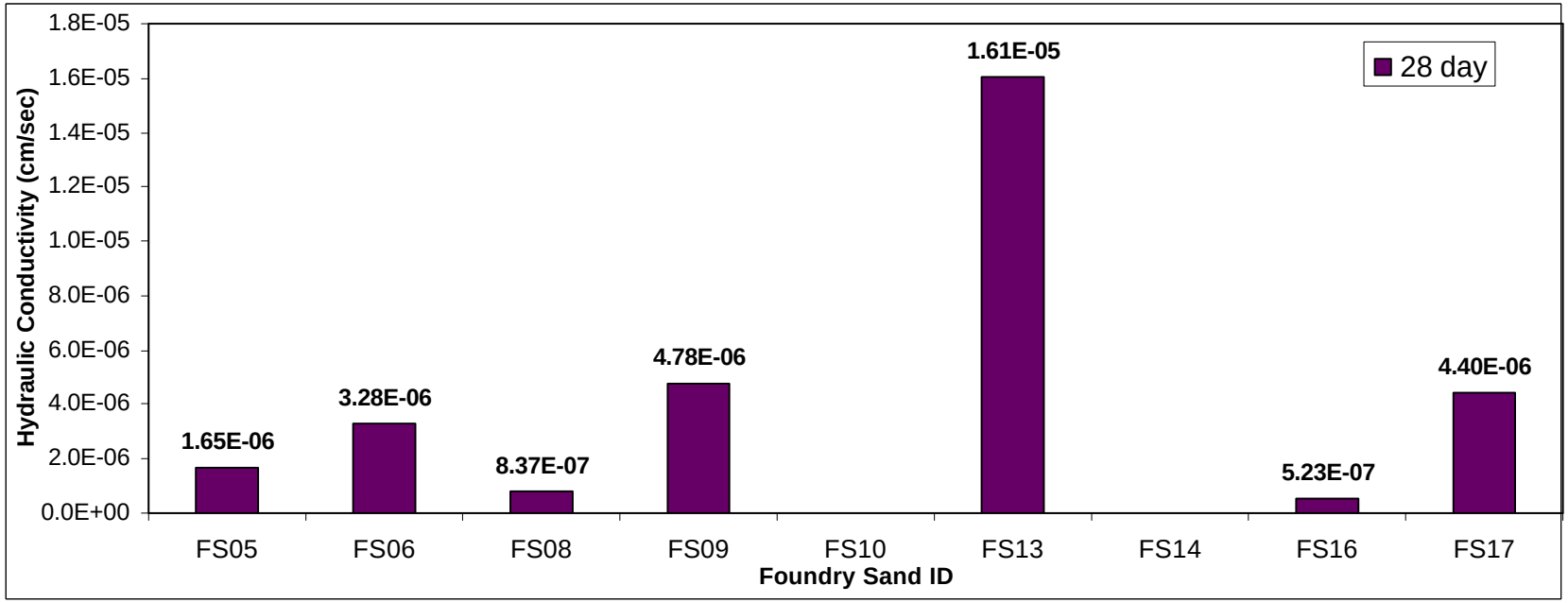

Figure **7-5**: Hydraulic conductivity of excavatable CLSM phase II

7.3.2.3 Compressive Strength

The unconfined compressive strength of CLSM cylinders (*f* 10.2 x 20.4 cm) was conducted at curing date: 3, 7, 14, 28, 90, and 180 days. At least three cylinders were measured for a curing time by compression machine. If the variation in strength was not acceptable, another 1-2 cylinders were supplemented to obtain acceptable variance. Strength is defined as the average strength of cylinders measured. The strength developments of the scouting experiment, excavatable CLSM phases I and II and structural CLSM are presented in Figure 7-6, Figure 7-7, Figure 7-8, and Figure 7-9, respectively.

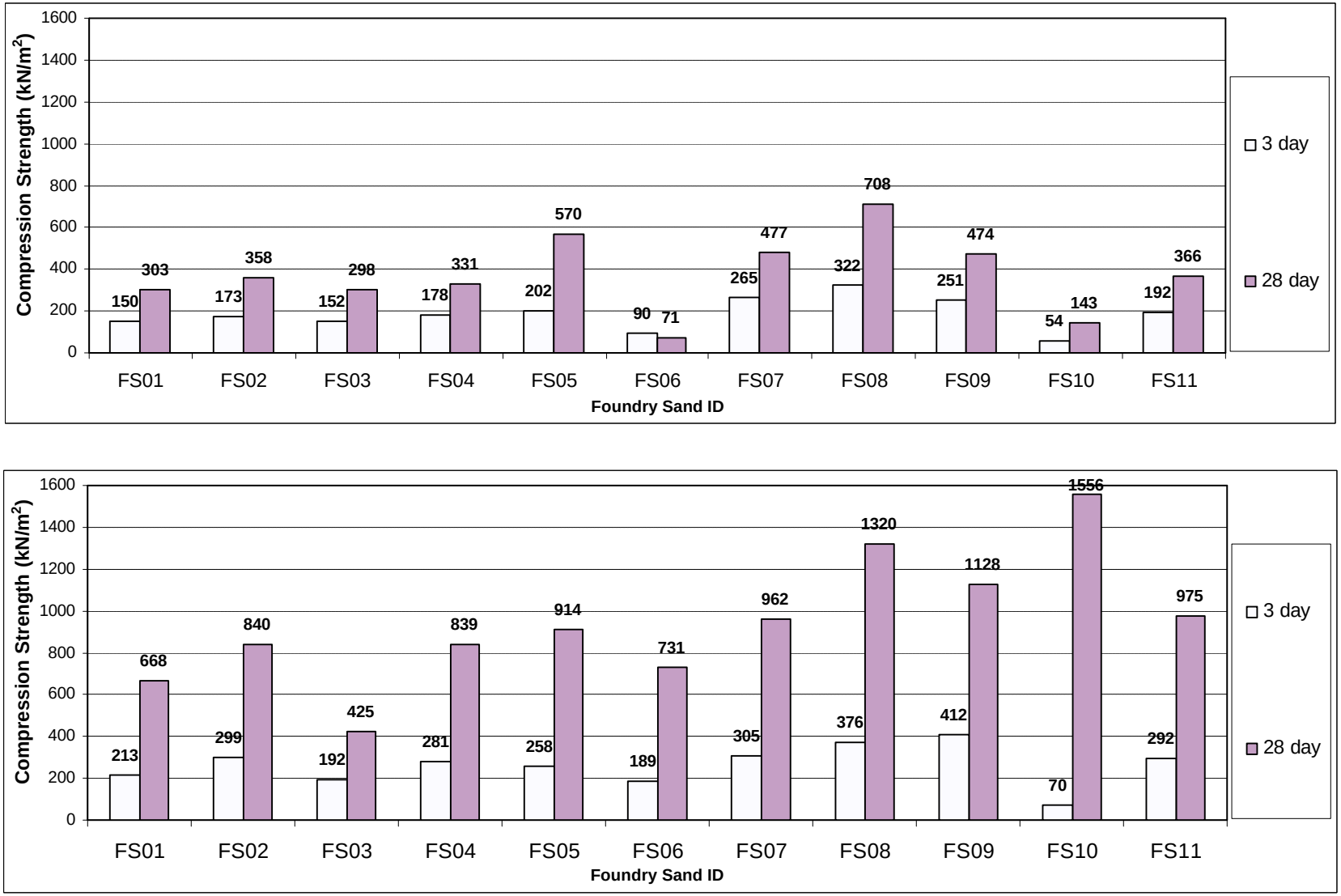

Figure **7-6**: Strength development of scouting CLSM

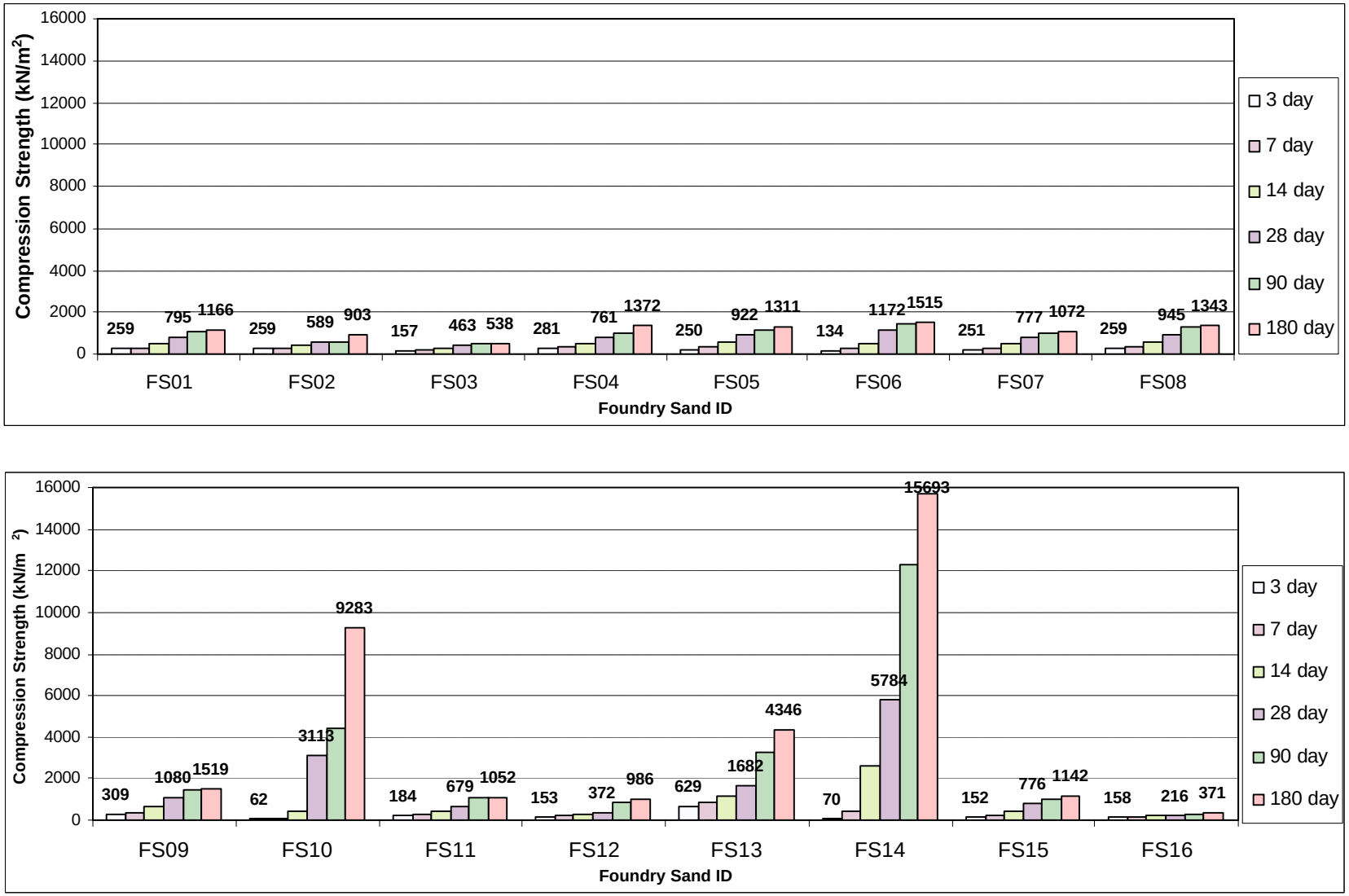

Figure **7-7**: Strength development of excavatable CLSM phase I

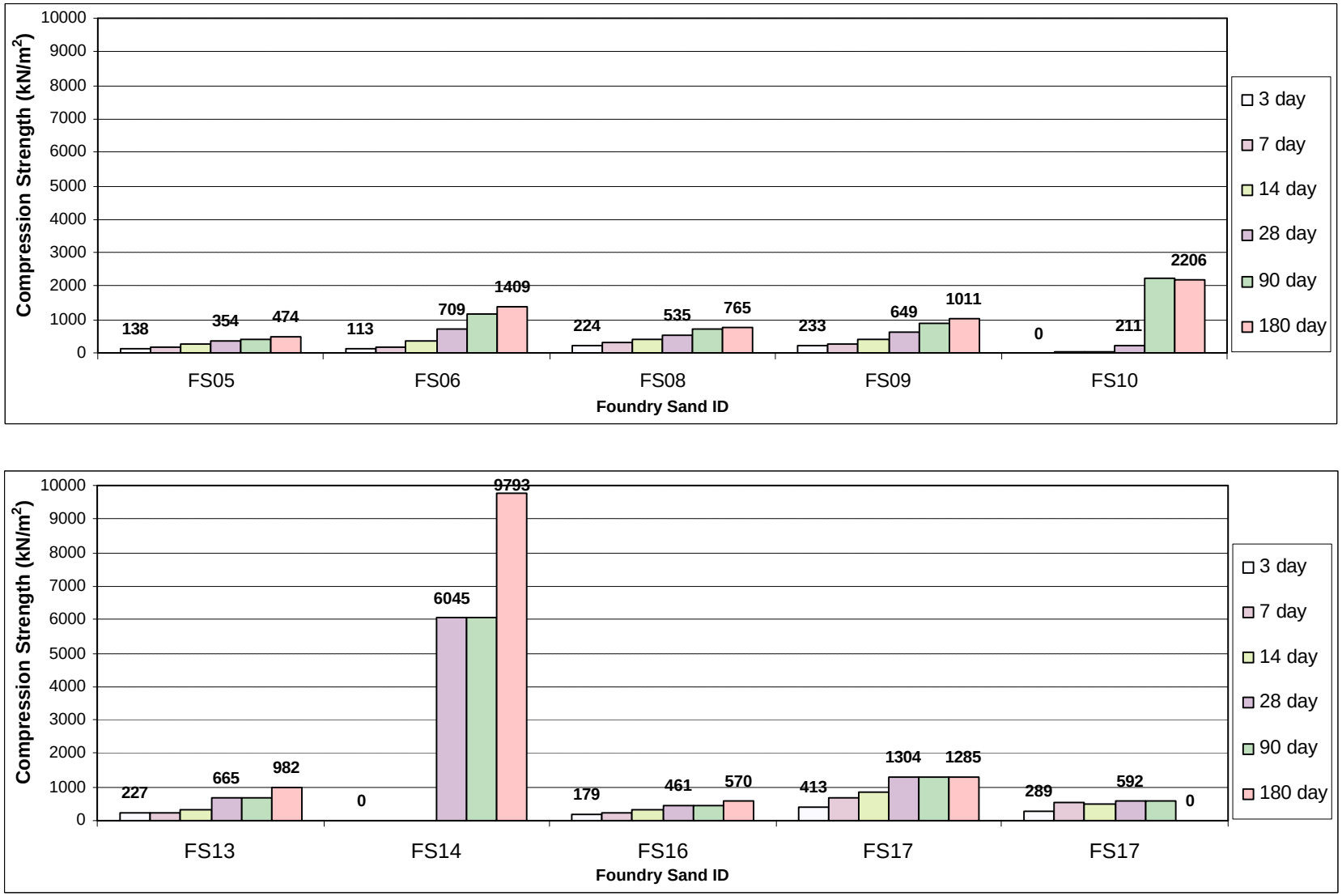

Figure **7-8**: Strength development of excavatable CLSM phase II

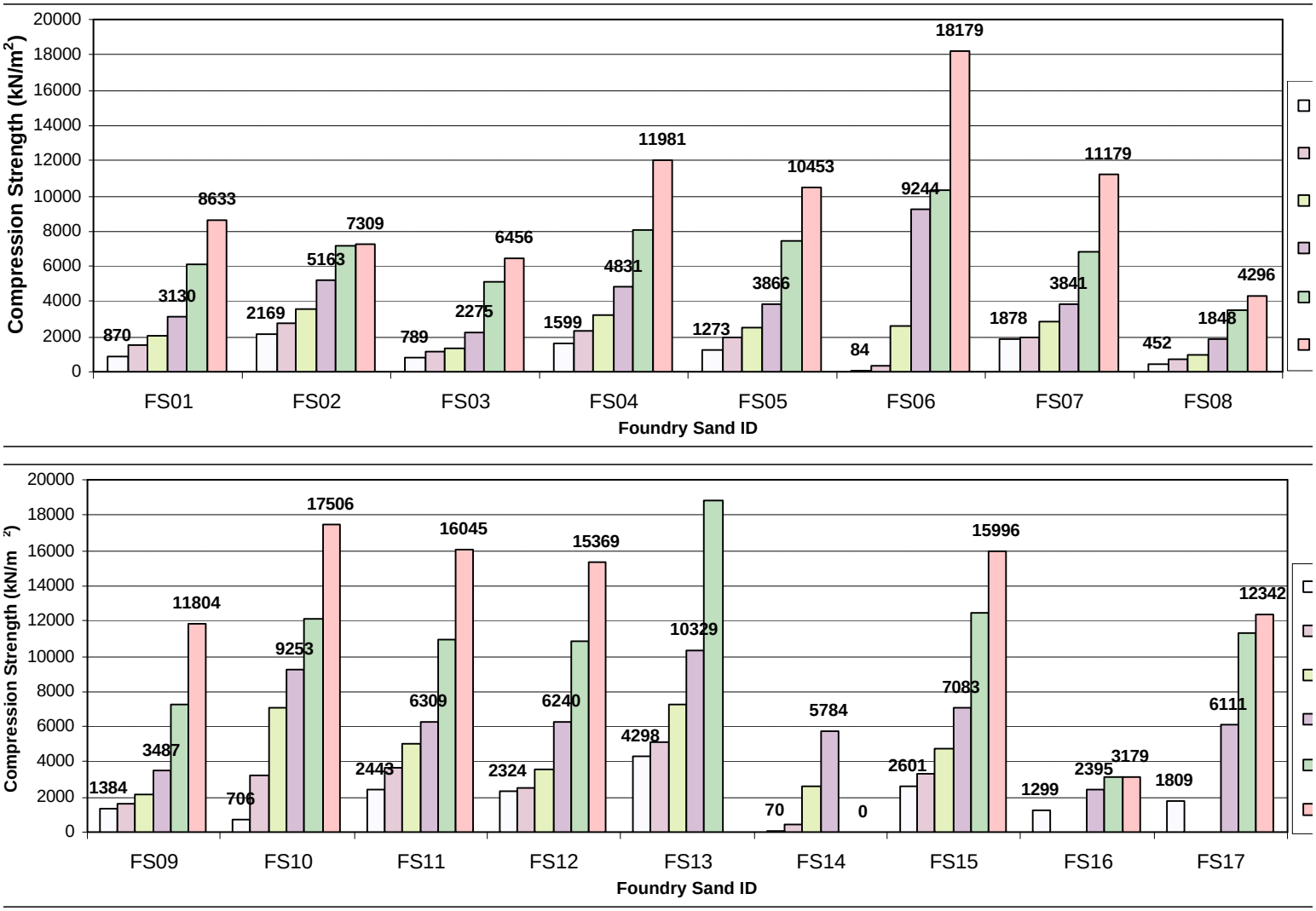

Figure **7-9**: Strength development of structural CLSM

Excavatable CLSM requires a compressive strength greater than 170 kPa (25 psi) at 3 days and in the range of 345-862 kPa (50-125 psi) at 28 days [PennDOT 1995]. It is indicated that in scouting experiments, the objective of probing specifications for CLSM with a strength of 345 kPa or 487 kPa at 28 days was achieved. The configured formulations for phase I excavatable CLSM indicate most excess foundry sands performing well as a component in CLSM. For those not attaining the strength requirement, supplemented mixings were conducted in the phase II experiment. After the two-phase investigation, the final formulations, listed in Table 7-10 and Table 7-11, were determined for 16 of 17 excess foundry sands in the application of excavatable CLSM. FS14 is not suitable for excavatable CLSM due to its high strength at 28 days and later (Figure 7-7 and Figure 7-8). Its cement proportion is the least in the phase II investigation, 15 kg/m^3 (Table 7-8) versus average proportion of 57 kg/m^3 (Table 7-10); however, its 28-day compressive strength is 6,045 kPa in Figure 7-8. This phenomenon is likely due to the CaO content and least content in SiO_2 (Table H-2), finest grains (Table 6-5), and too many particles passing sieve 200 (Table 6-5) among selected excess foundry sands. Although 16 out of 17 sands are qualified as a major component in CLSM, their variation in formulation and performance should be concerned. Examination on a source-specific basis is required when sands are reused.

7.3.3 Environmental Impact

The environmental impact of using foundry sand is a necessary issue that needs to be addressed before these materials are integrated into CLSM specifications. The ability

of the CLSM matrix to bind metallic elements and organic compounds affects the potential toxicity of CLSM using foundry sands. There are two discharges to environmental surroundings from the CLSM matrix, the bleed water of CLSM when it is placed, and the leachate from CLSM when it is extracted.

Based on the review of bulk chemical analyses of excess foundry sands discussed in Section 6.3, four top-risk sands, FS02, FS12, FS13, and FS16 were selected to evaluate the environmental impact of their CLSM, which was mixed in the phase I excavatable CLSM experiment.

7.3.3.1 Toxicity of Bleeding

The bleed water of the fresh CLSM was collected and sent to a commercial laboratory for chemical analysis and toxicity evaluation. Results are presented in Table 7-23. It is indicated that minimal amounts of metallic elements exist in the bleed water, and the levels are well below the RCRA toxicity thresholds. Hence, bleeding of CLSM poses little or no hazardous impact to the environment.

Table **7-23**: Toxicity of bleeding

		FS02	FS12	FS13	FS16	TCLP Toxicity Threshold
Arsenic	Unit: mg/kg	.0733	.0183	.0314	.378	5
Barium		.62	.505	.278	.289	100
Cadmium		.0064	.0064	.0077	.0102	1
Chromium		.0758	.0485	.189	.681	5
Lead		.0267	.0231	.0137	.0936	5
Mercury		<.0002	<.0002	<.0002	<.0002	0.2
Selenium		.1	.0317	.034	.0269	1
Silver		.0006	<.0003	<.0003	.002	5
Acetone	Unit: ug/kg	---	41	56	1540	---
Benzene		---	<5	<5	<5	500
Carbon Tetrachloride		---	<5	<5	<5	500
Chlorobenzene		---	<5	<5	<5	100000
Chloroform		---	<5	<5	<5	6000
1,4-Dichlorobenzene		---	<5	<5	<5	7500
1,2-Dichloroethane		---	<5	<5	<5	500
1,1-Dichloroethene		---	<5	<5	<5	700
Ethyl benzene		---	<5	<5	<5	
Methyl ethyl ketone		---	<10	<10	<10	200000
Methylene chloride		---	<5	<5	<5	---
Naphthalene		---	619	180	115	---
Styrene		---	<5	<5	<5	---
Tetrachloroethene		---	<5	<5	<5	700
Toluene		---	<5	<5	<5	---
1,1,1-Trichloroethane		---	<5	<5	<5	---
Trichloroethene		---	<5	<5	<5	500
Vinyl chloride		---	<10	<10	<10	200
M, P-Xylene		---	<5	<5	<5	---
Xylene-total		---	<10	<10	<10	---

7.3.3.2 Toxicity of Hardened CLSM

CLSM of four top-risk sands, FS02, FS12, FS13, and FS16 were sent to the commercial chemical laboratory for leaching toxicity evaluation. The results are presented in Table 7-24. It is indicated that minimal amounts of arsenic, barium, and chromium were detected in the leachate, but the levels are well below the toxicity thresholds. As with the bleed water, the leachate from CLSM containing foundry sand posed no significant hazard to the environment.

7.3.3.3 Corrosivity of Hardened CLSM

Corrosivity is designed to identify materials that potentially pose a hazard to human health or the environment due to their ability to mobilize toxic metals if discharged into a landfill environment; to corrode handling, storage, transportation, and management equipment; or to destroy human or animal tissue in the event of inadvertent contact [EPA SW-846 2000]. Corrosion can occur when water or leachate water reacts with metal plumbing. It may eventually cause leaky pipes, faucets, hot water heaters, or other plumbing fixtures. A solid waste exhibits the characteristic of corrosivity if a representative sample of the waste has the property that it is aqueous (leachate) and has a pH less than or equal to 2 or greater than or equal to 12.5, as determined by a pH meter using Method 9040 in “Test Methods for Evaluating Solid Waste, Physical/Chemical Methods,” EPA Publication SW-846 [40 CFR Part 261 1986]. However, this range is not applicable to the corrosion or passivity of all materials. For example, higher pH values provide passivity to exposed steel but may corrode glassy materials.

Table **7-24**: Toxicity of hardened CLSM

		FS02	FS12	FS13	FS16	TCLP Toxicity Threshold
Arsenic	Unit: mg/kg	.0572	<.05	<.5	<.05	5
Barium		.0784	.291	.338	<.01	100
Cadmium		<.01	<.01	<.01	<.01	1
Chromium		.025	.0609	.0722	<.01	5
Lead		<.03	<.03	<.03	<.03	5
Mercury		<.0002	<.0002	<.0002	<.0002	0.2
Selenium		<.05	<.05	<.05	<.05	1
Silver		<.05	<.05	<.05	<.05	5
Acetone	Unit: ug/kg	86	86	100	115	---
Benzene		<25	<25	<25	<25	500
Carbon Tetrachloride		<25	<25	<25	<25	500
Chlorobenzene		<25	<25	<25	<25	100000
Chloroform		<25	<25	<25	<25	6000
1,4-Dichlorobenzene		<25	<25	<25	<25	7500
1,2-Dichloroethane		<25	<25	<25	<25	500
1,1-Dichloroethene		<25	<25	<25	<25	700
Ethyl benzene		<25	<25	<25	<25	---
Methyl ethyl ketone		<50	<50	<50	<50	200000
Methylene chloride		<25	<25	<25	<25	---
Naphthalene		<25	616	527	<25	---
Styrene		<25	<25	<25	<25	---
Tetrachloroethene		<25	<25	<25	<25	700
Toluene		<25	<25	<25	<25	---
1,1,1-Trichloroethane		<25	<25	<25	<25	---
Trichloroethene		<25	<25	<25	<25	500
Vinyl chloride		<50	<50	<50	<50	200
M, P-Xylene		<25	<25	<25	<25	---
Xylene-total		<25	<25	<25	<25	---

Factors affecting the potential for soil corrosion include water content, degree of aeration, pH, resistivity, redox potential, chloride level, sulfate level, and microbiologically influenced corrosion (MIC) [Roberge 1999]. As for soil, its resistivity parameter is very widely used in practice and generally considered to be the dominant

variable in the absence of microbial activity. The generally adopted corrosion severity ratings are presented in Table 7-25. In the investigation of corrosivity of CLSM, which acts as a replacement of compacted soil, this severity rating is accepted as thresholds for resistivity evaluation of CLSM.

Table **7-25**: Scale of soil corrosion [Roberge 1999]

Soil Resistivity (ohm cm)	Corrosivity Rating
>20,000	Essentially non-corrosive
10,000 to 20,000	Mildly corrosive
5,000 to 10,000	Moderately corrosive
3,000 to 5,000	Corrosive
1,000 to 3,000	Highly corrosive
<1,000	Extremely corrosive

Not limited to resistivity, comprehensive aspects of corrosivity regarding CLSM include the pH of its bleeding and leachate. The bleeding is a single-phase media, whose pH is determined by EPA 150.1, "pH Electrometric." The pH of leachate from CLSM was measured in terms of EPA SW-846. Both of them were measured by the commercial laboratory. The corrosivity of solid CLSM was measured using ASTM G 57, "Standard Test Method for Field Measurement of Soil Resistivity Using the Wenner Four-Electrode Method" [ASTM G 57 2001].

Results of pH for bleeding and leachate of top-risk CLSM are presented in Table 7-26. The resistivity of solid CLSM is presented in Table 7-27. It is indicated that bleeding and leachate are alkaline and pose no corrosivity threat. The higher values of pH in the bleed water are primarily due to the calcium hydroxide released from the hydration of portland cement. Hydrate portland cement has a pH value between 12.6 and 13.0. Due to the relatively low hydraulic conductivity compared to background media, the core of

CLSM keep dry mostly. Hence, the embedded metal pipe would not be exposed to media of high resistivity.

Table **7-26**: pH of bleeding and leachate of CLSM

	FS02	FS12	FS13	FS16	Corrosivity Threshold	Testing Method
Bleeding	12.9	12.9	12.9	13.1	---	EPA 150.1
Leachate	10.5	10.9	11.5	11.7	2-12.5	SW-846 9040

Table **7-27**: Resistivity of hardened CLSM (Under Investigation)

FS ID	Wet at 28 Day	Oven-dry at 28 Day
	Unit (kom cm)	
FS01	4.2	*
FS02	20	*
FS03	10	*
FS04	8.6	*
FS05	5.1	*
FS06	5.8	*
FS07	8.0	*
FS08	5.1	*
FS09	32	*
FS10	25	*
FS11	15	*
FS12	8.5	*
FS13	12	*
FS14	4.2	*
FS15	7.6	*
FS17	7.6	*
Min.	4.2	---
Max.	32	---
Avg.	11.17	---
SD	8.04	---

*: Exceeding the capacity of instrument.

7.4 CLSM Correlations and Discussions

In this section, based on the experiment results, correlations among critical parameters of CLSM are addressed.

7.4.1 Flowability

The flow behavior of CLSM is an important property to control the workability, and therefore it is essential to understand critical factors affecting this behavior. The water is mainly responsible for flow. The amount of water required to produce flow depends mainly on the nature of the sand and the proportion of fly ash and sand in the mixture [Bhat and Lovell 1997]. The correlation of gradation of particles and water content is presented in Figure 7-10. Grain fineness indicates the grain size in the CLSM matrix contributed by fly ash and foundry sand. It was calculated through multiplying AFS GFN by individual component proportion. The AFS GFN of fly ash is assumed to be 200. The greater the grain fineness, the finer is the average grain size. A point represents a mixture that attains a flow spread of 23 cm (9 in). It is indicated that the finer the average grain size, the less water is required to attain the specified flow criteria for both excavatable CLSM and structural CLSM. For excavatable and structural CLSM, the fineness degree is negatively correlated with water proportion (r = -0.764, p = 0+; r = -0.825, p = 0+). The general absolute volume of water in the fresh CLSM matrix ranges from 30% to 50% to provide working flowability of CLSM.

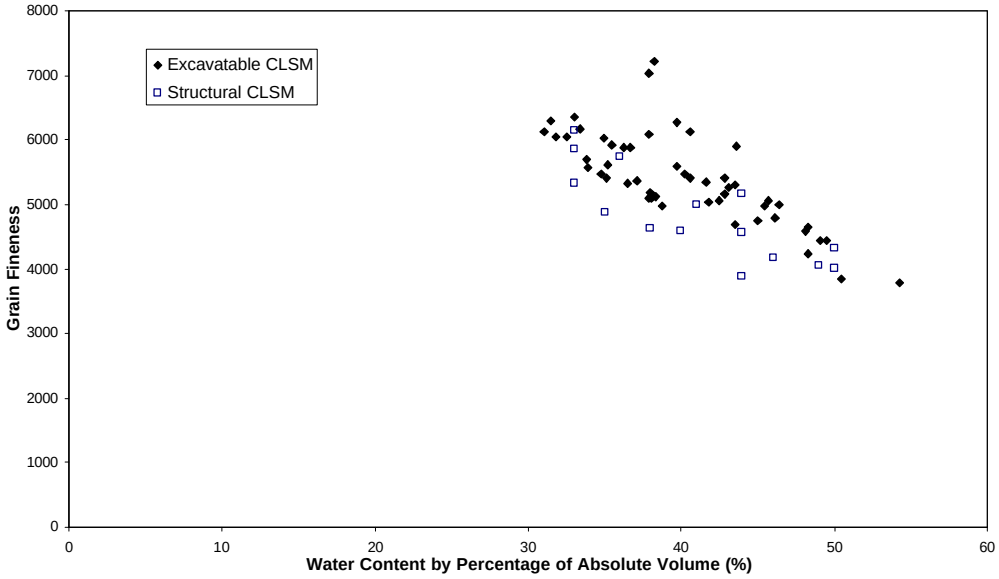

Figure **7-10**: Relation between grain fineness and water content regarding flowability

7.4.2 Setting Time

The early age strength is important to support foot traffic and allow further loading. Generally, the flowable fill is considered to have hardened if it can support foot traffic. The short-term strength is evaluated by measuring the development of penetration resistance using a mortar penetrometer. As the hydration of cement begins, the penetration resistance increases with time [Bhat and Lovell 1997]. It is indicated from Figure 7-1, Figure 7-2, and Figure 7-3 that the development of penetration resistance is diverse and with no apparent general trend, although it increases with time. Since the proportions of mixtures are roughly at the same level for excavatable CLSM and structural CLSM, variation of excess foundry sand results in the scattering of penetration resistance.

The comparison of penetration resistance is presented in Figure 7-11. Each point corresponds to a mixture. It is indicated that the variation in setting time of excavatable CLSM is greater than that of structural CLSM, in regard to penetration resistance of both 344 kPa and 689 kPa. The time to attain a penetration resistance of 344 kPa (50 psi) is regarded as the initial setting time. This is the level of resistance to support foot traffic without substantial settlement. The initial setting time for extractable CLSM starts from 6.7 hours and averages 15-20 hours. The penetration resistance gain from 344 kPa to 688 kPa requires an additional 2-3 hours for extractable CLSM. These two sets of setting times are heavily positive-correlated (r = 0.971, p = 0+). The initial setting time of structural CLSM is concentrated on 5-7 hours, which is contributed by the increased proportion of cement. And it requires less time, about 1 hour, to double penetration resistance. Hence, penetration resistance gain is more pronounced for structural CLSM than for excavatable CLSM. And for structural CLSM, the time to attain 344 kPa and time to attain 688 kPa are heavily positive-correlated (r = 0.991, p = 0+). It is also inferred from the comparison that in the case of excavatable CLSM, foundry sand controls the initial penetration resistance, and in the other case of structural CLSM, cement dominates the initial penetration resistance.

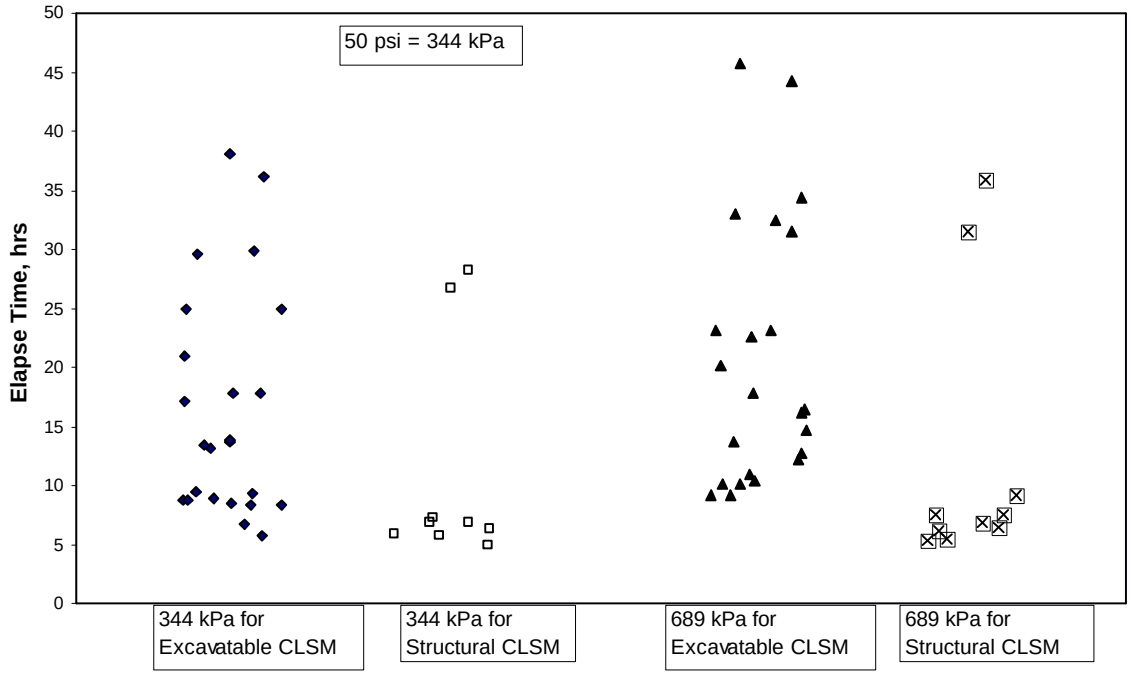

Figure **7-11**: Comparison of penetration resistance

7.4.3 Bleeding

Bleeding is another consideration in the design of CLSM. The phenomenon of bleeding is common to all flowable fill matrices. Bleeding helps the particles contact and enhances strength development. It is expected that a higher amount of bleeding will result in a more compact structure and a lower void ratio in the material, and thereby would give a higher frictional strength. However, excessive bleeding is not desirable because it is more often a sign of poor mixture optimization. Mixtures that are not optimized will result in segregation. It will result in excessive initial subsidence of the surface after placement [Bhat and Lovell 1997].

The relationship between cumulative bleeding and bleed time is presented in Figure 7-12. As pointed out in Section 7.3.1.2, bleeding is moderately positive-correlated (r = 0.469, p = 0.028) with bleed time for excavatable CLSM and strongly correlated (r = 0.827, p = 0+) for the structural CLSM, excluding FS16. Bleeding of excavatable CLSM is slightly more in volume and longer in elapse than that of structural CLSM because these formulations contain more water and less cement to minimize strength development. Bleeding of CLSM normally takes 2-5 hours, with volume up to 6% of fresh CLSM.

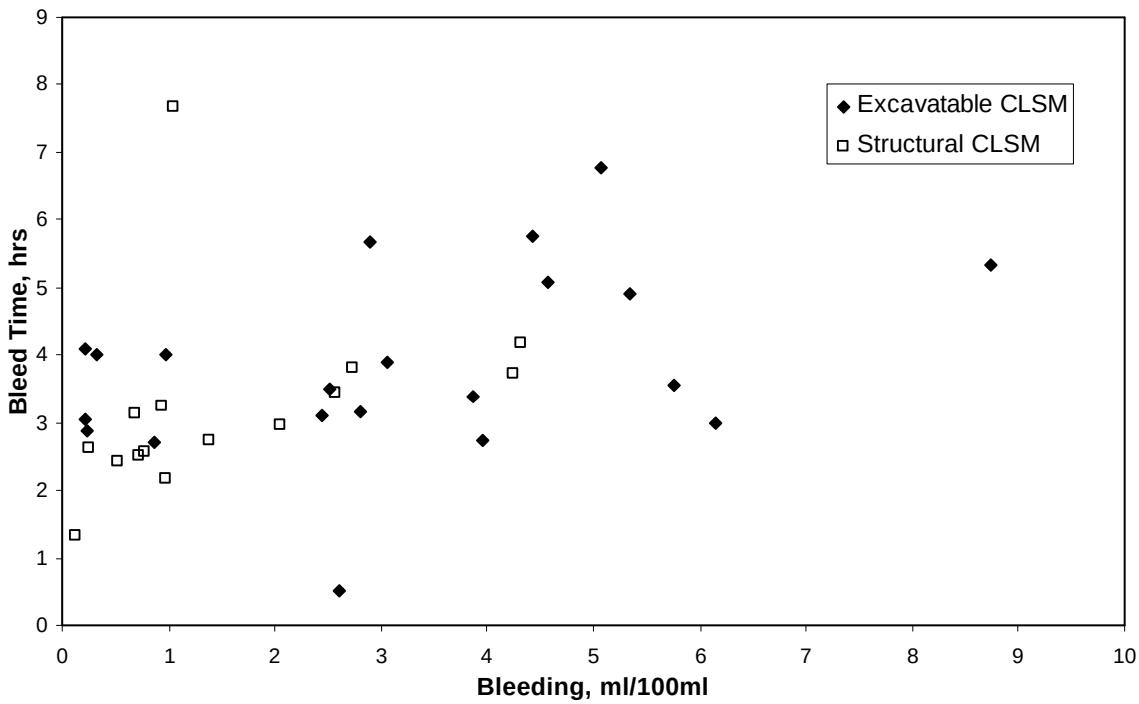

Figure **7-12**: Relation between bleeding and bleed time

The relation of bleeding to water proportion is presented in Figure 7-13. The quantity of cement in structural CLSM does not influence water proportion significantly compared to that of excavatable CLSM. This indicates that water addition is exclusively

controlled by flowability, which is closely related to grain fineness (Section 7.4.1). However, as hydration proceeds less water is available for bleed in mixtures with higher cement contents.

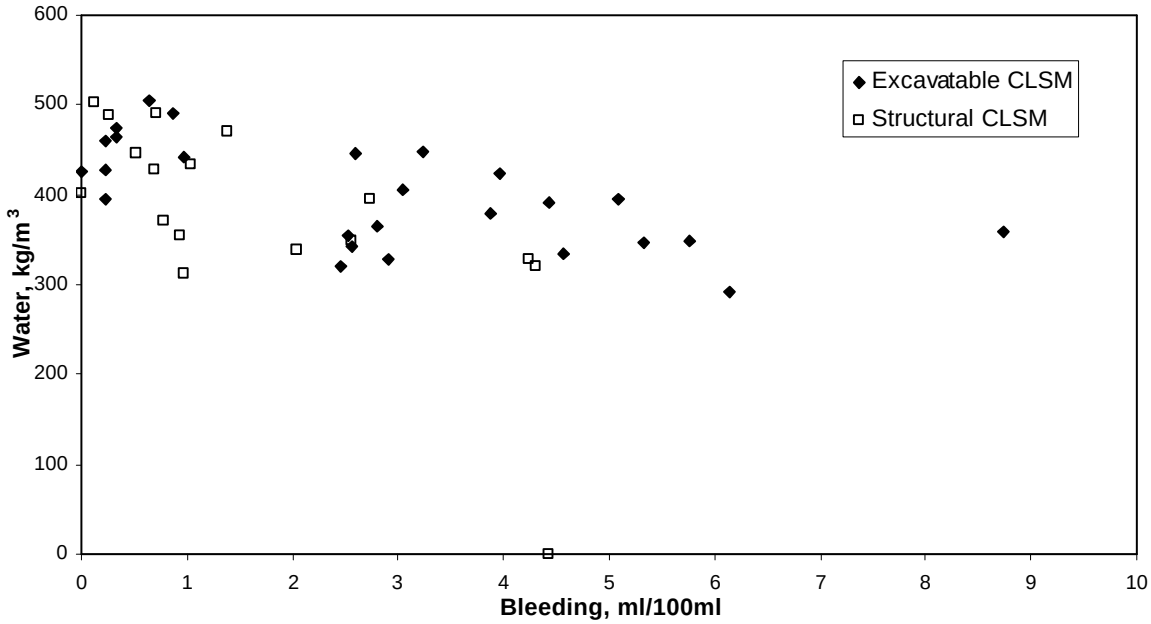

Figure **7-13**: Relation between bleeding and water proportion

The relation between bleed time and setting time to attain 344 kPa penetration resistance is presented in Figure 7-14. The time to attain 344 kPa penetration resistance does not correlate with bleed time.

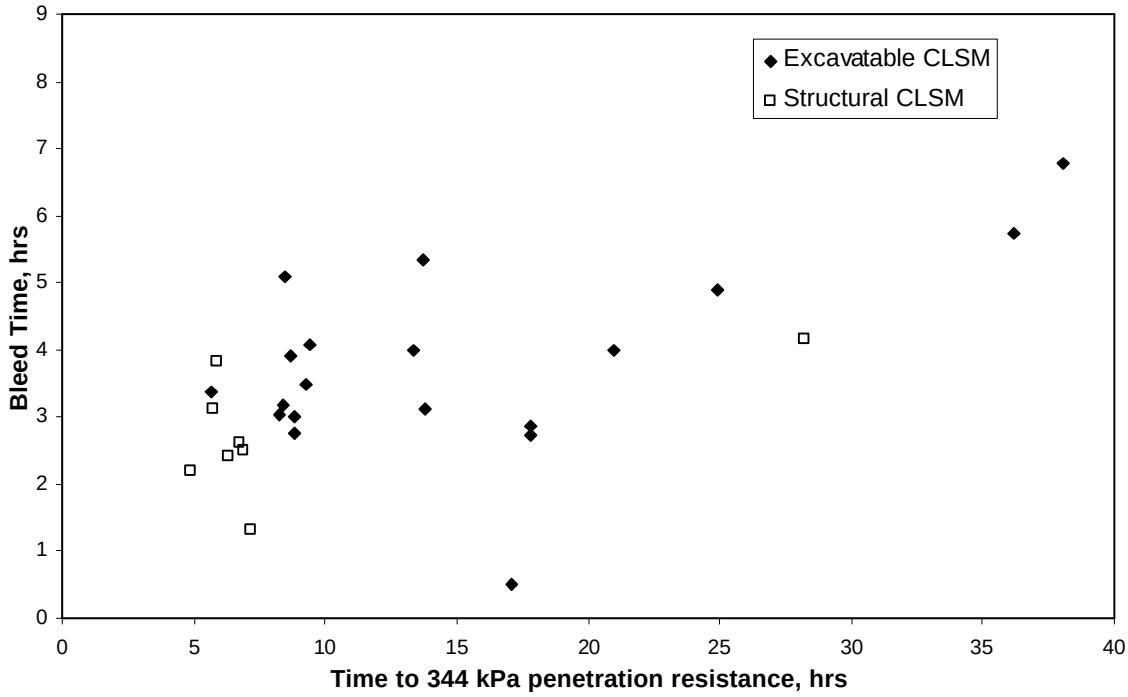

Figure **7-14**: Relation between bleed time and setting time

7.4.4 Strength

When the CLSM is placed, and particles do not have much internal friction or cohesion, the shear strength is almost zero. As the excess water bleeds out, particles tend to settle and establish interparticle shear strength. The bond strength gained through cement hydration contributes further to the strength increment. The strength of CLSM during hardening can be thought of as having two components: frictional strength and a bond strength which is somewhat similar to cohesion in soils [Bhat and Lovell 1997].

The relation between 12-hour penetration resistance and 28-day compressive strength is presented in Figure 7-15. There is no significant correlation between 12-hour penetration resistance and 28-day compressive strength for excavatable CLSM (r = 0.2, p = 0.385). For structural CLSM, after excluding two outliers, there is a correlation between 12-hour penetration resistance and 28-day compressive strength (r = 0.892, p = 0.001). It is suggested that increases in cement proportion enhance the correlation of high early penetration resistance and long-term compressive strength.

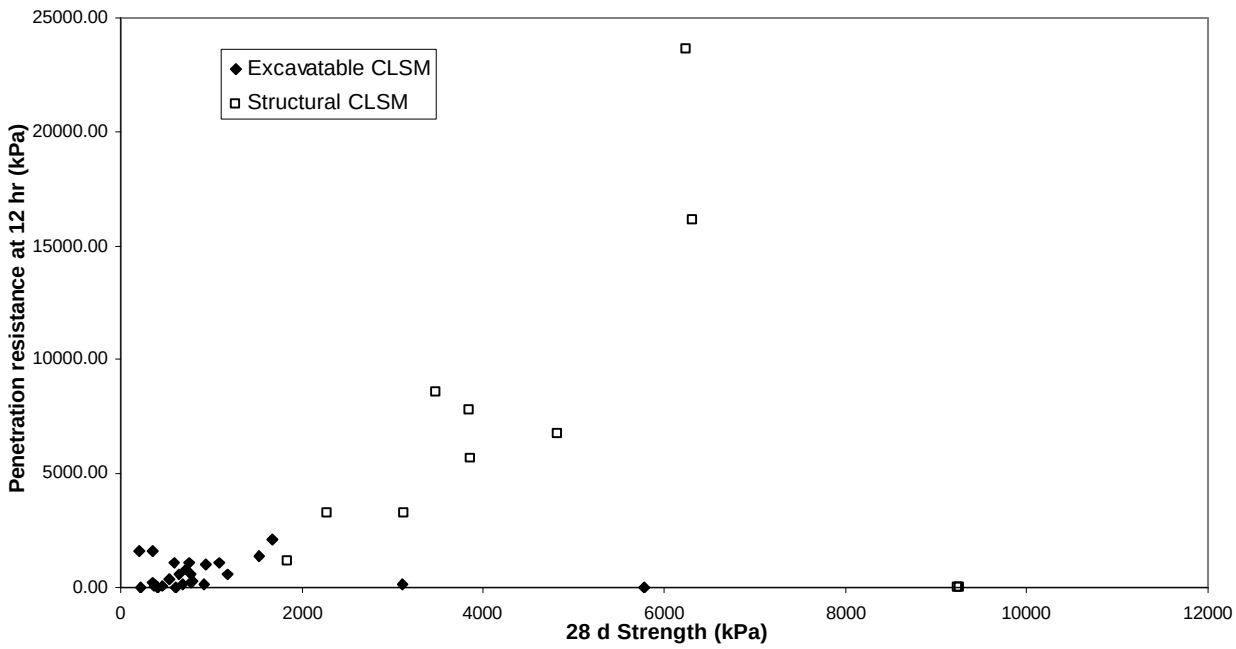

Figure **7-15**: Relation between 28-day compressive strength and 12-hour penetration resistance

The relation between water-cement ratio and 28-day unconfined compressive strength is presented in Figure 7-16. It coincides with the curve tendency suggested in Figure 7-17, which was suggested by Bhat and Lovell [Bhat and Lovell 1997]. The

variation in Figure 7-16 suggests that 28-day strength varies inversely with water-cement ratio, and that the variation of water-cement ratio needed for excavatable CLSM is greater than that for structural CLSM.

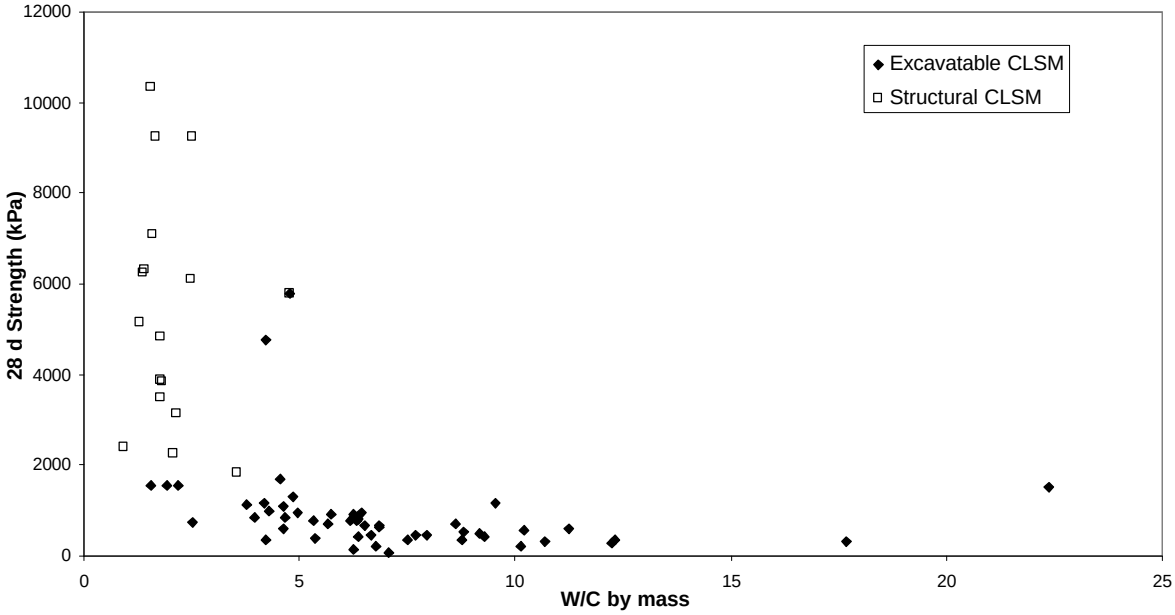

Figure **7-16**: Relation between 28-day compressive strength and water-cement ratio

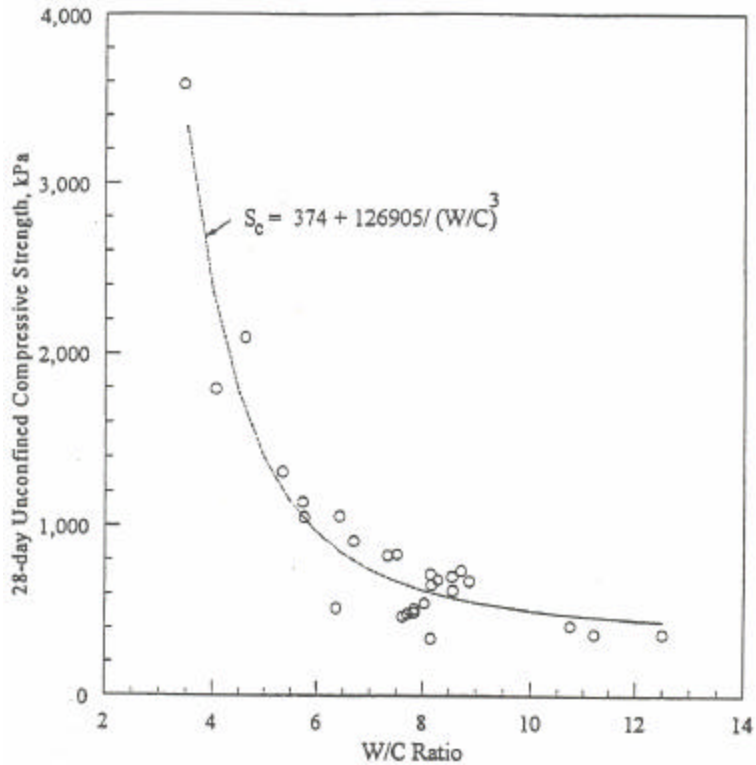

Figure **7-17**: Relation between 28-day compressive strength and water-cement ratio [Bhat and Lovell 1997]

The relation between 28-day compressive strength and cement proportion is presented in Figure 7-18. It is indicated that increment in cement proportion contributes much to strength gain. For either class of CLSM, no significant regression line can be approximated. However, there is a general relationship between cement proportion and 28-day compressive strength.

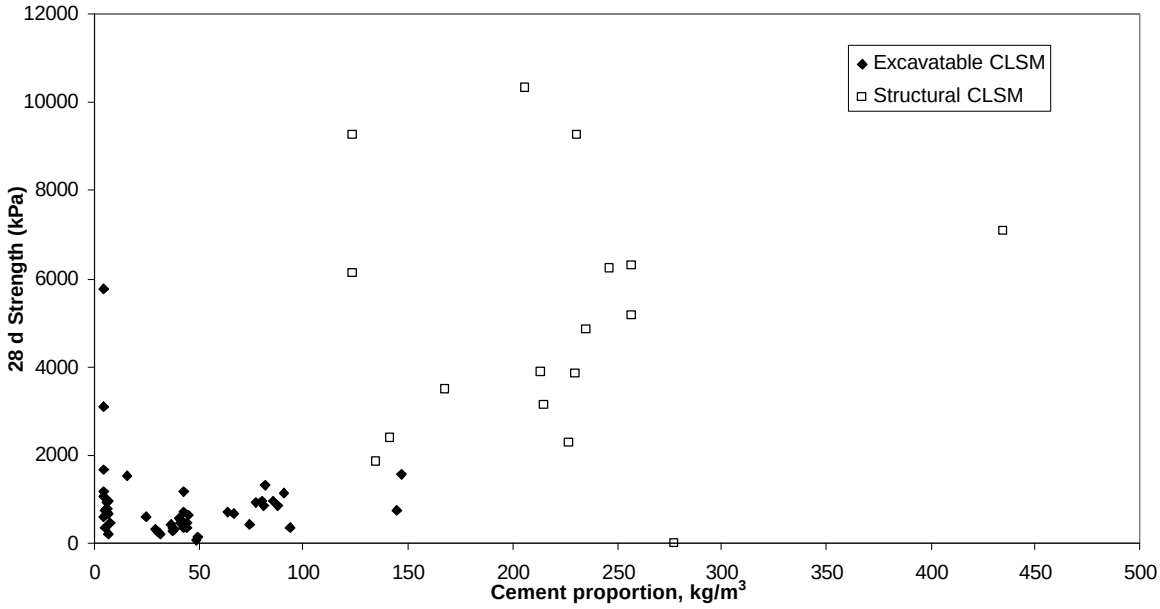

Figure **7-18**: Relation between 28-day compressive strength and cement proportion

The relation between 28-day compressive strength and 90-day compressive strength is presented in Figure 7-19. It is indicated that the correlation between 28-day compressive strength and 90-day compressive strength is significant (r = 0.932, p = 0+ for excavatable CLSM, and r = 0.927, p = 0+ for structural CLSM). The relation of 28-day compressive strength and 180-day compressive strength is presented in Figure 7-20. It is indicated that the correlation between 28-day compressive strength and 180-day compressive strength is significant (r = 0.92, p = 0+ for excavatable CLSM, and r = 0.51, p = 0.036 for structural CLSM). Hence, the long-term strength of CLSM can be estimated based on 28-day strength with statistical confidence.

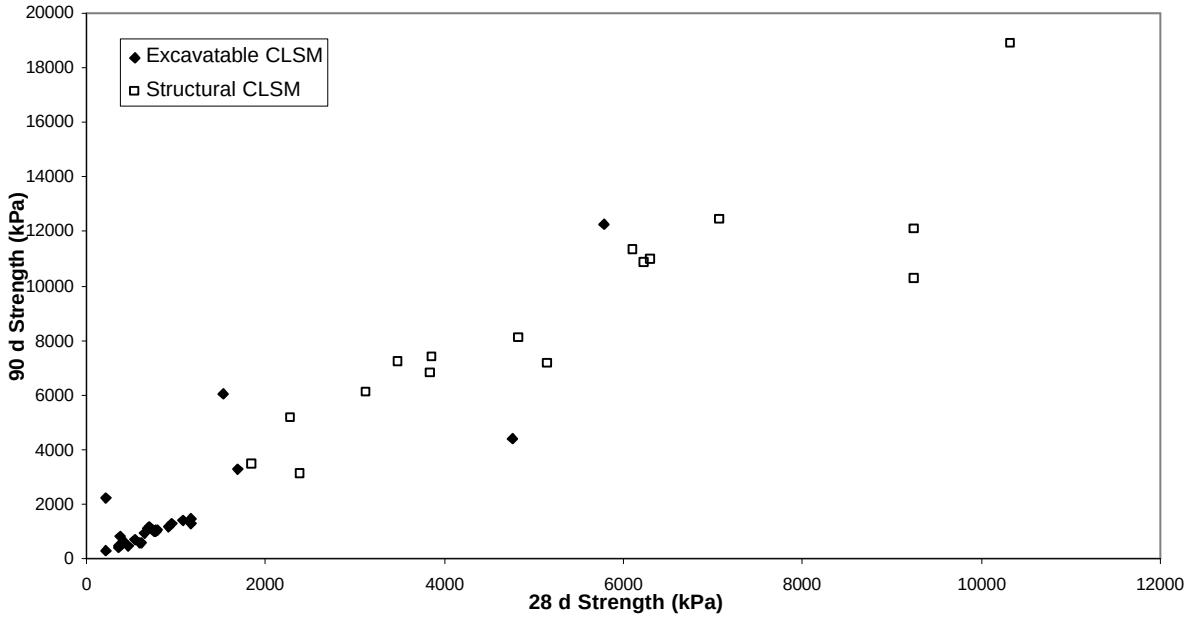

Figure **7-19**: Relation between 28-day compressive strength and 90-day compressive strength

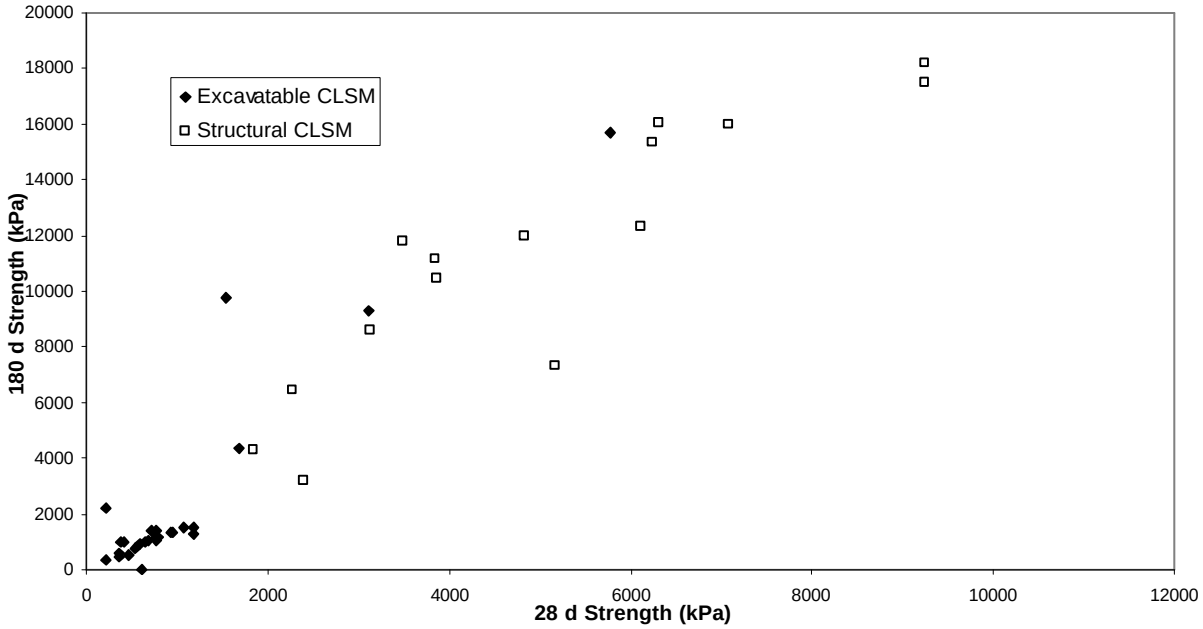

Figure **7-20**: Relation between 28-day compressive strength and 180-day compressive strength

Chapter 8

EXPERIMENTS QUALIFYING HMA USING EXCESS FOUNDRY SAND

Seventeen identical foundry sands were incorporated into an HMA mixture at a level of 10% by mass. The aggregates used came from a limestone quarry in close vicinity to the city of Madison, WI. The control gradation was a low-volume, fine gradation. The job mix formula for each of the 17 mixes was kept the same as the control job mix formula. Volumetric properties of the mixes were determined according to Superpave mix design criteria. The mixtures were also tested for moisture sensitivity through the use of the indirect tension test. The following sections give a summary of the findings pertaining to each measurement collected in the study.

8.1 Experimental Methodology with Examples

The purpose of this section is to explain the methods used to collect the data and analyze results of this study, including the calculation of the maximum and bulk density of aggregates, angularity of aggregates, the maximum density of loose mix, the bulk specific gravity of compacted asphalt mix samples, and the absorption of asphalt into aggregates, the calculations used for the volumetric properties, the energy indices, the indirect tension test results, and the rutting results.

8.1.1 Density, Absorption and Angularity

A relatively new instrument for measuring density called the CoreLok™ device, created by a company called Instrotek®, is becoming popular for used among state DOTs and asphalt contractors. This allows air to be removed from an aggregate or asphalt sample and then the sample is sealed in a bag. The sample can then be placed in water and weighed or the bag can be cut open and the sample completely saturated with water. The device can also be used to find the quantity of surface pores on an aggregate. This allows a more scientific method to determine the absorption of aggregates compared to methods used previously to measure indirectly the saturated surface dry volumetric properties.

8.1.1.1 Aggregate Maximum Density

The maximum density of the aggregates, foundry sands, and aggregate-bitumen mixtures were determined according to the procedure outlined in ASTM D6857-03 "Standard Test Method for Maximum Specific Gravity and Density of Bituminous Paving Mixtures Using Automatic Vacuum Sealing Method" [ASTM D 6857 2003]. Equation 8.1 illustrates the steps needed to calculate the maximum density.

$$r_{MD} = \frac{M_S}{\frac{M_S + M_Y + M_C - M_{IW}}{r_W} - \frac{M_Y}{r_Y} - \frac{M_C}{r_C}} \qquad \text{Equation } \mathbf{8.1}$$

Where, M_C = Mass of Channel Bag = 23.9g

M_Y = Mass of Large Yellow Bag = 51.0g

M_S = Mass of Sample = 1,798.8g

M_{IW} = Mass of Sample, Channel Bag, and Yellow Bag in Water = 1,149.3g

ρ_W = Density of Water = 0.997 g/ccm

ρ_C = Density of Channel Bag = 0.985 g/ccm

ρ_Y = Density of Yellow Bag = 0.918 g/ccm

ρ_{MD} = Maximum Density of Sample = 2.7812 g/ccm

8.1.1.2 Bulk Density of Coarse and Fine Aggregates Using the InstroTek® Method

The procedure used to determine the bulk density of aggregates and aggregate-foundry sand mixes is the same as outlined in the AggPlus™ System manual [InstroTek 2002], which is given with the CoreLok™ device, for the bulk density of coarse aggregates, with the following exception:

1) After placing the lid on the volumeter and filling the volumeter with water as directed using the syringe, place the filled volumeter in the water bath on the padded weigh basket.

2) Record the mass, once the mass reading has stabilized.

Originally, the Gravity Suit Software [InstroTek 2001] was used to perform the calculations. Due to erroneous results, a second method was developed to determine the bulk density of the foundry sands.

The calculation of the bulk density of the sample is according to Equation 8.2.

$$r_{BD} = \frac{M_S r_W}{M_S - M_{SIW} - M_{BIW}}$$ Equation **8.2**

where: M_{BIW} = Mass of Volumeter and Lid in Water = 1749.7g

M_S = Mass of Sample = 1806.1 g

M_{SIW} = Mass of Sample, Volumeter and Lid in Water = 2877.2g

ρ_W = Density of Water = 0.997 g/ccm

ρ_{BD} = Bulk Density of Sample = 2.6535 g/ccm

8.1.1.3 Water Absorption/Percentage of Micro Voids in Aggregates

There is no testing procedure used to determine the percentage of micro voids. The percentage of micro voids is determined by a calculation based on the maximum and bulk densities of aggregate samples. The percentage absorption is usually calculated using the mass of fluid absorbed divided by the mass of aggregates. However, it is recognized that a volume percentage can also be calculated. Equation 8.3 and Equation 8.4 can be used to determine the percentage of micro voids per aggregate sample.

$$\%Voids = \left[1 - \frac{r_B}{r_M}\right] \times 100$$ Equation **8.3**

$$\%Abs. = \left[\frac{r_W}{r_B} - \frac{r_W}{r_M}\right] \times 100$$ Equation **8.4**

ρ_M = Maximum Density = 2.7812 g/ccm

ρ_B = Bulk Density = 2.6535 g/ccm

ρ_W = Density of Water = 0.997 g/ccm

%Voids = Volume of Micro Voids Divided By Volume of Aggregate = 4.59%

%Abs. = Mass of Water Able to be Absorbed Divided By Mass of Aggregate = 1.73%

8.1.1.4 Indirect Method to Determine the Apparent Density of Foundry Sand

One of the most difficult tasks is to determine the apparent specific gravity of foundry sands. The difficulty is related to the fact that some sands have a tendency to absorb and retain water. While running the apparent *and* bulk density tests, a film was observed to be covering the foundry sand, possibly preventing the water from penetrating the sand, and seemed to be due to surface tension between the water and the sand. It was thought that by mixing the sand with larger aggregates, the film or skin due to the surface tension could be disrupted and allow water to penetrate the sand more thoroughly. Unfortunately, due to lack of time, data could not be gathered using the indirect method, and the results from the direct method could not be compared to those of the indirect method. The indirect method includes using Equation 8.5.

$$r_{F.S.} = \frac{P_{F.S.}}{\frac{1}{r_S} - \frac{P_A}{r_A}} \qquad \text{Equation } \mathbf{8.5}$$

where, ρ_A = Apparent Density of Aggregates = 2.7812 g/ccm

ρ_S = Apparent Density of Sample w/FS14 = 2.7758 g/ccm

$P_{F.S.}$ = Mass Fraction of FS14 in Sample = 0.1

P_A = Mass Fraction of Aggregate in Sample = 0.9

$\rho_{F.S.}$ = Apparent Density of FS14 = 2.7279 g/ccm

8.1.1.5 Indirect Method to Determine the Bulk Density of Foundry Sand

As mentioned in the previous section, the direct methods may include error due to the surface tension between the sand and the water. The following procedure could be used to determine the bulk density of foundry sands. The indirect method includes using Equation 8.6.

$$r_{F.S.} = \frac{P_{F.S.}}{\frac{1}{r_S} - \frac{P_A}{r_A}} \qquad \text{Equation } \mathbf{8.6}$$

where, ρ_A = Bulk Density of Aggregates = 2.6535 g/ccm

$\rho_{F.S.}$ = Bulk Density of Sample Containing FS14 = 2.6161 g/ccm

$P_{F.S.}$ = Mass Fraction of FS14 = 0.1

P_A = Mass Fraction of Aggregates = 0.9

$\rho_{F.S.}$ = Bulk Density of F.S. #1 = 2.3299 g/ccm

8.1.1.6 Uncompacted Void Content of Fine Aggregates and Foundry Sands

The angularity of sands is determined using the ASTM standard C1252-98 "Standard Test Method for Uncompacted Void Content of Fine Aggregate (as Influenced by Particle Shape, Surface Texture, and Grading)." The procedure includes Equation 8.7.

$$U_V = \frac{V - M/D_{sb}}{V} \times 100 \qquad \text{Equation } \mathbf{8.7}$$

where ρ_{sb} = Bulk Density of FS14 = 2.3299 g/ccm

V = Volume of Cylinder = 100 ccm

M = Mass of Loose Fine Aggregates to Fill Cylinder = 137.7 g

U_V = Uncompacted Void Content = 40.9%

8.1.1.7 Bulk Density of Compacted Bitumen Samples

The bulk density of compacted asphalt mixture samples is measured using the ASTM standard procedure D6752-02a, "Bulk Specific Gravity and Density of Compacted Bituminous Mixtures Using Automatic Vacuum Sealing Method." This procedure is also used for mixtures containing foundry sands. Equation 8.8 is used to calculate the bulk density,

$$r_{BD} = \frac{M_S}{\frac{M_S + M_Y - M_{IW}}{r_W} - \frac{M_Y}{r_Y}} \qquad \text{Equation } \mathbf{8.8}$$

where, M_S = Mass of Compacted Bitumen Sample = 4941.1g

M_Y = Mass of Yellow Bag = 44.7g

M_{IW} = Mass of Sample and Bag in Water = 2912.1

ρ_Y = Density of Yellow Bag = 0.918 g/ccm

ρ_W = Density of Water = 0.997 g/ccm

ρ_{BD} = Bulk Density of Sample = 2.4325 g/ccm

8.1.1.8 Effective Density of Aggregates

The effective density of aggregate samples is determined using Equation 8.9.

$$r_E = \frac{1 - P_{A.S.}}{\frac{1}{r_M} - \frac{P_{A.S.}}{r_{A.S.}}} \qquad \text{Equation } \mathbf{8.9}$$

where, ρ_M = Maximum Density of Bituminous Sample = 2.5207 g/ccm

ρ_W = Density of Water = 0.997 g/ccm

$\rho_{A.S.}$ = Density of Asphalt = 1.0228 g/ccm

$P_{A.S.}$ = Mass Fraction of Asphalt = 0.052

ρ_E = Effective Density of Aggregate = 2.7409 g/ccm

8.1.1.9 Asphalt Absorption of Bituminous Samples

The asphalt absorption of asphalt mixtures is calculated using Equation 8.10 and Equation 8.11.

$$\%Abs._1 = \frac{\left(r_{Eff} - r_B\right) r_{A.S.}}{r_{App}^2 \left(\frac{1}{1 - P_{A.S.}} - 1\right)} \times 100 \qquad \text{Equation } \mathbf{8.10}$$

$$\%Abs._2 = \frac{\left(r_{Eff} - r_B\right) r_{A.S.}}{r_{App}^2} \times 100 \qquad \text{Equation } \mathbf{8.11}$$

where, ρ_{App} = Apparent Density of Control Aggregates = 2.7812 g/ccm

ρ_{Eff} = Effective Density of Control Aggregate = 2.7464 g/ccm

ρ_B = Bulk Density of Control Aggregates = 2.6523 g/ccm

$\rho_{A.S.}$ = Density of Asphalt = 1.0228 g/ccm

$P_{A.S.}$ = Mass Fraction of Asphalt = 0.055

$\%Abs._1$ = Absorbed Asphalt Per Total Asphalt = 21.4%

$\%Abs._2$ = Absorbed Asphalt Mass Per Aggregate Mass = 1.24%

8.1.2 Surface Area & Average Asphalt Film Thickness

The asphalt film thickness was determined using a method described in Chapter 3 of the book, "Hot Mix Asphalt Materials, Mixture Design and Construction" [Roberts et al 1996]. According to this method, the surface area of all aggregate blends used should be the same, because the gradation was kept constant and the surface area calculation is totally dependent on gradation. Each sieve size is allocated a surface area factor. This means that for every pound of material retained on that particular sieve, it will have a certain surface area regardless of mineralogy or surface texture. Table 8-1 includes the surface area factors in both English and SI units.

Table **8-1**: Surface area factors for each sieve size

Sieve Size	S.A. Factor ft^2/lb.	S.A. Factor m^2/kg
P25.00-R19.00 mm	2	0.41
P19.00-R12.50 mm	2	0.41
P12.50-R9.50 mm	2	0.41
P9.50-R4.75 mm	2	0.41
P4.75-R2.36 mm	2	0.41
P2.36-R1.18 mm	4	0.82
P1.18-R0.60 mm	8	1.64
P0.60-R0.30 mm	14	2.87
P0.30-R0.15 mm	30	6.15
P0.15-R0.075 mm	60	12.29
P0.075 mm	160	32.78

Using the gradation of the aggregate blend used in this study (as shown in Table 8-2), the total surface area is calculated by multiplying the percentage retained on each sieve by the surface area factors listed in Table 8-1. The surface area is calculated to be 3.33 m^2/kg of aggregates.

Table **8-2**: Job mix formula according to percent retained

Sieve Size	% Retained
P25.00-R19.00 mm	0.0
P19.00-R12.50 mm	5.6
P12.50-R9.50 mm	10.4
P9.50-R4.75 mm	17.5
P4.75-R2.36 mm	17.6
P2.36-R1.18 mm	12.8
P1.18-R0.60 mm	9.1
P0.60-R0.30 mm	10.8
P0.30-R0.15 mm	7.6
P0.15-R0.075 mm	3.6
P0.075 mm	5.0

To determine the average asphalt film thickness for the mixture, Equation 8.12 could be used.

$$T_A = \frac{P_{A.S.}(1 - Abs._1)}{r_{A.C.}(1 - P_{A.S.})S.A. \times 1000} \qquad \text{Equation } \mathbf{8.12}$$

$P_{A.S.}$ = Mass Fraction of Asphalt = 0.055

%Abs.1 = Absorbed Asphalt per Total Asphalt = 21.4%

ρ_{AC} = Density of Asphalt = 1.0228 g/ccm

S.A. = Surface Area = 3.33 m^2/kg

T_A = Average Asphalt Film Thickness = 1.343E^{-5} m = 13.43 µm

8.1.3 Densities at Different Gyrations, Energy Indices, and Indirect Tension Test

8.1.3.1 Densities at Different Gyrations

The optimum asphalt content is the asphalt content that gives 4% air voids, when a 5,000 g HMA sample is compacted using a Superpave Gyratory Compactor. The samples were mixed at a temperature of 145 EC, and cured and compacted at a temperature of 135 EC. The AASHTO Standard Procedure T 312-01 was followed to mix and compact the samples, as well as the calculations used to determine the %Gmm at each gyration. Since all the samples were E-3 mixes, N_{ini} was at 7 gyrations, N_{des} was at 75 gyrations, and N_{max} was at 115 gyrations. All samples used to determine the optimum asphalt content were compacted to 115 gyrations. This means the volume correction factor required in the standard procedure was calculated at 115 gyrations. To show the specific steps for calculations of densities, Equation 8.13 is used.

$$D_{\max-theo.} = \frac{4000M}{pD^2 H_{\max}} \qquad \text{Equation } \mathbf{8.13}$$

M = Mass of puck after 115 gyrations = 4959.1 g

H_{ini} = Height of sample at the 7th gyration as reported by the Superpave Gyratory Compactor (SGC) = 125.7 mm

H_{des} = Height of sample at the 75th gyration as reported by SGC = 116.9 mm

H_{max} = Height of sample at the 115th gyration as reported by the SGC = 115.7 mm

D = Diameter of sample, constant = 150 mm

$D_{Theo.}$ = Theoretical Density at 115th gyration = 2.4255 g/ccm

D_{bulk} = Bulk density at 115 gyrations = 2.4273 g/ccm

$$C.F. = \frac{D_{bulk}}{D_{Theo}}$$

C.F. = Correction Factor = 1.00075

The theoretical density should be calculated for each gyration and then multiplied by the correction factor to get the actual density. We can see that the theoretical density and that determined by the Corelock device are very similar.

D_{Max} = Maximum density = 2.5134 g/ccm

$$\%D_{Max} @ N_{Max} = \frac{D_{Bulk}}{D_{Max}} \times 100$$

$\%D_{Max}$ @ N_{Max} = Percent of maximum density at 115 gyrations = 96.57%

$$D_{ini-theo} = \frac{4000M}{pD^2 H_{ini}}$$

$D_{ini\text{-}theo}$ = Theoretical density at 7 gyrations = 2.2325 g/ccm

$$\%D_{\max} @ N_{ini} = \frac{D_{ini-theo} \times C.F.}{D_{Max}} \times 100$$

$\%D_{max}@N_{ini}$ = Percent of maximum density at 7 gyrations = 89.0%

$$D_{des-theo} = \frac{4000M}{pD^2 H_{des}}$$

$D_{des\text{-}theo}$ = Theoretical density at 75 gyrations = 2.4006 g/ccm

$$\%D_{\max} @ N_{des} = \frac{D_{des-theo} \times C.F.}{D_{Max}} \times 100$$

$\%D_{max}@N_{des}$ = Percent of maximum density at 75 gyrations = 95.6%

It can be seen that the percent of maximum density at 7, 75, and 115 gyrations are 89.0%, 95.6%, and 96.6%, respectively.

8.1.3.2 Paver, Roller, and Traffic Energy Indices

The paver, roller, and traffic energy indices (PEI, REI, and TEI) are construction and rutting performance indicators based on the densification curve created during compaction. Since the height at each gyration is recorded and the correction factor at the 115th gyration is known, the percent of maximum density can be calculated at each gyration. A plot of gyrations versus the percent of maximum density creates a curve called the densification curve.

For an E-3 mix, a mix designed to carry up to 3 million ESALs, the area under the densification curve from the first gyration to the 7th gyration, minus the area below the horizontal line created by the percent maximum density at the 0th gyration, is the PEI. The area under the densification curve from the 7th gyration to the point where the percent of maximum density reaches 92% minus the area below the horizontal line created by the percent maximum density at the 7th gyration, is the REI. Last, the area under the densification curve from 92% of maximum density to 98% of maximum density minus the area below the horizontal line created by the 92% maximum density line, is the TEI. Figure 8-1 shows these areas.

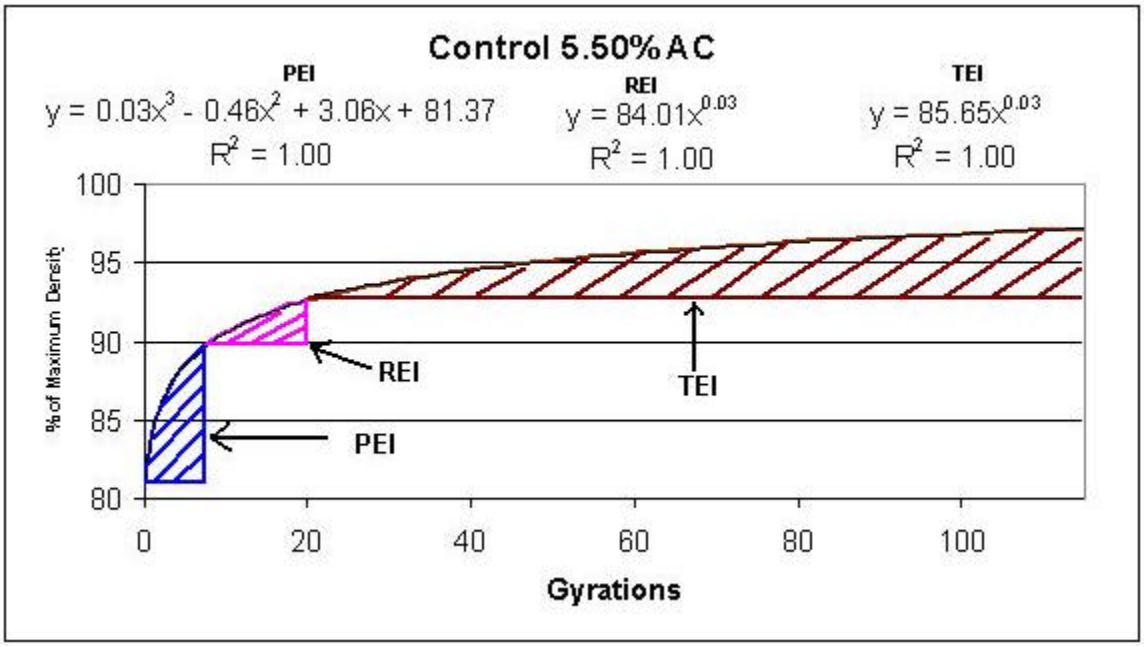

Figure **8-1**: Areas from left to right are PEI, REI, TEI

The following is a procedure for how to calculate the PEI, REI, and TEI.

PEI

1) Using Excel, plot the gyrations versus the % of maximum density.

2) Fit a curve to the points including and between the 0th and 7th gyrations for the PEI.

3) Increase the degree of the fit curve until the R^2 value is above 0.99.

4) Integrate the curve from the 0th to 7th gyration and subtract away the area created by the rectangle whose width is that from the 0th gyration to the 7th gyration and whose height is that from 0% of maximum density to the percent of maximum density at the 0th gyration.

REI

1) Using Excel, plot the gyrations versus the % of maximum density.

2) Fit a curve to the points including and between the 7th gyration and the lowest gyration that gives at least 92% of the maximum density.

3) Increase the degree of the fit curve until the R^2 value is above 0.99.

4) Using the fit equation, find the gyration to the nearest hundredth of a gyration, that gives 92% of maximum density.

5) Integrate the curve from the 7th gyration to the gyration that was calculated to the nearest hundredth.

6) Subtract away the area created by the rectangle whose width is that from the 7th gyration to the gyration at 92% of maximum density and whose height is that from 0% of maximum density to 92% of maximum density.

TEI

1) Using Excel, plot the gyrations versus the % of maximum density.

2) Fit a curve to the points including and between the lowest gyration that gives at least 92% of the maximum density, and the 115th gyration.

3) Increase the degree of the fit curve until the R^2 value is above 0.99.

4) Using the fit equation, find the gyration, to the nearest hundredth of a gyration, that gives 98% of maximum density.

5) Integrate the curve from the calculated gyration that will give 92% of maximum density, to the calculated gyration that will give 98% of maximum density.

6) Subtract away the area created by the rectangle whose width is that from the calculated gyration that will give 92% of maximum density to the calculated gyration that

will give 98% of maximum density, and whose height is that from 0% of maximum density to 98% of maximum density.

8.1.3.3 Strength Measured by the Indirect Tension Test

The ASTM D4867 standard procedure was used to prepare samples and test for indirect tension strength and modulus before and after conditioning in water. The test is also used to measure the moisture sensitivity of each of the mixes. In the standard procedure, only vertical deflection is measured. In this study, the horizontal deflection on the face of the sample was also measured through use of a laser and reflective tape, a technique commonly used with the direct tension test of asphalt binders. The details of the procedure used are as follows:

1) Compact a 5,000 g sample to 7% air voids, plus or minus 1%.

2) After it has cooled, the bulk density of the sample should be determined.

3) The sample should then be placed in the volumeter used for rice tests and covered completely with water.

4) Using the Corelock device, the sample should be saturated so that between 55% and 80% of the air voids are filled with water. Since the Corelock is automated, it gives a more repeatable level of saturation.

5) By knowing the density of the water and the percent air voids, the theoretical mass at 55% and 80% saturation can be calculated. After the sample has been saturated,

it should be removed and dried by rolling it on a damp towel, so that it is saturated surface dried.

6) If the sample is below the 55% saturation point, the sample should be subjected to a more intense vacuum, which can be adjusted on the Corelock device. If the sample is between the two saturation points, it is ready to be submerged in the hot water bath for 24 hours. If the sample is above the 80% saturation point, it should be disposed of.

8.1.3.4 Secant Modulus Using Indirect Tension

Data to determine the secant modulus were gathered during the indirect tension test using horizontal displacement measurements. To measure horizontal deflection, reflective tape was placed on the face of the sample, approximately 5 cm away from each other. Figure 8-2 shows the paper guide/mask used to position the pieces of reflective tape. The diameter of the guide is the same as the diameter of the sample, 150 mm. The two vertical slits are used to position the pieces of reflective tape, and the horizontal slit is used to make a white paint mark on the sample to better align the laser. The horizontal slit is meant to go through the center of the face of the sample, and each vertical slit is 25 mm from the center.

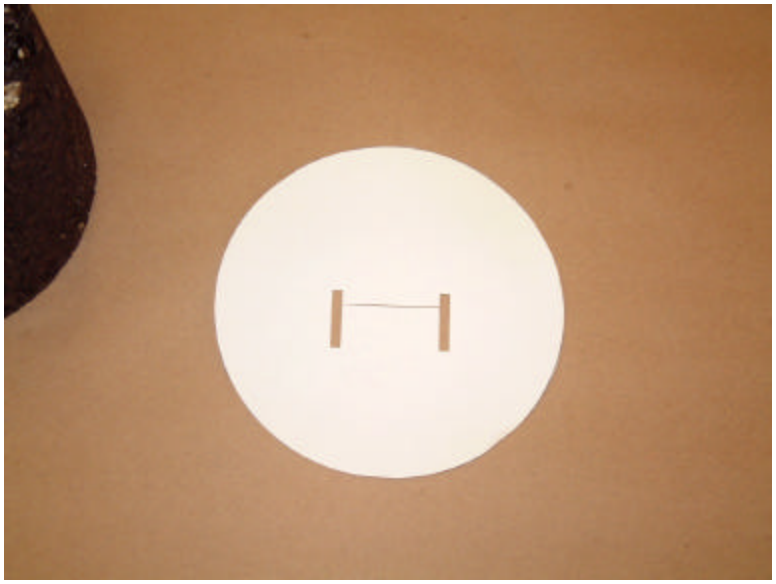

Figure **8-2**: Guide for placing the reflective tape

Figure 8-3 shows what a prepared sample looks like. The two vertical strips are the reflective tape, and the horizontal strip is white paint. The sample should be prepared with reflective tape and white paint after it has already been placed in the hot water bath for 24 hours and cooled off in room temperature water for one hour. If they are prepared before, the reflective tape will come off in the water.

Figure **8-3**: Prepared sample ready for crushing

Figures 8-4 through 8-6 show the positioning of the laser with respect to the sample. For the laser used, the face of the sample was placed 254 mm from the face of the laser. The laser was also balanced using the tripod setup, so that it was level with the ground. The sample was then positioned so that the beam from the laser was shining on and parallel to the white painted strip on the sample, as shown in Figure 8-6.

Figure **8-4**: Overall setup of indirect tension test

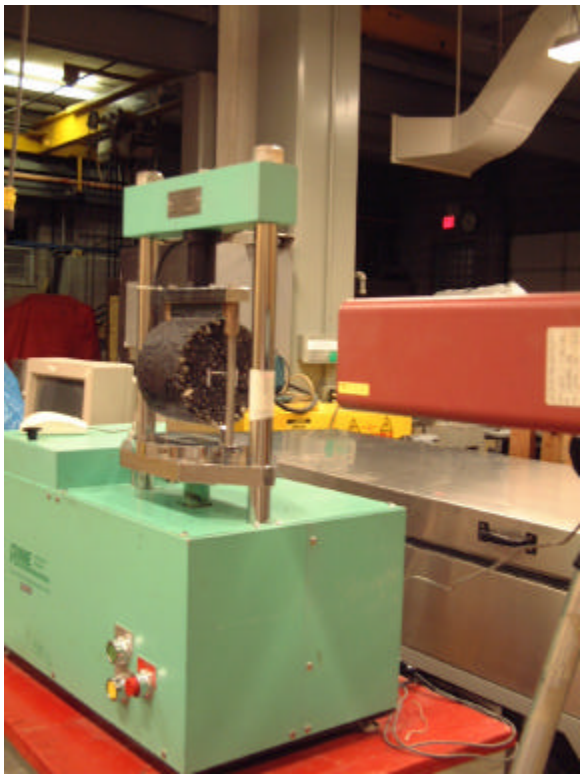

Figure **8-5**: Positioning of laser with respect to sample

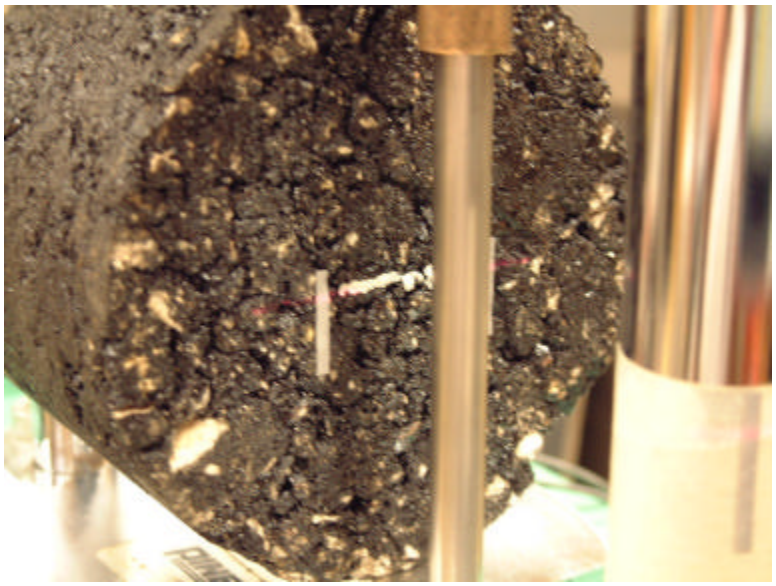

Figure **8-6**:Close up of sample

While the sample is being crushed, the laser extensiometer measures the distance between the two pieces of reflective tape and sends the data to the computer. A USB-based data acquisition system is also recording the voltage from the load cell and sending the data to the computer. A LabVIEW program was written to record the data and store them as a text file. The data acquisition setup can be seen in Figure 8-7. The horizontal stress is calculated using the equation found in ASTM Designation D4867 and is presented in Equation 8.14.

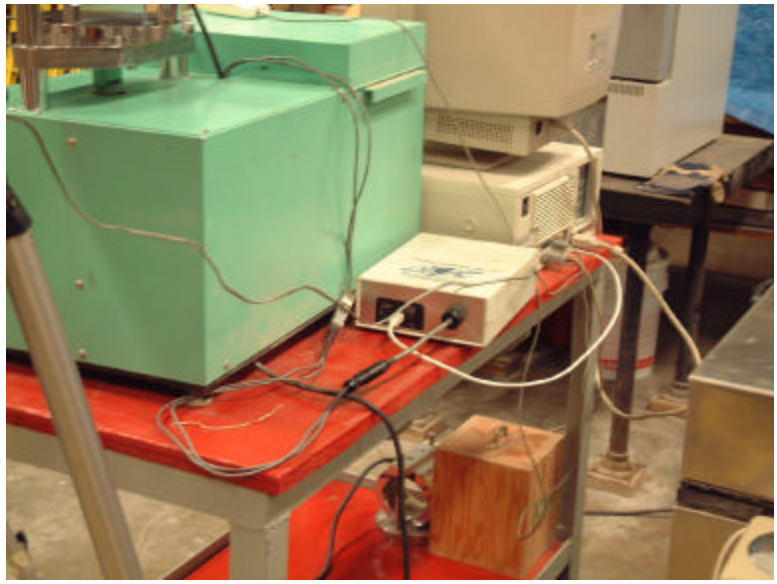

Figure **8-7**: Data acquisition setup for gathering load cell and laser data

$$s = \frac{2000P}{ptD}$$ Equation **8.14**

σ = Horizontal stress (kPa)

P = Force applied (N)

t = Sample height (mm)

D = Sample diameter (mm)

The strain is calculated in Equation 8.15.

$$e = \frac{L_C - L_O}{D}$$ Equation **8.15**

ε = Strain

L_C = Current distance between pieces of reflective tape (mm)

L_O = Original distance between pieces of reflective tape (mm)

D = Diameter of sample (mm)

The secant modulus is the ratio of the maximum stress to the strain when the maximum stress occurs, as presented in Equation 8.16.

$$E_{Secant} = \frac{s_{Max}}{e_{@Max}} \qquad \text{Equation } \mathbf{8.16}$$

E_{Secant} = Secant modulus

σ_{Max} = Maximum tensile stress = Tensile strength

$\varepsilon_{@Max}$ = Strain at which the maximum tensile stress occurs

8.2 Results and Discussion

Section 8.1 describes the methodology and procedures used to determine selected physical properties of the foundry sands and aggregates, as well as the volumetric properties and performance indicators for Hot Mix Asphalt (HMA) produced in the laboratory. In this section, the results from these tests are shown along with the possible conclusions available from these results. These include the apparent and bulk densities of the sands and aggregates, as well as the difference between using the direct and indirect method for determining the bulk density on the angularity of the foundry sand; the volumetric properties of the HMA mixes; and an attempt to relate the physical properties of the foundry sands to the volumetric properties of the HMA, as well as to relate the physical and volumetric properties to the performance indicators.

8.2.1 Densities and Angularity of Sands

Two different methods, a direct and indirect method, were used to determine the apparent and bulk density of the foundry sands used in this study. When using the direct method, it was noticed that a film was developing on the foundry sand and was not allowing the water to penetrate its voids. To overcome this an indirect method was developed, but due to time constraints the method could not be tested.

Results are presented in Table 8-3. The data for the ¼" screenings, manufactured sand, and natural sand came directly from the contractor who supplied the aggregates and asphalt mix design. The control (P0.60) is all the control material passing the 0.6 mm sieve. A better comparison could be made between the control aggregates and the foundry sand if the P0.60 material were separated from the total control mix and tested in a similar manner as the foundry sands. From Table 8-3, the angularities of the foundry sands appear to be higher when compared to the natural sand. Sand FS13 had the lowest angularity of 43.1, which is higher than the natural sand. Sand FS06 had the highest angularity of 57.6, which is a very high angularity. This can be explained because the sand has a very low fines content, which means there are no fines to fill the packing voids (Figure 2-9). Since there are no fines to fill the packing voids, the packing density decreases, thus increasing the angularity. The remaining sands appear to have reasonable angularities comparable to the manufactured sand. Generally, manufactured sands are desirable because they promote aggregate interlock and help resist against rutting.

Because of their high angularities, foundry sands would be a good replacement of natural sands in HMA.

Table **8-3**: Apparent and bulk densities, and angularity of sands

Sand No.	Apparent Density (g/ccm)	Bulk Density (g/ccm)	Angularity (%)
¼" Screenings	N.R.	2.699	50.5
Man. Sand	N.R.	2.660	48.9
Natural Sand	N.R.	2.684	41.5
Control (P0.60)	2.766	2.757	45.5
FS01	2.760	2.415	45.4
FS02	2.779	2.698	47.5
FS03	2.764	2.448	50.5
FS04	2.759	2.502	47.3
FS05	2.776	2.488	48.1
FS06	2.778	2.615	57.6
FS07	2.763	2.529	47.5
FS08	2.763	2.470	48.2
FS09	2.763	2.569	46.3
FS10	2.779	2.628	44.8
FS11	2.776	2.593	46.2
FS12	2.769	2.578	43.7
FS13	2.776	2.591	43.1
FS14	2.784	2.64	47.9
FS15	2.752	2.545	54.4
FS16	2.775	2.644	47.7
FS17	2.771	2.669	46.7

8.2.2 Volumetric Properties

In this section the results from the volumetric analysis for each of the mixes, including the control and the 17 mixes that had 10% foundry sand incorporated into them, are presented. The volumetric data include the optimum asphalt content, maximum and bulk densities of mixtures at optimum asphalt content, effective density of mixtures,

and average asphalt film thickness. In several cases, the 95% confidence intervals are given.

8.2.2.1 Volumetric Properties of Aggregate Blends

Each aggregate blend is considered to have three different densities, an apparent density, an effective density, and a bulk density. The apparent density is the mass of the aggregate divided by the volume of just the aggregate material and the impermeable voids. The bulk density is the mass of the aggregate divided by the volume of the aggregate, impermeable voids, and microvoids of the aggregate. The effective density is the mass of the aggregate divided by the volume of the aggregate, impermeable voids, and microvoids not filled with asphalt. So in the case where all the voids are filled with asphalt, the effective density would be the same as the apparent density. Table 8-4 shows a summary of these properties. Also shown in the table is the volume of voids per volume of aggregate. This gives an indication of the level of voids in the aggregate. The last column in the table shows the maximum amount of water that can be absorbed into the aggregate per mass of aggregate. This is more commonly known as the percent absorption value.

Table **8-4**: Volumetric properties of aggregates

Sand No.	Apparent Density (g/ccm)	Effective Density @ Opt. A.C. (g/ccm)	Bulk Density (g/ccm)	Vol. Void/Vol. Agg. (%)	M. Water/M Agg. (%)
Control	2.781	2.746	2.652	4.9%	1.7%
FS01	2.752	2.717	2.627	4.7%	1.7%
FS02	2.771	2.748	2.652	4.5%	1.6%
FS03	2.756	2.716	2.628	4.9%	1.8%
FS04	2.751	2.726	2.648	3.9%	1.4%
FS05	2.767	2.724	2.645	4.6%	1.7%
FS06	2.770	2.741	2.656	4.3%	1.5%
FS07	2.754	2.725	2.612	5.5%	2.0%
FS08	2.755	2.710	2.611	5.5%	2.0%
FS09	2.755	2.725	2.653	3.8%	1.4%
FS10	2.770	2.739	2.678	3.4%	1.2%
FS11	2.768	2.723	2.649	4.5%	1.6%
FS12	2.760	2.733	2.662	3.7%	1.3%
FS13	2.768	2.741	2.677	3.4%	1.2%
FS14	2.776	2.741	2.616	6.1%	2.2%
FS15	2.743	2.718	2.621	4.7%	1.7%
FS16	2.766	2.733	2.668	3.7%	1.3%
FS17	2.769	2.743	2.647	4.6%	1.7%

As seen in Table 8-4, the apparent densities of aggregate blends with foundry sand seem to be lower than the control, but the differences are marginal. The same can be said for the effective and bulk densities. Sands FS07, FS08, and FS14 seem to have a higher amount of permeable voids, with sand FS14 having 6.1% permeable voids, sand FS08, 5.5% and sand FS07, 5.5%. This is also reflected in the last column. Generally it is thought that the greater the number of pores, or the greater the amount of water the aggregate can absorb, the more asphalt can be absorbed. From Figure 8-8, one can see there is a good correlation between the voids and the asphalt absorbed, with it being stated that as the percent voids increases, so does the percent asphalt absorbed. It might also be assumed that the optimum asphalt content would increase if the voids were to

increase, but from Figure 8-9, it can be seen there is no correlation between them. The optimum asphalt contents are listed in Table 8-5.

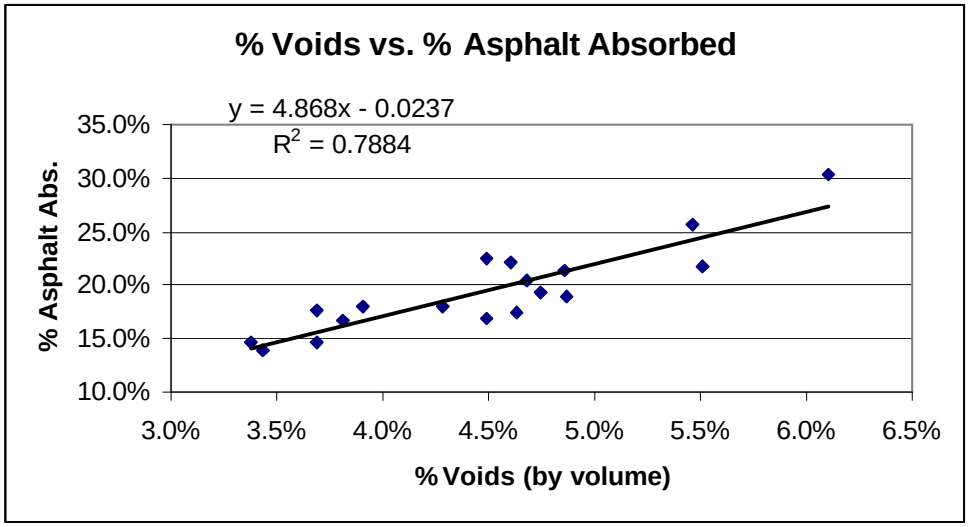

Figure **8-8**: Relation between voids and asphalt absorbed

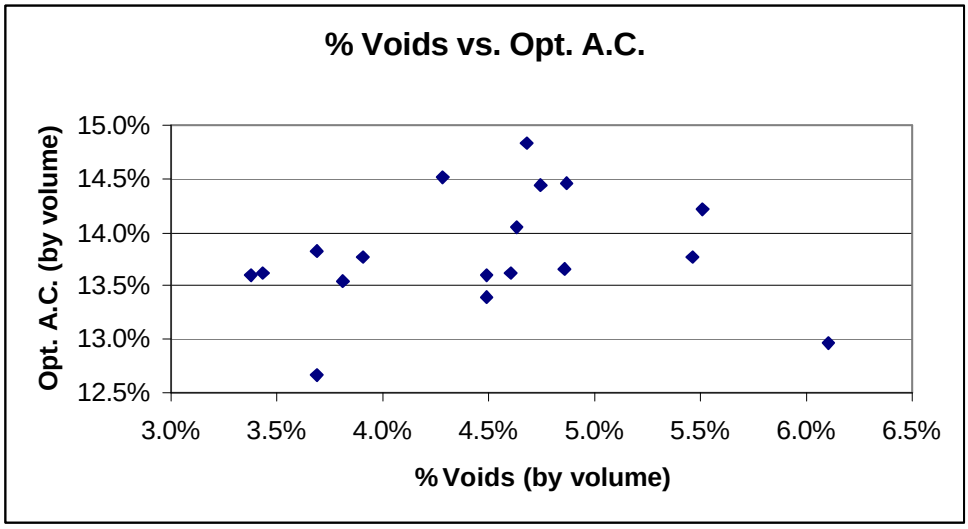

Figure **8-9**: Relation between voids and optimum asphalt content

Table **8-5**: Volumetric properties at optimum asphalt content

Column	1	2	3	4	5	6	7	8
Sand No.	**Opt. A.C. (by mass)**	**Opt. A.C. (by volume)**	**M. Water/M. Agg. @ Opt. AC**	**Vol. Voids/Vol. Agg. @ Opt. A.C.**	**Vol Asphalt/Vol. Voids (%)**	**M. Asphalt Abs./M. Agg.**	**Vol Asphalt Abs/Vol Asphalt Total (%)**	**Film Thickness (µm)**
Control	5.5%	13.7%	0.5%	1.3%	73.9%	4.2%	21.4%	13.4
FS01	5.9%	14.4%	0.5%	1.3%	73.0%	4.5%	19.4%	14.8
FS02	5.4%	13.4%	0.3%	0.8%	81.8%	4.6%	22.5%	13.0
FS03	5.9%	14.5%	0.5%	1.5%	69.7%	4.3%	18.9%	14.9
FS04	5.6%	13.8%	0.3%	0.9%	76.9%	4.5%	17.9%	14.3
FS05	5.7%	14.1%	0.6%	1.6%	65.5%	3.9%	17.5%	14.6
FS06	5.9%	14.5%	0.4%	1.1%	75.2%	4.6%	18.0%	15.1
FS07	5.6%	13.8%	0.4%	1.1%	79.9%	4.6%	25.6%	12.9
FS08	5.8%	14.2%	0.6%	1.6%	70.4%	4.2%	21.8%	14.1
FS09	5.5%	13.6%	0.4%	1.1%	71.7%	4.1%	16.6%	14.2
FS10	5.5%	13.6%	0.4%	1.1%	66.6%	3.8%	13.9%	14.7
FS11	5.5%	13.6%	0.6%	1.7%	63.2%	3.6%	17.0%	14.2
FS12	5.1%	12.7%	0.4%	1.0%	72.6%	3.8%	17.6%	13.0
FS13	5.5%	13.6%	0.3%	1.0%	71.3%	4.1%	14.7%	14.6
FS14	5.2%	13.0%	0.5%	1.3%	79.2%	4.2%	30.2%	11.2
FS15	6.1%	14.8%	0.3%	0.9%	80.1%	5.1%	20.4%	15.2
FS16	5.6%	13.8%	0.4%	1.2%	66.5%	3.9%	14.6%	14.9
FS17	5.5%	13.6%	0.3%	0.9%	79.7%	4.5%	22.1%	13.3

8.2.2.2 Volumetric Properties of HMA Mixtures

The data appearing in Table 8-5 show that including foundry sand in mixtures can either raise or lower the optimum asphalt content. The optimum asphalt content for the control is 5.5%, with the lowest asphalt content being 5.1%, and the highest content being 6.1%. Typically, bentonite will cause the optimum asphalt content to increase [Braham 2002]. This is because bentonite has a very large surface area, and thus would require more asphalt to coat its surface. Sodium silicate appears to have little or no effect on the optimum asphalt content, and phenols generally lower it. This is shown in Figure 8-10.

