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16. Abstract

The use of abrasive blasting to remove paint containing lead, cadmium, and chromium from steel bridges is producing contaminated spent blasting media which may be classified as hazardous by the Environmental Protection Agency based on the Toxicity Characteristic Rule. Recent environmental regulations are making the transportation and disposal of this material difficult and costly. One method of handling the spent material is by using solidification/stabilization (S/S) technology to reuse and/or recycle the contaminated material and render it non-toxic. This report investigates the use of portland cement concretes and mortars to solidify/stabilize the contaminated blasting media and produce a usable construction material. The effects of type I-II portland cement, fly ash, silica fume, superplasticizers, retarders, and corrosion inhibitors on the effectiveness of S/S systems were investigated in terms of compressive strength, rapid chloride ion permeability, and leachability as measured by the Toxicity Characteristic Leaching Procedure (TCLP). The contaminated spent blasting media were characterized by both Total Constituent Analysis and the TCLP, and over 1300 specimens were tested. The study has revealed the effectiveness of portland cement based S/S systems in recycling contaminated spent blasting media in portland cement concretes and mortars.

17. Key Words

abrasive blasting, contaminated spent blasting media, solidification/stabilization (S/S) technology, portland cement concretes, mortars, non-toxic, hazardous

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by

A. G. Garner, R. C. Loehr, R. L. Carrasquillo, and D. W. Fowler

Research Report 1315-1

Research Project 3-9-92/3-1315
Solidification/Stabilization of Hazardous Blast Sand

conducted for the

Texas Department of Transportation

in cooperation with the

U.S. Department of Transportation
Federal Highway Administration

by the

CENTER FOR TRANSPORTATION RESEARCH
Bureau of Engineering Research
THE UNIVERSITY OF TEXAS AT AUSTIN

March 1993

IMPLEMENTATION STATEMENT

This report summarizes the findings of the first year of a two-year study on the Solidification/Stabilization (S/S) of contaminated spent blasting media. The results show the effectiveness of a portland cement based S/S system in recycling the spent blasting abrasives.

Guidelines for the S/S of spent blasting abrasives with portland cement concretes and mortars are suggested. They emphasize the following: establish the job requirements and environmental limits to be met by the S/S material in terms of compressive strength, setting time, and TCLP leaching; characterize all raw materials using TCLP and Total Constituent Analysis; make a trial batch and adjust the mix design if needed for strength, setting, and leaching requirements; ensure that the same materials and job conditions are used both in the trial batches and in the field applications; and ensure that proper mixing sequence is used and that adequate mixing is achieved.

The guidelines developed in this study have been successfully implemented in the recycling of spent blasting material at the Rainbow Bridge in Port Arthur, Texas.

Prepared in cooperation with the Texas Department of Transportation and
the U.S. Department of Transportation, Federal Highway Administration.

DISCLAIMERS

The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented within. The contents do not necessarily reflect the official views or policies of the Federal Highway Administration or the Texas Department of Transportation (TxDOT). This report does not constitute a standard, a specification, or regulation.

NOT INTENDED FOR CONSTRUCTION,
BIDDING, OR PERMIT PURPOSES

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Research Supervisors

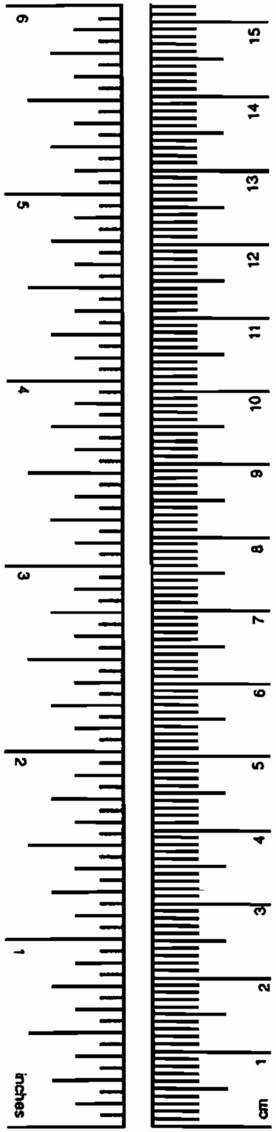
METRIC (SI*) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	2.54	centimeters	cm
ft	feet	0.3048	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	millimeters squared	mm^2
ft^2	square feet	0.0929	meters squared	m^2
yd^2	square yards	0.836	meters squared	m^2
mi^2	square miles	2.59	kilometers squared	km^2
ac	acres	0.395	hectares	ha
		MASS (weight)		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2,000 lb)	0.907	megagrams	Mg
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.0328	meters cubed	m^3
yd^3	cubic yards	0.0765	meters cubed	m^3

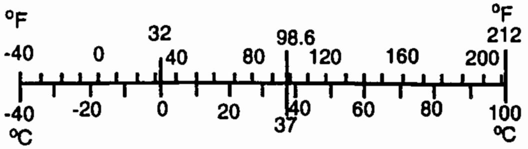
NOTE: Volumes greater than 1,000 L shall be shown in m^3.