But in reality, if a contractor were to use foundry sand for actual production, there would be a sand hump at around the 0.30 mm (#50) sieve. This sand hump would most likely cause an increase in asphalt content no matter what binder system was used in the foundry sand. A phenolic bound sand would cause less of an increase in the optimum asphalt content, where as a bentonite bound sand would cause a greater increase in the optimum asphalt content.

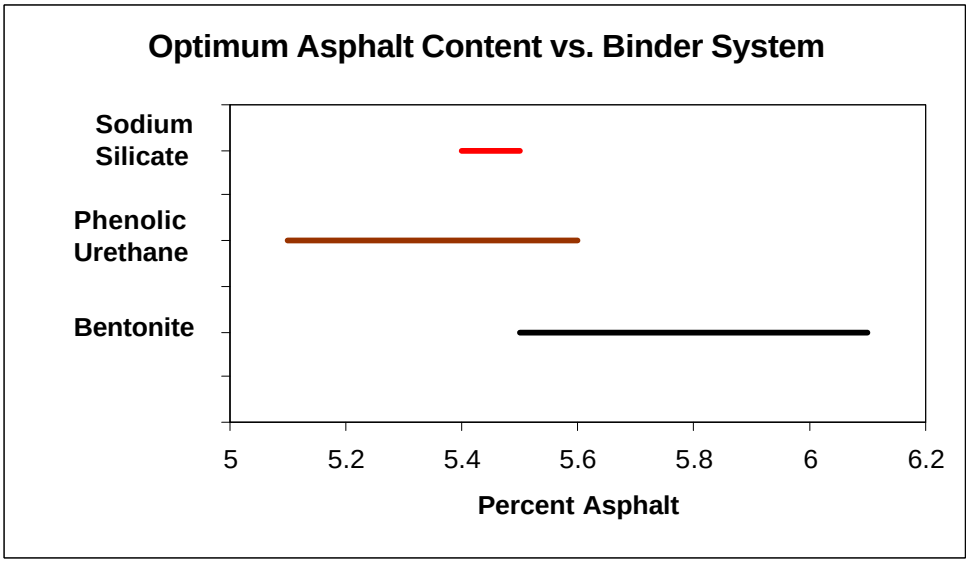

Figure **8-10**: Relation between optimum asphalt content and binder system

Columns 3 and 4 of Table 8-5 show the level of asphalt penetration into the voids of the aggregate. Column 3 shows the mass of water that could be absorbed into the voids as a percentage of the mass of the aggregate. Column 4 shows the volume of the voids that have not been penetrated to the volume of the aggregate. Surprisingly, asphalt is consistently not able to penetrate the remaining 1% of the voids (column 4). For

example, looking at the percentage of total voids of sands FS14 and FS16 in Table 8-4 (column 4), one would find them to be 6.1% and 3.7%. Then looking at the remaining voids after asphalt has been added at its optimum asphalt content, the remaining voids in sands FS14 and FS16 are 1.3 and 1.2% (Table 8-5, column 4). This trend is consistent for all the sands. On the other hand, the level of penetration with respect to the total amount of voids is not consistent. Column 5 shows the volume of asphalt absorbed compared to the total volume of the voids, or the percentage of voids that have been filled with asphalt. So, for the control, 73.9% of the total voids in the aggregate have been filled with asphalt. The remaining 26.1% of the voids are still filled with air.

Columns 6 and 7 are more for the asphalt contractor, and help to predict the amount of asphalt lost due to asphalt absorption. Column 6 shows the mass of asphalt absorbed compared to the mass of the aggregate. This number would be useful for the contractor because it allows quick calculation of the amount of asphalt lost based on the tonnage of aggregates. Aggregate bins used at HMA facilities are equipped with load sensors that continuously report the mass of aggregate being added to the mix. This allows the operator to control the gradation of the final HMA product. Column 7 shows a very similar concept, but stated in terms of the total asphalt added. So, based on columns 6 and 7, for the control mix, for every ton of aggregate, 42 kg of asphalt would be absorbed, or for every ton of asphalt added, 210 kg will be lost due to absorption. Based on column 7, sands FS14 and FS16 should probably be avoided because they take up a lot of asphalt in the voids rather than coating the aggregates.

Column 8 of Table 8-5 shows the average asphalt film thickness estimated for each mixture. It is the ratio of the volume of asphalt not absorbed to the surface area of the mixture. The surface area calculations are based on average surface areas for aggregates based on their size. It is believed that a mix should not have too low of a film thickness, or it will not maintain its durability. At the same time, the film thickness should not be too high, or the film will act more like a lubricant and cause the pavement to rut. Figure 8-11 shows that as the optimum asphalt content increases, the film thickness also increases. This only makes sense, because as more asphalt is added, the film thickness should increase.

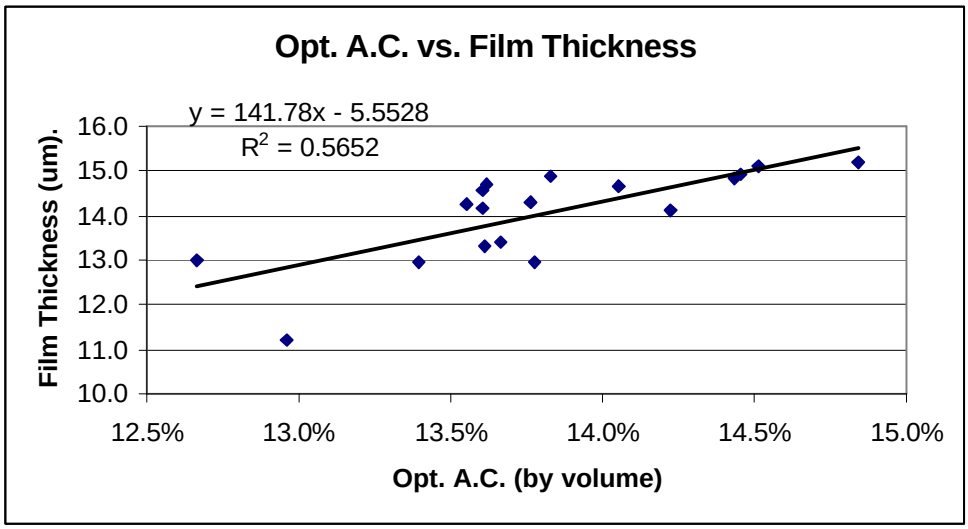

Figure **8-11**: Relation between the optimum asphalt content and film thickness

In order to show the accuracy and repeatability of the data due to elaborate sieving procedures, good quality control and making use of the Corelok™ device, the maximum and bulk densities are listed in the first and second columns of data of Table 8-6. For the control, and sands FS01, FS03, FS08, FS09, and FS14, the 95% confidence

intervals were calculated using Equation 8.16 with three replications. One can see that the average 95% confidence interval for the maximum density is ±0.007, and ±0.008 for the bulk density. Because of these tight confidence intervals, replicates often were not run when determining the optimum asphalt content. According to Superpave procedure, when determining the optimum asphalt content, the optimum asphalt content is first guessed based on experience. Duplicates are created at this asphalt content as well as duplicates at 0.5% above and 0.5% and 1.0% below the first guess. Based on these tests, a plot of asphalt content versus air voids in the mix at N_{des} is created. Based on this plot, the true optimum asphalt content is chosen, and duplicates are run to verify. The whole process takes 10 samples. Since more time was spent on sieving and batching together very uniform gradations, replicates did not need to be run. Initially the optimum asphalt content was estimated to be 5.5% for each of the mixes. Based on the volumetric data from the first estimate, a second optimum asphalt content was estimated. In some cases only two samples needed to be created in order to find the optimum asphalt content. This greatly reduced on the time needed for mixing and compacting, and the amount of asphalt and aggregates needed.

Table **8-6**: Volumetric properties of HMA mixtures

Sand No.	Maximum Density (g/ccm)	Bulk Density @ N_{max} (g/ccm)	$\%G_{mm}$ @ N_{ini}	$\%G_{mm}$ @ N_{des}	$\%G_{mm}$ @ N_{max}
Control	2.513 ± 0.003	2.430 ± 0.007	89.0 ± 0.2	95.7 ± 0.2	96.7 ± 0.2
FS01	2.475 ± 0.004	2.392 ± 0.009	88.9 ± 0.3	95.6 ± 0.3	96.6 ± 0.3
FS02	2.526	2.441	89.3	95.7	96.6
FS03	2.474 ± 0.002	2.396 ± 0.015	88.9 ± 0.4	95.8 ± 0.5	96.8 ± 0.5
FS04	2.502	2.415	89.0	95.6	96.5
FS05	2.489	2.391	88.9	95.6	96.6
FS06	2.501	2.415	89.0	95.6	96.6
FS07	2.500	2.416	89.2	95.7	96.6
FS08	2.474 ± 0.002	2.389 ± 0.008	88.5 ± 0.4	95.6 ± 0.4	96.6 ± 0.4
FS09	2.497 ± 0.016	2.418 ± 0.007	89.2 ± 0.5	95.9 ± 0.5	96.9 ± 0.5
FS10	2.515	2.432	89.4	95.7	96.6
FS11	2.502	2.423	89.1	95.9	96.8
FS12	2.526	2.4390	89.3	95.7	96.6
FS13	2.517	2.434	89.3	95.8	96.7
FS14	2.521 ± 0.012	2.433 ± 0.002	89.2 ± 0.5	95.6 ± 0.5	96.5 ± 0.4
FS15	2.476	2.397	88.8	95.8	96.8
FS16	2.506	2.416	88.7	95.4	96.4
FS17	2.518	2.434	88.6	95.6	96.7

The last three columns show the percent of maximum density at N_{ini}, N_{des}, and N_{max}. Again the 95% confidence intervals are shown for the percent of maximum densities. The confidence intervals were calculated using a different method than Equation 8.16 and involved the propagation of error. For the percent of maximum density at N_{ini}, N_{des}, and N_{max}, the confidence interval was calculated using Equation 8.17:

$$95\%C.I. = \frac{G \times t \times \sqrt{\left(\frac{S.D._1}{H}\right)^2 + \left(\frac{S.D._2}{M}\right)^2 + 2\left(\frac{S.D._3}{G_{mm}}\right)^2 + 2\left(\frac{S.D._4}{G_{mb}}\right)^2}}{\sqrt{n}} \qquad \text{Equation } \mathbf{8.17}$$

G = The percent of maximum density at N_{ini}, N_{des}, or N_{max}

t = Student's t-distribution = 2.57 when n = 6

$S.D._1$ = Standard deviation of heights at N_{ini}, N_{des}, or N_{max}

H = Average height at N_{ini}, N_{des}, or N_{max}

$S.D._2$ = Standard deviation of the masses of the gyrated samples

M = Average mass of the gyrated samples

$S.D._3$ = Standard deviation of the maximum density at the optimum asphalt content

G_{mm} = Average maximum density at the optimum asphalt content

$S.D._4$ = Standard deviation of the bulk density at N_{ini}, N_{des}, or N_{max}

G_{mb} = Average bulk density at N_{ini}, N_{des}, or N_{max}

n = number of samples = 6, there are three maximum densities and three bulk densities.

So, it can be seen from the confidence intervals that the process is under control and the data are reliable.

According to Superpave specifications, the percent of maximum density at N_{ini} should be under 89%. In column three of Table 8-6, all of the data are at or below 89%, when taking into account that the average 95% confidence interval is 0.4%. Also, according to Superpave specifications, the percent of maximum density at N_{des} should be at 96%. With an average 95% confidence interval of 0.4%, all of the data in column five meet this criteria except for sand FS16. The optimum asphalt could have been raised one or two tenths of a percent. For most asphalt contractors, this information is quite important, since they are allowed to produce HMA with a range 0.5% above or below the

optimum asphalt content. Last, the specification for the percent of maximum density at N_{max} is that it must be below 98%. Clearly the data in the last column show that all the mixes meet this specification. The average 95% confidence interval for the percent of maximum density at N_{max} is 0.4%. Overall, it can be said that mixes with foundry sand can meet volumetric specification requirements without a problem and with relatively small changes in asphalt content.

8.2.3 Performance Indicators

8.2.3.1 Paver, Roller and Traffic Energy Indices

The paver, roller, and traffic energy indices were calculated from the densification curves and are reported in Table 8-7. The 95% confidence intervals are also shown. They were calculated using Equation 8.16. The paver energy index is constant at about 39.0 with an average 95% confidence interval of 0.9. The roller energy index varied between 29.4 (sand FS8) and 15.4 (sand FS13). The average 95% confidence interval is 9.2. Because the confidence interval is so large it is difficult to notice any significant trends in the REI. The TEI varies between 750.3 (sand FS12) and 439.6 (sand FS15). The average 95% confidence interval is 69. Figure 8-12 shows that because of the large confidence interval, it is not clear how foundry sand affects this measure. All of the sands perform in the same range as the control. Figure 8-13 shows a plot of the optimum asphalt content versus the TEI. It is commonly known that as the asphalt content is increased above the optimum asphalt content, it is more prone to rut. So it would be

natural to reason that as the asphalt content increases, the TEI decreases. From Figure 8-13, this does not seem to be the case, since the R^2 value is small. One other reason for the TEI to be small is due to low angularity. It is believed that the more angular the particles are, the more they will interlock and be resistant against rutting. Figure 8-14 shows that this is not the case for these sands.

Table **8-7**: Paver, roller and traffic energy indices

Sand No.	PEI	REI	TEI
Control	39.0 ± 1.4	21.4 ± 8.7	670.9 ± 68.1
FS01	38.8 ± 0.4	23.0 ± 9.0	679.7 ± 76.9
FS02	39.5	16.6	730.2
FS03	38.8 ± 1.0	22.1 ± 9.9	609.7 ± 132.3
FS04	39.1	21.0	717.2
FS05	39.0	22.7	692.6
FS06	39.7	21.8	719.8
FS07	38.6	18.4	698.0
FS08	38.7 ± 0.5	29.4 ± 9.7	650.3 ± 63.5
FS09	39.4 ± 0.9	17.2 ± 5.1	631.4 ± 59.0
FS10	38.9	15.4	707.0
FS11	39.1	19.2	619.2
FS12	39.7	16.9	750.3
FS13	39.3	17.2	684.4
FS14	38.8 ± 0.9	16.3 ± 12.6	748.0 ± 13.9
FS15	39.2	23.4	439.6
FS16	39.2	27.0	735.4
FS17	39.1	27.4	640.8

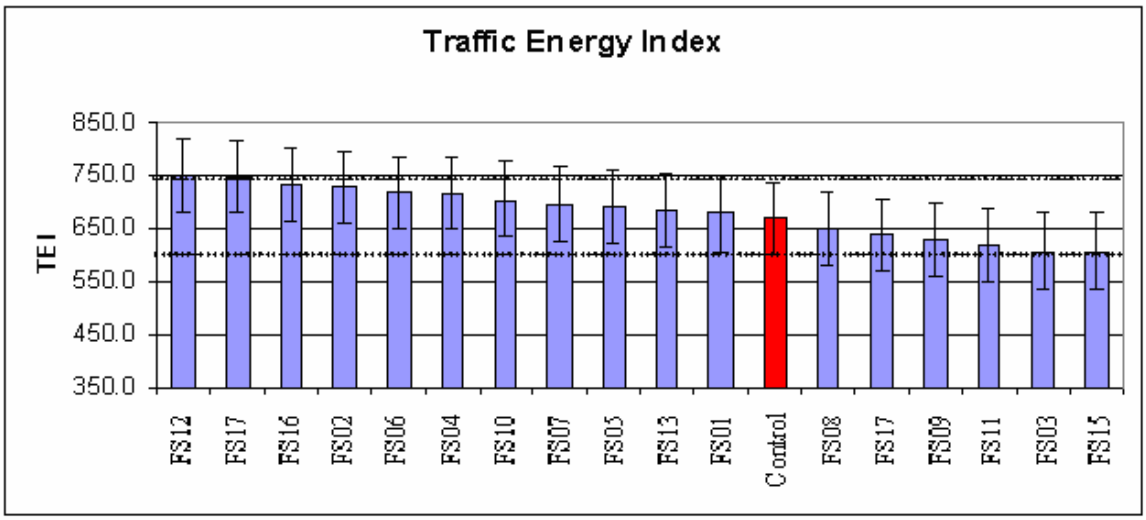

Figure **8-12**: Paver, roller and traffic energy indices

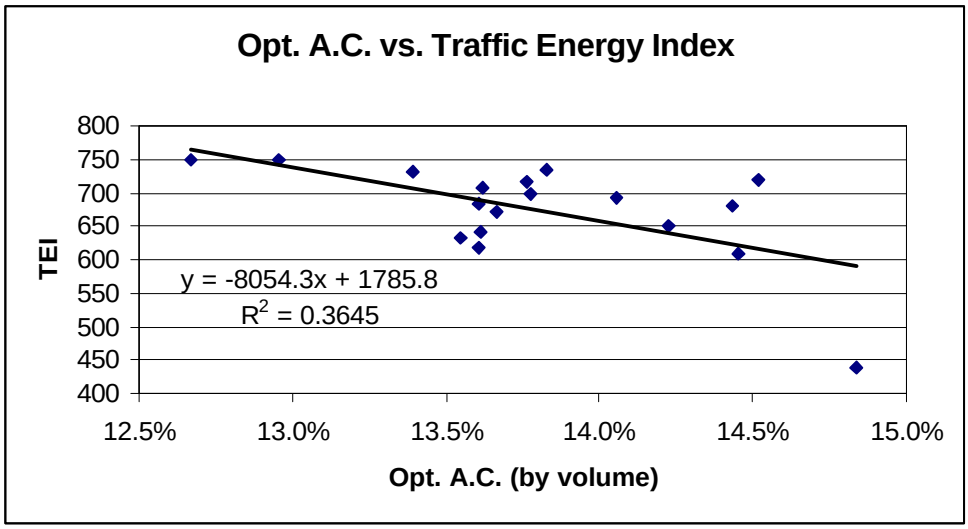

Figure **8-13**: Comparison between the optimum asphalt content and the TEI

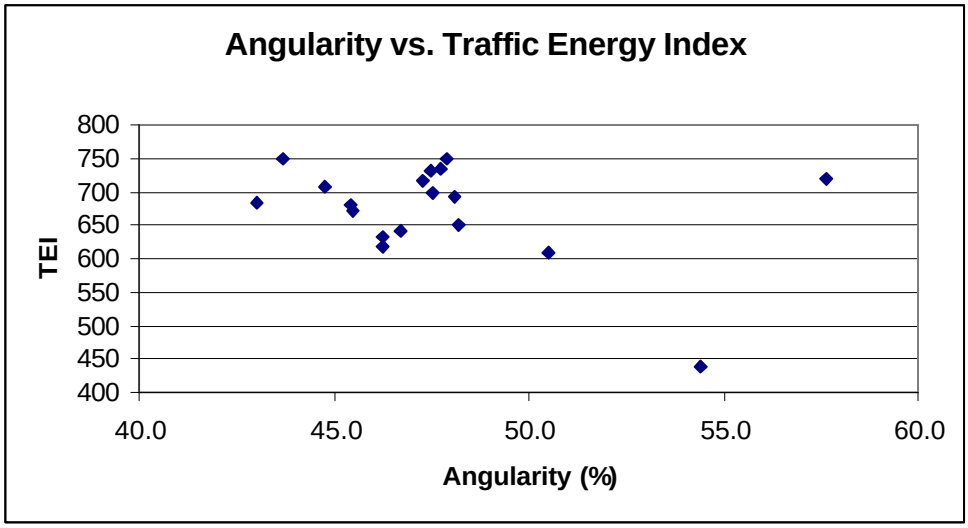

Figure **8-14**: Comparison between angularity and TEI

8.2.3.2 Tensile Strength and Secant Modulus Ratios

Braham [2002] showed that mixtures containing foundry sand tend to be more susceptible to moisture damage. In this study, all of the mixtures, the control mixture plus the 17 other mixtures each containing 10% foundry sand, were tested for moisture susceptibility. This was done using the indirect tension test, according to ASTM standard procedure D4867. For this test, six samples are compacted using the Superpave Gyratory Compactor to 7% air voids. Three of these six samples are saturated with water, so that about 65% of the air voids are filled with water. They are then placed in a 60 EC water bath for 24 hours. After the 24 hours, the samples are cooled to 25 EC and tested in indirect tension. The tensile strengths measured are shown in Table 8-8 and are expressed in kPa. The horizontal deflection across the face of the sample was measured using a laser measuring device. A typical plot of strain versus stress is shown in

Figure 8-15. This plot is for the second indirect tension test sample mixture produced with sand FS13. It was not moisture conditioned. From the strain and stress data, the secant modulus is calculated as the slope of the line connecting the origin to the maximum stress point. The tensile strengths and secant moduli for samples that were moisture conditioned are shown in columns 1 and 4 of Table 8-8. The strengths are in kPa and the moduli are in MPa. Also, for simplicity, the standard deviations are shown, and not the 95% confidence intervals. Columns 2 and 5 show the tensile strength and secant moduli of the samples that were not moisture conditioned. Column 3 shows the ratios of the tensile strengths, hence the term "tensile strength ratio," while column 6 shows the ratios of the secant moduli. The tensile strength ratios are shown with a 95% confidence interval. Equations 8.18 and 8.19 were used to calculate this confidence interval.

Table **8-8**: Tensile strengths and secant moduli

Sand No.	Tensile Strength w/ M.C. (kPa)	Tensile Strength w/o M.C. (kPa)	Tensile Strength Ratio (%)	Secant Modulus w/ M.C. (MPa)	Secant Modulus w/o M.C. (MPa)	Secant Modulus Ratio (%)
Control	596.7 ± 74.4	884.7 ± 8.4	67.4 ± 9.8	96.7 ± 12.2	207.5 ± 51.5	46.6 ± 25.4
FS01	322.1 ± 21.4	710.9 ± 16.5	45.3 ± 3.7	27.4 ± 4.7	150.8 ± 10.8	18.2 ± 3.5
FS02	484.0 ± 13.9	738.7 ± 29.3	65.5 ± 3.8	70.1 ± 14.8	221.7 ± 65.9	31.6 ± 12.1
FS03	349.3 ± 20.3	694.1 ± 14.1	50.3 ± 3.6	31.8 ± 10.4	183.2 ± 75.7	17.4 ± 9.6
FS04	489.4 ± 9.8	789.1 ± 62.7	62.0 ± 5.9	88.0 ± 18.5	216.5 ± 35.5	40.6 ± 13.4
FS05	348.7 ± 11.6	774.4 ± 21.8	45.0 ± 2.4	29.8 ± 4.6	164.6 ± 19.9	18.1 ± 3.7
FS06	NA	789.3 ± 41.9	NA	NA	149.4 ± 23.1	NA
FS07	409.8 ± 27.2	750.5 ± 38.5	54.6 ± 5.3	44.9 ± 5.9	152.7 ± 9.2	29.4 ± 4.5
FS08	378.4 ± 10.5	696.5 ± 28.5	54.3 ± 3.1	31.8 ± 3.7	129.5 ± 9.8	24.5 ± 3.6
FS09	478.3 ± 9.7	684.1 ± 19.6	69.9 ± 2.8	68.8 ± 7.7	189.0 ± 33.4	36.4 ± 8.0
FS10	416.3 ± 26.2	815.6 ± 17.0	51.0 ± 3.9	100.8 ± 28.9	251.0 ± 10.9	40.2 ± 12.2
FS11	463.4 ± 30.3	758.0 ± 18.4	61.1 ± 5.2	79.3 ± 7.2	173.4 ± 27.2	45.7 ± 8.7
FS12	535 ± 48	721.7 ± 20.5	74.1 ± 8.1	87.9 ± 9.3	186.3 ± 33.9	47.2 ± 7.9
FS13	556.6 ± 22.6	782.7 ± 10.8	71.1 ± 3.5	81.5 ± 17.0	223.3 ± 45.4	36.5 ± 11.1
FS14	704.8 ± 11.5	798.7 ± 9.9	88.2 ± 2.1	130.9 ± 26.1	186.6 ± 25.8	70.1 ± 17.9
FS15	440.5 ± 49.4	703.5 ± 44.1	62.6 ± 9.1	66.1 ± 10.6	118.8 ± 17.5	55.6 ± 12.7
FS16	358.1 ± 0.4	696.7± 20.1	51.4 ± 1.8	48.5 ± 5.0	170.5 ± 24.5	28.4 ± 6.2
FS17	89.4 ± 6.3	780.4 ± 18.0	11.5 ± 1.0	9.8 ± 2.2	137.0 ± 5.8	7.2 ± 1.7

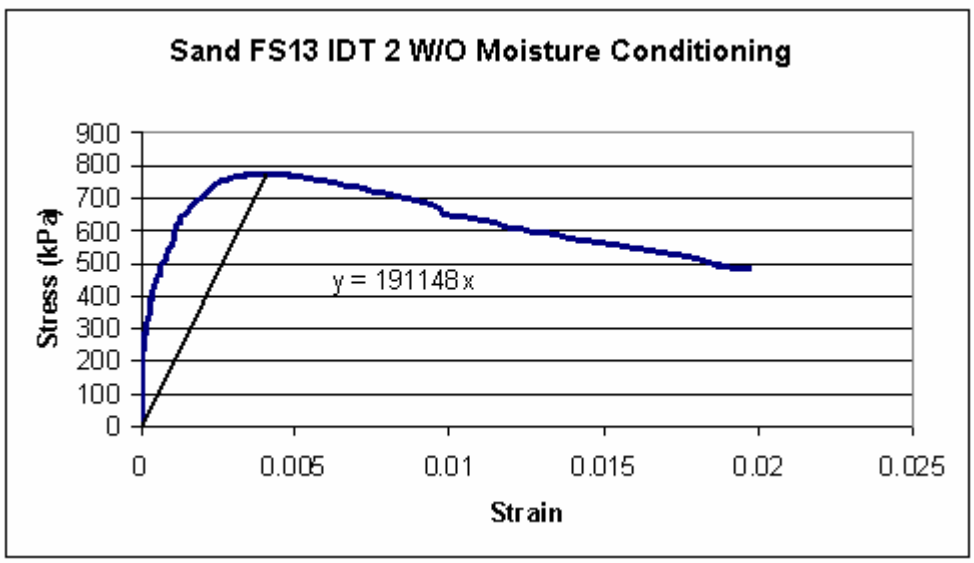

Figure **8-15**: Strain versus stress plot for the second IDT for sand FS13

$$Var = \left[\frac{X}{Y}\right]^2 \times \left[\frac{S_X^2}{n_X X^2} + \frac{S_Y^2}{n_Y Y^2}\right] \qquad \text{Equation } \mathbf{8.18}$$

$$95\% C.I. = 2\sqrt{Var} \qquad \text{Equation } \mathbf{8.19}$$

Var = Variance of TSR

X = Average tensile strengths for moisture conditioned

Y = Average tensile strengths for not moisture conditioned

S_X = Standard deviation of moisture conditioned tensile strengths

S_Y = Standard deviation of not moisture conditioned tensile strengths

n_X = Number of moisture conditioned samples

n_Y = Number of not moisture conditioned samples

95% C.I. = 95% confidence interval

Equations 8.18 and 8.19 were taken from a master's thesis written by Seemab Ahmad [Ahmad 1998]. His thesis topic was to evaluate procedures for assessing moisture damage of asphalt pavements in Wisconsin. The 95% confidence interval for the secant modulus ratio was calculated in more of a traditional way, similar to Equation 8.17, and is presented in Equation 8.20.

$$95\%C.I. = \frac{X}{Y} \times t \times \frac{\sqrt{\left(\frac{S_X}{X}\right)^2 + \left(\frac{S_Y}{Y}\right)^2}}{\sqrt{n}}$$ Equation **8.20**

X = Average secant modulus of moisture conditioned samples

Y = Average secant modulus of not moisture conditioned samples

t = Student's t-distribution = 2.57

S_X = Standard deviation of moisture conditioned samples

S_Y = Standard deviation of not moisture conditioned samples

n = Total number of samples = 6

A comparison between the tensile strength and secant modulus with moisture conditioning is shown graphically in Figures 8-16 and 8-17. The average 95% confidence interval for the average conditioned tensile strengths is 57.3 kPa and 27.6 MPa for the average conditioned secant modulus, and are shown in Figures 8-16 and 8-17. Figure 8-16 shows that only one sand increased the conditioned tensile strength, while two sands showed no change and the remaining sands decreased the tensile strength. This shows that the majority of foundry sands decrease the conditioned tensile strengths, which means they will most likely cause asphalt mixtures to be more susceptible to moisture damage. But at the same time, foundry sands should be tested on a case by case basis, since not all foundry sands encourage moisture damage. Although the error bars are much greater for the conditioned secant modulus (Figure 8-17), the same trend can be seen. For the conditioned secant modulus, 11 sands show no change in modulus, with the remaining 5 sands falling below the control.

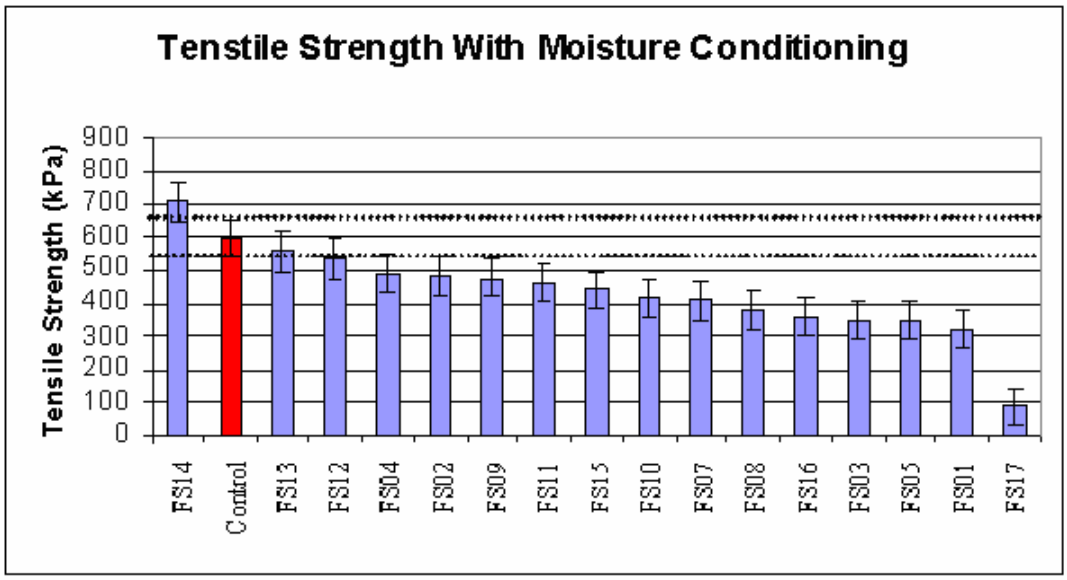

Figure **8-16**: Tensile strengths with moisture conditioning

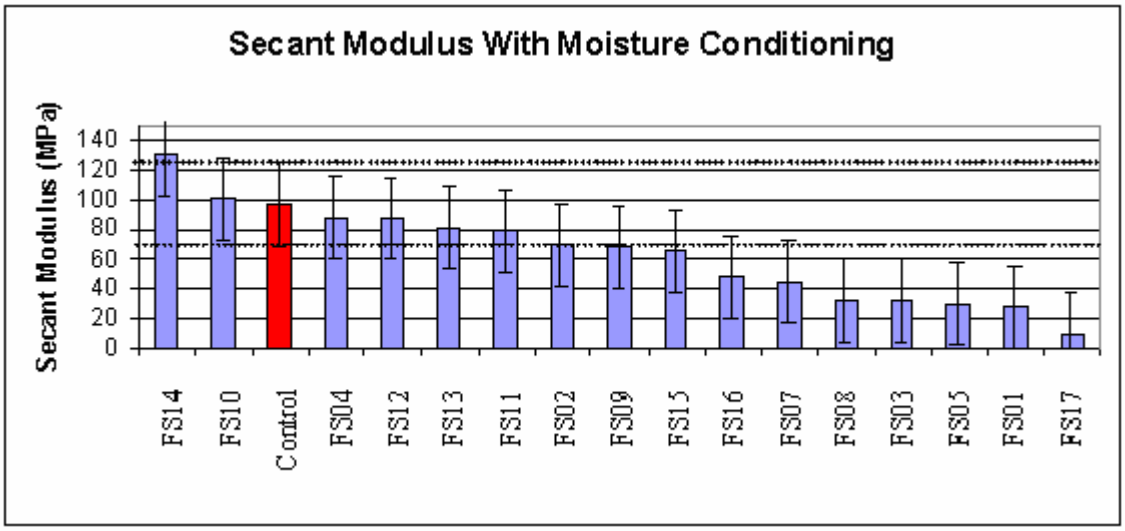

Figure **8-17**: Secant modulus with moisture conditioning

A similar trend is found in Figure 8-18 and Figure 8-19. Here the tensile strengths and secant moduli for unconditioned samples are plotted with respect to each other. The average 95% confidence interval was calculated for the unconditioned tensile

strengths (60.2 kPa) and for the unconditioned secant modulus (72.5 MPa). For the unconditioned tensile strengths, the control has the highest average unconditioned tensile strength, with six sands falling within its 95% confidence interval. The remaining 11 sands fall below. This suggests that foundry sands, on average, decrease the unconditioned tensile strength, and thus the durability of asphalt mixtures. For the secant modulus, it is difficult to tell the effect of foundry sands because of the large standard deviation. From inspection of the average unconditioned secant moduli, foundry sand appears to decrease the modulus and thus the modulus of asphalt mixtures.

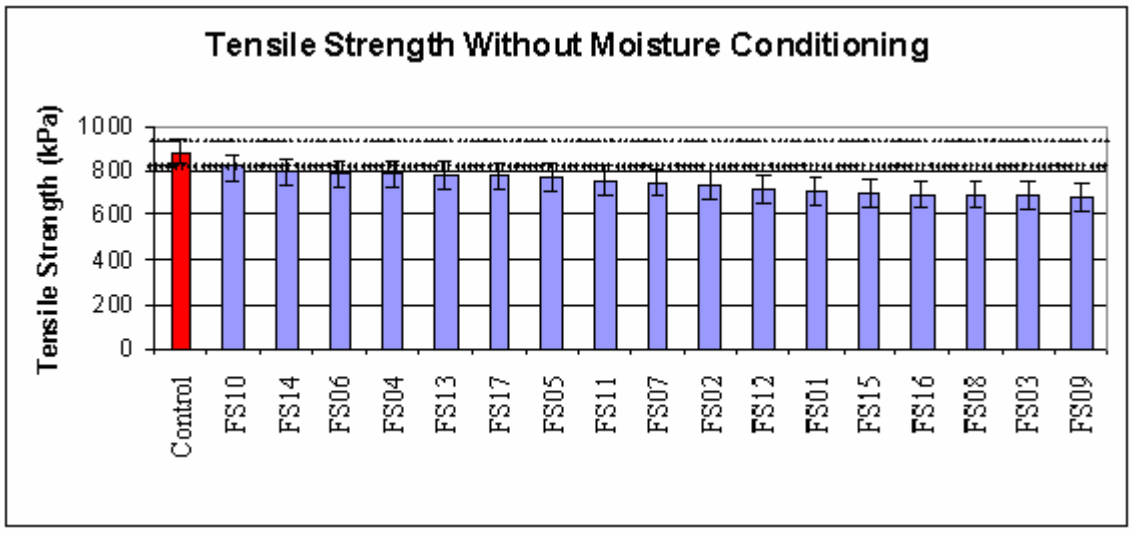

Figure **8-18**: Tensile strength without moisture conditioning

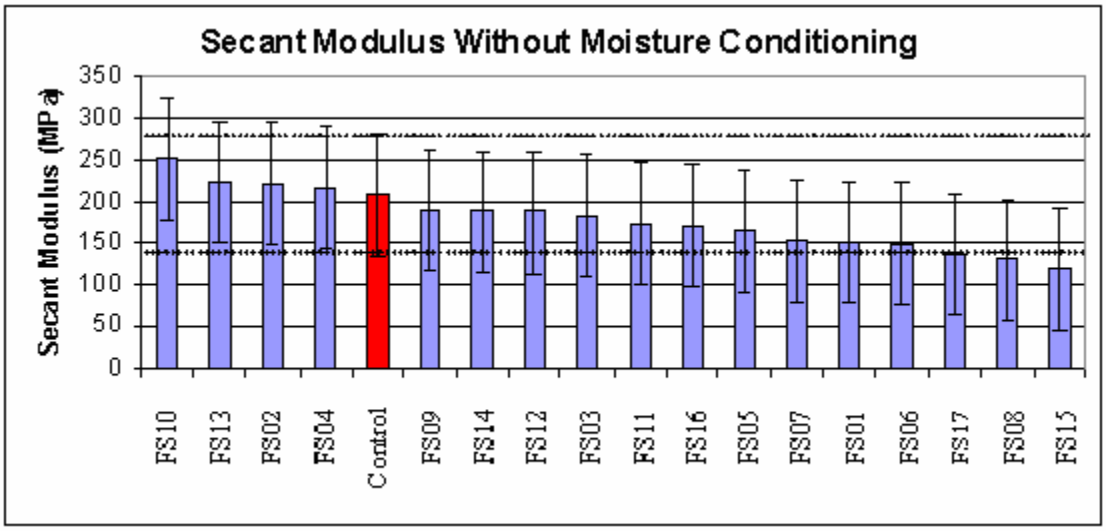

Figure **8-19**: Secant modulus without moisture conditioning

The data shown in Figure 8-20 and Figure 8-21 confirm that moisture conditioning causes the tensile strengths to decrease to a level that is unacceptable to most state departments of transportation. In Wisconsin, the minimum TSR allowed is 70%, meaning that moisture conditioning can decrease the tensile strength by no more than 30% of the unconditioned value. It can be seen from Table 8-6 that the control mix does not meet the Wisconsin DOT specifications. According to the data sheet that was provided by the contractor, the average tensile strength ratio was 76.7%. This was a mix that was designed in September 2000, and was used with aggregates that were crushed and sieved during this same time. On the other hand, it was not until the summer of 2002 that the aggregates were gathered and testing initiated for the optimum asphalt content, asphalt absorption, tensile strength ratios, etc. Because there was a lag between the time the mix was designed and when it was used for this project, the aggregates most likely

changed, not only in gradation but also in surface chemistry and other characteristics. Also, the asphalt binder used in 2000 was not the same binder used in 2002. These factors could have led to a decrease in the tensile strength ratio. Regardless of this, it is still possible to determine how foundry sands affect HMA performance by comparing to the control.

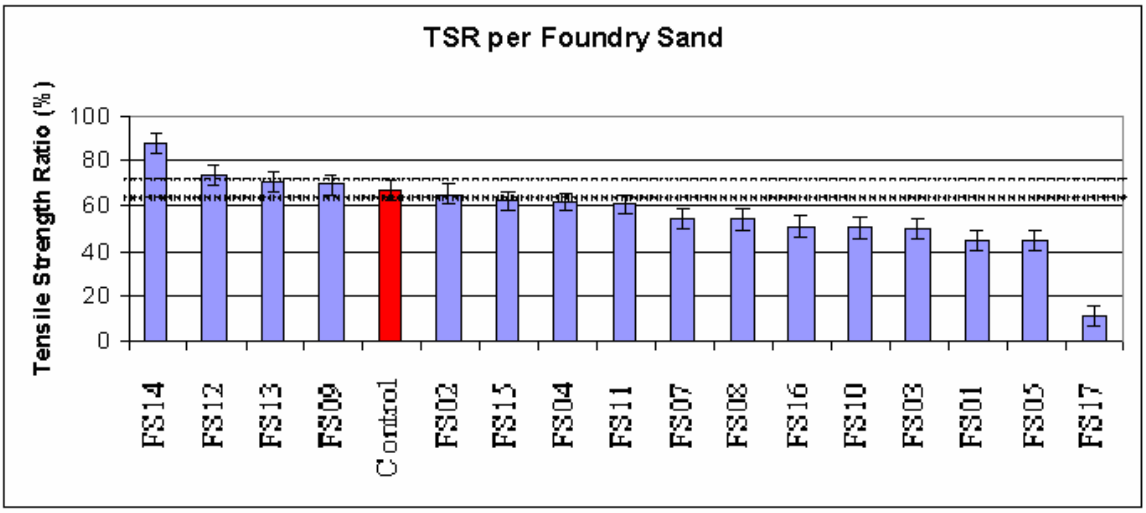

Figure **8-20**: Comparison of tensile strength ratios

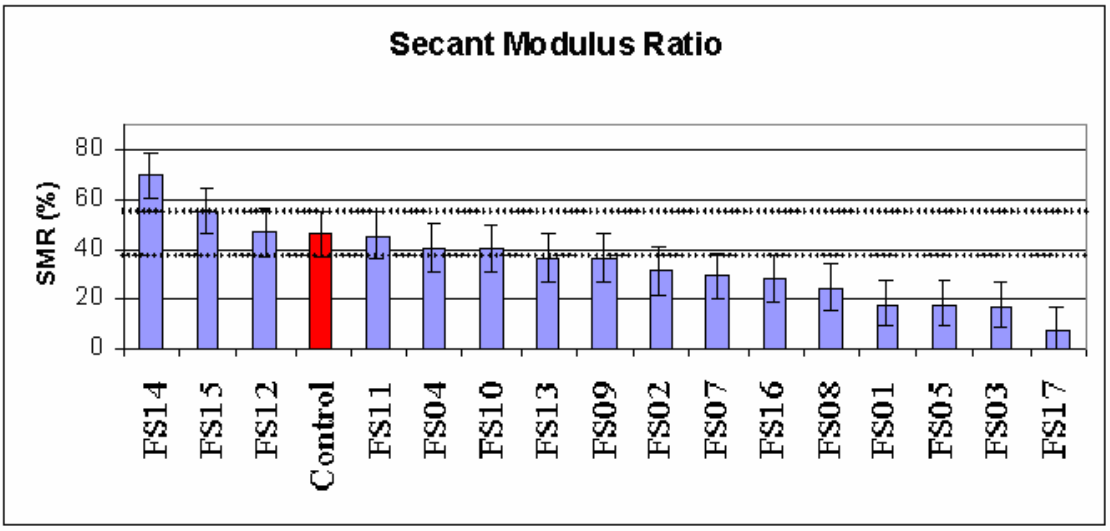

Figure **8-21**: Comparison of secant modulus ratios

Of the 17 sands, only one, sand FS14, increased the TSR above the 95% confidence interval. It had a TSR of 88.2%. Applying the average 95% confidence interval of 4.4%, this yields a 95% certainty that the TSR is between 92.6%, and 83.8 %. For the control, the confidence band is 71.8% and 63%. This confidence band overlaps the 95% confidence band of seven of the other sands: FS02, FS04, FS09, FS11, FS12, FS13, and FS15. The remaining nine sands all fell below the control confidence band. Sand FS06 performed so poorly that its moisture conditioned tensile strength could not be recorded. During the 24-hour soak in hot water, all three samples became so soft they crumbled under their own weight. Figure 8-22 shows there is a good correlation between the TSR and SMR, with the trend line having an R^2 of 0.70. Most of the discrepancy between the two could most likely be due to errors in measuring the displacement on the face of the asphalt sample.

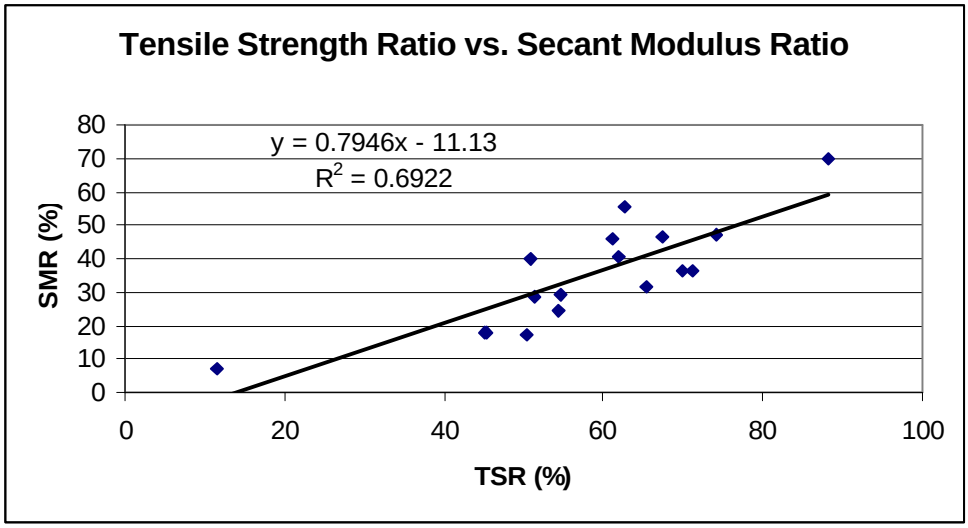

Figure **8-22**: Relation between TSR and SMR

8.2.3.3 Comparison of Tensile Strength Ratio to Clay Content

Since it is well known that clay causes mixes to be more susceptible to moisture damage, the methylene blue value was plotted versus the TSR. This is shown in Figure 8-23. From looking at the R^2 value, there does not seem to be a correlation between these two values. The main reason for this is because of sand FS17. It has a low MBV and a low TSR value. Since it is bound with sodium silicate and not bentonite, the MBV should be low. But this does not explain why the TSR value is low. Sands FS06 and FS10 were also bound with sodium silicate. As mentioned before, the mixture with sand FS06 was too soft to be tested, and the mixture with sand FS10 has a TSR value of 51%. Since all three sands performed worse than the control, two of them failing drastically, it can be said that sodium silicate is very detrimental to HMA moisture susceptibility performance. In light of this, only the sands that use bentonite as a binder

system were plotted versus the TSR. This is shown in Figure 8-24. When doing this, there is a better correlation between the MBV and TSR, with the linear trend line having an R^2 of 0.63. It can be generally stated that as the MBV increases, the TSR decreases.

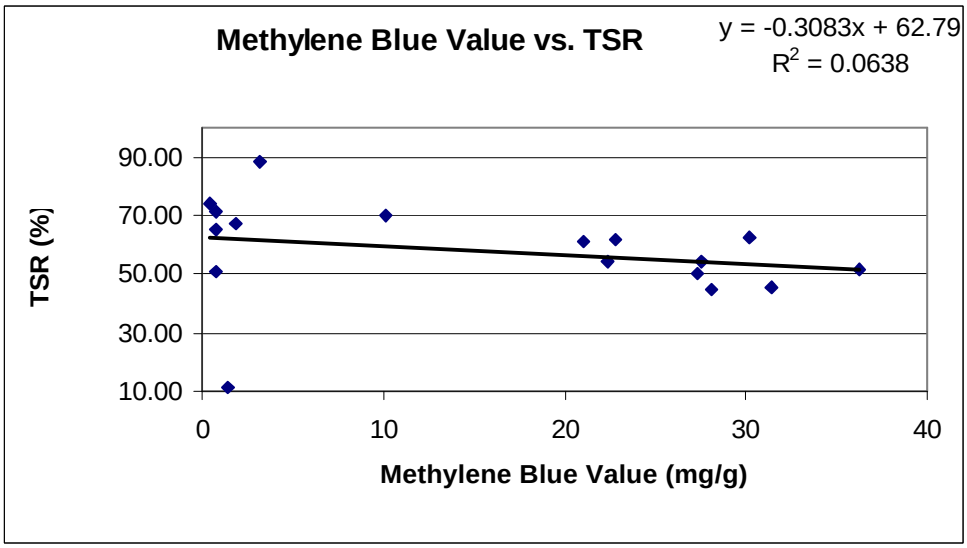

Figure **8-23**: Comparison of Methylene blue value to TSR

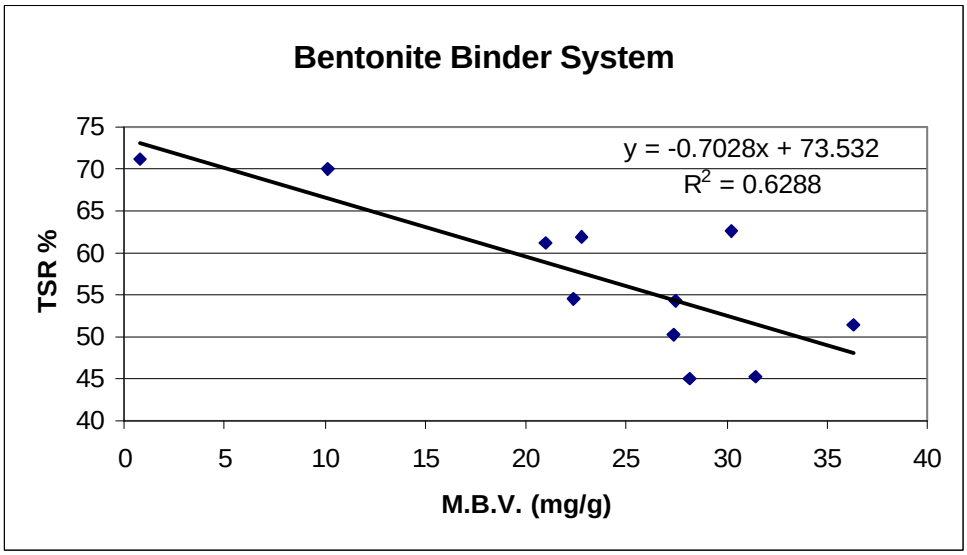

Figure **8-24**: Comparison of methylene blue value to TSR for only bentonite bound sands

8.2.3.4 The Use of Anti-Stripping Agents

In order to correct for the low TSR values, two different anti-stripping additives were added separately to four of the different mixes. The first anti-stripping additive was a liquid additive that was added to the asphalt binder at a level of 0.5% by mass of the total asphalt binder. The second additive was hydrated lime. It was added in at 2% of the total aggregate mass. Most contractors prefer to use the liquid additive because it is easier to use and more economical. Lime can be burdensome because the aggregates have to be wet before the lime is added and the job mix formula has to be changed. Since both of these materials are commonly used in practice, both were used for the study. First, the liquid anti-stripping additive, called Morelife 3300, was added to the control mixture at a level of 0.5% of the asphalt mass. This caused the TSR to increase from 67.4% to 94.3%. This verifies that the Morelife 3300 was working properly. This is shown graphically in Figure 8-25 and in table form in Table 8-9.

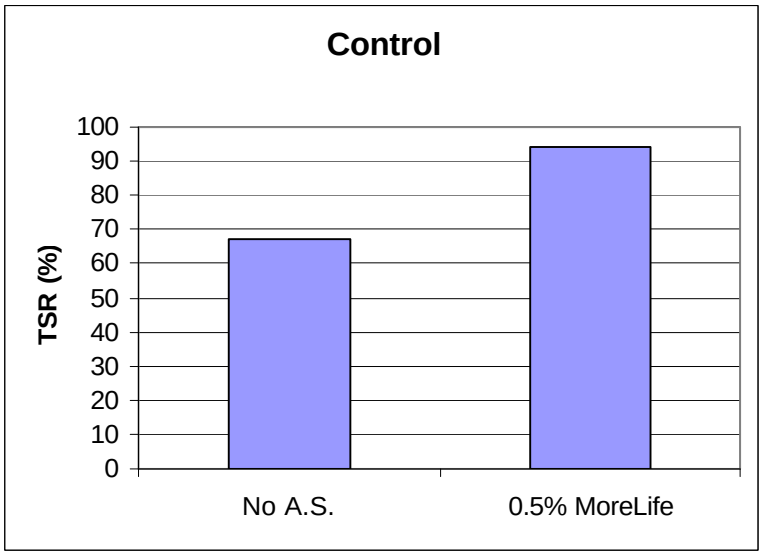

Figure **8-25**: Comparison of control with and without anti-stripping additive

Table **8-9**: Tensile strengths after anti-stripping agents

Sand No.	Tensile Strength w/ M.C. (kPa)	Tensile Strength w/o M.C. (kPa)	Tensile Strength Ratio (%)
Control @ 0.5% ML	675.1 ± 27.1	715.8 ± 28.9	94.3 ± 6.2
FS17 @ 0.5% ML	160.9 ± 17.4	749.0 ± 36.1	21.5 ± 2.9
FS17 @ 1% ML	282.6 ± 16.1	811.9 ± 11.1	34.8 ± 2.9
FS17 @ 2% Lime	311.8 ± 11.1	842.1 ± 11.1	37.0 ± 2.0
FS05 @ 0.5% ML	391.2 ± 28.2	669.3 ± 19.2	58.4 ± 5.2
FS16 @ 0.5% ML	369.7 ± 9.7	670.5 ± 23.5	55.1 ± 2.8
FS16 @ 1.0% ML	414.6 ± 14.4	717.3 ± 37.5	57.8 ± 5.1
FS16 @ 2% Lime	460.1 ± 13.1	789.8 ± 31.5	58.3 ± 4.0

Morelife was also added to sand FS17, since it was the worst performing sand that could be tested. At a level of 0.5%, the TSR was doubled to 21.5% from the original 11.5%. Since 21.5% was still well below the minimum of 75% (75% is the minimum when an anti-stripping agent is used), the level of Morelife was increased to 1%. This allowed the TSR to triple from its original value to 34.8%. Last, lime was used at a level of 2%. This caused the TSR to triple also to a value of 37%. This is shown in Figure 8-26. However, although there was a great improvement in TSR values, they remained well below the acceptance level. The same procedure was followed for sand FS16, but the same drastic improvements were not seen. After the addition of 0.5% of Morelife 3300, the TSR only increased from 51.4 to 55.1. After the addition of 1.0% Morelife, it increased to 57.8%. And again, when lime was added at a level of 2%, the TSR increased to 57.8%. This is shown in Figure 8-27. Due to lack of time and materials, sand FS05 was only tested using 0.5% Morelife, shown in Figure 8-28. The TSR value was increased from 45% to 58.4% but was still below the acceptance limit. So it can be

said that even though anti-stripping additives used at the 0.5-1.0% concentration increase the TSR, they may not be able to increase them enough for the HMA mixture to be accepted by most state DOTs.

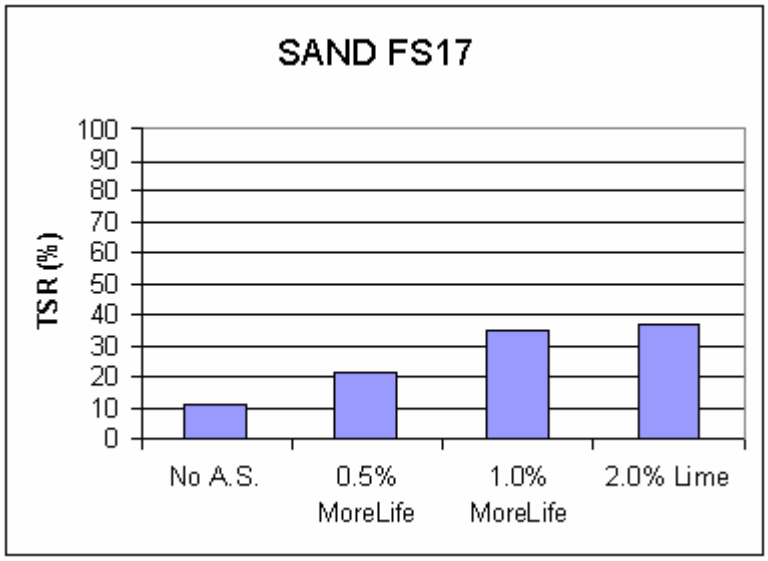

Figure **8-26**: Comparison of sand FS17 with and without anti-stripping additives

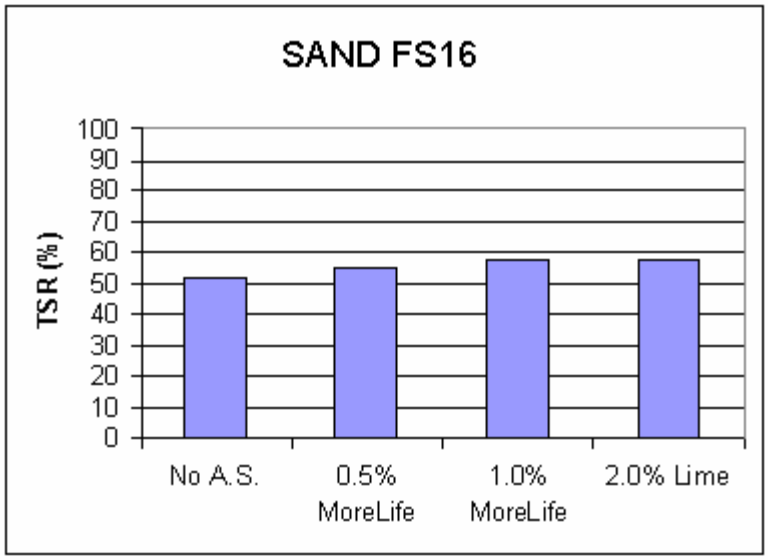

Figure **8-27**: Comparison of sand FS16 with and without anti-stripping additives

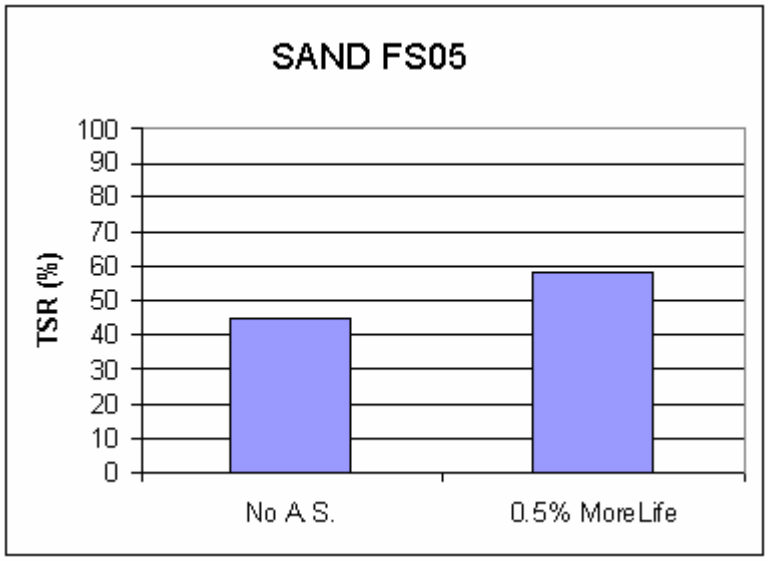

Figure **8-28**: Comparison of sand FS05 with and without anti-stripping additives

Chapter 9

CONCLUSIONS AND RECOMMENDATIONS

Based on the chemical characterization of foundry by-products and its experimental investigation in controlled low-strength materials and hot-mix asphalt, the following conclusions and recommendations are presented.

9.1 Characterization of Excess Foundry Sand

- Survival analysis processes the censored data characterizing foundry sands without any distribution assumption, which better matches the nature of data than other parametric methodologies.
- For as-received foundry sand, metal type cast in the facilities is not a significant factor regarding most metallic elements. The exceptions are lead, copper, and zinc, which are frequently of greater concentration in sand from copper-based facilities than from other alloy facilities.
- TCLP is more aggressive on sand than SPLP and ASTM D 3987. SPLP is most representative for fill applications.
- For TCLP sand leachate, metal cast in the facilities is not a significant factor regarding most metallic elements. One of the exceptions is lead, which is frequently of greater concentration in TCLP sand leachate from

copper-based facilities than in TCLP sand leachate from other alloy facilities.

- Excess foundry sand does not pose a greater threat to the environment than soil. The concentrations of most regulated metallic elements are less than or in the same level as those of soil. In comparison with soil, excess foundry sands contain more metallic elements that are frequently and heavily used in the casting process than soil, such ash aluminum, copper, and iron.
- Leachates from foundry sand by typical leaching protocols, including TCLP, SPLP, and ASTM D 3987, have 95th percentiles of metallic element concentrations well below the TCLP thresholds. Thus, foundry sands are generally not hazardous.
- Comparisons indicate that 95th percentiles of bulk metallic element composition in sand are well below the TCLP thresholds, except for lead and chromium. Hence, it is not necessary to leachate and measure the full spectrum of metallic elements in sand.
- Most of the organic compounds are significantly burned out during high-temperature melting. Twenty-three of 37 typical organic compounds are 100% below detection limits in sand leachate. Seven of the remaining 14 compounds are more than 80% censored; these are cresol_m, cresol_o, benzene, 2_4-Dimethylphenol, tetrachloroethylene, xylene_total, and methyl isobutkl ketone. Compounds with censoring fractions less than 80% include: acetone, ethyl benzene, naphthalene, phenanthrene, styrene,

toluene, and trichloroethylene. Those 23 organic compounds with 100% censoring are suggested to be eliminated from regulatory requirements, as inappropriate testing keeps foundry sand from beneficial reuse.

9.2 Physical Properties of Excess Foundry Sand

- The angularity of the sands varied from 43.1 to 57.6, with the control P0.6 being measured at 45.5, and the natural sand being reported by the contractor as 41.5. This shows that foundry sands have average to high angularities as compared to the control, and thus could promote aggregate interlock.
- The methylene blue values varied from 0.8 to 36.3 mg/g, showing that foundry sands contain varying amounts of clay, with some sands not containing any clay. If the methylene blue value is above 10 mg/g, the foundry sand will most likely lead to an increase in moisture damage susceptibility and will need to be washed before use.
- The organic contents ranged from 0.2% to 4.7% and were due to organic additives like sea coal, cereals, and starches. Since the level of organics is so low, they are not considered significant to the performance of the HMA mixtures.

9.3 CLSM Containing Excess Foundry Sand

- CLSM containing excess foundry sands can be a high-quality component of CLSM mixtures. It presents equivalent construction behavior and geotechnical performance with an identical design effort. Its design is generally accomplished by trial batching to attain the required performances of critical parameters, which are listed in Table 7-1.
- Water proportion and grain fineness are two main factors influencing the flowability. It is indicated that the finer the average grain size, the less water is required to attain specified flow criteria for both excavatable CLSM and structural CLSM. The general absolute volume of water in the fresh CLSM matrix ranges from 30% to 50% to provide working flowability of CLSM.
- Measurements of penetration resistance at early ages help compare the hardening behavior of different mixtures. For excavatable CLSM, the main factor affecting penetration resistance is found to be the factor of foundry sand. For structural CLSM, the penetration resistance is mainly dependent on the cement proportion.
- The initial setting time for extractable CLSM starts from 6.7 hours and averages 15-20 hours. The initial setting time of structural CLSM is concentrated at about 5-7 hours, which is contributed by the increased proportion of cement and can be accelerated or retarded with chemical

admixtures. The increase in cement proportion enhances the correlation of high early-penetration resistance and long-term compressive strength.

- Cumulative bleeding and bleed time are not significantly correlated. Bleeding of excavatable CLSM is slightly more in volume and longer in elapse time than that of structural CLSM. Bleeding of CLSM normally takes 2-5 hours, with volume up to 6% of fresh CLSM. Foundry sand has a significant influence on bleeding.
- Water addition is exclusively controlled by flowability, which is closely related to grain fineness.
- Water-cement ratio influences 28-day strength, although the relation is nonlinear. Water-cement ratios of 2 and 5-6 are suggested starting points for design excavatable CLSM and structural CLSM, respectively. The 28-day strength varies inversely with the water-cement ratio. An increase in cement proportion contributes substantially to strength gain. After 28 days, CLSM continues to gain strength. The long-term strength can be estimated by 28-day strength.
- The initial trial mixture design of excavatable CLSM containing excess foundry sands is presented in Table 9-1.

Table **9-1**: Starting mix of excavatable CLSM

	Bulk Proportion* (Unit: kg/m^3)				
	Cement	Fly Ash	Sand	Water	Total
Min.	25	334	818	291	1782
Max.	94	463	1264	504	2074
Avg.	57.3	383.1	1075.4	398.6	1914.4
SD	18.81	37.77	133.64	63.79	92.02

* Mass of raw material per unit of fresh CLSM.

9.4 HMA Containing Excess Foundry Sand

- The optimum asphalt contents ranged from 5.1 to 6.1%, with the control being 5.5%. The differences in asphalt content are minor, thus foundry sands are not expected to significantly change the optimum asphalt content of mixtures.
- **Volumetrics:** The percent of maximum density at N_{ini} for most of the HMA mixtures was at or below 89%, with several being slightly above 89%. The several that were above 89% were only above by a couple tenths of a percent. For the percent of maximum density at N_{max}, all the mixes were below 98%. This shows that mixtures containing foundry sand can meet volumetric design specifications.
- **Energy Indices:** Due to the unavoidable error associated with calculating the energy indices from the densification curves, the effects of foundry sand on rutting performance could not be determined. It can only be concluded that the effect of foundry sand is within the experimental error of the measurements.

- **Moisture Damage Susceptibility:** Seven of the 17 foundry sands did not alter the TSR of the mixture, one sand increased the TSR, and the remaining sands decreased the TSR. It was noticed that as the bentonite content increased, the TSR decreased. Also, sodium silicate seems to be extremely detrimental to HMA. Asphalt mixes should always be tested for their moisture susceptibility when foundry sands are used.
- **Anti-Stripping Additives:** Anti-stripping additives successfully increased the TSR of the control but were unable to increase the TSR of the mixtures containing foundry sands. Other methods may have to be used to increase TSR values of mixtures containing foundry sands.
- **Overall Effects of Sand on Performance:** Although all sands could be incorporated successfully in acceptable asphalt mix designs, based on collective review of the results, it is concluded that sands can vary significantly in their effects on performance. Effects can be either favorable or unfavorable, thus each sand needs to be treated as a unique source of aggregate.
- **Asphalt Contactors:** The two major obstacles to overcome are sodium silicate and bentonite. If the sand contains sodium silicate, it should be rejected. If it contains bentonite, consider washing the material.

Chapter 10

FUTURE STUDIES

The following future studies are suggested following the research reported herein:

- Continued dataset collection is needed to support the characterization of excess foundry sand. Due to improvements in the binding system and changes in the casting process, the characterization of foundry sand may vary over time. Ongoing updating of datasets would permit monitoring of the characterization trend over time. Tracking the trend would give the foundry industry an indication of the environmental impacts of their by-products.
- Survival function resolves the issue of left-censored data, which frequently exist in the environmental or chemical monitoring data. This kind of data is not restricted to the field of foundry by-products characterization. Correlating fields include characterization of water, air, and soil. All left-censored data in these fields can be analyzed by survival technique to estimate survival function, mean, and percentile and to make comparisons or do hypothesis testing.
- Excess foundry sand can be potentially reused in applications other than CLSM. It is not only reused solely in fills, embankments, road base, and barriers, but also integrated as a component for manufactured materials, such as concrete, portland cement, manufactured soils, and amendments. The by-products of iron foundry copula slag are being considered as a material usable

in cement kilns if iron foundry slag has similar chemistries to steel blast furnace slag.

- Only one source of aggregate was used for HMA research. A survey should be conducted to determine the areas that produce the largest amounts of foundry sand. Aggregate samples from quarries used by asphalt contractors in these areas should be taken and tested with foundry sands from these same areas.
- The indirect method for determining the apparent and bulk densities should be further developed. The direct method may give erroneous results, and the direct method should be verified with the indirect method.
- Other methods should be used to correct for decreased TSR values in HMA research. These include using other anti-stripping additives, washing the fines out of the sands, and exposing the sands to high temperatures to burn off organic material and destroy the clay structure.

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Appendix A

Glossary of Terms

A.1 Civil Engineering

Absorption – the process by which a liquid is drawn into and tends to fill permeable pores in a porous solid body; also, the increase in mass of a porous solid body resulting from the penetration of a liquid into its permeable pores. [ASTM C 125 2000].

AFS Grain Fineness Number (AFS GFN) – an estimate of the average sieve size of a sand sample [AFS 1106 2000].

Aggregate – granular material, such as sand, gravel, crushed stone, or iron blast-furnace slag, used with a cementing medium to form hydraulic-cement concrete or mortar [ASTM C 125 2000].

Attenuation – reduction of amplitude with time or distance [ASTM D 653 1997].

ASTM D 3987, Standard Test Method for Shake Extraction of Solid Waste with Water – a leaching protocol designed for leaching of solid waste to obtain an aqueous solution to be used to determine the materials leached under the specified testing conditions [ASTM D 3987 1985].

Bleeding – the autogenous flow of mixing water within, or its emergence from, newly placed concrete or mortar caused by the settlement of the solid materials within the mass, also called water gain [ASTM C 125 2000].

Bulk density (replaces the deprecated term "unit weight") – the mass of a unit volume of bulk aggregate material (the unit volume includes the volume of the individual particles and the volume of the voids between the particles) [ASTM C 125 2000].

Bulk specific gravity – the ratio of the mass of a volume of a material (including the permeable and impermeable voids in the material, but excluding the voids between particles of the material) at a stated temperature to the mass of an equal volume of distilled water at a stated temperature [ASTM C 125 2000].

Bulk specific gravity (saturated surface dry, SSD) – the ratio of the mass of a volume of a material including the mass of water within the pores in the material (but excluding the voids between particles) at a stated temperature, to the mass of an equal volume of distilled water at a stated temperature [ASTM C 125 2000].

Cementitious material (hydraulic) – an inorganic material or a mixture of inorganic materials that sets and develops strength through chemical reaction with water by formation of hydrates, and is capable of doing so under water [ASTM C 125 2000].

Compressive strength – the load per unit area at which an unconfined cylindrical specimen of soil or rock will fail in a simple compression test [ASTM D 653 1997].

Consistency – the relative mobility or ability to flow of fresh concrete, mortar, or grout [ASTM C 125 2000].

Controlled low-strength material (CLSM) – a mixture of soil or aggregates, cementitious material, fly ash, water and sometimes chemical admixtures, that hardens into a material with a higher strength that the soil, but less than 8,400 kPa (1200 psi); used as a replacement for compacted backfill, CLSM can be placed as a slurry, a mortar, or a compacted material and typically has strength of 350 to 700 kPa (50 to 100 psi) for most applications [ASTM D 6103 1997].

Curing – action taken to maintain moisture and temperature conditions in a freshly placed cementitious mixture to allow hydraulic cement hydration and (if applicable) pozzolanic reactions to occur so that the potential properties of the mixture may develop [ASTM C 125 2000].

Fine aggregate – aggregate passing the 3/8-in (9.5-mm) sieve and almost entirely passing the 4.75-mm (No. 4) sieve and predominantly retained on the 75-μm (No. 200) sieve; or the portion of an aggregate passing the 4.75-mm (No. 4) sieve and retained on the 75-μm (No. 200) sieve [ASTM C 125 2000].

Flow consistency (refer to **Consistency** in this section)

Fly ash – the finely divided residue that results from the combustion of ground or powdered coal and that is transported by flue gases from the combustion zone to the particle removal system [ASTM C 125 2000].

Gradation (grain-size distribution) – the proportions by mass of a soil or fragmented rock distributed in specified particle-size ranges [ASTM D 6103 1997].

Hydraulic conductivity – the volume of water at the existing kinematics viscosity that will move in a unit time under a unit hydraulic gradient through a unit area measured at right angles to the direction of flow [ASTM D 6103 1997].

Initial set – a degree of stiffening of a grout mixture generally stated as an empirical value indicating the time in hours and minutes that is required for a mixture to stiffen sufficiently to resist the penetration of a weighted test needle [ASTM D 6103 1997].

Resource Conservation and Recovery Act (RCRA) – legislation enacted in 1976 by Congress with the intent to "protect human health and the environment from the improper handling of solid waste and to encourage the conservation of natural resources."

Resistivity – the relative ability of a medium to carry electrical currents [ASTM G 57 2001].

Sand – fine aggregate resulting from natural disintegration and abrasion of rock or processing of completely friable sandstone [ASTM C 125 2000].

Segregation – the unintentional separation of the constituents of concrete or particles of an aggregate, causing a lack of uniformity in their distribution [ASTM C 125 2000].

Setting – the process, due to chemical reactions, occurring after the addition of mixing water, that results in a gradual development of rigidity of a cementitious mixture [ASTM C 125 2000].

Setting settlement / shrinkage – a reduction in volume of grout prior to the final set of cement caused by bleeding, by the decrease in volume due to the chemical combination of water with cement, and by syneresis [ASTM D 6103 1997].

Synthetic Penetration Leaching Protocol (SPLP) – a leaching protocol designed to determine the mobility of both organic and inorganic analytes present in liquids, soils, and wastes [EPA SW-846 2000].

Toxicity Characteristics Leaching Procedure (TCLP) – a leaching protocol designed to determine the mobility of both organic and inorganic analytes present in liquid, solid, and multiphasic wastes [EPA SW-846 2000].

Time of setting – the elapsed time from the addition of mixing water to cementitious mixture until the mixture reaches a specified degree of rigidity as measured by specific procedure [ASTM C 125 2000].

Void – the space between particles in an aggregate mass not occupied by solid mineral matter [ASTM C 29 1997].

Water-cement ratio, *w/c* – the ratio of the mass of water exclusive only of that absorbed by the aggregates, to the mass of portland cement in concrete, mortar, or grout, stated as a decimal [ASTM C 125 2000].

Water-cementitious material ratio, *w/cm* – the ratio of the mass of water, exclusive only of that absorbed by the aggregates, to the mass of cementitious material (hydraulic) in concrete, mortar, or grout, stated as a decimal [ASTM C 125 2000].

A.2 Statistics

Alternative hypothesis, H_1 – a statement of what a statistical hypothesis test is set up to establish.

Conditional probability, P **(A | B)** – the probability that event A will occur given that event B has already occurred.

Confidence interval – an estimated range of values that is likely to include an unknown population parameter, the estimated range being calculated from a given set of sample data.

Confidence level – the probability value $(1-a)$ associated with a confidence interval.

Correlation coefficient – a number between -1 and 1 that measures the degree to which two variables are linearly related.

Cumulative distribution function – a function giving the probability that the random variable X (discrete and continuous) is less than or equal to x.

Factor – a controlled independent variable for an experiment whose levels (treatments) are set by the experimenter.

Hypothesis test – used to test the two hypotheses and to accept one of them with significance level.

Kolmogorov-Smirnov test – used to test whether or not a single sample of data is consistent with a specified distribution function; or to test whether or not two samples of data come from the same distribution.

Nonparametric test – used in place of its parametric counterparts when certain assumptions about the underlying population are questionable.

Null hypothesis, H_0 – represents a theory that has been put forward, either because it is believed to be true or because it is to be used as a basis for argument, but has not been proven.

One-sided test – a statistical hypothesis test in which the values for which null hypothesis is rejected are located entirely in one tail of the probability distribution.

Outlier – an observation in a data set that is far removed in value from the others in the data set, unusually large or small compared to the others.

P **-Value** – the probability of wrongly rejecting the null hypothesis if it is in fact true in a statistical hypothesis test.

Parameter – a value, usually unknown (and which therefore has to be estimated), used to represent a certain population characteristic.

Percentile – a value that divides a sample of data into one hundred groups containing (as far as possible) equal numbers of observations; for example, 30% of the data values lie below the 30th percentile.

Population – any entire collection of people, animals, plants or things from which data may be collected. It is the entire group which is of interest and about which conclusions are to be drawn.

Probability – a quantitative description of the likely occurrence of a particular event.

Probability density function – a function that can be integrated to obtain the probability that a continuous random variable takes a value in a given interval.

Probability distribution – a list of probabilities associated with each of its possible values for a discrete random variable. It is also sometimes called the probability function or the probability mass function.

Quantile – a set of "cut points" that divide a sample of data into groups containing (as far as possible) equal numbers of observations.

Sample – a group of units selected from a larger group (the population); by studying the sample it is hoped that valid conclusions can be drawn about the larger group.

Sample mean – an estimator available for estimating the population mean.

Significance level – a fixed probability of wrongly rejecting the null hypothesis H_0, if it is in fact true in a statistical hypothesis test; the significance level is usually denoted by a and chosen to be 0.05 (or equivalently, 5%).

Skewness – asymmetry in the distribution of the sample data values; values on one side of the distribution tend to be further from the "middle" than values on the other side.

Standard deviation – a measure of the spread or dispersion of a set of data.

Survival function – the probability that a variable X takes on a value greater than a number x.

Test statistic – a quantity calculated from the sample of data. Its value is used to decide whether or not the null hypothesis should be rejected in hypothesis test.

Treatment – a condition or action administered to experimental units to compare its significance or effect; for example, a cornfield is divided into four plots, and each plot is "treated" with a different fertilizer to see which produces the most corn.

Two-sided test – a statistical hypothesis test in which the values for which null hypothesis is rejected are located in both tails of the probability distribution.

Appendix B

List of Testing Specifications (CLSM)

AFS 1105	Sieve Analysis (Particle Size Determination of Sand)
AFS 1106	Grain Fineness Number, AFS GFN, Calculation
AFS 1107	Grain Shape Classification
ASTM C 29	Standard Test Method for Bulk Density (Unit Weight) and Voids in Aggregate
ASTM C 117	Standard Test Method for Materials Finer than 75-µm (No. 200) Sieve in Mineral Aggregates by Washing
ASTM C 128	Standard Test Method for Density, Relative Density (Specific Gravity), and Absorption of Fine Aggregate
ASTM C 192	Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory
ASTM C 232	Standard Test Methods for Bleeding of Concrete
ASTM C 403	Standard Test Method for Time of Setting of Concrete Mixtures by Penetration Resistance
ASTM C 566	Standard Test Method for Total Evaporable Moisture Content of Aggregate by Drying
ASTM C 567	Standard Test Method for Determining Density of Structural Lightweight Concrete
ASTM C 827	Standard Test method for Change in Height at Early-ages of Cylindrical Specimens from Cementitious Mixtures
ASTM D 2434	Standard Test Method for Permeability of Granular Soils (Constant Head)
ASTM D 4832	Standard Test Method for Preparation and Testing of Controlled Low-Strength Material (CLSM) Test Cylinders
ASTM D 5971	Standard Practice for Sampling Freshly Mixed Controlled Low-Strength Material

ASTM D 6023 Standard Test Method for Unit Weight, Yield, Cement Content and Air Content (Gravimetric) of Controlled Low- Strength Material (CLSM)

ASTM D 6103 Standard Test Method for Flow Consistency of Controlled Low- Strength Material (CLSM)

ASTM G57 Standard Test Method for Field Measurement of Soil Resistivity Using the Wenner Four-Electrode Method

Appendix C

Solid Waste Hazardous Threshold, Drinking Water and Groundwater Standard

C.1 Metallic Elements

The thresholds regarding metallic elements of hazardous materials [EPA SW-846 2000, 40 CFR Part 261 1986], standard of drinking water [40 CFR Part 141 1986, 40 CFR Part 143 1986], and standard of groundwater [40 CFR Part 264 1986] are presented in Table C-1.

C.2 Organic Compounds

The thresholds regarding organic compounds of hazardous materials [EPA SW-846 2000, 40 CFR Part 261 1986], standard of drinking water [40 CFR Part 141 1986, 40 CFR Part 143 1986], and standard of groundwater [40 CFR Part 264 1986] are presented in Table C-2 and Table C-3.

Table **C-1**: Threshold for inorganic elements

	Hazardous Material		Drinking Water	Ground Water
Measuring Method	TCLP/EPA SW-846		Total Analysis	Total Analysis
	Unit: mg/L			
Aluminum	Toxicity by Leaching (TCLP)	---	0.05-0.2	---
Antimony		---	0.006	---
Arsenic		5.0	0.01	0.05
Barium		100.0	2.0	1.0
Beryllium		---	0.004	---
Cadmium		1.0	0.005	0.01
Chromium		5.0	0.1	0.05
Copper		---	1.0	---
Iron		---	0.3	---
Manganese		---	0.05	---
Mercury		0.2	0.002	0.002
Lead		5.0	0.015	0.05
Selenium		1.0	0.05	0.01
Silver		5.0	0.1	0.05
Thallium		---	0.002	---
Zinc		---	5	---
Reactive Cyanide	250		---	---
Reactive Sulfide	500		---	---
Ignitability	60 °C		---	---
pH for Corrosivity	2 ~ 12.5		---	---
Free Cyanide	---		0.2	---
Fluoride	---		4.0	---
Nitrate	---		10	---
Nitrite	---		1	---

Table **C-2**: Threshold for organic compounds

	Hazardous Material	Drinking Water	Ground Water
Measuring Method	TCLP/EPA SW-846	Total Analysis	Total Analysis
	Unit: ug/L		
Alachlor	---	2	---
Atrazine	---	3	---
Benzene	500	5	---
Benzo(a)pyrene	---	0.2	---
Carbofuran	---	40	---
Carbon tetrachloride	500	5	---
Chlordane	30	2	---
Chlorobenzene	100000	100	---
Chloroform	6000	---	---
o-Cresol	200000	---	---
m-Cresol	200000	---	---
p-Cresol	200000	---	---
Cresol	200000	---	---
2,4-D acid	10000	70	100
Dalapon	---	200	---
1,2-Dibromo-3-chloropropane (DBCP)	---	0.2	---
o-Dichlorobenzene		600	---
p-Dichlorobenzene	7500	75	---
1,2-Dichloroethane	500	5	---
1,1-Dichloroethylene	700	7	---
cis-1, 2-Dichloroethylene	---	70	---
trans-1,2-Dichloroethylene	---	100	---
Dichloromethane	---	5	---
1,2-Dichloropropane	---	5	---
2,4-Dinitrotoluene	130		---
Di(2-ethylhexyl)adipate	---	400	---
Di(2-ethylhexyl)phthalate	---	6	---
Dinoseb	---	7	---
Dioxin (2,3,7,8-TCDD)	---	0.00003	---
Diquat	---	20	---

Table **C-3**: Threshold for organic compounds (Cont.)

	Hazardous Material	Drinking Water	Ground Water
Measuring Method	TCLP/EPA SW-846	Total Analysis	Total Analysis
	Unit: ug/L		
Endothall	---	100	---
Endrin	20	2	0.2
Ethylbenzene	---	700	---
Ethylene dibromide	---	0.05	---
Glyphosate	---	700	---
Heptachlor	8	0.4	---
Heptachlor epoxide	---	0.2	---
Hexachlorobenzene	130	1	---
Hexachlorobutadiene	500	---	---
Hexachloroethane	3000	---	---
Hexachloropentadiene		50	---
Lindane	400	0.2	4
Methoxychlor	10000	40	100
Methyl ethyl ketone	200000	---	---
Nitrobenzene	2000	---	---
Oxamyl (Vydate)	---	200	---
Polychlorinated biphenyls (PCBs)	---	0.5	---
Pentrachlorophenol	100000	1	---
Picloram		500	---
Pyridine	5000	---	---
Simazine	---	4	---
Styrene	---	100	---
Tetrachloroethylene	700	5	---
Toluene		1000	---
Toxaphene	500	3	5
2,4,5-TP (Silvex)	1000	50	10
1,2,4-Trichlorobenzene	---	70	---
1,1,1-Trichloroethane	---	200	---
1,1,2-Trichloroethane	---	5	---
Trichloroethylene	500	5	---
2, 4, 5-Trichlorophenol	400000	---	---
2, 4, 6-Trichlorophenol	2000	---	---
2, 4, 5-TP (Silvex)	1000	---	---
Vinyl chloride	200	2	---
Xylenes, total	---	10000	---

Appendix D

Bulk Analysis of Excess Foundry Sand

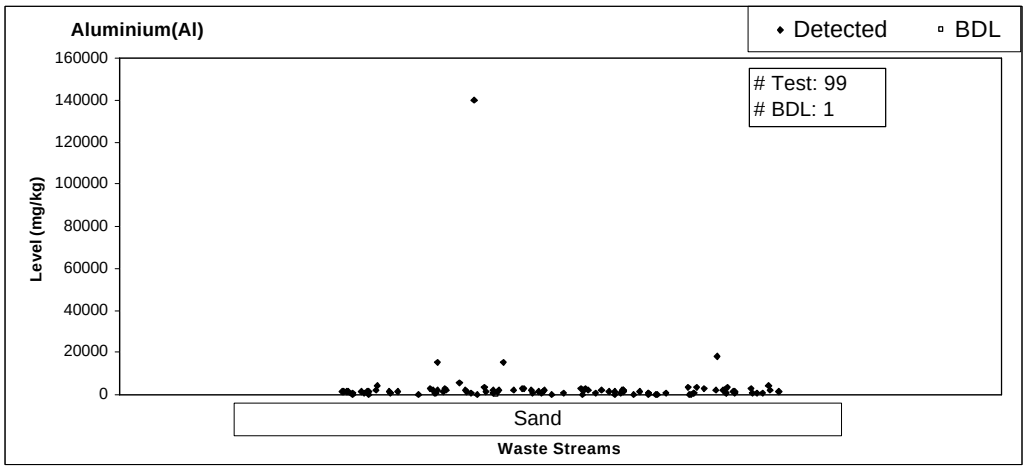
In this appendix, the composition of excess foundry sand is shown element by element, including 24 metallic elements, 17 general chemical parameters, and 30 organic compounds at the trace level. The datasets represented in this appendix are typical of those in the foundry industry. The matrix of the analysis is essentially the waste stream, not the leachate from the waste stream. The leachate-based composition is presented in Appendix E.

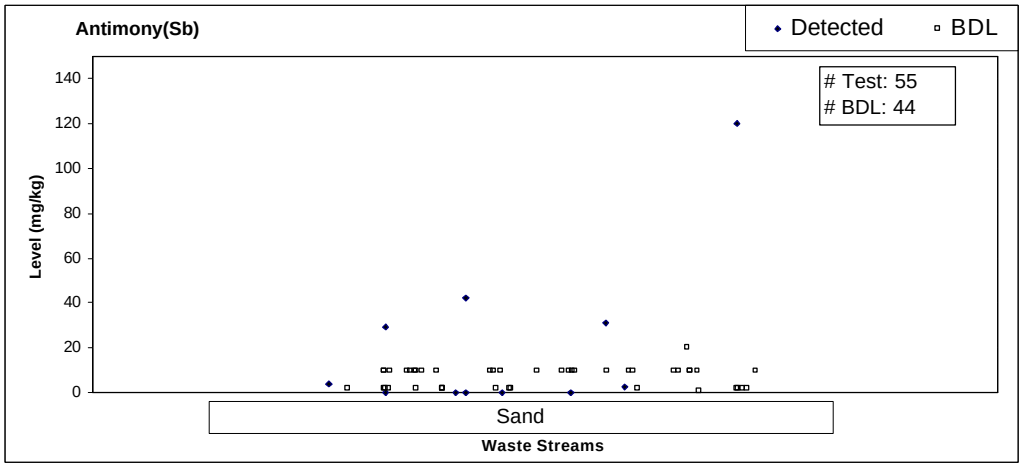
The notes to individual charts are defined as follows:

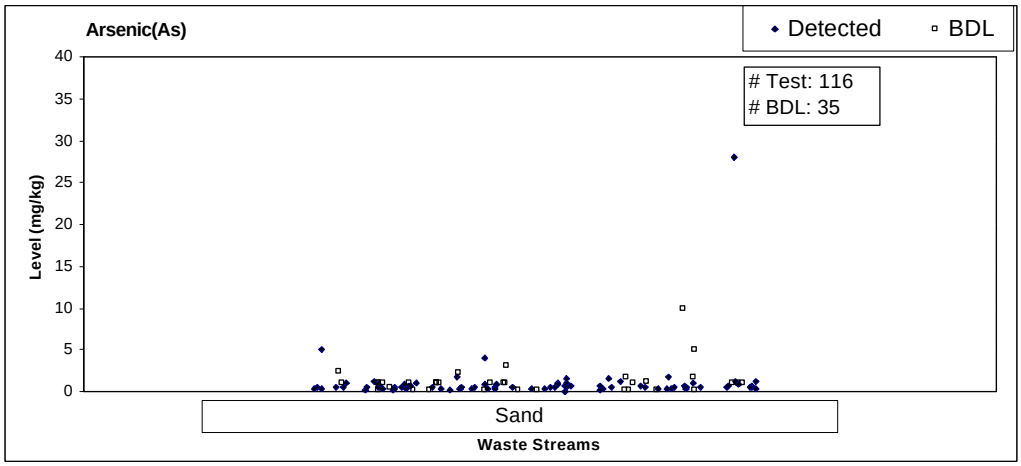
- The number following "# Tests" represents total observations for sand stream;
- The number following "# BDL" represents total censored observations for sand stream;
- The solid diamond legend "¨" represents an uncensored observation;
- The hollow square legend "o" represents a censored observation;
- The horizontal dashed line represents a hazardous threshold.

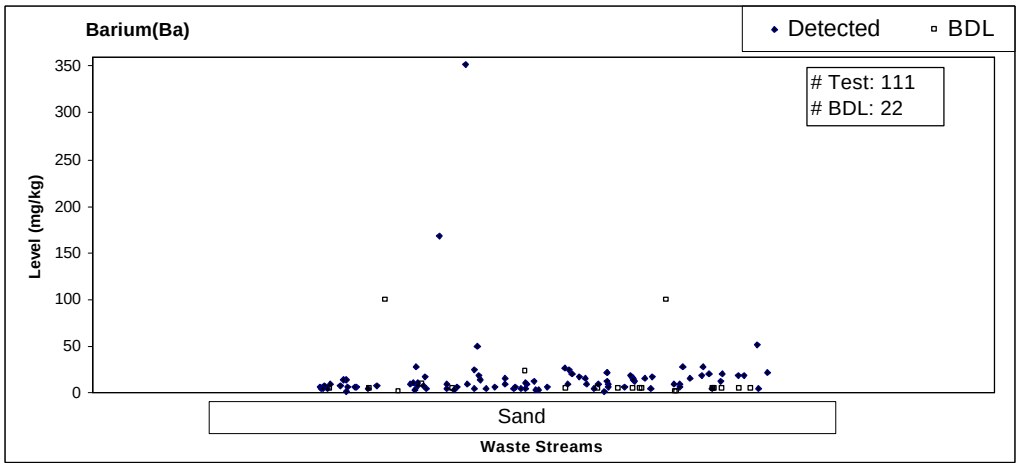
D.1 Trace Metallic Elements

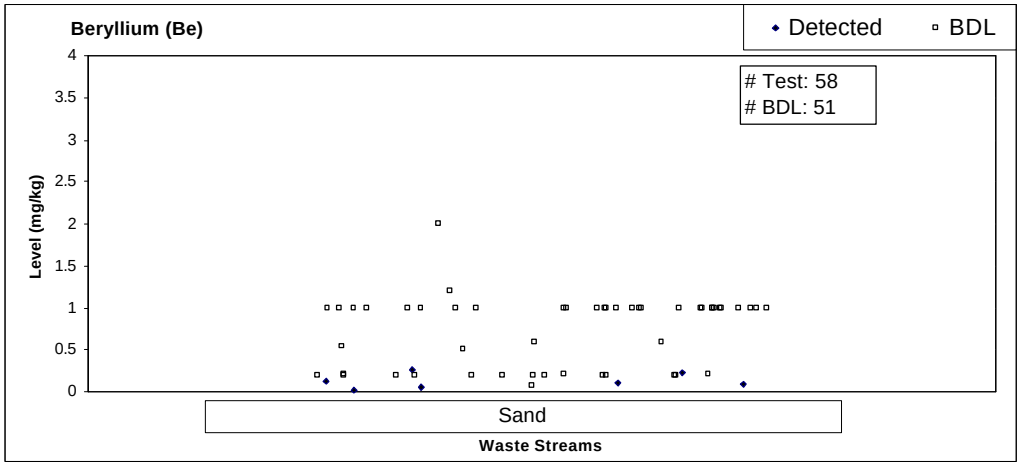
The following series of 24 charts, grouped into Figure D-1, presents the bulk analysis distribution for 24 trace metallic elements in individual waste stream.