Symbol	When You Know	Multiply by	To Find	Symbol
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C



APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	millimeters squared	0.0016	square inches	in^2
m^2	meters squared	10.764	square feet	ft^2
m^2	meters squared	1.20	square yards	yd^2
km^2	kilometers squared	0.39	square miles	mi^2
ha	hectares (10,000 m^2)	2.53	acres	ac
		MASS (weight)		
g	grams	0.0353	ounces	oz
kg	kilograms	2.205	pounds	lb
Mg	megagrams (1,000 kg)	1.103	short tons	T
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	meters cubed	35.315	cubic feet	ft^3
m^3	meters cubed	1.308	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



These factors conform to the requirement of FHWA Order 5190.1A.

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[*] SI is the symbol for the International System of Measurements

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SUMMARY

Lead-based paints have been used on structural steel buildings and bridges for many years because of their effectiveness against corrosion and because little surface preparation is required before the paint system is applied. With time, this protective coating deteriorates and must be removed before repainting. The most common method of removal is by abrasive blasting. Some of the advantages of abrasive blasting are that it is efficient, is cost-effective, and provides a clean, roughened surface for the new coating. However, as a result of blasting, byproducts are produced that may contain contaminants such as lead, chromium, and cadmium, which could pose environmental concerns if disposed of in a landfill. Because of recent environmental regulations, abrasive blasting of lead-based paints, and the disposal of the blasting by-products, have become increasingly difficult and costly.

This study investigated the use of solidification/stabilization (S/S) technology using a portland cement binder to recycle contaminated spent blasting abrasives into a usable construction material. The topics investigated included:

(1) characterization of spent blasting material;
(2) development of construction-oriented and environmentally sound S/S methods;
(3) strength testing of S/S matrices;
(4) permeability testing of S/S matrices; and
(5) leachability testing of S/S matrices.

Guidelines for the use of S/S technology at the construction site using portland cement binders were developed.

CHAPTER 1. INTRODUCTION

1.1 GENERAL

Lead-based paints have been used on structural steel buildings and bridges for many years because of their effectiveness against corrosion and because little surface preparation is required before the paint system is applied. With time, this protective coating deteriorates and must be removed before repainting. The most common method of removal is by abrasive blasting because it is efficient, is cost-effective, and provides a clean, roughened surface for the new coating. However, as a result of blasting, byproducts are produced that may contain contaminants which could pose environmental concerns if disposed of in a landfill. Because of recent environmental regulations [34], abrasive blasting of lead-based paints, and the disposal of the blasting by-products, have become increasingly difficult and costly.

Lead is toxic to humans and other life forms if it is inhaled and/or ingested even in small amounts. It is a cumulative poison that affects the nervous system; it can cause debilitating illness, and even death. It is estimated that 80% of U.S. highway bridges are painted with lead-based paints [13]. Further, a 1987 survey indicated that 23 of 40 states continue to use lead-based paints on bridges [34].

There are several conventional paint removal methods that are currently used to remove paints and coatings from highway bridges. They include: mechanical removal with power tools, vacuum blasting, and blasting with enclosures. The present concern is that abrasive blasting will create airborne material containing lead or other contaminants, which could remain airborne or be deposited on land or water, and thus could eventually come into contact with humans. As a result, a major concern is the safe disposal of the blasting by-products which contain the original spent abrasive, paint chips and dust, and other debris removed from the steel surface.

The U.S. Environmental Protection Agency (EPA) has recently imposed regulations governing the amount of airborne, land, and water waste generated by abrasive blasting, in addition to the amount of leachable lead and other contaminants present in the spent abrasive. The leachable lead content is defined as the percentage of lead in the spent abrasive that will leach into and contaminate the environment. The most common test for leaching is the EPA's Toxicity Characteristic Leaching Procedure (TCLP), which became effective in September of 1990. The following are two legislations relevant to the disposal of spent blasting material:

(a) In 1976, the Resource Conservation and Recovery Act went into effect. It states that any industrial waste with greater than 5 ppm of leachable lead must be treated as a hazardous waste.
(b) On August 8, 1990, the Third Land Disposal Restrictions Act (LandBan) became effective, requiring the treatment of identified hazardous wastes prior to their disposal.

Because of these environmental concerns, spent blasting material that is to be disposed of as waste must be tested by the TCLP. If the results of the TCLP are within the specified EPA limits, then the material can be disposed of in a sanitary landfill without further treatment. If the results do not meet the EPA requirements, then the material should be handled as a hazardous waste. However, the spent material can be recycled instead of being disposed of. In this case, the TCLP is a non-representative test because no waste is being produced, and, therefore, does not need to be performed on the material before it is reused.

One method of treating the spent abrasive and avoiding hazardous waste considerations is by on-site solidification and stabilization (S/S). Both solidification and stabilization processes are designed to: (a) improve the handling and physical properties of the material; (b) decrease the surface area of the material across which the transfer or loss of contaminants can occur; and (c) limit the solubility of any hazardous constituents in the material. The following is a definition of the S/S processes as used in this document:

- Solidification: This process fixates or encapsulates the contaminants into a monolith or solid matrix [24].
- Stabilization: This process limits the solubility or mobility of the contaminants by chemically and/or physically binding the material [24].

There are currently several studies being conducted in the United States and other countries on the properties of portland cement concrete as a S/S binder for various types of hazardous wastes. The study reported herein, which is being conducted at The University of Texas at Austin under the sponsorship of the Texas Department of Transportation (TxDOT), is concerned with investigating the S/S properties of portland cement concretes and mortars with and without chemical and mineral additives on contaminated spent blasting media.

1.2 JUSTIFICATION OF RESEARCH

With recent legislation becoming more restrictive on the classification of spent blasting media, the disposal of lead, chromium, and cadmium contaminated blasting media has become more costly and difficult. If this material is not disposed of properly, the results can be detrimental to both humans and the environment. One potentially inexpensive and practical solution to this problem is using S/S technology with portland cement concretes and mortars to recycle the spent material at the construction site in an environmentally safe manner. This solution applies conventional construction technology and uses readily available conventional materials, lending itself to most bridge maintenance, rehabilitation, and retrofitting programs. However, guidelines must be developed to aid in the disposal/reuse of contaminated spent blasting media.

The pretreatment prior to disposal of hazardous wastes required by the LandBan Act is a secondary yet important reason to provide the TxDOT with guidelines for the use of spent blasting media in portland cement concretes and mortars. The reuse of industrial byproducts benefits the general public by reducing the burden on landfills and reusing some of our resources.

1.3 PROBLEM STATEMENT

The past use of paints containing lead, chromium, cadmium, and aluminum poses unique demands in the maintenance and rehabilitation of existing steel bridges. The use of abrasive blasting to remove these paints and coatings can result in contaminated spent blasting material which may be classified as hazardous based on the Toxicity Characteristic (TC) Rule. The TC Rule specifies levels of constituents including metals which render a material toxic, and, therefore, hazardous, and the TCLP is used to determine if the concentration of toxic metals is hazardous according to the Resource Conservation and Recovery Act.

Lead, chromium, and cadmium are all included in the list of toxic metals and are commonly found in many existing paint systems. The most promising methods of rendering the spent blasting media containing these contaminants environmentally safe appear to involve chemical and physical S/S. However, mixing these contaminants with portland cement in S/S matrices can create problems. For instance, lead, when used in portland cement concretes and mortars, can act as a retarder. Aluminum, although not considered toxic, can be present in many paint systems and can cause problems with strength gain due to the generation of gases within the concrete or mortar.

The disposal of contaminated spent blasting material is costly and difficult. Further, with more stringent disposal requirements predicted for the future, the disposal of this material will become even more controversial and costly. The problem that this study addresses is determining which S/S procedures using portland cement concretes and mortars produce environmentally sound utilization of the contaminated spent blasting material.

1.4 RESEARCH OBJECTIVES

The main objective of this study is to investigate and report on the performance of portland cement concretes and mortars in solidifying and stabilizing contaminated spent blasting material. Another objective is to develop guidelines for the use of these S/S methods with spent blasting material that has different types and levels of contamination.