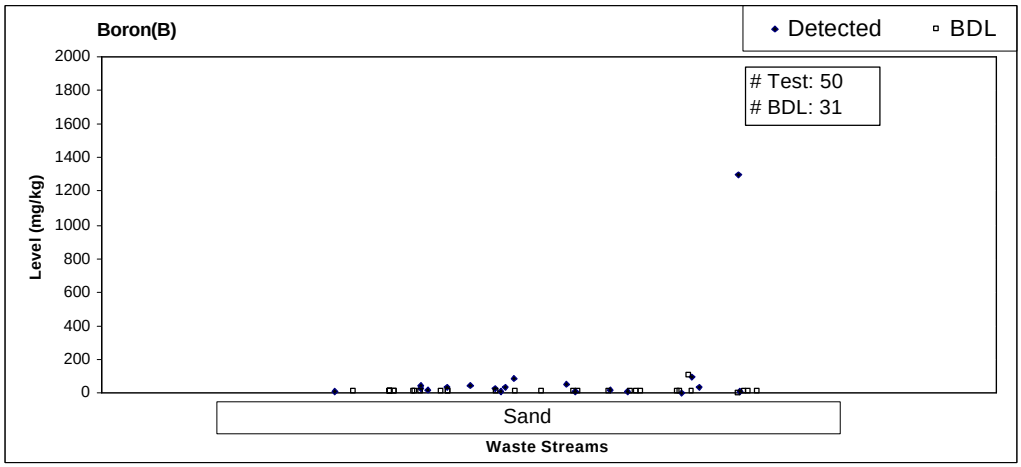


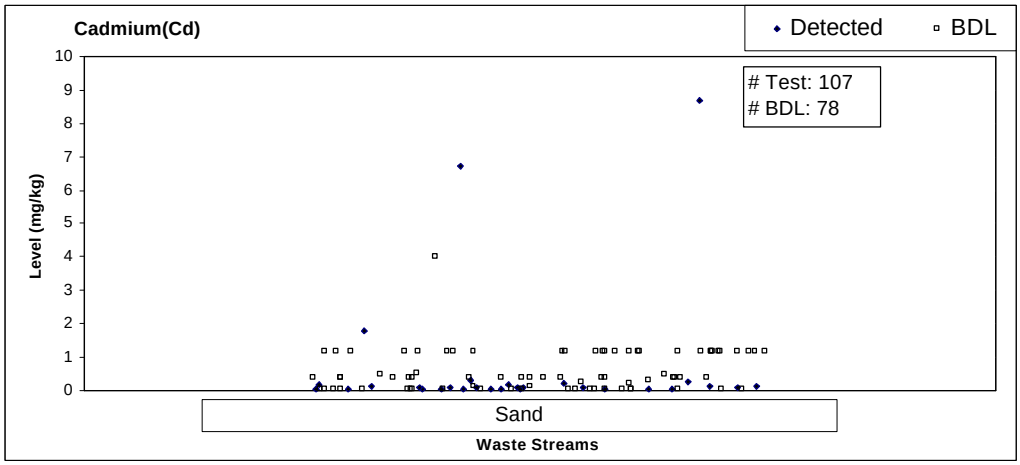


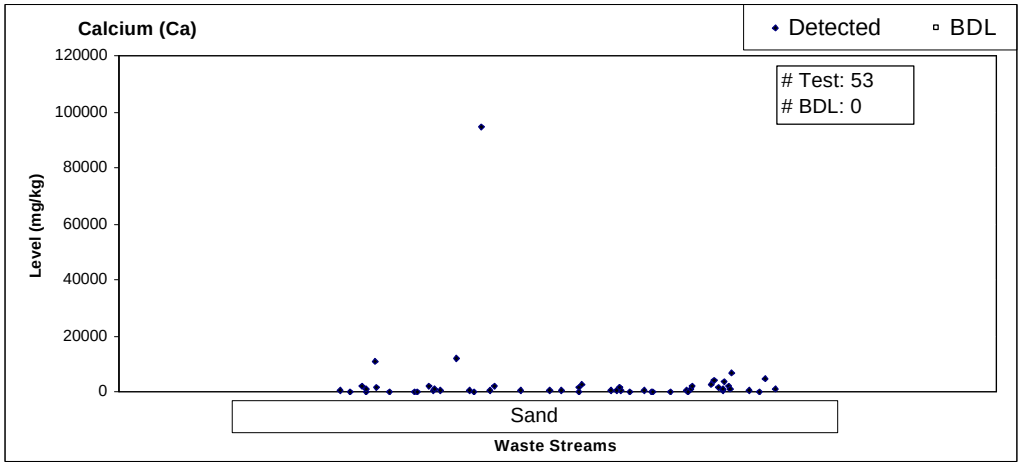

Arsenic(As)
Detected
BDL
Test: 116
BDL: 35
Level (mg/kg)
40
35
30
25
20
15
10
5
0
Sand
Waste Streams

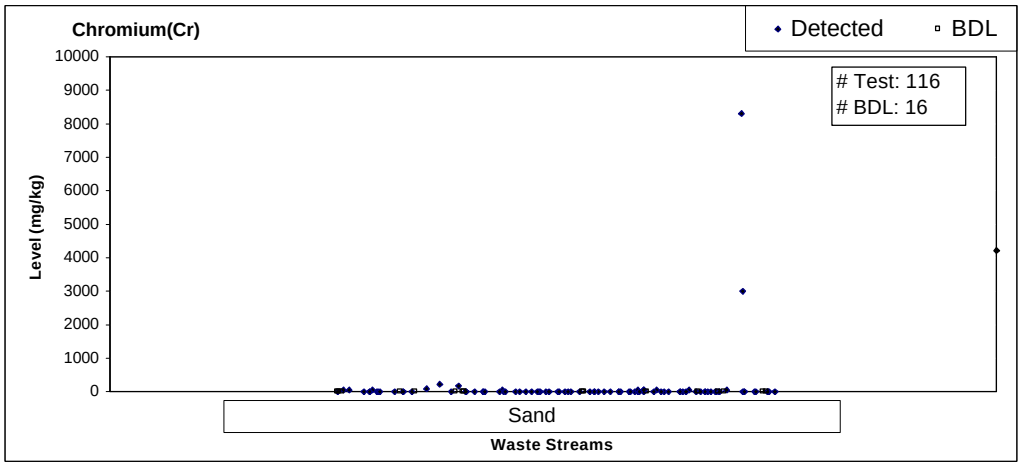

Barium(Ba)
Detected
BDL
Test: 111
BDL: 22
Level (mg/kg)
350
300
250
200
150
100
50
0
Sand
Waste Streams

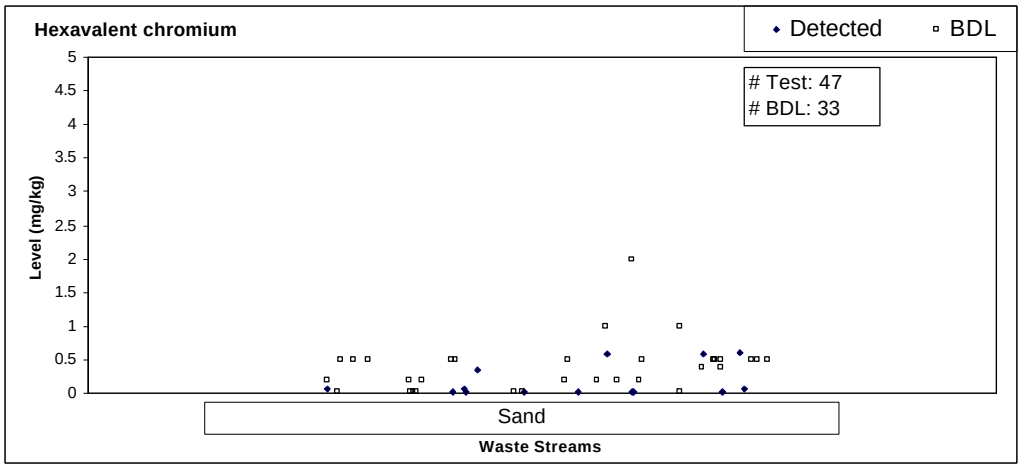

Beryllium (Be)
Detected
BDL
Test: 58
BDL: 51
Level (mg/kg)
4
3.5
3
2.5
2
1.5
1
0.5
0
Sand
Waste Streams

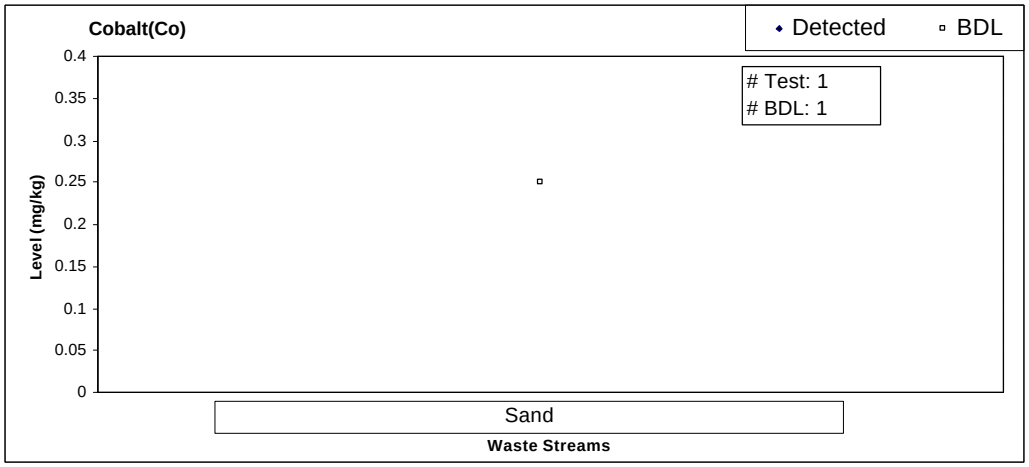

Boron(B)
Detected
BDL
Test: 50
BDL: 31
Level (mg/kg)
2000
1800
1600
1400
1200
1000
800
600
400
200
0
Sand
Waste Streams

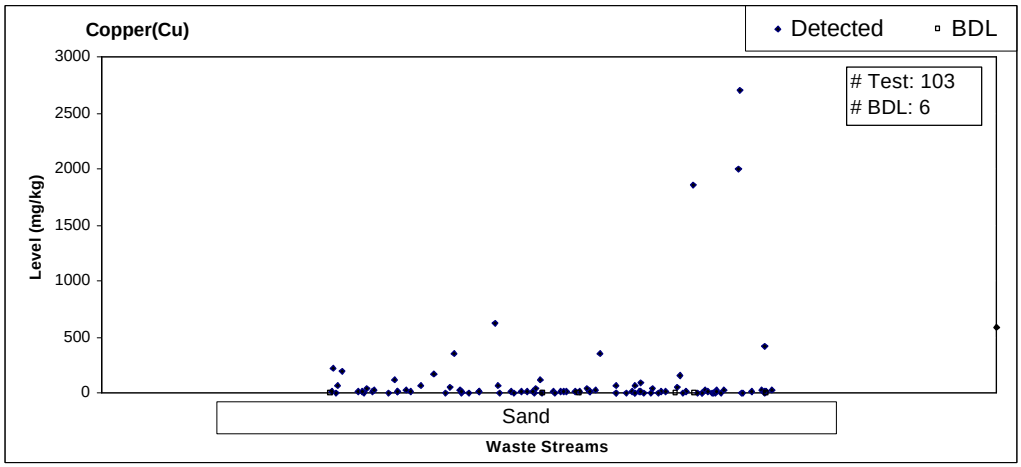

Cadmium(Cd)
Detected
BDL
Test: 107
BDL: 78
Level (mg/kg)
10
9
8
7
6
5
4
3
2
1
0
Sand
Waste Streams

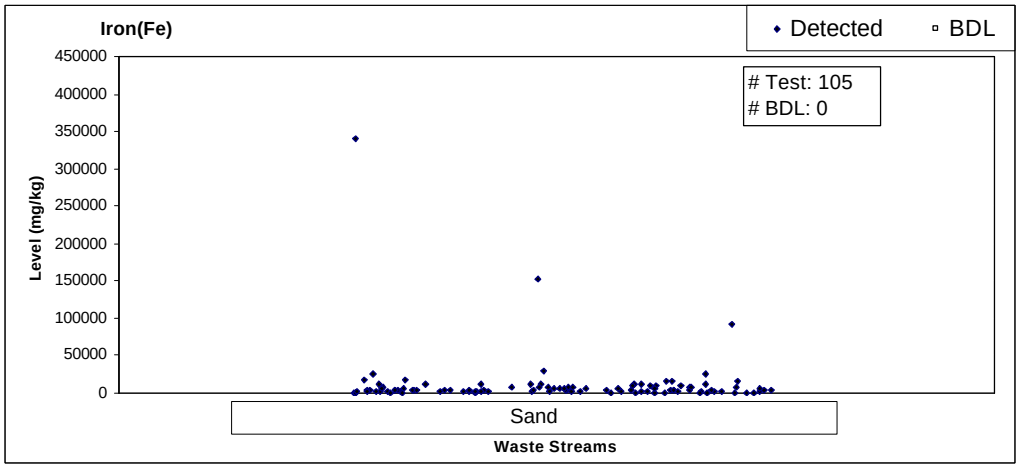

Calcium (Ca)
Detected
BDL
Test: 53
BDL: 0
Level (mg/kg)
120000
100000
80000
60000
40000
20000
0
Sand
Waste Streams

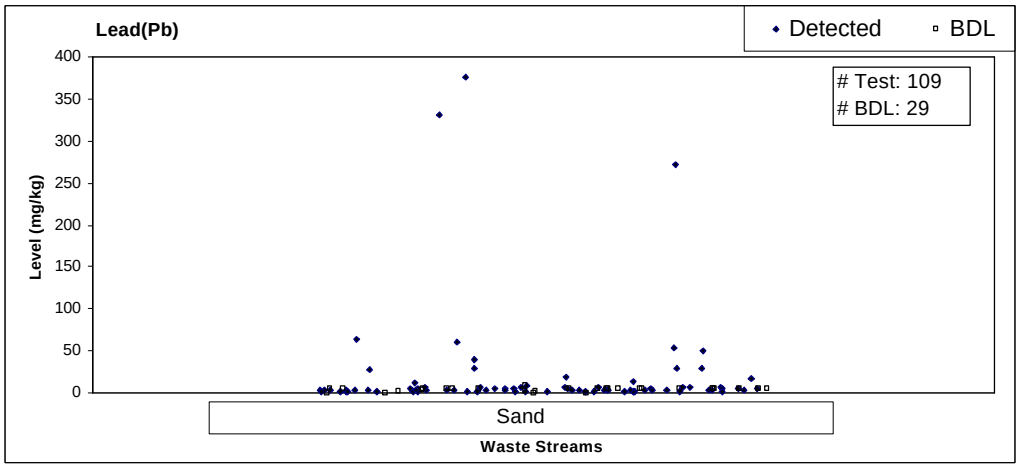

Chromium(Cr)
Detected
BDL
Test: 116
BDL: 16
Level (mg/kg)
10000
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
Sand
Waste Streams

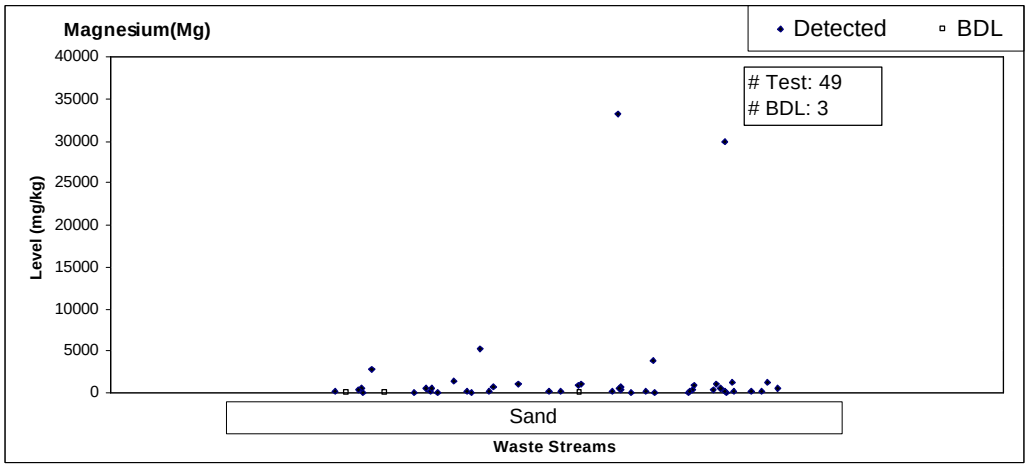

Hexavalent chromium
Detected
BDL
Test: 47
BDL: 33
Level (mg/kg)
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
Sand
Waste Streams

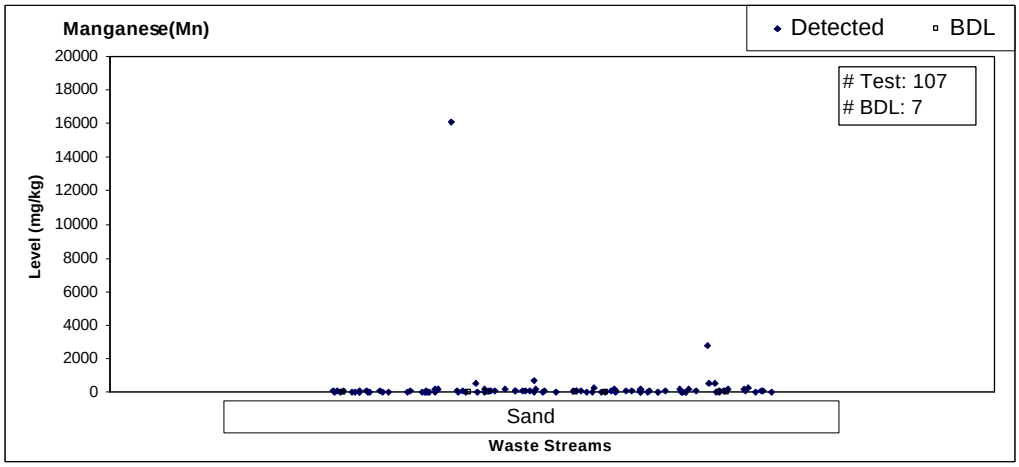

Cobalt(Co)
Detected
BDL
Test: 1
BDL: 1
Level (mg/kg)
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
Sand
Waste Streams

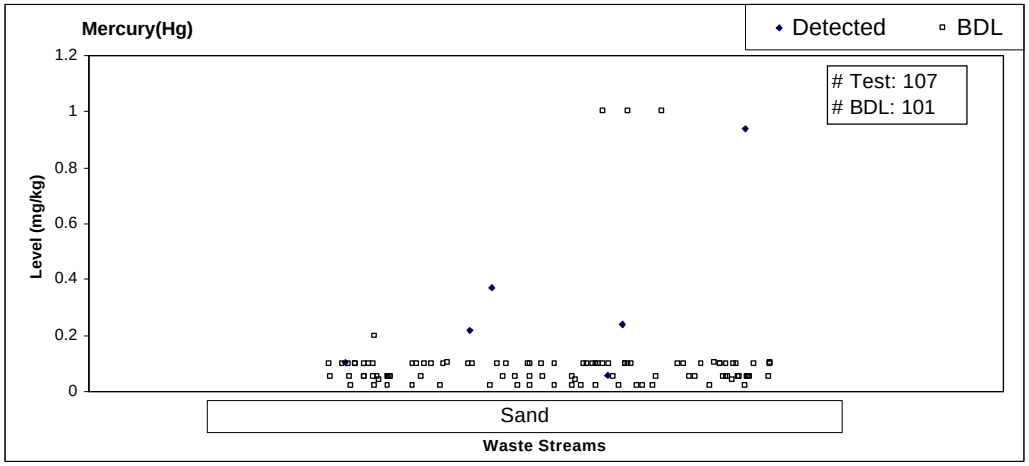

Copper(Cu)
Detected
BDL
Test: 103
BDL: 6
Level (mg/kg)
3000
2500
2000
1500
1000
500
0
Sand
Waste Streams

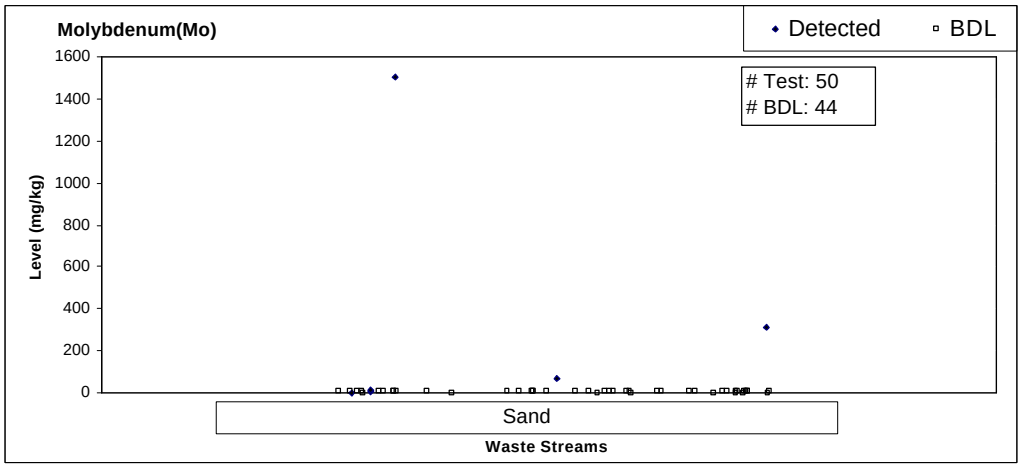

Iron(Fe)
Detected
BDL
Test: 105
BDL: 0
Level (mg/kg)
450000
400000
350000
300000
250000
200000
150000
100000
50000
0
Sand
Waste Streams

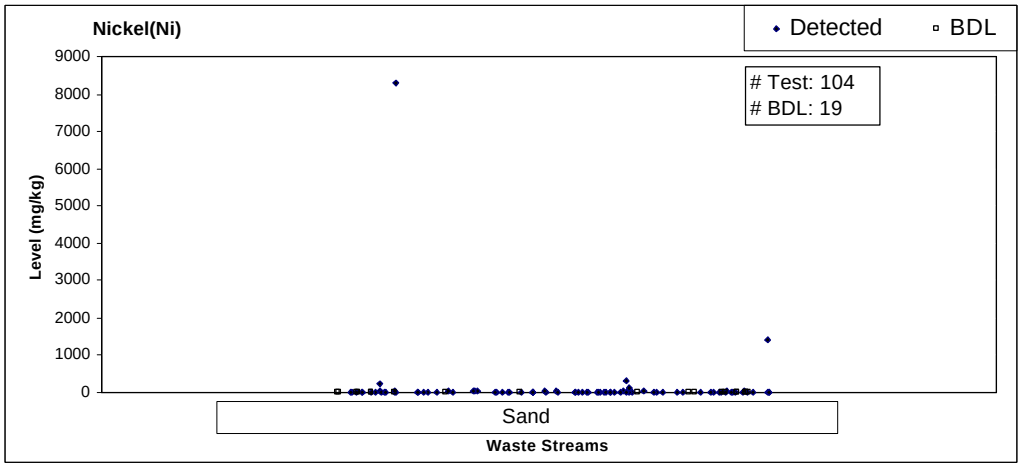

Lead(Pb)
Detected
BDL
Test: 109
BDL: 29
Level (mg/kg)
400
350
300
250
200
150
100
50
0
Sand
Waste Streams

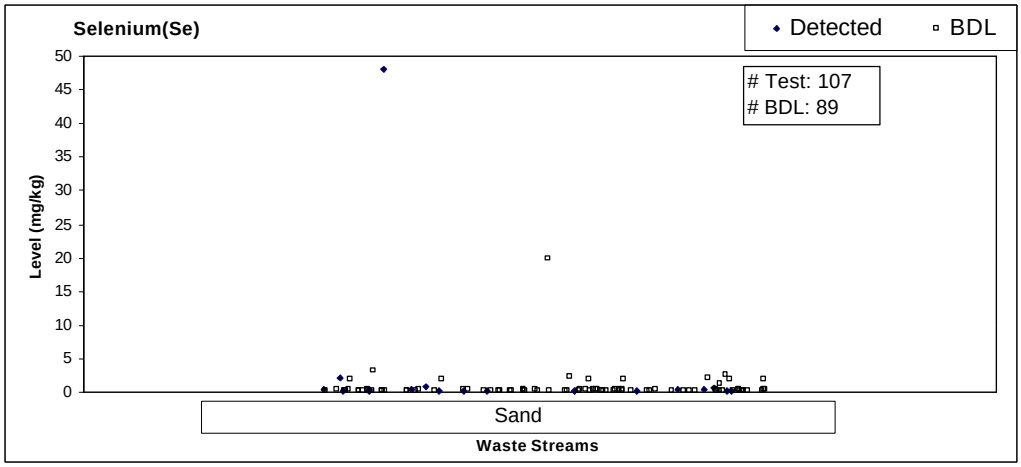

Magnesium(Mg)
Detected
BDL
Test: 49
BDL: 3
Level (mg/kg)
40000
35000
30000
25000
20000
15000
10000
5000
0
Sand
Waste Streams

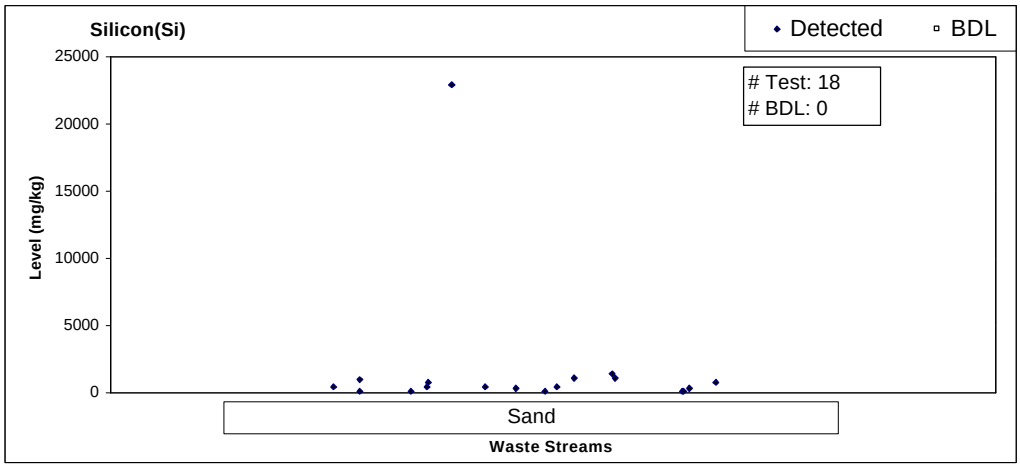

Manganese(Mn)
Detected
BDL
Test: 107
BDL: 7
Level (mg/kg)
20000
18000
16000
14000
12000
10000
8000
6000
4000
2000
0
Sand
Waste Streams

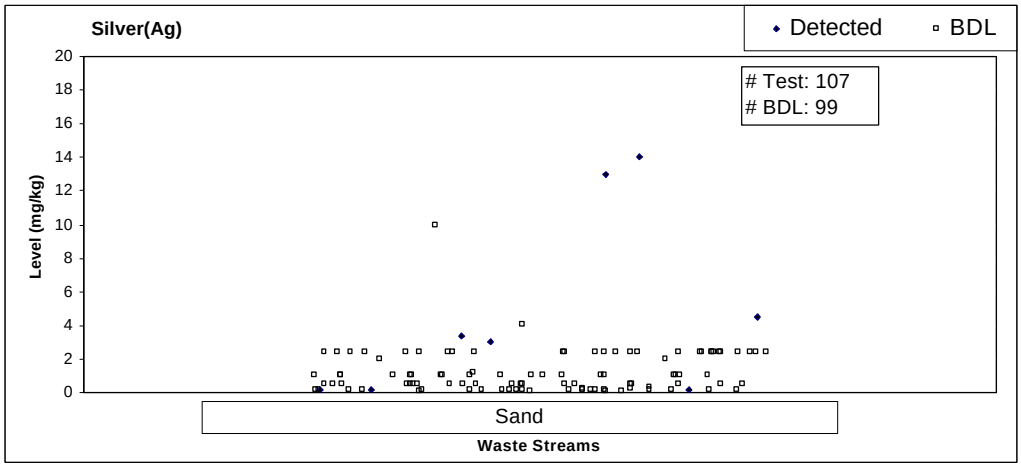

Mercury(Hg)
Detected
BDL
Test: 107
BDL: 101
Level (mg/kg)
1.2
1
0.8
0.6
0.4
0.2
0
Sand
Waste Streams

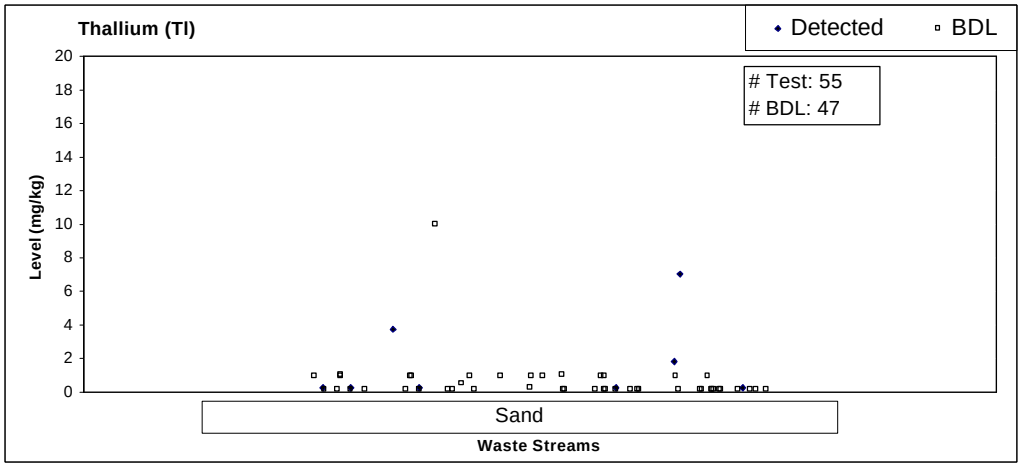

Molybdenum(Mo)
Detected
BDL
Test: 50
BDL: 44
Level (mg/kg)
1600
1400
1200
1000
800
600
400
200
0
Sand
Waste Streams


Nickel(Ni)
Detected
BDL
Test: 104
BDL: 19
Level (mg/kg)
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
Sand
Waste Streams


Selenium(Se)
Detected
BDL
Test: 107
BDL: 89
Level (mg/kg)
50
45
40
35
30
25
20
15
10
5
0
Sand
Waste Streams


Silicon(Si)
Detected
BDL
Test: 18
BDL: 0
Level (mg/kg)
25000
20000
15000
10000
5000
0
Sand
Waste Streams


Silver(Ag)
Detected
BDL
Test: 107
BDL: 99
Level (mg/kg)
20
18
16
14
12
10
8
6
4
2
0
Sand
Waste Streams


Thallium (Tl)
Detected
BDL
Test: 55
BDL: 47
Level (mg/kg)
20
18
16
14
12
10
8
6
4
2
0
Sand
Waste Streams

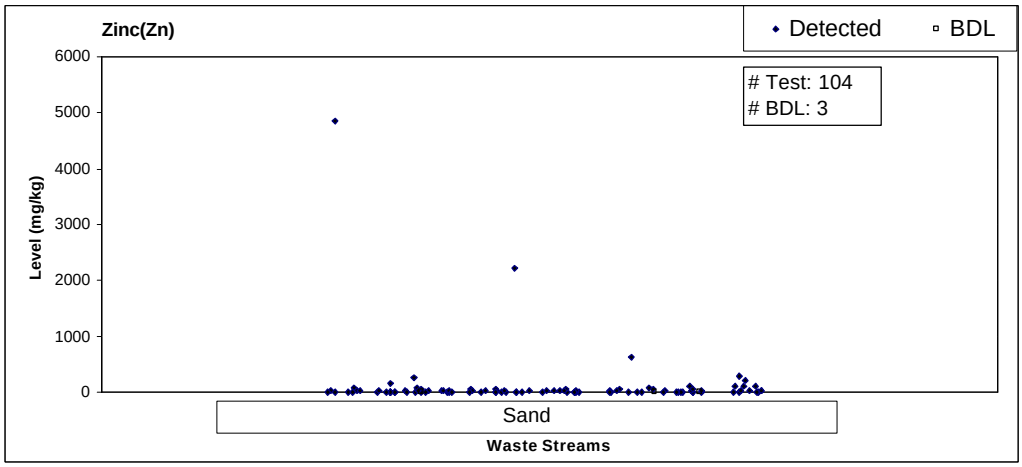
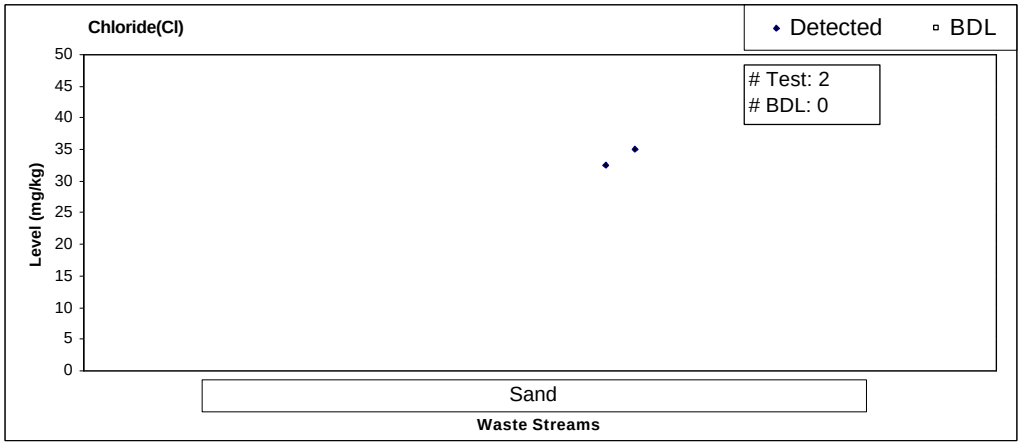
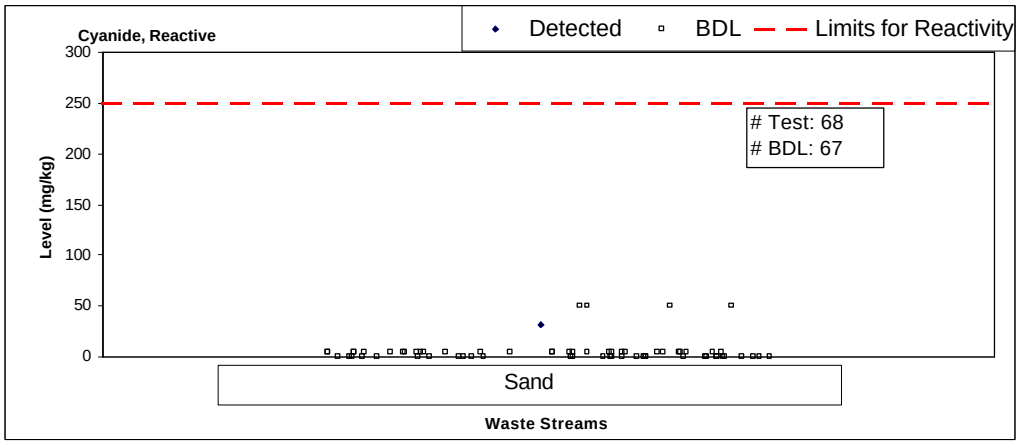


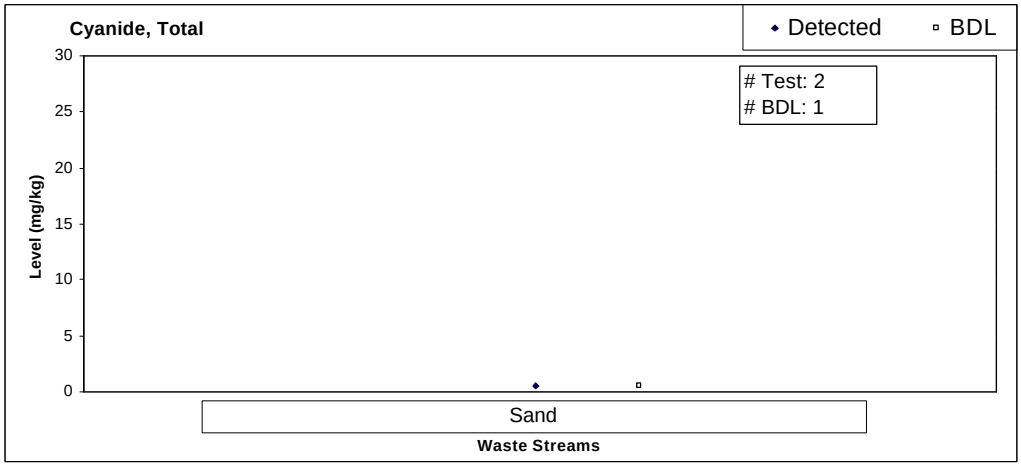
Figure **D-1**: Bulk analysis of trace metallic elements (24 charts)

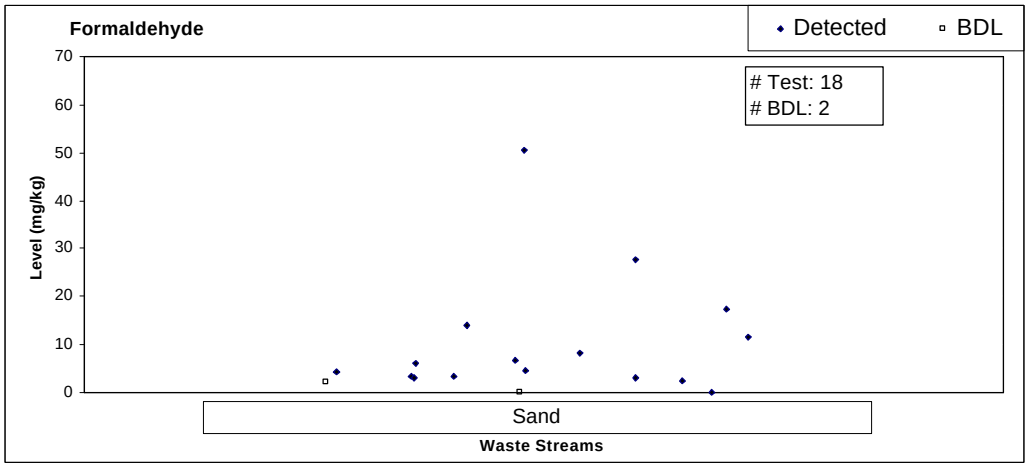
D.2 General Chemical Parameters

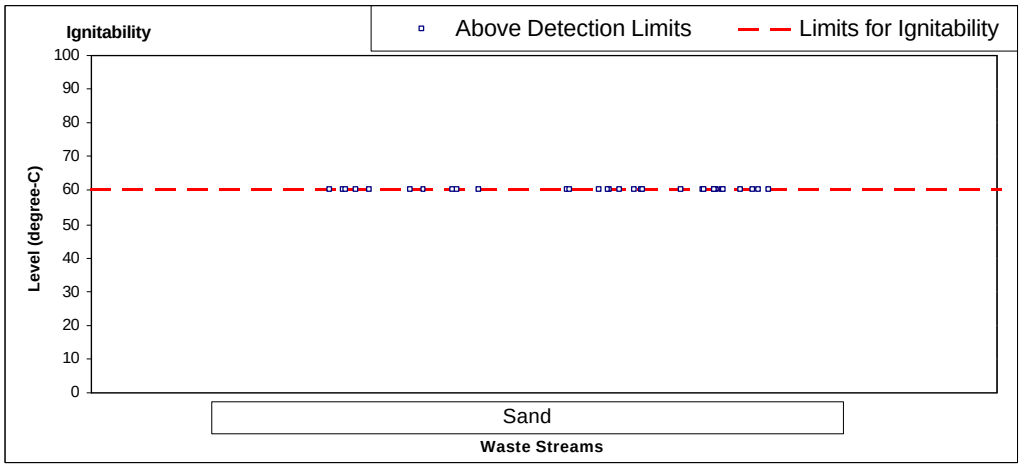
Following a series of 17 charts, grouped into Figure D-2, present the bulk analysis distribution for 17 general chemical parameters in individual waste stream.

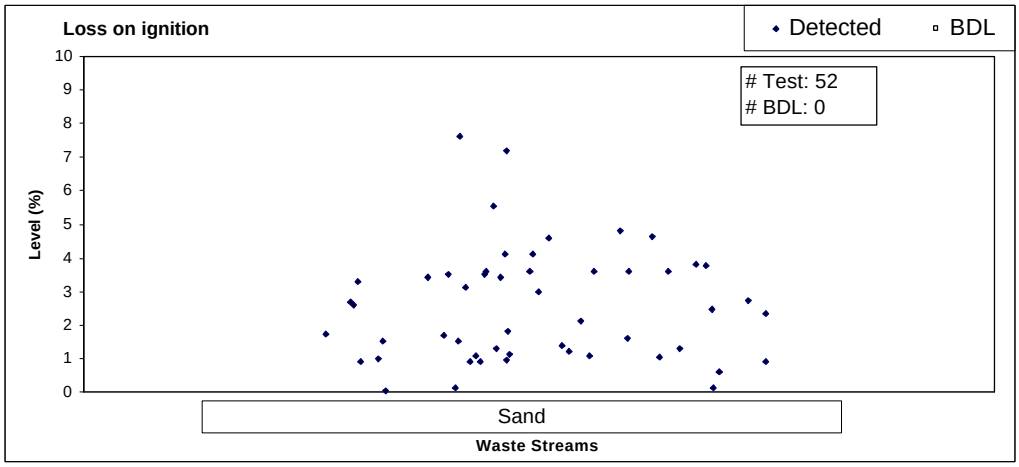


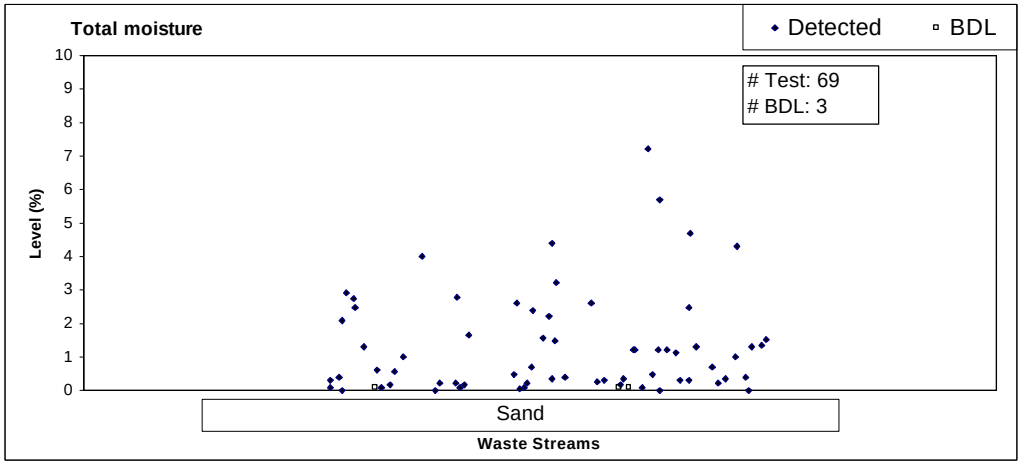

Cyanide, Reactive
Detected
BDL
Limits for Reactivity
300
250
200
150
100
50
0
Level (mg/kg)
Test: 68
BDL: 67
Sand
Waste Streams

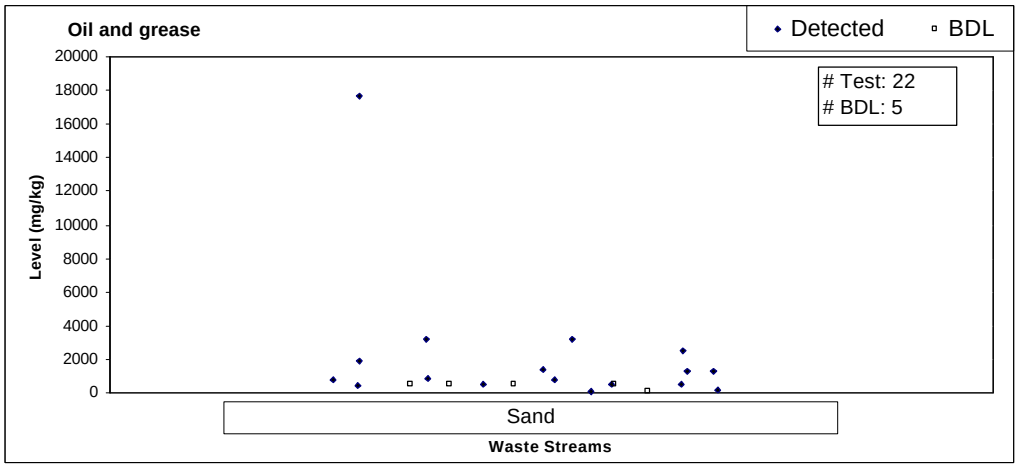

Cyanide, Total
Detected
BDL
30
25
20
15
10
5
0
Level (mg/kg)
Test: 2
BDL: 1
Sand
Waste Streams

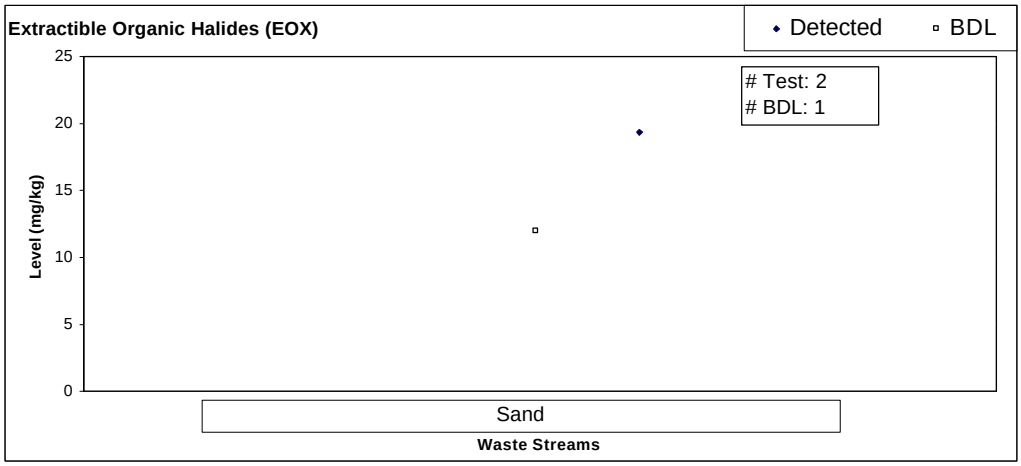

Formaldehyde
Detected
BDL
70
60
50
40
30
20
10
0
Level (mg/kg)
Test: 18
BDL: 2
Sand
Waste Streams

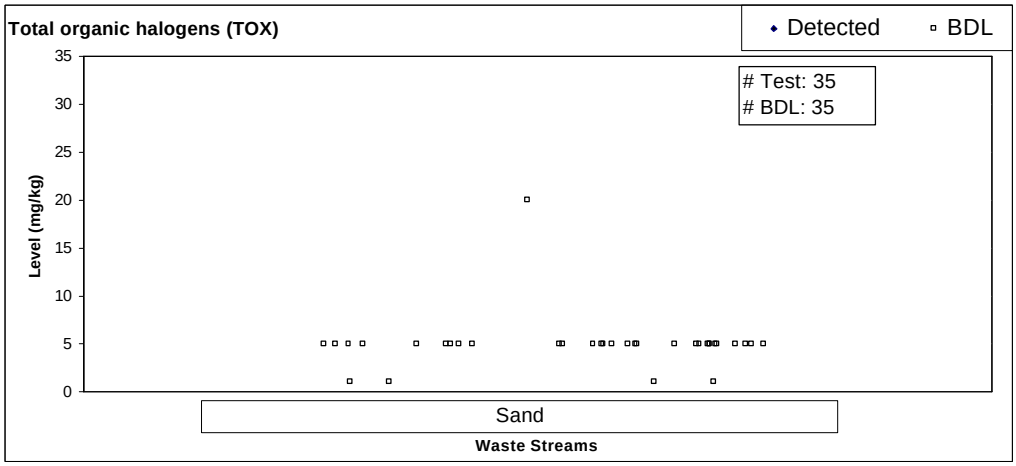

Ignitability
Above Detection Limits
Limits for Ignitability
Level (degree-C)
100
90
80
70
60
50
40
30
20
10
0
Sand
Waste Streams

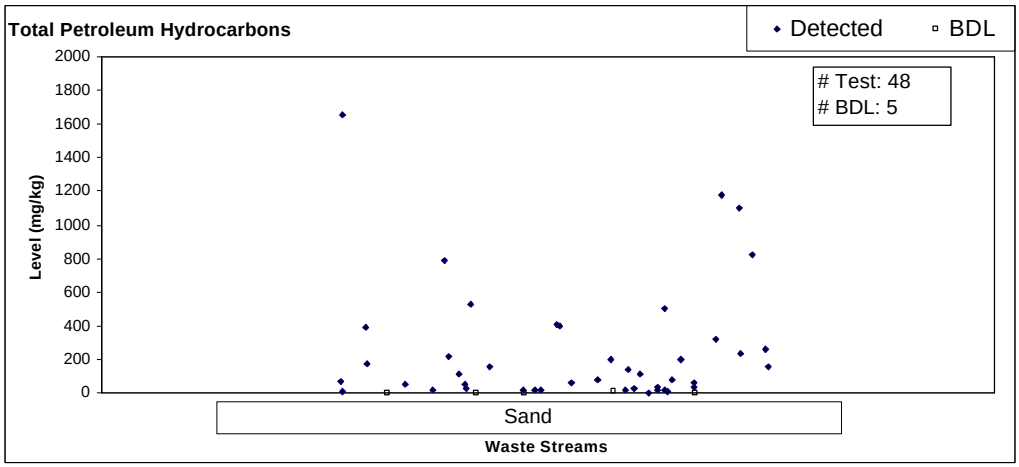

Loss on ignition
Detected
BDL
Test: 52
BDL: 0
Level (%)
10
9
8
7
6
5
4
3
2
1
0
Sand
Waste Streams

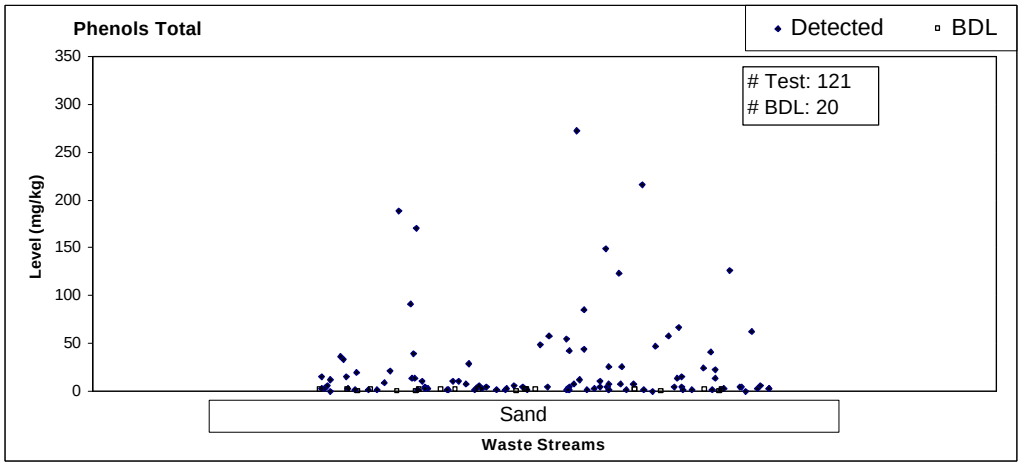

Total moisture
Detected
BDL
Test: 69
BDL: 3
Level (%)
10
9
8
7
6
5
4
3
2
1
0
Sand
Waste Streams

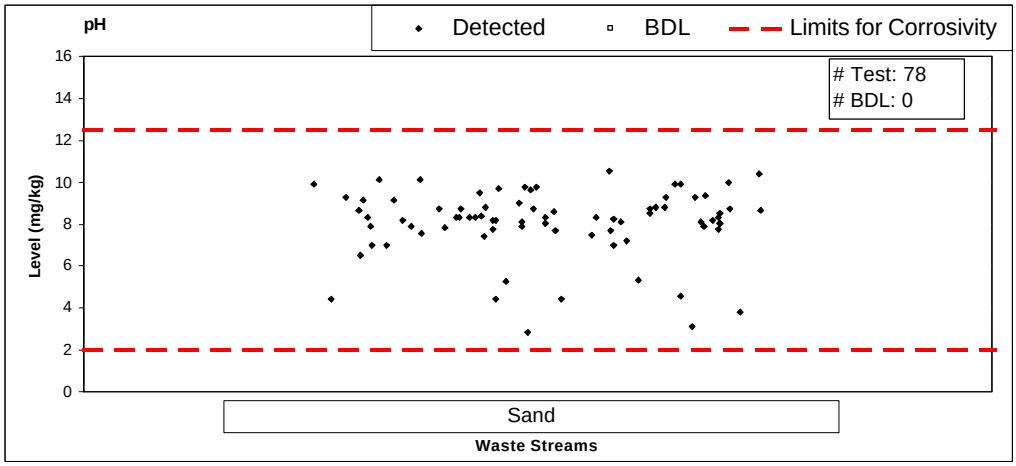

Oil and grease
Detected
BDL
Test: 22
BDL: 5
Level (mg/kg)
20000
18000
16000
14000
12000
10000
8000
6000
4000
2000
0
Sand
Waste Streams

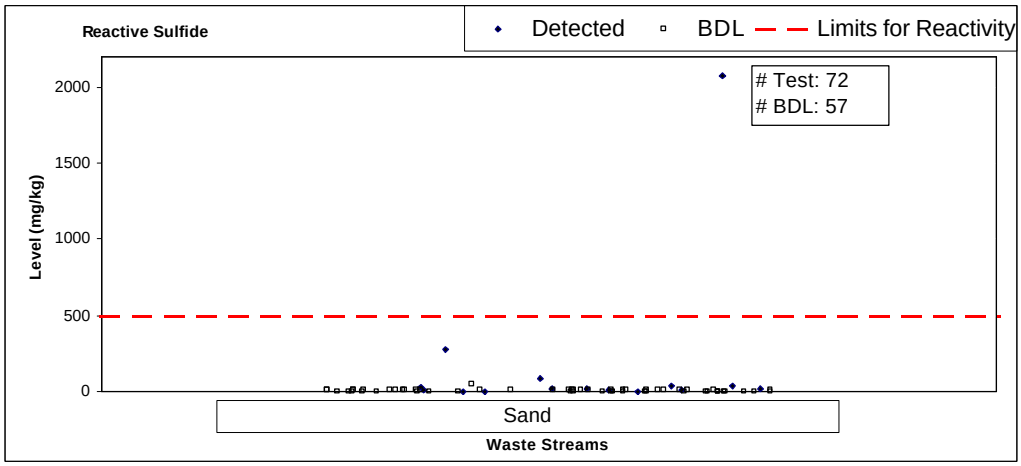

Extractible Organic Halides (EOX)
Detected
BDL
Test: 2
BDL: 1
Level (mg/kg)
25
20
15
10
5
0
Sand
Waste Streams

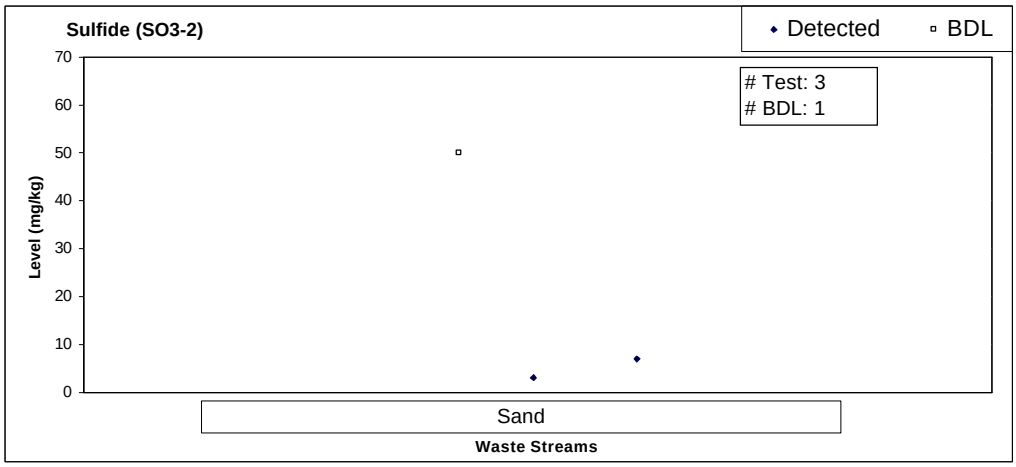

Total organic halogens (TOX)
Detected
BDL
Test: 35
BDL: 35
Level (mg/kg)
35
30
25
20
15
10
5
0
Sand
Waste Streams

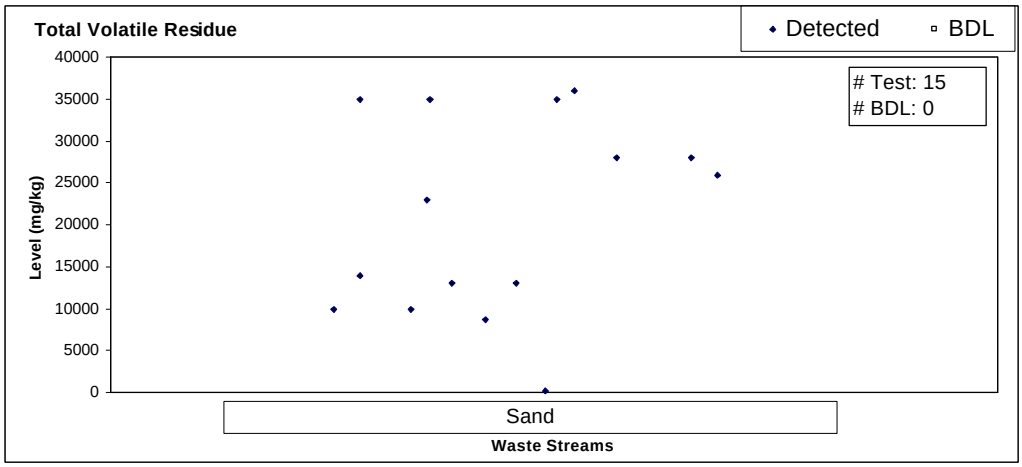

Total Petroleum Hydrocarbons
Detected
BDL
Test: 48
BDL: 5
Level (mg/kg)
2000
1800
1600
1400
1200
1000
800
600
400
200
0
Sand
Waste Streams


Phenols Total
Detected
BDL
Test: 121
BDL: 20
Level (mg/kg)
350
300
250
200
150
100
50
0
Sand
Waste Streams


pH
Detected
BDL
Limits for Corrosivity
Test: 78
BDL: 0
Level (mg/kg)
16
14
12
10
8
6
4
2
0
Sand
Waste Streams


Reactive Sulfide
Detected
BDL
Limits for Reactivity
Test: 72
BDL: 57
Level (mg/kg)
2000
1500
1000
500
0
Sand
Waste Streams


Sulfide (SO3-2)
Detected
BDL
Test: 3
BDL: 1
Level (mg/kg)
70
60
50
40
30
20
10
0
Sand
Waste Streams


Total Volatile Residue
Detected
BDL
Test: 15
BDL: 0
Level (mg/kg)
40000
35000
30000
25000
20000
15000
10000
5000
0
Sand
Waste Streams

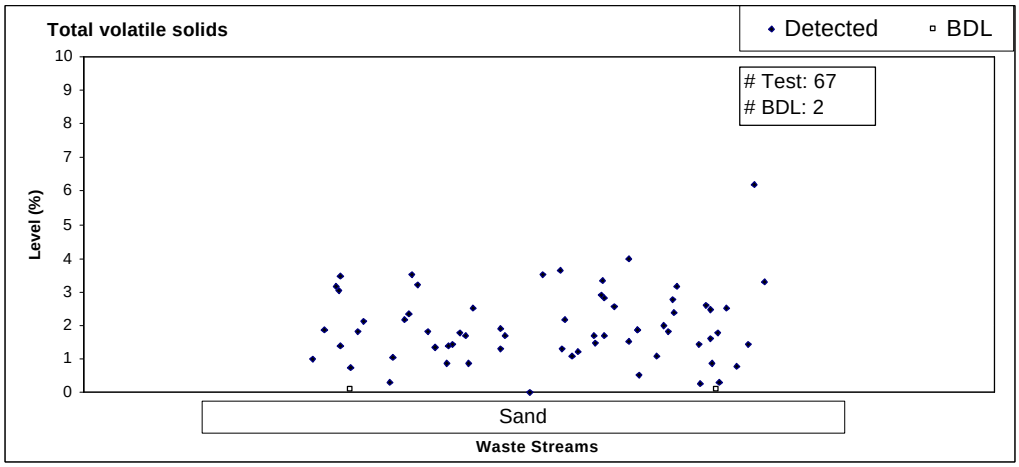
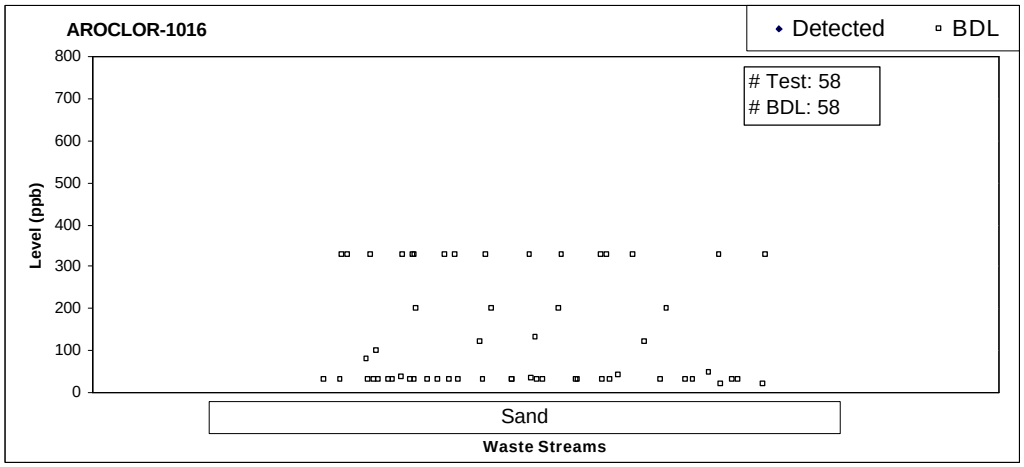
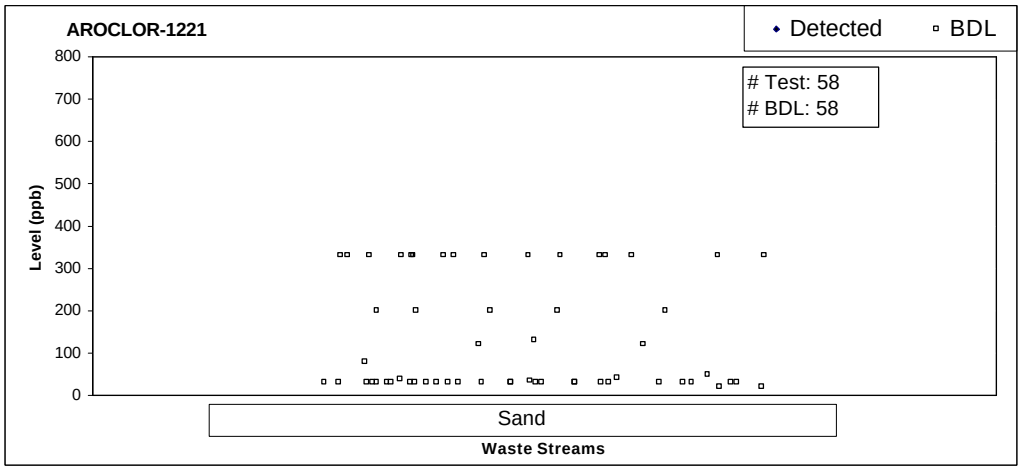


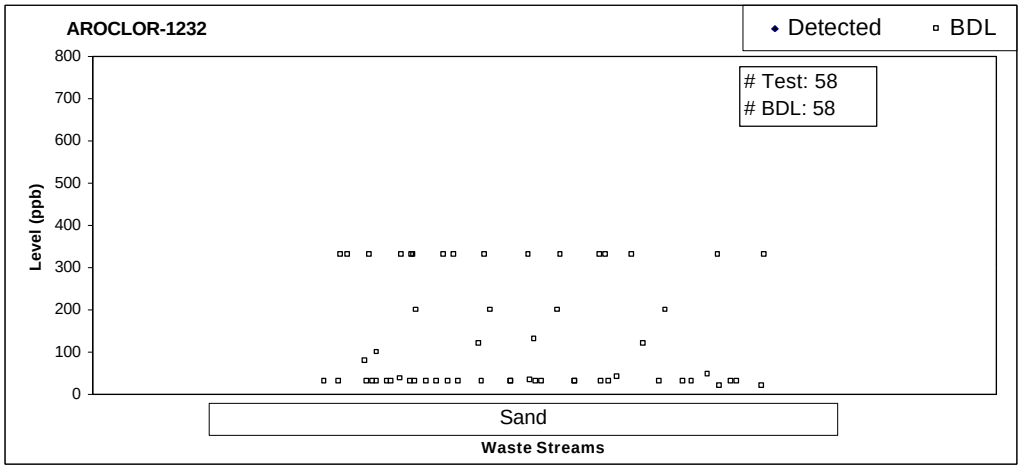
Figure **D-2**: Bulk analysis of general chemical parameters (17 charts)

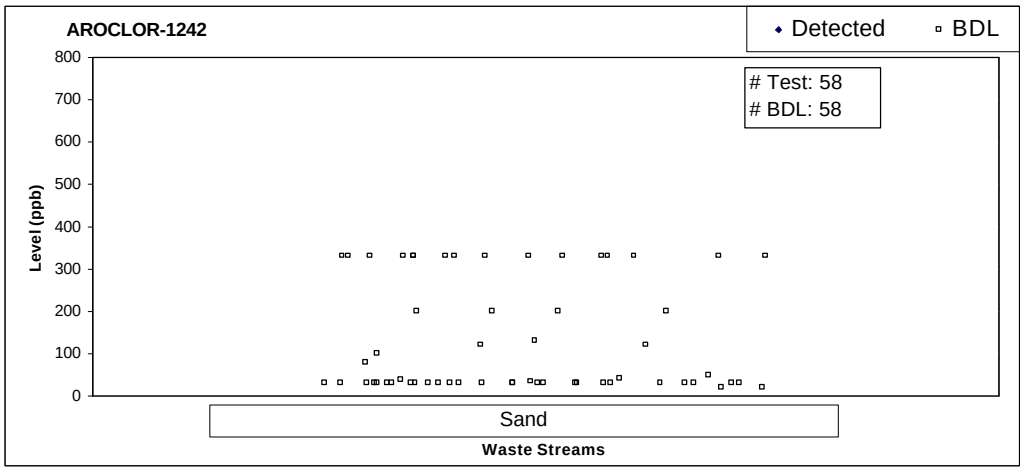
D.3 Organic Compounds

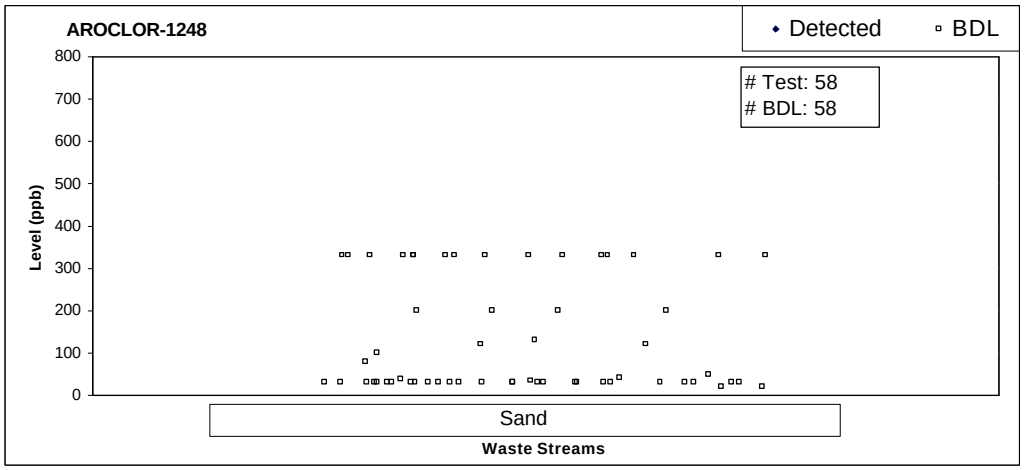
Following a series of 30 charts, grouped into Figure D-3, present the bulk analysis distribution for 30 organic compounds in individual waste stream.

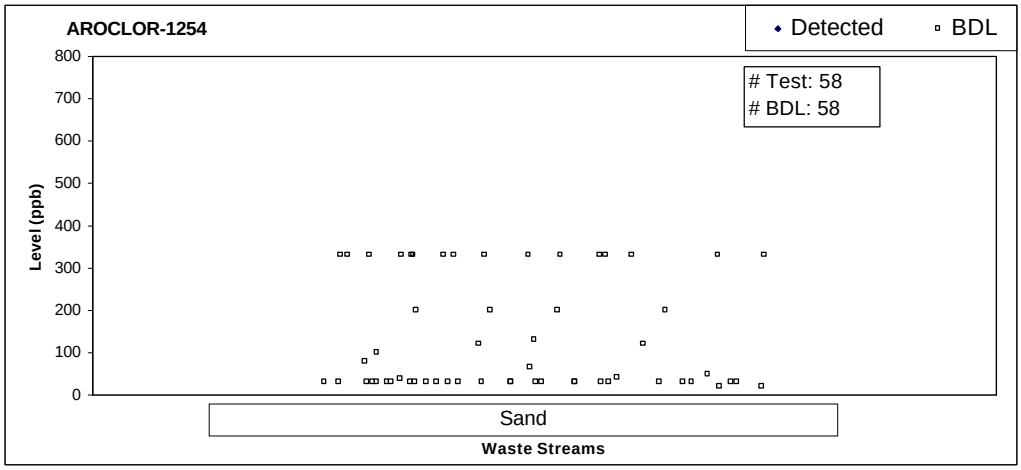


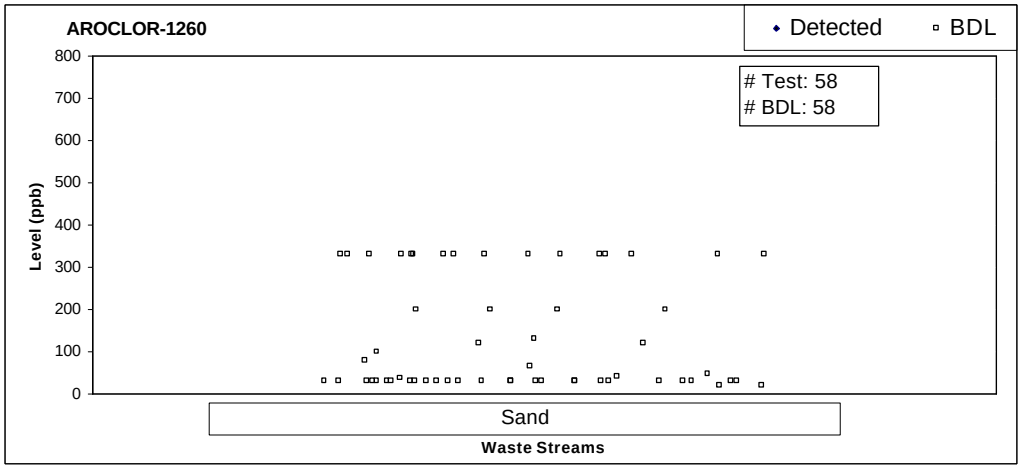

AROCLOR-1221
Detected
BDL
Test: 58
BDL: 58
Level (ppb)
800
700
600
500
400
300
200
100
0
Sand
Waste Streams

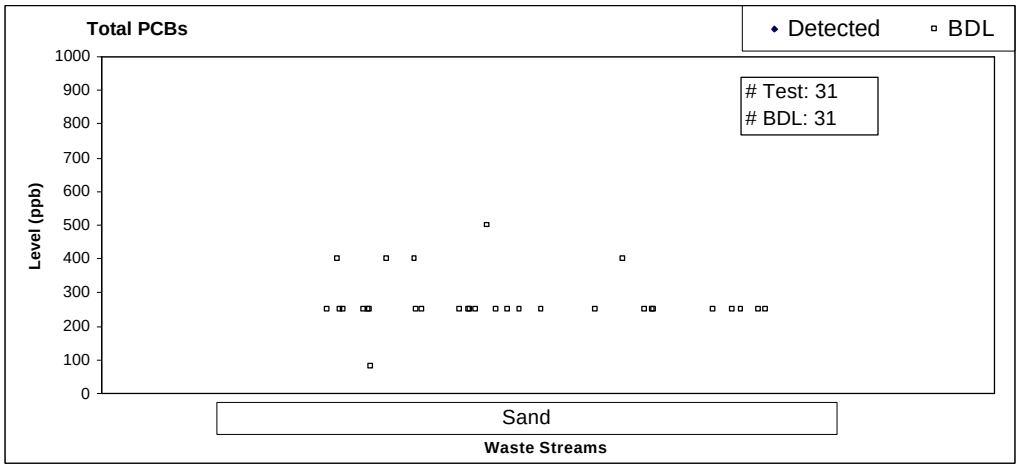

AROCLOR-1232
Detected
BDL
Test: 58
BDL: 58
Level (ppb)
800
700
600
500
400
300
200
100
0
Sand
Waste Streams

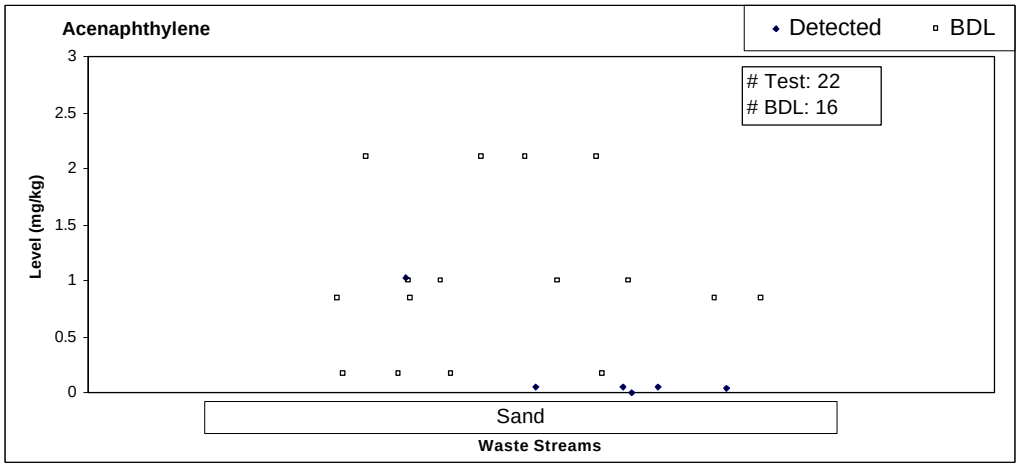

AROCLOR-1242
Detected
BDL
Test: 58
BDL: 58
Level (ppb)
800
700
600
500
400
300
200
100
0
Sand
Waste Streams

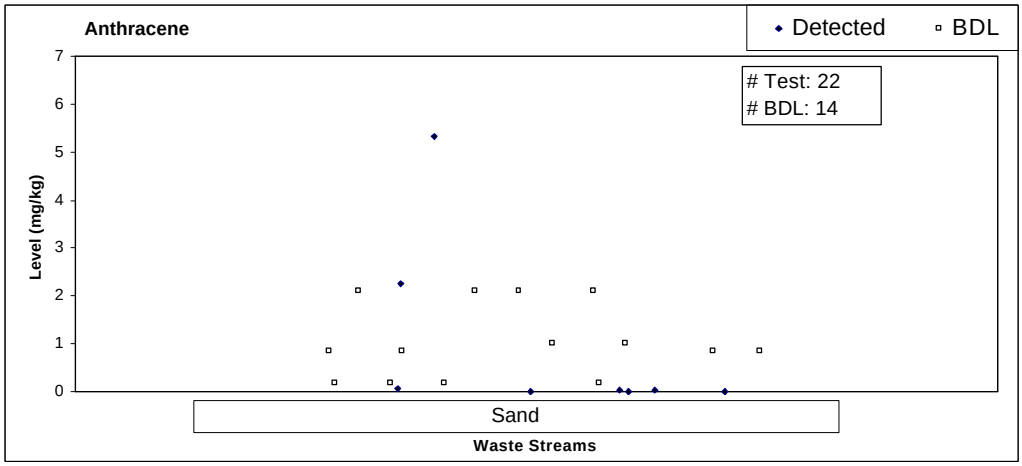

AROCLOR-1248
Detected
BDL
Test: 58
BDL: 58
Level (ppb)
800
700
600
500
400
300
200
100
0
Sand
Waste Streams

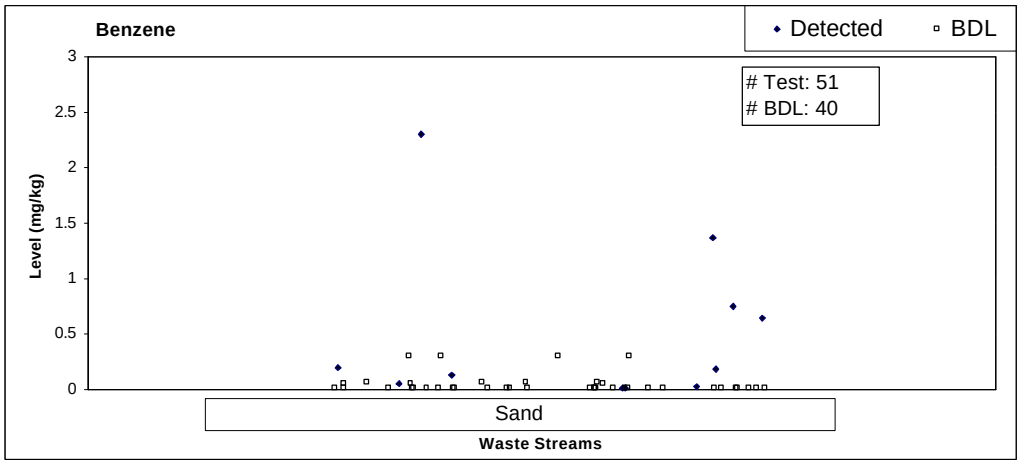

AROCLOR-1254
Detected
BDL
Test: 58
BDL: 58
Level (ppb)
800
700
600
500
400
300
200
100
0
Sand
Waste Streams

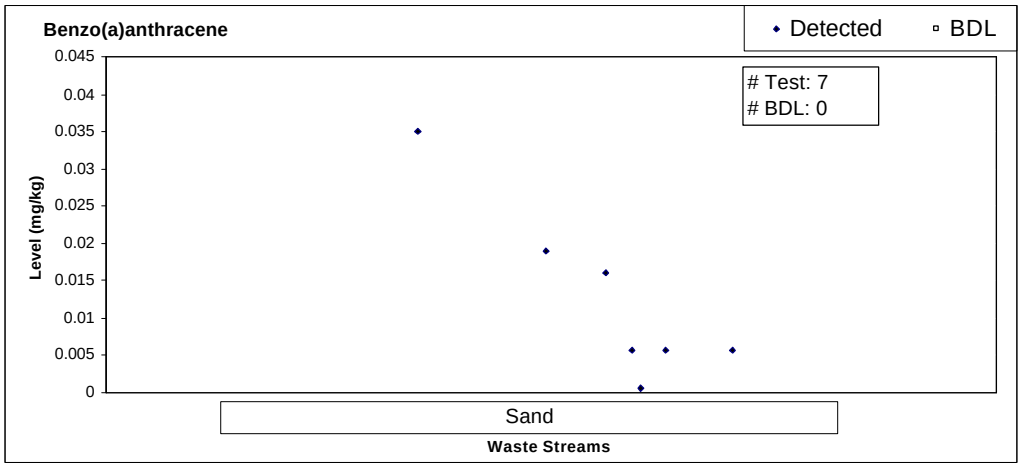

AROCLOR-1260
Detected
BDL
Test: 58
BDL: 58
Level (ppb)
800
700
600
500
400
300
200
100
0
Sand
Waste Streams

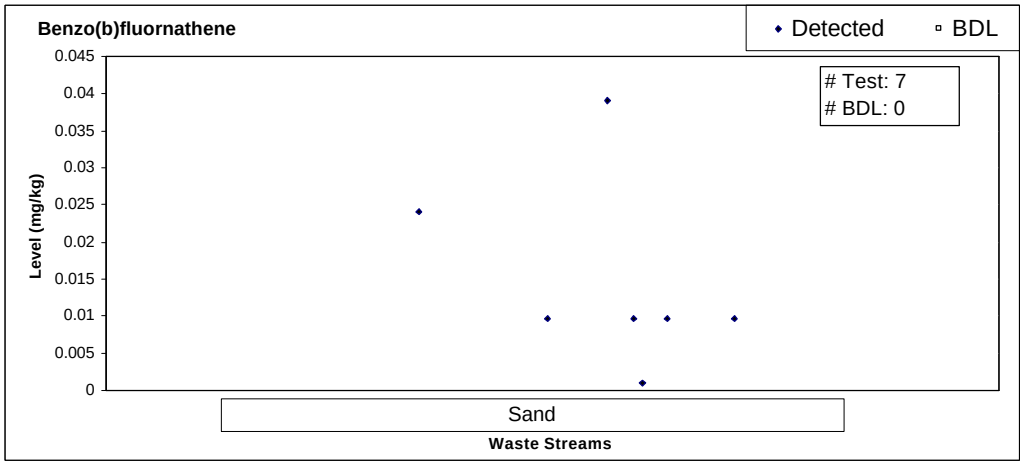

Total PCBs
Detected
BDL
Test: 31
BDL: 31
Level (ppb)
1000
900
800
700
600
500
400
300
200
100
0
Sand
Waste Streams

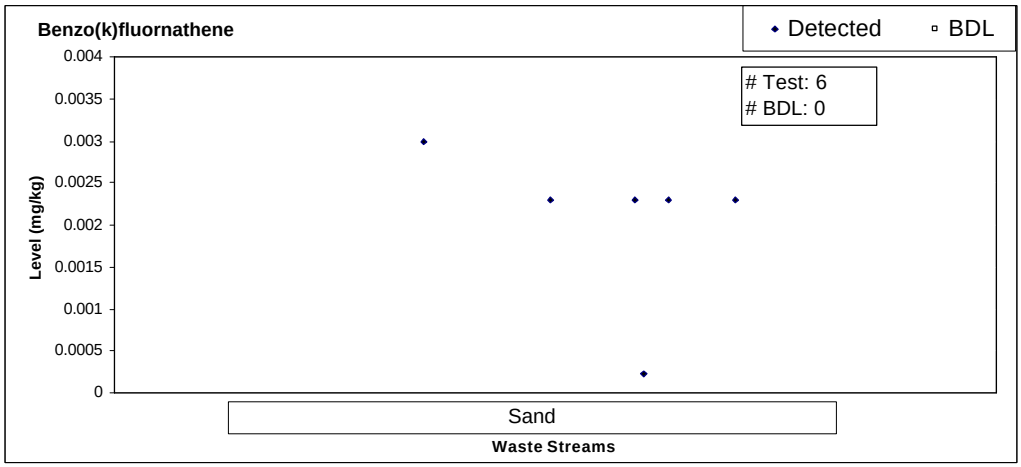

Acenaphthylene
Detected
BDL
Test: 22
BDL: 16
Level (mg/kg)
3
2.5
2
1.5
1
0.5
0
Sand
Waste Streams

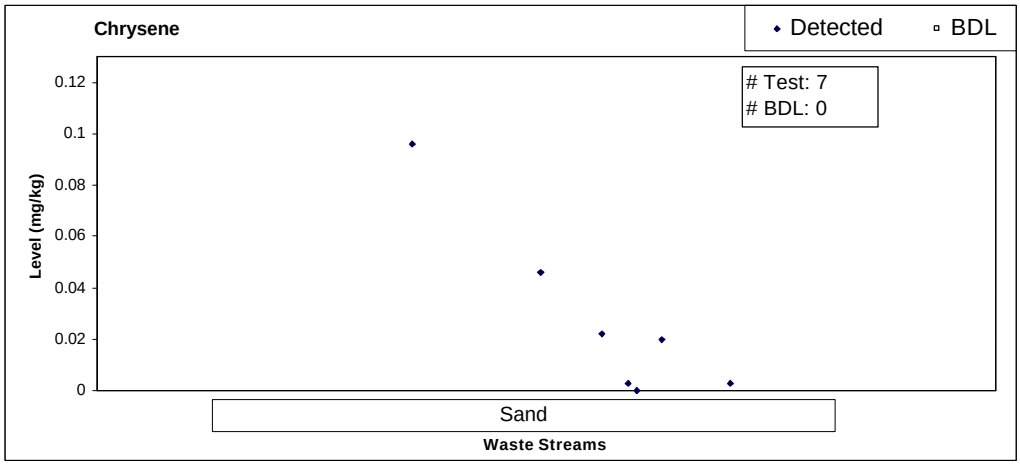

Anthracene
Detected
BDL
Test: 22
BDL: 14
Level (mg/kg)
7
6
5
4
3
2
1
0
Sand
Waste Streams

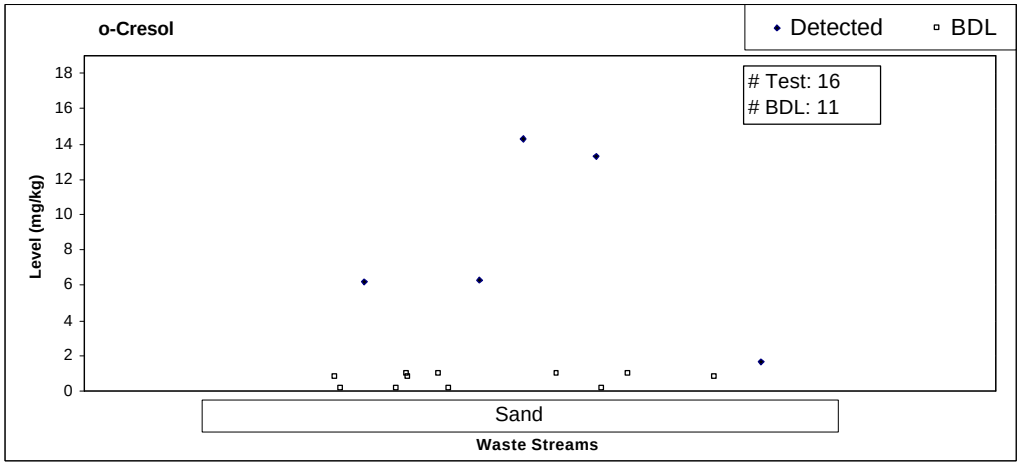

Benzene
Detected
BDL
Test: 51
BDL: 40
Level (mg/kg)
3
2.5
2
1.5
1
0.5
0
Sand
Waste Streams

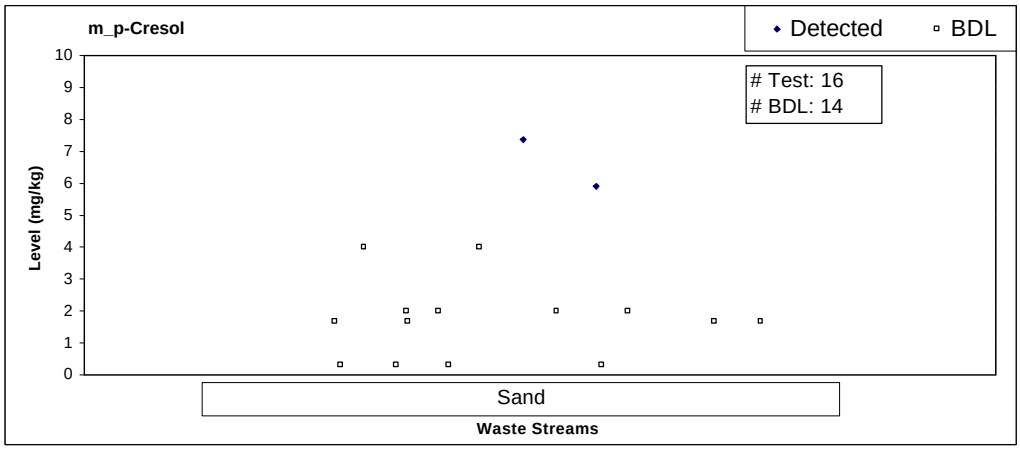

Benzo(a)anthracene
Detected
BDL
Test: 7
BDL: 0
Level (mg/kg)
0.045
0.04
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
Sand
Waste Streams

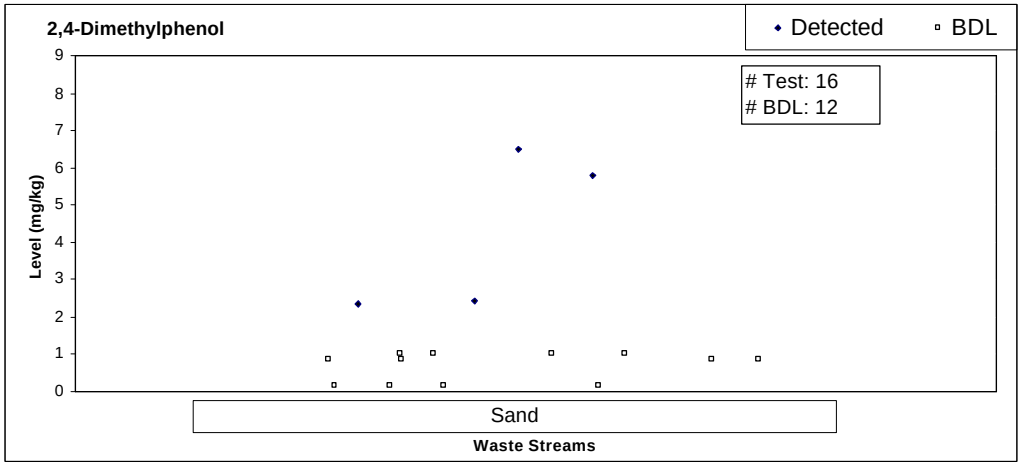

Benzo(b)fluornathene
Detected
BDL
Test: 7
BDL: 0
Level (mg/kg)
0.045
0.04
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
Sand
Waste Streams

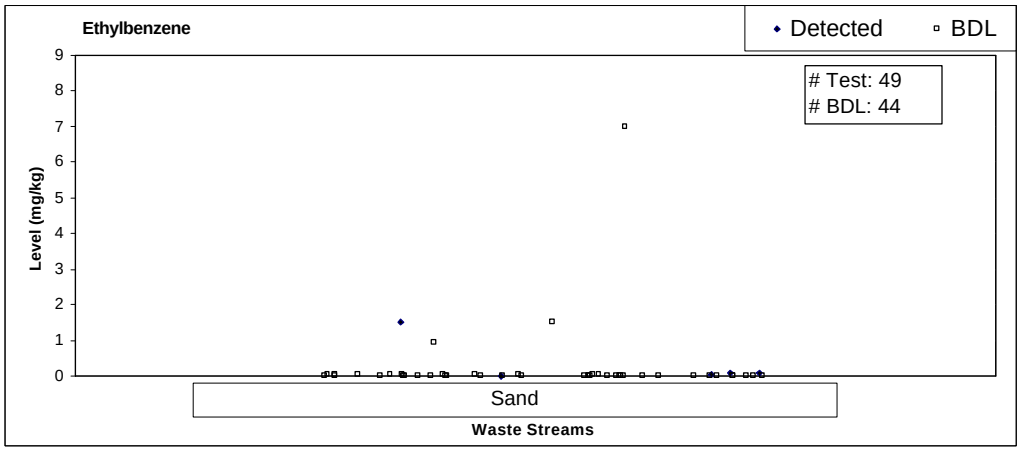

Benzo(k)fluornathene
Detected
BDL
Test: 6
BDL: 0
Level (mg/kg)
0.004
0.0035
0.003
0.0025
0.002
0.0015
0.001
0.0005
0
Sand
Waste Streams

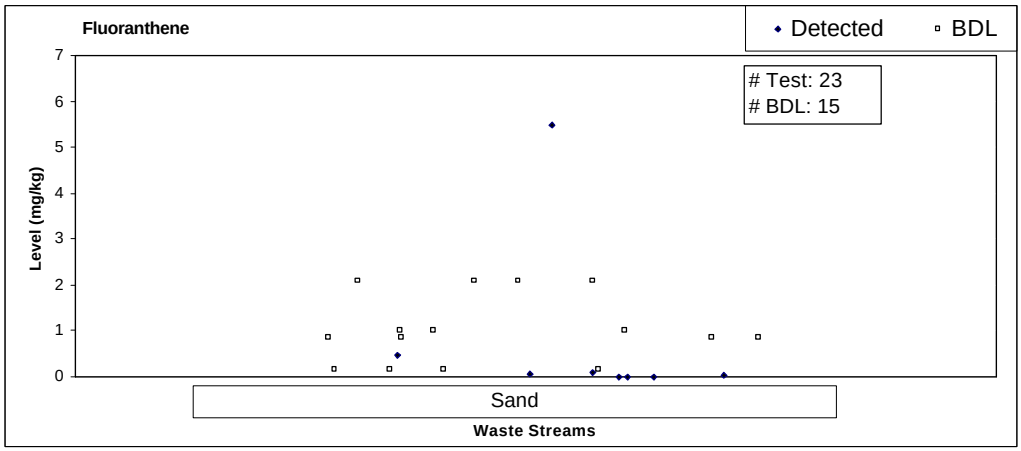

Chrysene
Detected
BDL
Test: 7
BDL: 0
Level (mg/kg)
0.12
0.1
0.08
0.06
0.04
0.02
0
Sand
Waste Streams

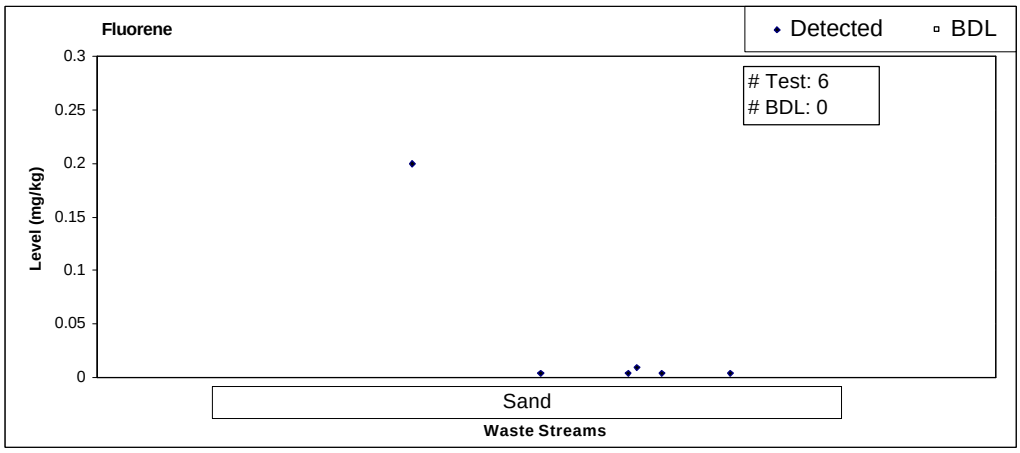

o-Cresol
Detected
BDL
Test: 16
BDL: 11
Level (mg/kg)
18
16
14
12
10
8
6
4
2
0
Sand
Waste Streams

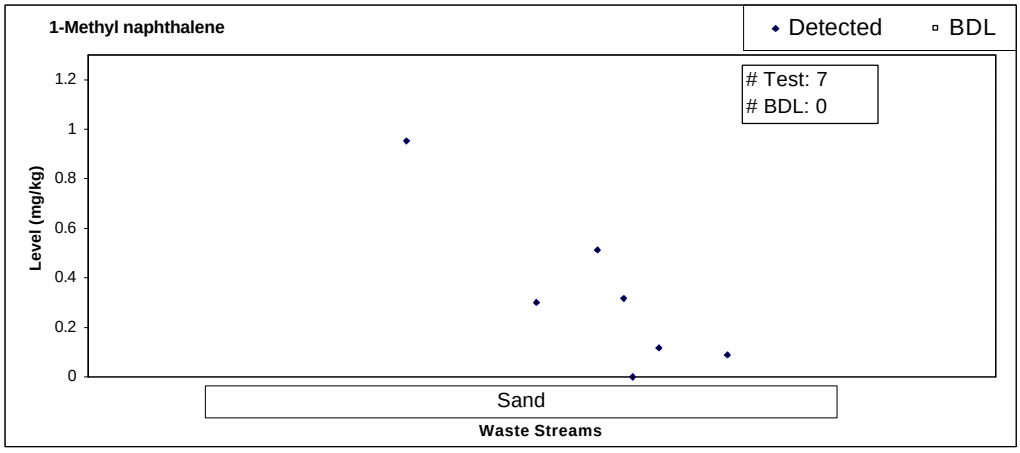

m_p-Cresol
Detected
BDL
Test: 16
BDL: 14
Level (mg/kg)
0
1
2
3
4
5
6
7
8
9
10
Sand
Waste Streams

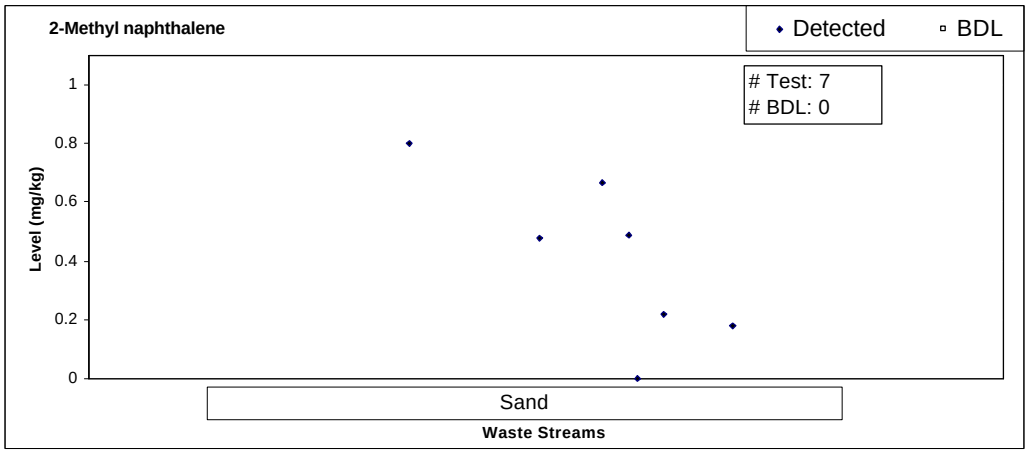

2,4-Dimethylphenol
Detected
BDL
Test: 16
BDL: 12
Level (mg/kg)
0
1
2
3
4
5
6
7
8
9
Sand
Waste Streams

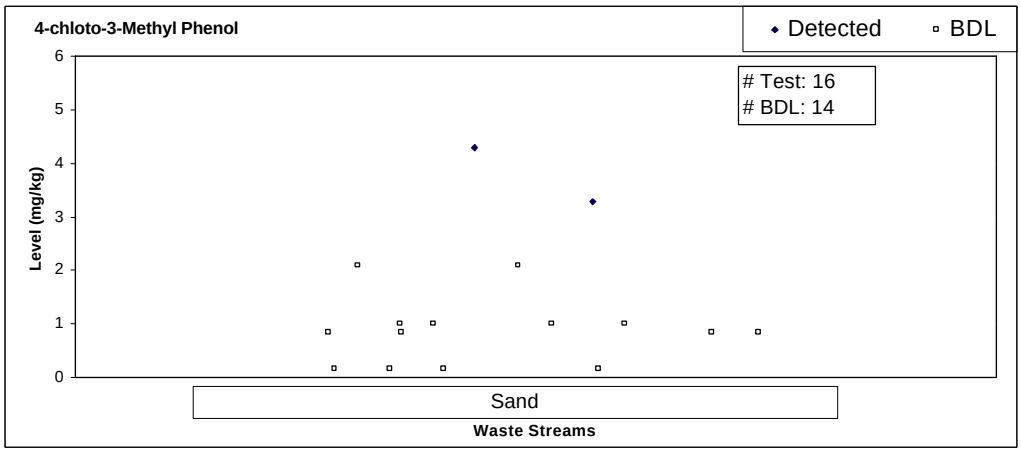

Ethylbenzene
Detected
BDL
Test: 49
BDL: 44
Level (mg/kg)
0
1
2
3
4
5
6
7
8
9
Sand
Waste Streams

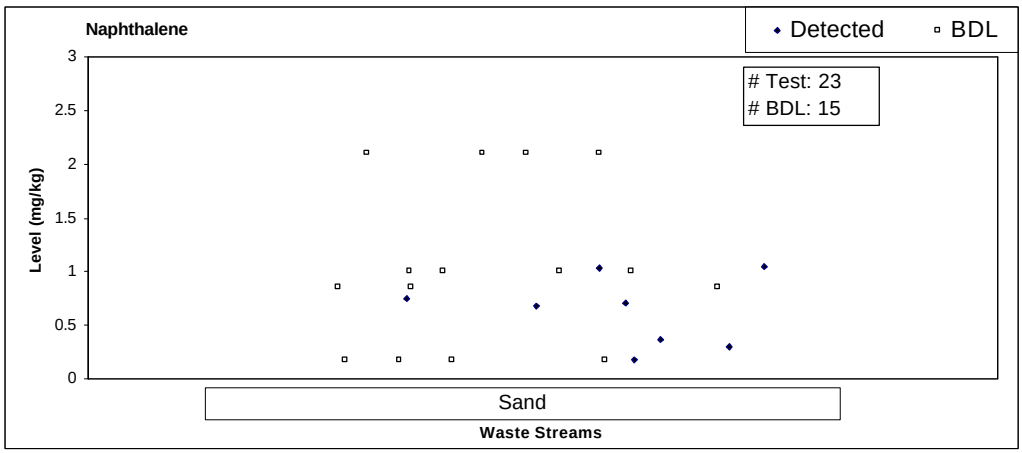

Fluoranthene
Detected
BDL
Test: 23
BDL: 15
Level (mg/kg)
0
1
2
3
4
5
6
7
Sand
Waste Streams

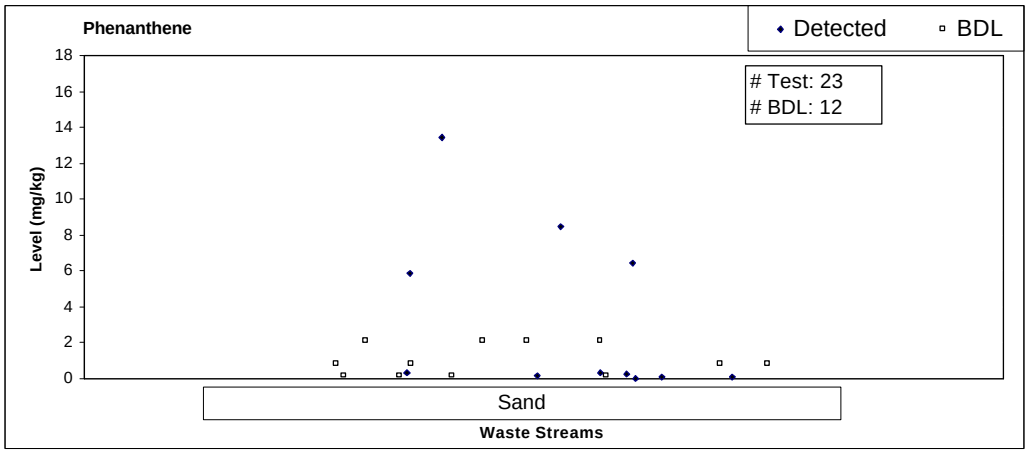

Fluorene
Detected
BDL
Test: 6
BDL: 0
Level (mg/kg)
0
0.05
0.1
0.15
0.2
0.25
0.3
Sand
Waste Streams

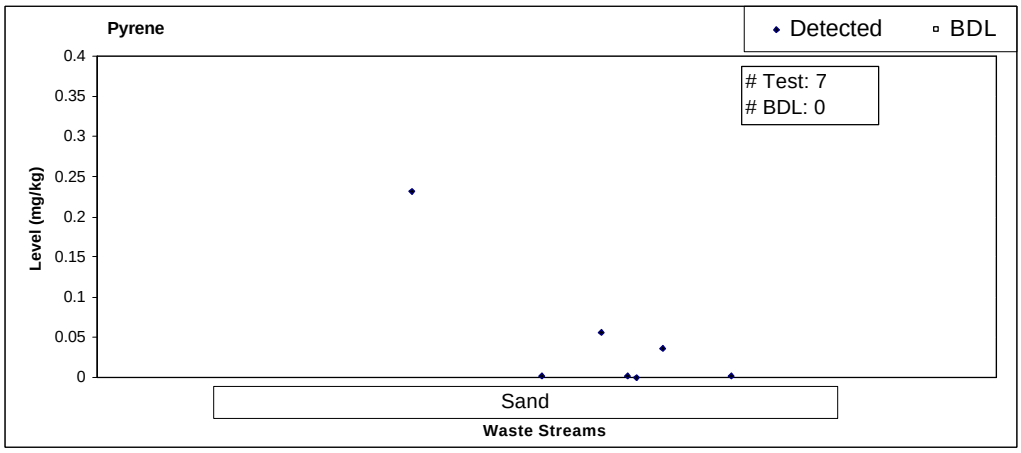

1-Methyl naphthalene
Detected
BDL
Test: 7
BDL: 0
Level (mg/kg)
0
0.2
0.4
0.6
0.8
1
1.2
Sand
Waste Streams

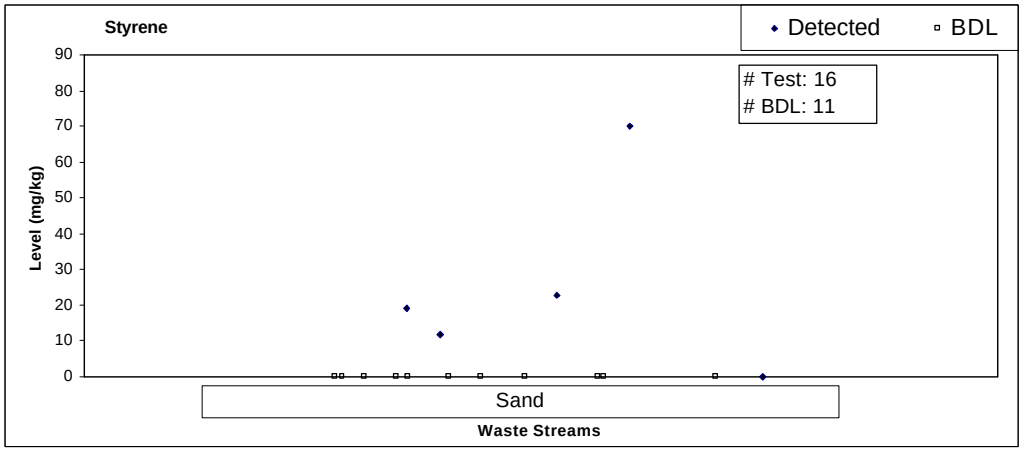

2-Methyl naphthalene
Detected
BDL
Test: 7
BDL: 0
Level (mg/kg)
1
0.8
0.6
0.4
0.2
0
Sand
Waste Streams

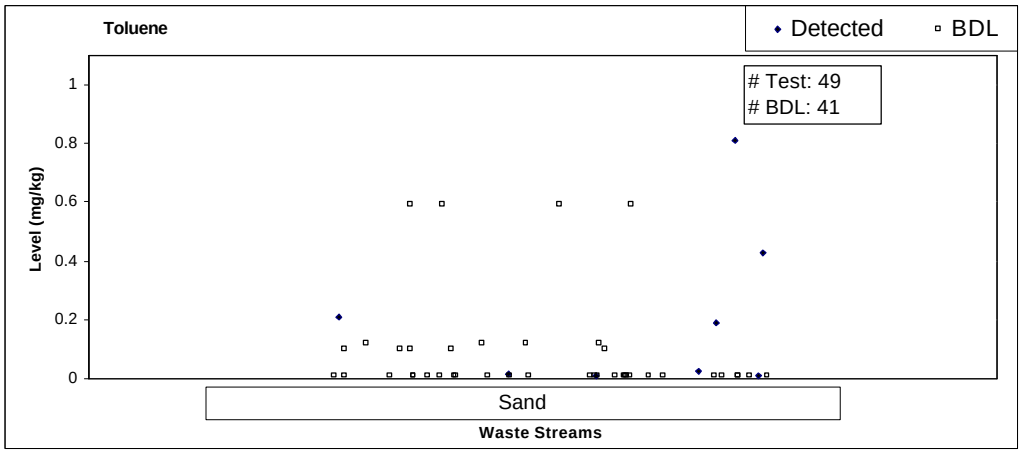

4-chloto-3-Methyl Phenol
Detected
BDL
Test: 16
BDL: 14
Level (mg/kg)
6
5
4
3
2
1
0
Sand
Waste Streams


Naphthalene
Detected
BDL
Test: 23
BDL: 15
Level (mg/kg)
3
2.5
2
1.5
1
0.5
0
Sand
Waste Streams


Phenanthene
Detected
BDL
Test: 23
BDL: 12
Level (mg/kg)
18
16
14
12
10
8
6
4
2
0
Sand
Waste Streams


Pyrene
Detected
BDL
Test: 7
BDL: 0
Level (mg/kg)
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
Sand
Waste Streams


Styrene
Detected
BDL
Test: 16
BDL: 11
Level (mg/kg)
90
80
70
60
50
40
30
20
10
0
Sand
Waste Streams



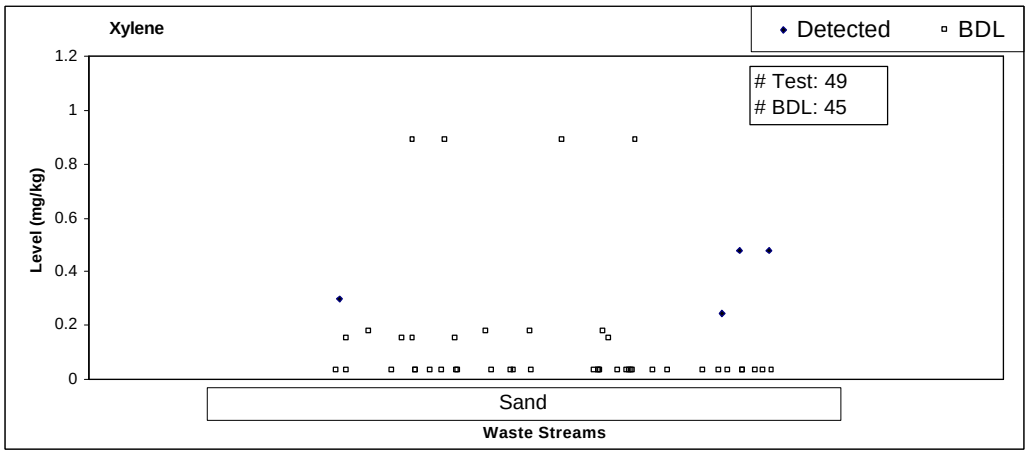


Figure **D-3**: Bulk analysis of organic compounds (30 charts)

Appendix E

Composition of Leachate Extracted from Sand Stream

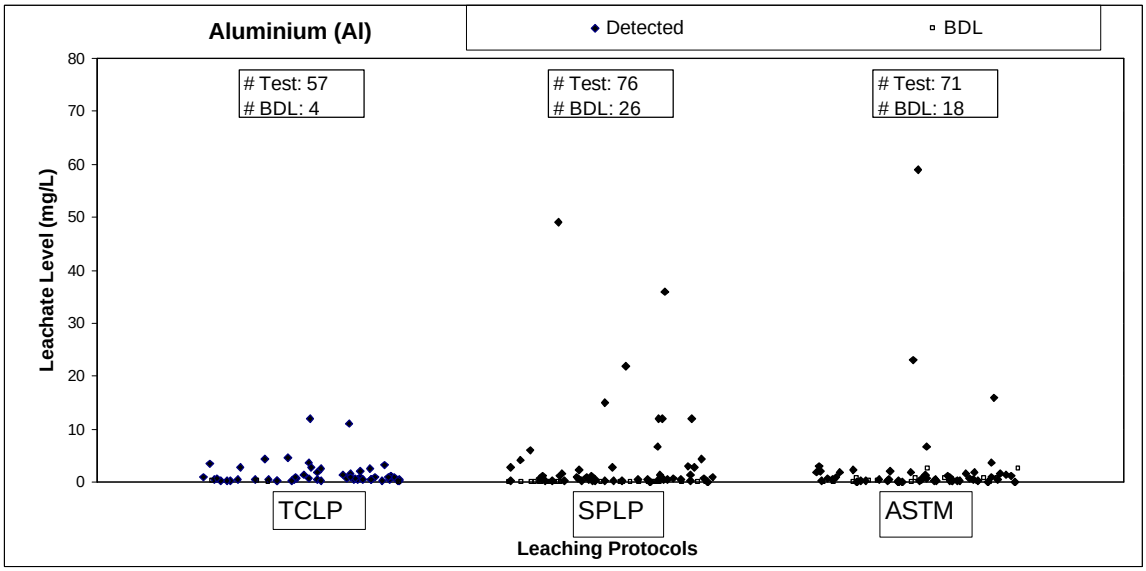
In this appendix, the composition of leachate extracted from foundry sand streams is shown element by element, including 23 metallic elements, 21 general chemical parameters, and 37 organic compounds at trace level. The matrix of the composition is essentially leachate extracted from the waste streams, not as-received waste streams. The waste stream-based analysis is presented in Appendix D.

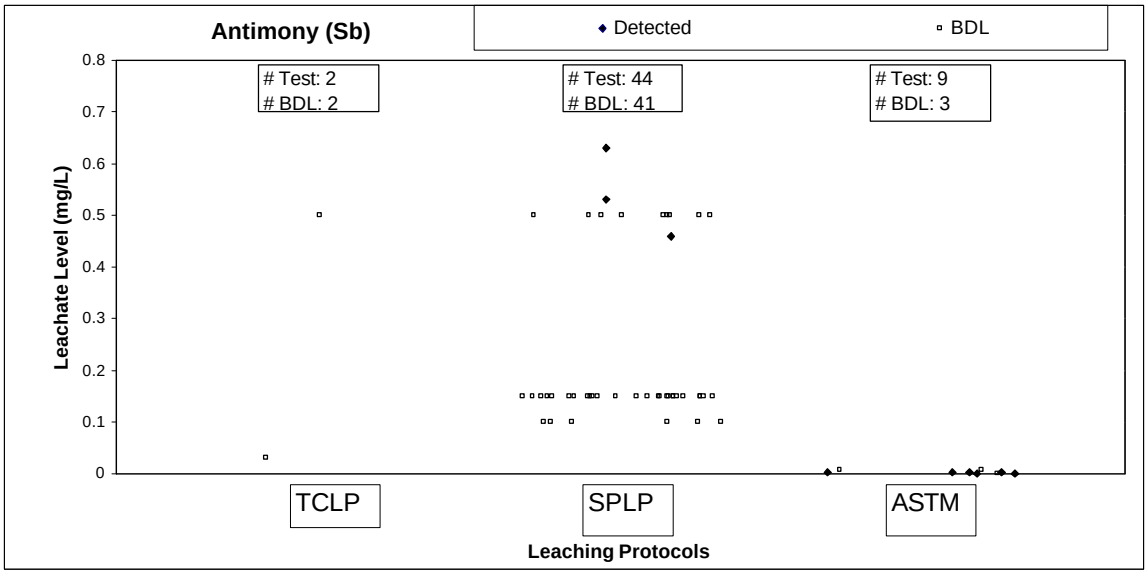
The notes to individual charts are defined as follows:

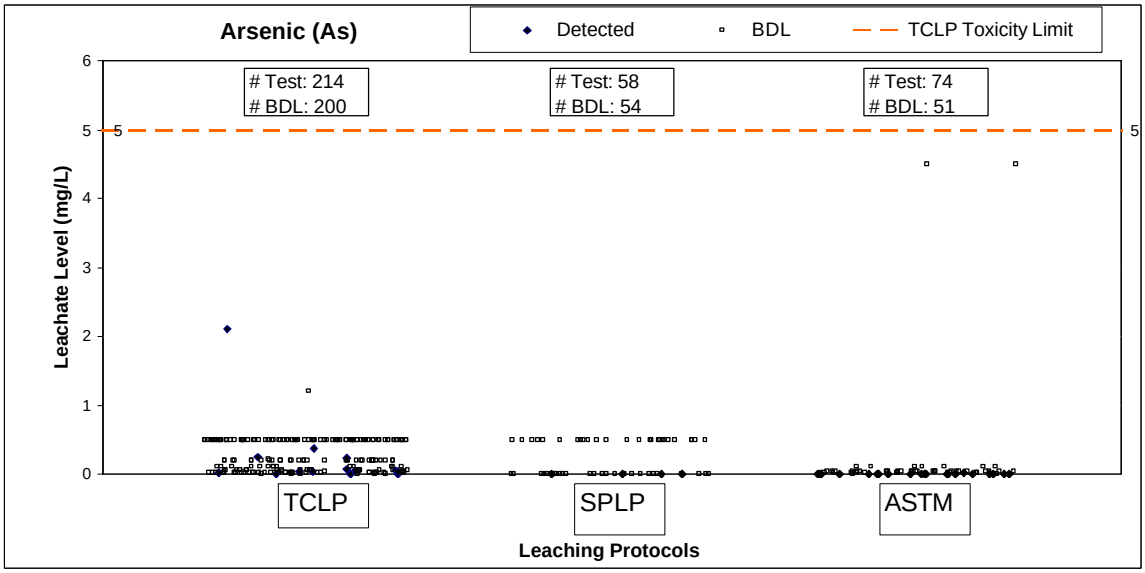
- The number following "# Tests" represents total observations for corresponding leachates;
- The number following "# BDL" represents total censored observations for corresponding leachates;
- The solid diamond legend "♦" represents an uncensored observation;
- The hollow square legend "▫" represents a censored observation;
- The horizontal dashed line represents TCLP threshold.

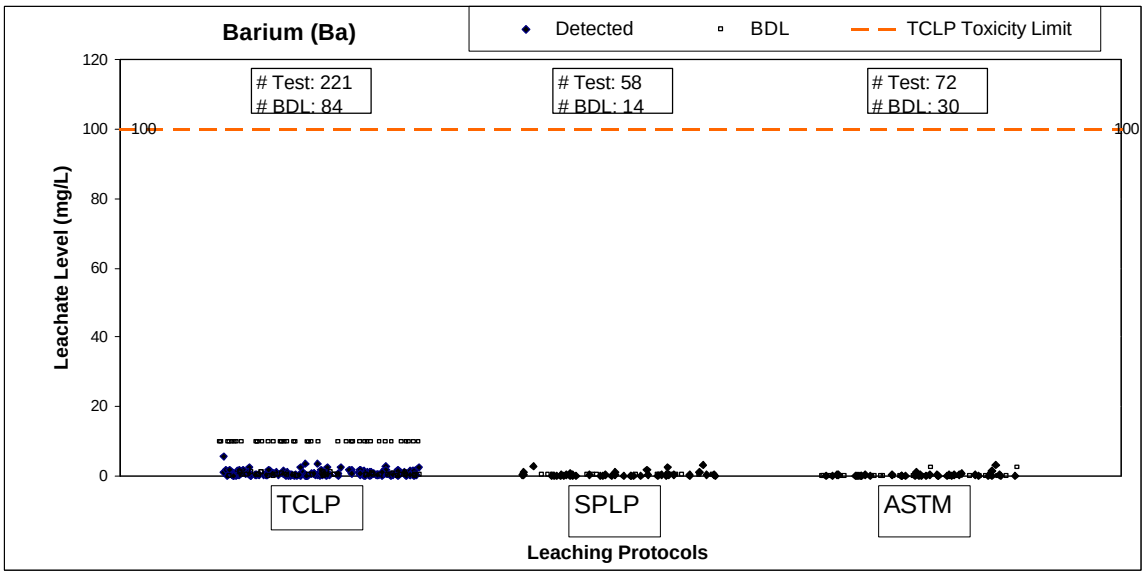
E.1 Metallic Elements

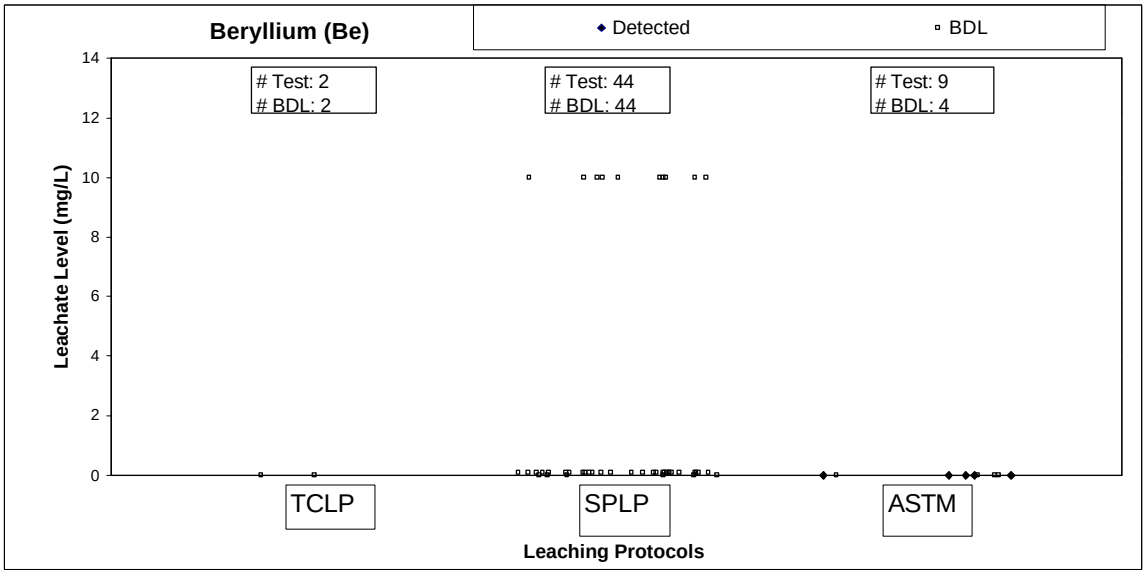
The following series of 23 charts, grouped into Figure E-1, presents the concentration distribution for 23 trace metallic elements in sand leachates per leaching protocol.

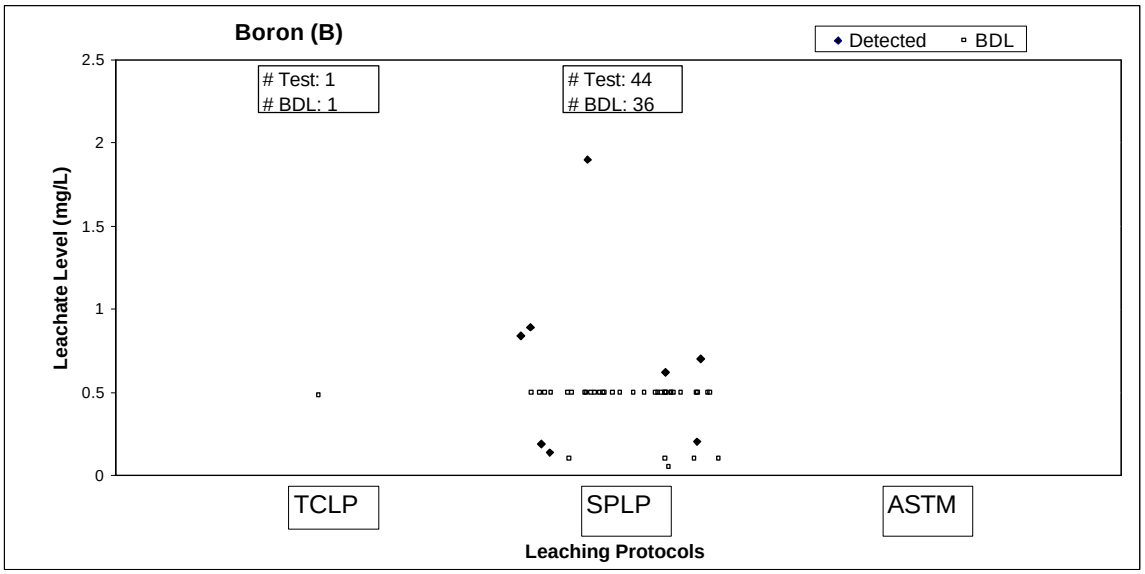


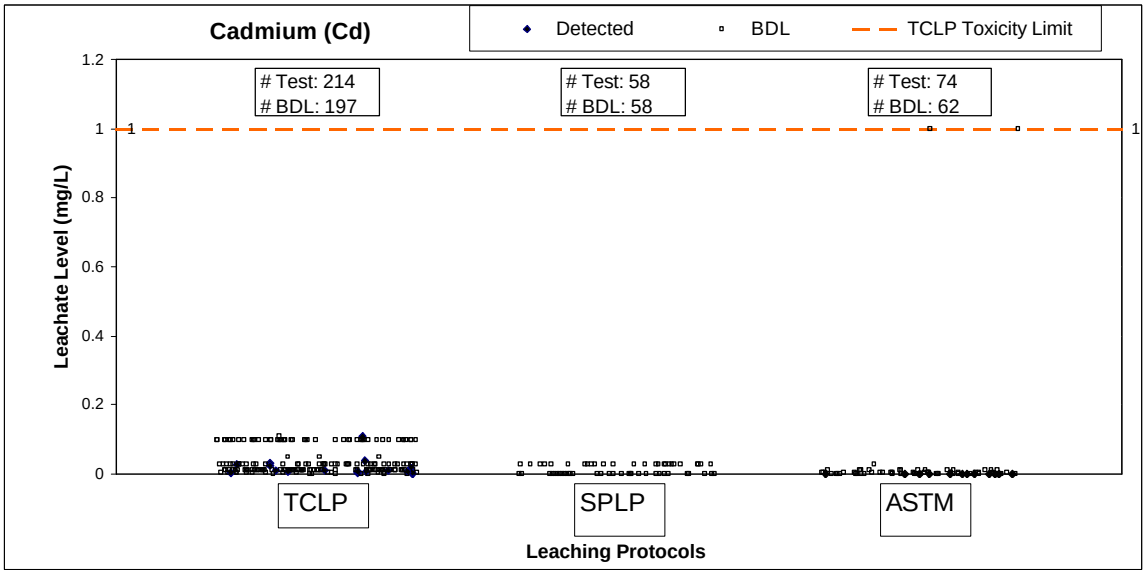


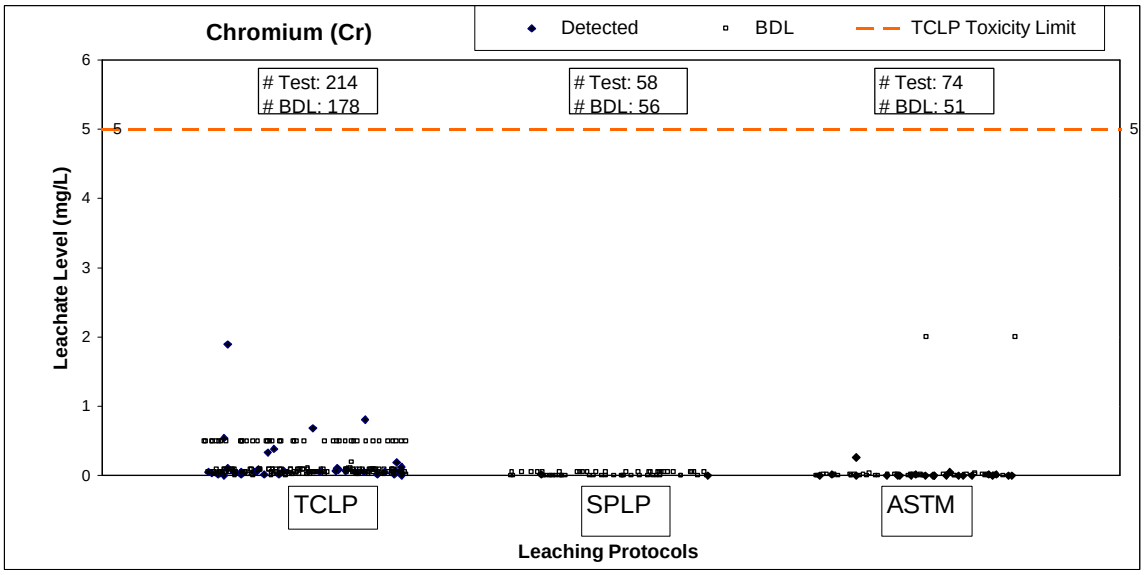

Arsenic (As)
Detected
BDL
TCLP Toxicity Limit
Test: 214
BDL: 200
Test: 58
BDL: 54
Test: 74
BDL: 51
5
Leachate Level (mg/L)
0
1
2
3
4
5
6
TCLP
SPLP
ASTM
Leaching Protocols

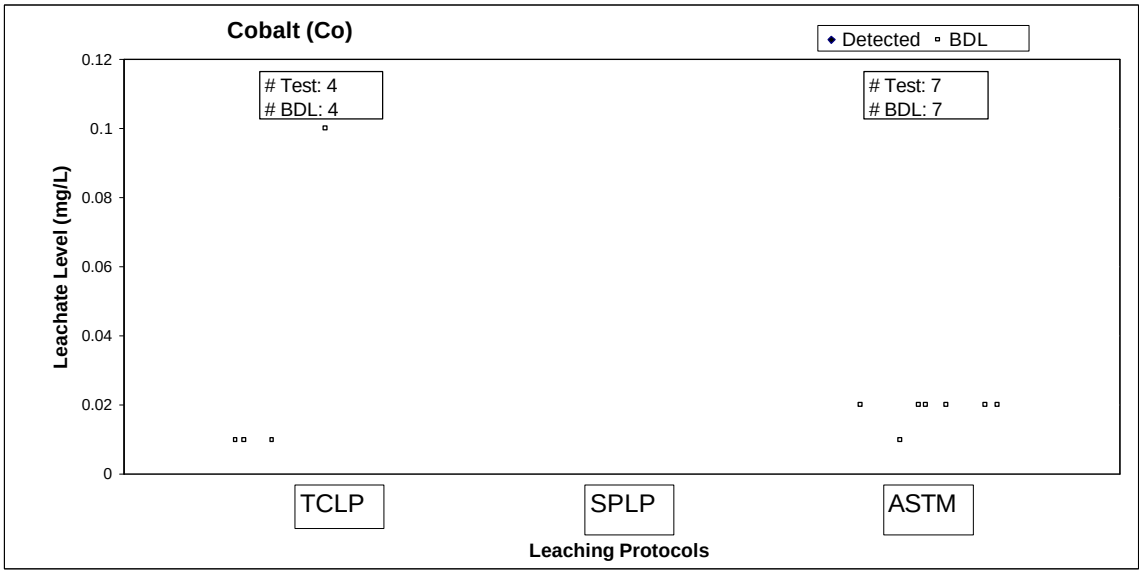

Barium (Ba)
Detected
BDL
TCLP Toxicity Limit
Test: 221
BDL: 84
Test: 58
BDL: 14
Test: 72
BDL: 30
100
Leachate Level (mg/L)
0
20
40
60
80
100
120
TCLP
SPLP
ASTM
Leaching Protocols

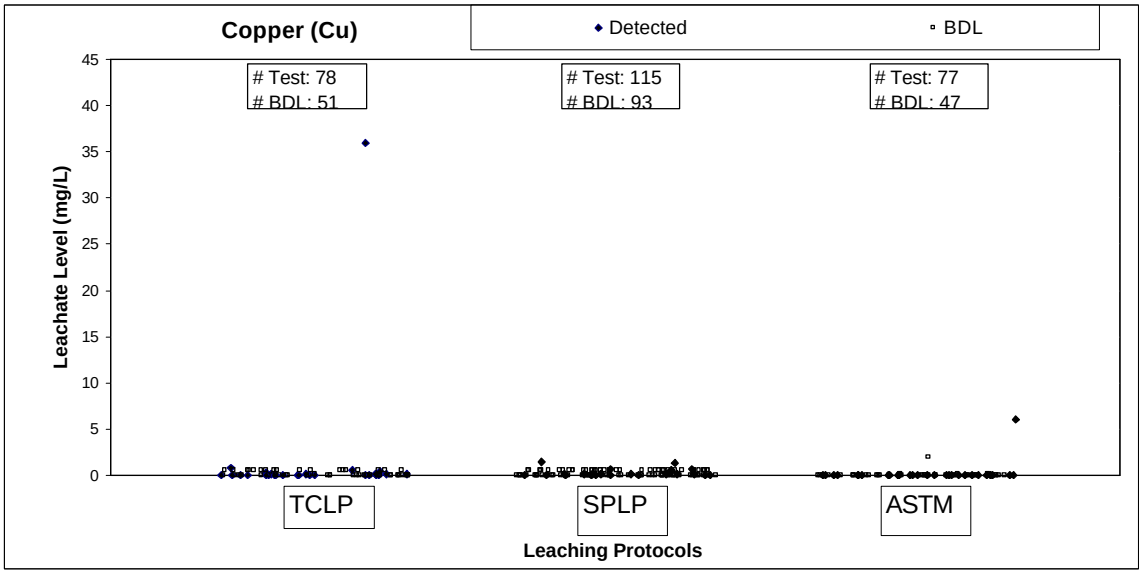

Beryllium (Be)
Detected
BDL
Test: 2
BDL: 2
Test: 44
BDL: 44
Test: 9
BDL: 4
Leachate Level (mg/L)
0
2
4
6
8
10
12
14
TCLP
SPLP
ASTM
Leaching Protocols

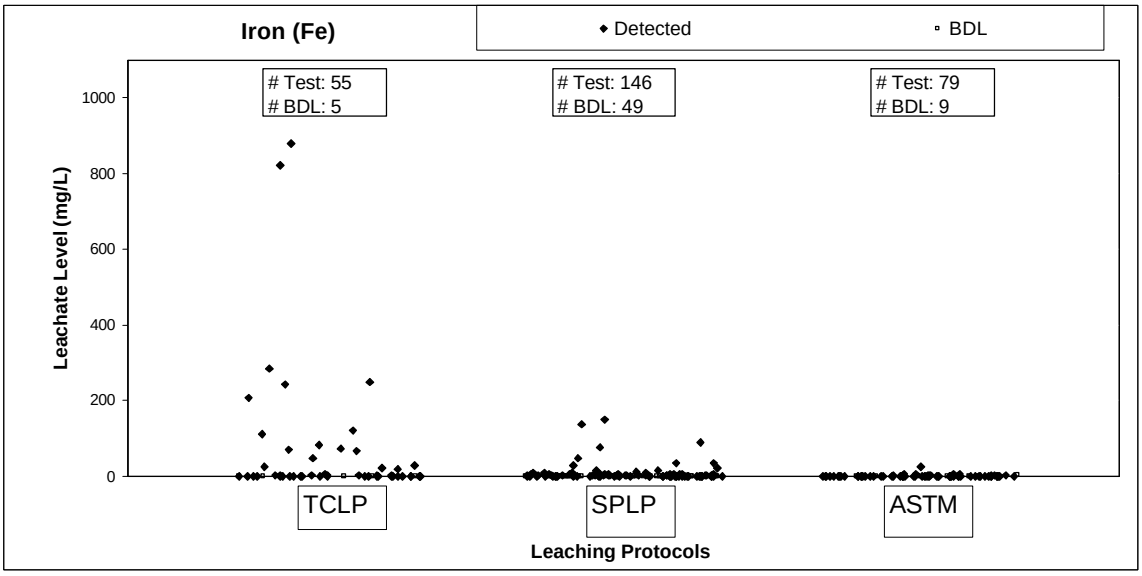

Boron (B)
Detected
BDL
Test: 1
BDL: 1
Test: 44
BDL: 36
Leachate Level (mg/L)
0
0.5
1
1.5
2
2.5
TCLP
SPLP
ASTM
Leaching Protocols

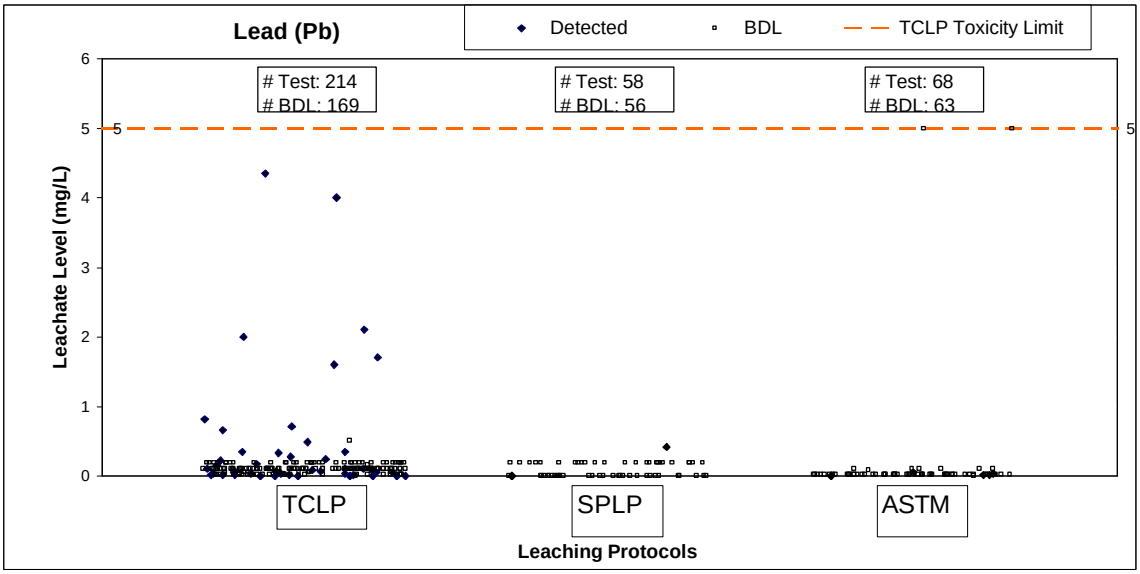

Cadmium (Cd)
Detected
BDL
TCLP Toxicity Limit
Test: 214
BDL: 197
Test: 58
BDL: 58
Test: 74
BDL: 62
Leachate Level (mg/L)
1.2
1
0.8
0.6
0.4
0.2
0
TCLP
SPLP
ASTM
Leaching Protocols

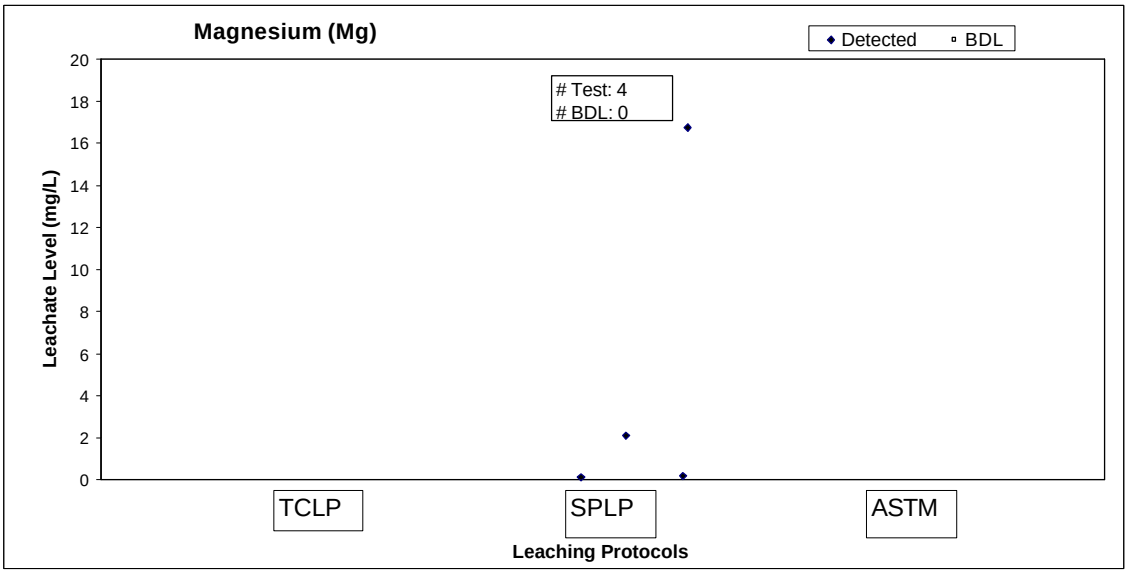

Chromium (Cr)
Detected
BDL
TCLP Toxicity Limit
Test: 214
BDL: 178
Test: 58
BDL: 56
Test: 74
BDL: 51
Leachate Level (mg/L)
6
5
4
3
2
1
0
TCLP
SPLP
ASTM
Leaching Protocols

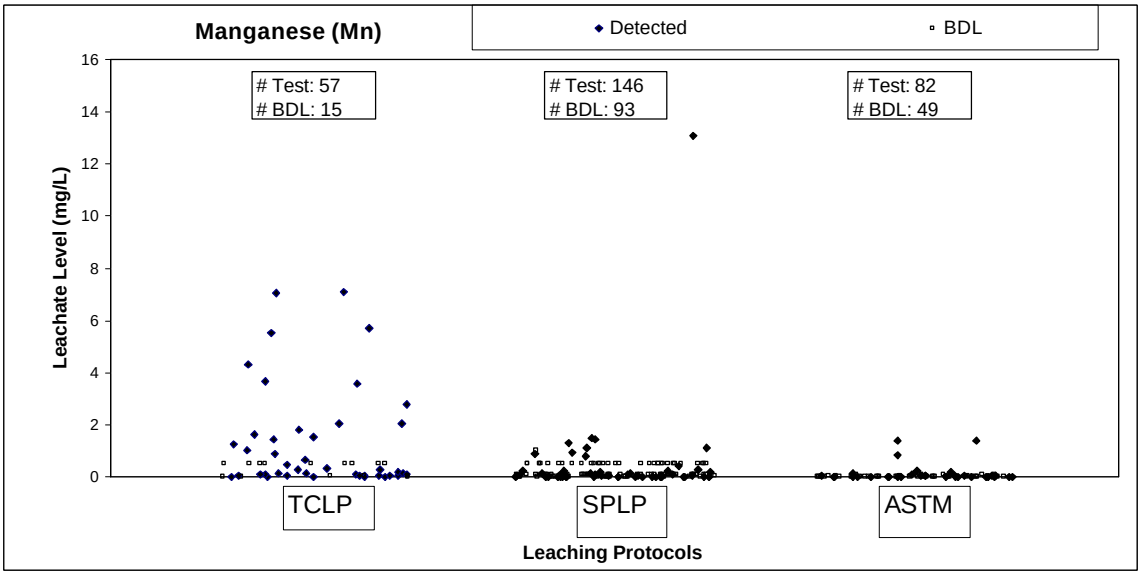

Cobalt (Co)
Detected
BDL
Test: 4
BDL: 4
Test: 7
BDL: 7
Leachate Level (mg/L)
0.12
0.1
0.08
0.06
0.04
0.02
0
TCLP
SPLP
ASTM
Leaching Protocols

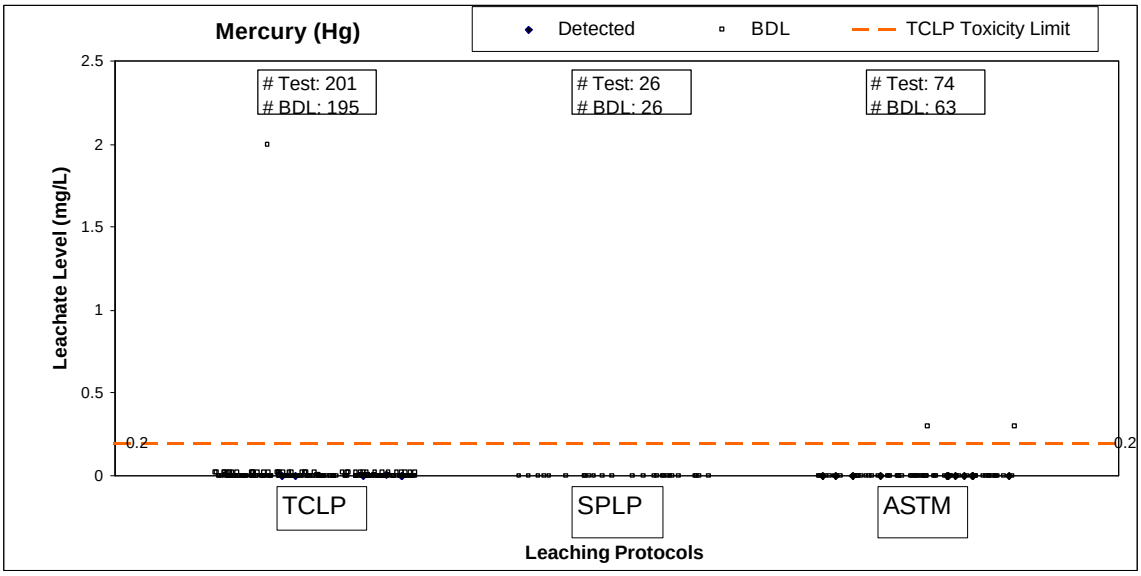

Copper (Cu)
Detected
BDL
Test: 78
BDL : 51
Test: 115
BDL : 93
Test: 77
BDL : 47
Leachate Level (mg/L)
45
40
35
30
25
20
15
10
5
0
TCLP
SPLP
ASTM
Leaching Protocols

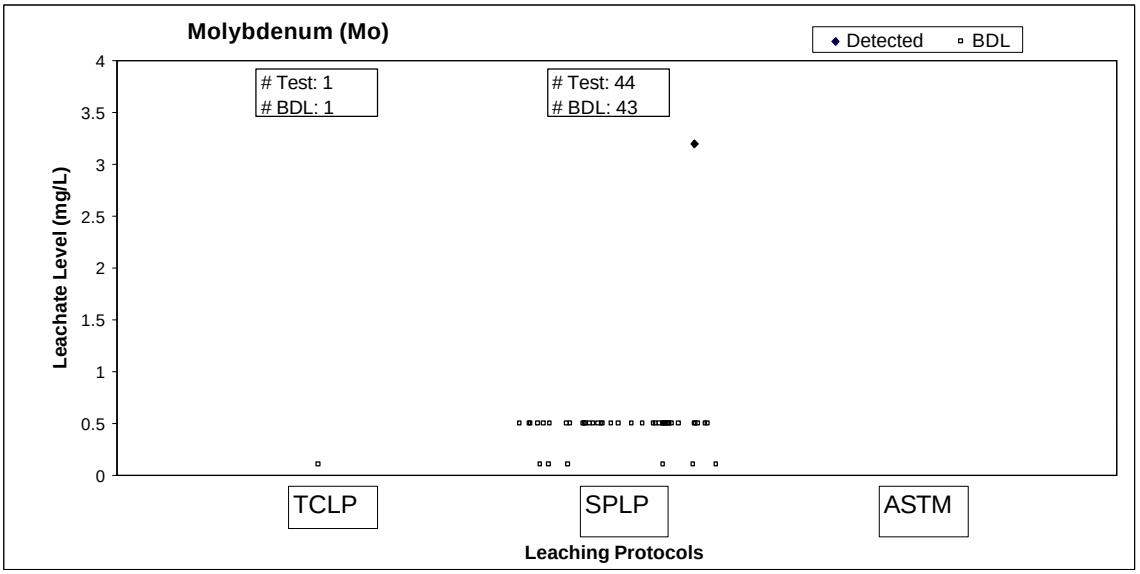

Iron (Fe)
Detected
BDL
Test: 55
BDL: 5
Test: 146
BDL: 49
Test: 79
BDL: 9
Leachate Level (mg/L)
1000
800
600
400
200
0
TCLP
SPLP
ASTM
Leaching Protocols

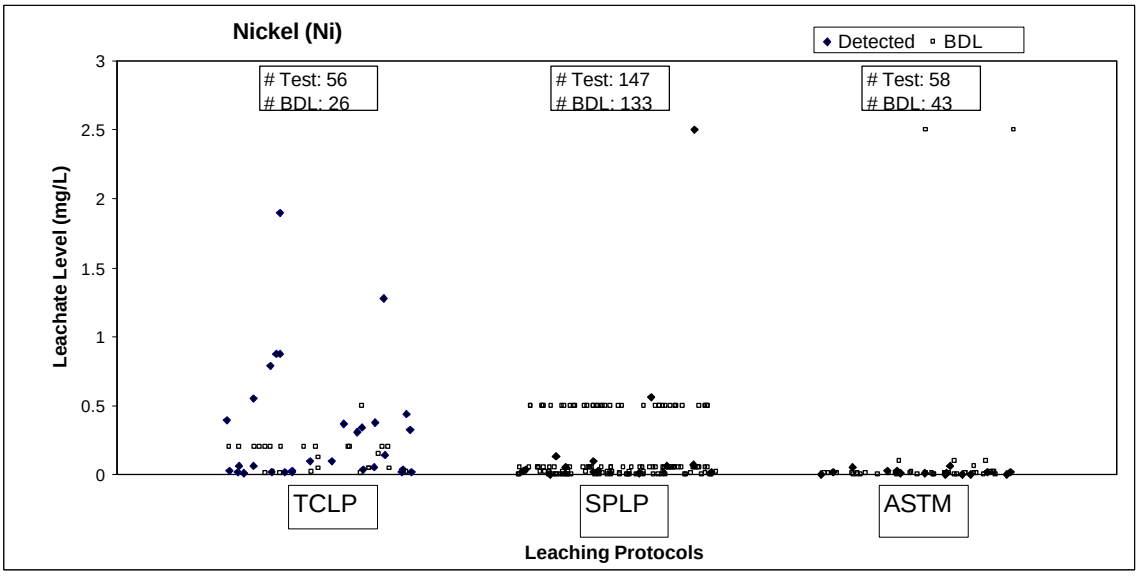

Lead (Pb)
Detected
BDL
TCLP Toxicity Limit
Test: 214
BDL: 169
Test: 58
BDL: 56
Test: 68
BDL: 63
5
5
Leachate Level (mg/L)
6
5
4
3
2
1
0
TCLP
SPLP
ASTM
Leaching Protocols

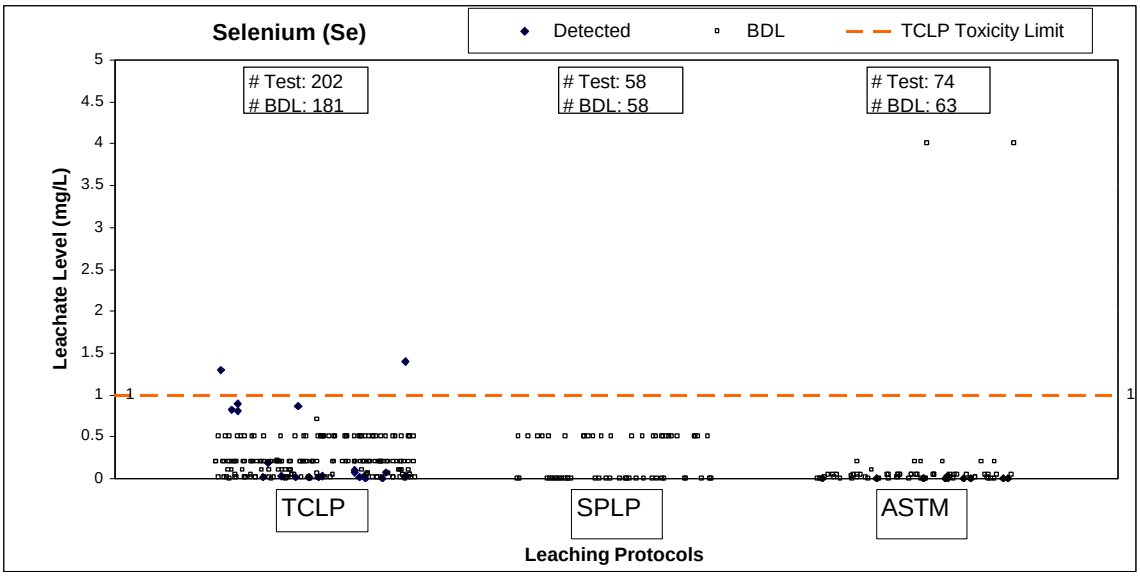

Magnesium (Mg)
Detected
BDL
Test: 4
BDL: 0
Leachate Level (mg/L)
20
18
16
14
12
10
8
6
4
2
0
TCLP
SPLP
ASTM
Leaching Protocols

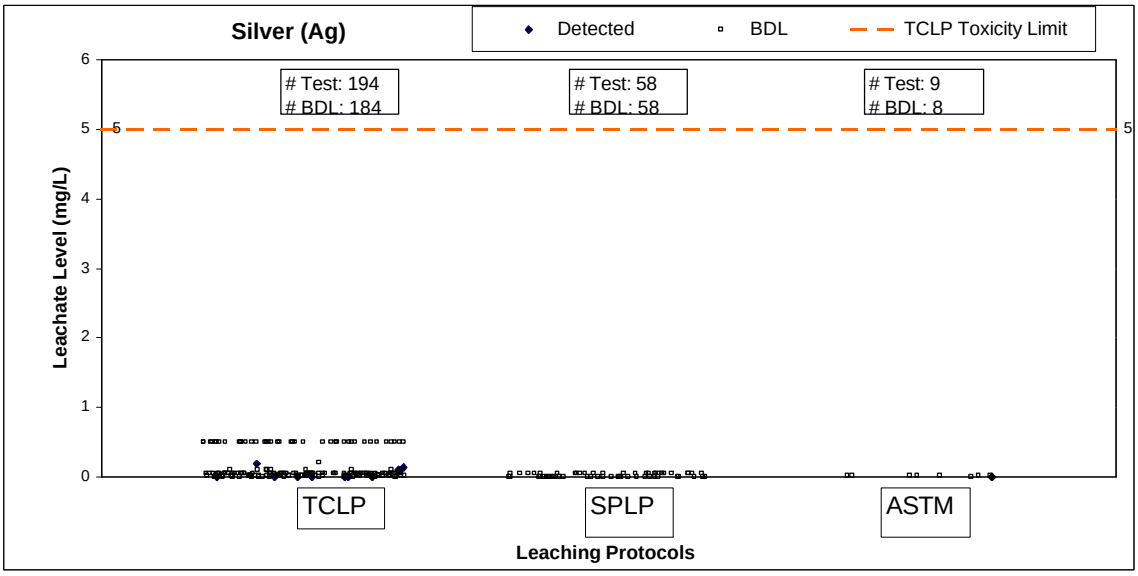

Manganese (Mn)
Detected
BDL
Test: 57
BDL: 15
Test: 146
BDL: 93
Test: 82
BDL: 49
Leachate Level (mg/L)
16
14
12
10
8
6
4
2
0
TCLP
SPLP
ASTM
Leaching Protocols

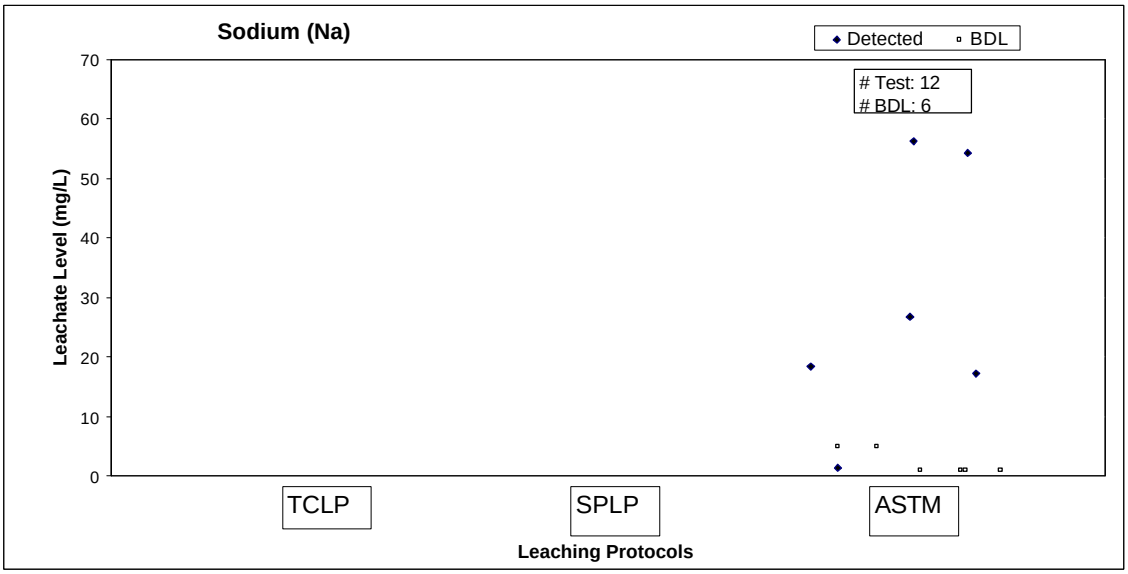

Mercury (Hg)
Detected
BDL
TCLP Toxicity Limit
Test: 201
BDL: 195
Test: 26
BDL: 26
Test: 74
BDL: 63
Leachate Level (mg/L)
2.5
2
1.5
1
0.5
0.2
0
0.2
TCLP
SPLP
ASTM
Leaching Protocols

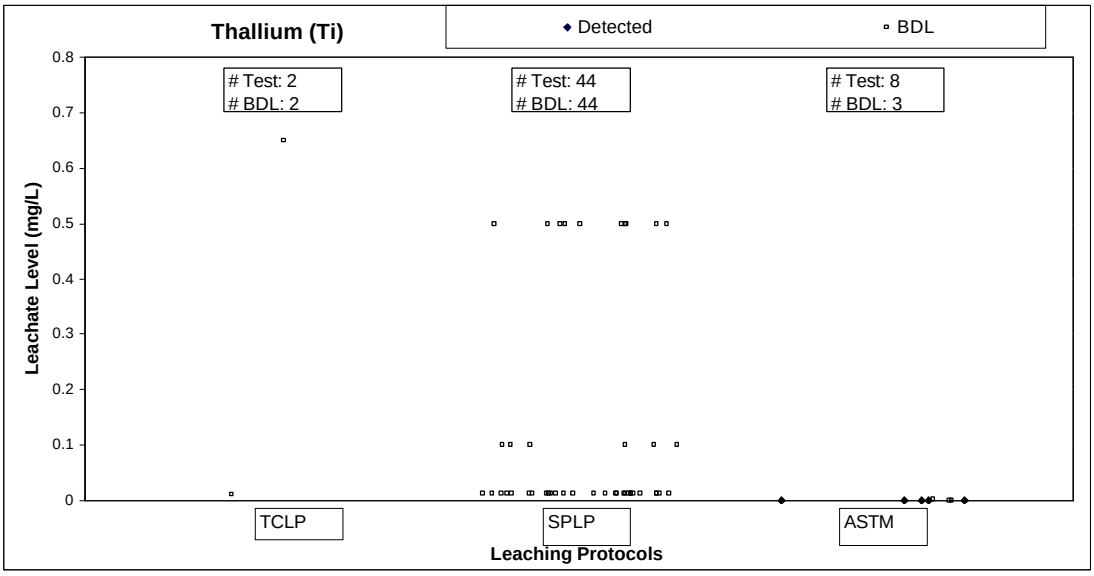

Molybdenum (Mo)
Detected
BDL
Test: 1
BDL: 1
Test: 44
BDL: 43
Leachate Level (mg/L)
4
3.5
3
2.5
2
1.5
1
0.5
0
TCLP
SPLP
ASTM
Leaching Protocols

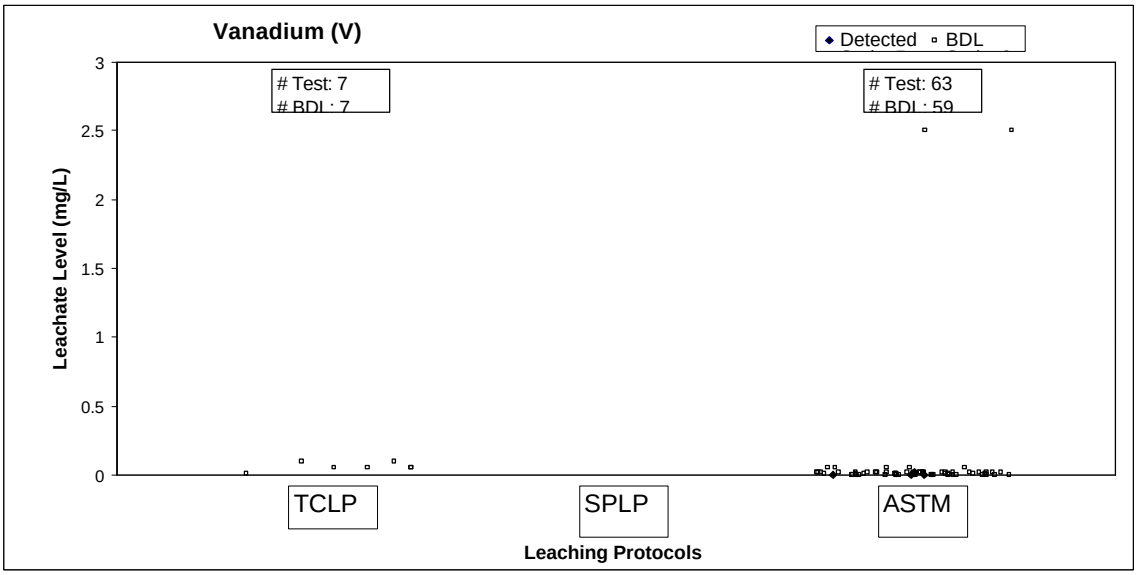

Nickel (Ni)
Detected
BDL
Test: 56
BDL: 26
Test: 147
BDL: 133
Test: 58
BDL: 43
Leachate Level (mg/L)
3
2.5
2
1.5
1
0.5
0
TCLP
SPLP
ASTM
Leaching Protocols


Selenium (Se)
Detected
BDL
TCLP Toxicity Limit
Test: 202
BDL: 181
Test: 58
BDL: 58
Test: 74
BDL: 63
Leachate Level (mg/L)
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
1
1
TCLP
SPLP
ASTM
Leaching Protocols


Silver (Ag)
Detected
BDL
TCLP Toxicity Limit
Test: 194
BDL: 184
Test: 58
BDL: 58
Test: 9
BDL: 8
5
5
Leachate Level (mg/L)
0
1
2
3
4
5
6
TCLP
SPLP
ASTM
Leaching Protocols


Sodium (Na)
Detected
BDL
Test: 12
BDL: 6
Leachate Level (mg/L)
0
10
20
30
40
50
60
70
TCLP
SPLP
ASTM
Leaching Protocols


Thallium (Ti)
Detected
BDL
Test: 2
BDL: 2
Test: 44
BDL: 44
Test: 8
BDL: 3
Leachate Level (mg/L)
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
TCLP
SPLP
ASTM
Leaching Protocols


Vanadium (V)
Detected
BDL
Test: 7
Test: 63
Leachate Level (mg/L)
3
2.5
2
1.5
1
0.5
0
TCLP
SPLP
ASTM
Leaching Protocols

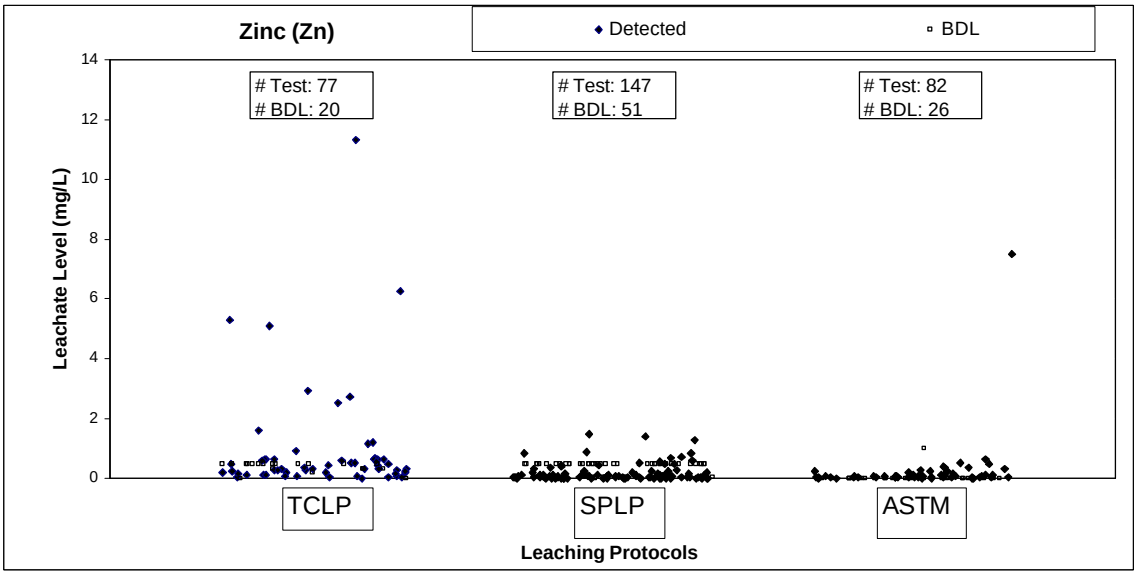
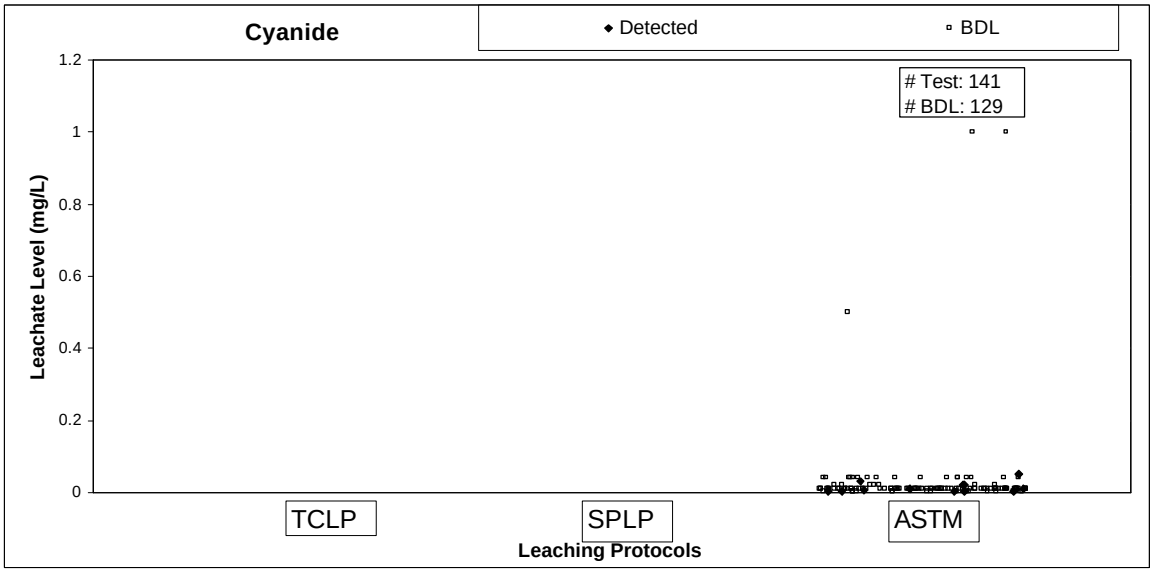
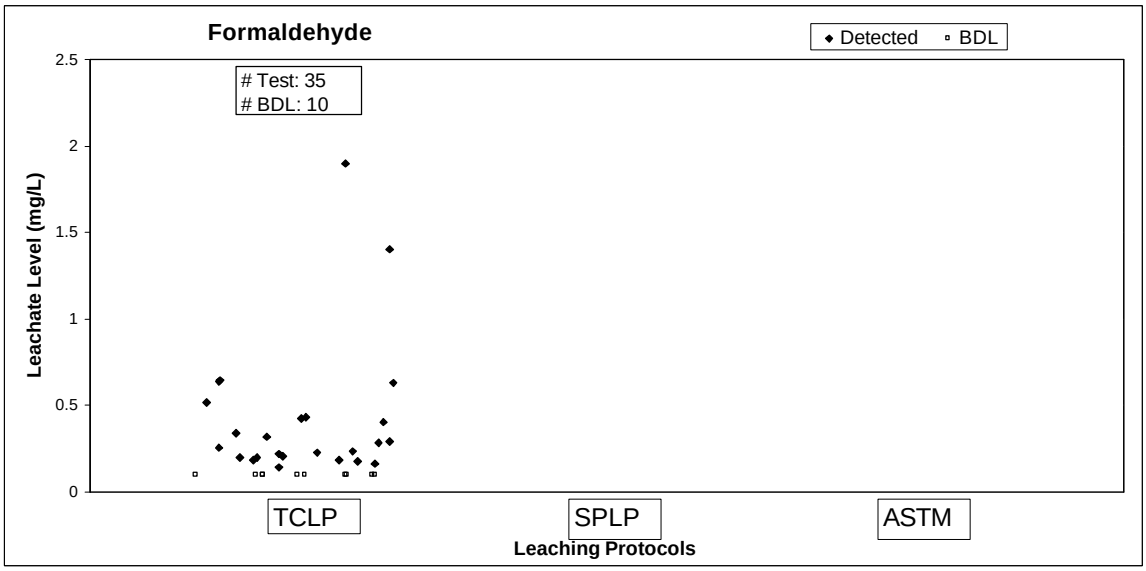


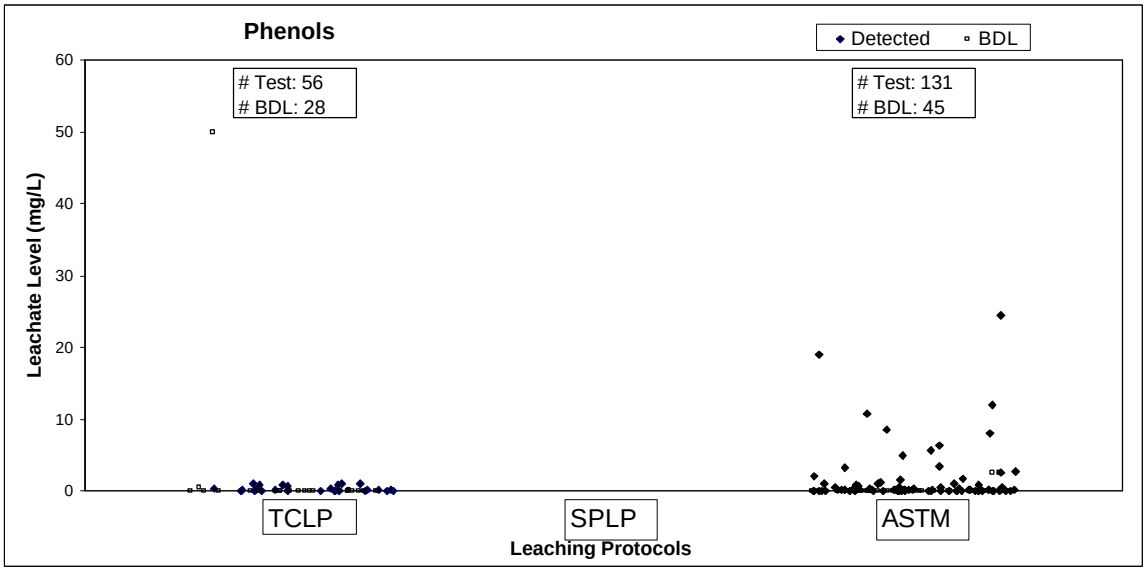
Figure **E-1**: Leachate concentration of metallic elements per leaching protocol (23 charts)

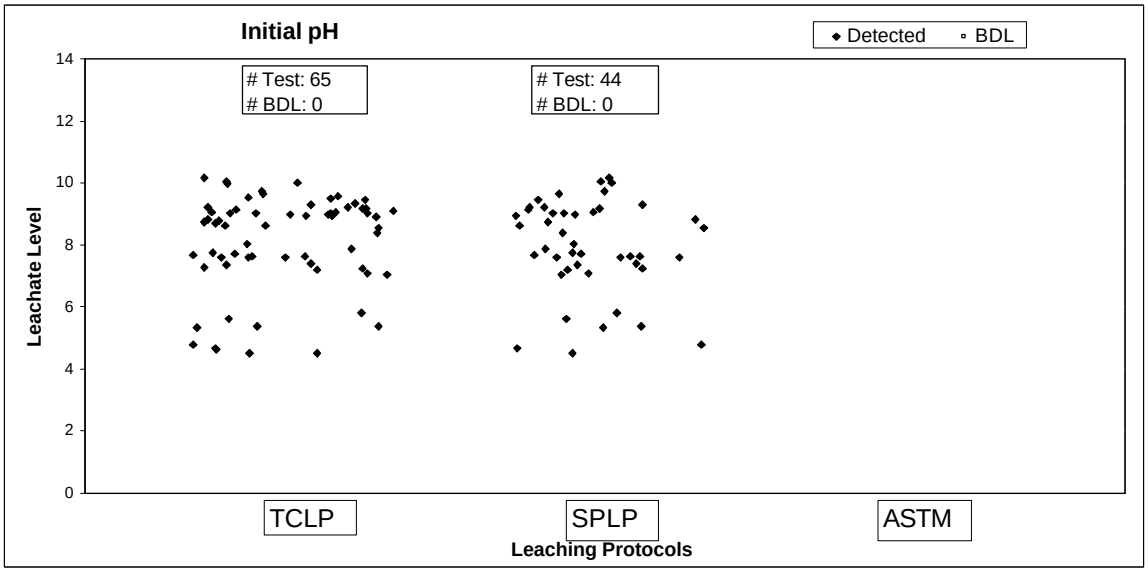
E.2 General Chemical Parameters

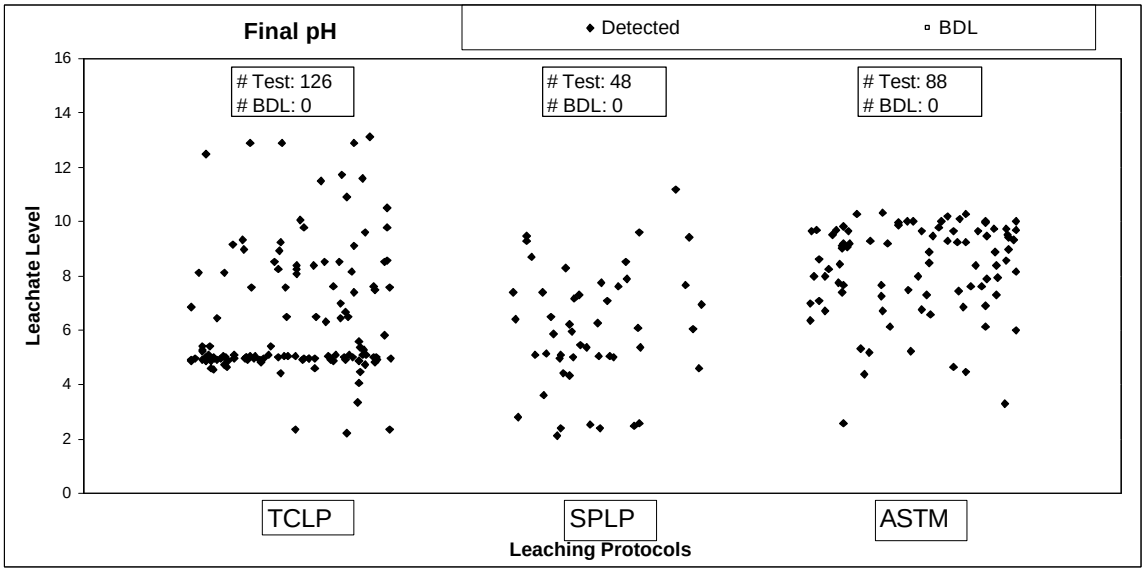
Following a series of 21 charts, grouped into Figure E-2, present the concentration distribution for 21 general chemical parameters in sand leachate per leaching protocol.

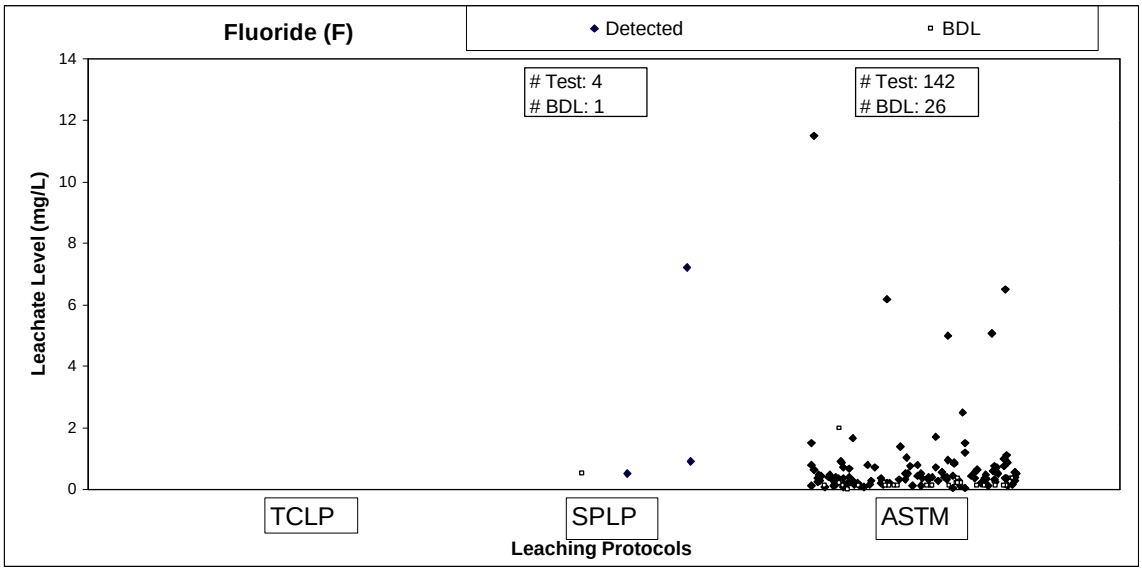

Cyanide
Detected
BDL
Test: 141
BDL: 129
Leachate Level (mg/L)
1.2
1
0.8
0.6
0.4
0.2
0
TCLP
SPLP
ASTM
Leaching Protocols

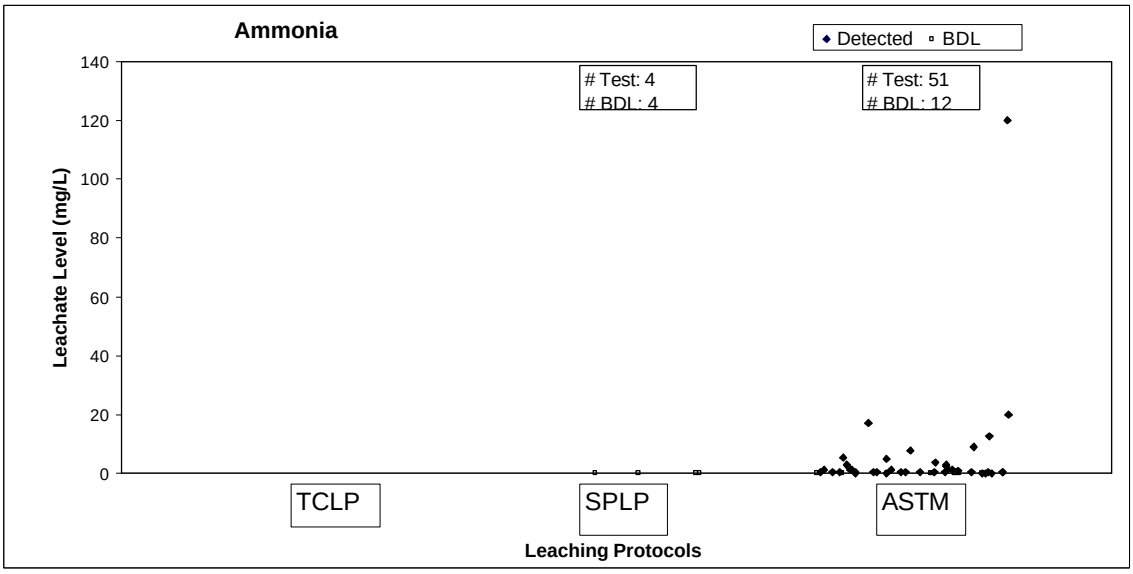

Formaldehyde
Detected
BDL
Test: 35
BDL: 10
Leachate Level (mg/L)
2.5
2
1.5
1
0.5
0
TCLP
SPLP
ASTM
Leaching Protocols

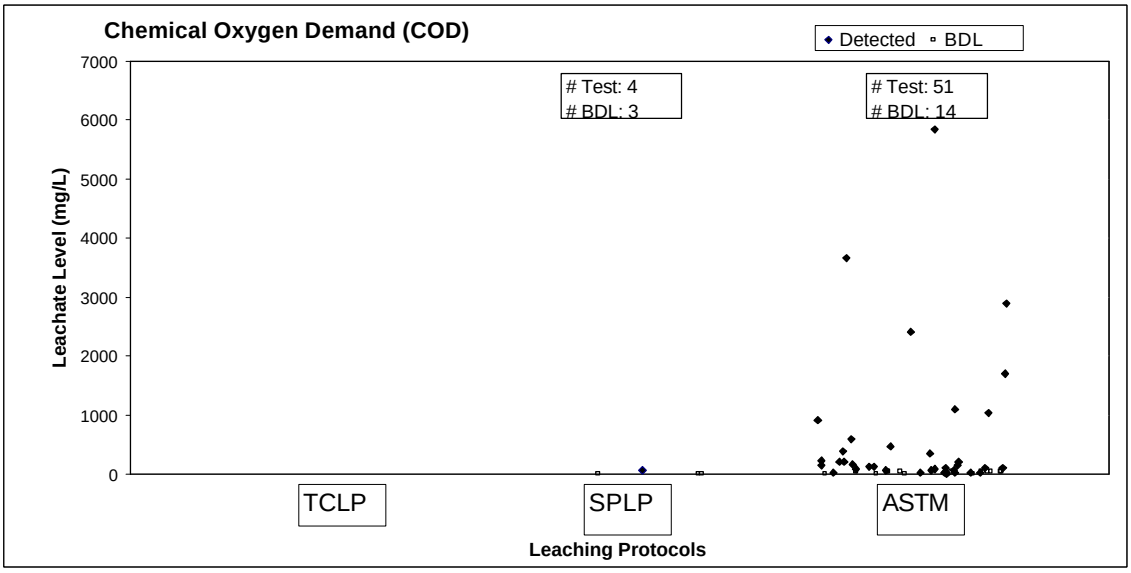

Phenols
Detected
BDL
Test: 56
BDL: 28
Test: 131
BDL: 45
Leachate Level (mg/L)
60
50
40
30
20
10
0
TCLP
SPLP
ASTM
Leaching Protocols

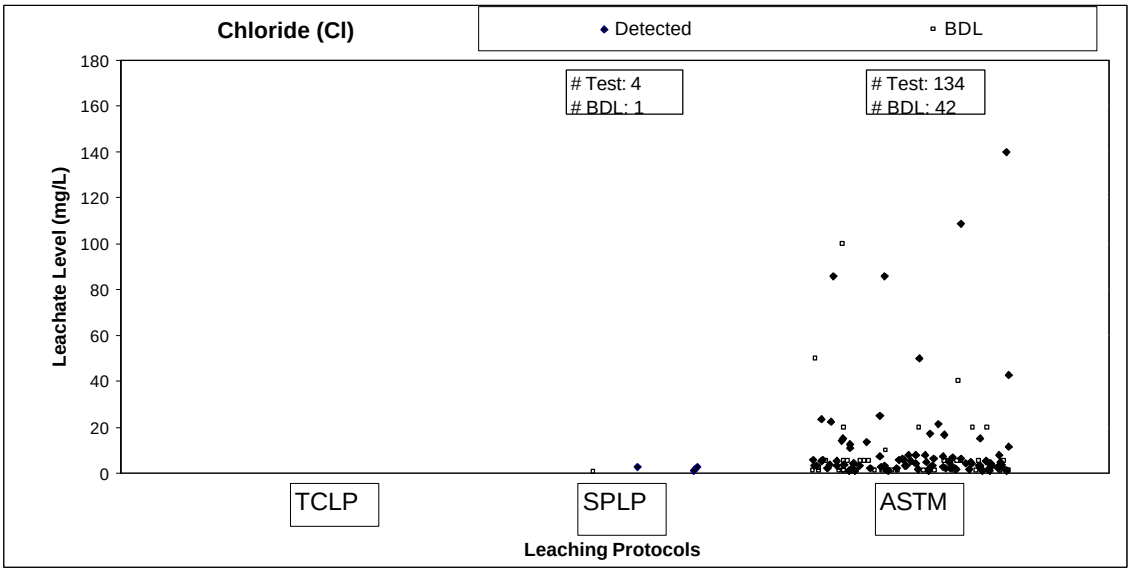

Initial pH
Detected
BDL
Test: 65
BDL: 0
Test: 44
BDL: 0
Leachate Level
14
12
10
8
6
4
2
0
TCLP
SPLP
ASTM
Leaching Protocols

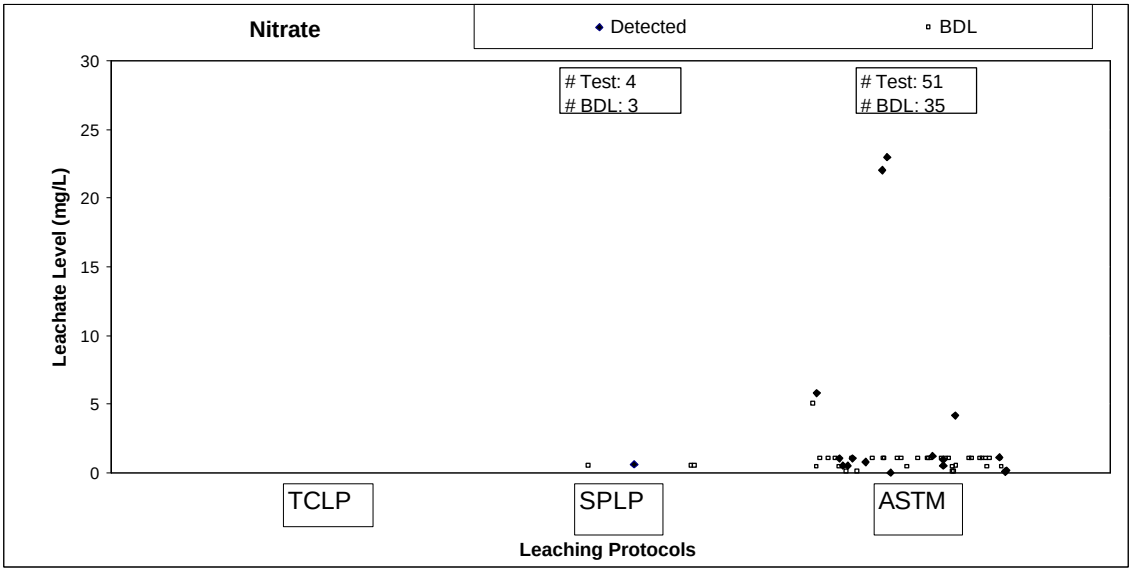

Final pH
Detected
BDL
Test: 126
BDL: 0
Test: 48
BDL: 0
Test: 88
BDL: 0
Leachate Level
0
2
4
6
8
10
12
14
16
TCLP
SPLP
ASTM
Leaching Protocols

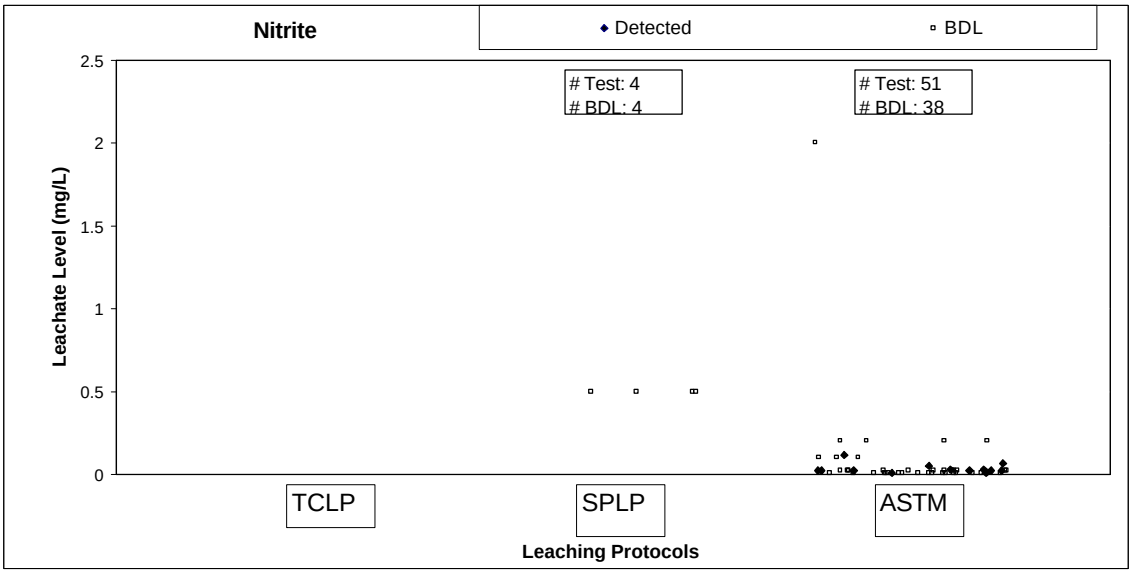

Fluoride (F)
Detected
BDL
Test: 4
BDL: 1
Test: 142
BDL: 26
Leachate Level (mg/L)
0
2
4
6
8
10
12
14
TCLP
SPLP
ASTM
Leaching Protocols

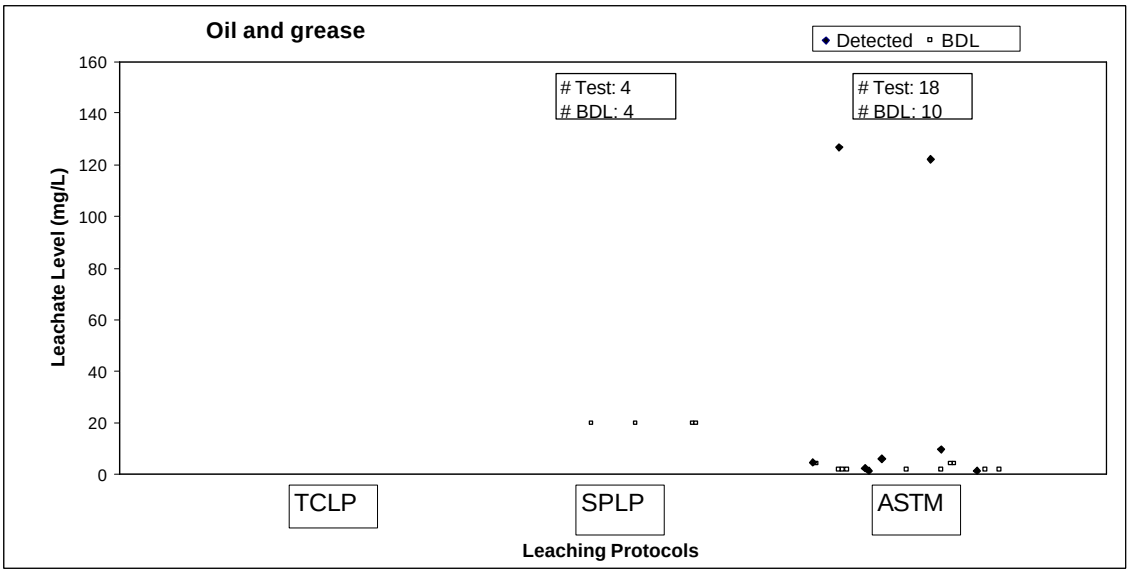

Ammonia
Detected
BDL
Test: 4
BDL: 4
Test: 51
BDL: 12
Leachate Level (mg/L)
140
120
100
80
60
40
20
0
TCLP
SPLP
ASTM
Leaching Protocols

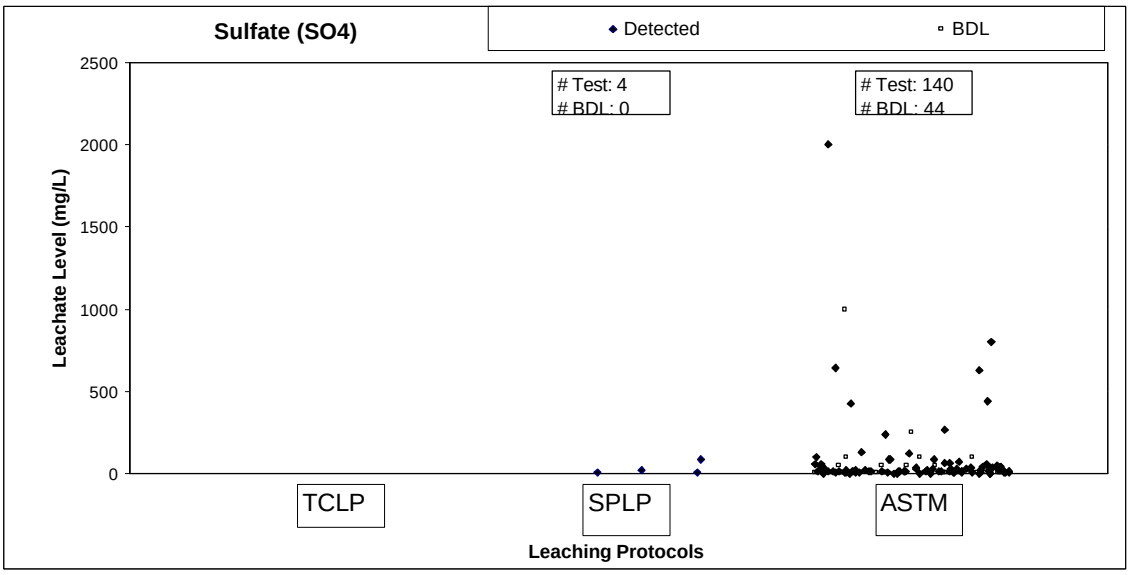

Chemical Oxygen Demand (COD)
Detected
BDL
Test: 4
BDL: 3
Test: 51
BDL: 14
Leachate Level (mg/L)
7000
6000
5000
4000
3000
2000
1000
0
TCLP
SPLP
ASTM
Leaching Protocols

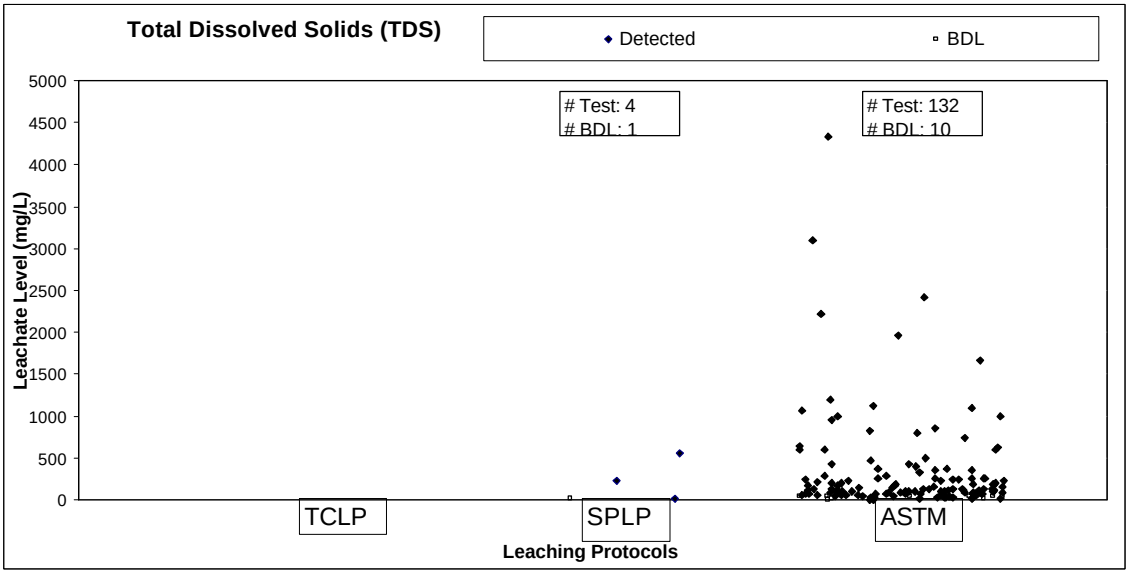

Chloride (Cl)
Detected
BDL
Test: 4
BDL: 1
Test: 134
BDL: 42
Leachate Level (mg/L)
180
160
140
120
100
80
60
40
20
0
TCLP
SPLP
ASTM
Leaching Protocols

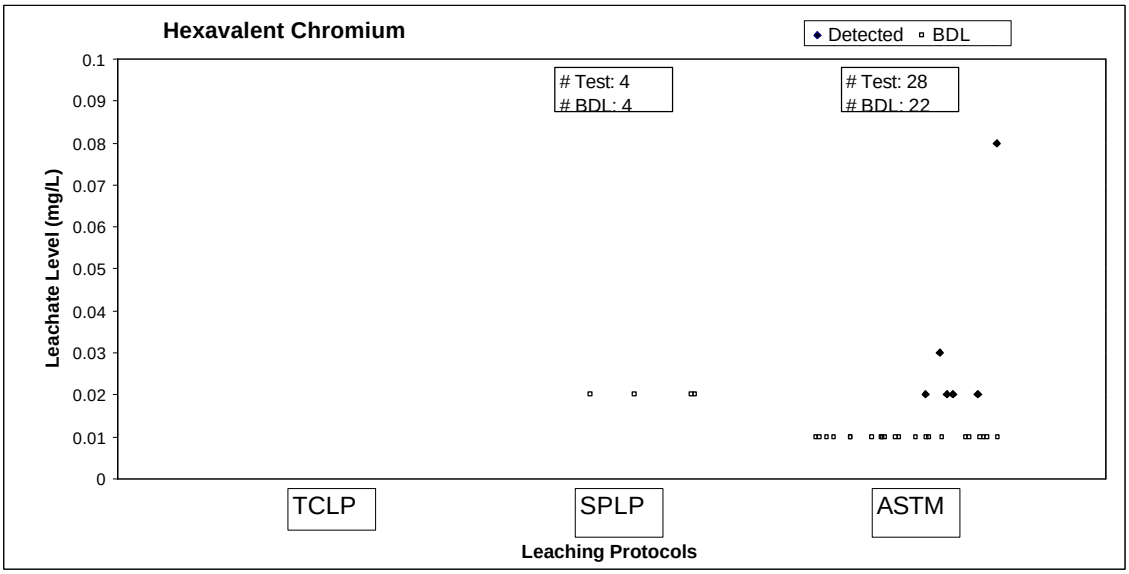

Nitrate
Detected
BDL
Test: 4
BDL: 3
Test: 51
BDL: 35
Leachate Level (mg/L)
30
25
20
15
10
5
0
TCLP
SPLP
ASTM
Leaching Protocols

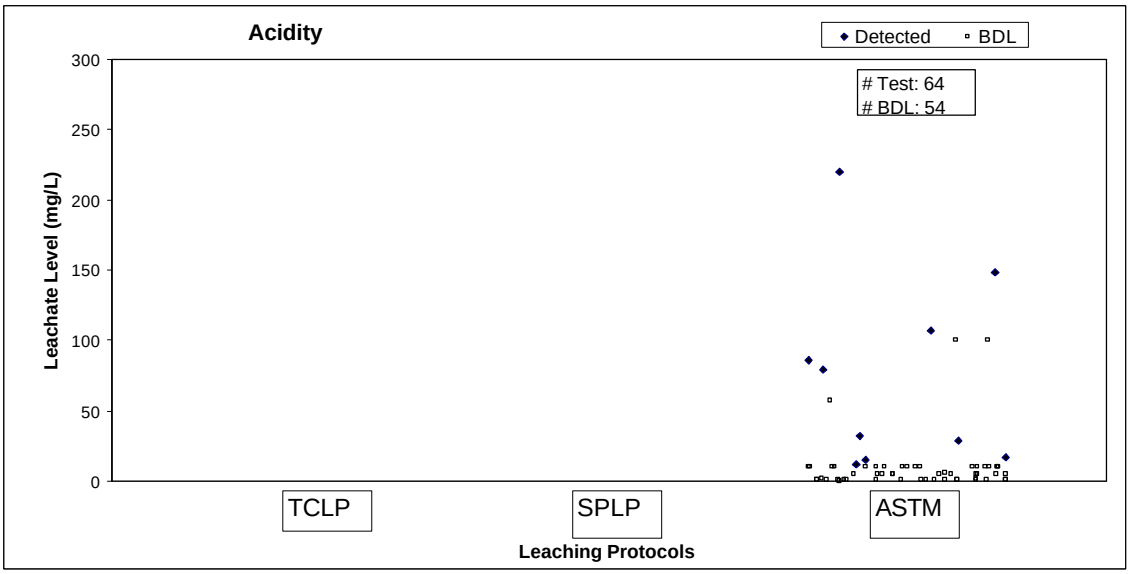

Nitrite
Detected
BDL
Test: 4
BDL: 4
Test: 51
BDL: 38
Leachate Level (mg/L)
2.5
2
1.5
1
0.5
0
TCLP
SPLP
ASTM
Leaching Protocols

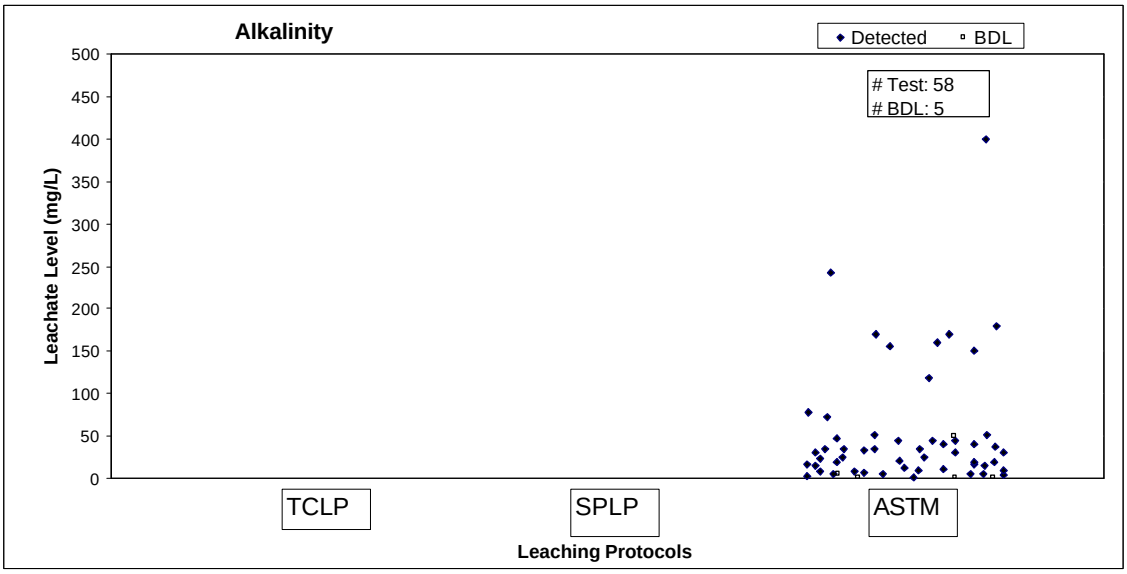

Oil and grease
Detected
BDL
Test: 4
BDL: 4
Test: 18
BDL: 10
Leachate Level (mg/L)
160
140
120
100
80
60
40
20
0
TCLP
SPLP
ASTM
Leaching Protocols

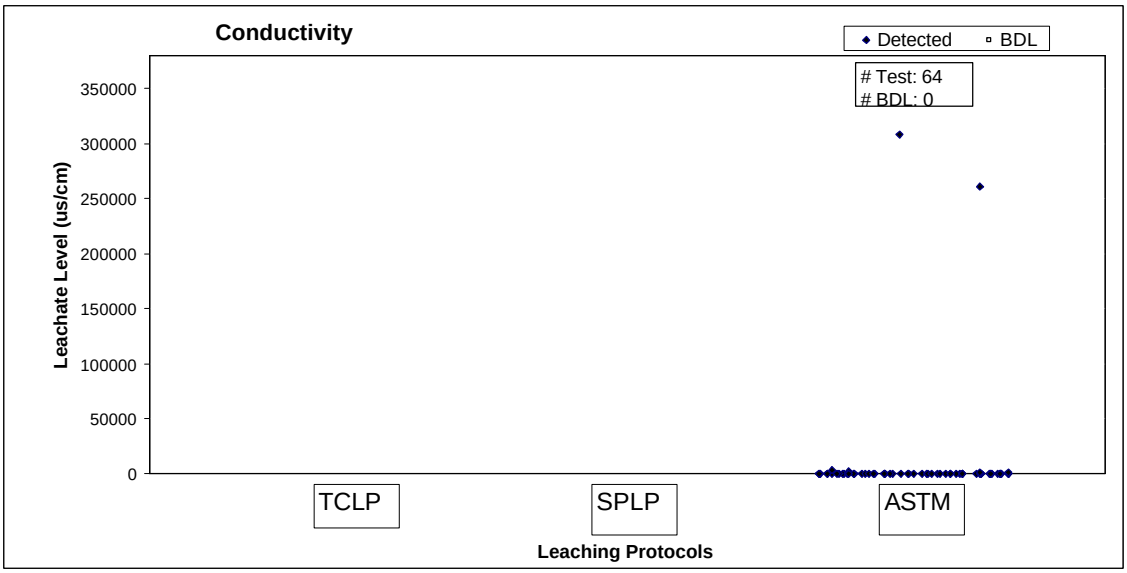

Sulfate (SO4)
Detected
BDL
Test: 4
BDL: 0
Test: 140
BDL: 44
Leachate Level (mg/L)
2500
2000
1500
1000
500
0
TCLP
SPLP
ASTM
Leaching Protocols

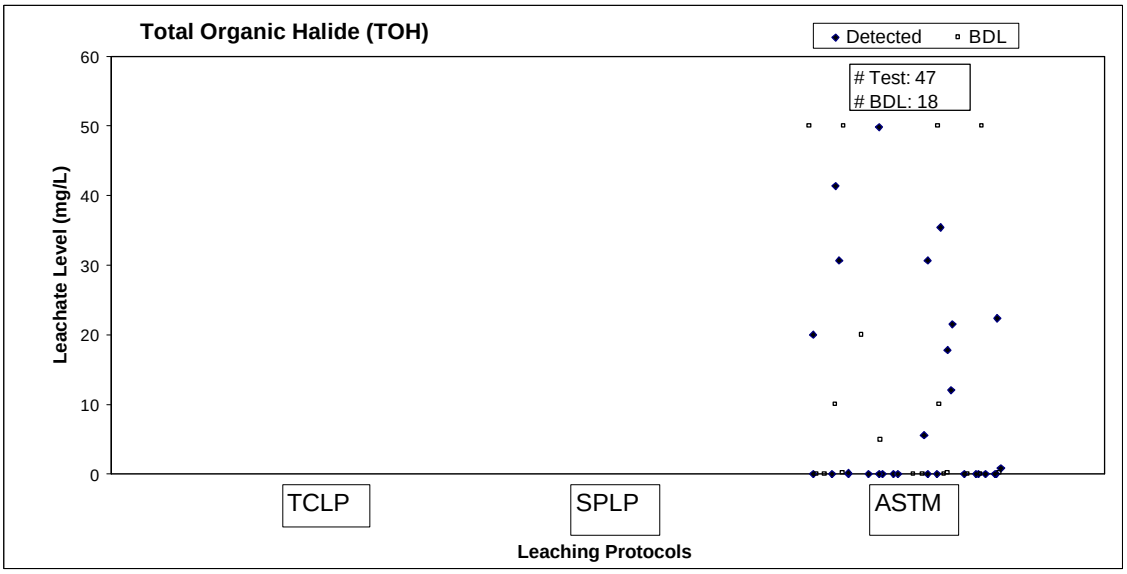

Total Dissolved Solids (TDS)
Detected
BDL
Test: 4
BDL: 1
Test: 132
BDL: 10
Leachate Level (mg/L)
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
TCLP
SPLP
ASTM
Leaching Protocols

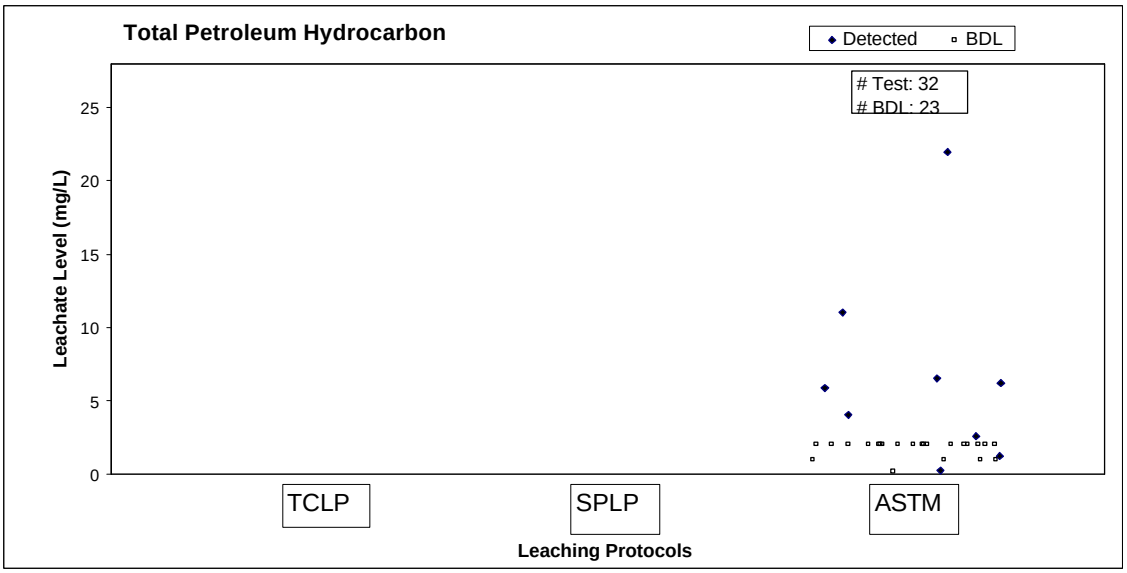

Hexavalent Chromium
Detected
BDL
Test: 4
BDL: 4
Test: 28
BDL: 22
Leachate Level (mg/L)
0.1
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
TCLP
SPLP
ASTM
Leaching Protocols


Acidity
Detected
BDL
Test: 64
BDL: 54
Leachate Level (mg/L)
300
250
200
150
100
50
0
TCLP
SPLP
ASTM
Leaching Protocols


Alkalinity
Detected
BDL
Test: 58
BDL: 5
Leachate Level (mg/L)
500
450
400
350
300
250
200
150
100
50
0
TCLP
SPLP
ASTM
Leaching Protocols


Conductivity
Detected
BDL
Test: 64
BDL: 0
Leachate Level (us/cm)
350000
300000
250000
200000
150000
100000
50000
0
TCLP
SPLP
ASTM
Leaching Protocols


Total Organic Halide (TOH)
Detected
BDL
Test: 47
BDL: 18
Leachate Level (mg/L)
60
50
40
30
20
10
0
TCLP
SPLP
ASTM
Leaching Protocols


Total Petroleum Hydrocarbon
Detected
BDL
Test: 32
BDL: 23
Leachate Level (mg/L)
25
20
15
10
5
0
TCLP
SPLP
ASTM
Leaching Protocols

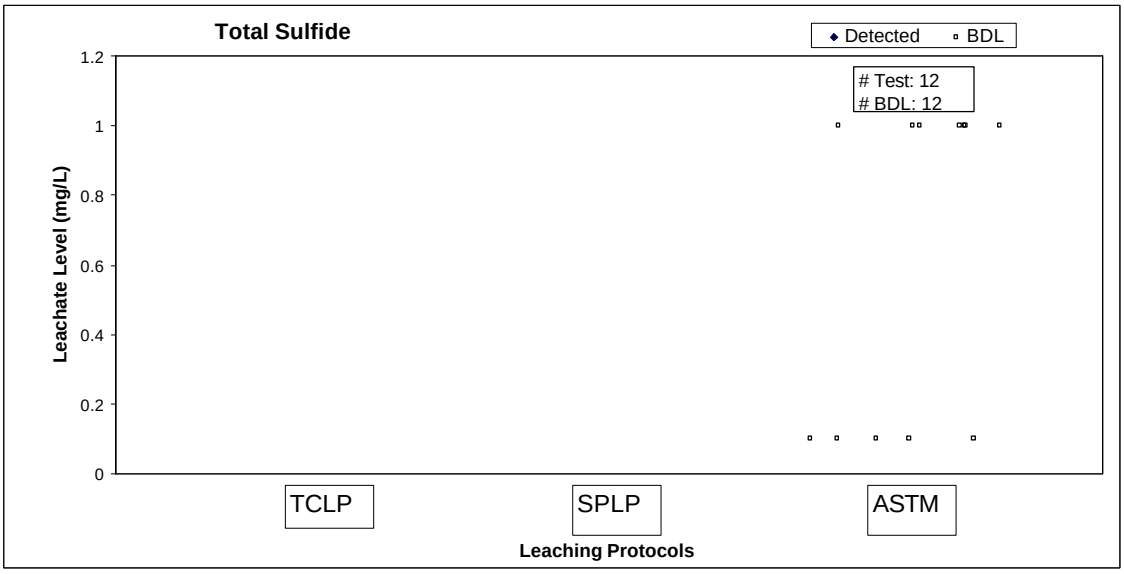
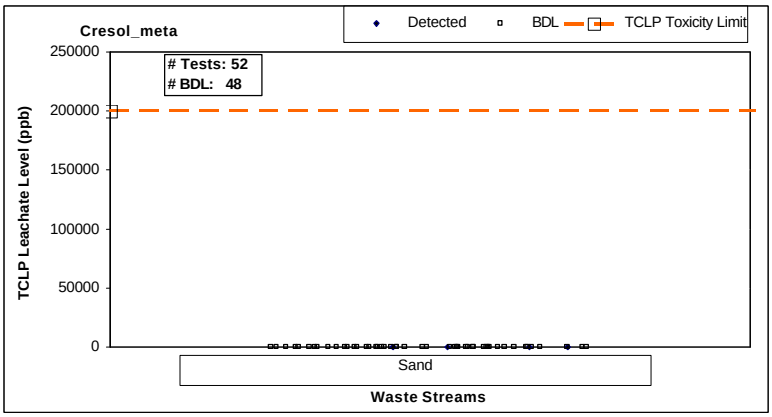
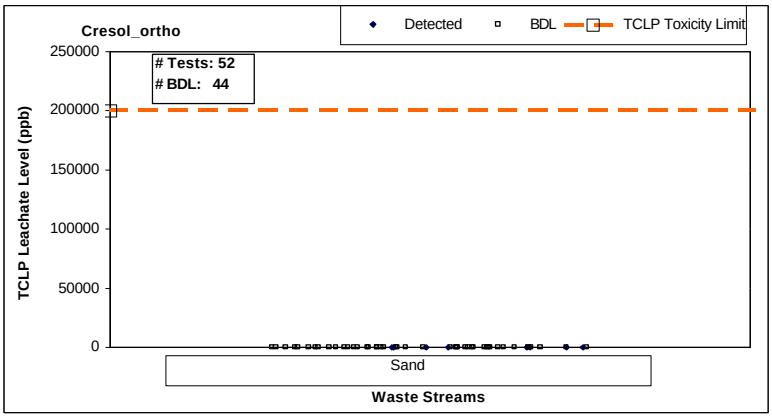


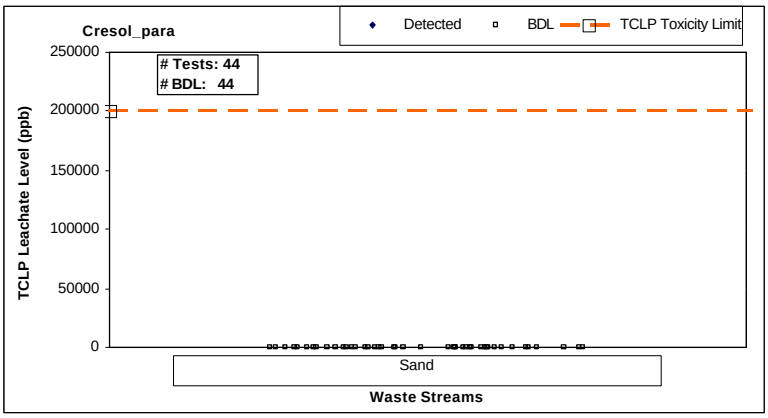
Figure **E-2**: Leachate concentration of general chemical parameters (21 charts)

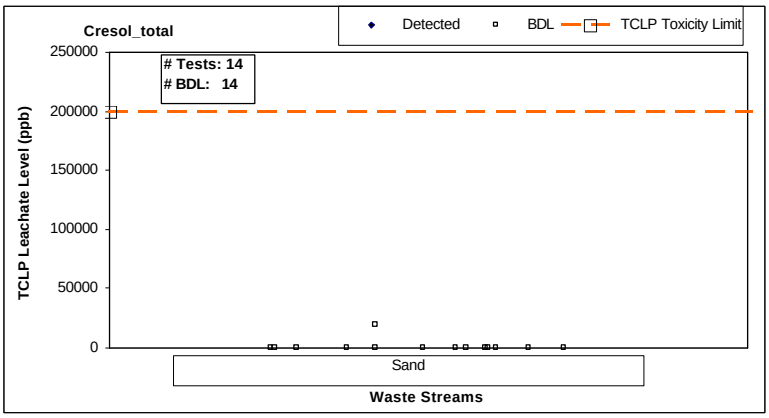
E.3 Organic Compounds

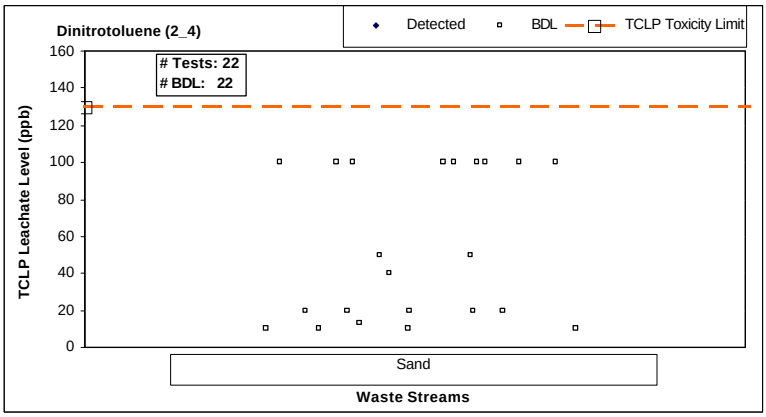
Following a series of 37 charts, grouped into Figure E-3, present the concentration distribution for 37 organic compounds in TCLP leachate extracted from sand stream.