This study will also investigate the permeability, strength, and leachability of portland cement concretes and mortars used in the S/S of spent blasting material. The permeability and strength of these matrices will affect their durability and serviceability, and the leachability will determine the effectiveness of the S/S method.

1.5 RESEARCH PLAN

The research plan reported herein concentrated on six different areas:

(1) review of past research results;
(2) characterization of spent blasting material;
(3) development of construction-oriented and environmentally sound S/S methods;
(4) strength testing of S/S matrices;
(5) permeability testing of S/S matrices; and
(6) leachability testing of S/S matrices.

The review of other research included past studies as well as ongoing investigations on S/S of hazardous wastes. Characterization of the spent abrasive was performed by total constituent analysis and by the TCLP. Development of S/S methods was based on mix designs providing 3,500 psi strength at 28 days and meeting the EPA's environmental regulations. Strength testing of concretes and mortars used in S/S processes was performed according to ASTM C39-79, Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens. Permeability was determined according to AASHTO T-277, Rapid Chloride Ion Permeability Test. Leachability was investigated by crushing the S/S matrices and testing them according to the TCLP.

The entire research program was conducted in cooperation with the Division of Materials and Tests of TxDOT and with the Federal Highway Administration (FHWA). These agencies have provided valued information and input into the research program.

1.6 FORMAT

The format of this report consists of a review of pertinent literature and research conducted in the area of S/S treatment of hazardous wastes in Chapter 2. Detailed descriptions of materials and test procedures used in this study are contained in Chapter 3. The experimental results are presented in Chapter 4. Chapter 5 provides a discussion of these results. A summary, conclusions, recommendations, and guidelines for the treatment of contaminated spent blasting media are presented in Chapter 6.

CHAPTER 2. LITERATURE REVIEW

2.1 INTRODUCTION

The following is a review of relevant literature dealing with Solidification/Stabilization (S/S) of contaminated materials. Topics covered include types and methods of sandblasting, pertinent EPA regulations, permeability of concrete, silica fume and fly ash, portland cement, superplasticizers, and calcium nitrite.

2.2 REMOVAL OF LEAD-BASED BRIDGE PAINTS

2.2.1 Lead-based Paints

There are several different types of lead-based paints that have been used as protective coating systems on steel bridges. They are:

(1) Red Lead,
(2) Basic Lead Silicochromate,
(3) Basic Lead Chromate,
(4) Basic Lead Sulfate, and
(5) Basic Lead Carbonate.

The first two, however, have been the most commonly used in lead-based systems [50].

2.2.2 Environmental Toxicity

Abrasive blasting can produce airborne material containing lead or other contaminants which can remain airborne or be deposited on land or water. These contaminants can be assimilated by vegetation, animals, and humans and cause sickness and death.

Airborne particles produced by abrasive blasting range in size from 2.5 μm to 50 μm, with the inhalable fraction, less than 15 μm, making up approximately 10 percent of the total blasting emissions [50]. These particles can be deposited on soil, water, streets, and sidewalks, and can be picked up and transported into homes and offices by shoes, pets, and clothing.

The fate of contaminated particles that are deposited on water depends on the particle size and the turbulence of the water. Large particles will sink quickly, whereas smaller particles will float and create surface scum and thus can be incorporated into the aquatic environment.

Contaminated material that is deposited on the soil can either remain on the soil surface, be resuspended by wind, be carried away by surface runoff from rain, be tracked into homes and offices, or be assimilated by vegetation's roots and leaves. The soil residence time for contaminated particles containing lead is several thousand years [50], and background soil lead levels in the U.S. are approximately 16 ppm. Soil lead levels at the site of blasting operations have been as high as 4,800 ppm [50].

In humans, lead and other contaminants can be absorbed by inhalation and/or ingestion. Once in the body, all inorganic forms of lead tend to act in a similar manner, and their effects can be categorized as follows:

(a) hematological effects,
(b) neurobehavioral effects,
(c) reproductive/developmental effects, and
(d) renal effects.

Lead can cause anemia, comas, mental retardation, kidney damage, and even death.

2.2.3 Methods of Blasting, Containing, and Collecting Abrasive Blasting Material

There are a variety of methods for blasting, containing, and collecting abrasive blasting material. They can be categorized as follows [50]:

(1) Vacuum Blasters consist of a vacuum system around a blast nozzle that simultaneously removes the paint system and collects all the debris. Hand-held units suitable for use on bridges are heavy and awkward and are slow compared to open nozzle blasting.