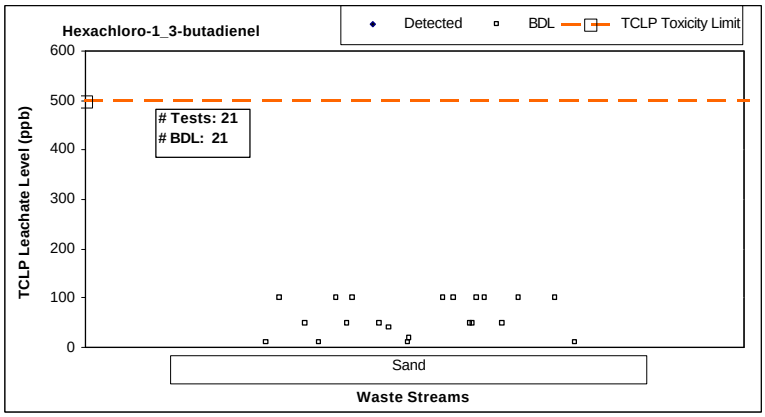


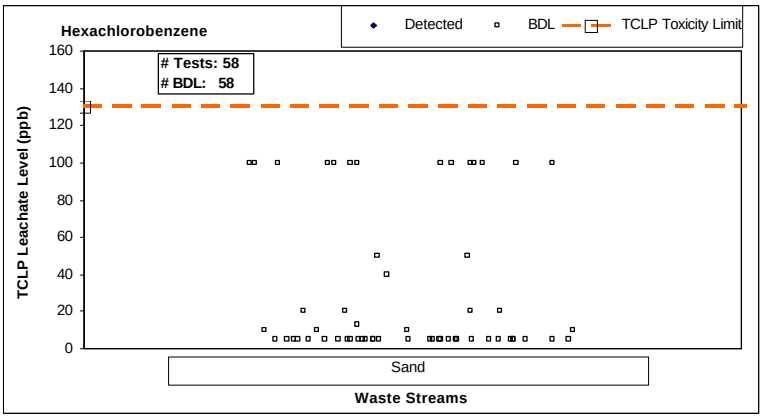

Cresol_ortho
Detected
BDL
TCLP Toxicity Limit
Tests: 52
BDL: 44
250000
200000
150000
100000
50000
0
TCLP Leachate Level (ppb)
Sand
Waste Streams

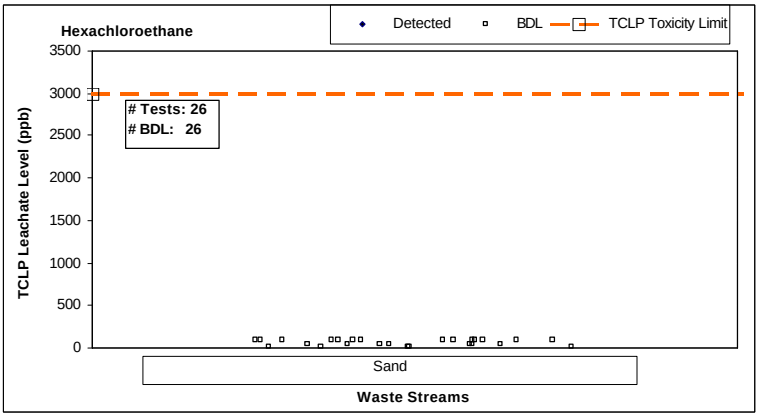

Cresol_para
Detected
BDL
TCLP Toxicity Limit
Tests: 44
BDL: 44
250000
200000
150000
100000
50000
0
TCLP Leachate Level (ppb)
Sand
Waste Streams

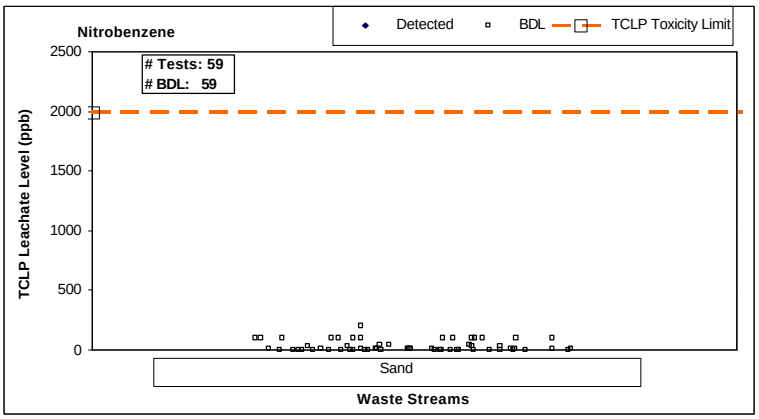

Cresol_total
Detected
BDL
TCLP Toxicity Limit
Tests: 14
BDL: 14
250000
200000
150000
100000
50000
0
TCLP Leachate Level (ppb)
Sand
Waste Streams

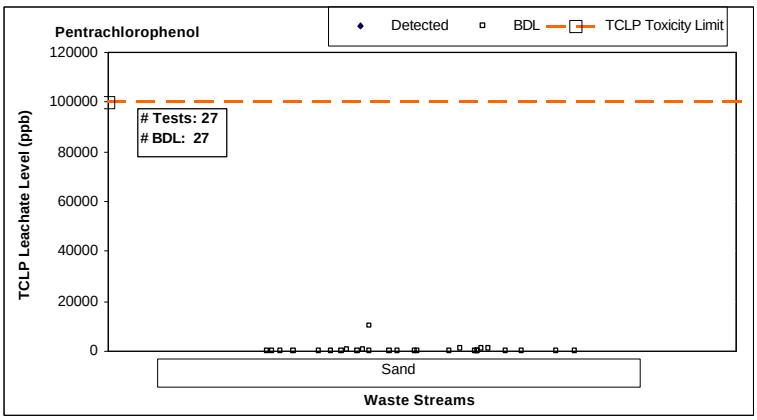

Dinitrotoluene (2_4)
Detected
BDL
TCLP Toxicity Limit
Tests: 22
BDL: 22
TCLP Leachate Level (ppb)
160
140
120
100
80
60
40
20
0
Sand
Waste Streams

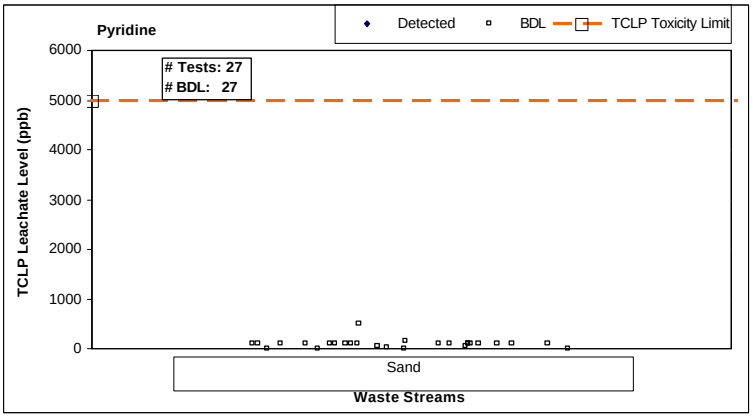

Hexachloro-1_3-butadienel
Detected
BDL
TCLP Toxicity Limit
Tests: 21
BDL: 21
TCLP Leachate Level (ppb)
600
500
400
300
200
100
0
Sand
Waste Streams

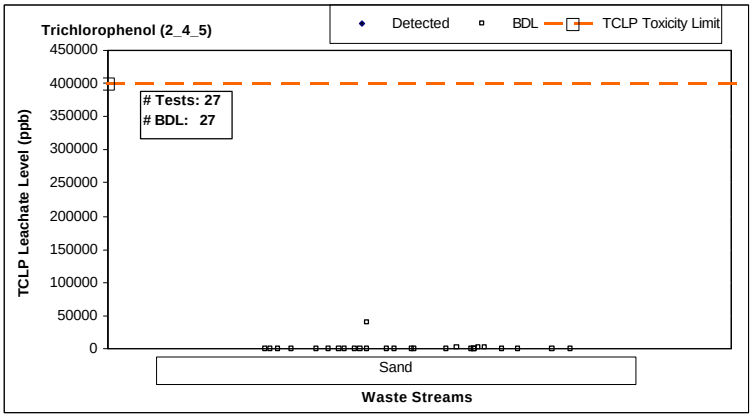

Hexachlorobenzene
Detected
BDL
TCLP Toxicity Limit
Tests: 58
BDL: 58
TCLP Leachate Level (ppb)
160
140
120
100
80
60
40
20
0
Sand
Waste Streams

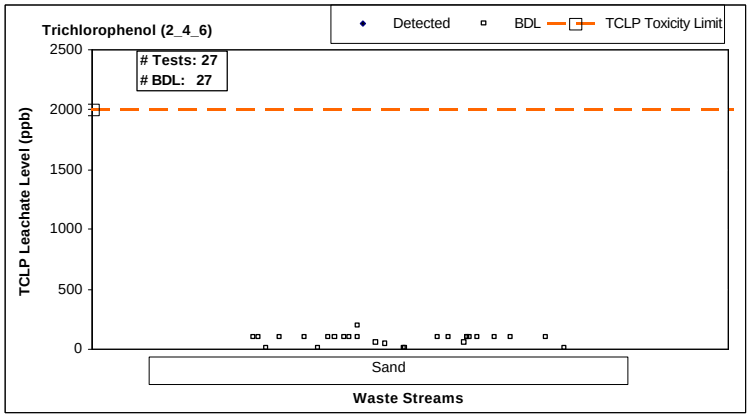

Hexachloroethane
Detected
BDL
TCLP Toxicity Limit
Tests: 26
BDL: 26
TCLP Leachate Level (ppb)
3500
3000
2500
2000
1500
1000
500
0
Sand
Waste Streams

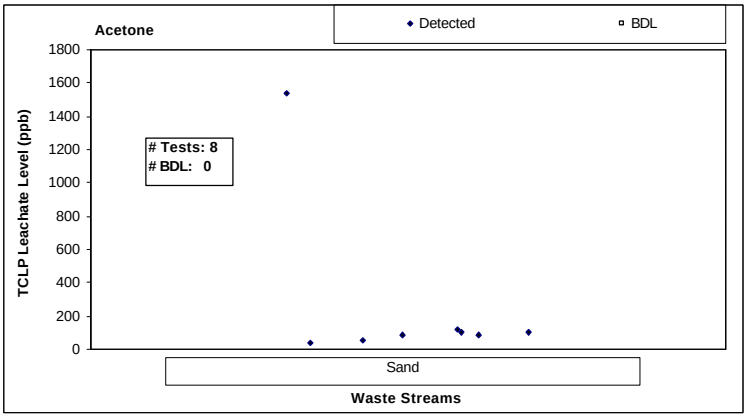

Nitrobenzene
Detected
BDL
TCLP Toxicity Limit
Tests: 59
BDL: 59
TCLP Leachate Level (ppb)
2500
2000
1500
1000
500
0
Sand
Waste Streams

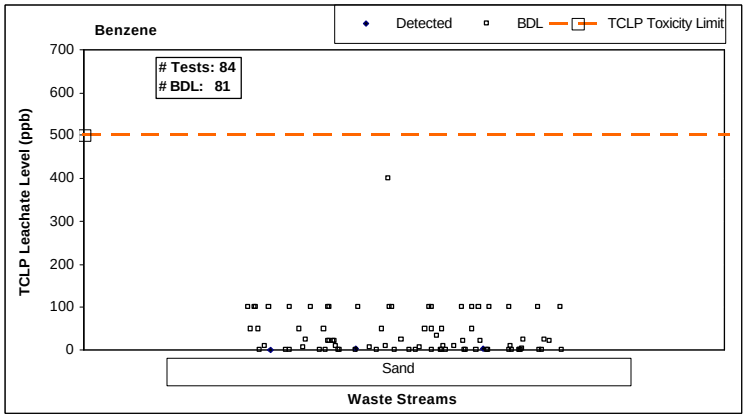

Pentrachlorophenol
Detected
BDL
TCLP Toxicity Limit
Tests: 27
BDL: 27
TCLP Leachate Level (ppb)
120000
100000
80000
60000
40000
20000
0
Sand
Waste Streams

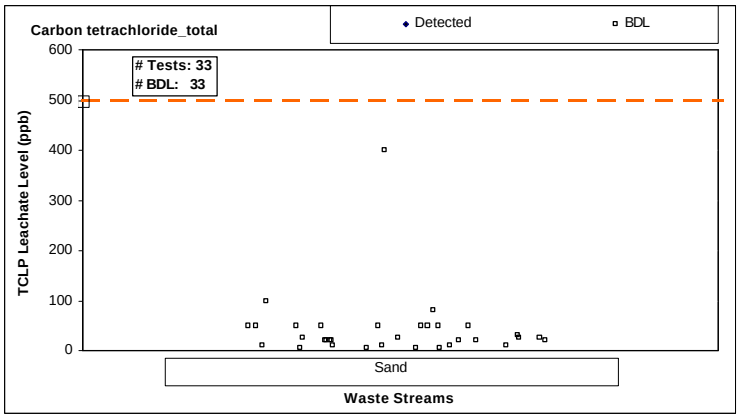

Pyridine
Detected
BDL
TCLP Toxicity Limit
Tests: 27
BDL: 27
TCLP Leachate Level (ppb)
6000
5000
4000
3000
2000
1000
0
Sand
Waste Streams

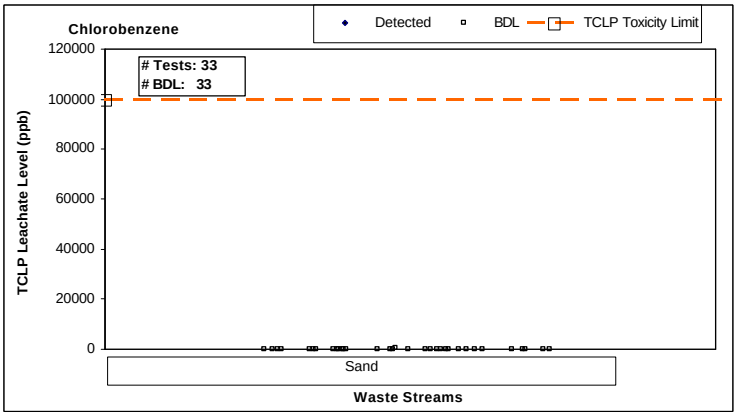

Trichlorophenol (2_4_5)
Detected
BDL
TCLP Toxicity Limit
Tests: 27
BDL: 27
TCLP Leachate Level (ppb)
450000
400000
350000
300000
250000
200000
150000
100000
50000
0
Sand
Waste Streams

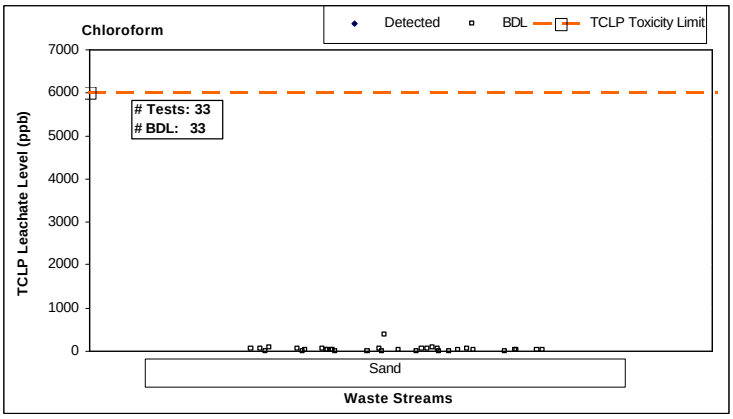

Trichlorophenol (2_4_6)
Detected
BDL
TCLP Toxicity Limit
Tests: 27
BDL: 27
TCLP Leachate Level (ppb)
2500
2000
1500
1000
500
0
Sand
Waste Streams

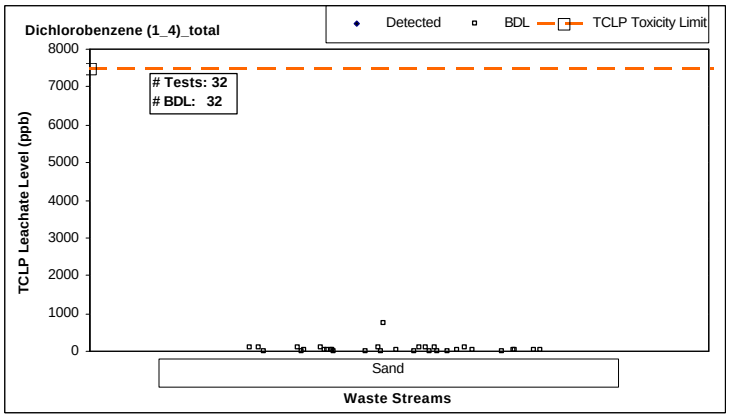

Acetone
Detected
BDL
Tests: 8
BDL: 0
TCLP Leachate Level (ppb)
1800
1600
1400
1200
1000
800
600
400
200
0
Sand
Waste Streams

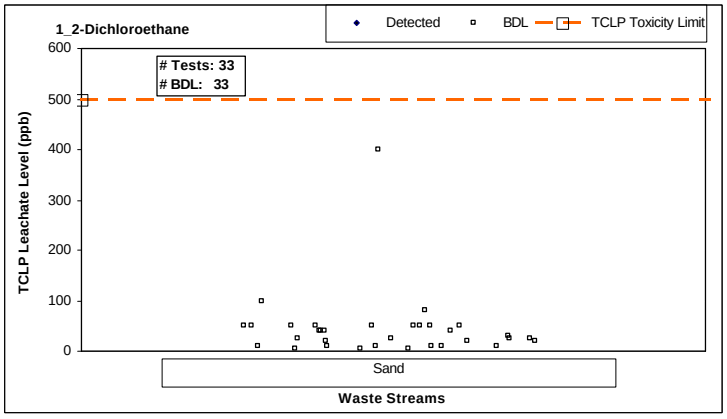

Benzene
Detected
BDL
TCLP Toxicity Limit
Tests: 84
BDL: 81
TCLP Leachate Level (ppb)
700
600
500
400
300
200
100
0
Sand
Waste Streams

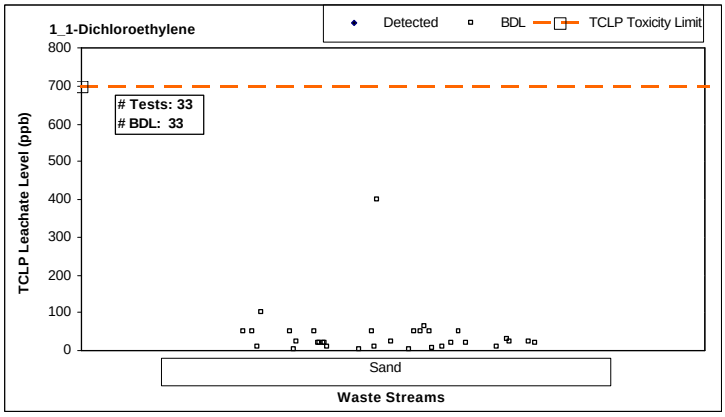

Carbon tetrachloride_total
Detected
BDL
Tests: 33
BDL: 33
TCLP Leachate Level (ppb)
600
500
400
300
200
100
0
Sand
Waste Streams

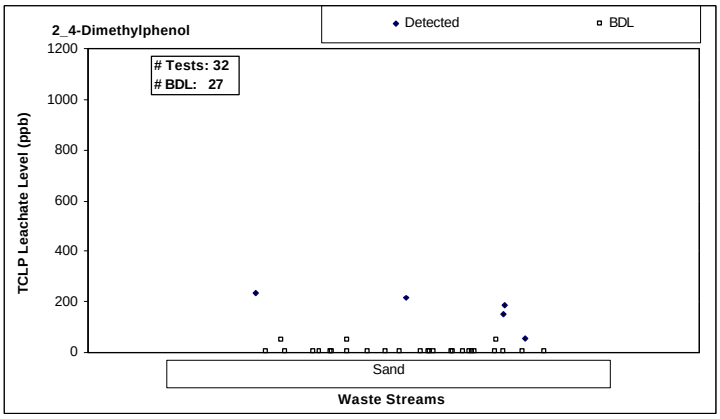

Chlorobenzene
Detected
BDL
TCLP Toxicity Limit
Tests: 33
BDL: 33
TCLP Leachate Level (ppb)
120000
100000
80000
60000
40000
20000
0
Sand
Waste Streams

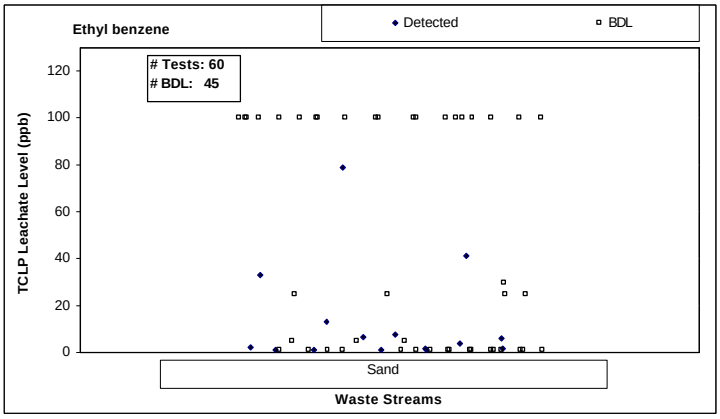

Chloroform
Detected
BDL
TCLP Toxicity Limit
Tests: 33
BDL: 33
TCLP Leachate Level (ppb)
7000
6000
5000
4000
3000
2000
1000
0
Sand
Waste Streams

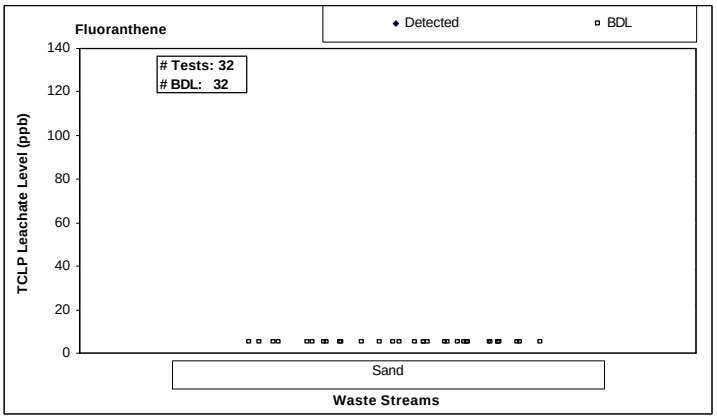

Dichlorobenzene (1_4)_total
Detected
BDL
TCLP Toxicity Limit
Tests: 32
BDL: 32
TCLP Leachate Level (ppb)
8000
7000
6000
5000
4000
3000
2000
1000
0
Sand
Waste Streams

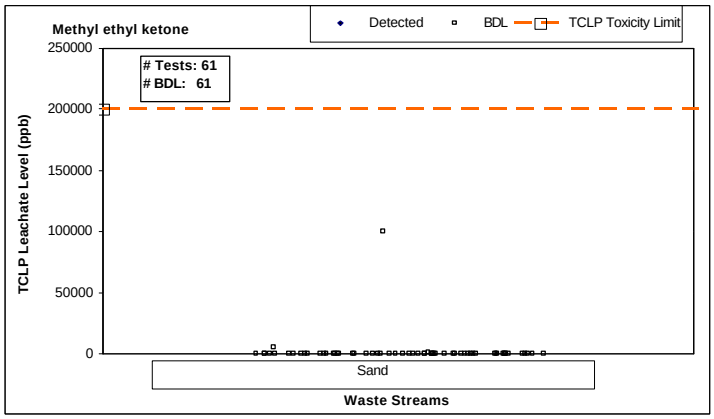

1_2-Dichloroethane
Detected
BDL
TCLP Toxicity Limit
Tests: 33
BDL: 33
TCLP Leachate Level (ppb)
600
500
400
300
200
100
0
Sand
Waste Streams

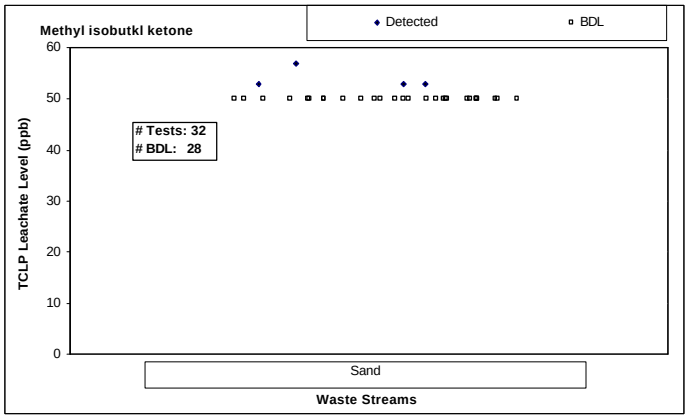

1_1-Dichloroethylene
Detected
BDL
TCLP Toxicity Limit
Tests: 33
BDL: 33
TCLP Leachate Level (ppb)
800
700
600
500
400
300
200
100
0
Sand
Waste Streams

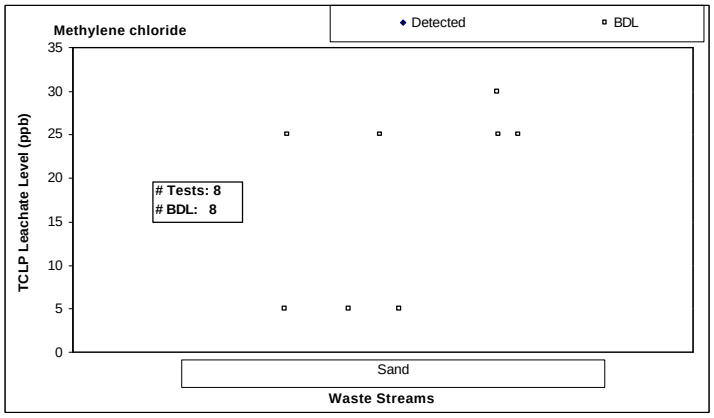

2_4-Dimethylphenol
Detected
BDL
Tests: 32
BDL: 27
TCLP Leachate Level (ppb)
1200
1000
800
600
400
200
0
Sand
Waste Streams

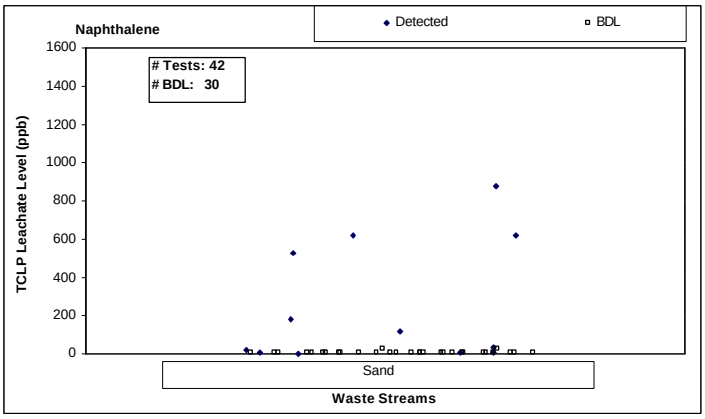

Ethyl benzene
Detected
BDL
Tests: 60
BDL: 45
TCLP Leachate Level (ppb)
120
100
80
60
40
20
0
Sand
Waste Streams

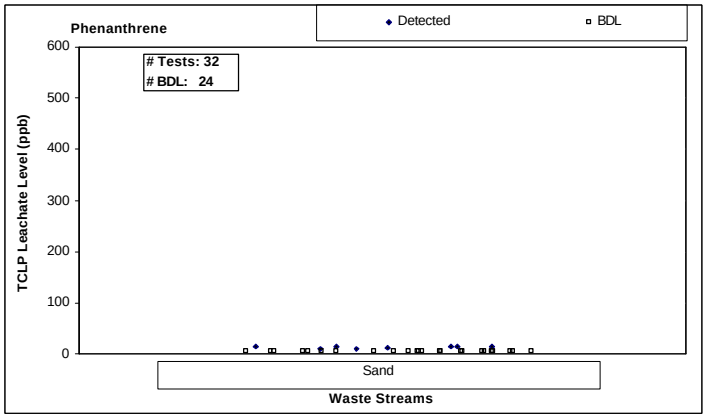

Fluoranthene
Detected
BDL
Tests: 32
BDL: 32
TCLP Leachate Level (ppb)
140
120
100
80
60
40
20
0
Sand
Waste Streams

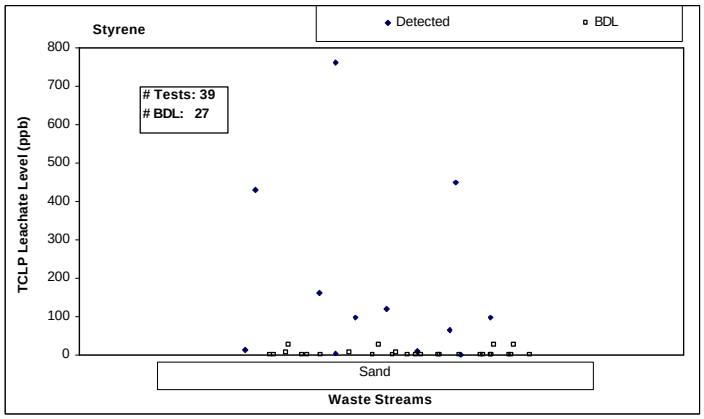

Methyl ethyl ketone
Detected
BDL
TCLP Toxicity Limit
Tests: 61
BDL: 61
TCLP Leachate Level (ppb)
250000
200000
150000
100000
50000
0
Sand
Waste Streams

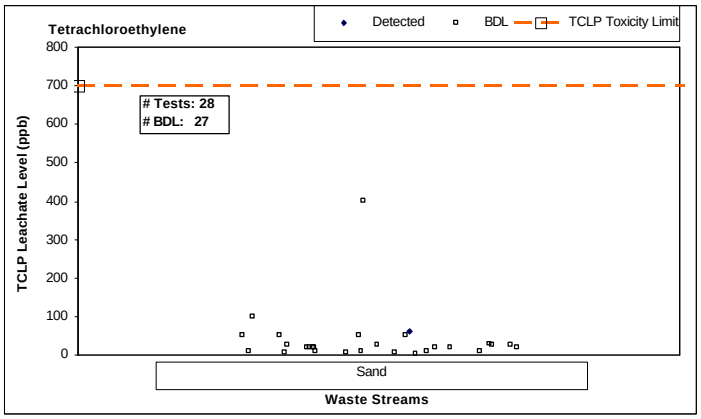

Methyl isobutkl ketone
Detected
BDL
Tests: 32
BDL: 28
TCLP Leachate Level (ppb)
0
10
20
30
40
50
60
Sand
Waste Streams

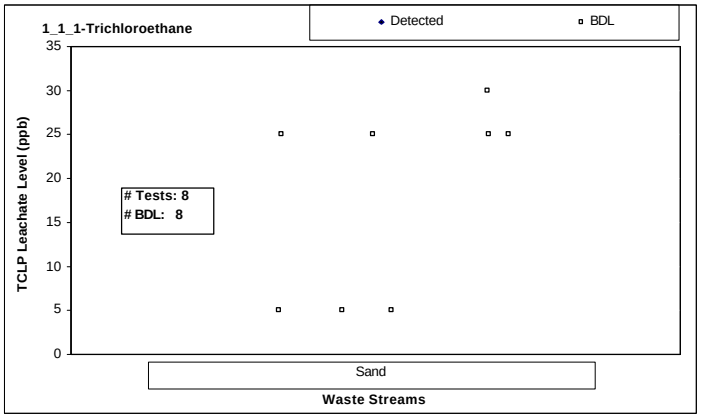

Methylene chloride
Detected
BDL
Tests: 8
BDL: 8
TCLP Leachate Level (ppb)
0
5
10
15
20
25
30
35
Sand
Waste Streams

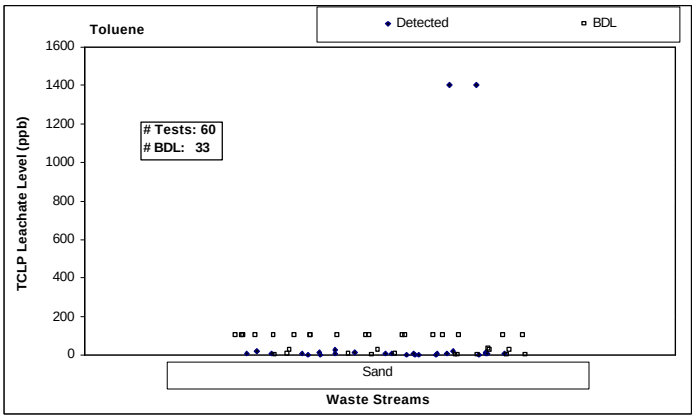

Naphthalene
Detected
BDL
Tests: 42
BDL: 30
TCLP Leachate Level (ppb)
0
200
400
600
800
1000
1200
1400
1600
Sand
Waste Streams

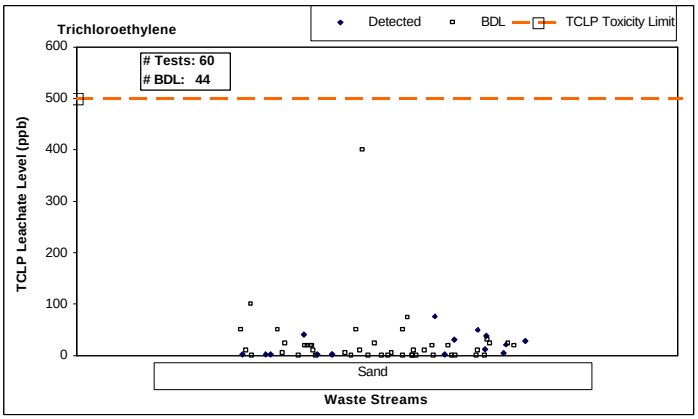

Phenanthrene
Detected
BDL
Tests: 32
BDL: 24
TCLP Leachate Level (ppb)
600
500
400
300
200
100
0
Sand
Waste Streams

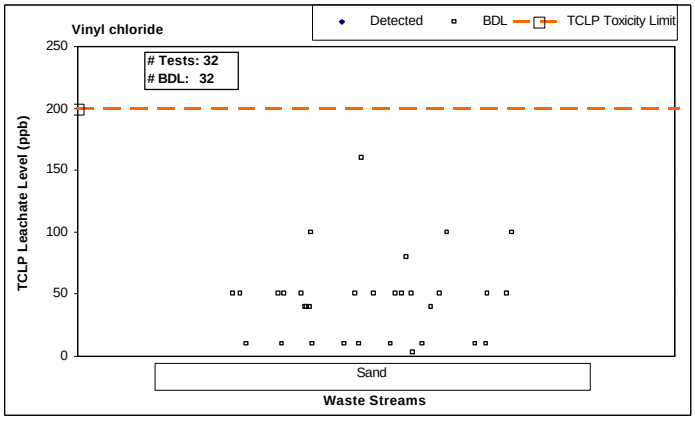

Styrene
Detected
BDL
Tests: 39
BDL: 27
TCLP Leachate Level (ppb)
800
700
600
500
400
300
200
100
0
Sand
Waste Streams

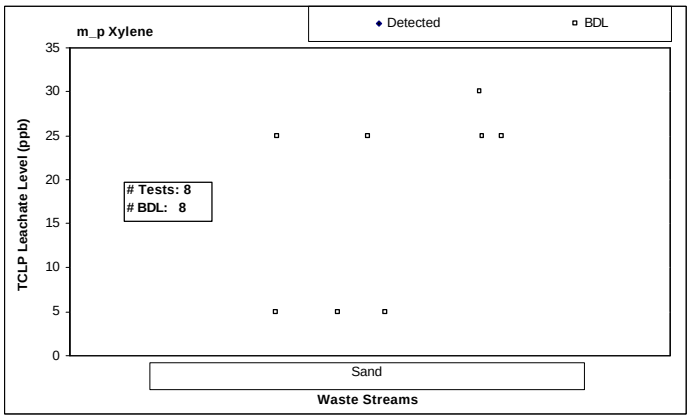

Tetrachloroethylene
Detected
BDL
TCLP Toxicity Limit
Tests: 28
BDL: 27
TCLP Leachate Level (ppb)
800
700
600
500
400
300
200
100
0
Sand
Waste Streams


1_1_1-Trichloroethane
Detected
BDL
TCLP Leachate Level (ppb)
35
30
25
20
15
10
5
0
Tests: 8
BDL: 8
Sand
Waste Streams


Toluene
Detected
BDL
TCLP Leachate Level (ppb)
1600
1400
1200
1000
800
600
400
200
0
Tests: 60
BDL: 33
Sand
Waste Streams


Trichloroethylene
Detected
BDL
TCLP Toxicity Limit
TCLP Leachate Level (ppb)
600
500
400
300
200
100
0
Tests: 60
BDL: 44
Sand
Waste Streams





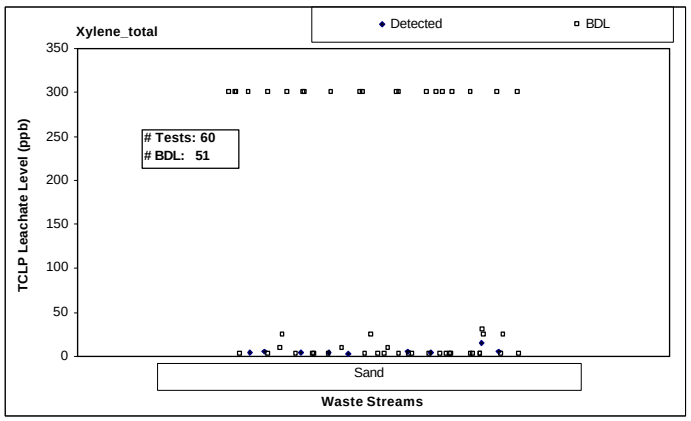


Figure **E-3**: Leachate concentration of organic compounds (37 charts)

Appendix F

Survival Plot and Estimated Mean

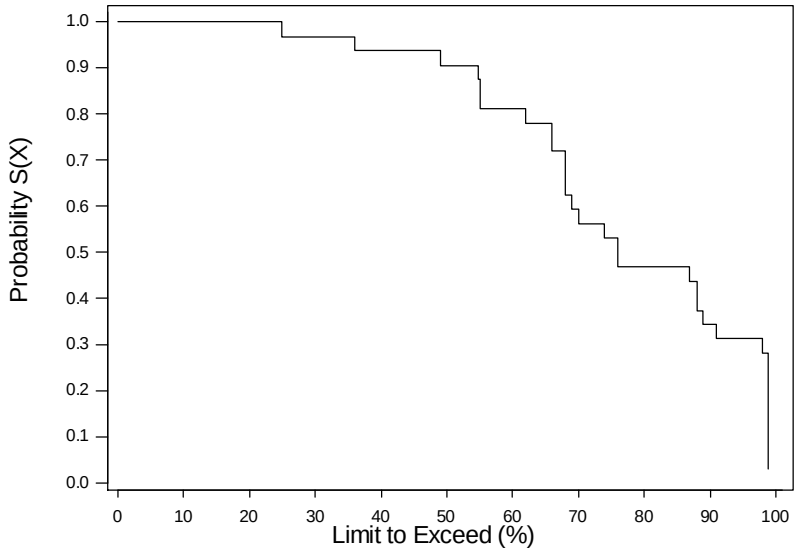
Precise quantification of chemical characterization of excess foundry sand is important for the marketability of the excess foundry sand. In this appendix, survival plot is used to demonstrate the survival probabilities for up to 27 general chemical parameters, up to 24 metallic elements, and up to 55 organic compounds in both as-received condition and leachate (Table **3-3** to Table **3-8**), and to present the effects of two factors: leaching protocol and metal cast. Treatments of leaching protocol include TCLP, SPLP, and ASTM D 3987. Treatments of metal cast include iron-based facility, steel-based facility, aluminum-based facility, and copper-based facility. Estimated mean corresponding to the individual survival plot is presented after each individual legend. Further discussion is presented in Sections 5.1 through 5.7 of the body of the report. Due to the occurrences that data for a parameter may be censored completely, the survival plot for that parameter is not available.

F.1 Bulk Characterization of Excess Foundry Sand

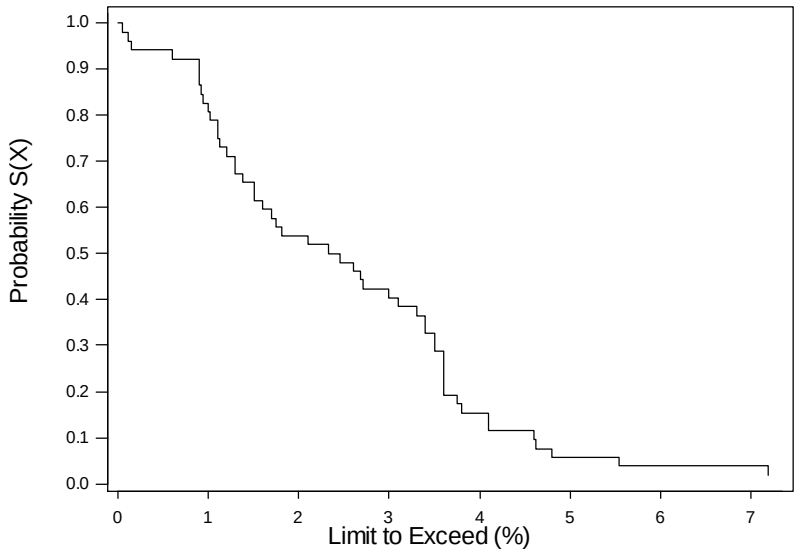
In this section, a series of 55 charts present the bulk characterization of excess foundry sand. The first 11 charts, grouped into Figure F-1, are for general chemical parameters. The second 23 charts, grouped into Figure F-2, are for metallic elements. The remaining 21 charts, grouped into Figure F-3, are for organic compounds.

F.1.1 General Chemical Parameters

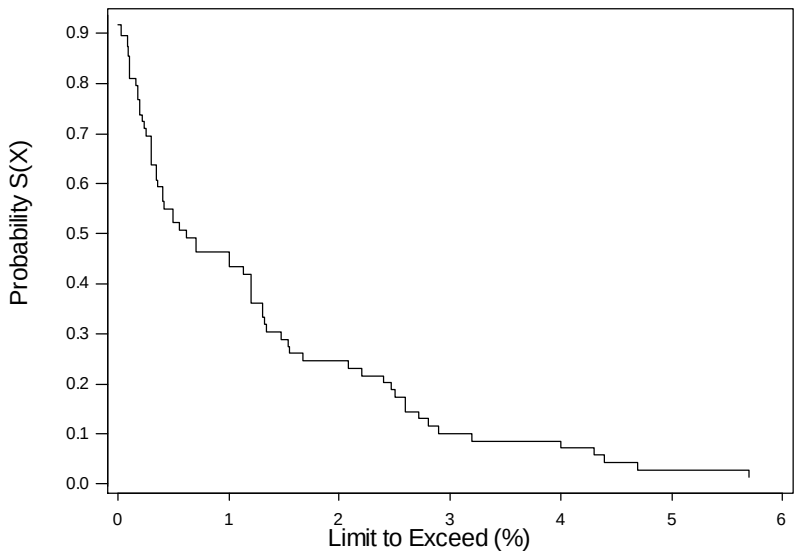
Nonparametric Survival Plot for Silica (Mean=77.2%)



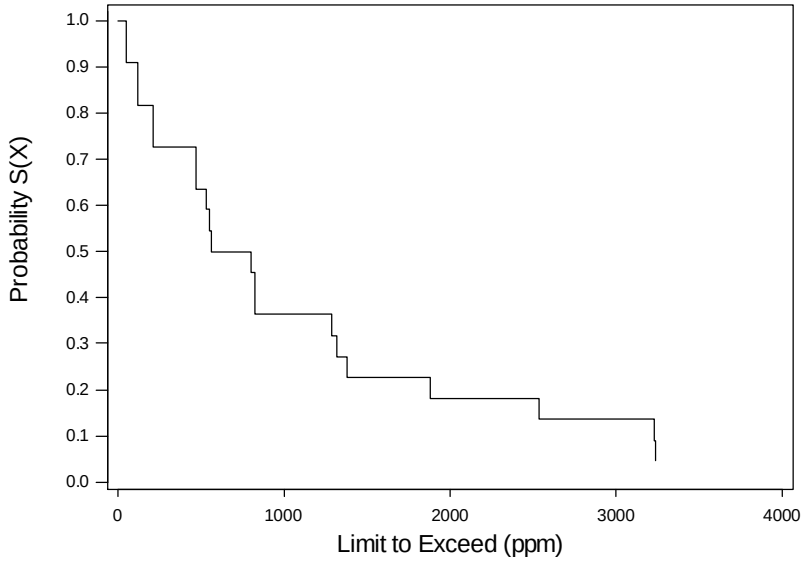
Nonparametric Survival Plot for Loss on ignition (Mean=2.54%)



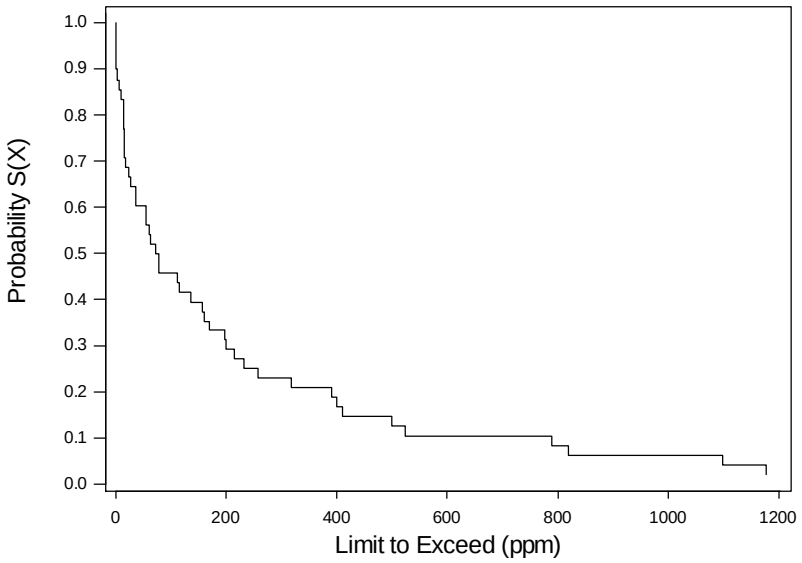
Nonparametric Survival Plot for Total moisture
(Mean=1.27%)



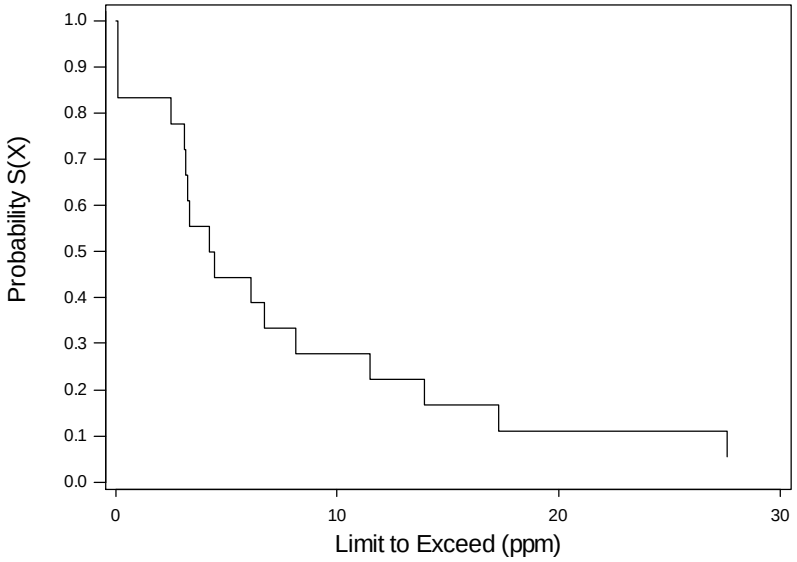
Nonparametric Survival Plot for Oil and grease
(Mean=1774 ppm)



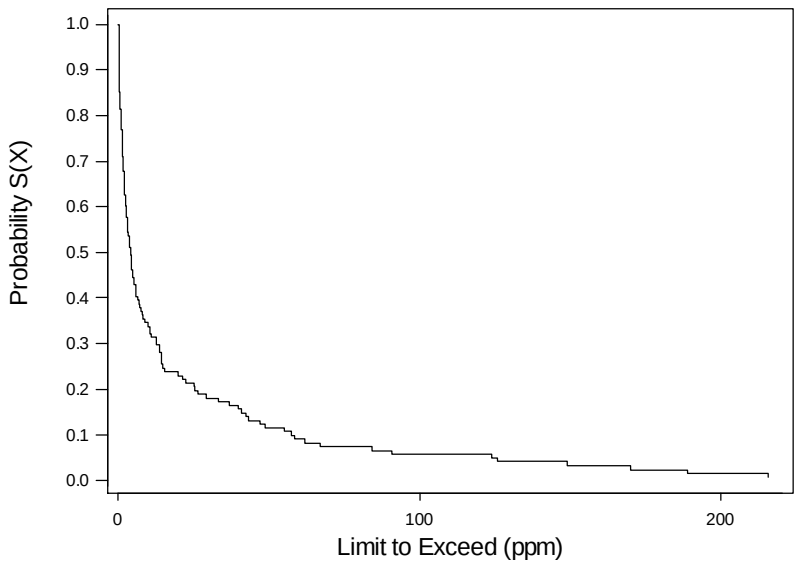
Nonparametric Survival Plot for Total Petroleum
(Mean=223.52 ppm)



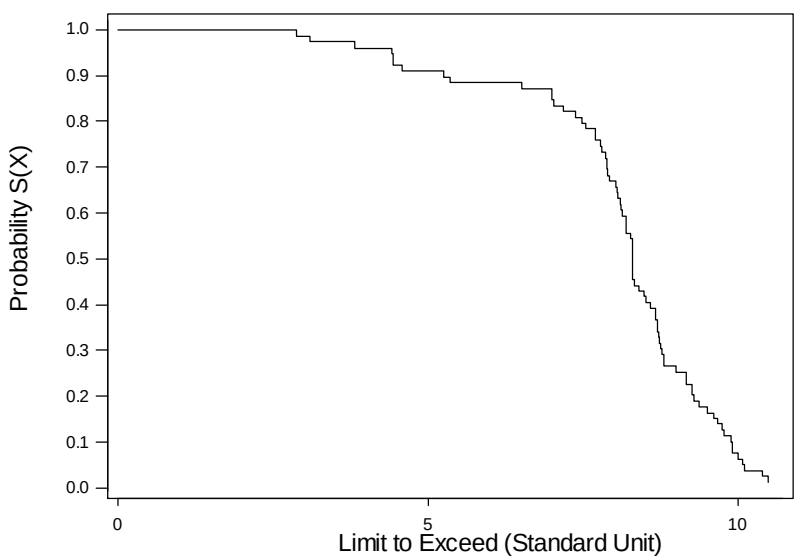
Nonparametric Survival Plot for Formaldehyde
(Mean=9.21ppm)



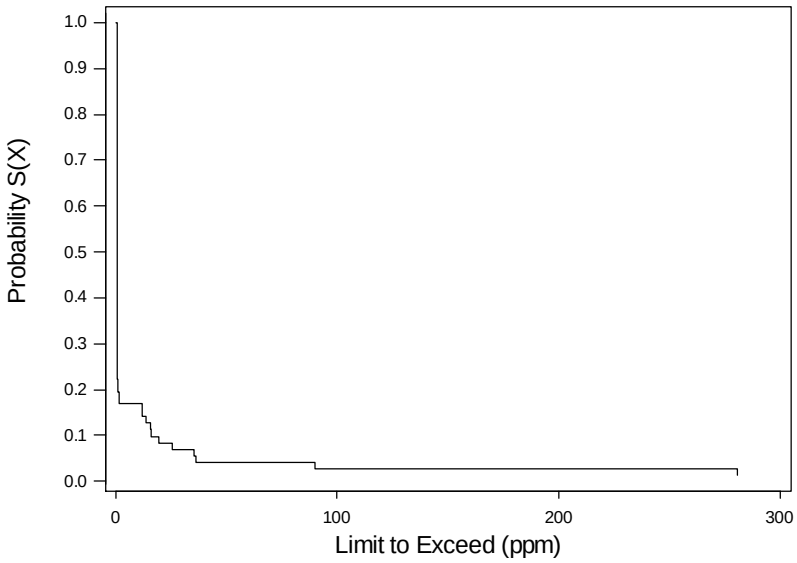
Nonparametric Survival Plot for Phenols Total
(Mean = 21.45 ppm)



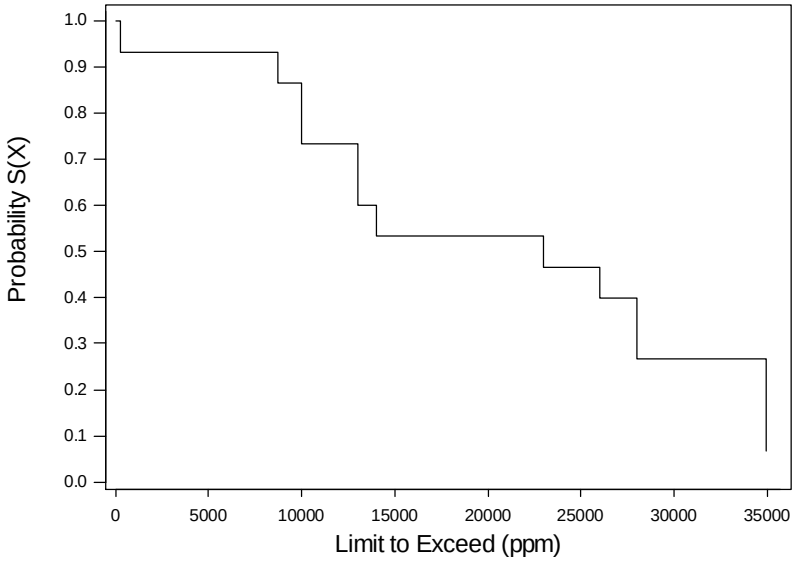
Nonparametric Survival Plot for PH (Mean=8.11)



Nonparametric Survival Plot for Reactive Sulfide (Mean = 37.02 ppm)



Nonparametric Survival Plot for Total Volatile Residue (Mena=20995 ppm)



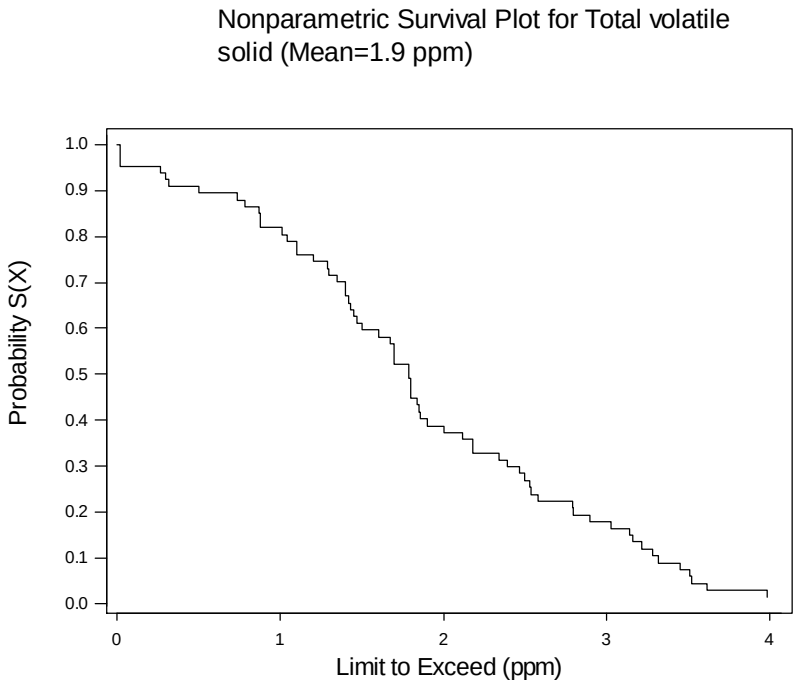
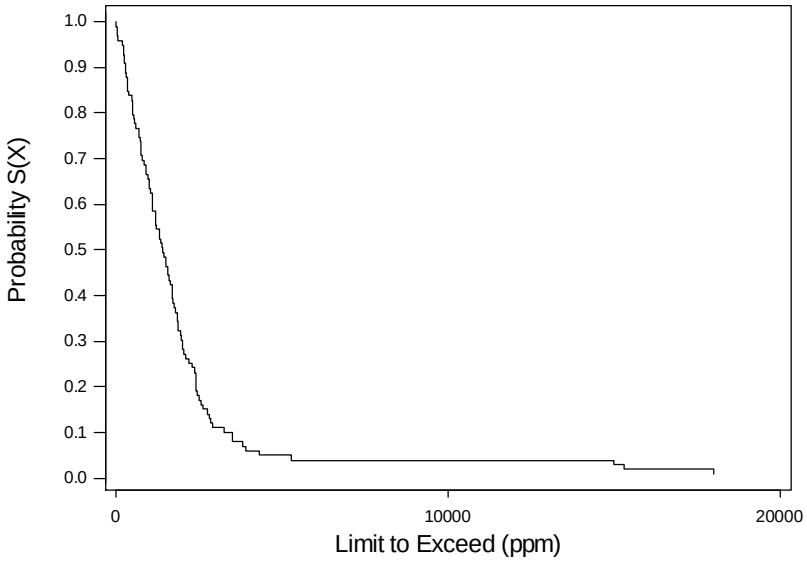


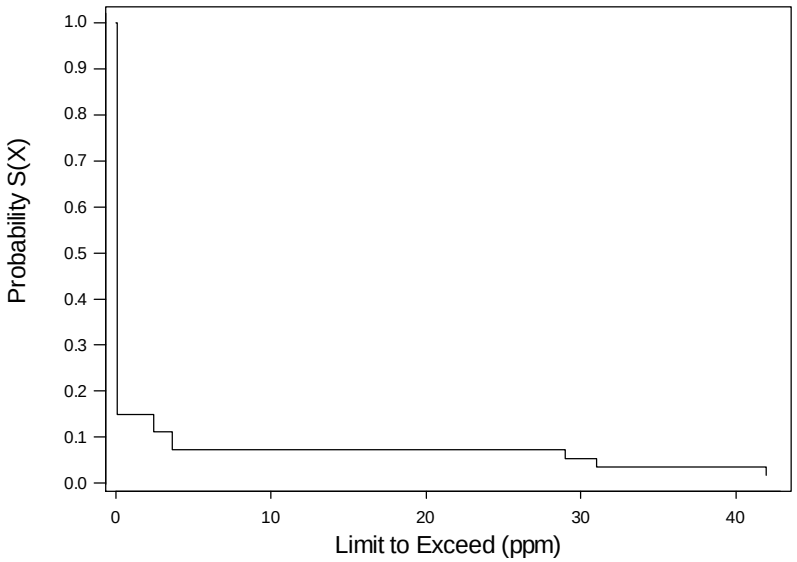
Figure **F-1**: Survival plots for bulk general chemical parameters (11 charts)

F.1.2 Metallic Elements

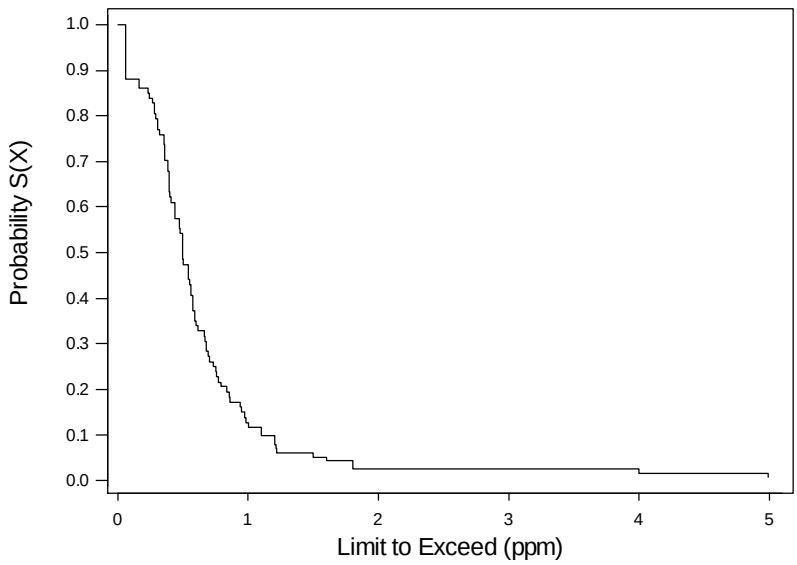
Nonparametric Survival Plot for Aluminium(Al)
(Mean=3326 ppm)



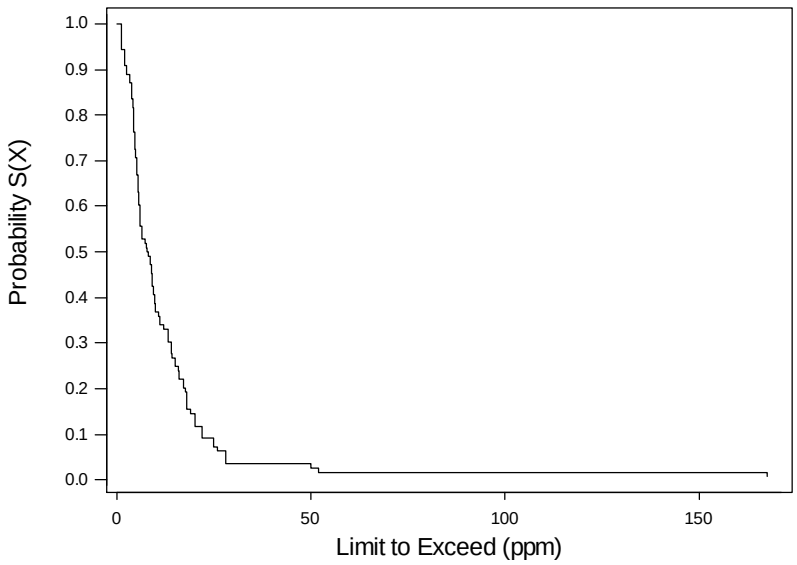
Nonparametric Survival Plot for Antimony(Sb)
(Mena=4.34 ppm)



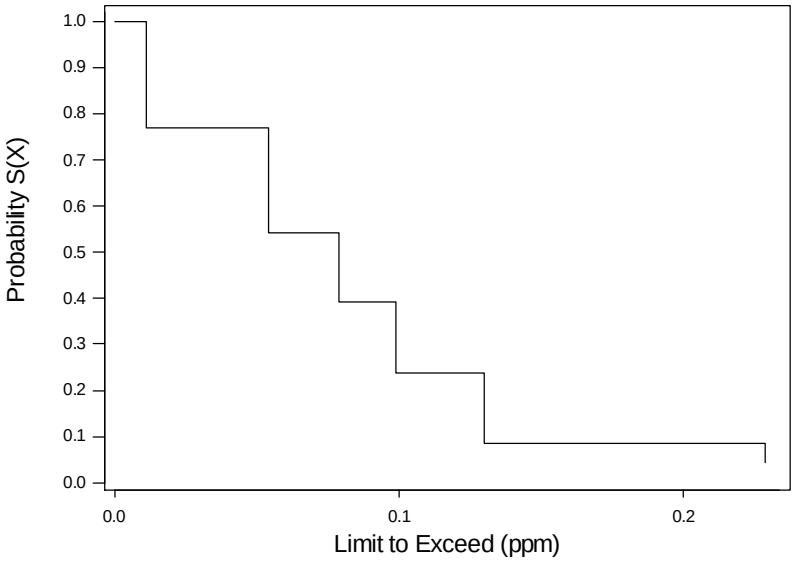
Nonparametric Survival Plot for Arsenic(As)
(Mena=0.86 ppm)



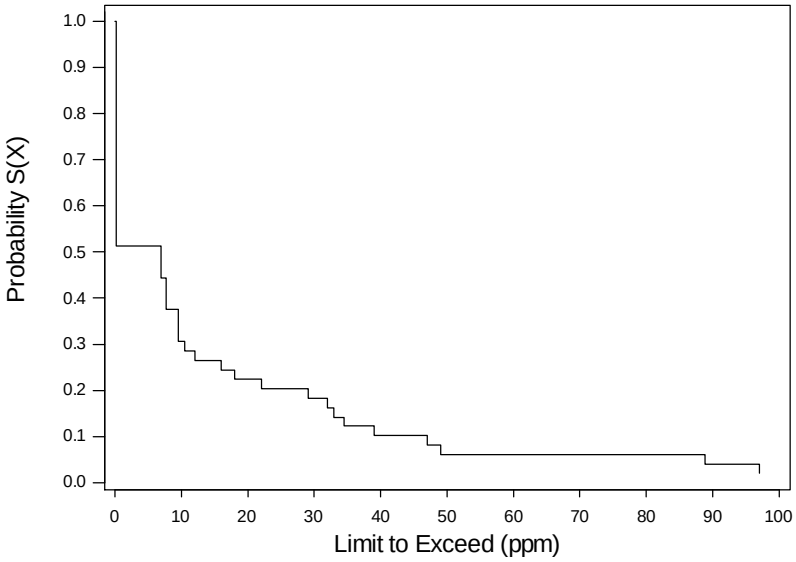
Nonparametric Survival Plot for Barium(Ba)
(Mean=14.95 ppm)



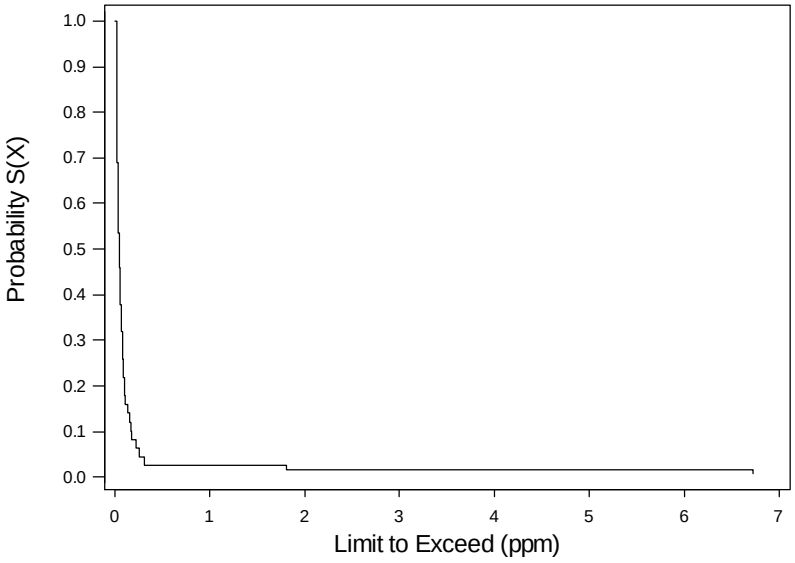
Nonparametric Survival Plot for Beryllium (Be)
(Mean=0.08 ppm)



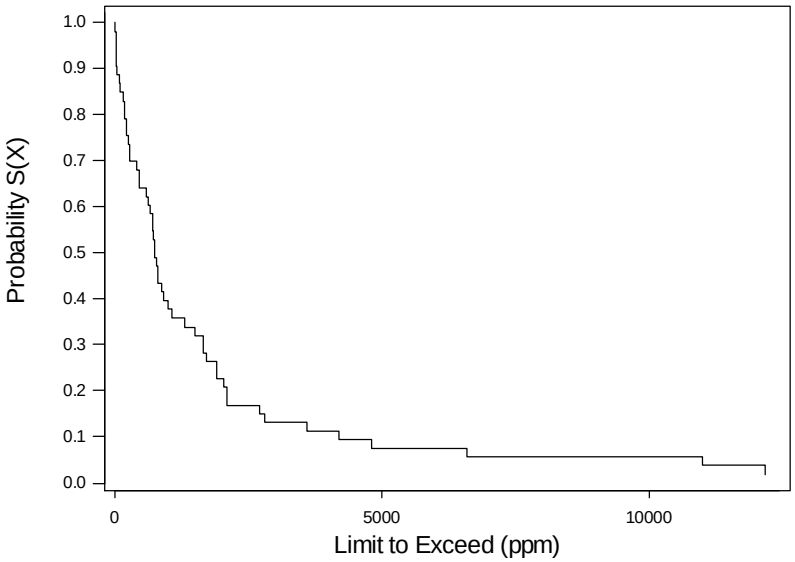
Nonparametric Survival Plot for Boron(B)
(Mean=38.53 ppm)



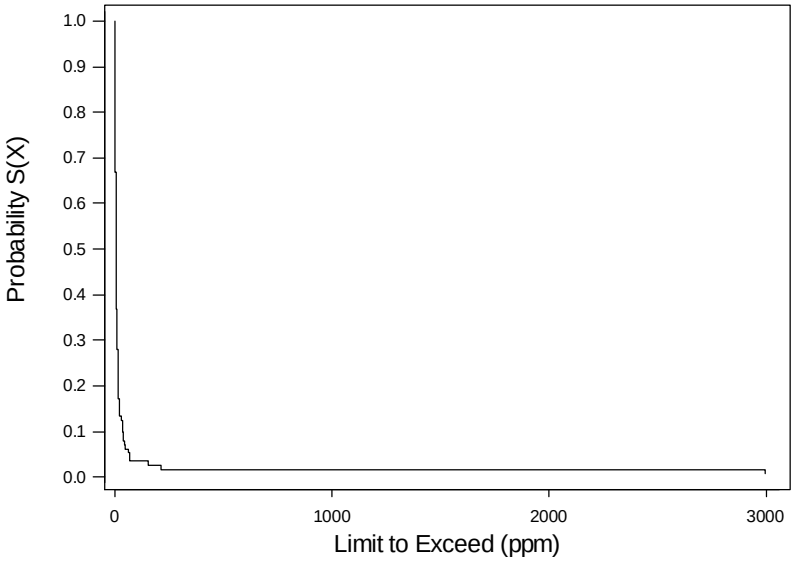
Nonparametric Survival Plot for Cadmium(Cd)
(Mean=0.22 ppm)



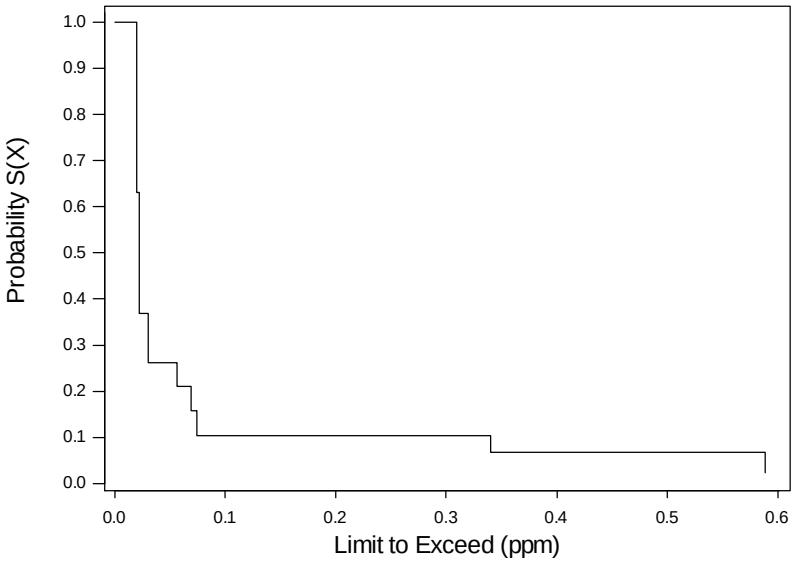
Nonparametric Survival Plot for Calcium (Ca)
(Mean=3309 ppm)



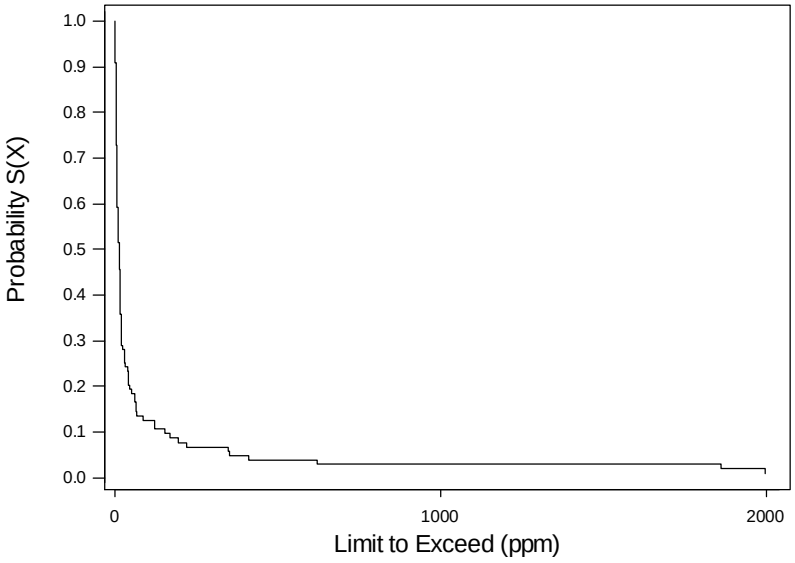
Nonparametric Survival Plot for Chromium(Cr)
(Mean=114 ppm)



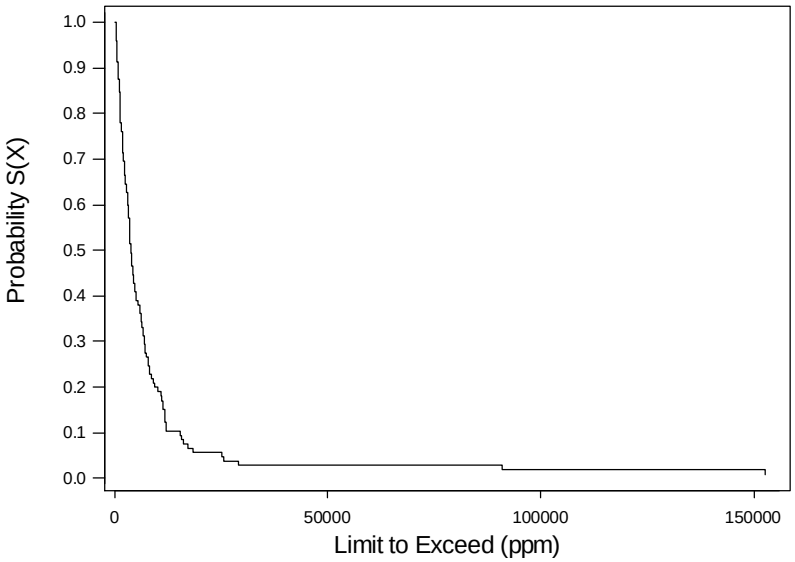
Nonparametric Survival Plot for Hexavalent
chromium (Mean=0.08 ppm)



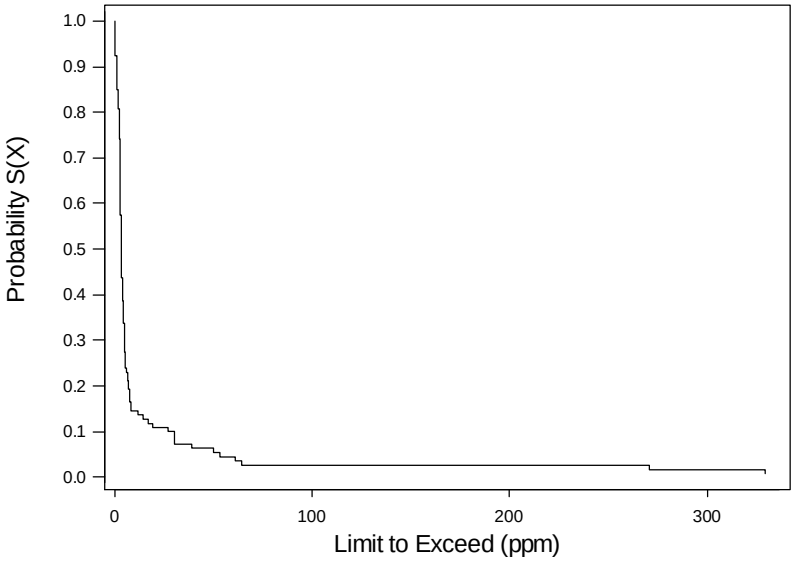
Nonparametric Survival Plot for Copper(Cu)
(Mean=103.6 ppm)



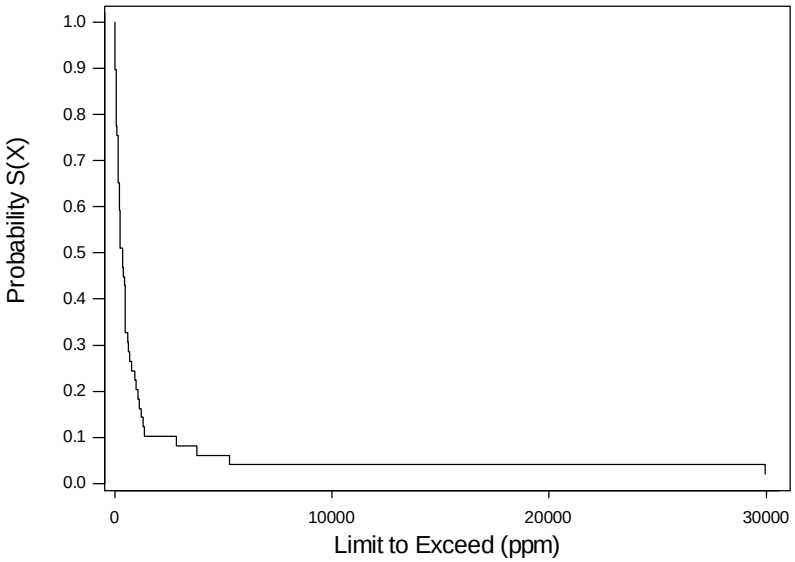
Nonparametric Survival Plot for Iron(Fe)
(Mean=10912 ppm)



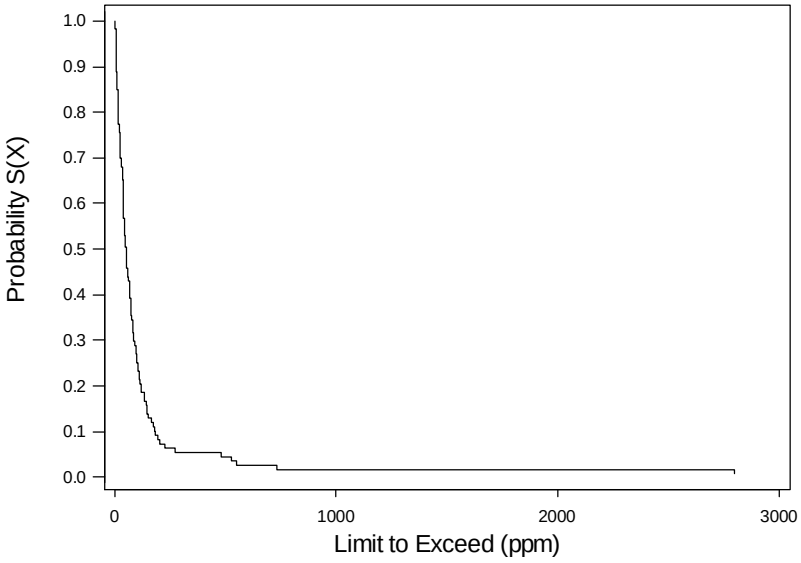
Nonparametric Survival Plot for Lead(Pb)
(Mean=15.72 ppm)



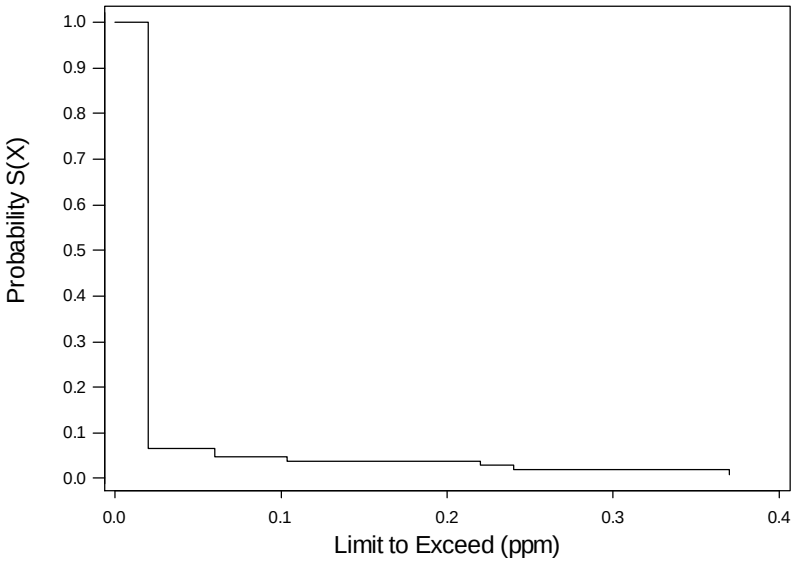
Nonparametric Survival Plot for Magnesium(Mg)
(Mean=1881 ppm)



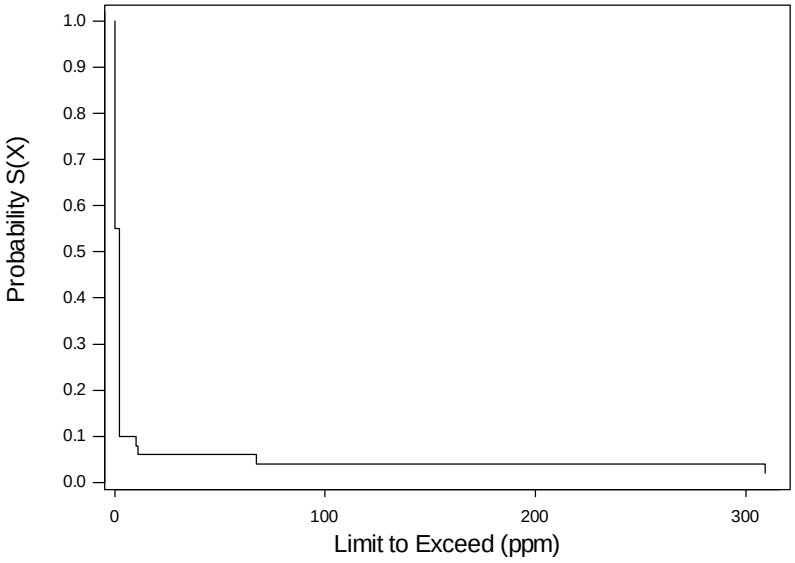
Nonparametric Survival Plot for Manganese(Mn)
(Mean=256.9 ppm)



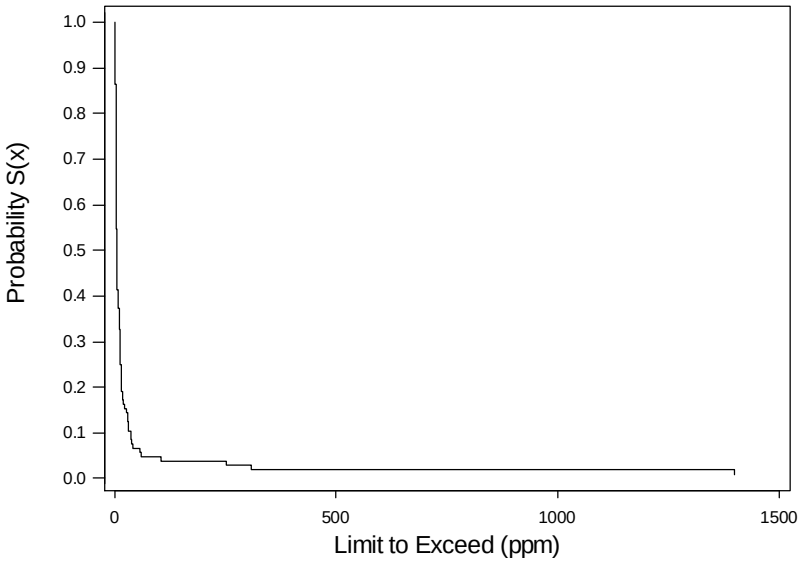
Nonparametric Survival Plot for Mercury (Hg)
(Mean=0.04 ppm)



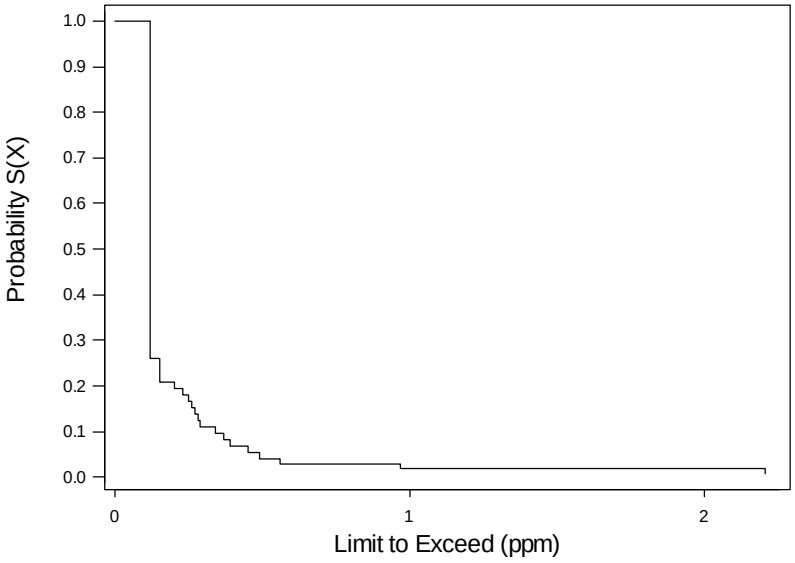
Nonparametric Survival Plot for Molybdenum(Mo)
(Mean=38.84 ppm)



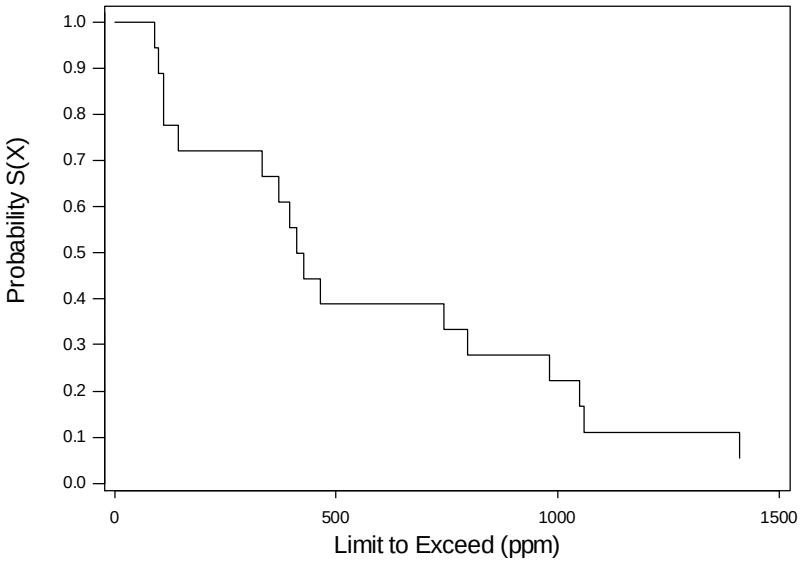
Nonparametric Survival Plot for Nickel(Ni)
(Mean=107.94 ppm)



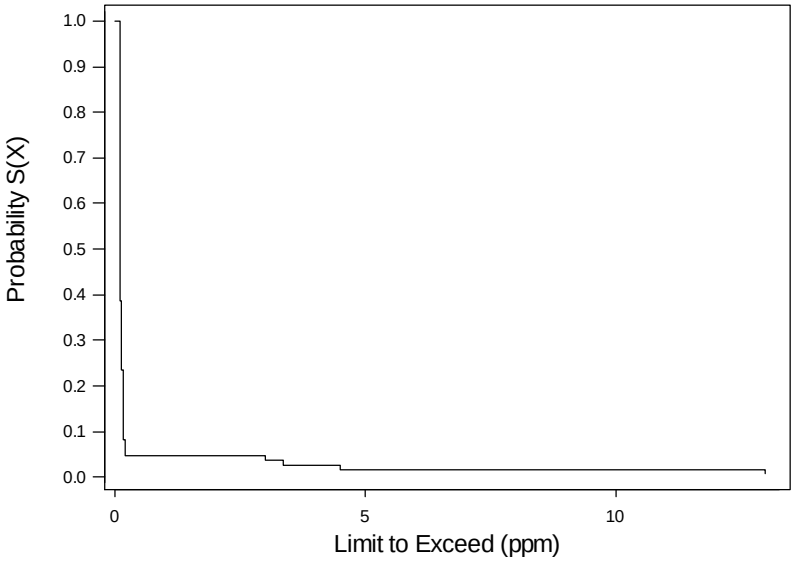
Nonparametric Survival Plot for Selenium(Se)
(Mean=0.64 ppm)



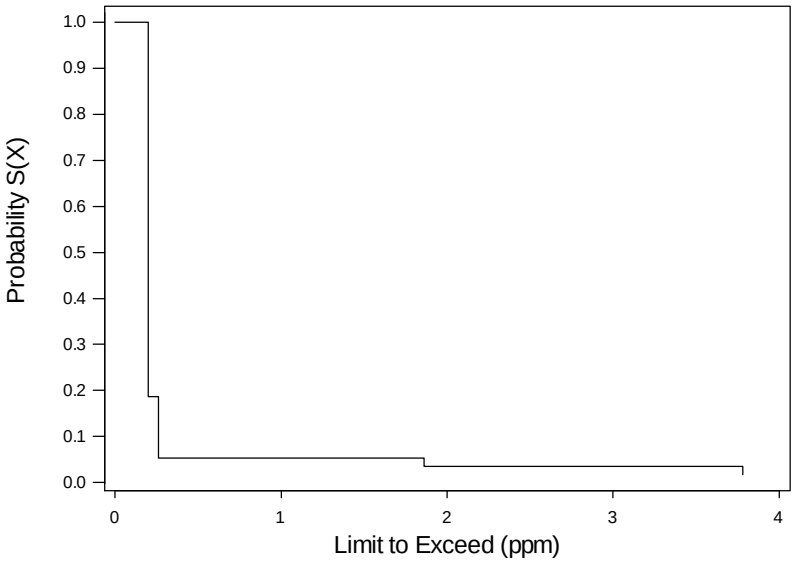
Nonparametric Survival Plot for Silicon(Si)
(Mean=1771.88 ppm)



Nonparametric Survival Plot for Silver (Ag)
(Mean=0.47 ppm)



Nonparametric Survival Plot for Thallium (Tl)
(Mean=0.43 ppm)



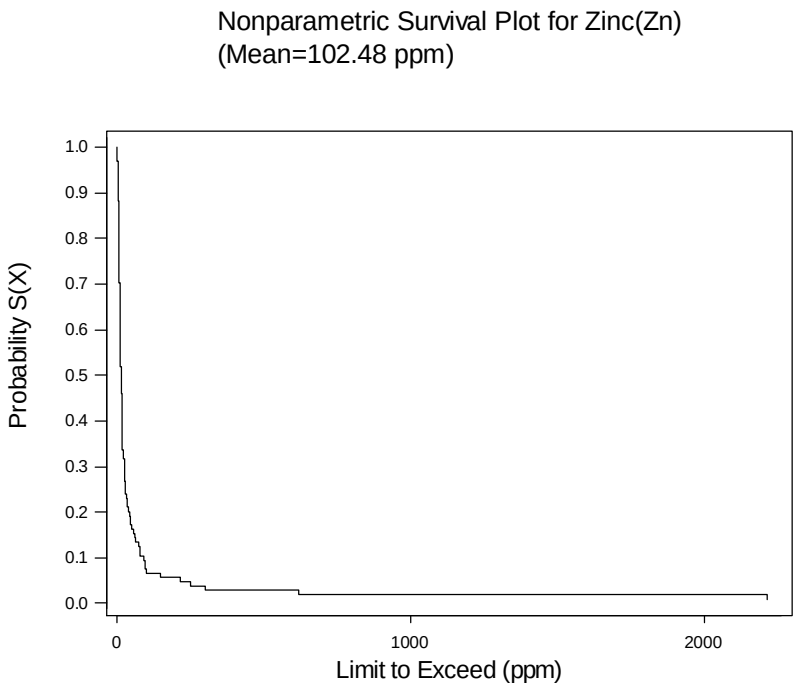
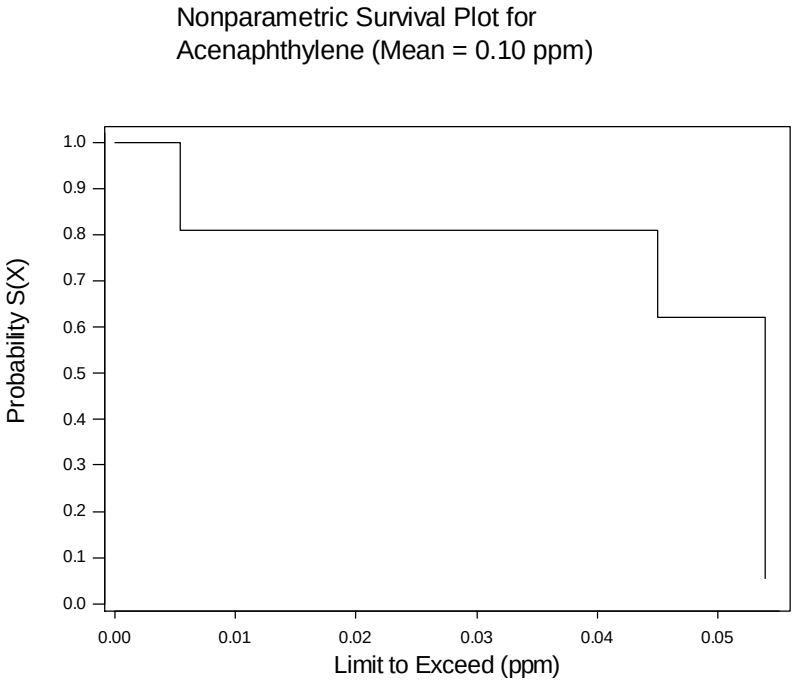
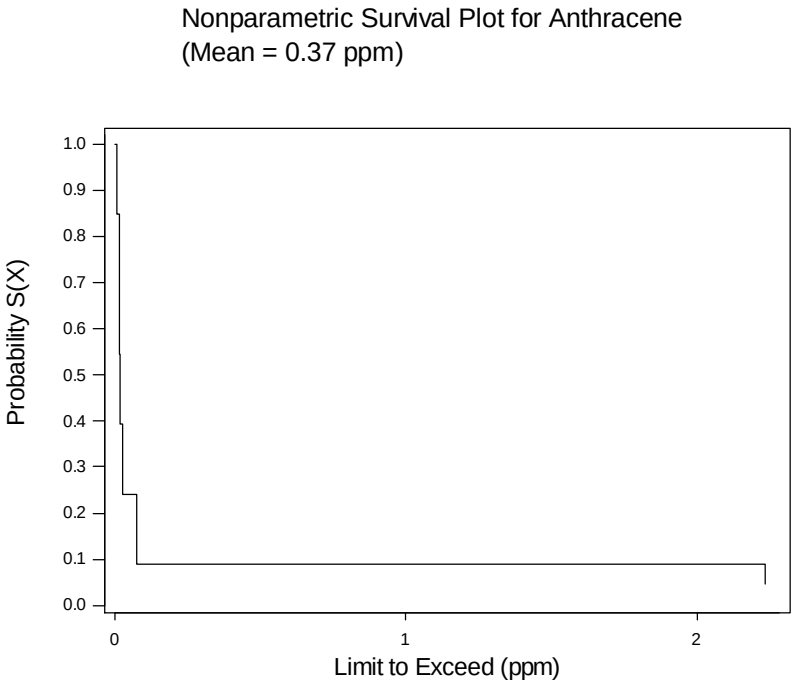


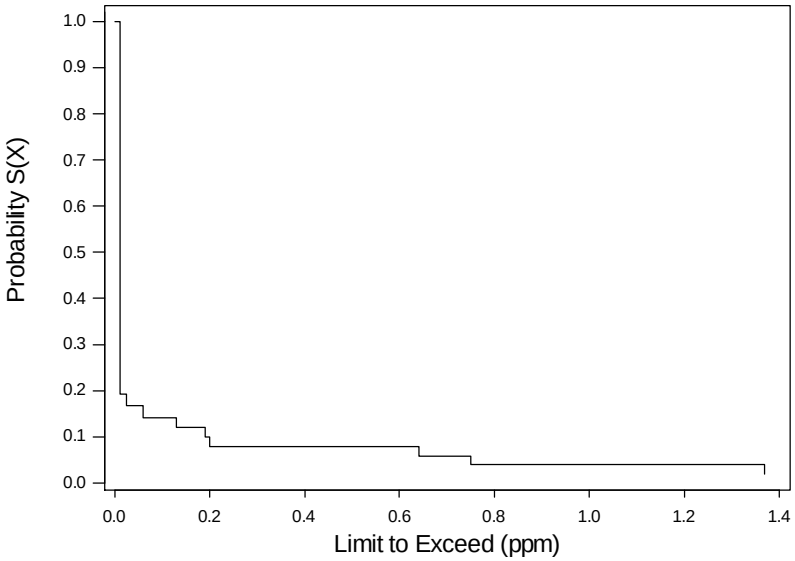
Figure **F-2**: Survival plots for bulk metallic elements (23 charts)

F.1.3 Organic Compounds

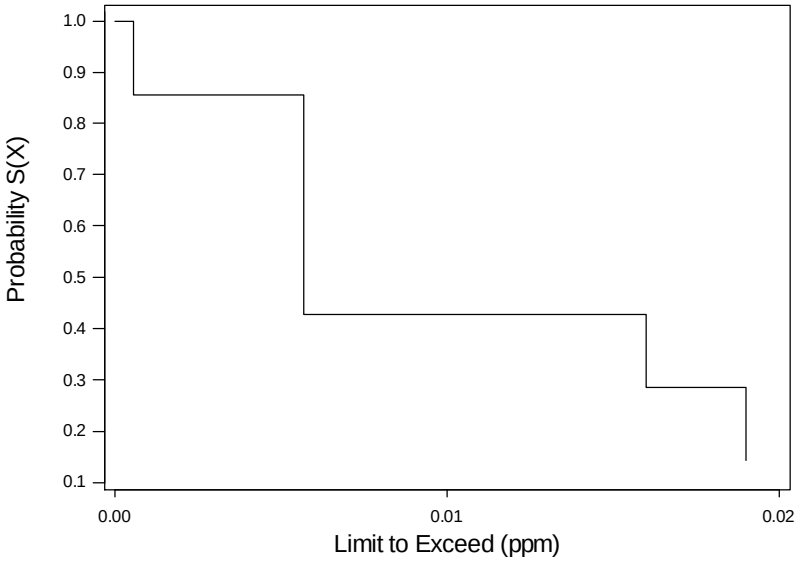




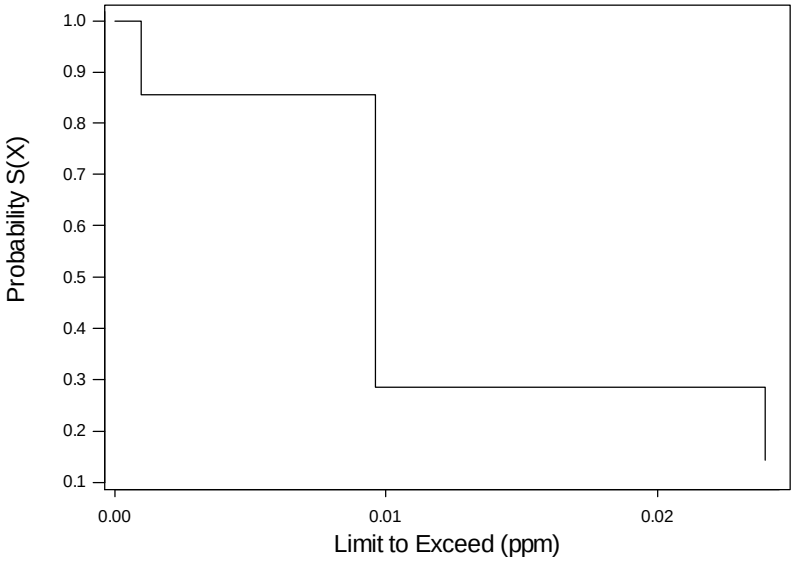
Nonparametric Survival Plot for Benzene
(Mean=0.12 ppm)



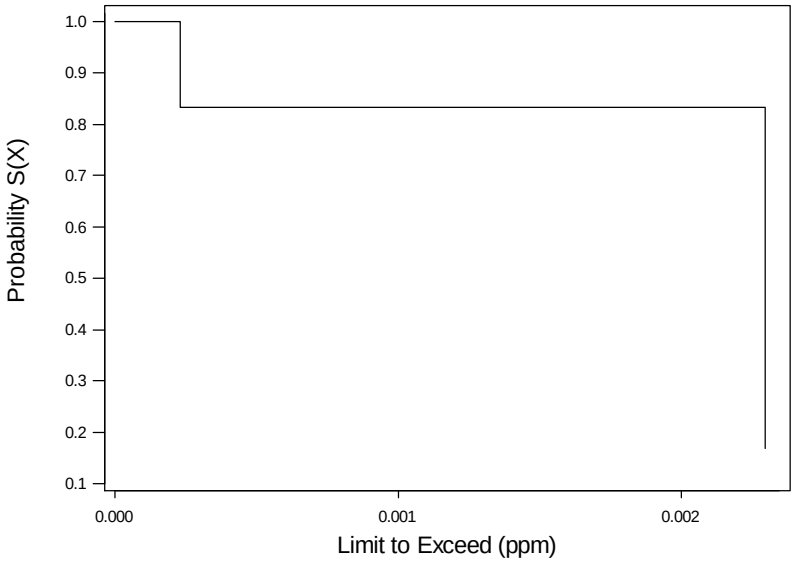
Nonparametric Survival Plot for
Benzo(a)anthrace (Mean = 0.01 ppm)



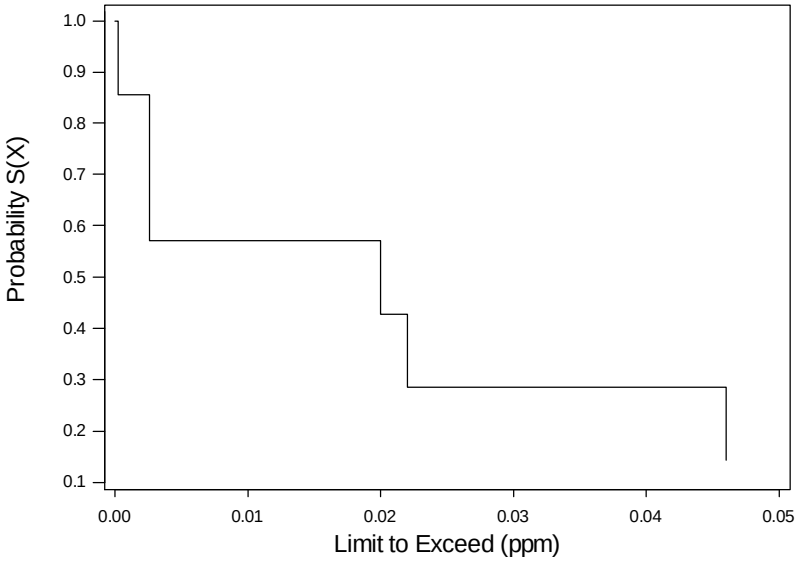
Nonparametric Survival Plot for
Benzo(b)fluornat (Mean = 0.01 ppm)



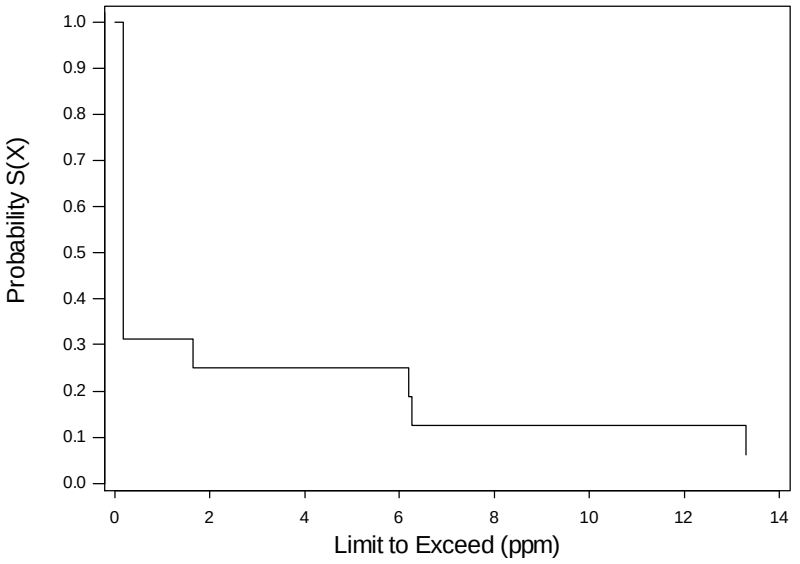
Nonparametric Survival Plot for Benzo(k)fluornat
sand_0.002 ppm



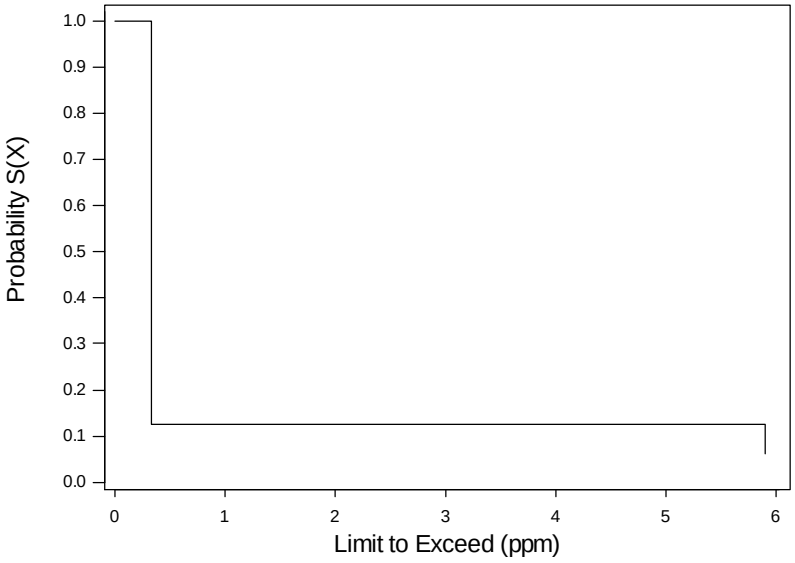
Nonparametric Survival Plot for Chrysene
(Mean = 0.027 ppm)



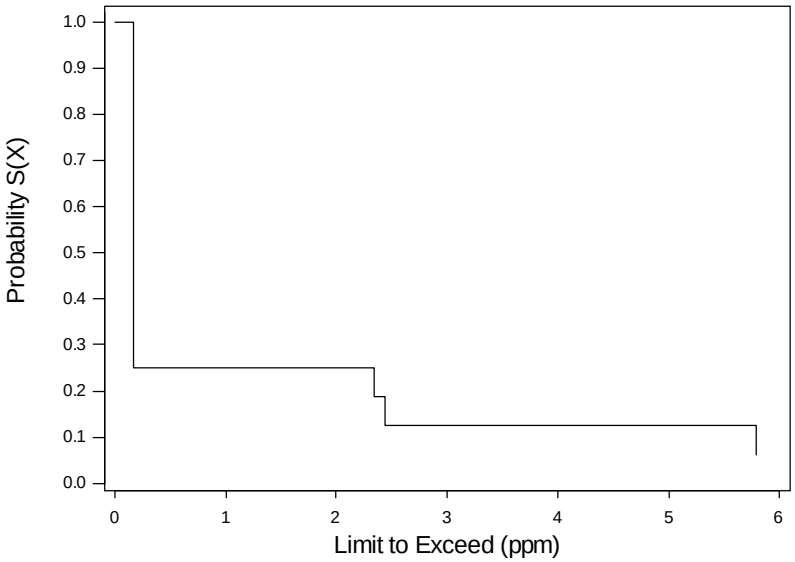
Nonparametric Survival Plot for o-Cresol
(Mean = 2.722 ppm)



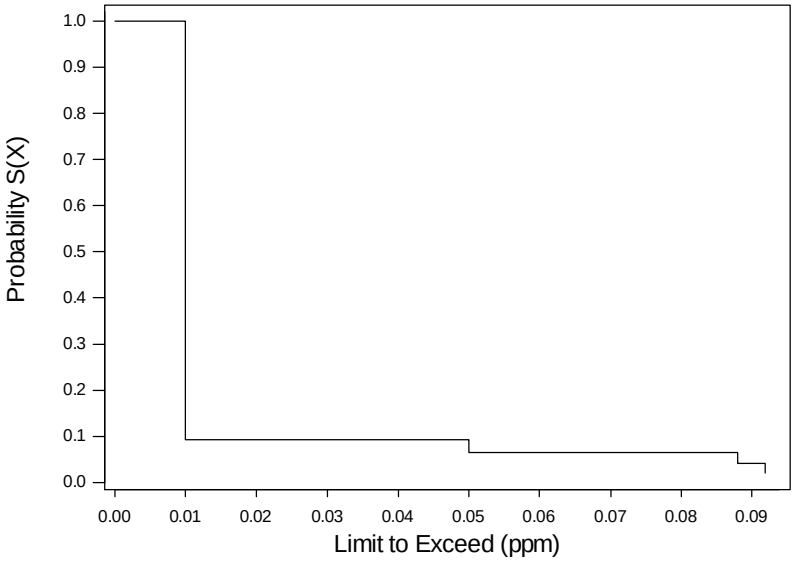
Nonparametric Survival Plot for m_p-Cresol
(Mean = 1.119 ppm)



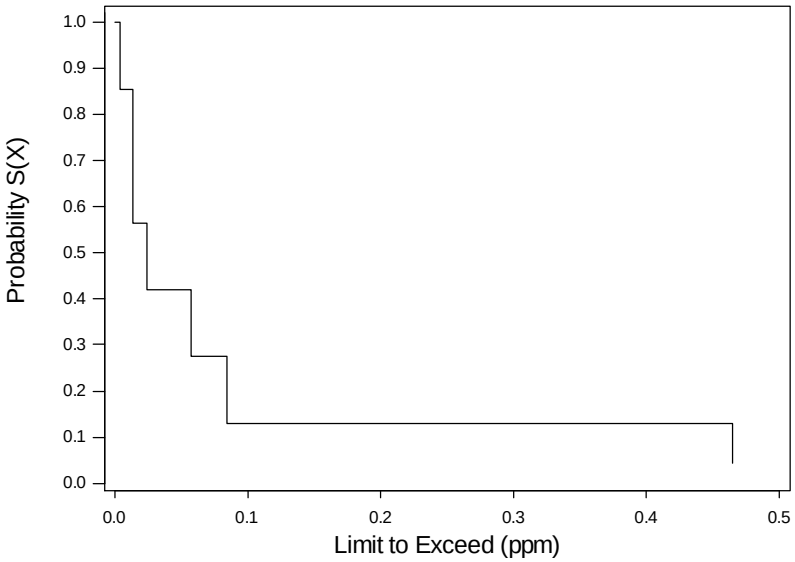
Nonparametric Survival Plot for
2,4-Dimethylphen (Mean = 1.194 ppm)



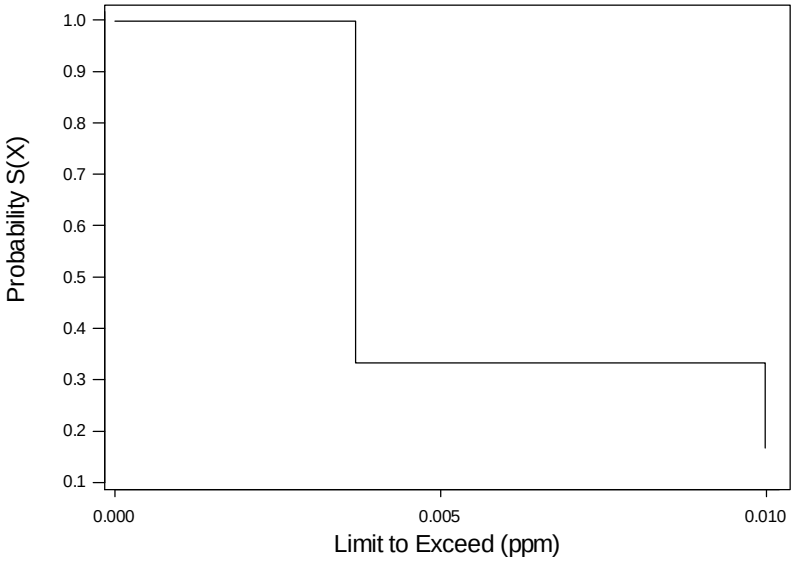
Nonparametric Survival Plot for Ethylbenzene
(Mean = 0.046 ppm)



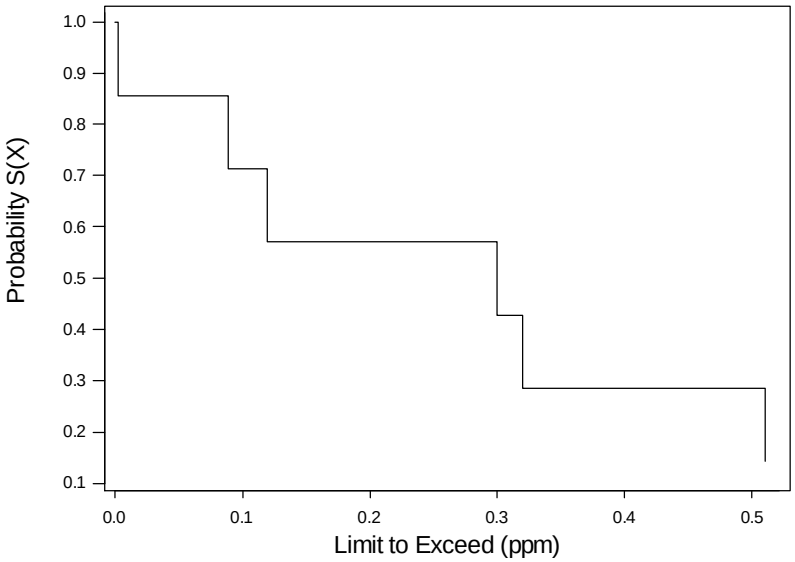
Nonparametric Survival Plot for Fluoranthene
(Mean = 0.306 ppm)



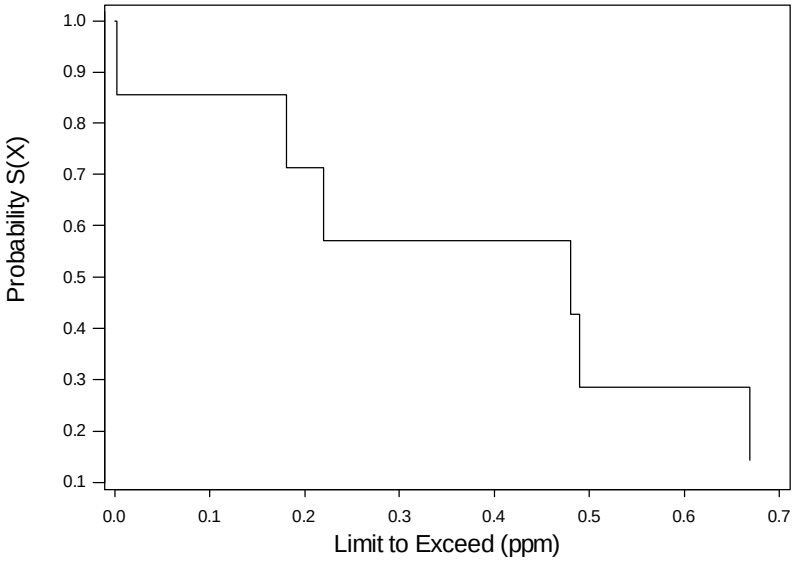
Nonparametric Survival Plot for Fluorene
(Mean=0.037 ppm)



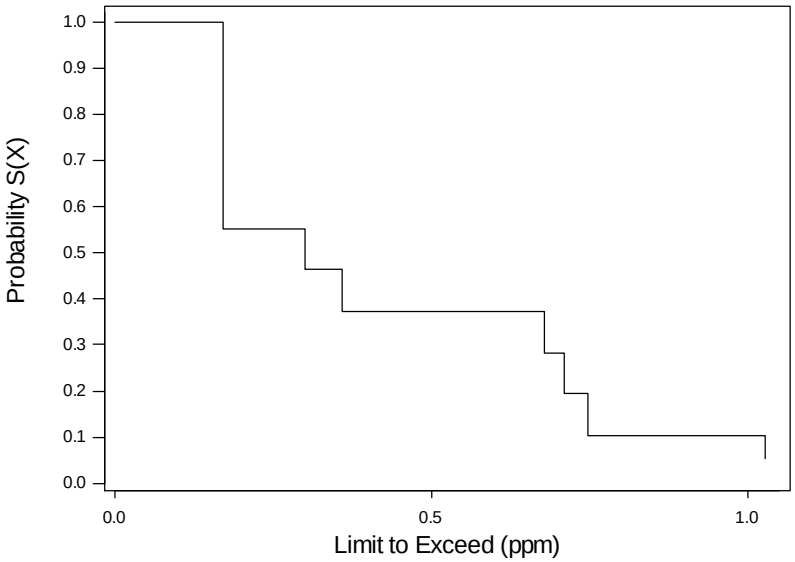
Nonparametric Survival Plot for 1-Methyl naphtha
(Mean=0.328 ppm)



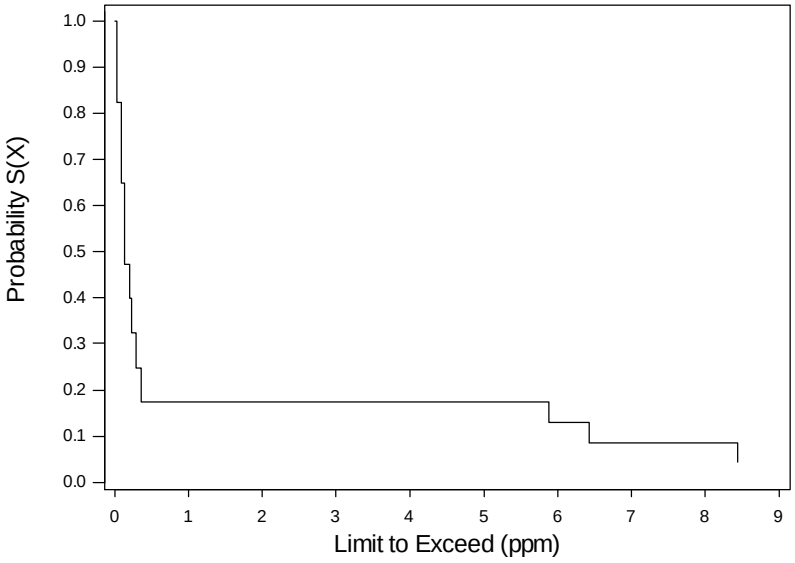
Nonparametric Survival Plot for 2-Methyl naphtha (Mean = 0.406 ppm)



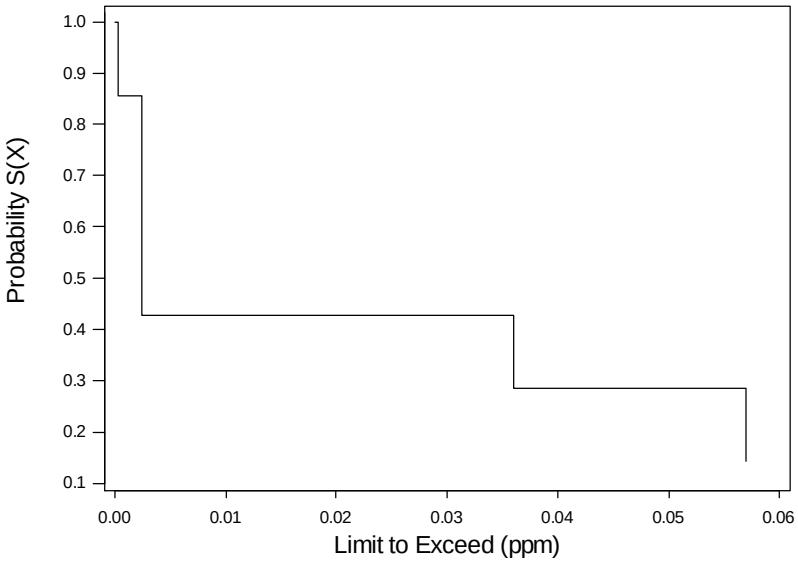
Nonparametric Survival Plot for Naphthalene (Mean = 0.435 ppm)



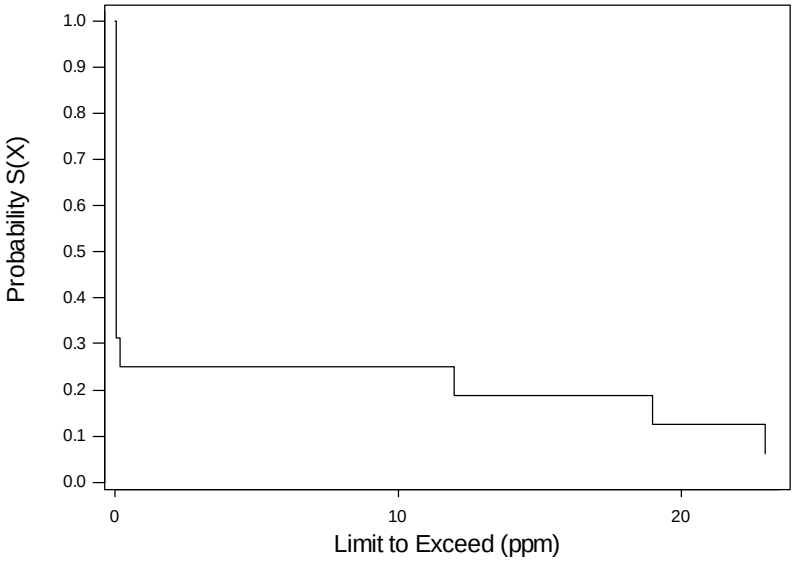
Nonparametric Survival Plot for Phenanthene
(Mean = 1.604 ppm)



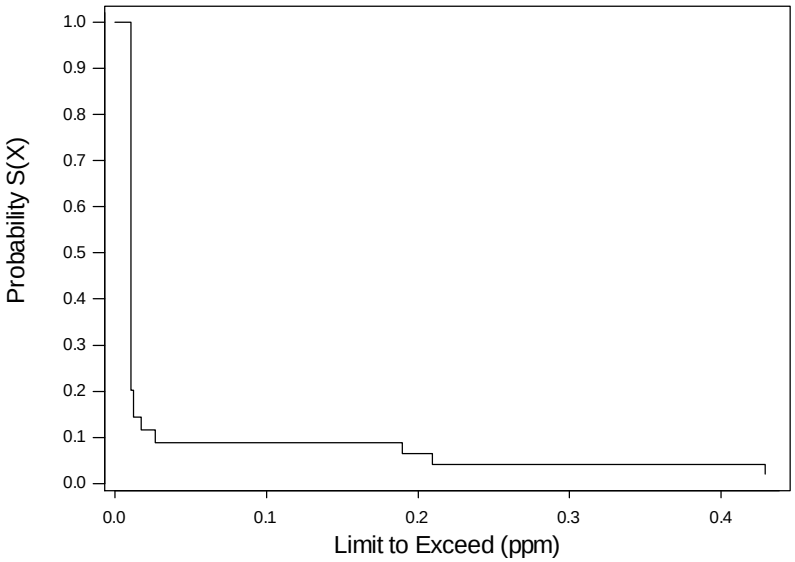
Nonparametric Survival Plot for Pyrene
(Mean = 0.047 ppm)



Nonparametric Survival Plot for Styrene
(Mean = 7.796 ppm)



Nonparametric Survival Plot for Toluene
(Mean = 0.045 ppm)



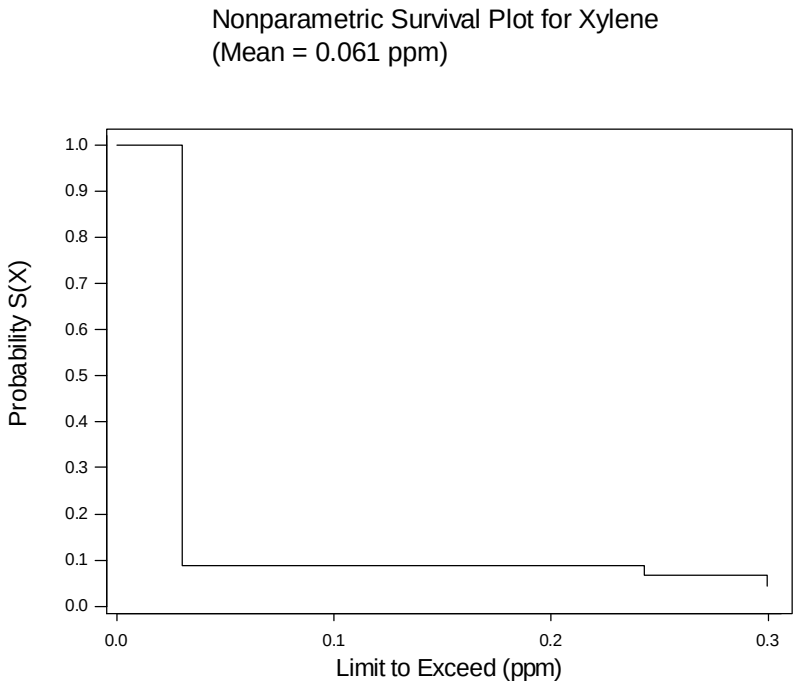


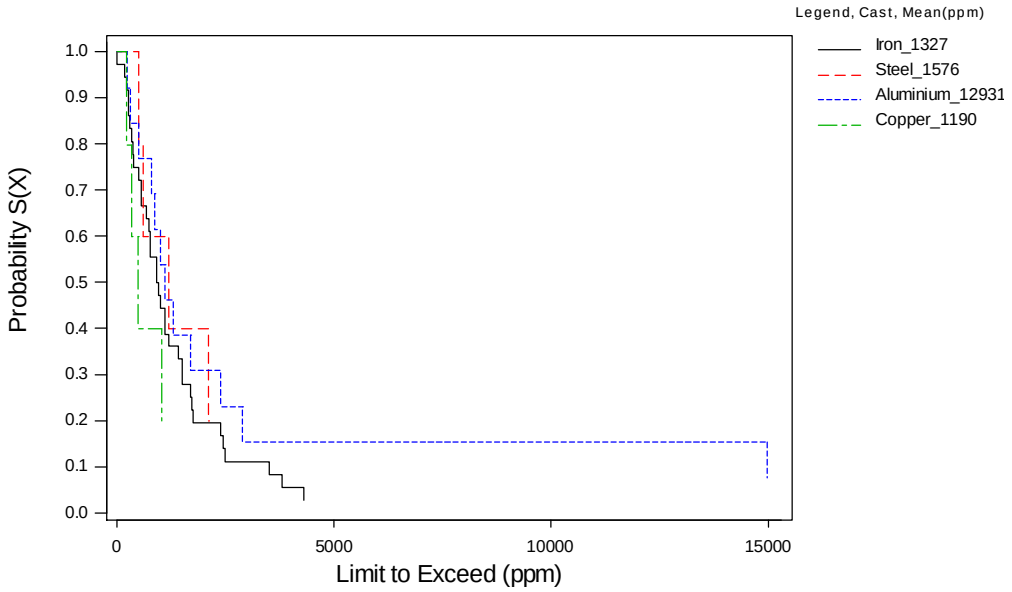
Figure **F-3**: Survival plots for bulk organic compounds (21 charts)

F.2 Bulk Characterization of Excess Foundry Sand per Metal Cast

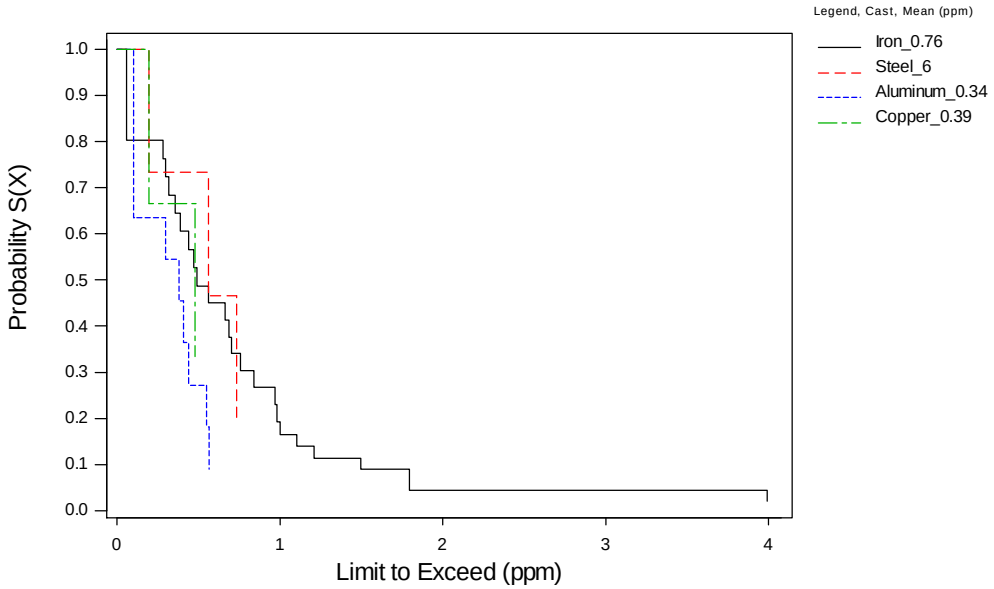
In this section, a series of 12 charts, grouped into Figure F-4, present bulk metallic characterization of excess foundry sand per metal cast.

F.2.1 Metallic Elements

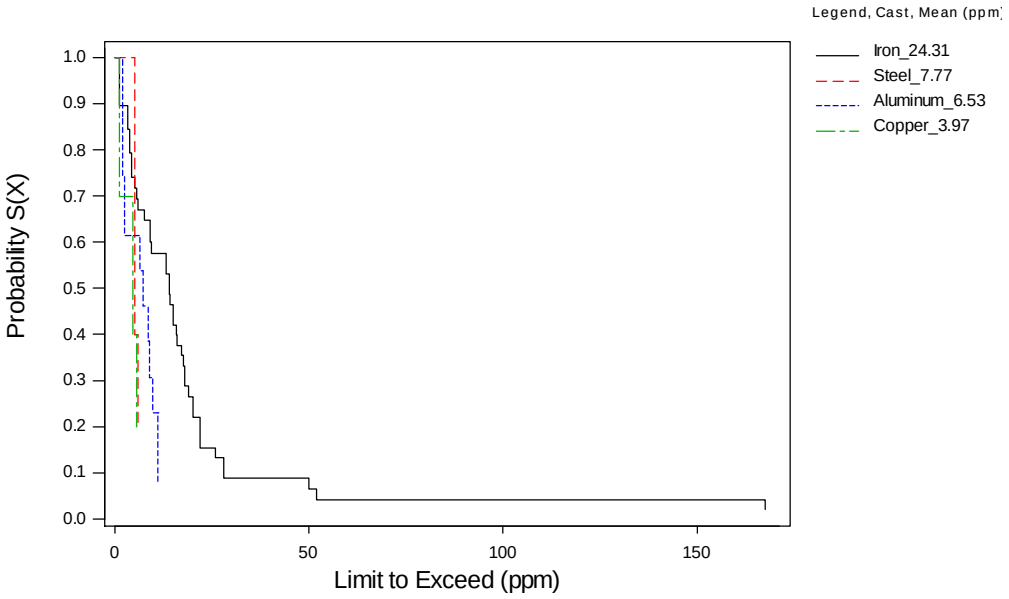
Nonparametric Survival Plot for Aluminium (Al)



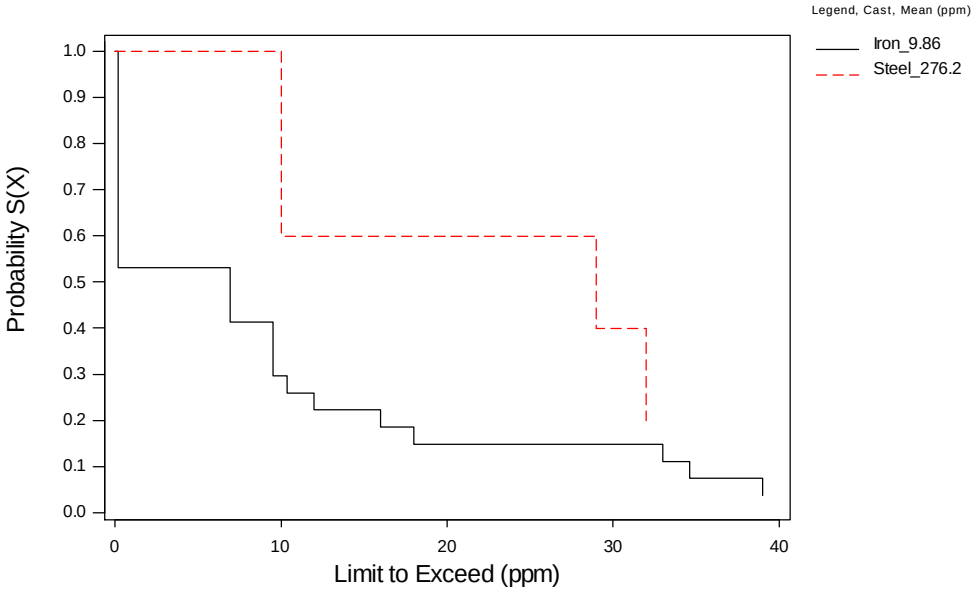
Nonparametric Survival Plot for Arsenic (As)



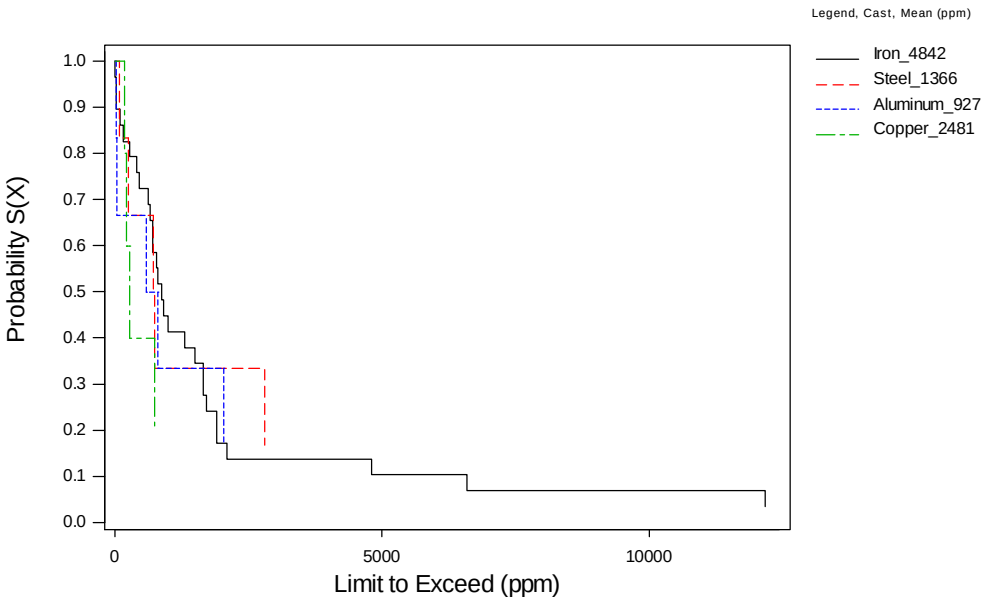
Nonparametric Survival Plot for Barium (Ba)



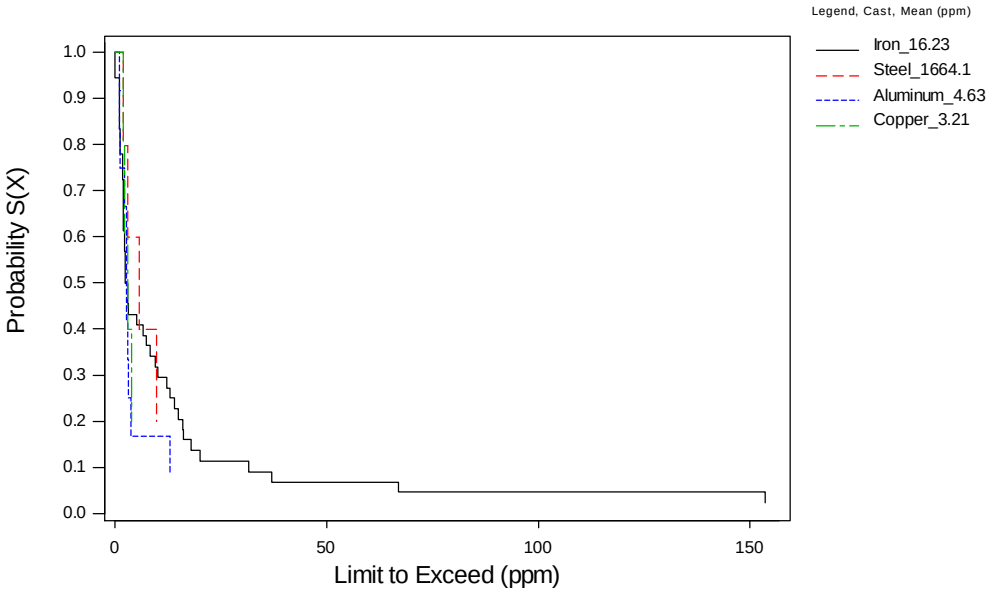
Nonparametric Survival Plot for Boron (B)



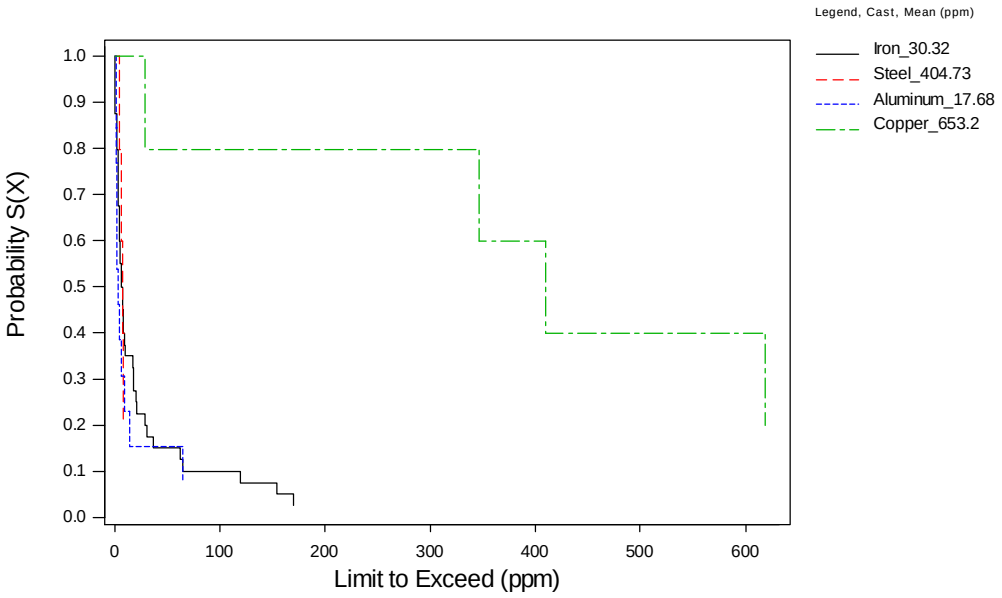
Nonparametric Survival Plot for Calcium (Ca)



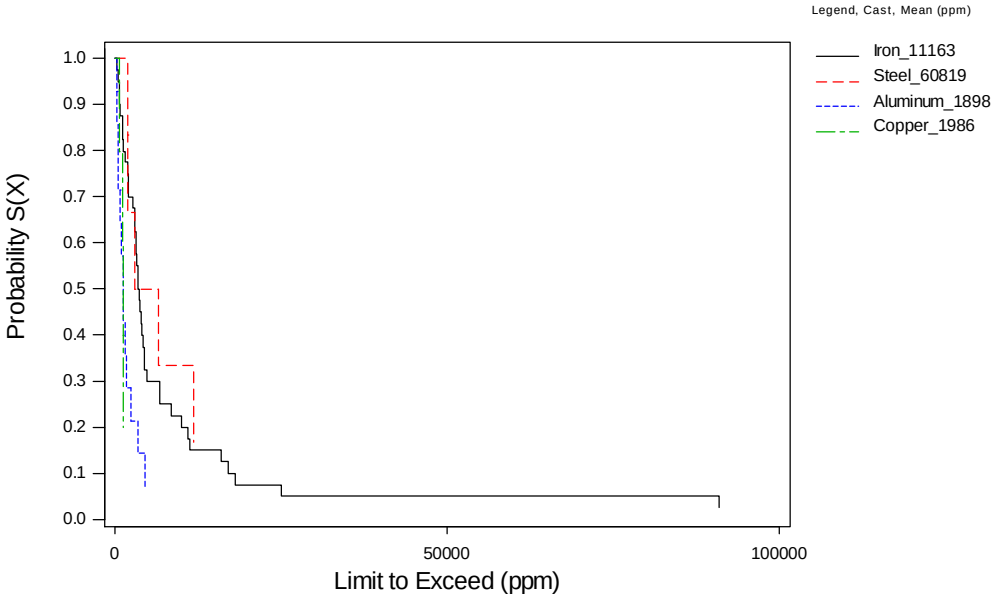
Nonparametric Survival Plot for Chromium (Cr)



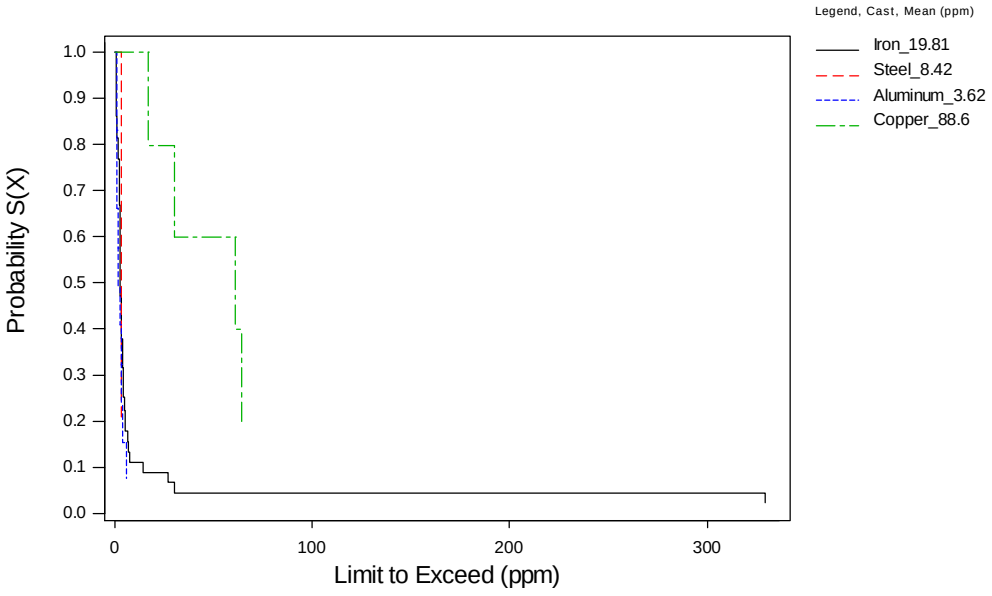
Nonparametric Survival Plot for Copper (Cu)



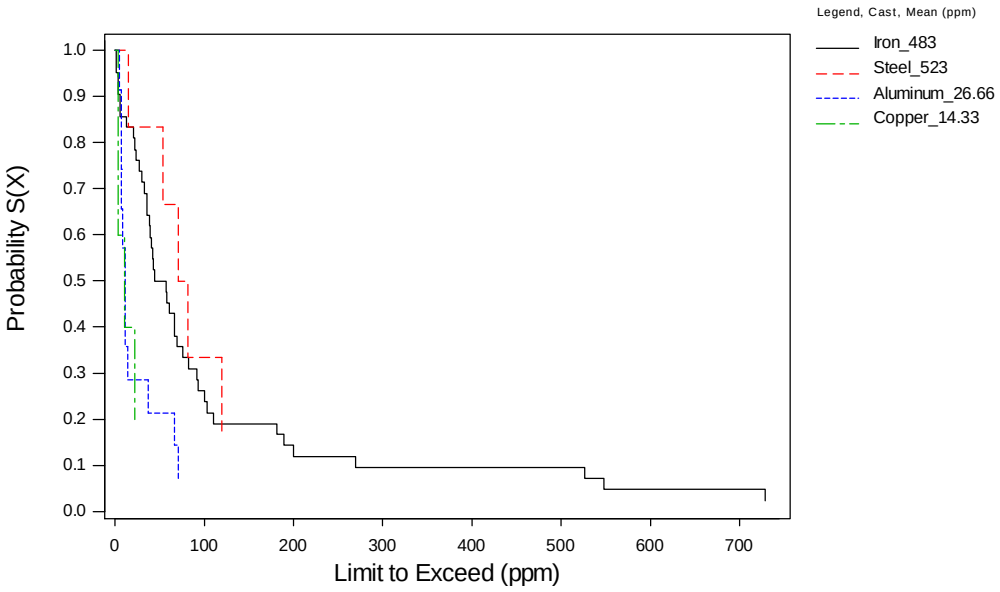
Nonparametric Survival Plot for Iron (Fe)

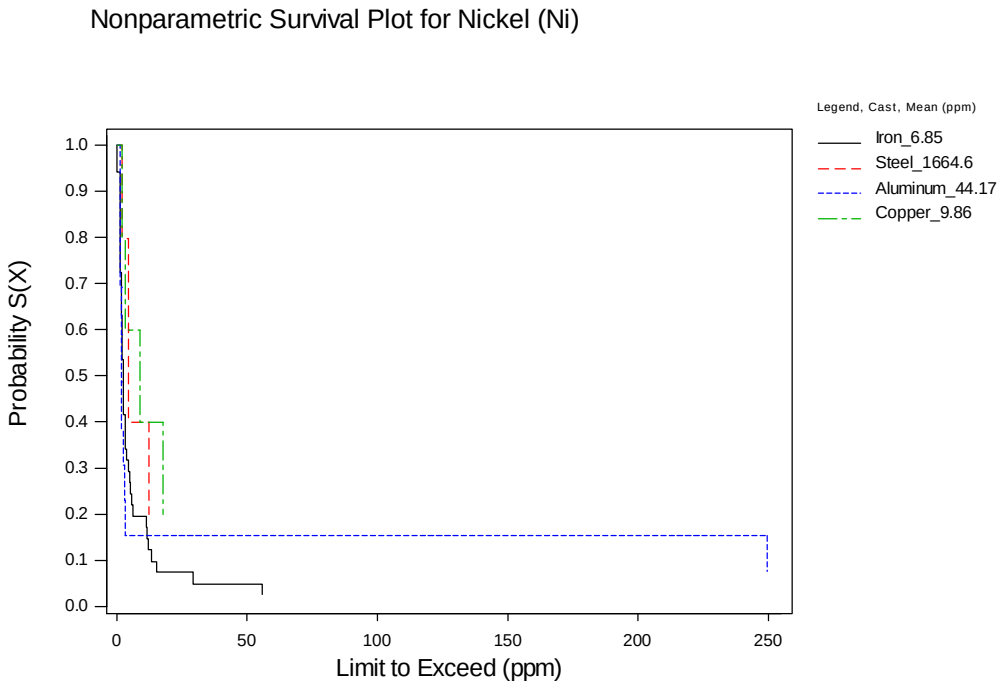


Nonparametric Survival Plot for Lead (Pb)



Nonparametric Survival Plot for Manganese (Mn)





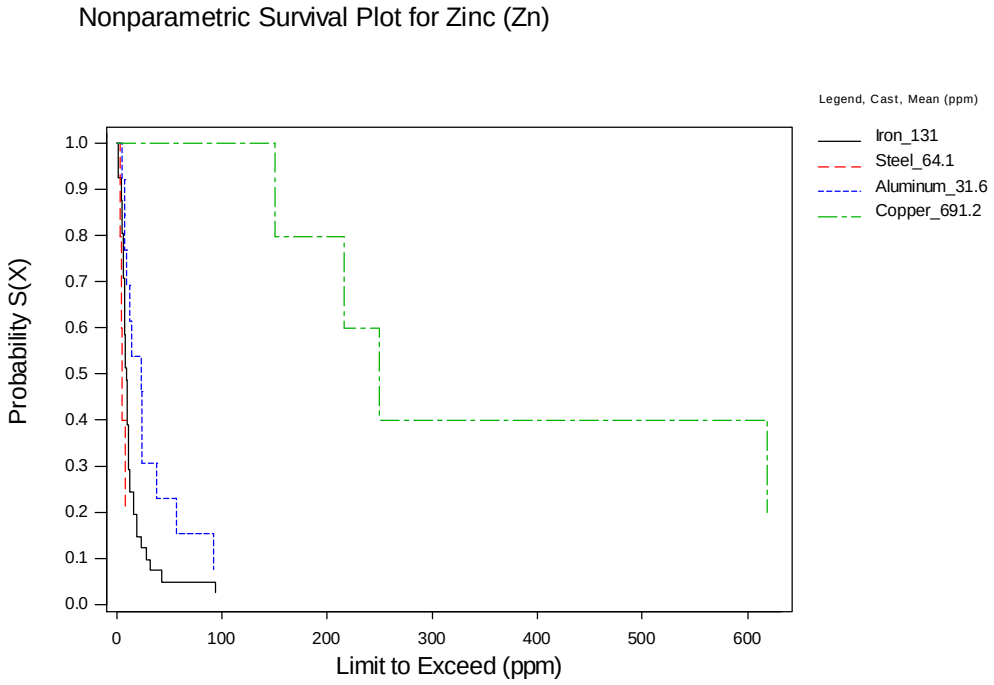
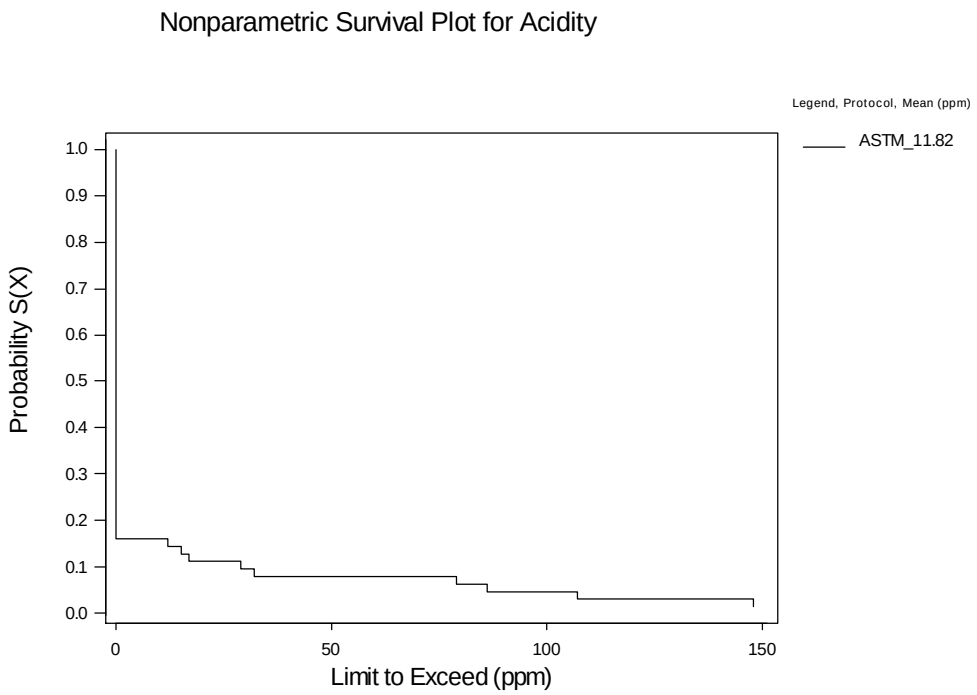


Figure **F-4**: Survival plots for bulk metallic elements per metal cast (12 charts)

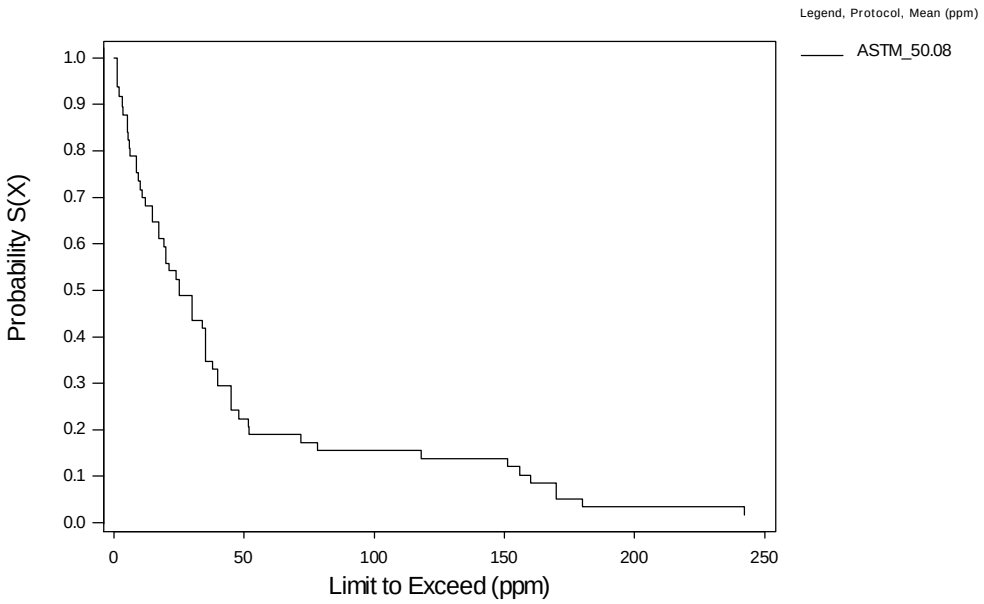
F.3 Leaching Characterization of Excess Foundry Sand per Leaching Protocols

In this section, a series of 49 charts present the leaching characterization of excess foundry sand per leaching protocol. The first 16 charts, grouped into Figure F-5, are for general chemical parameters. The second 20 charts, grouped into Figure F-6, are for metallic elements. The remaining 13 charts, grouped into Figure F-7, are for organic compounds exclusively in TCLP leachate.

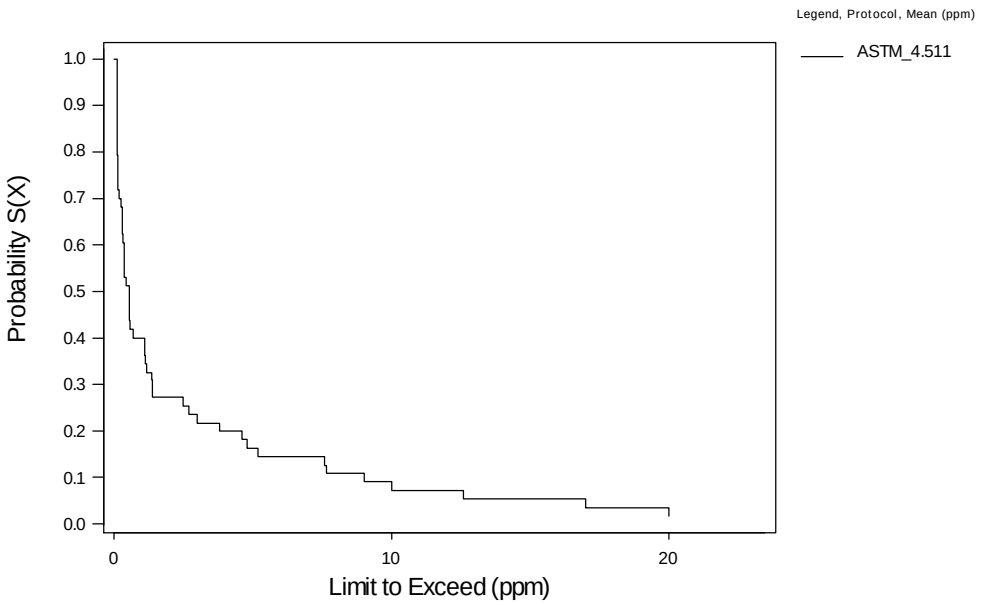
F.3.1 General Chemical Parameters



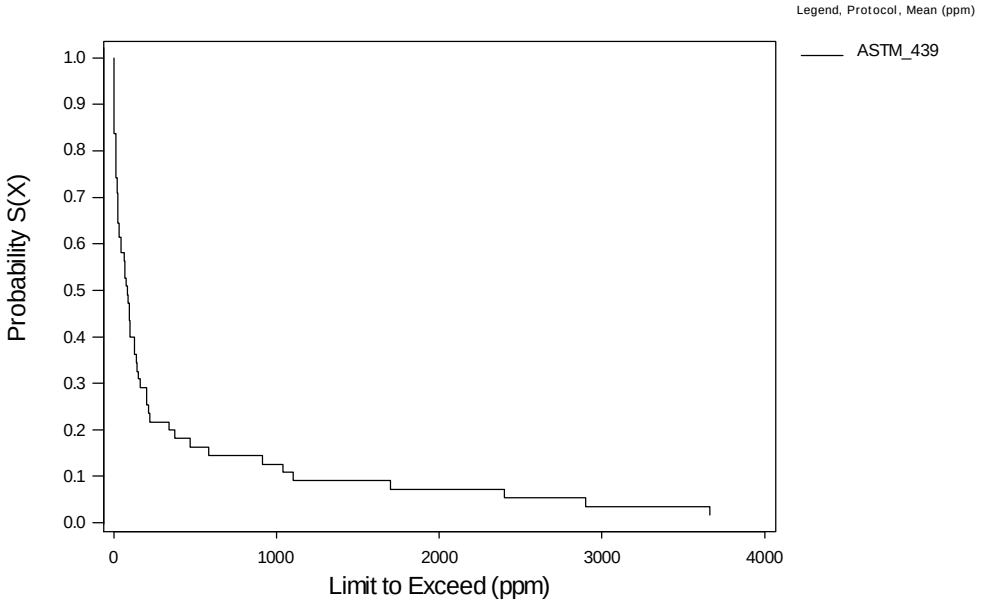
Nonparametric Survival Plot for Alkalinity



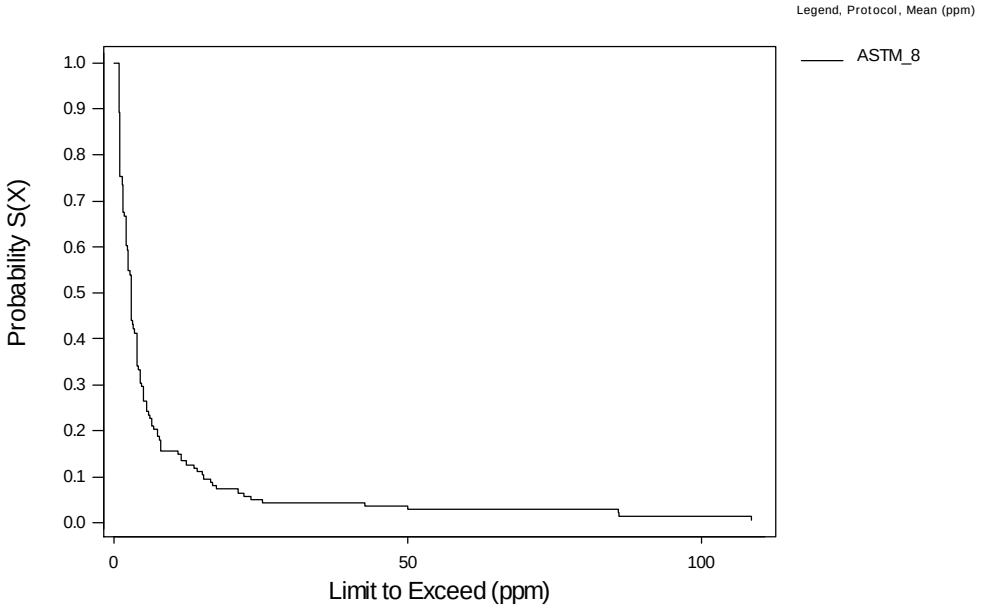
Nonparametric Survival Plot for Ammonia



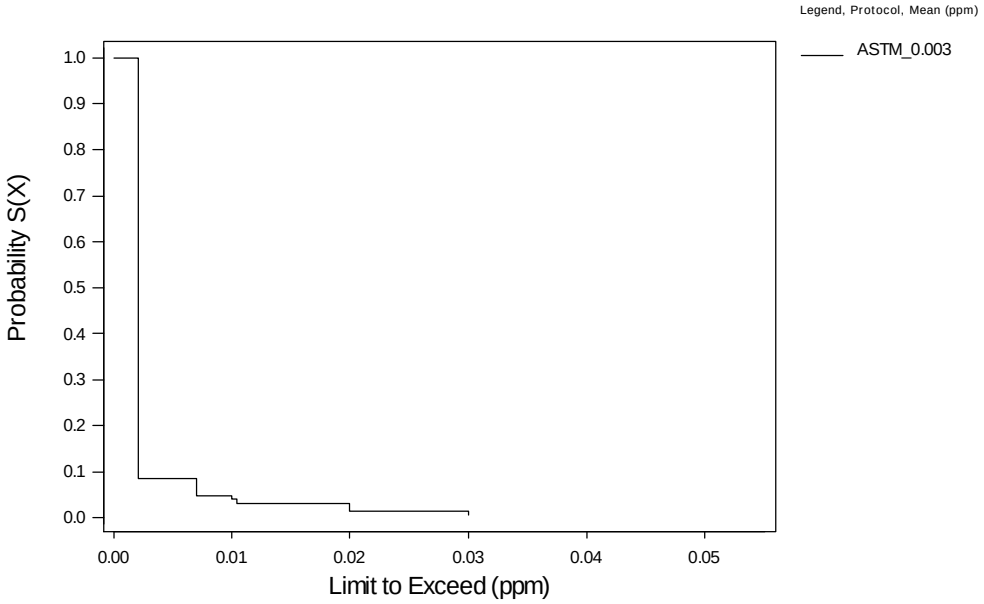
Nonparametric Survival Plot for Chemical Oxygen Demand (COD)



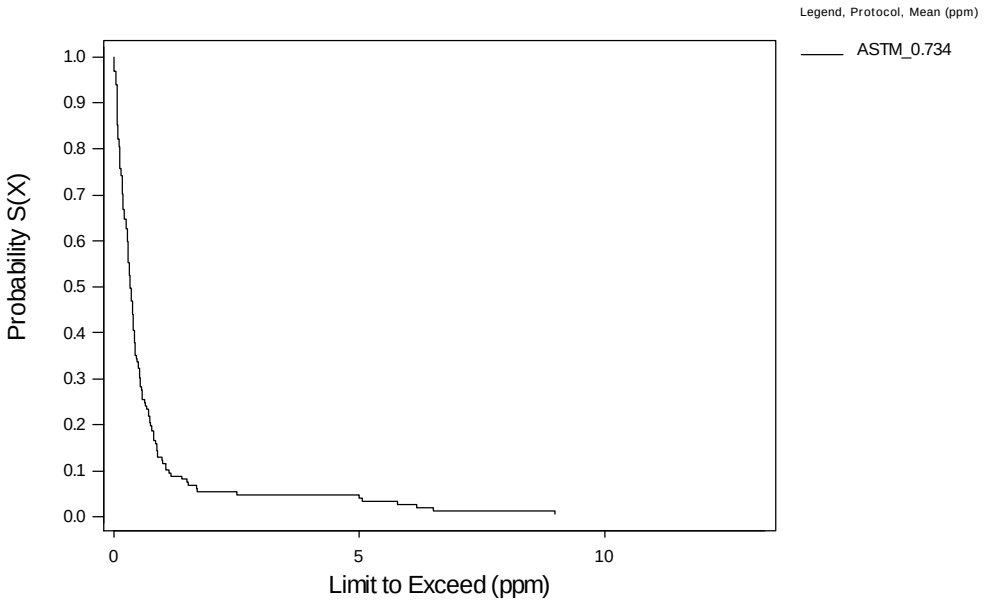
Nonparametric Survival Plot for Chlorides (Cl)



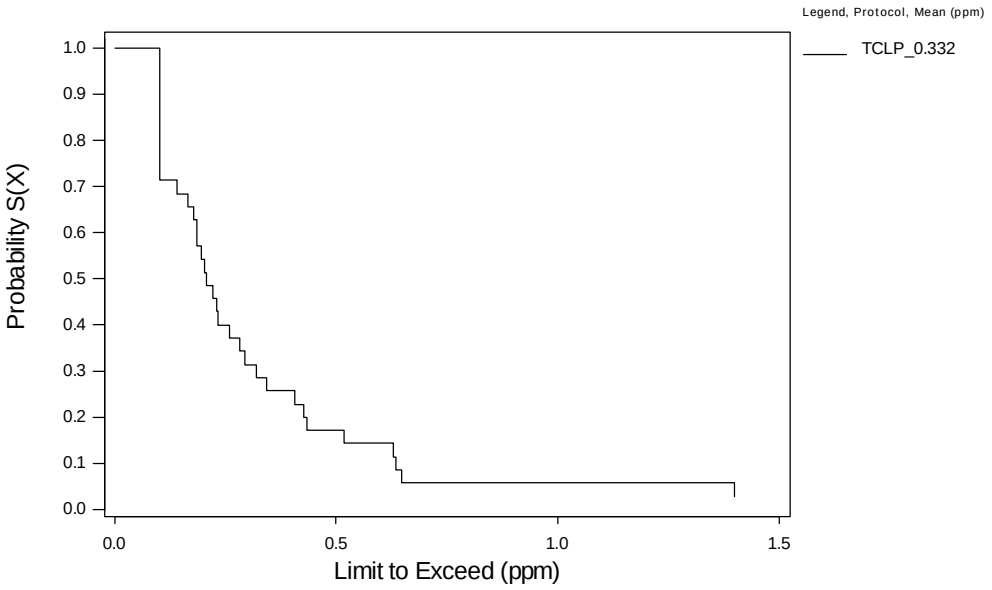
Nonparametric Survival Plot for Cyanide (Cy)



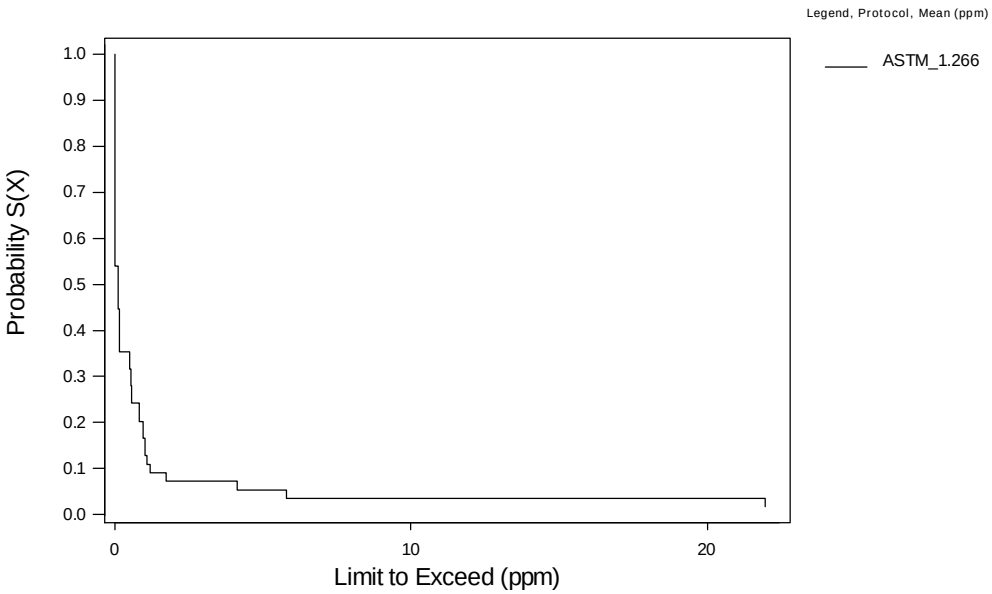
Nonparametric Survival Plot for Fluoride (F)



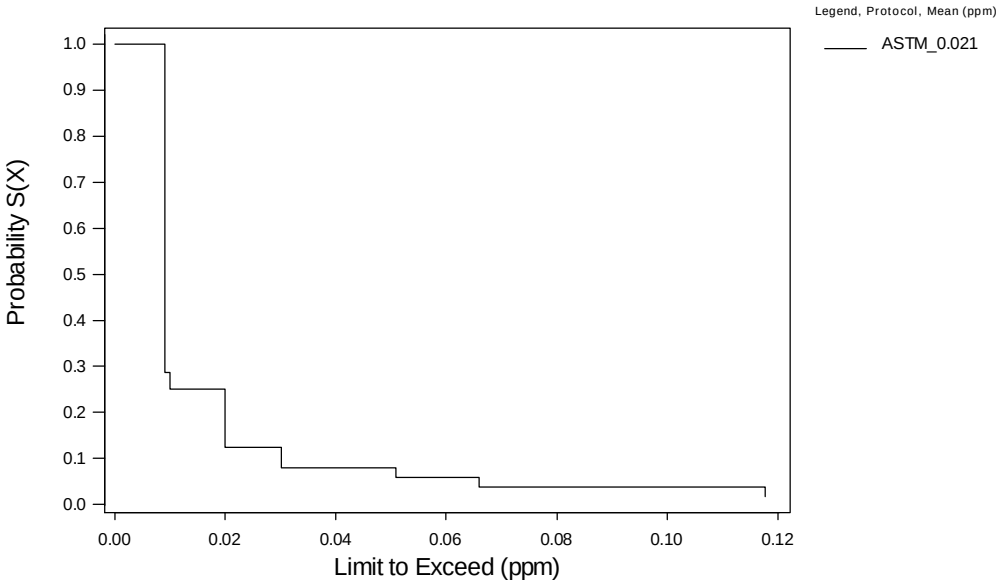
Nonparametric Survival Plot for Formaldehyde



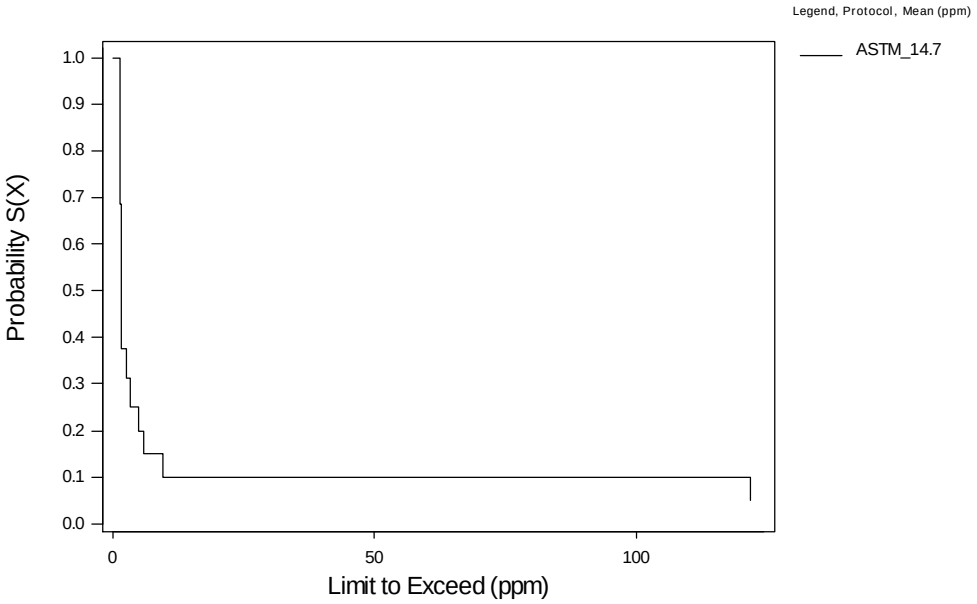
Nonparametric Survival Plot for Nitrate

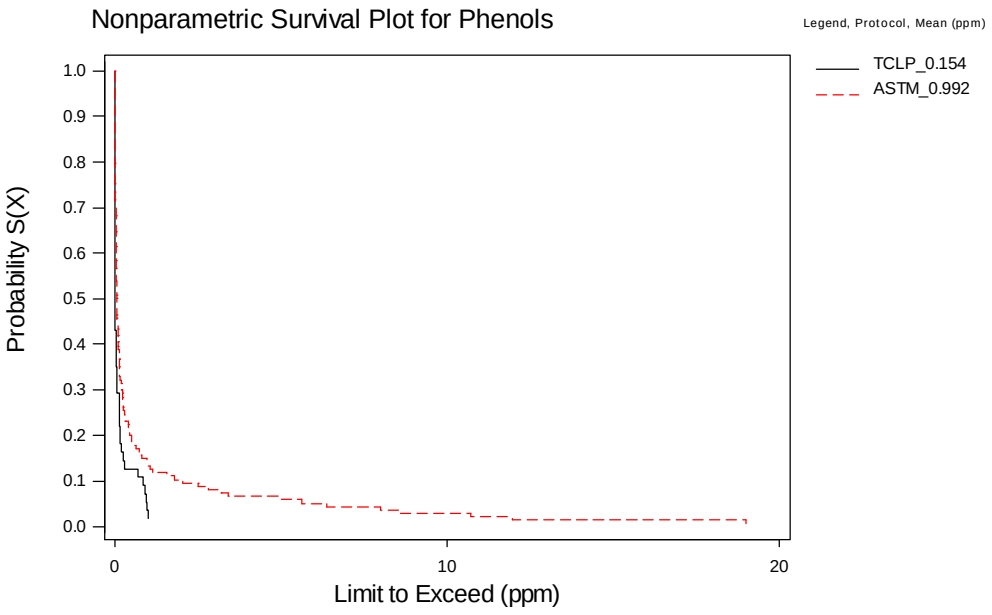


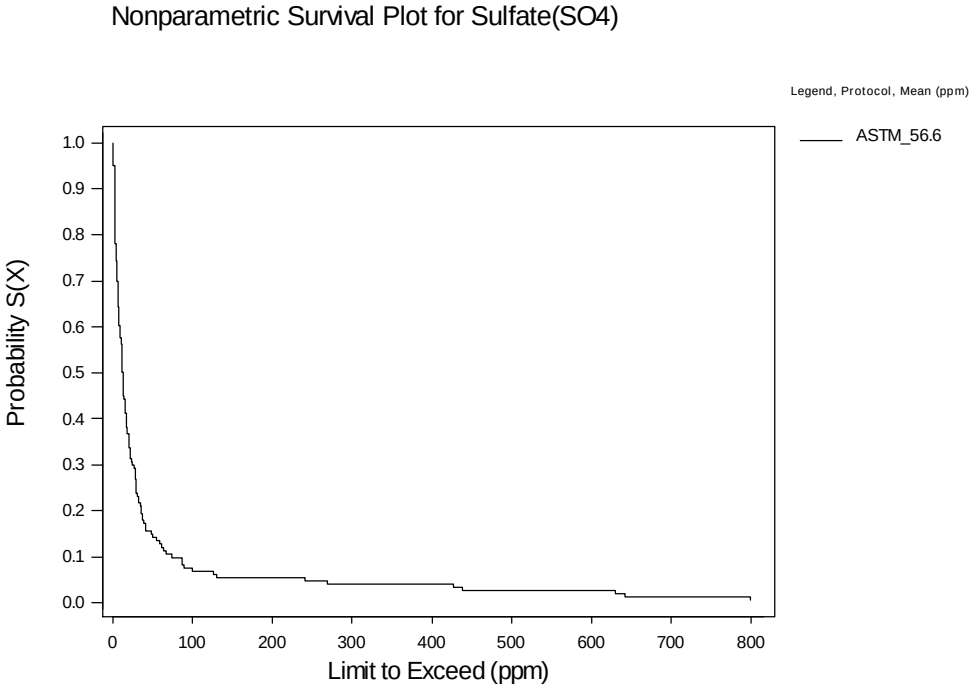
Nonparametric Survival Plot for Nitrite



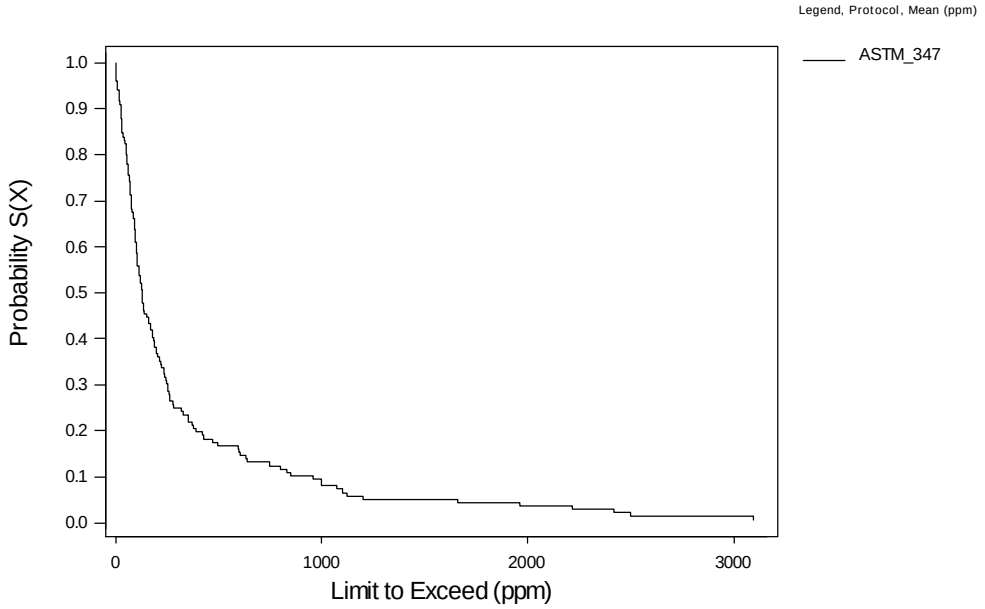
Nonparametric Survival Plot for Oil and grease



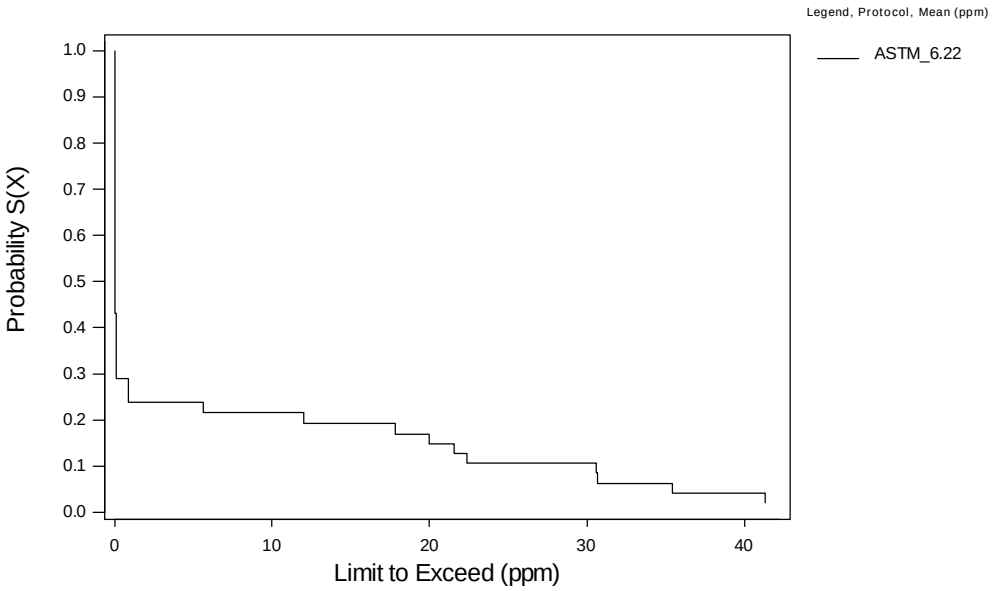

Nonparametric Survival Plot for Phenols
Legend, Protocol, Mean (ppm)
TCLP_0.154
ASTM_0.992
Probability S(X)
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0
10
20
Limit to Exceed (ppm)


Nonparametric Survival Plot for Sulfate(SO4)
Legend, Protocol, Mean (ppm)
ASTM_56.6
Probability S(X)
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0
100
200
300
400
500
600
700
800
Limit to Exceed (ppm)

Nonparametric Survival Plot for Total Dissoluble Solid



Nonparametric Survival Plot for Total Organic Haligen (TOH)



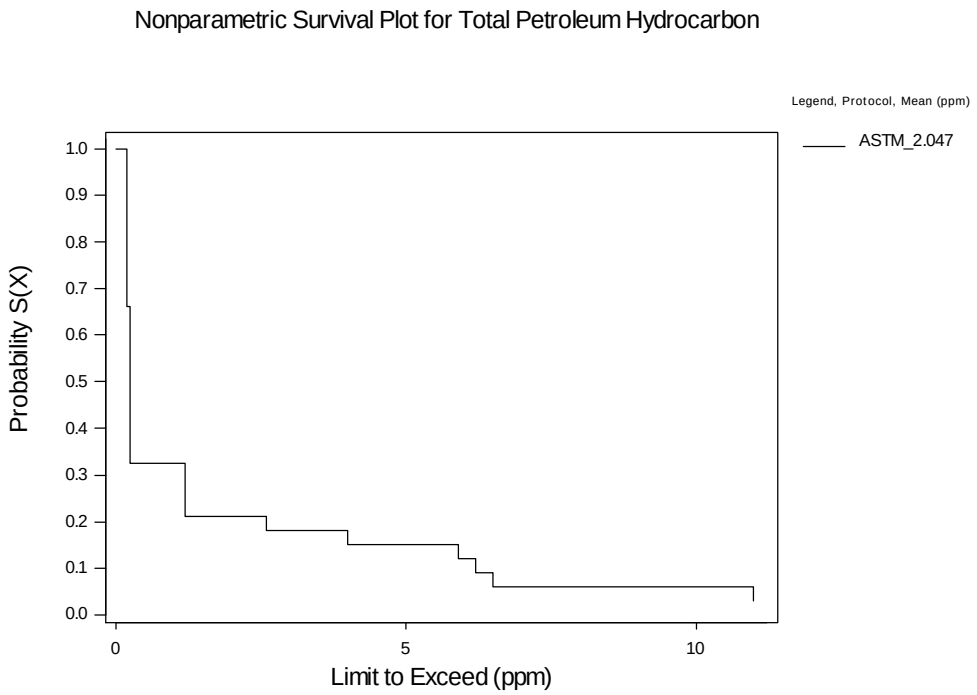
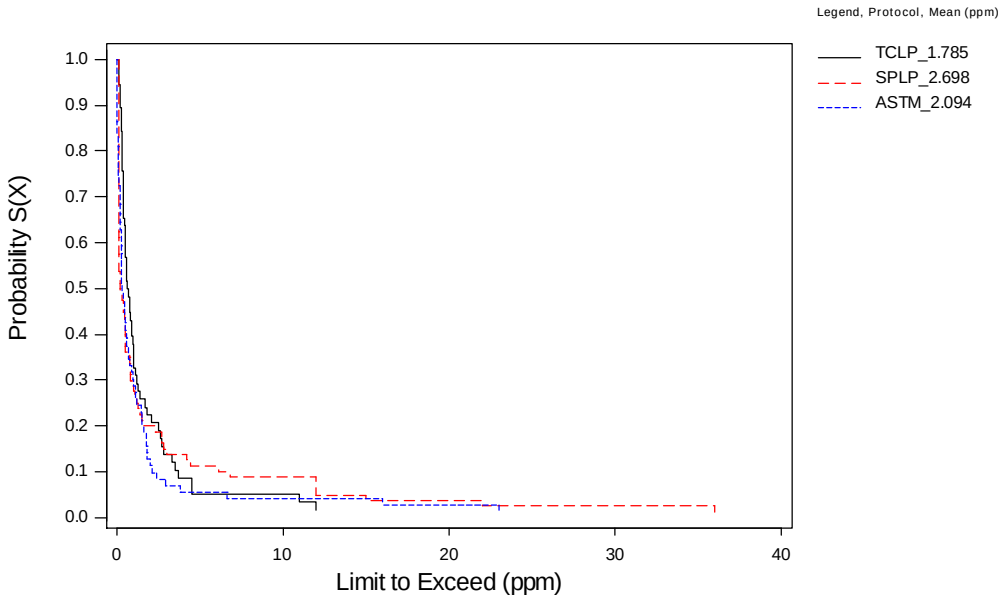


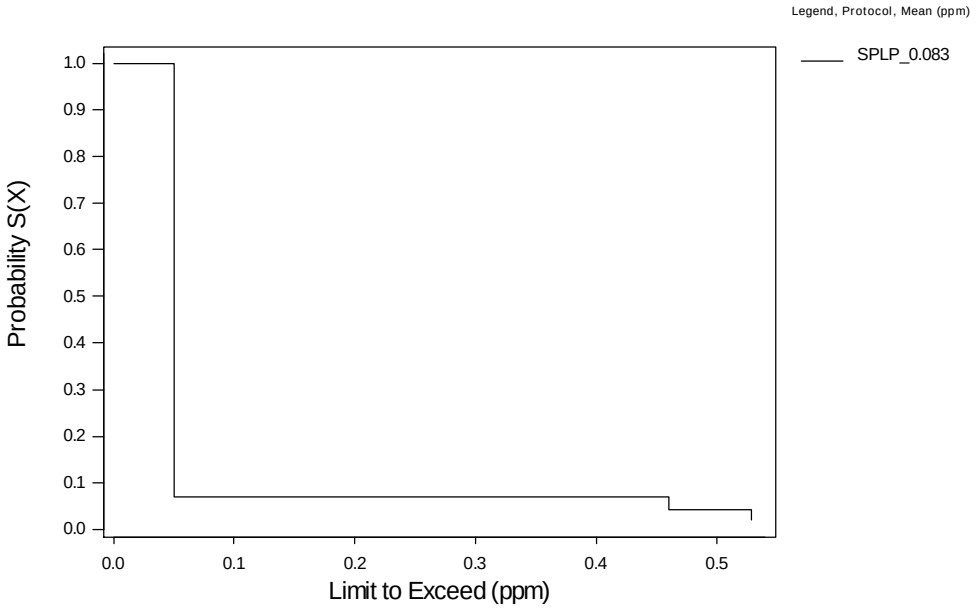
Figure **F-5**: Survival plots for general chemical parameters in leachates (16 charts)

F.3.2 Metallic Elements

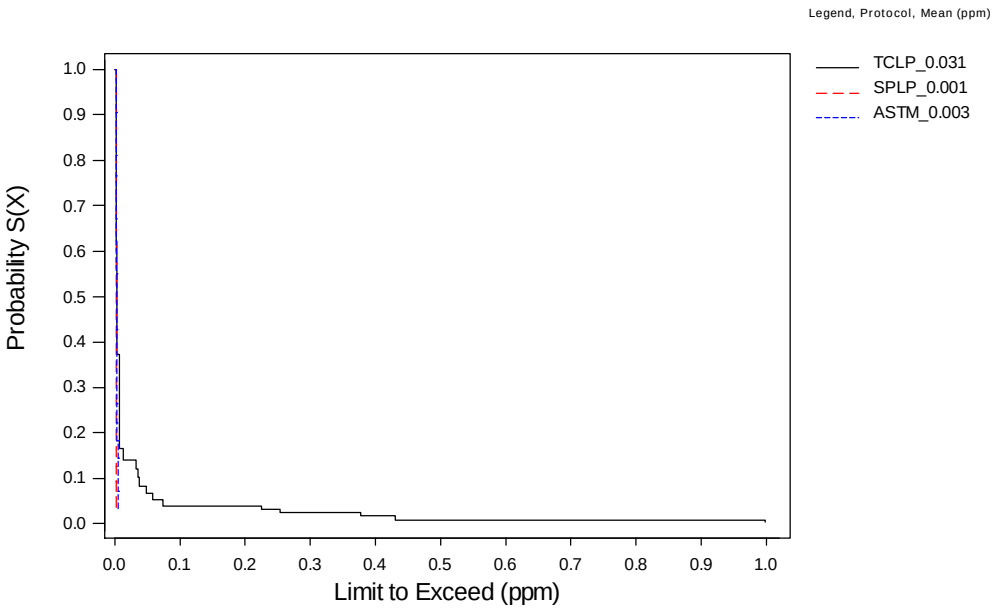
Nonparametric Survival Plot for Aluminium (Al)



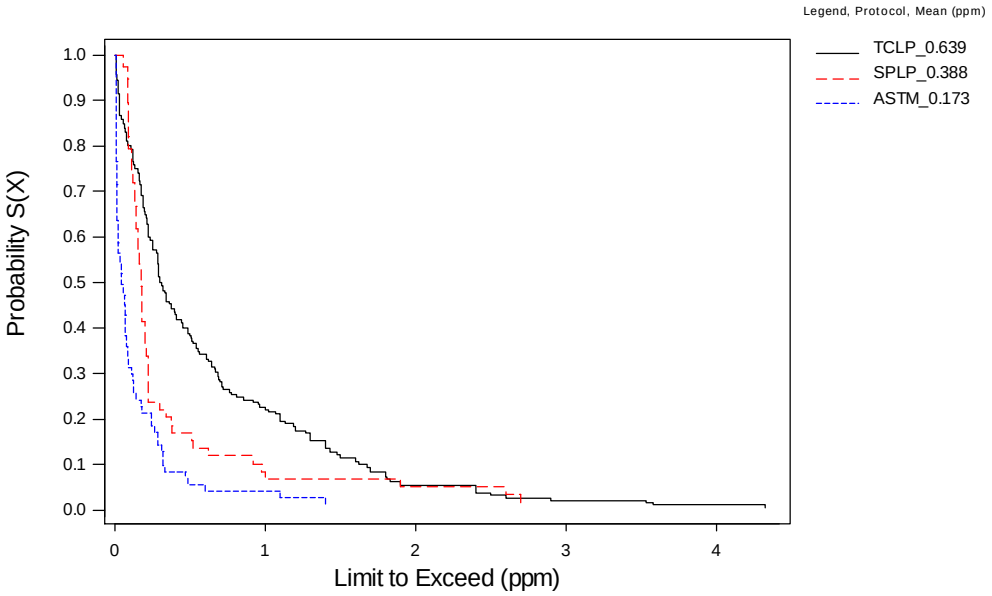
Nonparametric Survival Plot for Antimony (Sb)



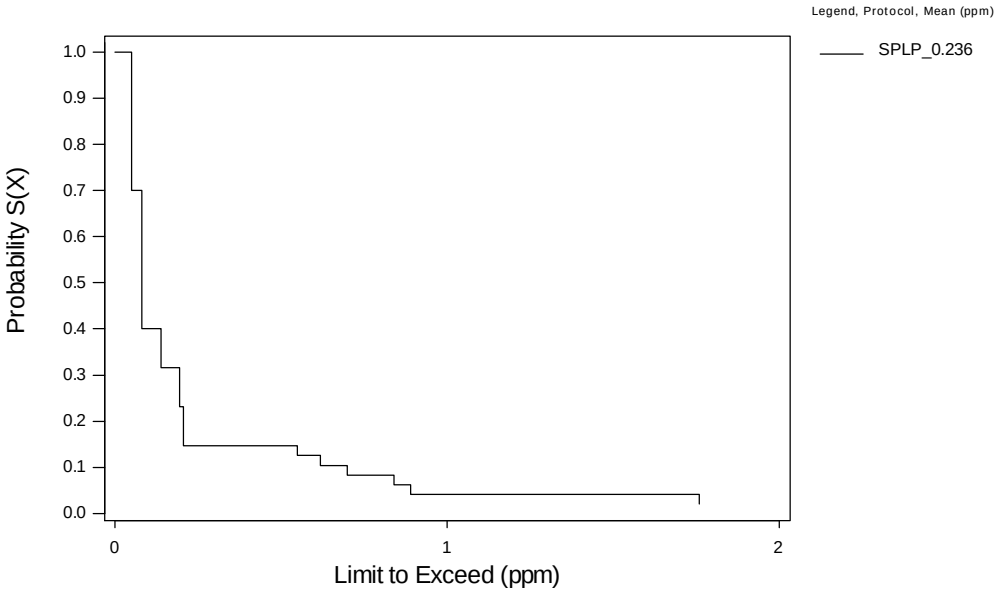
Nonparametric Survival Plot for Arsenic (As)



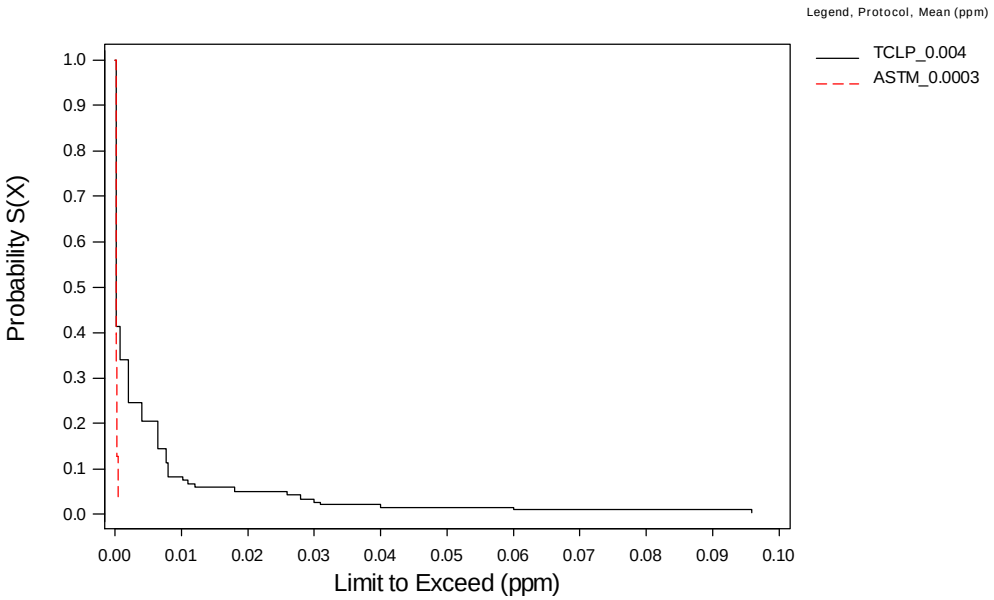
Nonparametric Survival Plot for Barium(Ba)



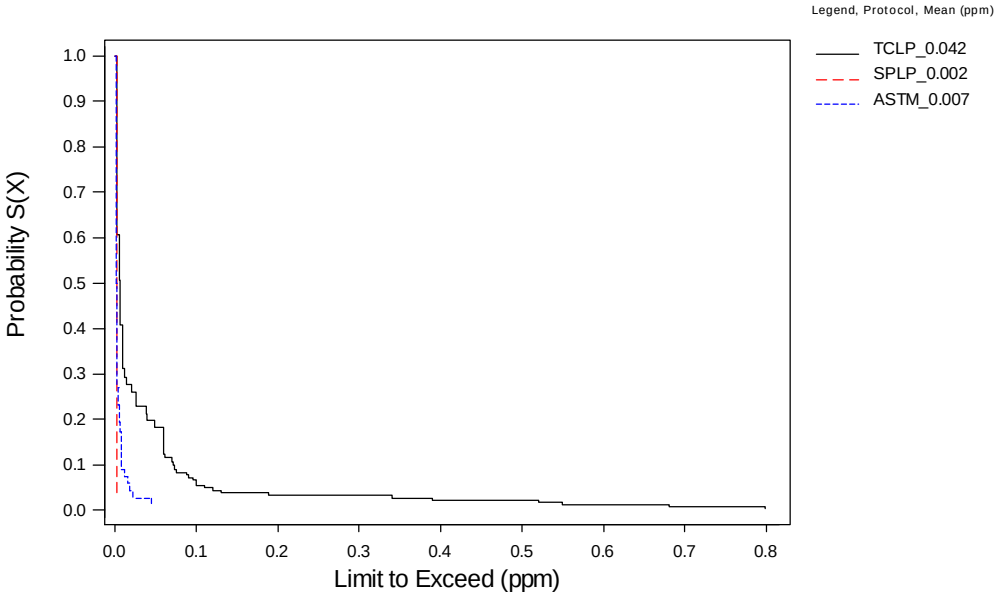
Nonparametric Survival Plot for Boron(B)



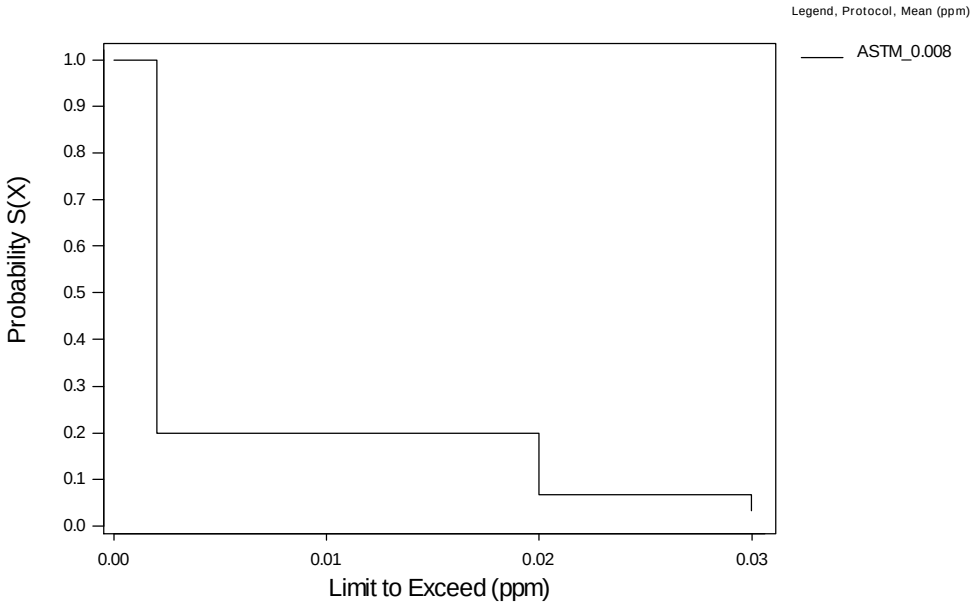
Nonparametric Survival Plot for Cadmium (Cd)



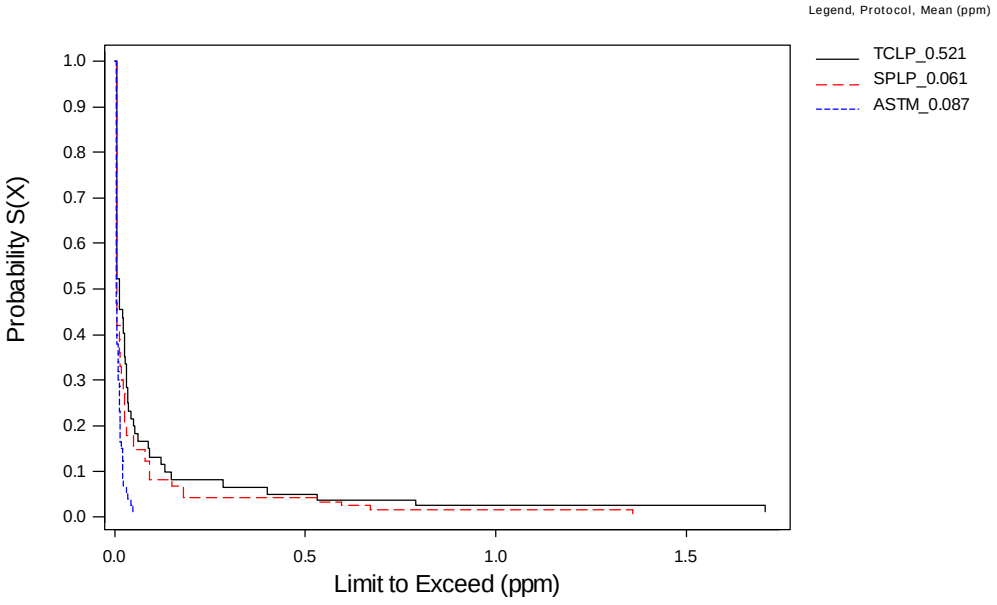
Nonparametric Survival Plot for Chromium (Cr)



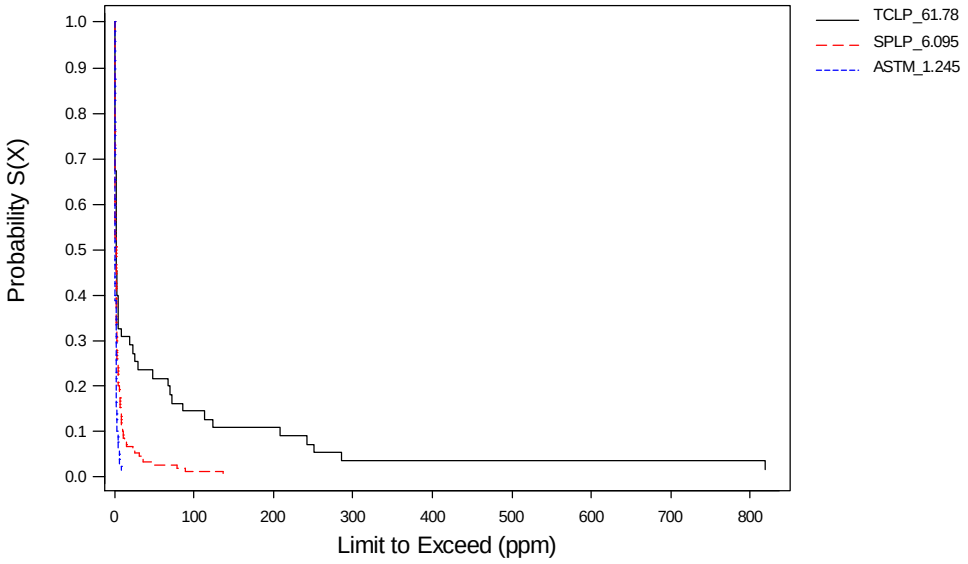
Nonparametric Survival Plot for Hexavalent Chromium