(2) Wet Blasters include wet abrasive blasting, high-pressure water blasting, and air and water abrasive blasting. Low amounts of dust are produced using this method; however, it is difficult to contain and collect the blasting water and debris.

(3) Centrifugal Blasters consist of high-speed rotating blades that propel the abrasive. These systems are generally large units that also retrieve and recycle the spent material and are mainly used on large flat surfaces such as ship hulls.

(4) Vacuum-Shrouded Hand Tools include a variety of hand-held grinders and scrapers, some of which include vacuum systems for debris recovery. They are ineffective in that they remove only a small amount of the paint system at a time and are difficult to use in hard-to-reach places.

(5) Ground and Water Covers consist of canvas or plastic tarps that are placed on the ground or suspended under the bridge to capture spent blasting material which is then collected manually. This method is ineffective in windy conditions.

(6) Water Screens are generally made of straw-faced dams that collect blasting debris from the surface of the water underneath the bridge. This method is effective only on small, slow-flowing streams.

(7) Blast Enclosures completely enclose the blast operator and contain funnels in the floor to divert the spent material to collection bins beneath the bridge. Negative atmosphere can be utilized within the enclosure to facilitate debris collection. This method is efficient in that it provides a high degree of containment; however, enclosures must be designed for each bridge and are inefficient because they must be moved as the work progresses.

(8) Drapes are made of porous material to reduce wind effects and are suspended vertically on both sides of the bridge. They funnel the spent blasting material into bins or barges below the bridge. They are not effective for total containment because they allow dust to escape through their pores.

(9) Water Curtains are created by spray nozzles that form walls of water on both sides of the bridge that contain and deposit blasting debris on the ground. They are effective for reducing airborne dust, but not for recovery since the spent material is carried away by the runoff water.

2.3 DEFINITION OF HAZARDOUS WASTES AND ENVIRONMENTAL REGULATIONS

2.3.1 Definition of Hazardous Wastes

In the United States, land disposal of wastes has been the general practice for many years, even though some of these wastes have been harmful to humans and to the environment. The need for regulations governing the generation, handling, treatment, and disposal of wastes brought about the Resource Conservation Recovery Act of 1976 (RCRA), which dictates what can and cannot be disposed of in a landfill.

Under Subtitle C of RCRA, the EPA gives criteria for identifying the characteristics of a hazardous waste, and also lists particular wastes as hazardous. The following is a definition of the criteria for the characteristics of a hazardous waste:

(a) Criterion 1: Wastes known to be harmful to the environment and to humans are listed wastes.

(b) Criterion 2: To be hazardous, a waste must exhibit one of the following four traits, and is therefore subject to RCRA Subtitle C regulations:

    (1) Be characterized by ignitability, corrosivity, reactivity, TCLP toxicity.
    (2) Be listed as a hazardous waste.
    (3) Be a mixture of a listed hazardous waste and a non-hazardous waste.
    (4) Have not been excluded from regulation as a hazardous waste.

In terms of contaminated spent blasting media, the only applicable criterion is the TCLP toxicity, since this material is not listed as a hazardous waste. Recycled or reclaimed spent blasting material whose TCLP toxicity is within EPA limits is not considered a solid waste under the RCRA. It is therefore not subject to RCRA regulations and is not considered hazardous. Under the RCRA, spent material is considered reclaimed if it is treated to recover a usable product. By reclaiming through a physical process, spent blasting media can be used without regulation in a construction process. It can be recycled by blasting with it again or using it as an anti-skid agent, or it can be reused as an aggregate in a S/S process.

2.3.2 Environmental Regulations

As mentioned above, the RCRA sets forth the criteria for defining the characteristics of a hazardous waste. However, it also dictates the special measures that need to be taken for the disposal of a hazardous waste. They are [35]:

(a) Notification of the proper agencies;
(b) Careful record keeping;
(c) Special shipping requirements; and
(d) Use of an approved hazardous waste disposal facility.

Recently, the EPA proposed the rule, "Hazardous Waste Management System: Identification and Listing of Hazardous Waste," in the May 20, 1992, edition of the Federal Register. The rule proposes to lower the level at which lead-based wastes are considered hazardous from a TCLP value of 5.0 mg/L to 1.5 mg/L [30].

2.3.3 Toxicity Characteristic Leaching Procedure

For spent blasting media, the TCLP is the only applicable criterion for determining if the material has the characteristics of a hazardous waste. The following is background information on the TCLP.