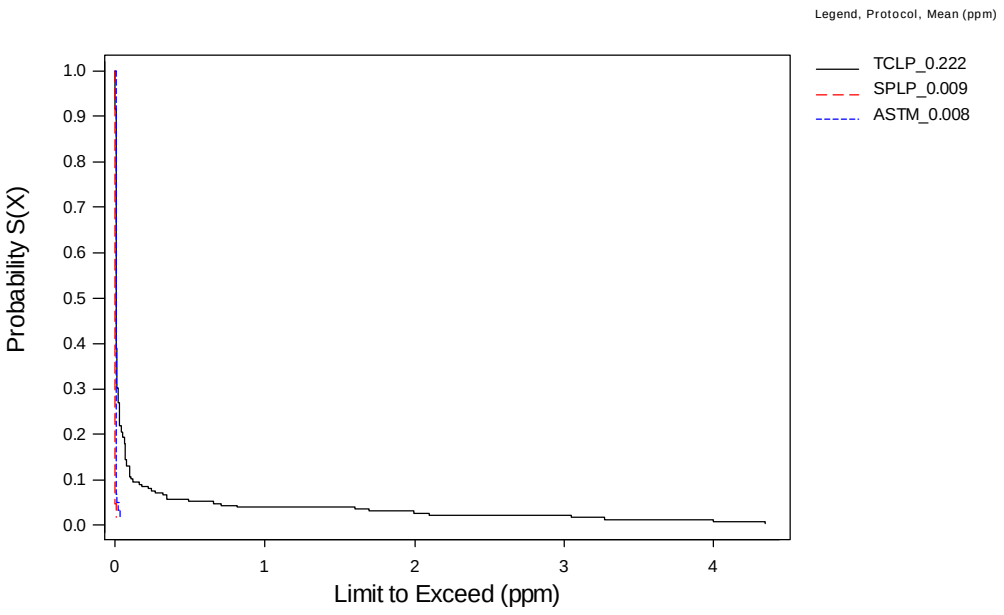
Nonparametric Survival Plot for Copper (Cu)



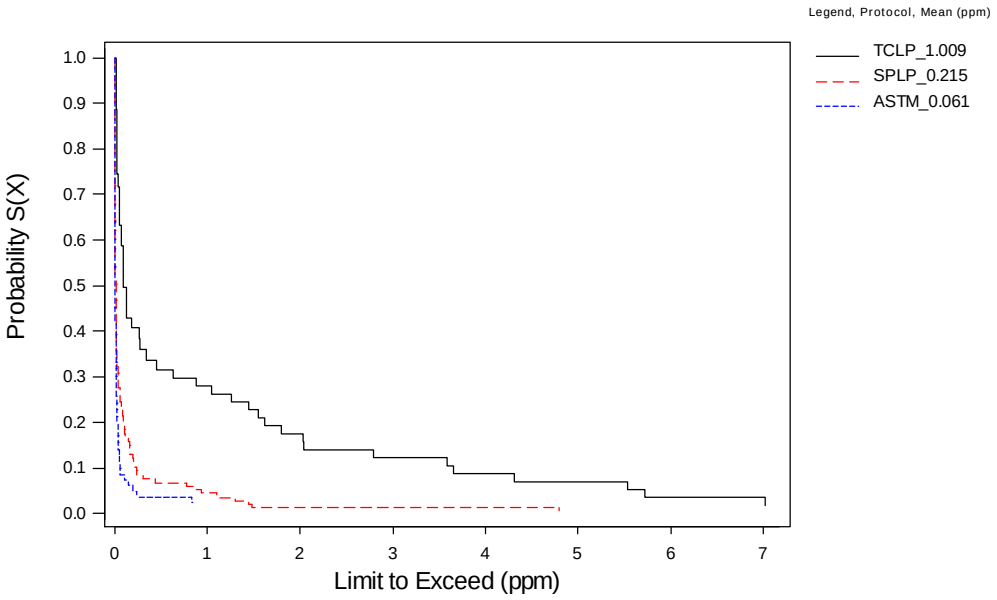
Nonparametric Survival Plot for Iron (Fe)



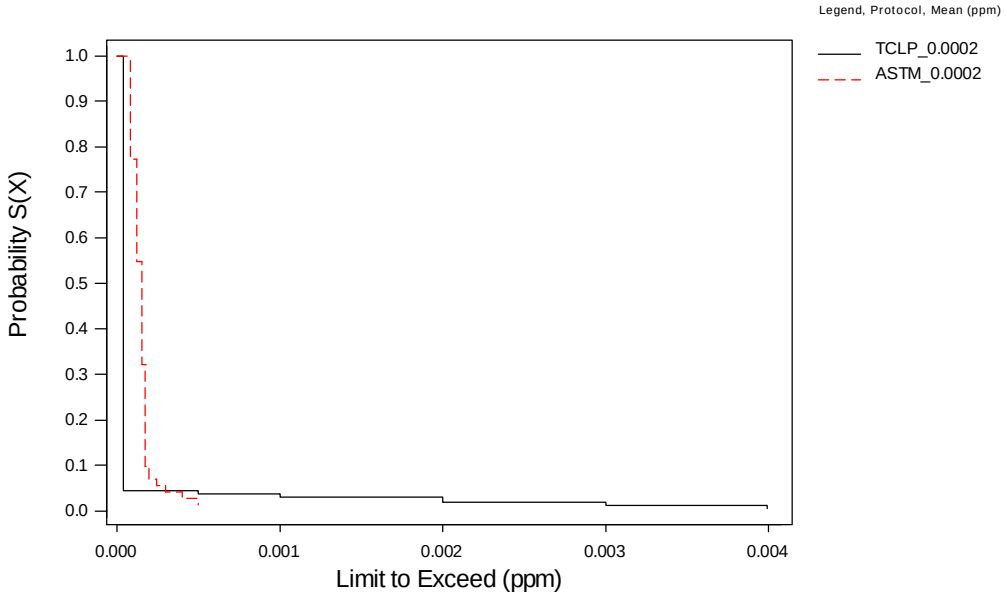
Nonparametric Survival Plot for Lead (Pb)



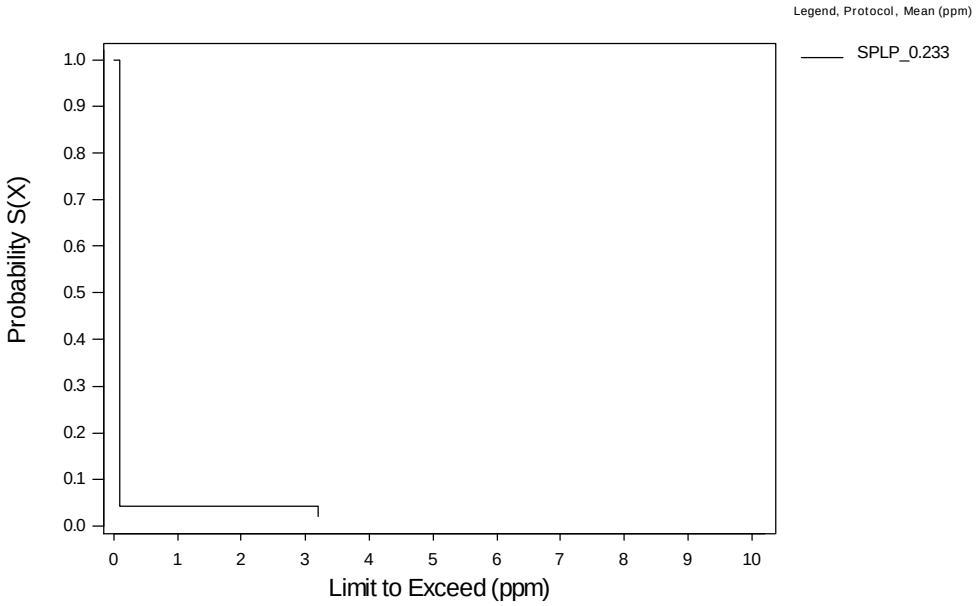
Nonparametric Survival Plot for Manganese (Mn)



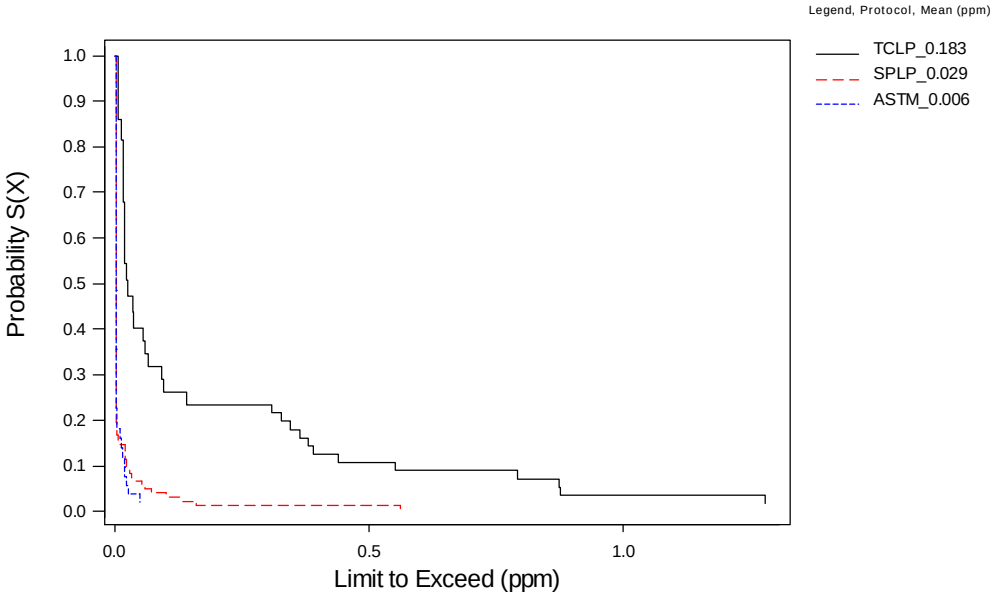
Nonparametric Survival Plot for Mercury (Hg)



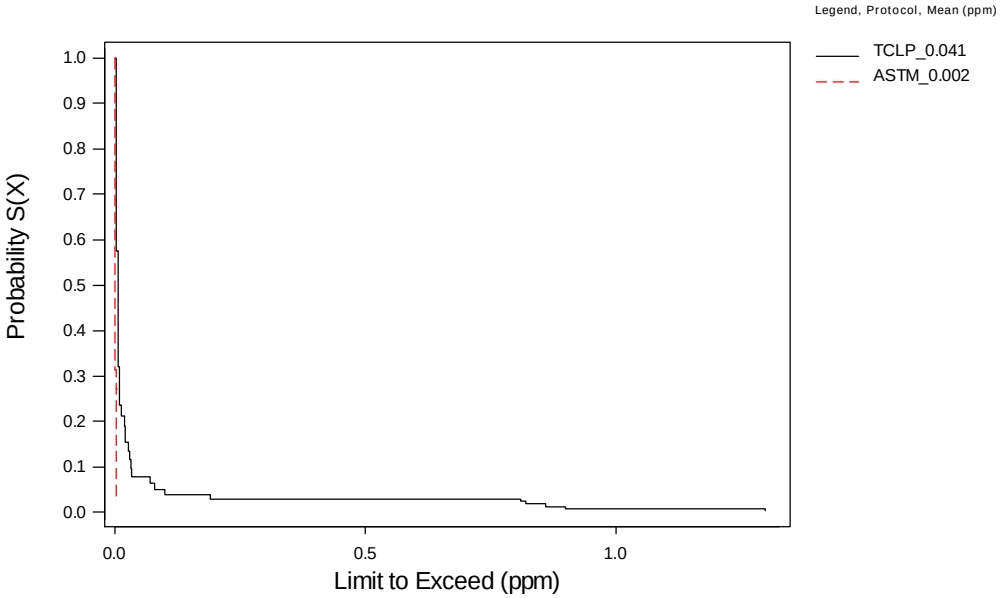
Nonparametric Survival Plot for Molybdenum (Mo)



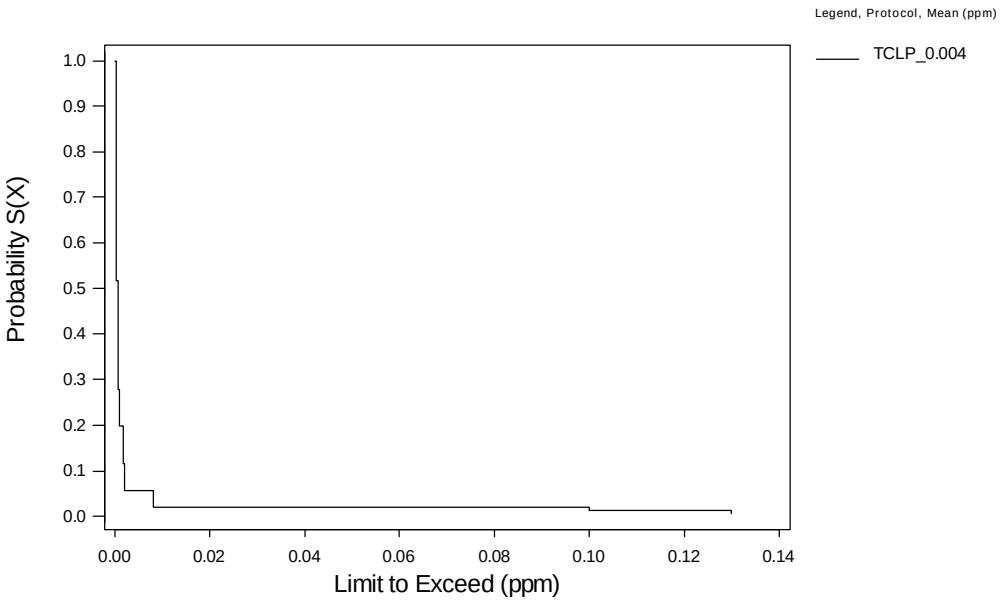
Nonparametric Survival Plot for Nickel (Ni)



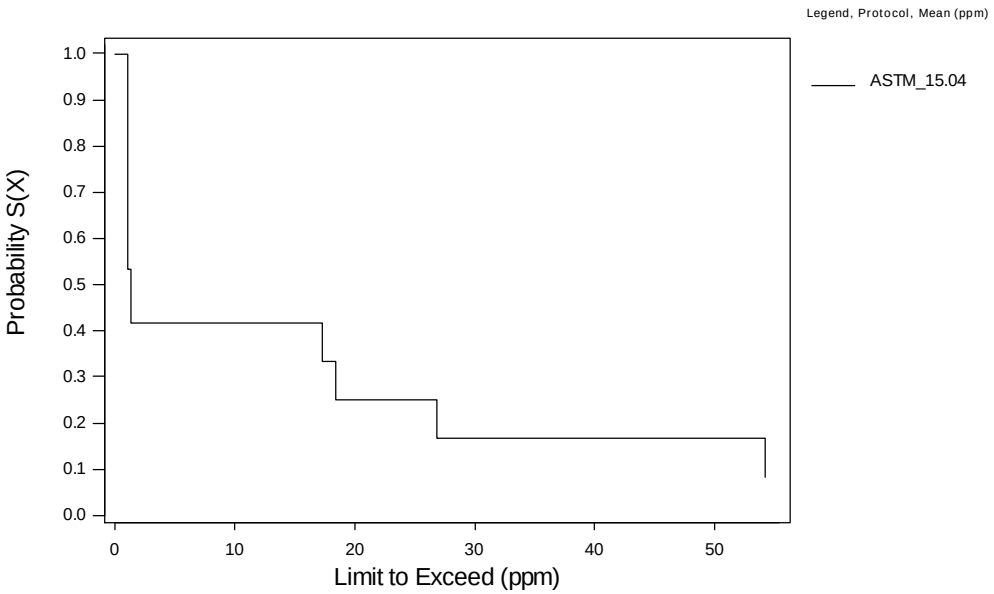
Nonparametric Survival Plot for Selenium (Se)

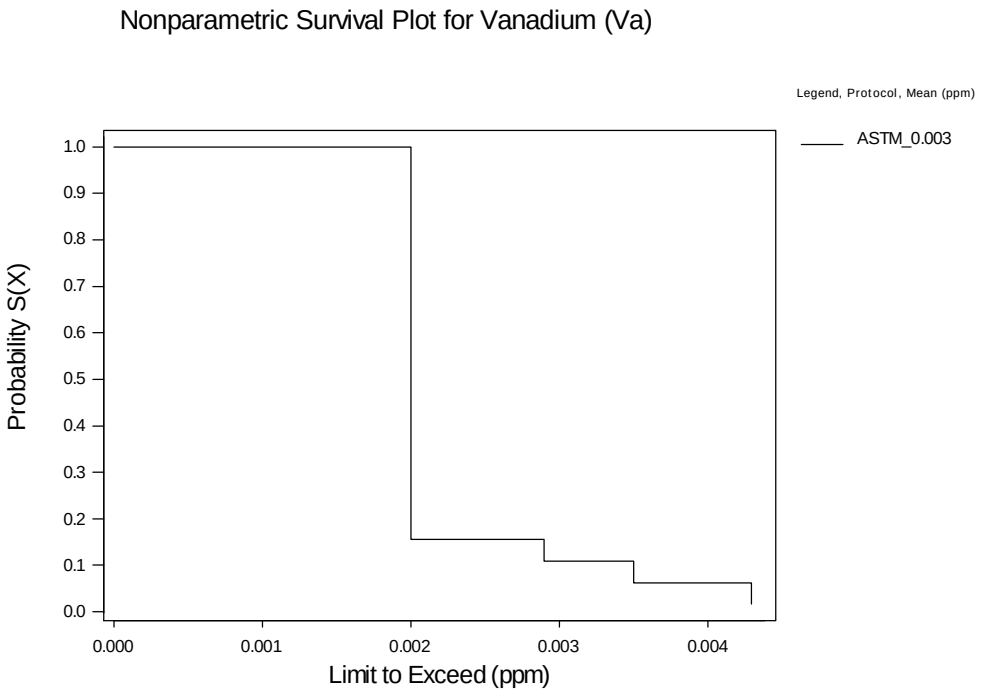


Nonparametric Survival Plot for Silver (Ag)



Nonparametric Survival Plot for Sodium (Na)





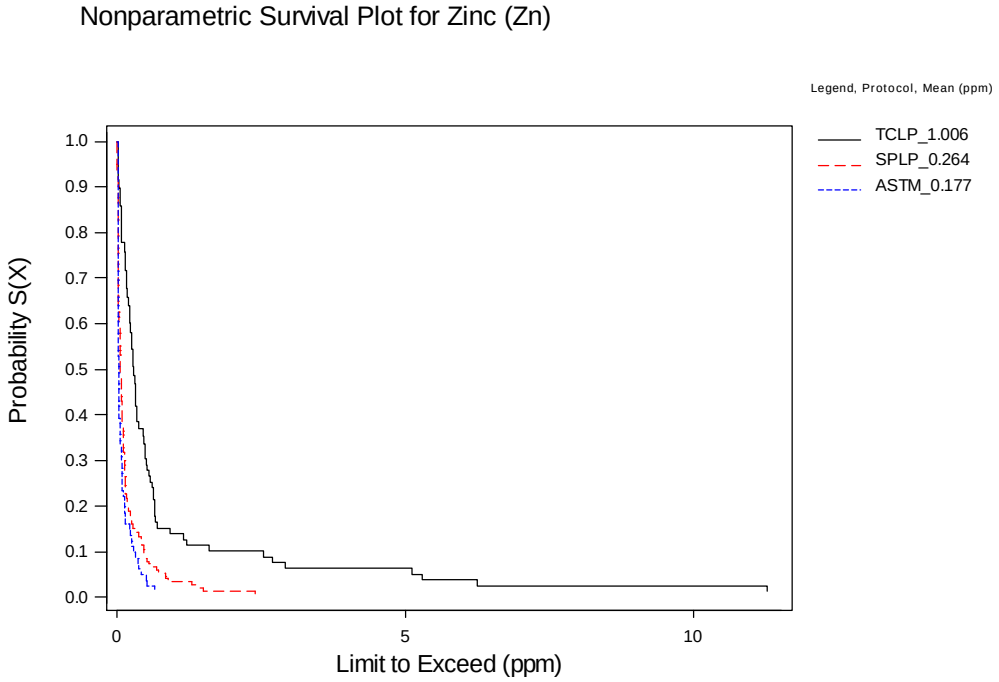
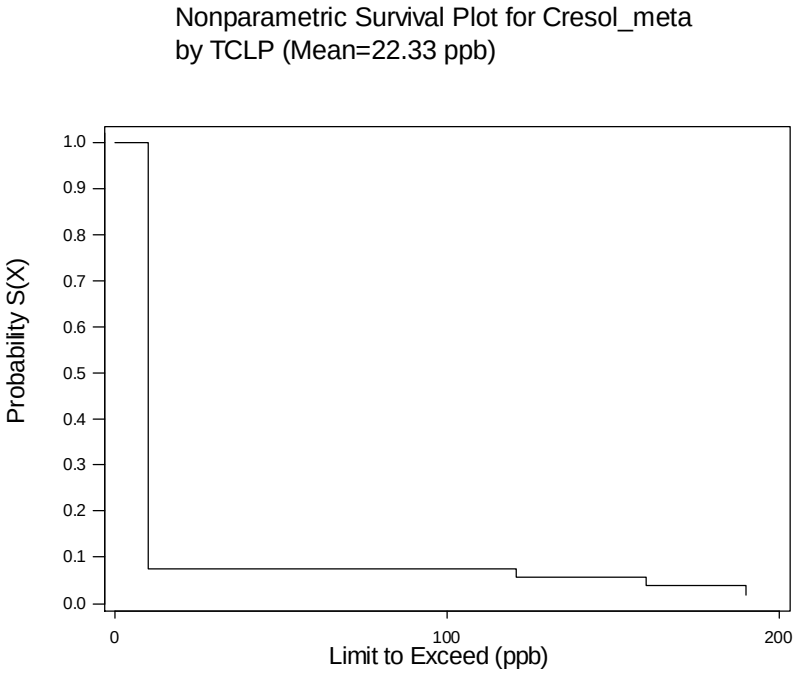
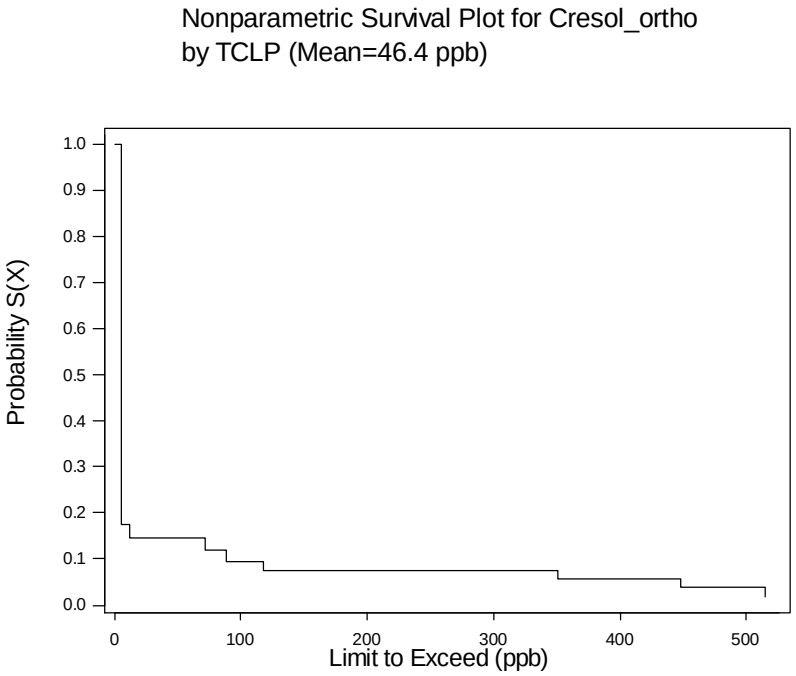


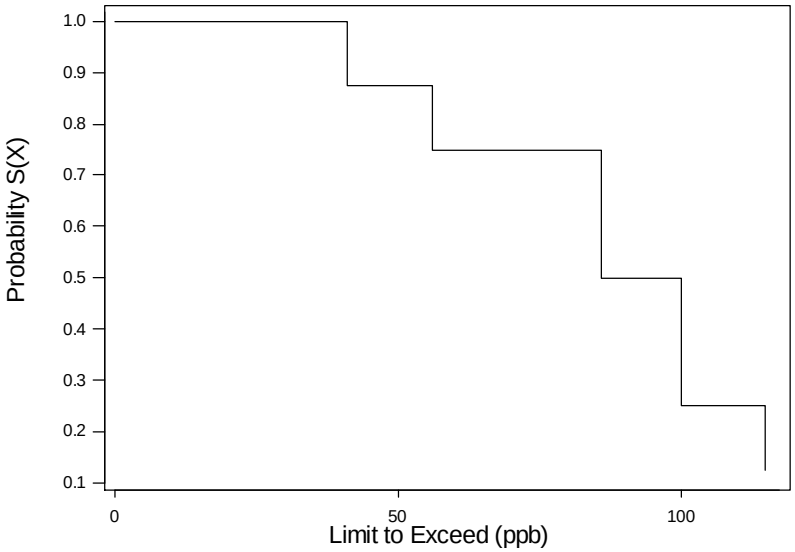
Figure **F-6**: Survival plots for metallic elements in leachates (20 charts)

F.3.3 Organic Compounds

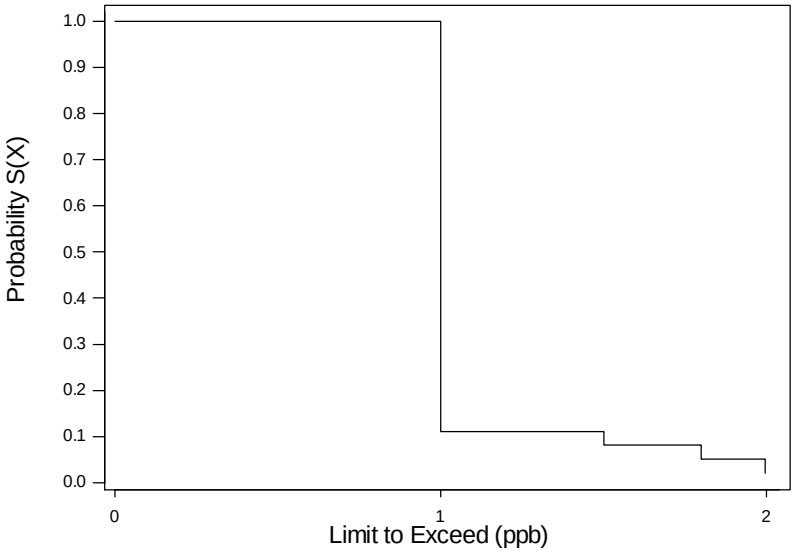




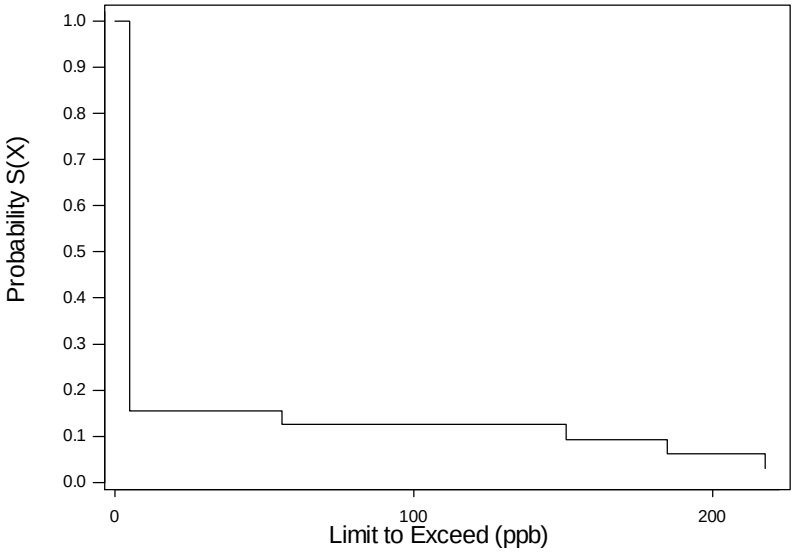
Nonparametric Survival Plot for Acetone
by TCLP (Mean=265.5 ppb)



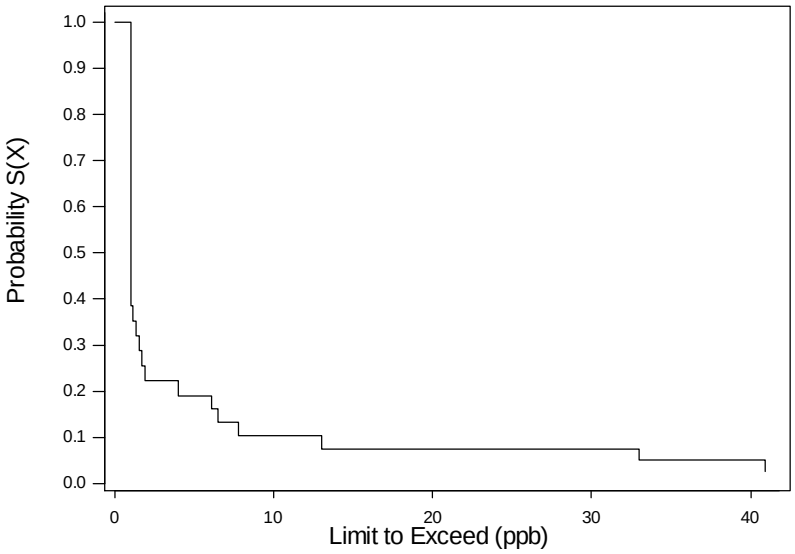
Nonparametric Survival Plot for Benzene
by TCLP (Mean=1.46 ppb)



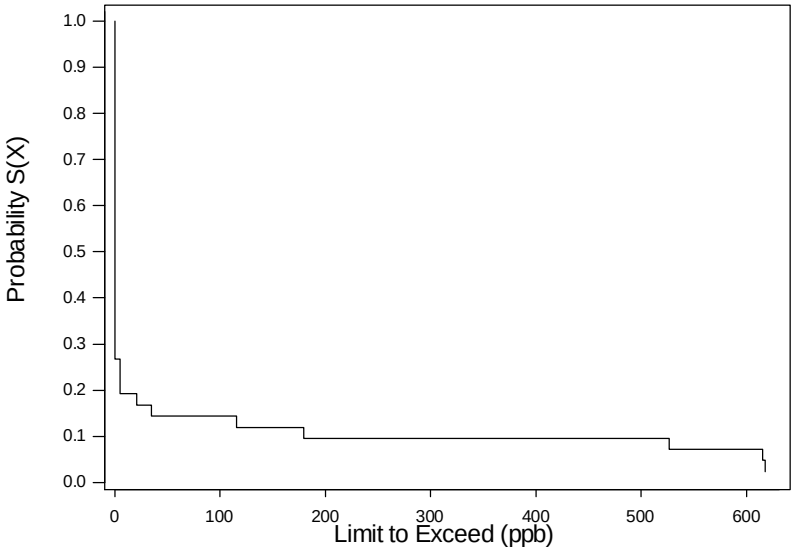
Nonparametric Survival Plot for 2_4-Dimethylphen
by TCLP (Mean=30.6 ppb)



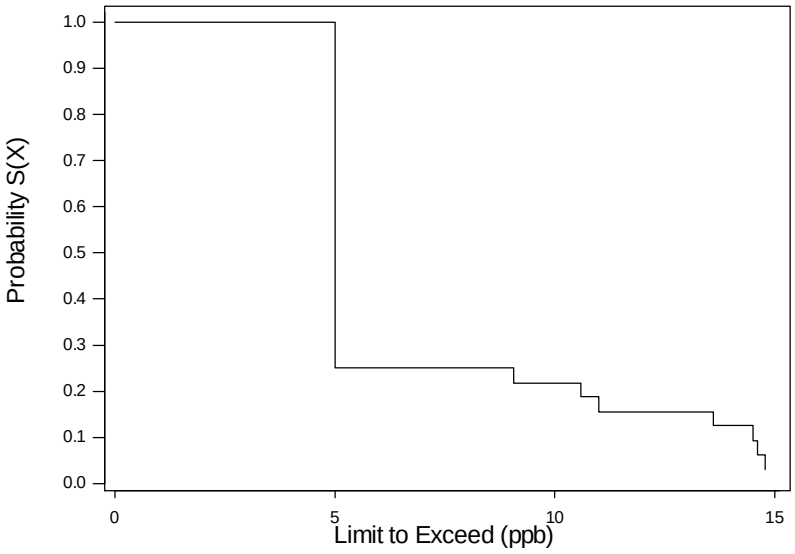
Nonparametric Survival Plot for Ethyl benzene
by TCLP (Mean=5.78 ppb)



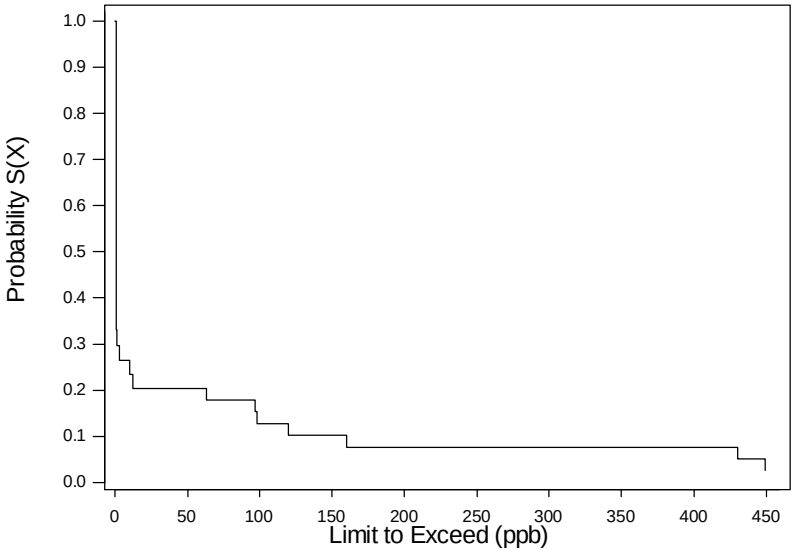
Nonparametric Survival Plot for Naphthalene
by TCLP (Mean=71.69 ppb)



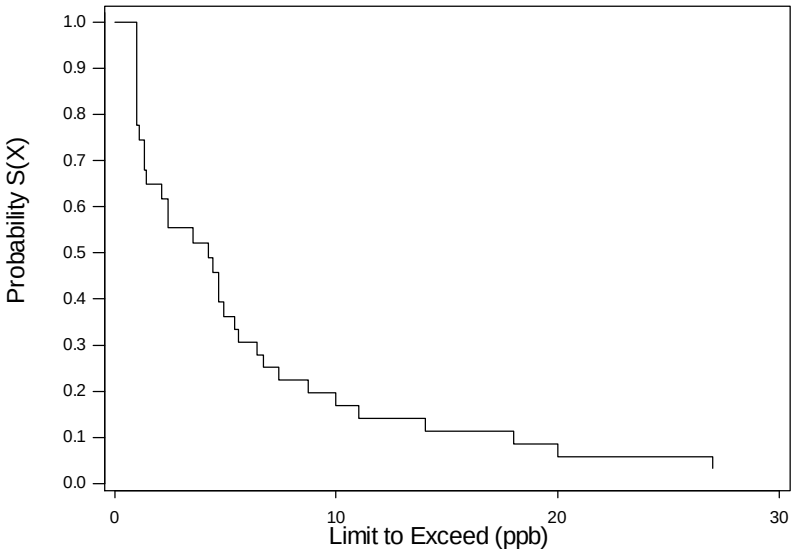
Nonparametric Survival Plot for Phenanthrene
by TCLP (Mean=6.99 ppb)



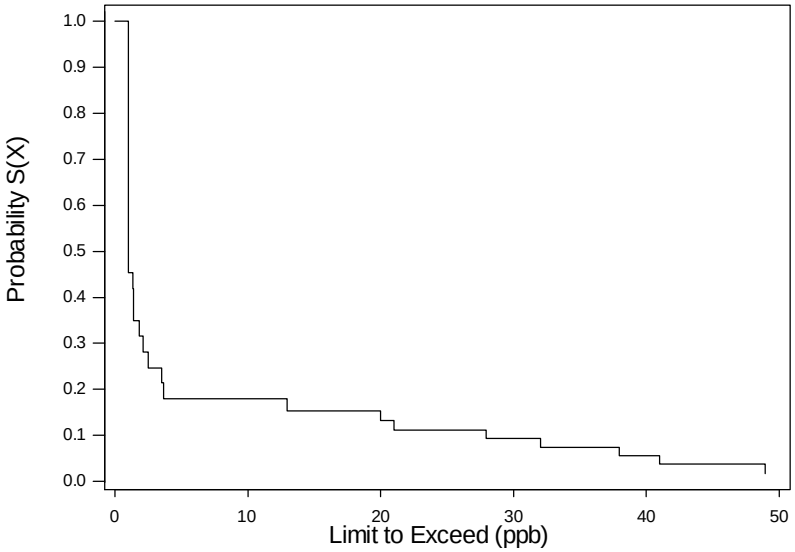
Nonparametric Survival Plot for Styrene
by TCLP (Mean=57.30 ppb)



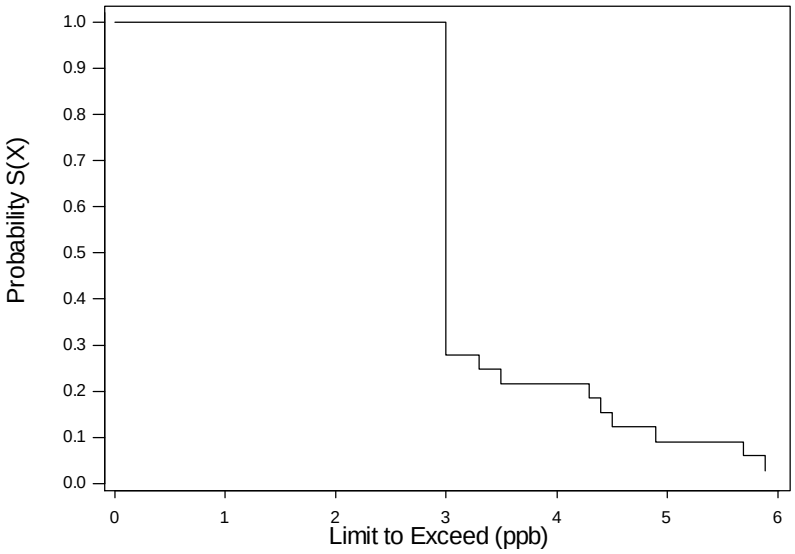
Nonparametric Survival Plot for Toluene
by TCLP (Mean=51.92 ppb)



Nonparametric Survival Plot for Trichloroethylen
by TCLP (Mean=7.23 ppb)



Nonparametric Survival Plot for Xylene_total
by TCLP (Mean=3.73 ppb)



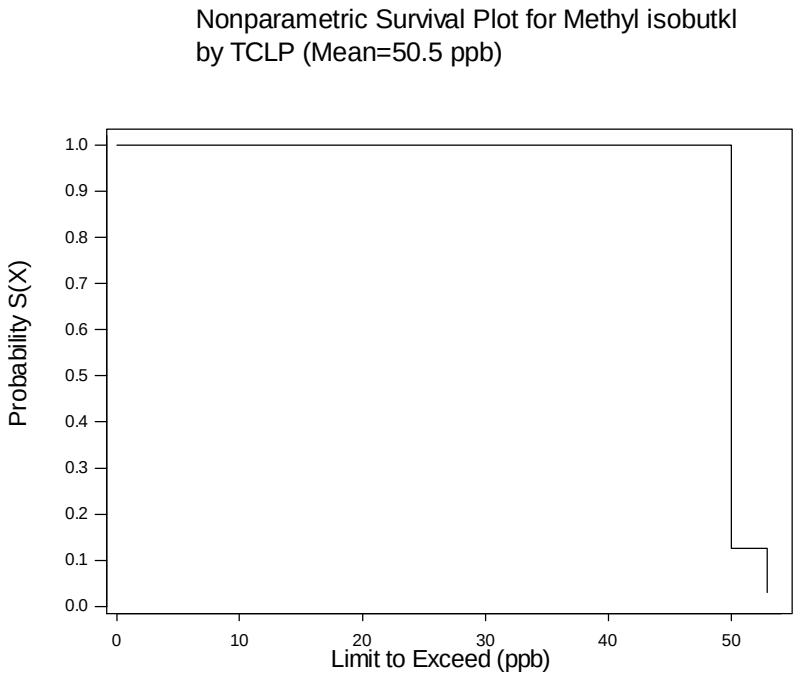


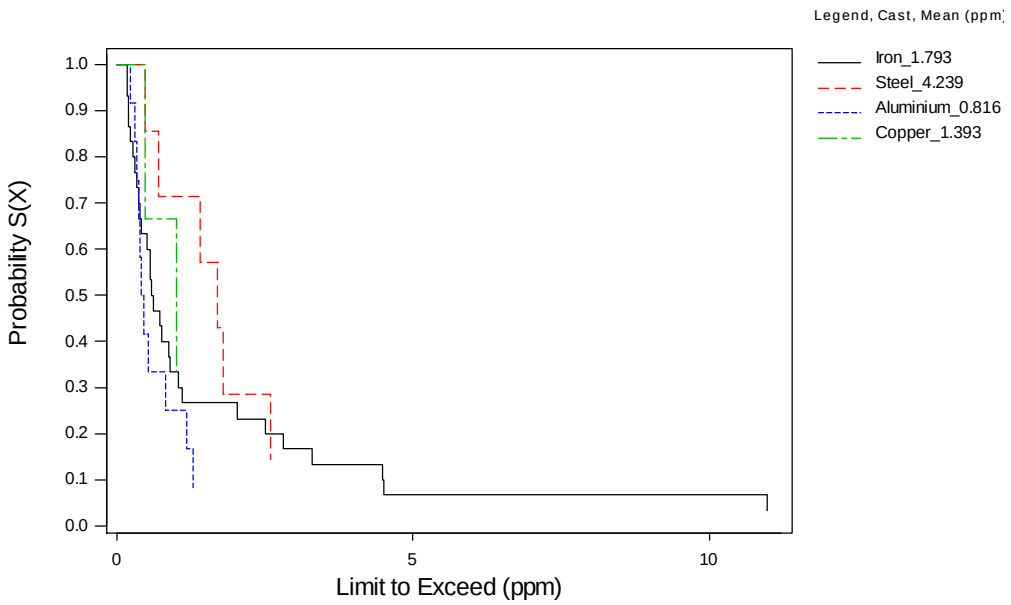
Figure **F-7**: Survival plots for organic compounds in TCLP leachate (13 charts)

F.4 TCLP Leaching Characterization of Excess Foundry Sand per Metal Cast

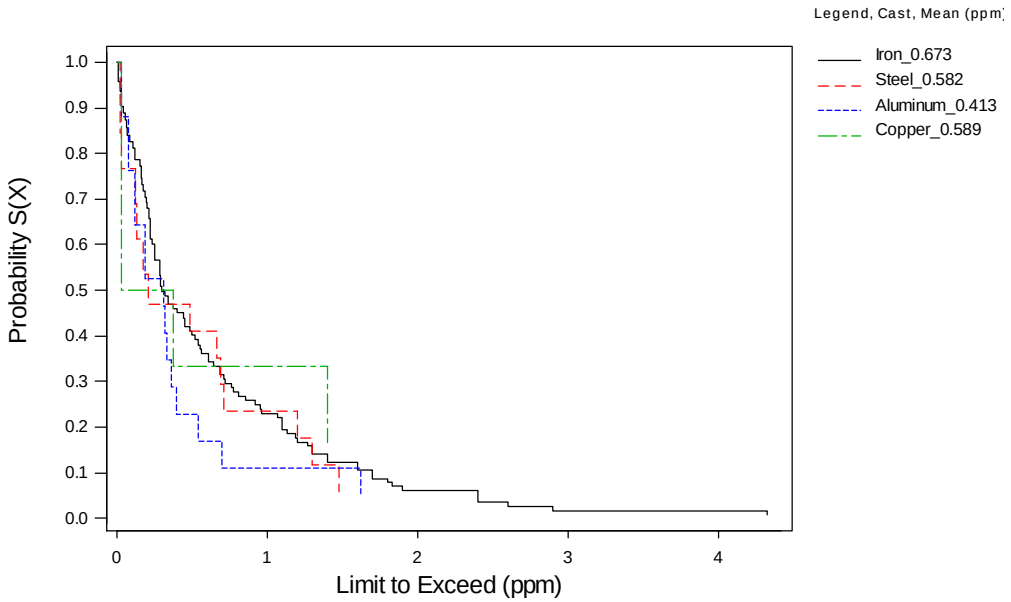
In this section, a series of 11 charts, grouped into Figure F-8, present TCLP leaching characterization of excess foundry sand per metal cast.

F.4.1 Metallic Elements

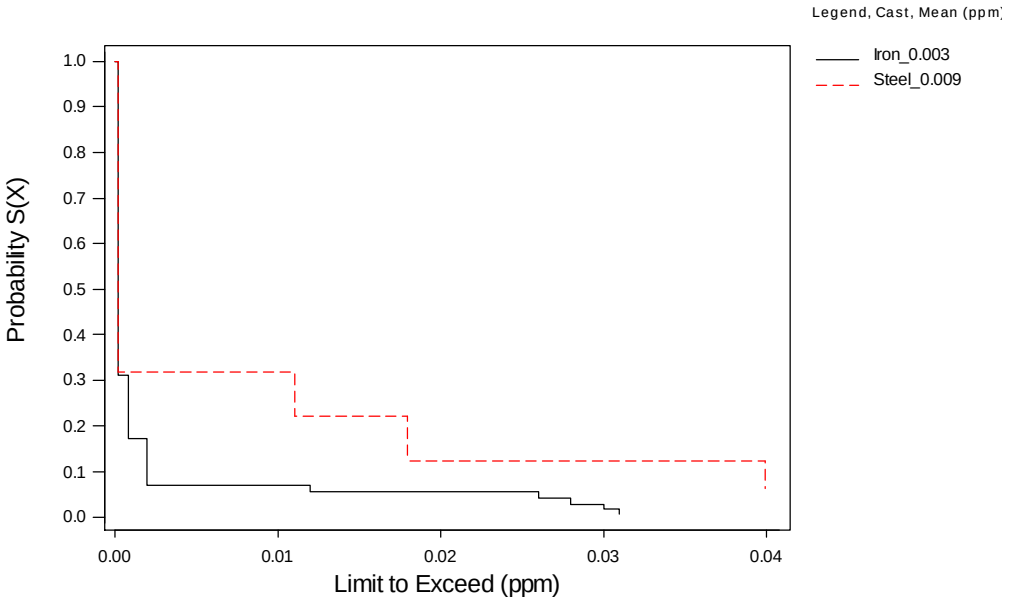
Nonparametric Survival Plot for Aluminium (Al)



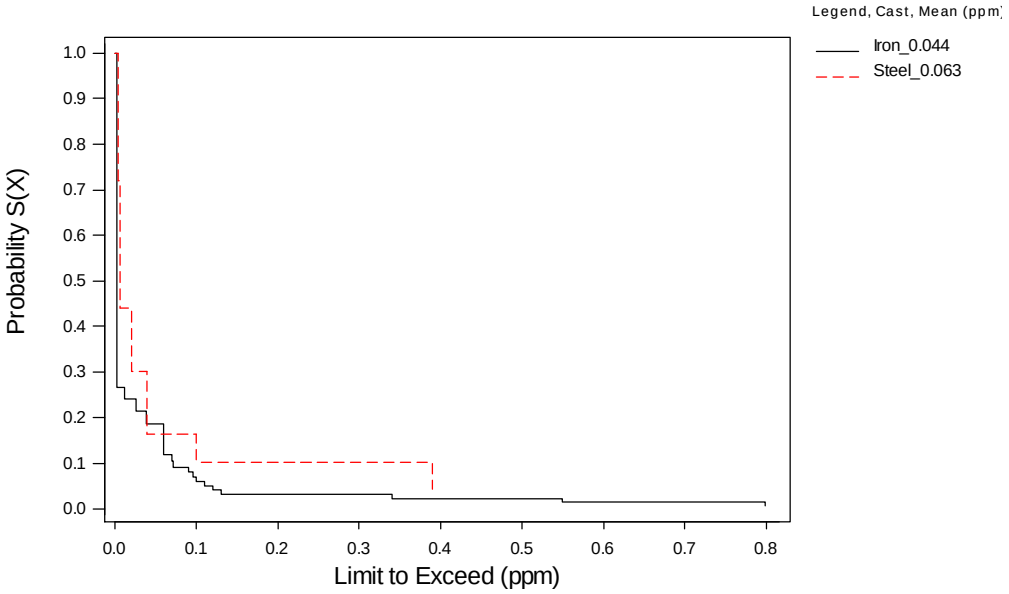
Nonparametric Survival Plot for Barium (Ba)



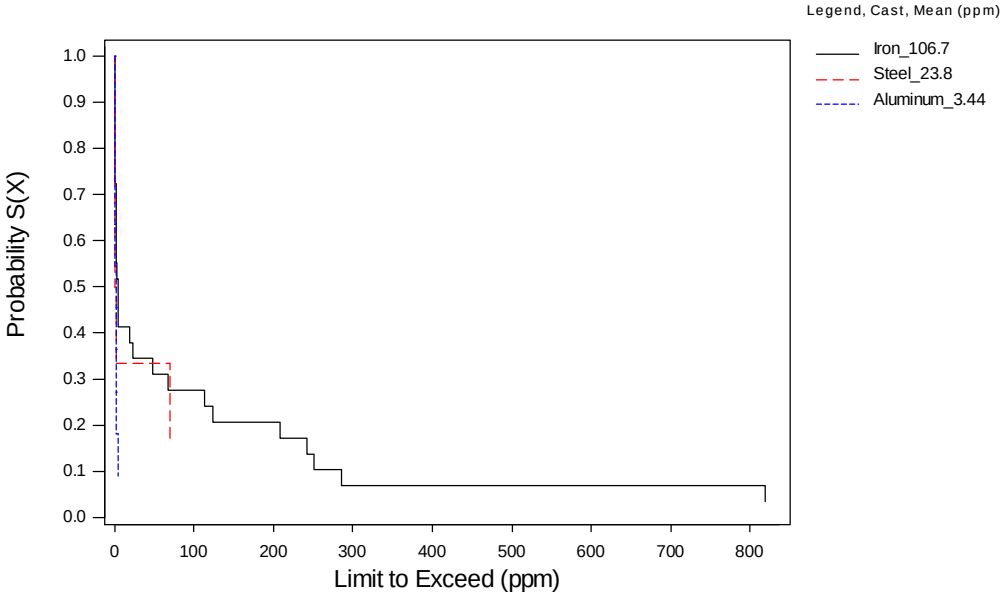
Nonparametric Survival Plot for Cadmium (Cd)



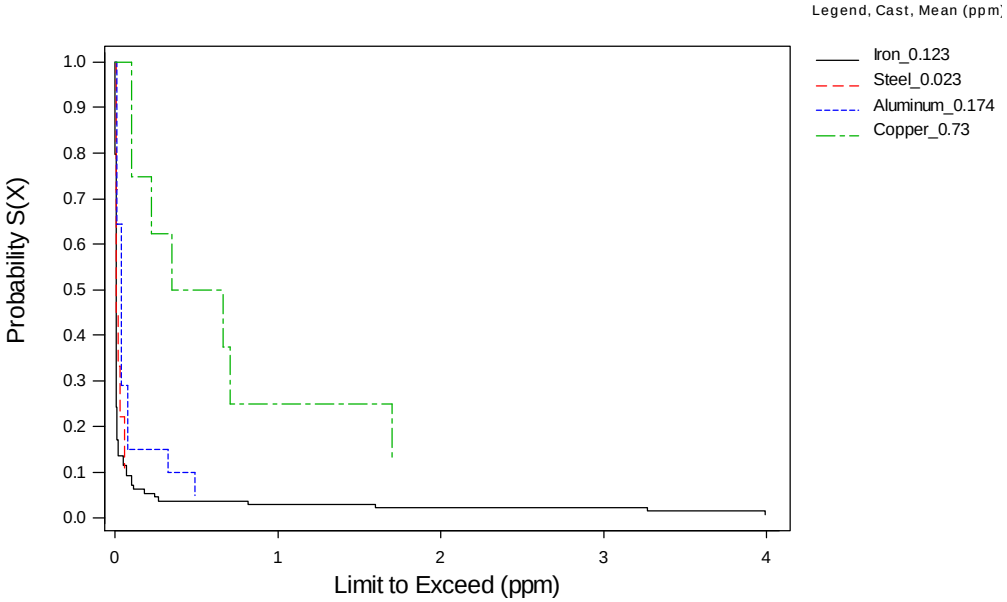
Nonparametric Survival Plot for Chromium (Cr)



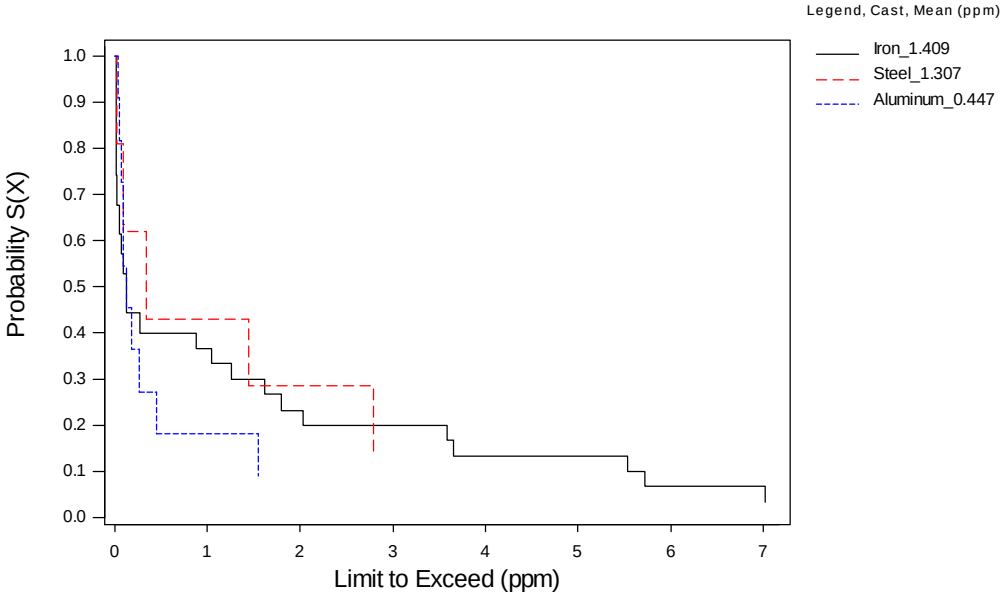
Nonparametric Survival Plot for Iron (Fe)



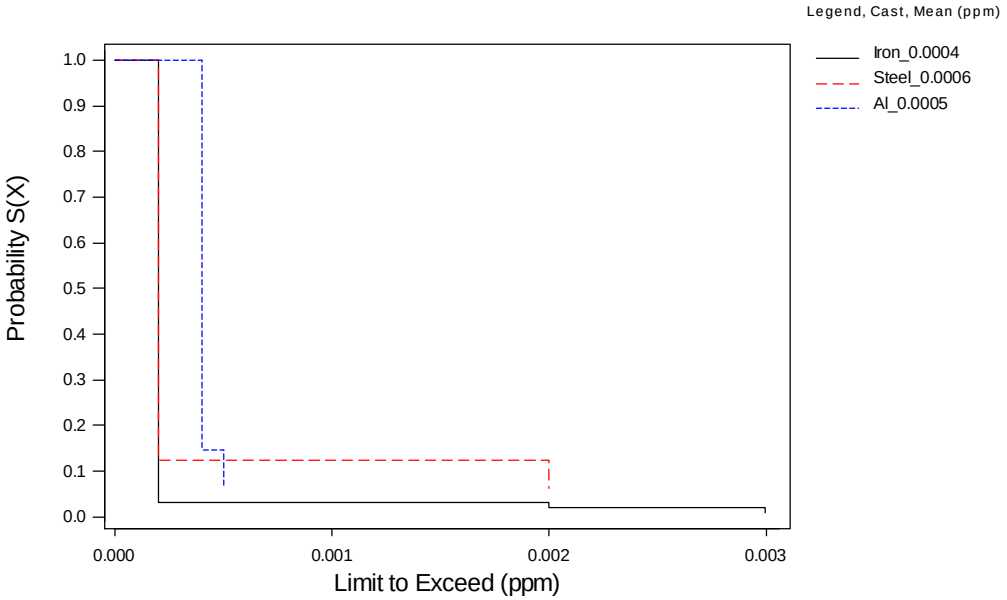
Nonparametric Survival Plot for Lead (Pb)



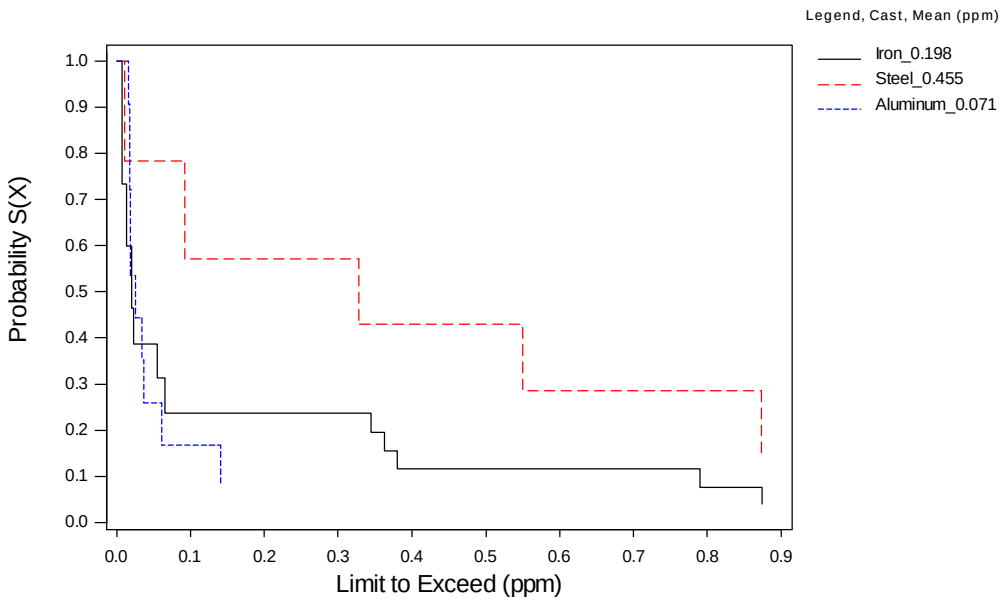
Nonparametric Survival Plot for Manganese (Mn)



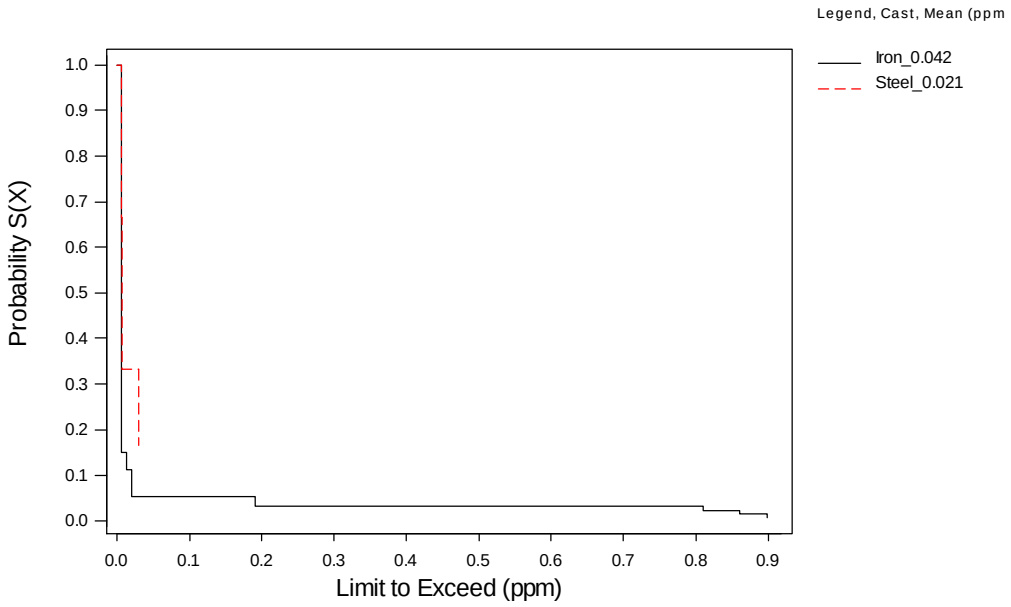
Nonparametric Survival Plot for Mercury (Hg)



Nonparametric Survival Plot for Nickel (Ni)



Nonparametric Survival Plot for Selenium (Se)



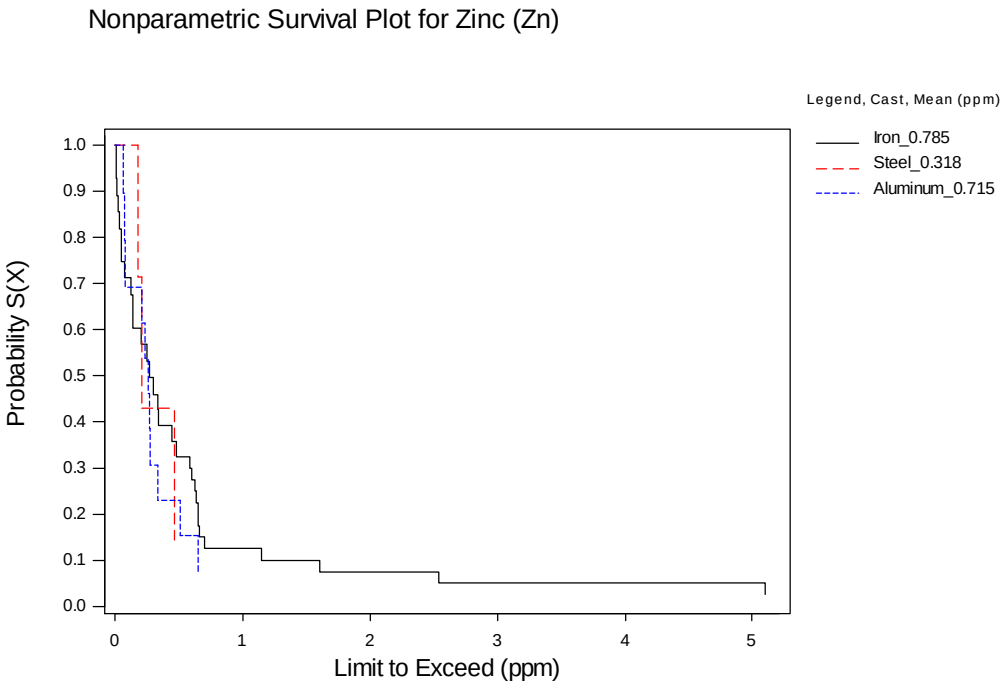


Figure **F-8**: Survival plots for metallic elements in TCLP leachate per metal cast (11 charts)

Appendix G

Gradation and Grain Shape

G.1 Gradation

The sieve analysis is conducted on the oven-dry excess foundry sand to investigate its gradation. The results are presented in Table G-1 and Table G-2.

Table **G-1**: Summary of oven-dry sieve analysis of excess foundry sand ---percentage passing by weight (%)

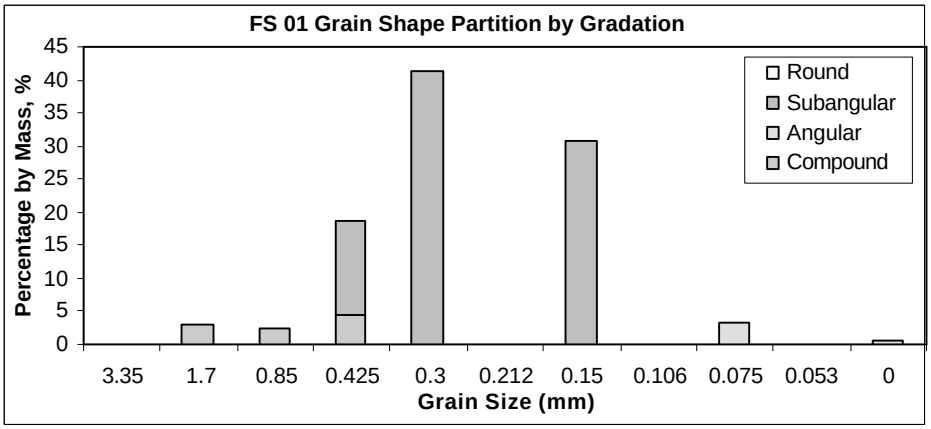
	# 6	# 12	# 20	# 40	# 50	# 70	# 100	# 140	# 200	# 270	# 325
FS ID	3.35 mm	1.7 mm	0.85 mm	0.425 mm	0.3 mm	0.212 mm	0.15 mm	0.106 mm	0.075 mm	0.053 mm	0.045 mm
FS01	100.00	97.08	94.56	75.85	34.56	---	3.86	---	0.48	---	0.13
FS02	100.00	99.95	98.77	75.88	35.34	---	1.97	---	0.08	---	0.03
FS03	100.00	99.43	99.15	85.12	38.28	---	2.31	---	0.17	---	0.07
FS04	100.00	98.11	97.71	95.89	85.74	---	14.66	---	1.19	---	0.29
FS05	100.00	99.39	98.65	85.43	55.15	---	8.12	---	0.49	---	0.16
FS06	97.24	92.94	90.24	65.32	23.75	---	0.97	---	0.00	---	0.00
FS07	100.00	99.96	99.60	91.56	55.41	---	5.05	---	0.66	---	0.19
FS08	99.01	96.87	95.47	83.94	48.80	---	5.03	---	0.50	---	0.17
FS09	99.79	99.56	99.12	86.22	53.01	---	5.74	---	0.52	---	0.20
FS10	99.83	99.09	98.30	90.25	44.24	---	3.74	---	1.35	---	0.78
FS11	99.99	99.86	98.53	67.09	30.81	---	1.64	---	0.08	---	0.01
FS12	100.00	99.26	98.77	98.52	96.80	72.29	16.75	1.97	0.37	0.25	---
FS13	100.00	100.00	100.00	84.81	45.95	23.29	8.75	2.06	0.51	0.13	---
FS14	100.00	99.74	96.89	93.77	89.11	69.39	32.81	15.18	9.21	7.39	---
FS15	100.00	99.93	99.86	79.28	37.02	12.15	2.76	0.69	0.41	0.28	---
FS16	99.71	98.84	96.81	85.05	64.73	33.09	7.69	1.60	0.73	0.44	---
FS17	98.61	98.14	97.22	80.28	45.94	17.40	4.99	1.86	0.93	0.46	---
Min.	*97.24*	*92.94*	*90.24*	*65.32*	*23.75*	*12.15*	*0.97*	*0.69*	*0*	*0.13*	*0*
Max.	*100*	*100*	*100*	*98.52*	*96.8*	*72.29*	*32.81*	*15.18*	*9.21*	*7.39*	*0.78*
Avg.	*99.66*	*98.71*	*97.63*	*83.78*	*52.04*	*37.94*	*7.46*	*3.89*	*1.04*	*1.49*	*0.18*
SD	*0.74*	*1.78*	*2.42*	*9.21*	*21.05*	*26.44*	*7.85*	*5.55*	*2.14*	*2.89*	*0.22*

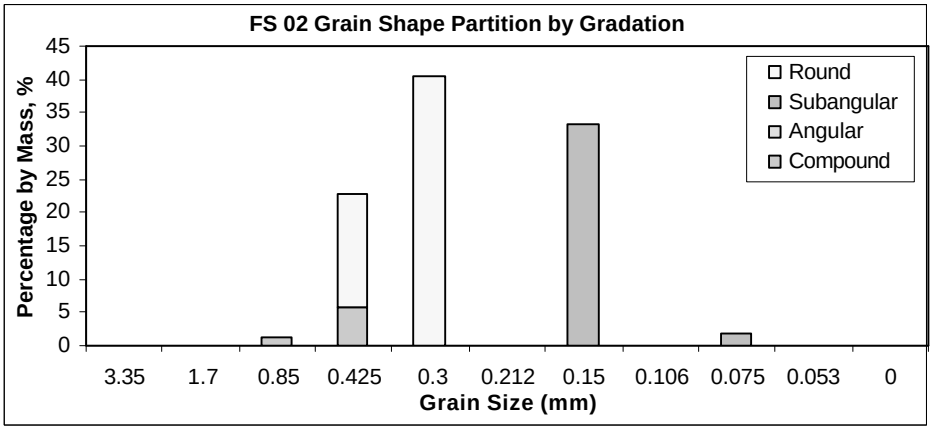
Table **G-2**: Summary of oven-dry sieve analysis of foundry sand ---percentage retained by weight (%)

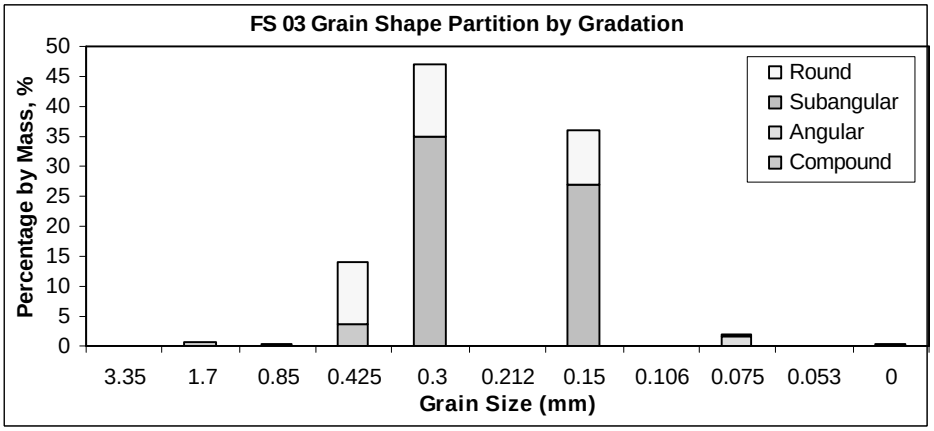
	# 6	# 12	# 20	# 40	# 50	# 70	# 100	# 140	# 200	# 270	# 325	pan
FS ID	3.35 mm	1.7 mm	0.85 mm	0.425 mm	0.3 mm	0.212 mm	0.15 mm	0.106 mm	0.075 mm	0.053 mm	0.045 mm	
FS01	0.00	2.92	2.52	18.71	41.29	---	30.71	---	3.37	---	0.36	0.13
FS02	0.00	0.05	1.18	22.89	40.55	---	33.36	---	1.89	---	0.05	0.03
FS03	0.00	0.57	0.27	14.03	46.84	---	35.97	---	2.14	---	0.10	0.07
FS04	0.00	1.89	0.40	1.83	10.14	---	71.09	---	13.47	---	0.90	0.29
FS05	0.00	0.61	0.74	13.22	30.28	---	47.03	---	7.63	---	0.33	0.16
FS06	2.76	4.30	2.71	24.92	41.57	---	22.78	---	0.97	---	0.00	0.00
FS07	0.00	0.04	0.36	8.04	36.15	---	50.36	---	4.39	---	0.46	0.19
FS08	0.99	2.14	1.40	11.53	35.14	---	43.77	---	4.53	---	0.33	0.17
FS09	0.21	0.23	0.43	12.91	33.21	---	47.27	---	5.22	---	0.32	0.20
FS10	0.17	0.74	0.79	8.05	46.01	---	40.50	---	2.39	---	0.57	0.78
FS11	0.01	0.13	1.33	31.44	36.28	---	29.17	---	1.56	---	0.06	0.01
FS12	0.00	0.74	0.49	0.25	1.72	24.51	55.54	14.78	1.60	0.12	---	0.25
FS13	0.00	0.00	0.00	15.19	38.87	22.65	14.54	6.69	1.54	0.39	---	0.13
FS14	0.00	0.26	2.85	3.11	4.67	19.71	36.58	17.64	5.97	1.82	---	7.39
FS15	0.00	0.07	0.07	20.58	42.27	24.86	9.39	2.07	0.28	0.14	---	0.28
FS16	0.29	0.87	2.03	11.76	20.32	31.64	25.40	6.10	0.87	0.29	---	0.44
FS17	1.39	0.46	0.93	16.94	34.34	28.54	12.41	3.13	0.93	0.46	---	0.46
Min.	*0.00*	*0.00*	*0.00*	*0.25*	*1.72*	*19.71*	*9.39*	*2.07*	*0.28*	*0.12*	*0.00*	*0.00*
Max.	*2.76*	*4.30*	*2.85*	*31.44*	*46.84*	*31.64*	*71.09*	*17.64*	*13.47*	*1.82*	*0.90*	*7.39*
Avg.	*0.34*	*0.94*	*1.09*	*13.85*	*31.74*	*25.32*	*35.64*	*8.40*	*3.46*	*0.54*	*0.32*	*0.65*
SD	*0.74*	*1.20*	*0.93*	*8.36*	*14.04*	*4.24*	*16.28*	*6.36*	*3.30*	*0.64*	*0.27*	*1.75*

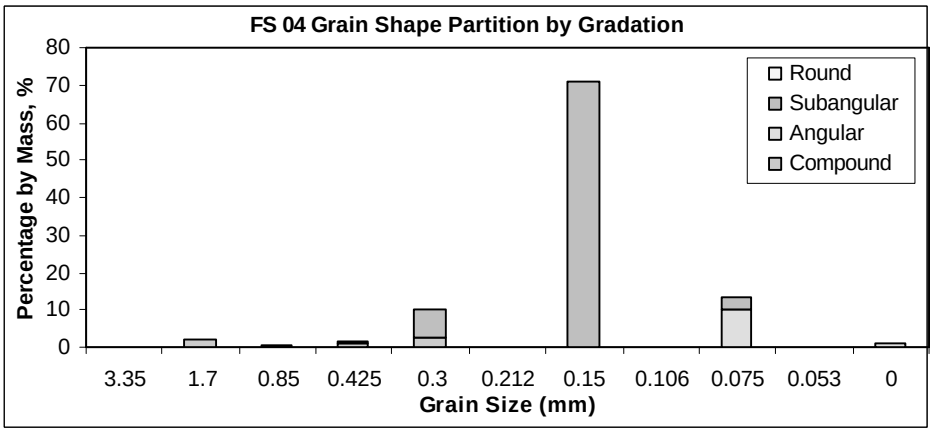
G.2 Grain Shape

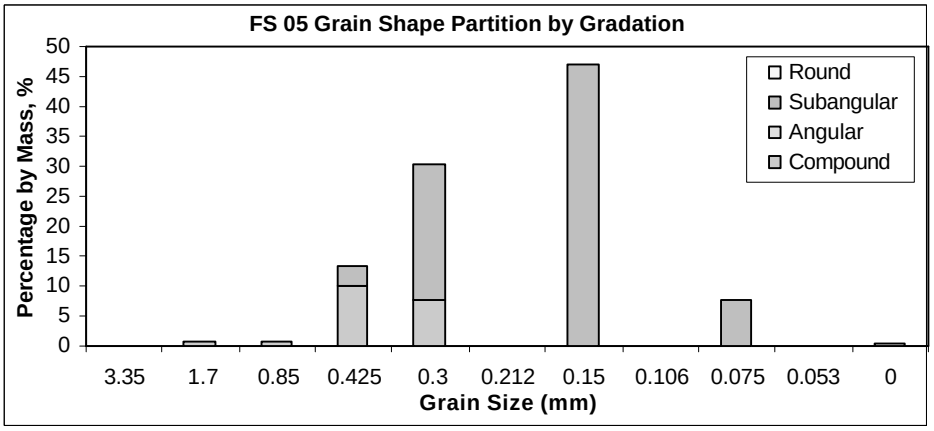
A series of 17 charts, corresponding to individual excess foundry sand, is grouped into Figure G-1 to address the grain shape of excess foundry sand partitioned by gradation.

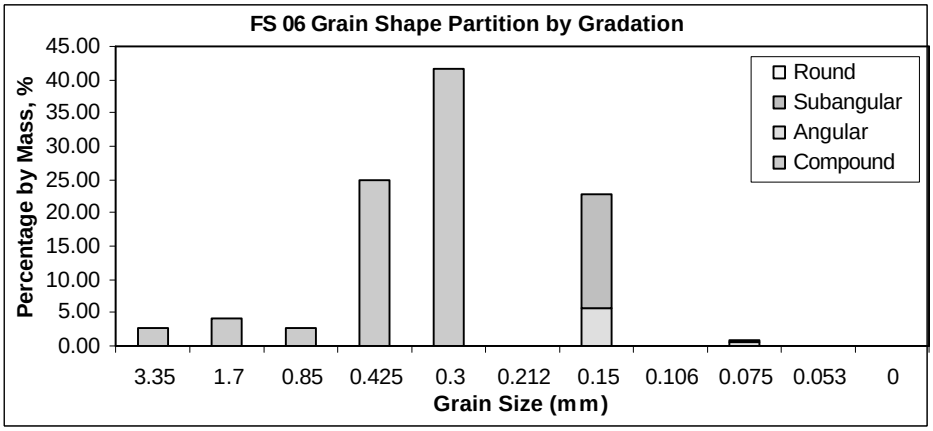


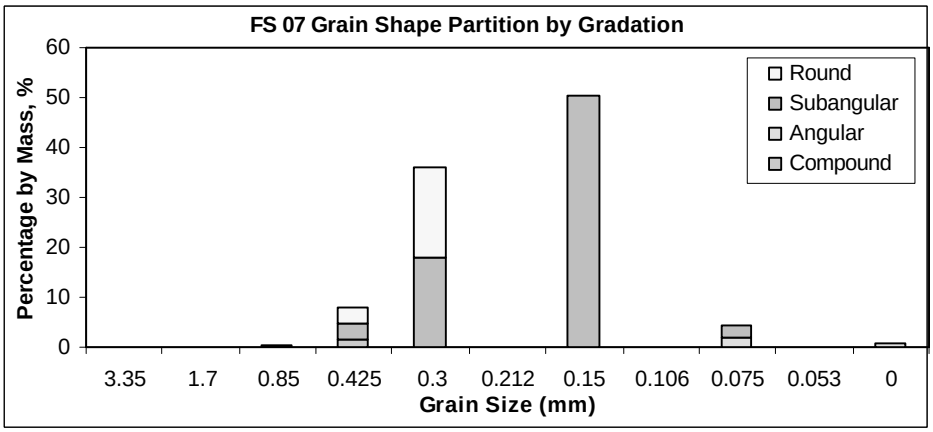


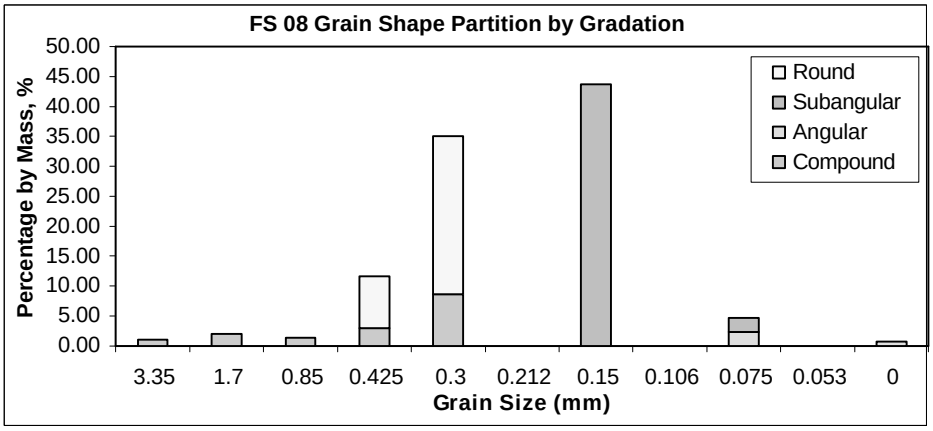

FS 03 Grain Shape Partition by Gradation
Percentage by Mass, %
50
45
40
35
30
25
20
15
10
5
0
Round
Subangular
Angular
Compound
3.35
1.7
0.85
0.425
0.3
0.212
0.15
0.106
0.075
0.053
0
Grain Size (mm)

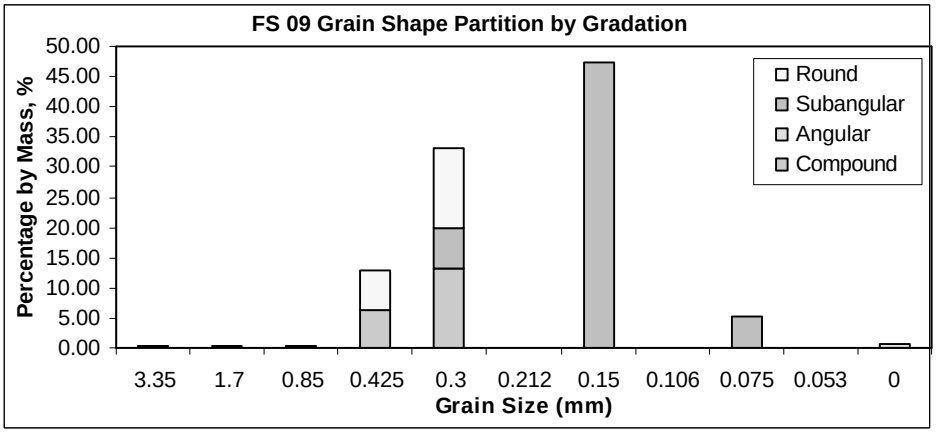

FS 04 Grain Shape Partition by Gradation
Percentage by Mass, %
80
70
60
50
40
30
20
10
0
Round
Subangular
Angular
Compound
3.35
1.7
0.85
0.425
0.3
0.212
0.15
0.106
0.075
0.053
0
Grain Size (mm)

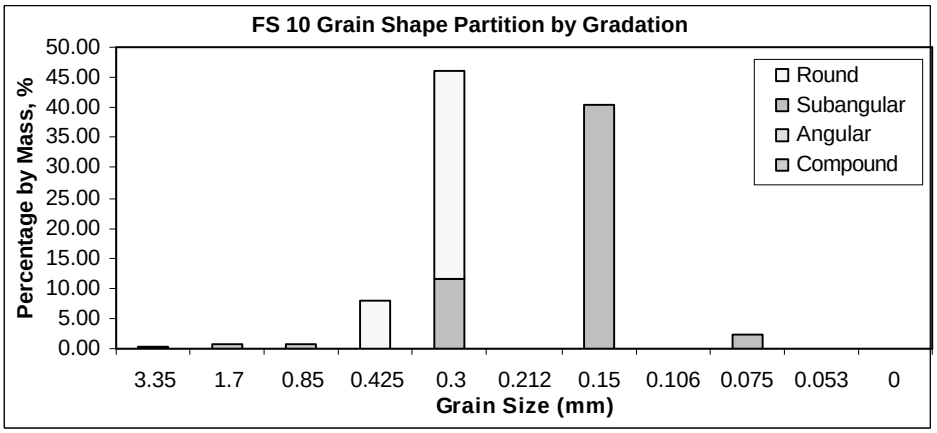

FS 05 Grain Shape Partition by Gradation
Percentage by Mass, %
50
45
40
35
30
25
20
15
10
5
0
Round
Subangular
Angular
Compound
3.35
1.7
0.85
0.425
0.3
0.212
0.15
0.106
0.075
0.053
0
Grain Size (mm)

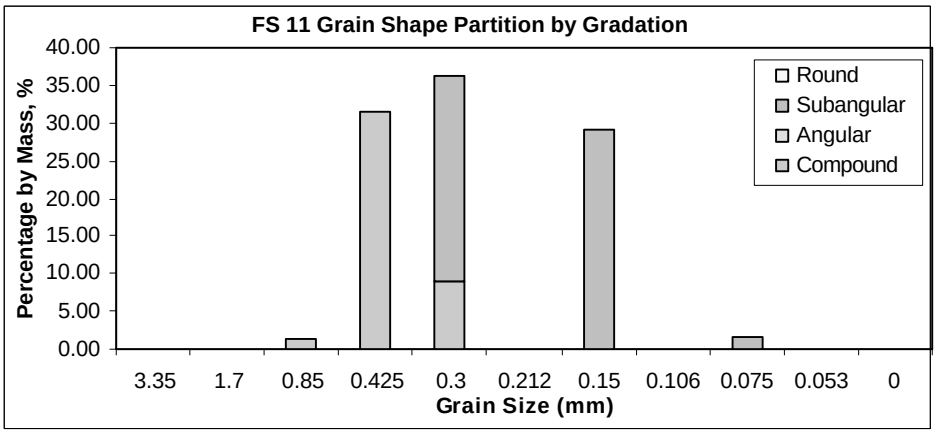

FS 06 Grain Shape Partition by Gradation
Percentage by Mass, %
45.00
40.00
35.00
30.00
25.00
20.00
15.00
10.00
5.00
0.00
Round
Subangular
Angular
Compound
3.35
1.7
0.85
0.425
0.3
0.212
0.15
0.106
0.075
0.053
0
Grain Size (mm)

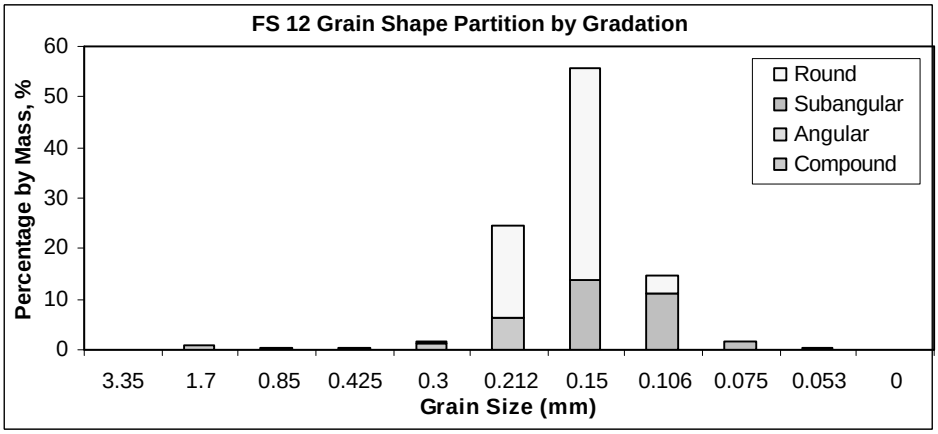

FS 07 Grain Shape Partition by Gradation
Percentage by Mass, %
60
50
40
30
20
10
0
Round
Subangular
Angular
Compound
3.35
1.7
0.85
0.425
0.3
0.212
0.15
0.106
0.075
0.053
0
Grain Size (mm)

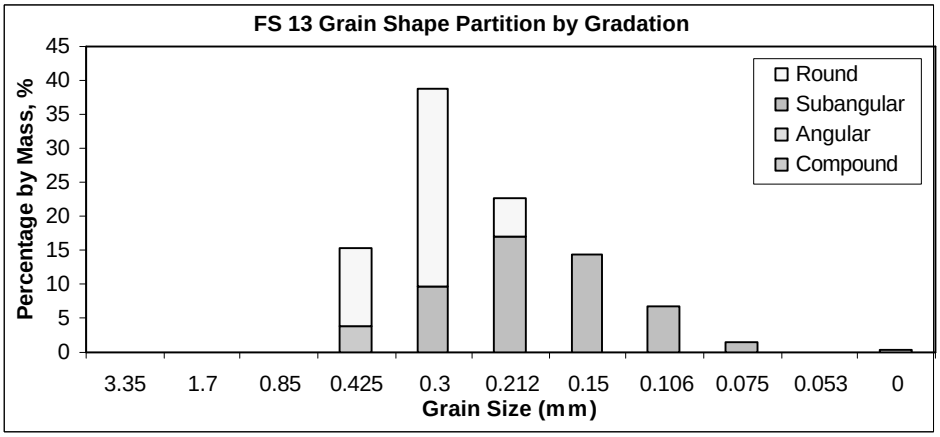

FS 08 Grain Shape Partition by Gradation
Percentage by Mass, %
50.00
45.00
40.00
35.00
30.00
25.00
20.00
15.00
10.00
5.00
0.00
Round
Subangular
Angular
Compound
3.35
1.7
0.85
0.425
0.3
0.212
0.15
0.106
0.075
0.053
0
Grain Size (mm)

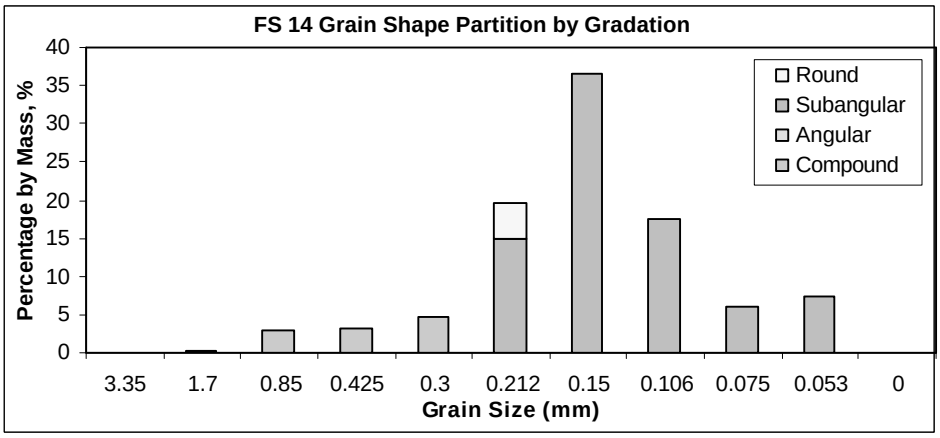

FS 09 Grain Shape Partition by Gradation
Percentage by Mass, %
50.00
45.00
40.00
35.00
30.00
25.00
20.00
15.00
10.00
5.00
0.00
Round
Subangular
Angular
Compound
3.35
1.7
0.85
0.425
0.3
0.212
0.15
0.106
0.075
0.053
0
Grain Size (mm)

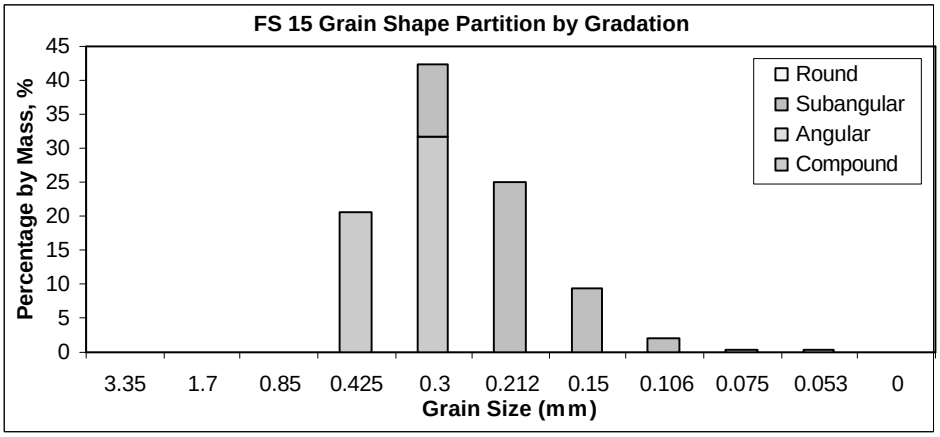

FS 10 Grain Shape Partition by Gradation
Percentage by Mass, %
50.00
45.00
40.00
35.00
30.00
25.00
20.00
15.00
10.00
5.00
0.00
Round
Subangular
Angular
Compound
3.35
1.7
0.85
0.425
0.3
0.212
0.15
0.106
0.075
0.053
0
Grain Size (mm)

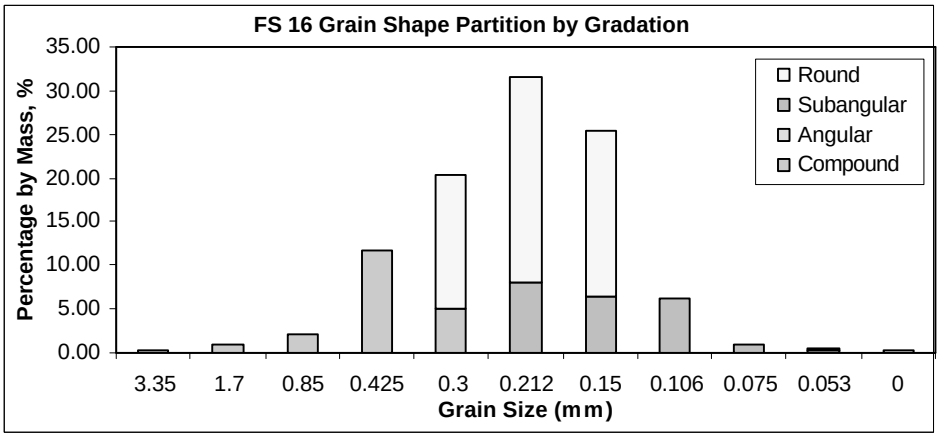

FS 11 Grain Shape Partition by Gradation
Percentage by Mass, %
40.00
35.00
30.00
25.00
20.00
15.00
10.00
5.00
0.00
Round
Subangular
Angular
Compound
3.35
1.7
0.85
0.425
0.3
0.212
0.15
0.106
0.075
0.053
0
Grain Size (mm)


FS 12 Grain Shape Partition by Gradation
Percentage by Mass, %
60
50
40
30
20
10
0
Round
Subangular
Angular
Compound
3.35
1.7
0.85
0.425
0.3
0.212
0.15
0.106
0.075
0.053
0
Grain Size (mm)


FS 13 Grain Shape Partition by Gradation
Percentage by Mass, %
45
40
35
30
25
20
15
10
5
0
Round
Subangular
Angular
Compound
3.35
1.7
0.85
0.425
0.3
0.212
0.15
0.106
0.075
0.053
0
Grain Size (mm)


FS 14 Grain Shape Partition by Gradation
Percentage by Mass, %
40
35
30
25
20
15
10
5
0
Round
Subangular
Angular
Compound
3.35
1.7
0.85
0.425
0.3
0.212
0.15
0.106
0.075
0.053
0
Grain Size (mm)





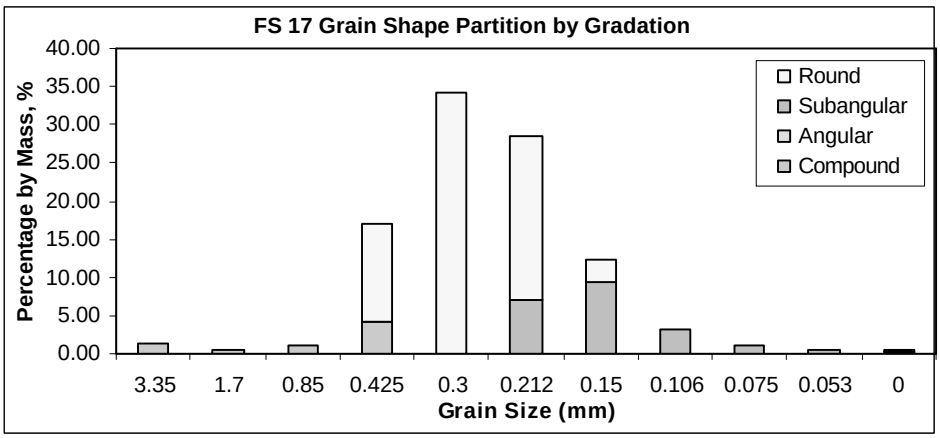


Figure **G-1**: Grain shape partitioned by gradation (17 charts)

Appendix H

Bulk Chemical Analysis of Excess Foundry Sands in Experiments

H.1 Organic Compounds

The bulk analyses of organic compounds for 16 excess foundry sands involved in the experimental investigation are presented in Table H-1. The analyses were performed by a third-party professional chemical laboratory using methods presented in EPA SW-846, "Test Methods For Evaluating Solid Waste Physical Chemical Methods."

H.2 Oxides

The bulk analyses of oxides for 16 excess foundry sands involved in the experimental investigation are presented in Table H-2. The analyses were performed by a third-party professional chemical laboratory using X-ray fluoresce method.