The TCLP was preceded by the EP Toxicity test, which identified materials that had the potential to leach hazardous concentrations of toxic constituents into the environment if placed in a landfill. The TCLP, which became effective September 25, 1990, is a quicker, less expensive, and more reproducible version of the EP Toxicity test. It simulates the environment of a municipal landfill with acidic solutions that can dissolve contaminants in the material. The solution is then checked for concentrations of 26 organic compounds, eight metals, and six pesticides for which the EPA has set TCLP concentration limits.

This study focused on three metals that are commonly found in many paint systems. The metals and their TCLP limits are given in Table 2.1:

Table 2.1 EPA Metal TCLP Limits

Metal	TCLP Limit
Chromium	5.0 mg/l
Cadmium	1.0 mg/l
Lead	5.0 mg/l

2.4 SOLIDIFICATION/ STABILIZATION BACKGROUND

Solidification/Stabilization technology has been in use for nearly 30 years in industrial waste applications. Materials and binders used in S/S methods physically and chemically alter the waste to reduce the mobility of the contaminants, thereby rendering the S/S material non-polluting.

2.4.1 Definition of Solidification/ Stabilization

Solidification/Stabilization technology uses additives to transform contaminated material into a more manageable or less toxic form by physically or chemically altering the materials makeup. The following is a definition of Solidification and Stabilization as used in this document:

- Solidification: This process fixates or encapsulates the contaminants into a monolith or solid matrix [24].
- Stabilization: This process limits the solubility or mobility of the contaminants by chemically and/or physically binding the material [24].

2.4.2 Definitions of Other Related Terms

The following are definitions of terms related to S/S technologies [63]:

- Chemical Fixation: Transforms toxic contaminants into non-toxic forms. It involves chemical bonding of toxins to the binder.
- Encapsulation: The complete coating and/or enclosure of the contaminant with a S/S additive or binder.
- Microencapsulation: The encapsulation of individual particles of contaminant.
- Macroencapsulation: The encapsulation of an aggregation of waste particles.

2.4.3 Solidification/Stabilization Binders

There are three categories of binders used in S/S technology. They are [62]:

(1) Inorganic Binders: Hydraulic cements, lime, pozzolans, gypsum, and silicates.
(2) Organic Binders: Epoxies, polyesters, asphalt/bitumens, polyolefins, and urea-formaldehyde.

(3) Combination of Inorganic and Organic Binders: Diatomaceous earth with cement, and polystyrene, polyurethane and cement.

2.4.4 Binding Mechanisms

There are four major mechanisms of binding in S/S technology which are used in one of four types of processes: in-drum processing, in-plant processing, mobile plant processing, and in-situ processing. The binding mechanisms are [63]:

(1) Sorption: Uses solids to take up any free liquid in the waste. It removes the liquids from the waste solid like a sponge but it does not reduce the potential for leaching.
(2) Lime/Fly Ash Pozzolan Reactions: Produce low-strength cementation that traps contaminants in a solid pozzolan matrix.
(3) Pozzolan/Portland Cement Reactions: Trap wastes in a water-cement matrix. Soluble silicates may be added to contain metals by forming silicate gels.
(4) Thermoplastic Microencapsulation: Blends the waste material with melted asphalt or a similar material and uses physical entrapment as the primary containment method for solids and liquids.

2.4.5 Objectives of Solidification/ Stabilization

The objectives of S/S are to contain a contaminated material and prevent it from entering the environment by producing a solid, improving the material's handling characteristics, reducing the surface area across which the transport of a contaminant can occur, and limiting the mobility of contaminants exposed to leaching.

2.4.6 Factors Affecting the Choice of Solidification/Stabilization Methods

There are five important factors which affect the choice of S/S methods. They are [63]:

(1) Characteristics of the Waste: These will affect the strength and durability of the S/S system and may affect set times and workability.
(2) Process Type and Process Requirements: The process type, waste modification, mixing methods, and material transportation will all affect the choice of a S/S method.
(3) S/S Product Management: The S/S method will be affected by the methods of disposal, storage, and transportation.
(4) Regulatory Factors: These will dictate the acceptability of a certain S/S technology.
(5) Economics: These are based on the waste's characteristics, the process type, transportation methods, and regulatory requirements.

2.5 METHODS OF SOLIDIFICATION/ STABILIZATION AND REUSE OF SPENT BLASTING MEDIA

The following is a summary of S/S methods of spent blasting media compiled from the literature search.

Khosla and Lemming [37] followed two approaches in the S/S of spent blasting media. They investigated the use of portland cement and asphalt concretes as the binding mechanism. For the purposes of this study, only the findings of the portland cement-stabilized material will be presented. The researchers found that aluminum paint particles in the spent blasting media corrode quickly in the highly alkaline environment of portland cement concrete, creating hydrogen gas as a byproduct, and that this reaction could take place over the course of several days. The gas can cause the concrete to swell, crack, and lose its integrity.

To avoid the hydrogen gas problem, the researchers used two approaches. First, they tried blending the spent material with clean sand to reduce the amount of aluminum in the mix. This solution did not work, primarily because large amounts of clean sand were needed to dilute the aluminum, therefore diluting the spent material's contamination to the point of being negligible. The second approach was to create a material that would either set so quickly that no hydrogen gas expansion could occur or would set so slowly that hydrogen gas production would be complete before the material would harden.

For the rapid set alternative, a Class C fly ash with a low W/C ratio was used. The gas production was sensitive to the timing of the addition of mix water. Early addition of the mix water sensitized the aluminum so that when the fly ash was added, large amounts of gas were formed. When the dry materials were mixed first, the gas production was reduced; however, mixing materials were lost due to the creation of dust. This method was determined unsuitable because of the sensitivity of the products to variations in mixing, the amount of dust and moisture control required, and unpredictable end products.

For the slow set alternative, various combinations of portland cement, retarders, recompaction, and remixing have been used without success. However, good results were achieved by using the spent blasting media with building lime in slurry form. Different combinations of agitation and rest periods were used to create a stable, degassed material after four days. Class F fly ash and portland cement were added to the mix, which produced a S/S matrix with a compressive strength of 1,000 psi.

The leaching tests conducted on the material used an acetic acid solution on a finely ground and broken-up matrix. It was observed that the high pH of the cement and lime buffered the acetic acid and reduced the solubility of the contaminating lead. It was also noted that the lead was physically, not chemically, bound in the S/S matrix.

Danaili [27] investigated the use of portland cement and polymer latex to solidify/stabilize aqueous solutions of lead and chromium nitrate of up to 15 percent by weight. It was observed that a latex film formed on the surface of the specimen, sealing in water which was then used in the hydration process. Final set of the S/S matrix occurred between 6 and 14 hours, and little degradation of the matrix was apparent after 50 freeze/thaw cycles. The 28-day compressive strength of the S/S system was between 950 to 1,000 psi, and at the time of publication, no TCLP leaching data were available.

Tseng [55] investigated waste sludges added to Type I portland cement, quick lime, sodium silicate, and calcium chloride which were tested by the EP Toxicity test. It was found that impurities such as organic materials, silts, clays, and coal will delay the set of ordinary portland cement mixes by several days. Large amounts of sulfates will react with the tricalcium aluminate in cement to form calcium sulfoaluminate hydrate which will cause swelling and spalling of the solidified matrix. Salts of zinc, copper, lead, and cadmium were found to cause variations in set times and strengths of the S/S matrices. In general, however, the metal concentrations in the leachate had an inverse relationship with cure time and compressive strength. That is, the longer the curing time and the higher the compressive strength, the lower the concentration of the metal in the leachate. Holmes [33] also found that increased portland cement binder concentrations yield increased treatment efficiencies and better immobilization of the contaminants in the majority of the S/S systems studied.

Poon, Clark, and Perry [44] investigated the strength of ordinary portland cement concrete with sodium silicate used to solidify/stabilize spent blasting media. It was observed that the W/C ratio was the most important factor for the strength of the final product and that the sodium silicate accelerates initial set and early strength, but does not improve final strength. Porosity and pore size distribution were also found to be vital to strength; however, they are dependent on the type of metals being solidified/ stabilized.

2.6 PERMEABILITY OF CONCRETE

2.6.1 General

The permeability of concrete is a physical property representing the ease by which fluids, gases, and ions pass through hardened concrete. There are three principal methods of transport through concrete: capillary attraction, vapor transmission, and ionic diffusion. Each is discussed below .

(a) Capillary attraction transports water, other fluids, dissolved solids, and aggressive agents such as acids, sulfates, and chlorides through concrete.
(b) Vapor transmission is the mechanism by which gases are transported into and out of concrete.
(c) Ionic diffusion is the mechanism that allows ions to move from areas of high concentration to areas of low concentration, irrespective of fluid or vapor transport.