Table **H-1**: Organic compounds of excess foundry sands

		FS01	FS02	FS03	FS04	FS05	FS06	FS07	FS08	FS09	FS10	FS11	FS12	FS13	FS14	FS15	FS16
O-Cresol	Unit: mg/kg (dry)	.829	<.341	.716	1.27	26.8	<.363	.986	1.47	.514	<.357	3.20	1.97	.672	<.324	.366	2.64
M,P-Cresol		.550	<.341	<.392	1.33	15.6	<.363	.509	.666	<.368	<.357	1.05	.828	<.342	<.324	<.355	1.46
Cresol-Total		1.38	<.341	.716	2.60	42.4	<.363	1.50	2.14	.514	<.357	4.25	2.80	.672	<.324	.366	4.10
2,4-Dinitrotoluene		<.358	<.341	<.392	<.334	<.342	<.363	<.332	<.354	<.368	<.357	<.346	<.328	<.342	<.324	<.355	<.354
1,3-Hexachlorobutadiene		<.358	<.341	<.392	<.334	<.342	<.363	<.332	<.354	<.368	<.357	<.346	<.328	<.342	<.324	<.355	<.354
Hexachlorobenzene		<.358	<.341	<.392	<.334	<.342	<.363	<.332	<.354	<.368	<.357	<.346	<.328	<.342	<.324	<.355	<.354
Hexachloroethane		<.358	<.341	<.392	<.334	<.342	<.363	<.332	<.354	<.368	<.357	<.346	<.328	<.342	<.324	<.355	<.354
Nitrobenzene		<.358	<.341	<.392	<.334	<.342	<.363	<.332	<.354	<.368	<.357	<.346	<.328	<.342	<.324	<.355	<.354
Pentachlorophenol		<.358	<.341	<.392	<.334	<.342	<.363	<.332	<.354	<.368	<.357	<.346	<.328	<.342	<.324	<.355	<.354
Pyridine		<.358	<.341	<.392	<.334	<.342	<.363	<.332	<.354	<.368	<.357	<.346	<.328	<.342	<.324	<.355	<.354
2,4,5-trichlorophenol		<.358	<.341	<.392	<.334	<.342	<.363	<.332	<.354	<.368	<.357	<.346	<.328	<.342	<.324	<.355	<.354
2,4,6-trichlorophenol		<.358	<.341	<.392	<.334	<.342	<.363	<.332	<.354	<.368	<.357	<.346	<.328	<.342	<.324	<.355	<.354
Benzo(a)anthracene		<.358	<.341	<.392	<.334	<.342	<.363	<.332	<.354	<.368	<.357	<.346	<.328	<.342	<.324	<.355	<.354
Chrysene		<.358	<.341	<.392	<.334	<.342	<.363	<.332	<.354	<.368	<.357	<.346	<.328	<.342	<.324	<.355	<.354
2,4-Dimethylphenol		<.358	<.341	<.392	.602	8.81	<.363	<.332	<.354	<.368	<.357	1.89	<.328	4.14	<.324	<.355	<.354
Fluoranthene		<.358	<.341	<.392	.619	<.342	<.363	<.332	<.354	<.368	<.357	<.346	<.328	<.342	<.324	<.355	<.354
Phenanthrene		0.358	<.341	.596	2.11	1.29	<.363	.556	.686	.500	<.357	<.346	<.328	<.342	<.324	.399	<.354
Acetone	Unit: ug/kg (dry)	**33**	**49**	<10	**81**	**37**	**12**	**242**	**23**	**15**	<10	**16**	**247**	**11**	**57**	**10**	**740**
Benzene		<5	5	5	13	9	<5	9	<4	<4	<5	<5	<5	<4	<5	<5	32
Carbon Tetrachloride		<5	<5	<5	<5	<5	<5	<4	<4	<4	<5	<5	<5	<4	<5	<5	<5
Chlorobenzene		<5	<5	<5	<5	<5	<5	<4	<4	<4	<5	<5	<5	<4	<5	<5	<5
Chloroform		<5	<5	<5	<5	<5	<5	<4	<4	<4	<5	<5	<5	<4	<5	<5	<5
1,4-Dichlorobenzene		<5	<5	<5	<5	<5	<5	<4	<4	<4	<5	<5	<5	<4	<5	<5	<5
1,2-Dichloroethane		<5	<5	<5	<5	<5	<5	<4	<4	<4	<5	<5	<5	<4	<5	<5	<5
1,1-Dichloroethene		<5	<5	<5	<5	<5	<5	<4	<4	<4	<5	<5	<5	<4	<5	<5	<5
Ethyl benzene		<5	<5	<5	<5	<5	<5	<4	<4	<4	<5	<5	<5	<4	<5	<5	<5
Methyl ethyl ketone		<10	<10	<10	19	<9	<10	31	<9	<9	<10	<10	<9	<8	<10	<10	**146**
Methylene chloride		<5	<5	<5	7	<5	<5	<4	<4	5	<5	12	<5	<4	16	<5	11
Naphthalene		<10	<10	<10	10	<9	<10	<9	<9	<9	<10	<10	**89600**	**37700**	<10	<10	13
Styrene		<5	<5	<5	<5	<5	<5	<4	<4	<4	<5	<5	<5	<4	<5	<5	<5
Tetrachloroethene		<5	<5	<5	<5	<5	<5	<4	<4	<4	<5	<5	<5	<4	<5	<5	<5
Toluene		<5	<5	<5	11	<5	<5	4	<4	<4	<5	<5	<5	<4	<5	<5	19
1,1,1-Trichloroethane		<5	<5	<5	<5	<5	<5	<4	<4	<4	<5	<5	<5	<4	<5	<5	<5
Trichloroethene		<5	<5	<5	<5	<5	<5	<4	<4	<4	<5	<5	<5	<4	<5	<5	<5
Vinyl chloride		<10	<10	<10	<9	<9	<10	<9	<9	<9	<10	<10	<9	<8	<10	<10	<10
M, P-Xylene		<5	<5	<5	6	<5	<5	<4	<4	<4	<5	<5	<5	<4	<5	<5	8
Xylene-total		<5	<5	<5	6	<5	<5	<4	<4	<4	<5	<5	<5	<4	<5	<5	8

Table **H-2**: Oxides of excess foundry sands

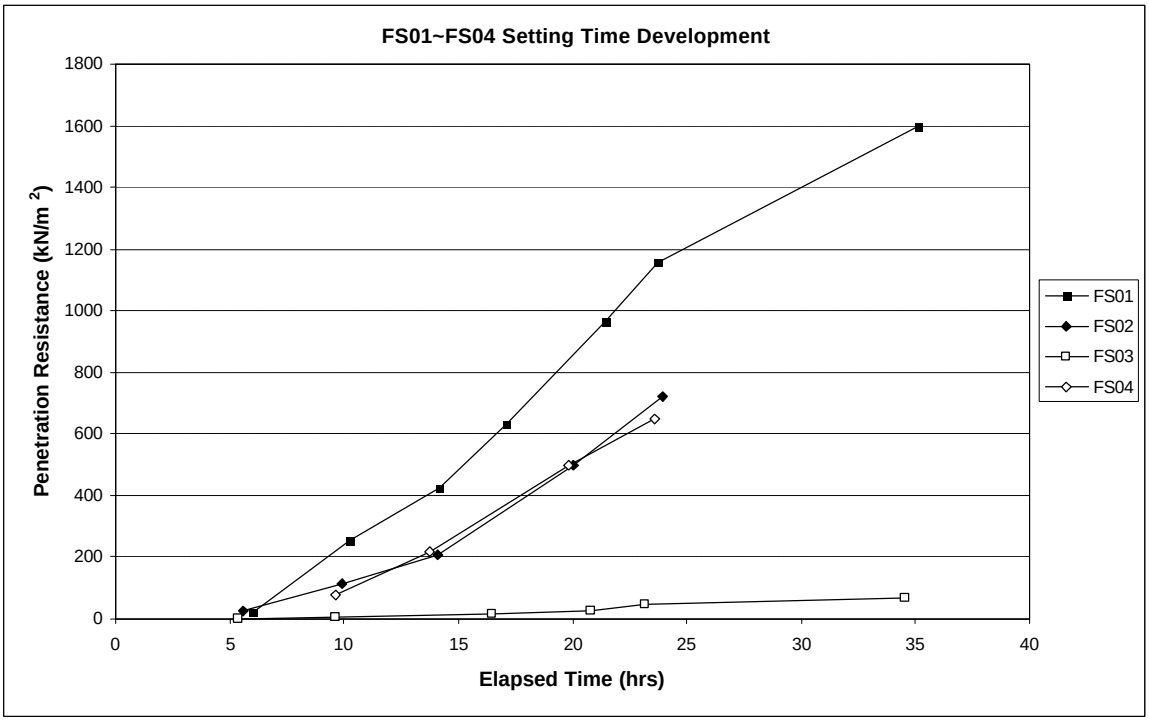
		FS01	FS02	FS03	FS04	FS05	FS06	FS07	FS08	FS09	FS10	FS11	FS12	FS13	FS14	FS15	FS16
Na_2O	Unit: % by weight	.28	<.009	<.009	.28	<.009	2.11	.19	.14	.21	<.009	.05	<.009	<.009	.20	.01	.32
MgO		.89	.09	.38	.49	.52	<.003	.60	.91	<.003	**2.32**	.33	<.003	<.003	**2.08**	.50	.62
Al_2O_3		6.54	1.19	5.30	6.41	4.17	4.28	5.22	6.96	3.08	.17	3.80	.30	.68	3.25	5.05	5.88
SiO_2		84.1	92.0	86.5	85.0	88.9	87.0	88.4	83.1	92.1	90.5	91.9	98.0	96.9	**64.8**	83.1	86.0
P_2O_5		.03	.02	.03	.06	.03	.04	.04	.04	.04	.01	.06	.02	.03	<.001	.04	.05
SO_3		.23	.57	.22	.19	.19	<.001	.21	.28	.06	**3.00**	.11	<.001	<.001	.89	.33	.10
K_2O		.84	.17	.24	.86	.14	2.13	.93	.83	1.18	<.001	1.02	<.001	.54	.30	.18	.23
CaO		.91	<.001	.17	.49	.35	.74	.52	.55	.38	**2.72**	.41	<.001	<.001	**21.8**	.32	.73
TiO_2		.07	.05	.07	.13	.06	.11	.04	.07	.04	<.001	.04	<.001	.08	.12	1.61	.04
Cr_2O_3		.02	1.99	.02	.02	.02	.02	.02	.02	.02	.03	.02	.02	.02	.02	.02	.06
MnO		.02	.04	.02	.03	.02	.03	.02	.04	.02	.01	.02	.01	.02	.04	.03	.03
Fe_2O_3		2.01	1.61	1.15	2.01	1.08	1.24	1.06	1.95	1.00	.37	.87	.29	0.50	1.22	1.82	3.12
C		4	2.2	5.9	4.0	4.5	2.3	2.7	5.1	1.8	.9	1.4	1.4	1.2	2.2	7.0	2.8
CuO		---	---	---	---	---	---	---	---	---	---	---	---	---	.36	---	---
ZnO		---	---	---	---	---	---	---	---	---	---	---	---	---	2.44	---	---
PbO		---	---	---	---	---	---	---	---	---	---	---	---	---	.24	---	---

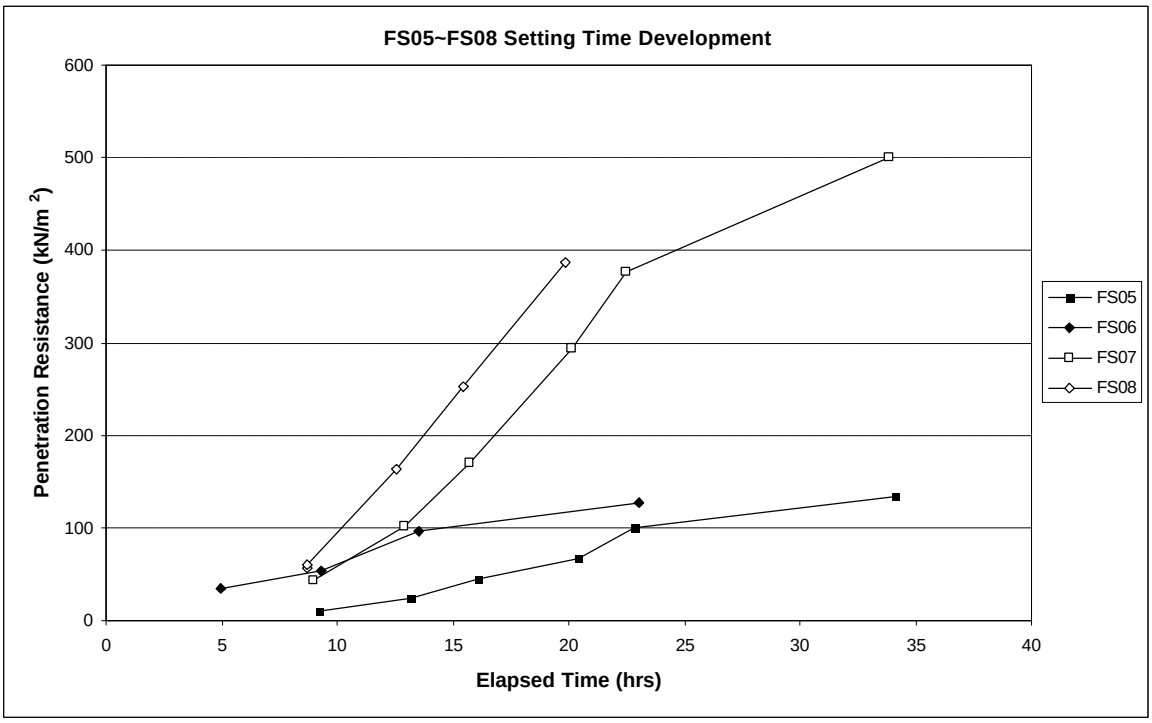
Appendix I

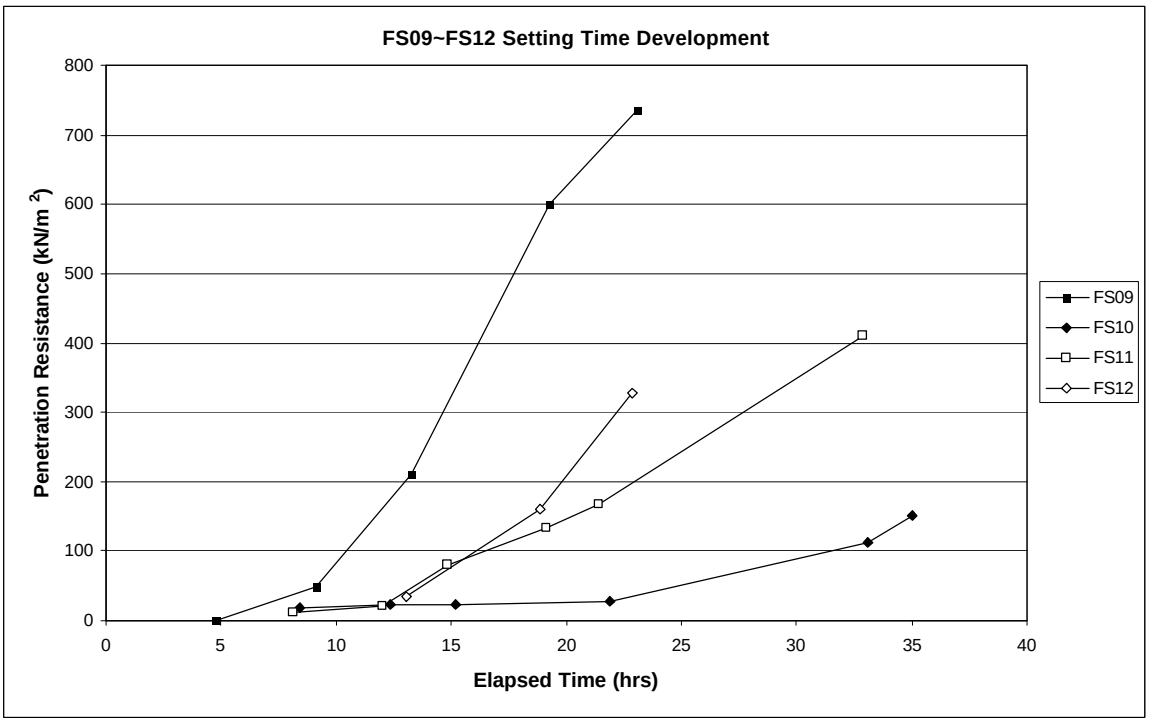
Setting Time and Penetration Resistance for CLSM

I.1 Excavatable CLSM

The charts of setting time versus penetration resistance for excavatable CLSM phase I and II are presented in Figure I-1 (4 charts) and Figure I-2 (2 charts), respectively.




FS05~FS08 Setting Time Development
Penetration Resistance (kN/m 2)
Elapsed Time (hrs)
0
100
200
300
400
500
600
0
5
10
15
20
25
30
35
40
FS05
FS06
FS07
FS08


FS09~FS12 Setting Time Development
Penetration Resistance (kN/m 2)
Elapsed Time (hrs)
0
100
200
300
400
500
600
700
800
0
5
10
15
20
25
30
35
40
FS09
FS10
FS11
FS12

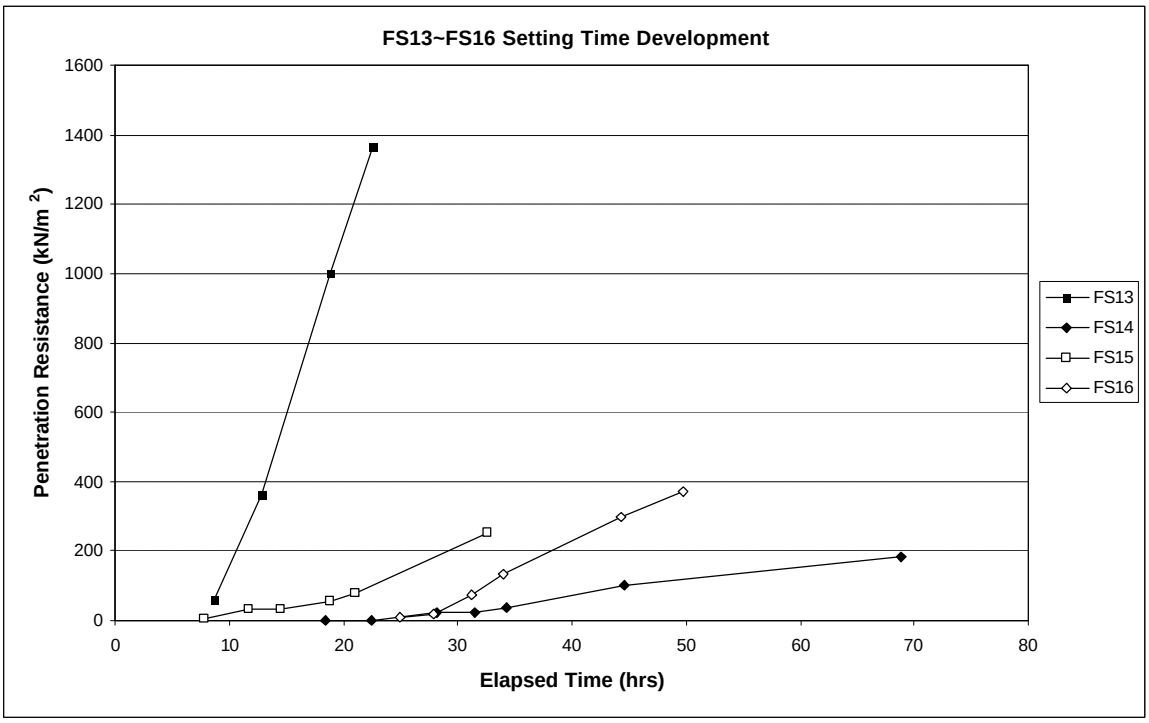
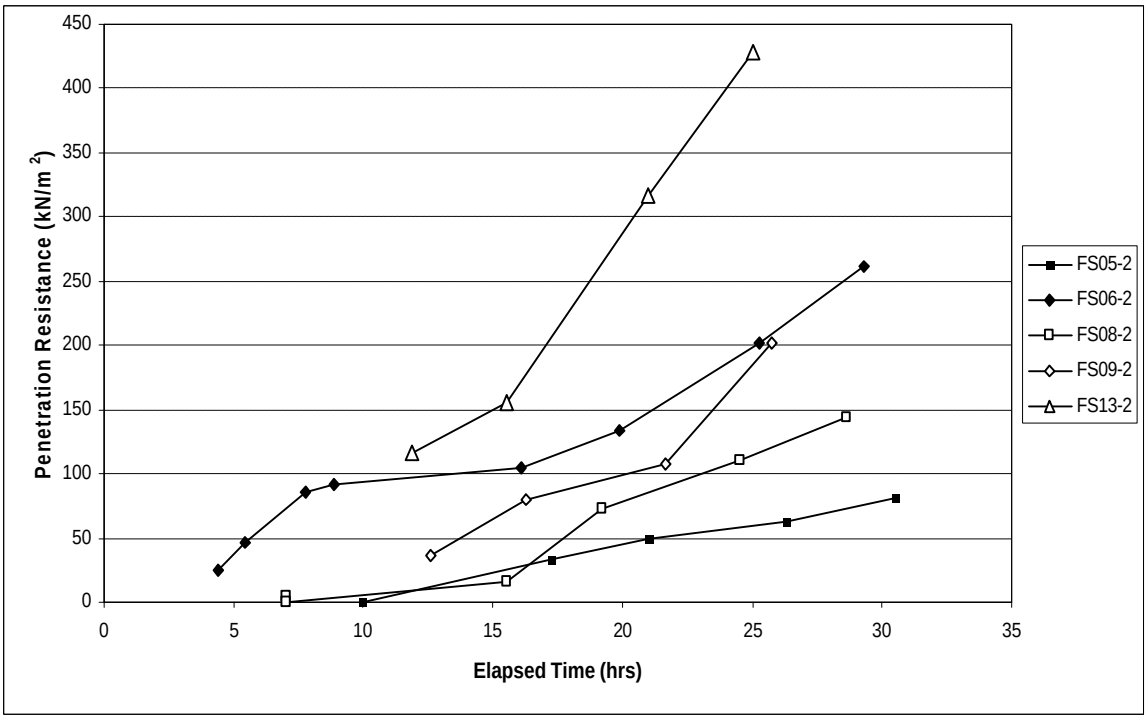


Figure **I-1**: Setting time of excavatable CLSM phase I (4 charts)



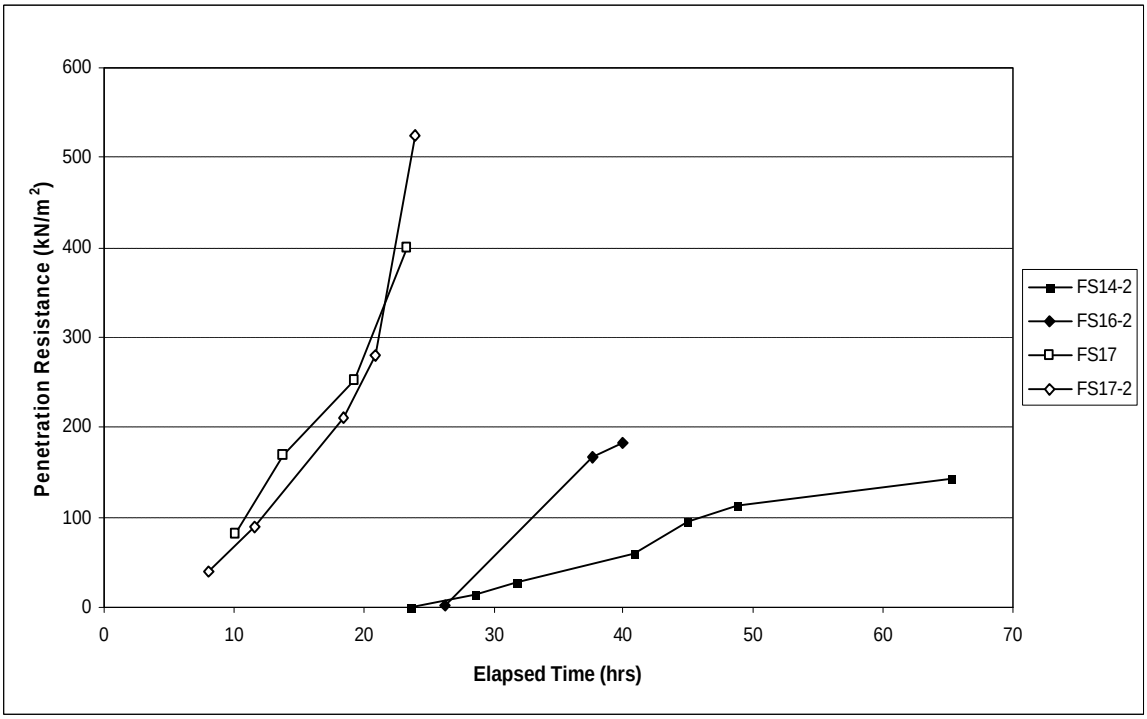
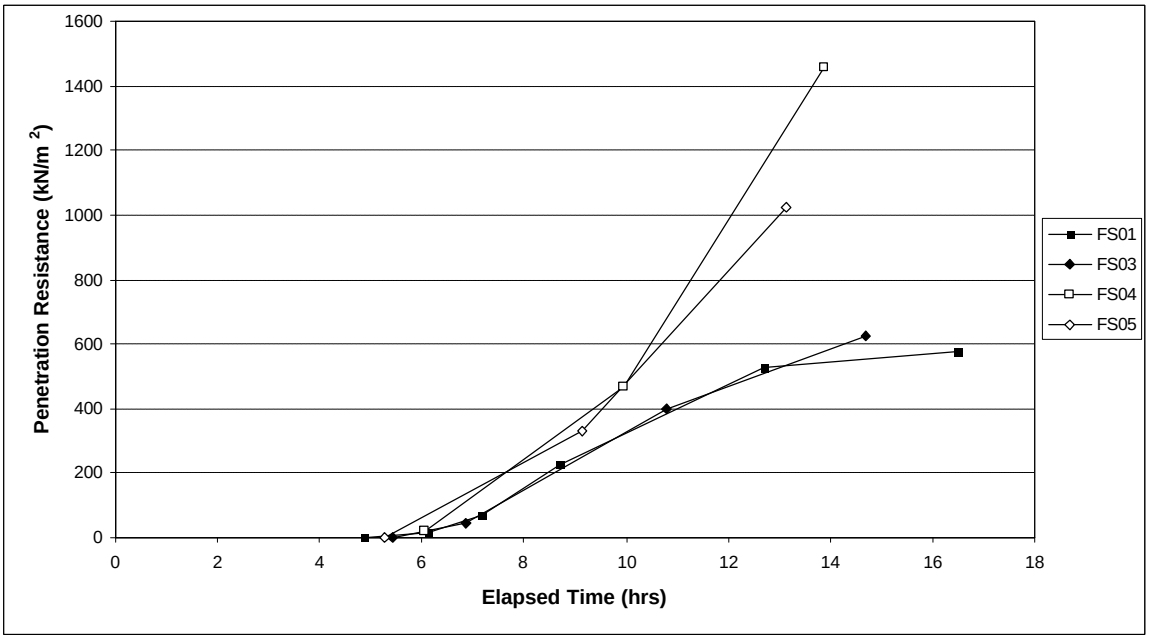
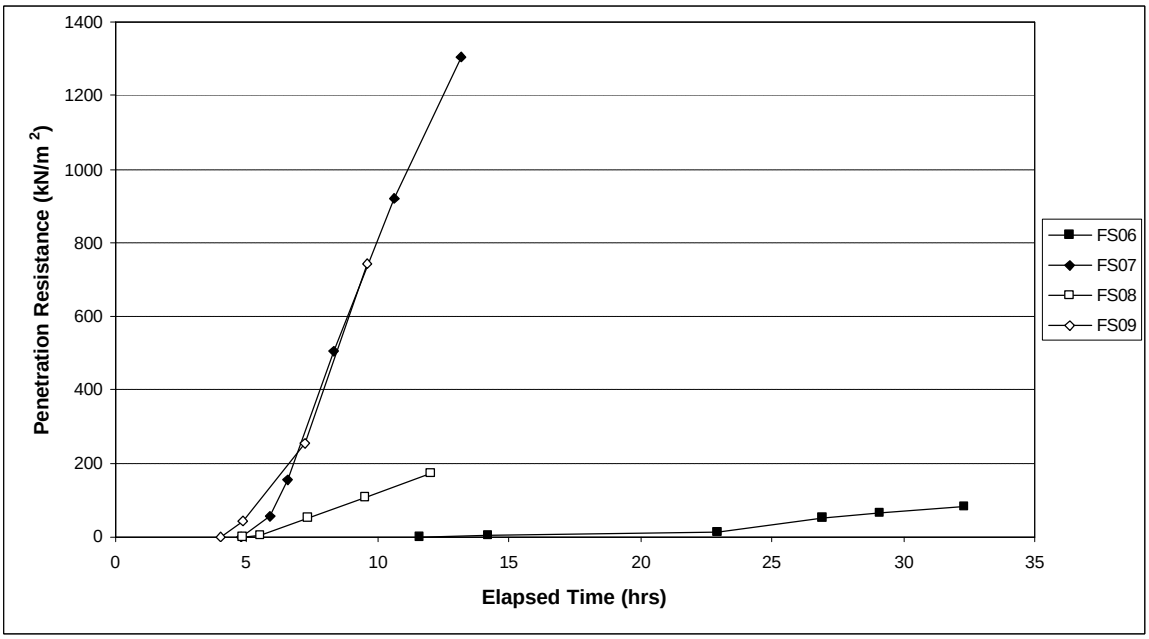


Figure **I-2**: Setting time of excavatable CLSM phase II (2 charts)

I.2 Structural CLSM

The charts of setting time versus penetration resistance for structural CLSM are presented in Figure I-3 (3 charts).


Penetration Resistance (kN/m 2)
Elapsed Time (hrs)
FS01
FS03
FS04
FS05


Penetration Resistance (kN/m 2)
Elapsed Time (hrs)
FS06
FS07
FS08
FS09

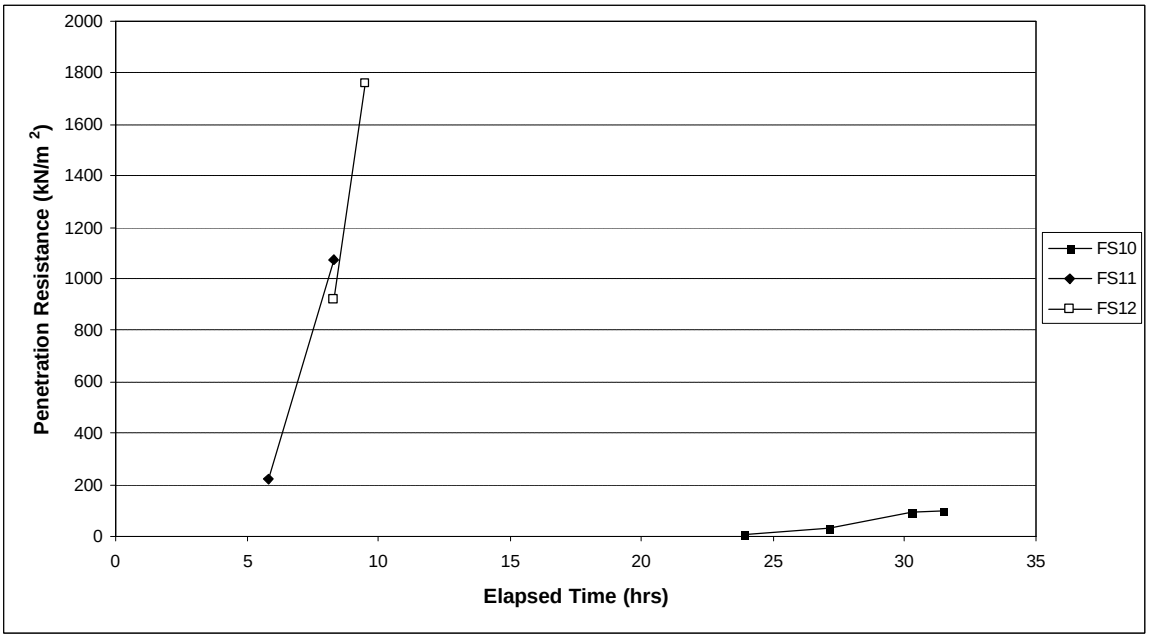


Figure **I-3**: Setting time of structural CLSM (3 charts)

Appendix J

Proof of Mean

J.1 Proof of Mean

In this appendix, the proof that the mean of a nonnegative random variable is equal to the area under the corresponding survival function is presented. Visualized aid of demonstrated survival function is presented in Figure J-1.

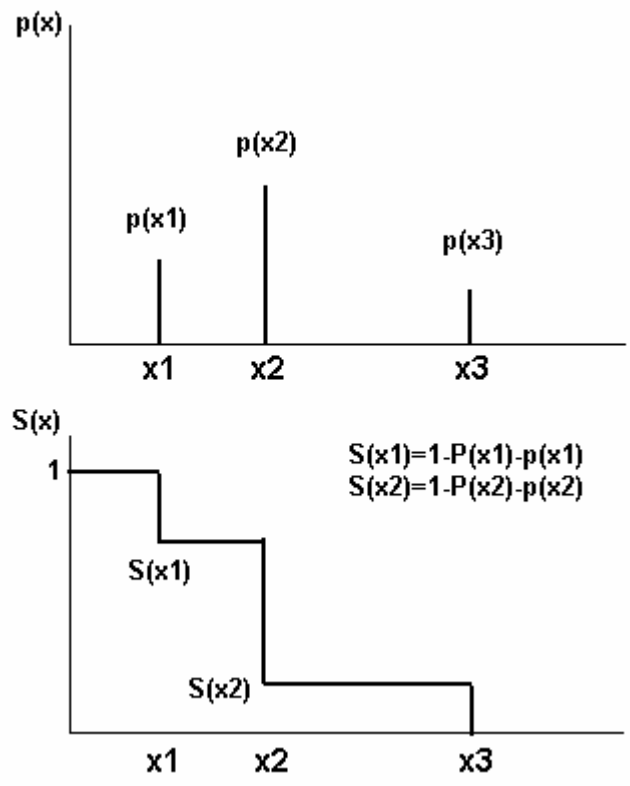


Figure **J-1**: Demonstration of probability function and survival function

$$\int_0^{x_n} S(\mathrm{x})\mathrm{dx} = \int_0^{x_1} S(\mathrm{x})\mathrm{dx} + \int_{x_1}^{x_2} S(\mathrm{x})\mathrm{dx} + \int_{x_2}^{x_3} S(\mathrm{x})\mathrm{dx} + \ldots\ldots + \int_{x_{n-2}}^{x_{n-1}} S(\mathrm{x})\mathrm{dx} + \int_{x_{n-1}}^{x_n} S(\mathrm{x})\mathrm{dx}$$

$$= \int_0^{x_1} 1\mathrm{dx} + \int_{x_1}^{x_2} S(\mathrm{x}_1)\mathrm{dx} + \int_{x_2}^{x_3} S(\mathrm{x}_2)\mathrm{dx} + \ldots\ldots + \int_{x_{n-2}}^{x_{n-1}} S(\mathrm{x}_{\text{n-2}})\mathrm{dx} + \int_{x_{n-1}}^{x_n} S(\mathrm{x}_{\text{n-1}})\mathrm{dx}$$

$$= \mathrm{x}_1 + S(\mathrm{x}_1)(\mathrm{x}_2 - \mathrm{x}_1) + S(\mathrm{x}_2)(\mathrm{x}_3 - \mathrm{x}_2) + \ldots\ldots$$

$$+ S(\mathrm{x}_{\text{n-2}})(\mathrm{x}_{\text{n-2}} - \mathrm{x}_{\text{n-1}}) + S(\mathrm{x}_{\text{n-1}})(\mathrm{x}_{\text{n}} - \mathrm{x}_{\text{n-1}})$$

$$= \mathrm{x}_1 + [1 - P(\mathrm{x}_1)](\mathrm{x}_2 - \mathrm{x}_1) + [1 - P(\mathrm{x}_2)](\mathrm{x}_3 - \mathrm{x}_2) + \ldots\ldots$$

$$+ [1 - P(\mathrm{x}_{\text{n-2}})](\mathrm{x}_{\text{n-1}} - \mathrm{x}_{\text{n-2}}) + [1 - P(\mathrm{x}_{\text{n-1}})](\mathrm{x}_{\text{n}} - \mathrm{x}_{\text{n-1}})$$

$$= \mathrm{x}_1 + [\mathrm{x}_2 - \mathrm{x}_1 - P(\mathrm{x}_1)(\mathrm{x}_2) + P(\mathrm{x}_1)(\mathrm{x}_1)] + [\mathrm{x}_3 - \mathrm{x}_2 - P(\mathrm{x}_2)(\mathrm{x}_3) + P(\mathrm{x}_2)(\mathrm{x}_2)]$$

$$+ \ldots\ldots\ [\mathrm{x}_{\text{n-1}} - \mathrm{x}_{\text{n-2}} - P(\mathrm{x}_{\text{n-2}})(\mathrm{x}_{\text{n-1}}) + P(\mathrm{x}_{\text{n-2}})(\mathrm{x}_{\text{n-2}})] +$$

$$[\mathrm{x}_{\text{n}} - \mathrm{x}_{\text{n-1}} - P(\mathrm{x}_{\text{n-1}})(\mathrm{x}_{\text{n}}) + P(\mathrm{x}_{\text{n-1}})(\mathrm{x}_{\text{n-1}})]$$

$$= p(\mathrm{x}_1)(\mathrm{x}_1) + p(\mathrm{x}_2)(\mathrm{x}_2) + \ldots\ldots + p(\mathrm{x}_{\text{n-1}})(\mathrm{x}_{\text{n-1}}) + \mathrm{x}_{\text{n}} - S(\mathrm{x}_{\text{n-1}})(\mathrm{x}_{\text{n}})$$

$$= p(\mathrm{x}_1)(\mathrm{x}_1) + p(\mathrm{x}_2)(\mathrm{x}_2) + \ldots\ldots + p(\mathrm{x}_{\text{n-1}})(\mathrm{x}_{\text{n-1}}) + p(\mathrm{x}_{\text{n}})\mathrm{x}_{\text{n}}$$

$$= \hat{m}$$

where, $\mathrm{x}_1, \mathrm{x}_2, \ldots\ldots, \mathrm{x}_{\text{n}} = \text{observations}$

$S(\mathrm{x}) = \text{survival function}$

$P(\mathrm{x}) = \text{cumulative distribution function}$

$p(\mathrm{x}) = \text{probability function}$

$\hat{m} = \text{estimated population mean}$

Appendix K

Flow Chart of Procedure for CLSM

K.1 Characterization of Foundry Waste Streams

The flow chart for characterization of foundry waste streams is presented in Figure K-1.

K.2 Experimental Investigation of CLSM

The flow chart for experimental investigation of CLSM containing excess foundry sand is presented in Figure K-2.

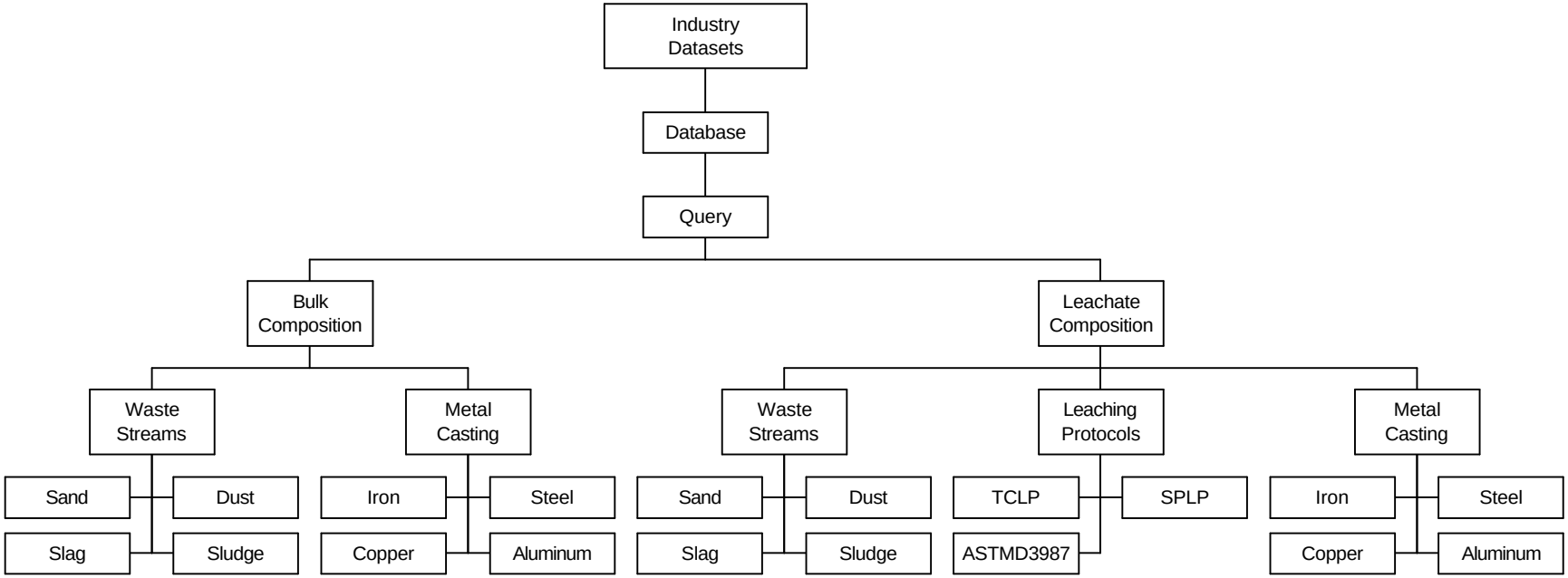


Figure **K-1**: Flow chart for characterization of foundry waste streams

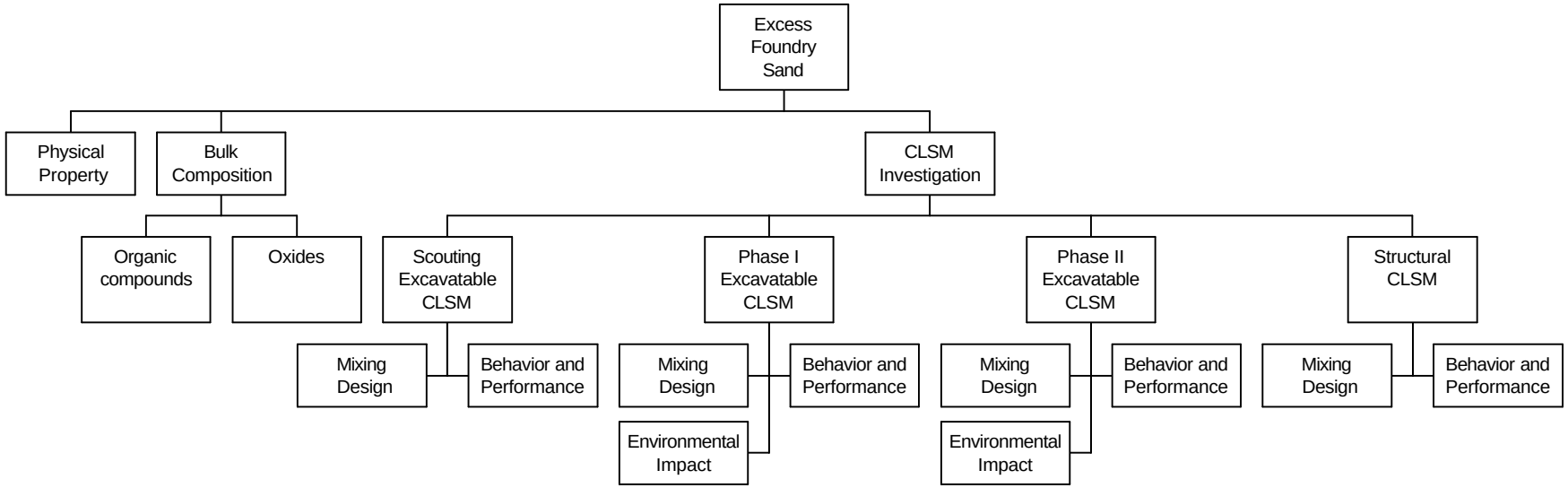


Figure **K-2**: Flow chart for experimental investigation of CLSM

Appendix L

Standard Specification for Excess Foundry Sand for Use in Controlled Low-Strength Material (CLSM)

1. Scope

1.1 This specification covers the requirements for excess foundry sand used as a fine aggregate in controlled low-strength material (CLSM).

1.2 The specification is for use by contractor, excess foundry sand or CLSM supplier, or other purchaser as part of the purchase document describing the material to be furnished. Those responsible for selecting the proportions for the CLSM mixture shall have the responsibility of determining the proportions of excess foundry sand as a fine aggregate.

1.3 The values stated in SI units are to be regarded as the standard. The values given in parentheses are for information only.

1.4 The text of this standard references notes and footnotes which provide explanatory information. These notes and footnotes (excluding those in tables and figures) shall not be considered as requirements of this standard.

2. Referenced Documents

2.1 ASTM Standards

C 88 Test Method for Soundness of Aggregates by Use of Sodium Sulfate or Magnesium Sulfate[1]

C 117 Standard Test Method for Materials Finer than 75-µm (No. 200) Sieve in Mineral Aggregates by Washing[2]

C 125 Standard Terminology Relating to Concrete and Concrete Aggregates[2]

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[1] Annual Book of ASTM Standards, Vol 04.02, available from the ASTM, 100 Barr Harbor Drive, West Conshocken, PA 19428-2959

C 128 Standard Test Method for Density, Relative Density (Specific Gravity), and Absorption of Fine Aggregate[2]

C 566 Standard Test Method for Total Evaporable Moisture Content of Aggregate by Drying[3]

D 75 Standard Practice for Sampling Aggregates[3]

D 653 Standard Terminology Relating to Soil, Rock, and Contained Fluids[3]

D 3665 Standard Practice for Random Sampling of Construction Materials[4]

2.2 Federal Registrar

SW846 1312 EPA Test Method, Synthetic Precipitation Leaching Procedure (SPLP)[4]

SW846 7.3.3 EPA Test Method, Interim Guidance For Reactive Cyanide[5]

SW846 7.3.4 EPA Test Method, Interim Guidance For Reactive Sulfide[5]

SW846 9045 EPA Test Method, Soil And Waste pH[5]

2.3 AFS Mold & Core Test Handbook:

AFS 1105-00-S Sieve Analysis (Particle Size Determination of Sand)[5]

AFS 1106-00-S Grain Fineness Number (GFN)[6]

AFS 1107-00-S Grain Shape Classfication[6]

AFS 1116-00-S Specific Gravity of Sand[6]

3. Terminology

3.1 foundry sand — a fine aggregate to produce mold or core in foundry facilities, which is used to cast ferrous and non-ferrous metals, consisting mostly silica sand, sometime lake sand, olivine sand, and zircon sand.

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[2] Annual Book of ASTM Standards, Vol 04.02, available from the ASTM, 100 Barr Harbor Drive, West Conshocken, PA 19428-2959

[3] Annual Book of ASTM Standards, Vol 04.03, available from the ASTM, 100 Barr Harbor Drive, West Conshocken, PA 19428-2959

[4] EPA SW-846: Test Methods for Evaluating Solid Wastes-Physical/Chemical Methods, available from the Department of Commerce, National Technical Information Center, 5285 Port Royal Road, Springfield, VA 22161. Tel: (800) 553-NTIS (553-6847)

[5] AFS Mold & Core Test Handbook, available from American Foundry Society, 505 State Street Des Plaines, Illinois 60016-8399

3.2 excess foundry sand — excess foundry sand is disposed after several cycles of reclamation when a typical foundry facility wants to maintain the casting quality and removes those less servable foundry sand.

3.3 environmental stability — foundry sand shall be evaluated for environmental consideration (air quality, water quality, and storage) using the required local, state, and federal test methods in effect at the time of use.

3.4 Other definitions of terms used in this standard, refer to ASTM C 125, ASTM D 653, AFS Mold & Core Test Handbook, and EPA SW-846: Test Methods for Evaluating Solid Wastes-Physical/Chemical Methods.

4. Ordering Information

4.1 Order for the material under this specification shall include the following information:

4.1.1 Quantity, in metric tons,

4.1.2 Whether the soundness of the material in 6.7.2 is required. If it is applied, which salt is to be used. If none is stated, either sodium sulfate or magnesium sulfate shall be used,

4.1.4 Any exceptions or additions to this specification.

5. General Characteristics

5.1 The foundry sand shall consist of hard, tough, durable pieces of fine aggregates. The aggregates shall be processed, as necessary to meet the requirements of this specification, by crushing and or screening, and magnetic separation for the removal of metallics.

5.2 The foundry sand shall be free of potential waste streams in foundry facilities: slag, dust, sludge, and other waste streams.

5.3 At the time of delivery, the foundry sand shall be free of injurious amounts of foreign materials such as clay, loams, wood, tramp metal, hard cores and other mill wastes.

6. Physical Requirements

6.1 The grading of the foundry sand shall conform to the requirements for grading.

Sieve	Percentage Passing by Weight
3.35-mm (No. 6)	97 to 100 [A]
1.7-mm (No. 12)	92 to 100
850- m (No. 20)	90 to 100
425- m (No. 40)	65 to 99
300- m (No. 50)	23 to 97
212- m (No. 70)	12 to 73
150- m (No. 100)	1 to 33
106- m (No. 140)	0.5 to 15
75- m (No. 200)	0 to 2 [B]
53- m (No. 270)	0 to 0.5

Grain Fineness Number [C]: 45 - 75

Note: [A] Exercise care to avoid sand agglomerations, hard core, and other mill wastes.
[B] Too much clay or dust content interferes the strength development of CLSM.
[C] Grain fineness number indicates the grain size distribution is fine moderately to enhance the flowability and self-compaction of CLSM.

6.2 The maximum percentage by weight of particle finer than 75- m (No. 200) sieve by washing is 15%.

6.3 The major (>50%) grain shape of foundry sand particles is subangular to round to facilitate the flowability and self-compaction of CLSM.

6.4 The bulk specific gravity of foundry sand applied to CLSM is recommended between 2.4 and 2.7. Too low or too high specific gravity interferes the flowability and strength controlling of CLSM.

6.5 Foundry sand failing to meet 6.1-6.4 shall meet the requirements of relevant properties provided that the supplier can demonstrate to the purchaser or specifier that CLSM of the class specified, made with foundry sand under consideration, will have relevant properties at least equal to those of CLSM made with the same ingredients, with the exception that the reference foundry sand shall be selected from a source having an acceptable performance record in similar CLSM construction.

6.6 The maximum evaporable moisture content of the foundry sand shall be 5% to ensure the uniformly blending of raw materials prior to water addition.

6.7 Optional physical requirements.

6.7.1 The optional physical requirements apply to non-excavatable CLSM or are applied at the request of the purchaser.

6.7.2 Soundness: except as provided in 6.7.3 and 6.7.4, foundry sand subject to five cycles of the soundness test shall have a weighted average loss not greater than 15% when sodium sulfate is used or 20% when magnesium sulfate is used.

6.7.3 Foundry sand failing to meet the requirements of 6.7.2 shall be regarded as meeting the requirements of soundness provided that the supplier demonstrates to the purchaser or specifier that CLSM of comparable properties, made from similar foundry sand from the same source, has given satisfactory service when exposed to weathering similar to that to be encountered.

6.7.4 Foundry sand not having a demonstrable service record and failing to meet the requirements of 6.7.2 shall be regarded as meeting the requirements of soundness provided that the supplier demonstrates to the purchaser or specifier it gives satisfactory results in CLSM subjected to freezing and thawing tests.

7. Chemical Composition Requirements

7.1 Excess foundry sand contains less than 3% CaO by its bulk composition.

8. Environmental Requirements

8.1 Excess foundry sand from bronze/brass foundry is not recommended for the application of CLSM.

8.2 The foundry sand shall meet all applicable local, state, and federal environmental requirements in effect following testing program in 8.3 and 8.4.

8.2.1 Toxicity: the characteristics of leachate from the foundry sand shall be tested using the SPLP or appropriate test method as approved by the purchaser. Results shall indicate that all areas tested (inorganic chemicals and organic chemicals) are below regulatory limits.

8.2.2 Reactivity: the amount of reactive cyanide and reactive sulfide in the foundry sand shall be tested using Interim Guidance For Reactive Cyanide (EPA Method SW846 7.3.3) and Interim Guidance For Reactive Sulfide (EPA Method SW846 7.3.4)

respectively. Results shall be below regulatory limits: 250 mg HCN/kg waste, and 500 mg HS/kg waste.

8.2.3 Corrosivity: the pH of foundry sand shall be tested using Soil And Waste pH (EPA Method SW846 9045) or appropriate test method as approved by the purchaser. Result shall indicate that the pH is between 2 and 12.5.

8.3 For an individual excess sand source, only if its metals cast, binder systems employed, and waste streams are not changed, hazardous evaluation testing is applied each month for three months, and annually thereafter.

8.4 In each testing, no less than 3 tests out of every 1000 yd^3 per sand source are required. If the yield is less than 1000 yd^3 per sand source, no less than 3 tests are required per sand source.

9. Sampling and Testing Methods

9.1 Sample and test the foundry sand in accordance with the following methods, except as otherwise provided in this specification. It is not intended to prohibit use of separated sizes from the sieve analysis for preparation of samples for soundness test. For determination of all other testes and for evaluation of potential alkali reactivity where required, use independent test specimens.

9.2 Sampling — ASTM D75 and ASTM D 3665.

9.3 Grading and GFN — AFS 1105-00-S and AFS 1106-00-S

9.4 Particles Finer Than 75 - m (No. 200) Sieve by Washing — ASTM C 117

9.5 Grain Shape — AFS 1107-00-S

9.6 Evaporable Moisture Content — ASTM C566

9.7 Specific Gravity — AFS 1116-00-S or ASTM C 128

9.8 Soundness — ASTM C 88

9.9 Reactivity — ASTM G 57

9.10 Toxicity — EPA Test method SW846 1312

9.11 Reactivity — EPA Test method SW846 7.3.3 and 7.3.4

9.12 Corrosivity — EPA Test Method SW846 9045

10. Rejection and Rehearing

10.1 The purchaser has the right to reject material that fails to conform to the requirements of this specification. Rejection shall be reported to the producer or supplier promptly and in writing. In case of dissatisfaction with the results of the tests, the producer or supplier is not prohibited from making a claim for retesting.

11. Certification

11.1 When specified in the purchase order or contract, the purchaser shall be furnished certification that samples representing each lot have been tested as directed in this specification and the specified requirements have been met. When specified in the purchase order or contract, a report of the test results shall be furnished.

12. Manufacture's Statement

12.1 At the request of the purchaser, the manufacture shall state in writing the nature of the foundry sand, including metal cast, the material mineral type, the cast processing type (mold or core), the binder materials and the binding methods. The amount and any processing to foundry sand shall be furnished as the request of purchaser.

13. Package Marking and Shipping Information

13.1 When the foundry sand is delivered in package, the name and the brand of the manufacturer, the weight of the foundry sand contained therein shall be plainly marked on each package. Similar information shall be provided in the shipping invoices accompanying the shipment of packaged or bulk foundry sand. All packages shall be in good condition at the time of inspection.

14. Keywords

14.1 CLSM; environmental stability; fine aggregate; foundry sand

National Solid Wastes Management Association

June 20, 2013

Re: Beneficial Use Conceptual Draft Rule Language

Michelle Braun
Ohio Environmental Protection Agency
P.O. Box 1049
Columbus, Ohio 43216-1049

Dear Ms. Braun:

The Ohio Chapter of the National Solid Wastes Management Association (NSWMA) is pleased to provide comments on the Conceptual Draft Rule Language for the Beneficial Use of waste materials.

At this time, please consider our comments preliminary in nature. While we appreciate the time and effort that the staff of the Ohio EPA has put into the development of the Draft Rule Language, it is clear that this is really a conceptual document and there are many issues yet to be resolved and questions to be answered. We are fully aware that the staff of the Ohio EPA realizes this and do not mean this comment to minimize the time and effort that has been put into this project thus far.

Having noted that, in general we find the approach being proposed by the Ohio EPA to be a sound approach. As waste management professionals, we recognize that there are some waste streams that can and should be beneficially reused. We also recognize that not all proposed beneficial uses are environmentally sound. We acknowledge that some proposed beneficial re-uses such as the use of fly ash in the production of cement are well understood and due to the nature of cement production do not warrant the level of review that other proposed beneficial uses might warrant.

We believe that the three-tiered approach, i.e. pre-approved uses, general permits and waste specific permits is a sound approach. We do however; encourage the Ohio EPA to proceed cautiously in deciding how the various wastes fit into these categories. While many generators understand what types of wastes they are generating we have found that others do not have a good grasp on the constituents that are potentially in their wastes and the potential environmental harm if they are not managed properly.

We support the concept of requiring waste analysis plans for candidate waste streams. As you know, as an industry we pre-qualify the non-MSW wastes that we receive and manage. Clearly, it is appropriate to require detailed waste analysis if a waste is going to be removed from the classification of a waste and allowed to be re-used. Again, we can tell you from experience that there in fact may be surprises when wastes are subjected to a waste analysis program and wastes and their constituents can change over time.

115 E. Ogden Avenue, Suite 117-313, Naperville, IL 60563
800-679-6269 630-848-1101 630-848-1102 fx
www.nswma.org

We believe that this program appears to be on the right track. There are many questions and issues still to be resolved such as what will be the standards for a waste to be excluded from the definition of a waste. We look forward to working with you as this project proceeds.

Sincerely,

Kathy Trent

Kathy Trent
Chair, Ohio Chapter NSWMA

Cc: Dan Harris, OEPA

115 E. Ogden Avenue, Suite 117-313, Naperville, IL 60563
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June 6, 2013

Ms. Michelle Braun, R.S.
Solid Waste Rules Coordinator
Ohio EPA - Division of Materials and Waste Management
P.O. Box 1049
Columbus, Ohio 43216-1049

Re: Beneficial Use Conceptual Draft

Dear Ms. Braun:

The Ohio Ready Mixed Concrete Association has reviewed the conceptual draft of the planned Beneficial Use rules dated May 24, 2013 and our comments are presented below. We are submitting these comments in writing as we will not be able to attend the meeting scheduled for June 12.

We are in favor of the exclusion for the use of "select waste" in cement concrete products. We also recommend the definition of “Cement concrete” included in 3745-599-02(C)(2)(c) be modified to read “Chemical admixtures and fibers”. Fibers are typically manufactured of nylon, polypropylene, steel or fiberglass and are used to control cracking.

Returned concrete and associated materials generated at a ready mixed concrete plant that cannot be reused in the manufacturing of cement concrete products are processed and reused as construction aggregates or are used as fill material meeting the definition of “clean hard fill” per OAC 3745-400-01(E). It appears these materials will be exempt from regulation under the proposed Beneficial Use rules and we would like to receive confirmation in writing that this is the case.

Thank you for your assistance with this matter and please contact the writer at (614) 891-0210 or greg@ohioconcrete.org or Curt Spence, P.E. with Spence Environmental Consulting, Inc. at (614) 837-4750 or curt@spenceenv.com.

Respectfully Submitted,
Ohio Ready Mixed Concrete Association

Greg Colvin
President and Executive Director

June 28, 2013

(via email michelle.braun@epa.ohio.gov)

Michelle Braun
Post Office Box 1049
Columbus, Ohio 43216-1049

Re: Comments from the Ohio Manufacturers' Association to Ohio EPA Beneficial Use Regulatory Program Development (May 2013)

Dear Ms. Braun:

The Ohio Manufacturers' Association (OMA) is hereby providing its written comments to Ohio EPA's May 2013 "Early Stakeholder Outreach – Beneficial Use Regulatory Program Development" rule package and concept. OMA is dedicated to protecting and growing manufacturing in Ohio, and for more than 100 years, has supported reasonable, necessary, and transparent environmental regulations promoting the health and well-being of Ohio's citizens.

The OMA, as a trade organization representing over 1,000 manufacturers throughout Ohio, appreciates Ohio EPA's efforts in tackling the issue of regulating and authorizing the beneficial use of high volume, low toxicity waste materials. Certain members of the OMA and certain industries within the general manufacturing sector may have unique concerns with this rulemaking effort, and as a result, these comments, on behalf of the OMA in general, are being provided in a broader context allowing others to weigh in with specific concerns unique to their respective manufacturing processes.

In summary, the challenge we[1] all face with these rules is how to develop a regulatory framework that encourages beneficial use of waste-like products while still maintaining adequate protection to the environment and human health. The OMA would like to emphasize the "encouragement" portion of this process. If the rules or requirements are too demanding or too complicated, they will have no "beneficial" use. So, for starters, OMA would like to caution Ohio EPA from over-complicating the issue. As currently drafted, the rule package includes some fairly stringent obligations and requirements that do not readily appear to be necessary, either for Ohio EPA or for the protection of the environment. If the requirements are too onerous without any corresponding purpose or benefit, there will be a disincentive for business to participate in the program, thereby defeating the purpose of the rule package, which is to encourage the beneficial use of industrial by-products in a safe and economical manner.

[1] These rules should not only benefit the regulated community but are also in the best interests of Ohio EPA and the citizens of Ohio because they should encourage further reuse of valuable resources.

A. Framework

The OMA suggests that the general framework be re-evaluated starting with what materials are subject to further regulation. Only "wastes" should be regulated. Ohio Rev. Code § 3734.01(E) defines "solid waste" as "unwanted" residual solid or semisolid material resulting from industrial, commercial, agricultural and community operations with specific exclusions, including nontoxic fly ash and bottom ash, spent nontoxic foundry sand, and slag. If a material or by-product is not "unwanted," it is not a waste. While Ohio EPA has previously indicated that the term "unwanted" is viewed from the perspective of the generator, even this limited interpretation means that if a generator "wants" the material or by-product, it is not a waste.

Therefore, if a material or by-product is sold in a commercially reasonable manner for value (e.g., slag), it is not "unwanted" by the generator, and should not be subject to further regulation under O.R.C. Chapter 3734 or O.R.C. Chapter 6111. There is no need to regulate the further disposition or use of such valuable material or by-product.

The beneficial use rules should only apply to true "wastes" to encourage their reuse in a constructive manner so as to avoid the costly and environmentally harmful landfilling of such waste streams. Even under Ohio EPA's interpretation, if a material or by-product is "unwanted" by the generator, the beneficial use of such material should still be allowed and encouraged to promote the "3 R's" (reduce, reuse, recycle), an underpinning of Ohio EPA's solid waste program.

B. Draft Rules

OMA strongly encourages Ohio EPA to drop the description of "select waste." The mere fact that these materials are going to be "beneficially used" takes them outside of the "waste" context. We suggest that the program be based on the reuse of "industrial by-products."

1. Exclusions

The program is currently set up to include three tiers, the first of which is pre-approved beneficial uses. We suggest that a new category (perhaps a Tier 0?) be incorporated into the rule package to clarify that certain industrial by-products are not "wastes" and are therefore exempt or excluded from further regulation. These materials include those discussed above that are not "unwanted" by the generator and are sold in a commercially reasonable manner in the stream of commerce. This concept could be incorporated into draft OAC 3745-599-10 ("Beneficial use - exclusion for select work incorporated into certain construction materials"), by revising the title to clarify that the listed materials are not wastes and are not regulated if sold in the stream of commerce. Clarification in this part of the rule would provide certainty to the regulated community

that such materials are not regulated, which would encourage the greater beneficial use of such materials.

2. Tier 1 – Pre-Approved Uses

As noted above, the rules need to be simplified so as to promote the program's use. A rule needs to be drafted to address "Tier 1" materials. It is assumed that Ohio EPA has initially left OAC 3745-599-100 ("Pre-approval for beneficial use") blank or "reserved" for Tier 1 materials. This category should include those materials that are "unwanted" by the generator but wanted by the recipient, distributor or end user and are ultimately used in a manner constituting disposal (e.g., land application). There are many common applications of these types of materials that Ohio EPA has routinely approved under its Integrated Alternative Waste Management Program (IAWMP) (e.g., materials used as soil amendments).

This portion of the rule should identify what materials and uses are permitted and under what circumstances. The required testing (including intervals, parameters and acceptance levels) can be set forth in a separate rule. Since these are common applications widely accepted by both Ohio EPA and industry, the testing and recordkeeping should be simple and straight-forward. Inclusion of waste characterization and a waste analysis plan (WAP) is overkill for these types of materials.

3. Tier 2 – General Permits

The general permits also need to be simplified. The requisite testing and waste characterization can be set forth in the specific general permit. While some materials and uses may warrant more rigorous oversight, not all general permits should be burdened with all of these onerous requirements. Also, reporting of locations and amounts of disposition is unnecessary. If the material and use are approved, there is no reason to report where and how much.

OMA suggests that the following rules be deleted and, if necessary, aspects of these rules be customized for the particular material in the authorizing general permit:

1. 3745-599-40 Beneficial use – notice information for distribution.
2. 3745-599-45 Beneficial use – recordkeeping and reporting.
3. 3745-599-50 Select waste characterization and analysis plan.

Also, if an applicant qualifies for a general permit, there should be no need to wait for the Director's written notification that the beneficial use is authorized. Similar to the stormwater general permits, coverage under the general permit should occur upon submittal of a "Notice of Intent" (NOI) to come under and comply with the general permit. The requirement to submit a NOI "not later than 60 days prior to the anticipated date of commencing beneficial use" of the material serves no useful purpose if one must

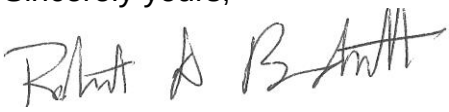
still wait until the Director provides written authorization to qualify for the permit. Regardless of how much or how little advanced notice is given, an applicant can still not proceed under the permit until receipt of the Director's authorization. Instead, the rule should be revised to require advance notice to Ohio EPA (e.g., 30 days) by filing a NOI to come under the general permit in question, but no need to wait for the Director's authorization.

4. Tier 3 – Individual Permits

Finally, an individual permit is the appropriate place to require the more stringent oversight. These are materials and uses that are approved by the Director on a case-by-case basis, i.e., they are not common situations. Because they are not the typical situation, more protection may be warranted because of the unknown. Again, Ohio EPA should not burden common uses and materials with requirements that are only applicable to these unknown or unique situations. These should be handled in the individual permits.

If you have any questions regarding the foregoing or attached, please feel free to contact me or OMA's environmental counsel, Frank L. Merrill with Bricker & Eckler LLP (614-227-8871).

Sincerely yours,



Rob Brundrett
Director, Public Policy Services
Ohio Manufacturers' Association

cc: Frank L. Merrill

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June 28, 2013

VIA ELECTRONIC MAIL

Michelle Braun
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Re: Comments of The Ohio Steel Group With Respect to Ohio EPA's Conceptual Draft Rules to Implement a Program to Regulate the Beneficial Use of Solid, Industrial or Other Wastes

Dear Ms. Braun:

The following are the comments of the AK Steel Corporation, ArcelorMittal USA LLC, The Timken Company, Thomas Steel Strip Corporation, a Division of Tata Steel Plating, and U. S. Steel Corporation, Lorain Tubular Operations (collectively, the "Ohio Steel Group") with regard to Ohio EPA's conceptual draft rules to implement a program to regulate the beneficial use of solid, industrial and other wastes. Steel is the most recycled material on the planet and the steel industry, as part of its environmental stewardship, has long been a leader in the use of the co-products and byproducts generated by the production of steel. The objective of the Ohio Steel Group's comments is to assure a continued favorable environment for the continued use, reuse and recycling of these materials.

I. INTRODUCTION

Ohio EPA has for some time been interested in developing a program governing the beneficial use of solid, industrial and other wastes. Last month, Ohio EPA's Division of Materials & Waste Management circulated draft conceptual rules to regulate the beneficial use of "solid wastes" as defined in R.C. §3734.01(E) and "industrial wastes" or "other wastes" as defined in R.C. §6111.01 when these uses involve placement on land or burning. The conceptual draft rules reflect the Division's initial effort at how a beneficial use program might be structured.

The conceptual draft rules would generally prohibit the "beneficial use" of a "select waste" without the approval of Ohio EPA. The term "beneficial use" is defined at OAC 3745-

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599-02(B)(1) as "the legitimate use of a select waste as an ingredient or product in a manner that contributes to a manufacturing process or product, that does not constitute disposal or cause pollution of any waters of the state." The term "select waste" is defined at OAC 3745-599-02(S)(1) as "a solid waste, industrial waste or other waste specifically identified for properties necessary or preferred for beneficial use." The conceptual draft rules contemplate that the approval takes the form of compliance with either a general permit issued pursuant to draft OAC 3745-599-200 or an individual permit issued pursuant to draft OAC 3745-599-300. Beneficial use would be subject to a host of general requirements outlined in draft OAC 3745-599-30, certain "legitimacy" criteria outlined in draft OAC 3745-599-35, certain notice and information requirements for downstream users in accordance with OAC 3745-599-40, recordkeeping and reporting requirements in accordance with draft OAC 3745-599-45, extensive waste characterization and analysis in accordance with draft OAC 3745-599-50 and annual sampling to confirm constituent characterization in accordance with draft OAC 3745-599-53.

The Division announced a comment deadline on the draft conceptual rules of June 21, 2013. John Schierberl, Division of Materials & Waste Management, has advised that a brief extension of time to **June 28, 2013** in which to file comments on behalf of the Group would be acceptable. As a result, these comments are timely filed.

II. COMMENTS

The Ohio Steel Group is concerned that a prohibition against use, without the approval of Ohio EPA, of certain co-products and byproducts generated by the steel industry would restrict or even eliminate the markets for continued use of these valuable materials. This is particularly so with respect to the established markets for materials such as mill scale and slag.

Mill scale forms on the surface of steel during reheating, conditioning, hot rolling or hot forming operations and is removed from the surface using high pressure water sprays, mechanical scarfing and/or abrasive blasting. The removed mill scale is recovered and can be sintered for metals recovery or sold to a third party, such as a cement manufacturer, for its iron content.

Slag is a co-product that is produced as a result of processes that occur in either the blast furnace, the basic oxygen furnace, or the electric arc furnace. Slag has a variety of recognized uses, including use as an aggregate in bituminous mixes, a concrete aggregate or ingredient in cement, as a road base, as an agricultural soil amendment, as landfill daily cover material and as environmental remediation material. Ohio Steel Group members produce significant amounts of slag annually, virtually all of which is sold to slag processors that sort and size the material for sale in the market. Indeed, the Ohio General Assembly has long recognized slag's value as a useful product, having exempted "slag, and other substances that are not harmful or inimical to public health" from the definition of "solid waste" for purposes of R.C. §3734.01(E).

Depressed markets for these materials would mean lost sales, which, when coupled with the cost of landfilling the material, would present a significant (and needless) financial burden on Ohio Steel Group members who are competing regionally, nationally and globally. In addition,

landfilling these materials would take up significant landfill space contributing to the Country's waste problem while additional raw materials would need to be mined to replace the currently acceptable uses for these materials.

Specific comments regarding the conceptual draft rules are as follows:

- Ohio EPA's jurisdiction under R.C. Chapter 3745 is limited to the transfer and disposal of "solid waste" within the meaning of R.C. §3734.01(E) which defines that term as:

  > …Such unwanted residual solid or semi-solid material as results from industrial, commercial, agricultural, community operations, excluding earth or material from construction, mining or demolition operations, or other waste materials of the type that normally would be included in demolition debris, nontoxic fly ash and bottom ash, including at least ash that results from the combustion of coal and ash that results from the combustion of coal in combination with scrap tires where scrap tires comprise not more than fifty percent of heat input in any month, spent nontoxic foundry sand, ***and slag, and other substances not harmful or inimical to public health*** and includes, but is not limited to garbage, scrap tires, combustible and noncombustible material, street dirt and debris. "Solid wastes" does not include any material that is an infectious waste or a hazardous waste.

  (Emphasis added). Similarly, Ohio EPA's jurisdiction under R.C. Chapter 6111 is limited to "industrial wastes" within the meaning of R.C. §6111.01(C) which defines the term as:

  > …Any liquid, gaseous, or solid waste substances resulting from any process of industry, manufacture, trade or business, or from the development, processing or recovery of any natural resource, together with such sewage as is present.

  as well as "other wastes" within the meaning of R.C. §6111.01(D) which defines the term as:

  > …Garbage refuse, decayed wood, sawdust, shavings, bark and other wood debris, lime, sand, ashes, offal, night soil, oil tar, coal dust, dredged or fill material, or silt, other substances that are not sewage, sludge, sludge materials, or industrial waste and any other "pollutants" or "toxic pollutants" as defined in the Federal Water Pollution Control Act that are not sewage, sludge, sludge materials, or industrial waste.

  There is nothing in either R.C. Chapter 3734 and/or Chapter 6111 which suggests that Ohio EPA can regulate the beneficial use of solid waste, industrial waste or other wastes, let alone the co-products and byproducts under discussion as part of this rulemaking initiative.

- In its conceptual draft rules, Ohio EPA has indicated its intent to exempt any select wastes that are governed by an established program at draft OAC 3745-599-05, evidencing the narrow focus of this rulemaking. Its clearest targets seem to be the impermissible inclusion of those materials like slag that the Ohio General Assembly has declared to be exempt from regulation as solid waste under R.C. Chapter 3734 by virtue of R.C. §3734.01(E). At the same time, Ohio EPA offers no technical justification, other than anecdotal, for regulation of slag in

particular as a waste. Slag has been successfully used for over 100 years in construction applications throughout Ohio and the nation.

- While Ohio EPA has included a limited exemption for select waste incorporated into construction material at draft OAC 3745-599-10, that exemption is not sufficiently expansive to include the co-products and byproducts being used by the Ohio steel industry. Draft OAC 3745-599-10 excludes a select waste from regulation under the program if that waste is incorporated into one of a number of construction materials meeting engineering construction specifications and placed on land as part of a construction project. However, the language "meeting construction specifications and placed on land as part of a construction project" is vague and standardless and the identification of the construction materials subject to the exemption do not include many established uses for the materials generated by the Ohio steel industry.

- Ohio EPA borrows concepts from rulemakings recently finalized or proposed by U.S. EPA under the federal hazardous waste program established under Subtitle C of the Resource Conservation and Recovery Act ("RCRA"), 42 U.S.C. §§6901. Those concepts include, for example, the "legitimacy" of the recycling of a select waste, the "adequate containment" of a select waste and/or its "speculative accumulation" pending recycling. These concepts are applicable by definition to wastes which would be characterized as hazardous wastes and are overly proscriptive when applied to the co-products and byproducts being reused by the steel industry.

- The conceptual draft rules will not achieve Ohio EPA's own objectives for the program, those being, "to reduce disposal costs for generators, provide sources of raw materials for end users, extend the capacity of landfills and conserve resources, and make byproducts resources instead of wastes." *See Fact Sheet: Early Stakeholder Outreach Beneficial Use Regulatory Program Development* (June 2012), http://epa.ohio.gov/dmwm/dmwmnonhazrules.aspx. In fact, the overly proscriptive nature of the requirements outlined in the conceptual draft rules virtually guarantees a reduced market for these materials. Specific provisions of concern are the following:

  The requirement of draft OAC 3745-599-35 that the select waste be "adequately contained" and not be "accumulated speculatively", which includes, *inter alia*, a demonstration that approximately 75% of a select waste being accumulated is used over a calendar year.

  The requirement of draft OAC 3745-599-40 that permittees provide a host of information to downstream users regarding the material, including a statement that the material is a select waste and a summary of the results of the characterization of the material in accordance with draft OAC 3745-599-50, as well as continued updates regarding that information and/or wherever the material undergoes a material change.

The fact that coverage under either a general permit or an individual permit may be denied, suspended or revoked, and individual permits are limited in duration to five years; and

The extensive waste characterization and analysis required by draft OAC 3745-599-50 and the annual sampling to confirm chemical characterization required by draft OAC 3745-599-53.

These requirements do not recognize the realities of many construction projects and the manner in which these materials are used and, in the case of slag, make selection of virgin aggregates with which slag competes more likely while placing slag at a market disadvantage. This outcome is neither beneficial to the environment nor does it make good economic sense.

III. CONCLUSION

Thank you for the opportunity to comment on the conceptual draft rules. Given the significance of these issues to the Ohio Steel Group, we would appreciate meeting with you to discuss this rulemaking initiative in further detail.

Very truly yours,

Karen A. Winters

KAW/jaw
cc: Ohio Steel Group Representatives

Ohio Water Environment Association
Preserving & Enhancing Ohio's Water Environment

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Kim Riddell

Executive Manager
Judi Henrich

Executive Assistant
Amy Davis

June 21, 2013

Ohio EPA, Division of Surface Water
Attn: Michelle Braun
P.O. Box 1049
Columbus, Ohio 43216-1049

Re: Ohio EPA's (OEPA) Early Stakeholder Outreach/Developing Rules Beneficial Use

Dear Rule Coordinator:

The Ohio Water Environment Association (OWEA) is comprised of over 2000 wastewater professionals from varying backgrounds, including operators, engineers, regulators, educators and manufacturer representatives. Our mission is as follows:

- Educate our members through sharing information and networking
- Educate the public on preserving and enhancing our water quality
- Be proactive on water environment issues
- Build a positive professional image within and outside the Association

Based on our mission, we have a Technical Review Group, who bring forth their knowledge in their representative areas to review upcoming rules and regulations that impact our industry.

We would like to offer the following for consideration in the development of this rule.

Overall

1. We suggest adding liquid wastes to the definition of "select wastes" so generators and waste management companies have a regulatory path defined for permitting beneficial use of liquid waste such as cheese whey.

2. We suggest adding water softening lime (managed as cake or liquid) into the rule when not regulated by the Ohio Department of Agriculture. Alternatively, lime should be made exempt from regulation as a solid waste. This clarification would address concerns municipalities and manufacturers have in understanding whether or not lime is considered part of the regulation.

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3. 3745-599-210 (A) 1 (g) requires notification in the General Permit to identify the "location" where select material will be distributed on land. In practice, site identifications will be on-going as customers are identified. Therefore, we suggest identification of locations not be required as part of the initial permit application process. Rather, we suggest establishing site standards and best management practices (BMPs) for sites. We also suggest notification of the use of new sites be allowed for submission to OEPA as those sites are identified.

4. The draft rule states the Director may deny a permit for a location with a well head for potable water within 500 feet of the land application site. We suggest matching the sewage sludge standard which uses a 300 feet buffer area around wells, but does not deny the site or permit; it excludes the buffer area only.

We appreciate the opportunity the OEPA provides for input and reviews of upcoming changes.

If you should have any questions, please contact Dianne Sumego at 330.607.5619 or sumegod@bv.com or the writer at 513.515.6253 or dan@sullivanenvtec.com.

Sincerely,

Daniel Sullivan
President, OWEA

c: Dianne M. Sumego, PE, OWEA Technical Review Group Chair

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June 27, 2013

VIA EMAIL AND U.S. MAIL

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Re: Early Stakeholder Outreach – Beneficial Use Regulatory Program
Our File No. 042895

Dear Ms. Braun:

The Ohio Environmental Protection Agency ("Ohio EPA") issued a notice for early stakeholder outreach for the Division of Materials and Waste Management's Beneficial Use Regulatory Program. The early stakeholder outreach is intended to address the development of a permitting program for the beneficial use of byproducts. The following comments regarding this action are submitted on behalf of the Ohio Utility Group and its member companies ("OUG" or "the Utilities"),[1] which is an association of individual electric utilities in the State of Ohio. The electric utilities own and operate power plants and other facilities that generate, transmit, and distribute electricity for residential, commercial, industrial, and institutional customers. These power plants and other facilities are subject to Ohio's solid and hazardous waste rules. OUG's purpose, in part, is to participate collectively on behalf of its members in administrative proceedings under various environmental laws and in litigation arising from those proceedings that affect electric generators. Thus, this notice affects the members of OUG.

The Utilities understand that the draft rules provided are conceptual and that the Agency is open to revisions to the rules. While the Utilities commend Ohio EPA for working with interested parties, the Utilities believe that substantial revisions to the rules are necessary to make them flexible across industries and to encourage the beneficial use of industrial and other byproducts.

[1] The member companies include: Buckeye Power, Inc., The Dayton Power and Light Company, Duke Energy Ohio, FirstEnergy Solutions, Ohio Power Company (a unit of AEP), and Ohio Valley Electric Corporation.

General Comments

Ohio EPA has attempted to develop a beneficial use program several times over the last decade. In each previous event, the Agency failed to promulgate proposed rules that would encourage beneficial use instead of regulating it out of existence. The current proposal again presents the same problem. As was evidenced multiple times throughout the BURT meetings, up to and including the June 12, 2013 meeting to discuss the rules' "concepts," the staff writing these rules remains focused on "preventing" a hypothetical problem or abuse rather than developing a program that would make beneficial use not only possible, but attractive.

During this process, Ohio EPA staff has consistently expressed its concerns with "sham" disposal masquerading as beneficial use and recounted anecdotal examples of supposed beneficial uses that turned out to be scams, creating an environmental problem instead of solving one. These rules reflect just that: the proposal is not written towards making beneficial use an attractive alternative to land filling. The rules attempt to completely encumber the beneficial use program with multiple layers of checks, tests, and requirements, making any beneficial use as draconian and prescriptive as placing the material in a landfill.

The rules, as conceptualized, are complex, restrictive, and will only discourage interested parties from participating in beneficial use. They will create such an administrative burden on interested parties that it will make beneficial use uncompetitive in cost and effort and make shipping the material to a landfill the more economic choice. With slight exception, no new rule would be more favorable than the current proposal. The Utilities already beneficially use their materials in a number of ways with existing approvals or permits. All of these in place now are far preferable to the rules in the current draft.

If Ohio EPA wants to develop a rule that will encourage beneficial use, the current framework needs significant revision. As detailed below, the Agency must delete most of the restrictive requirements of the rules and, instead, address these issues in a case-by-case manner through permitting. Further, Ohio EPA must not let concerns for "sham" uses drive it to develop demanding rules that will not eliminate "sham" uses but create an administrative burden on those parties that are committed to complying with the environmental regulations. Finally, the Agency must let go of the ideology that any beneficial use must have "zero" impact on the environment. No anthropogenic activity has "zero" impact. The use of raw materials in any construction project or building materials will have some impact on the environment. Ohio EPA must write rules that reflect this and not expect beneficial uses to somehow have less of an impact than unregulated activities utilizing virgin materials.

Ohio Adm.Code 3745-599-01

The Utilities object to the use of the term "select waste." The purpose of the beneficial use program is to take industrial and other byproduct and utilize it instead of managing it as solid waste. Thus, the Utilities recommend that Ohio EPA utilize the term "select byproduct" or "select material" instead of "select waste."

Ohio Adm.Code 3745-599-02

Agricultural Additive. The Utilities recommend that Ohio EPA revise the term "Agricultural additive." Currently, under Ohio R.C. §905.01(D), the term "agriculture additive" has a distinct definition that excludes gypsum and other materials as agriculture additives. Instead, the Agricultural Department treats gypsum as a fertilizer. Thus, the Utilities think that the use of the term "agricultural additive" is inconsistent with the treatment of gypsum in land application under the Agricultural Department's rules and the use of this term may impede in the beneficial use of gypsum in land application. An alternative term would clarify that the use of gypsum and other material in land application is a beneficial use.

Beneficial Use. The definition of "beneficial use" is too vague and restrictive. The Utilities recommend the following revisions:

> (1) "Beneficial use" means the ~~legitimate~~ use of a select ~~waste~~ byproduct or select material as an ingredient or product, ~~or~~ in a manner that contributes to a ~~manufacturing~~ process or product, as a replacement of raw material, as a soil additive, as a fertilizer, or as a structural fill ~~that does not constitute disposal or cause pollution of any waters of the state~~.

The Utilities make these revisions for the following reasons. First, by defining exactly what constitutes beneficial use, Ohio EPA is also defining what is not beneficial use. Thus, Ohio EPA can differentiate between beneficial use and "sham" use. Second, because this definition is descriptive, Ohio EPA does not need to include the language "does not constitute disposal." Third, the Utilities believe that Ohio EPA should also strike the language "or cause pollution of any waters of the state." This language presumes that there will be "zero impact" on the environment, which is misleading. For example, synthetic gypsum is used for land application in agriculture. It is likely that once applied, there can be runoff from rain events. Likewise, if natural gypsum was used for land application, there would still be the same chance of runoff due to rain events. Neither the use of synthetic gypsum nor natural gypsum results in "zero impact." In both cases, there may be some minimal impact on the environment.

Flowable Fill. The Utilities recommend that Ohio EPA should include a definition for flowable fill.

> (F)(1) "Flowable fill" means a self-compacting low strength material with a flowable consistency that is used as a fill or backfill material as an alternative to compacted granular fill.

Grout. It is unnecessary to specify what "generally" constitutes grout. Thus, the Utilities recommend that Ohio EPA revise the definition of "grout" to read:

(2) "Grout" means a construction material used to embed rebar in masonry walls, connect sections of pre-cast concrete, fill voids, and seal joints. ~~Grout is generally composed of a mixture of water, cement, sand and sometimes fine gravel.~~

Masonry Unit. The Utilities recommend the following revisions to the term masonry unit:

(M)(1) "Masonry Unit" means manufactured building product that includes materials such as burned clay, concrete, stone, glass, ~~and~~ gypsum, fly ash, or other coal combustion residuals.

Select Waste. As noted above, the Utilities discourage Ohio EPA from using the term "select waste." Instead, the Utilities recommend that Ohio EPA use the term "select byproduct" or "select material."

Wallboard. The Utilities recommend that Ohio EPA include a definition for wallboard.

(W)(1) "Wallboard" means a type of board made from wood pulp, plaster, gypsum, or other material, used for covering walls and ceilings.

Ohio Adm.Code 3745-599-03

The Utilities recommend that Ohio EPA include the following in Beneficial use – incorporation by reference: "The Design and Application of Controlled Low-Strength Materials (Flowable Fill), ASTM STP 1331," ed. A.K. Howard and J.L. Hitch, American Society for Testing and Materials, West Conshohocken, PA.

Ohio Adm.Code 3745-599-10

The Utilities are pleased that Ohio EPA has included this section, which excludes certain materials because these material are not under Ohio EPA's jurisdiction to regulate. However, the Utilities recommend that this section should be revised as follows:

3745-599-10 Beneficial use – exclusions for select waste incorporated into certain construction materials.

(A) A select ~~waste~~ byproduct or select material that is ~~incorporated into one of the following construction materials meeting engineering construction specifications and placed on land as part of a construction project~~ used in the manufacturing of any of the following ~~are~~ is excluded from regulation ~~under this beneficial use program chapter~~:

(1) Asphalt concrete.

(2) Cement concrete.

(3) Chip and seal pavement.

(4) Flowable fill.

~~(4)~~ (5) Grout.

~~(5)~~ (6) Glass.

~~(6)~~ (7) Masonry Unit.

(8) Wallboard or similar construction materials.

(B) Nothing in this rule limits the applicability of Chapters 3734., 6111., or 3704. of the Revised Code or rules adopted thereunder, or any other applicable environmental regulations.

(C) Ohio EPA will grant a variance on a case-by-case basis for other exempt wastes that may not be included in this provision.

The Utilities recommend these revisions to make it clear that the use of certain materials—such as synthetic gypsum—is not only excluded from regulation under this beneficial use program, but are also excluded from regulation as a solid waste. The rules must make clear that Ohio EPA does not have jurisdiction to regulate the use of these materials when these materials have not been disposed of as solid waste.

Ohio Adm.Code 3745-599-15

The Utilities reserve the right to comment on this section once Ohio EPA provides draft language on this section.

Ohio Adm.Code 3745-599-20

This section is too broad, and this section and the corresponding provisions should be removed. The purpose of the beneficial use of byproduct is to utilize that byproduct in a safe manner instead of using a raw material. Thus, one cannot "beneficially use" something if it is harmful to the environment or human health. Further, any enforcement should be tied to compliance with the rules and the permit. For these reasons this section is unnecessary.

Ohio Adm.Code 3745-599-25

The Utilities think that the requirement to have a principal executive officer sign any document associated with the beneficial use permit program is not appropriate. It is well-settled law that an officer of the corporation with properly delegated powers has the authority to execute documents that bind the company and that should be the requirement. Thus, it seems more logical

to have an individual that is familiar with the beneficial use of a byproduct sign the documents associated with the permit. Further, the certification language for every document is extremely cumbersome. The Utilities suggest that Ohio EPA revise the certification language.

Ohio Adm.Code 3745-599-30

The general requirements are too detailed and most of this information should be included in the general permit. Further, the Utilities seek clarification regarding the language in this section.

Ohio Adm.Code 3745-599-30(C) states that the Director may require a permittee under a general permit to obtain an individual permit. In what instances does Ohio EPA anticipate that a permittee will have to obtain an individual permit when it is already covered under a general permit? The criteria should be made explicit in the rules.

In the definition section, Ohio EPA defines "end-users." How do these rules apply to end-users? The Utilities also take issue with Ohio Adm.Code 3745-599-30(G). Some of the Utilities have permits to sell gypsum for land application. Frequently, this is sold to a vendor, who in turn sells it to farmers. How will the Utilities know if the farmers are properly complying with the use of the gypsum for land application? The Utilities are concerned that this rule will require them to oversee the application of the gypsum—this is neither practical nor feasible.

Ohio Adm.Code 3745-599-35

Like Ohio Adm.Code 3745-599-30, the Utilities seek clarification regarding how these will apply to "end-users." Further, these legitimacy criteria are too detailed and should be simplified. While the Utilities understand that Ohio EPA is concerned with "sham" disposal, it should be noted that these rules will not stop someone who is intent on "sham" disposal. As the Utilities mentioned above, the focus of these rules should be tied to compliance with an issued permit. Including these burdensome demonstrations such as the legitimacy criteria will only discourage those that intend to abide by the regulations from engaging in beneficial use. Instead, they will opt to dispose of the byproducts in landfills, thereby contradicting the whole purpose of the rules. Thus, the Utilities recommend that Ohio EPA remove this section or substantially revise this section to tie the criteria to compliance with an issued permit.

Ohio Adm.Code 3745-599-40 to -60

Ohio EPA should remove in its entirety Ohio Adm.Code 3745-599-40 to -60. The problem with these sections is that Ohio EPA is attempting to draft "one-size-fits-all" rules to address diverse types of beneficial uses. This is simply not plausible and if the rules were adopted as written, Ohio EPA would have to exempt or grant variances to many sections of the rules because they do not apply to certain types of beneficial uses. Instead of trying to create comprehensive rules that try to encompass all beneficial uses, the Agency should draft separate general permits that include specific provisions that are applicable to each type of beneficial use. The requirements in these rule sections should be included in permits, as needed, reflecting the application necessary to individual wastes and uses.

Ohio Adm.Code 3745-599-100

Ohio EPA appears hesitant to develop rules for preapproved beneficial use. For example, in the last meeting, Ohio EPA indicated that flowable fill was originally pre-approved for beneficial use. This was removed because one staff member had concerns about the pre-approval of flowable fill. The Utilities think that flowable fill should be exempted under Ohio Adm.Code 3745-599-10 because flowable fill is well documented for beneficial use. *See*, "The Design and Application of Controlled Low-Strength Materials (Flowable Fill), ASTM STP 1331," ed. A.K. Howard and J.L. Hitch, American Society for Testing and Materials, West Conshohocken, PA. In the alternative, the Utilities think that when a beneficial use is well documented, Ohio EPA should include these uses in the preapproved section. The Utilities recommend that Ohio EPA develop these preapproved beneficial uses to streamline the beneficial use program and encourage use rather than disposal in landfills. In addition, the Utilities reserve the right to comment on this section once Ohio EPA provides draft language on this section.

Ohio Adm.Code 3745-599-200

This rule is all Ohio EPA needs for a general permit program. This rule gives Ohio EPA the authority to establish a variety of provisions necessary for regulating beneficial use under a general permit program without trying to develop one-size-fits-all rules. By streamlining the rules, Ohio EPA can then draft general permits that are specific to each type of beneficial use. As an example of streamlined rules that cover general permits, Ohio EPA should refer to the NPDES General Permit Rules, Ohio Adm.Code 3745-38.

Ohio Adm.Code 3745-599-210

The Utilities recommend patterning the notice of intent to obtain coverage similar to the NPDES General Permit Rules – specifically Ohio Adm.Code 3745-38-02(E)(3). The NPDES General Permit Rule provides a brief description of what is necessary to operate under a general permit. Similar rules should be drafted for the Beneficial Use General Permit. The Utilities request that Ohio EPA revise this section to better reflect the Notice of Intent requirements that are found in the NPDES General Permit Rules.

Ohio Adm.Code 3745-599-220

This section is overly restrictive and should be substantially revised. Again, these provisions are burdensome and will discourage beneficial use.

Further, the Utilities seek clarification on Ohio Adm.Code 3745-599-220(C). Ohio EPA needs to clarify what exactly constitutes a change in the generating process so as to trigger the requirements in subsection (C).

The Utilities also disagree with subsection (D). If the byproduct characterization demonstrates that there is no risk in using the byproduct beneficially, then there should be no restrictions on where the beneficial use occurs. Thus, Ohio EPA needs to remove this subsection.

Finally, suspension or revocation of a general permit should be tied to compliance with the general permit. For this reason, Ohio EPA should remove subsection (E)(2), which addresses beneficial use that could impact public health, safety, or the environment. This provision contradicts the whole concept of beneficial use.

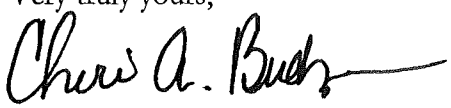
Individual Permits

Ohio Adm.Code 3745-599-310 to -350 contains provisions for an individual permit. Many of these provisions are similar to those outlined above in the general permit rules. The Utilities think that Ohio EPA should revise these rules as provided above so that the rules are protective but also provide flexibility and encourage beneficial use.

Conclusion

The Utilities thank Ohio EPA for the opportunity to comment at this time. Should you have any questions, please do not hesitate to contact me.

Very truly yours,



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June 21, 2013

DELIVERY VIA REGULAR U.S. MAIL AND E-MAIL

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Re: Comments of The Ohio Oil and Gas Association - Conceptual Draft Rule Language: Beneficial Use Regulatory Program Development

Dear Ms. Braun:

On May 24, 2013, Ohio EPA issued conceptual draft rule language for a Beneficial Use Regulatory Program, requesting comments from interested stakeholders. The Ohio Oil and Gas Association (Association), on behalf of its itself and its members, is pleased to submit these remarks as requested and looks forward to assisting Ohio EPA in the further development of a Beneficial Use Program for Ohio.[1]

I. Introduction

The Association is one of the largest and most active state-based oil and natural gas associations in the country and has been the representative of Ohio's oil and gas producing industry since 1947. Its over 3,300 members are involved in all aspects of the exploration, development, production and marketing of crude oil and natural gas resources in the State of Ohio. Because of the small size of many of the Association's members, they often rely on the Association as their primary source of information on industry trends, activities, tax changes, legislation and regulatory matters. The Association also serves to protect its members' interests by participating in federal and state regulatory actions involving the crude oil and natural gas industry.

[1] The Association submitted initial "early stakeholder response" comments on Ohio EPA's conceptual framework paper for a Beneficial Use of Industrial Materials Regulatory Program, on September 21, 2012, which it fully incorporates here and attaches as Exhibit A.

Ohio EPA's development of a Beneficial Use Regulatory Program offers stakeholders a potential alternative to unnecessary and expensive landfill disposal of materials that might otherwise be treated as waste or unwanted material. It has the potential to promote conservation of raw materials through recycling and reuse initiatives, and to facilitate the continued efficient and effective development of oil and natural gas resources in Ohio, while being protective of human health and the environment. Ohio EPA has stated that the draft rules are only conceptual at this point in the rulemaking process and that the agency is primarily concerned with establishing the general framework for a Beneficial Use Program. It is in this context that the Association submits these comments.

II. Specific Comments

A. The Mistaken Characterization of "Beneficial Use" as "Disposal"

The Association supports the overall concept of a Beneficial Use Regulatory Program for byproduct materials that would otherwise be considered an Ohio EPA-regulated solid waste sent to a regulated landfill for disposal. However, the draft rules are written such that the material subject to beneficial use is automatically assumed to be a "waste" and, thus, Ohio EPA appears to be treating "beneficial use" as a type of "disposal" rather than recycling or reuse of a wanted material. This mistaken characterization stems from the term used to identify the material destined for beneficial use. Under the draft rules, "beneficial use" is defined as "the legitimate use of a select waste as an ingredient or product in a manner that contributes to a manufacturing process or product, that does not constitute disposal or cause pollution of any waters of the state." Notably, Ohio EPA replaced the term "industrial byproduct," which was used to identify the subject material in the June 2012 early stakeholder outreach, with "select waste" in the draft rules.

The consequences of this characterization are two-fold: (1) the treatment of byproduct material from oil and natural gas production operations as a "waste" raises Ohio Department of Natural Resources (ODNR)-Ohio EPA jurisdictional issues, and (2) the Association, and other industries, will be discouraged from pursuing beneficial use alternatives to landfill disposal. While the draft rules provide an exclusion for materials generated from oil and gas exploration and production operations (see, OAC 3745-599-05(Q)), the Association understands that this provision was intended to exclude only materials managed on-site that are under ODNR jurisdiction. Yet, that fails to recognize ODNR's ongoing jurisdiction for off-site use as well. For example, drill cuttings, in addition to being managed at the well site where they are generated, can and are successfully used at other well sites (for fill material, for example). These practices historically have been regulated by ODNR under ORC 1509.02 (granting ODNR sole and exclusive authority to regulate oil and natural gas production operations). As drafted, the beneficial use rules cast too broad of a jurisdictional net, and would impermissibly treat all oil and natural gas

byproduct material as a waste subject to regulation by Ohio EPA as soon as it leaves the well site.[2]

Further, the Association believes that a mistaken characterization of beneficial use material as a waste could result in the creation of additional and potentially more stringent rules for disposal, thereby discouraging industry from pursuing acceptable beneficial use alternatives to landfill disposal. A Beneficial Use Regulatory Program with reasonable standards and implementation procedures will encourage the beneficial use of drill cuttings and other qualifying byproduct material that would unnecessarily consume landfill capacity. This type of beneficial use program is strongly supported by the Association.

Consistent with the above comments, the Association offers the following suggestions to revise the definition of "beneficial use" and replace "select waste" with a term avoiding the inherent involvement of the term "waste":

1. Revise the definition of **beneficial use** to mean – the legitimate use of a "**byproduct material**" as a raw material substitute in manufacturing, construction material, clean fill, fuel, or in agronomic utilization that does not constitute disposal, does not adversely affect human health or the environment, and is approved by the Director.

2. Replace "select waste" with "**byproduct material**" defined as – a material that has been recovered or diverted from a waste stream for purposes of beneficial use, recycling, or reclamation, a substantial portion of which is consistently used in the manufacture of products which may otherwise be produced from raw virgin materials. Byproduct/beneficial use material is not solid waste. However, byproduct/beneficial use material may become solid waste at such time, if any, as it is abandoned or disposed of rather than beneficially used, whereupon it will be solid waste with respect only to the person actually abandoning or disposing of the material. Byproduct/beneficial use material may be material that has been or is processed such that the material possesses properties that are necessary or preferred for beneficial use. Processing activities include, but are not limited to, extraction or separation of component materials, cleaning, or grinding.

[2] The Association notes that Ohio House Bill 59 (HB 59), as proposed, would clarify this issue in large part, maintaining ODNR's sole and exclusive authority with respect to these matters.

B. *The Association Supports the Development of a General Permit for the Beneficial Use of Byproduct Material from Oil and Natural Gas Production Operations*

In its initial comments, the Association supported the creation of a general permit for drill cuttings associated with the horizontal component of the wellbore as an appropriate method to facilitate the responsible reuse of drill cuttings that meet prescribed criteria or thresholds.[3] After reviewing the draft rules and attending Ohio EPA's Beneficial Use Stakeholder Meeting, the Association believes Ohio EPA is moving in the right direction regarding the development of a general permit program and would be available to work with the agency directly in the development of a Beneficial Use General Permit for the Beneficial Use of Byproduct Material from Oil and Natural Gas Production Operations.

The Association's participation in the development of a general permit is critical as several aspects of an industry specific beneficial use general permit, such as assigning responsibility between the generator and end user of the material to be beneficially used, waste characterization, and establishing treatment and stabilization standards prior to beneficial use, require detailed knowledge of the industry's operational and technical complexities. The Association, through its individual members, possesses this knowledge and requests that Ohio EPA utilize this expertise to develop and implement a General Permit for the Beneficial Use of Byproduct Material from Oil and Natural Gas Production Operations.

III. Conclusion

The Association supports Ohio EPA's intention to develop a Beneficial Use Regulatory Program for the responsible reuse of certain byproduct material. In this connection, the Association respectfully requests that Ohio EPA revise the definition of "beneficial use" and use the term "byproduct material" to address the mistaken characterization of beneficial use as a type of disposal. Further, the Association and its members offer their support to Ohio EPA in developing a functional program, particularly a General Permit for the Beneficial Use of Byproduct Material from Oil and Natural Gas Production Operations, that encourages the safe and economic beneficial use of qualifying byproducts that might otherwise be disposed of in solid waste landfills.

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[3] The Association reiterates that, historically, drill cuttings have been successfully reused in a number of different ways including road spreading, clean fill material, construction material, plugging abandoned wells, landfill cover, and wetlands restoration. Some, or all, of these existing beneficial uses of drill cuttings should be considered in developing a General Permit for the Beneficial Use of Byproduct Material from Oil and Natural Gas Production Operations.

VORYS
Legal Counsel

Very truly yours,

Gregory D. Russell
On behalf of the Ohio Oil and Gas Association

GDR/rde
Encl.

cc: John Schierberl, Ohio EPA w/encl.
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Exhibit A

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September 21, 2012

DELIVERY VIA REGULAR U.S. MAIL AND E-MAIL

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Re: *Initial Comments of the Ohio Oil and Gas Association - Early Stakeholder Outreach: Beneficial Use Regulatory Program Development*

Dear Ms. Braun:

In June 2012, Ohio EPA released a conceptual framework paper for a Beneficial Use of Industrial Materials Regulatory Program, requesting comments from interested stakeholders. The Ohio Oil and Gas Association (Association), on behalf of itself and its members, is pleased to submit these initial "early stakeholder response" comments on the Ohio EPA concept paper, as requested. The Association thanks Ohio EPA for this opportunity and looks forward to assisting in the further development of a Beneficial Use Program for Ohio.

I. Introduction

The Association is one of the largest and most active state-based oil and natural gas associations in the country and has served as the representative of Ohio's oil and gas producing industry since 1947. Its over 2,600 members are involved in all aspects of the exploration, development, production and marketing of crude oil and natural gas resources in the State of Ohio. Because of the small size of many of the Association's members, they often rely on the Association as their primary source of information on industry trends, activities, tax changes, legislation and regulatory matters. The Association also serves to protect its members' interests by participating in federal and state regulatory actions involving the crude oil and natural gas industry.

Ohio is experiencing a resurgence of economic energy activity today, due in large part to the development of the Marcellus and Utica Shale. The Association believes the continued

development of these natural resources can be accomplished in a manner that is efficient and effective, while being protective of our natural environment and human health. It is in that spirit that the Association submits these comments.

II. Initial Comments

A. *A Beneficial Use Program Will Benefit the Oil and Gas Industry and State of Ohio*

The Association supports the overall concept of a Beneficial Use Regulatory Program for industrial byproduct materials that otherwise would be considered a solid waste and need to be disposed of in a regulated landfill.[1] A beneficial reuse program could have a positive impact on the oil and gas industry, particularly with respect to drill cuttings. In general, drill cuttings are primarily naturally occurring materials removed from a borehole during the drilling process and can contain, for example, anhydrite, calcite, chalk, chert, clay, dolomite, feldspar, glauconite, granite, gypsum, hematite, iron, kaolinite, lime, marlstone, mica, mudstone, pisolite, pyrite, quartz, sand, sandstone, shale, silica, silt and sulfur. Under Division of Oil and Gas Resources Management regulations, drill cuttings can be (and have historically been) properly disposed of on-site in Ohio. However, the preferred method of disposal for many (but not all) large horizontal shale operators is by landfill, which can unnecessarily consume landfill capacity when safe and responsible reuse alternatives are available. A Beneficial Use Regulatory Program that establishes reasonable standards for allowing qualifying forms of drill cuttings that are already considered to be solid wastes to be reused is strongly supported by the Association.

The three-tiered approach being considered seems reasonable. Tier 1 would be for beneficial uses that have the least environmental or human health risks, and would be "pre-approved". Tier 2 uses would be approved via a stream-lined general permit, perhaps with the submission of a Notice of Intent to be Covered/Permit Application. The materials under a Tier 2 general permit may need some physical characterization data for the application/notice of intent, and some use specifications that would be included in the general permit issued in response to the application/notice of intent. Tier 3 would be reserved for individual customized permitting of materials that do not qualify for either Tier 1 or Tier 2 approval, but are still appropriate materials to consider for beneficial re-use. The tiered approach allows for a reasoned program that increases the level of regulation as the risk to the environment and human health increases. We think this approach, as a conceptual matter, is workable and should be considered further.

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[1] The Association understands the proposal to involve only industrial byproducts that are already considered waste materials over which Ohio EPA has jurisdiction, and does not understand the proposal to involve – and does not support – an expansion of that jurisdiction through this rulemaking.

B. *Classification of Vertical Drill Cuttings as Not a "Solid Waste"*

As a preliminary matter, the Association believes that it is important for Ohio EPA to clarify under current law whether certain drill cuttings are classified as "solid waste." Horizontal well drilling can be viewed in two components, the vertical (or tophole) portion and the horizontal (or lateral) portion. The vertical portion, similar to a conventional vertical well, is typically drilled using air, while the horizontal portion, including the "curve," typically also involves use of a drilling mud. It is the Association's understanding that Ohio EPA does not classify drill cuttings associated with the vertical portion of the wellbore (down to relatively 6,000 feet) as "solid waste," due to the fact that drilling operations for the vertical portion of a wellbore do not include drilling mud containing chemicals or other contaminates of concern. The Association believes that Ohio EPA should continue this understanding when drafting beneficial use guidelines, policies rules, or standards. As a result, drill cuttings from a vertical wellbore should not be regulated as a "solid waste" and can continue to be re-used wherever appropriate, and would not fall under a regulated beneficial use tier. On the other hand, the Association understands that Ohio EPA may consider drill cuttings associated with the horizontal component of a wellbore containing contaminants to be a "solid waste" and thus properly included in a beneficial re-use program at the appropriate tier level – which is discussed below.

C. *Existing Re-use of Drill Cuttings*

Historically, drill cuttings have been successfully reused in a number of different ways, such as:

- Road Spreading – Drill cuttings act to stabilize road surfaces that are subject to erosion.
- Clean fill material.
- Construction Material – Drill cuttings have been used in road pavements, bitumen, and asphalt, and cement manufacture.
- Plugging Abandoned Wells.
- Landfill Cover.
- Wetlands Restoration.

Some, or all, of these existing beneficial uses of solid waste drill cuttings should be considered under a Beneficial Use Program. There may be other uses for drill cuttings, and we welcome the opportunity to work with Ohio EPA to develop appropriate and reasonable standards for the reuse of drill cuttings that are appropriately classified as "solid waste." Some of these uses may even be appropriate for Tier 1 "pre-approval" of solid waste drill cuttings under the Ohio EPA three-tiered approach.

D. *General Permit for Solid Waste Drill Cuttings Containing Contaminants*

In the June 2012 concept paper, a "general permit" would be used for those industrial byproducts not qualifying for preapproved Tier 1 use and needing some physical characterization, while not requiring a full blown individual "custom" permit. The Association believes that the creation of a general permit for drill cuttings associated with the horizontal component of the wellbore is an appropriate regulatory method to facilitate the responsible reuse of drill cuttings that meet prescribed criteria or thresholds.

For example, when a drilling mud is used to drill a well, the solid waste drill cuttings may need to be cleaned, treated or remediated in some capacity in order to meet pre-determined criteria for the specific intended use (e.g., subsequent to using a saltwater-type mud, the cuttings may need to be washed to remove dissolved salts prior to beneficial use as road stabilization/erosion control). Similarly, some cuttings may need to be thermally treated to remove residual hydrocarbons to meet appropriate standards for reuse in construction materials. These types of common recurring uses of the solid waste drill cuttings would be appropriately handled under a stream-lined general permit. The Association looks forward to working with Ohio EPA to develop an acceptable general permit for appropriate solid waste drill cuttings, including providing characterization and reuse data and developing reasonable treatment and stabilization standards for certain solid waste drill cuttings prior to reuse.

III. Conclusion

The Association supports Ohio EPA's intention to develop a Beneficial Use Regulatory Program for the responsible reuse of industrial byproducts. In this connection, the Association respectfully requests that Ohio EPA continue to not consider clean drill cuttings associated with the vertical component of the wellbore as "solid waste." The Association and its members offer their support to Ohio EPA in developing Beneficial Use Concepts into a functional regulatory program, including developing a general permit, and particularly in the context of solid waste drill cuttings associated with the horizontal component of the wellbore.

VORYS

Very truly yours,

Gregory D. Russell

Gregory D. Russell
On behalf of the Ohio Oil and Gas Association

GDR/zms

cc: John Schierberl, Ohio EPA
john.schierberl.@epa.ohio.gov