Permeability is an important factor in the long-term durability of concrete. Impermeable concrete can resist the intrusion of aggressive agents, preventing degradation of the matrix and/or leaching of substances held within the matrix. These agents passing through concrete can damage the silicate binding structure, thereby reducing the integrity of the matrix.

2.6.2 Measurement of Permeability

There are many methods for measuring the permeability of concrete. The term 'measure' is used loosely here because of the variety of possible transport mechanisms. Each permeability-measuring method quantifies the property differently, and none considers both flow and diffusion.

Mercury intrusion porosimetry (MIP) is used to determine the volume and size of voids in concrete. This test pressure forces mercury into the concrete voids. As the pressure increases, smaller voids are saturated, allowing the test to quantify the volume and size distribution of the voids in the matrix.

There are several constant head tests for determining the hydraulic permeability due to capillary attraction. These tests are most effective in moderate to high permeability concretes, and when the fluid transmission is through the macropores of the matrix. Hydraulic pressure tests have the drawback that the procedure may damage the internal concrete structure.

Vapor transmission or gas permeability tests have been used by some researchers, but are not well standardized and are very dependent on the moisture content of the specimen at testing time. These tests do not measure the permeability of concrete in the saturated condition.

An ionic diffusion test has been recently developed by Whiting [62] that measures the flow of dc current through saturated concrete surrounded by electrolytes over a period of time. It is designated as AASHTO T-277, "Rapid Chloride Ion Permeability Test of Concrete." The major resistance in the circuit is a concrete sample saturated with water, and the procedure does not damage the internal structure of the concrete matrix. The test is most effective for measuring concretes with low to moderate permeabilities.

The permeability of concrete is considered an important factor in S/S applications. If the solidified/stabilized matrix has low permeability, then the level of contaminant leaching will be reduced, thereby making the system more effective. The "Rapid Chloride Ion Permeability Test of Concrete" is an efficient and accurate method for assessing the permeabilities of different S/S systems.

2.6.3 Review of Ion Permeability Research

The effects of W/C ratio, fly ash, and silica fume on the chloride ion permeability of concrete are reviewed in the following section.

2.6.3.1 Effect of W/C Ratio on Chloride Ion Permeability

Both the W/C ratio and the time of moist curing affect the water, gas, and ion permeability of concrete. The lower the W/C ratio and the longer the moist curing time, the lower the measured permeability.

2.6.3.2 Effect of Fly Ash on Chloride Ion Permeability

In general, portland cement concretes and mortars containing fly ash between 15 and 35 percent replacement by weight of cement have lower chloride ion permeabilities at later ages than ordinary portland cement concretes and mortars. This effect is observed more with ASTM Class F fly ashes than with ASTM Class C fly ashes and is enhanced by heat curing of the specimens.

2.6.3.3 Effect of Silica Fume on Chloride Ion Permeability

Silica fume in portland cement concretes and mortars greatly reduces the chloride ion permeability and increases the electrical resistivity compared to ordinary portland cement matrices. The reduced permeability from silica fume is observed at both early and later ages of the concrete or mortar.

2.7 FLY ASH IN PORTLAND CEMENT CONCRETE

In the past 25 years, the use of fly ash, a byproduct of power generation, in concrete has increased for economic and strength/durability reasons. The use of fly ash in portland cement concrete can reduce the concrete's cost significantly, and can improve its strength and durability over those of conventional concrete.

2.7.1 Definition of Fly Ash

Fly ash is a byproduct of the coal burning process used in power generation plants. This process produces an extremely fine fly ash material mixed with flue gases that escape the combustion chamber and are collected by mechanical or electrostatic precipitators in the smoke stacks before they can be released into the atmosphere.

The chemical makeup of fly ash depends on the type and origin of the coal from which it is produced. It consists of calcium, silica, aluminum, iron, and sulfur oxides as well as trace amounts of magnesium, sodium, potassium, and phosphorous.

Fly ash is a pozzolanic material which is defined as follows:

> [. . .] a siliceous or siliceous and aluminous material which itself possesses little or no cementitious value but which will, in finely divided form and in the presence of moisture react with calcium hydroxide at ordinary temperature to form compounds possessing cementitious properties [9].

2.7.2 Classification of Fly Ashes

The physical and chemical composition of fly ashes are influenced by:

(a) The composition and origin of the source coal;

(b) The degree of pulverization of the source coal;
(c) The design of the combustion unit; and
(d) The method of collecting and processing the fly ash.

The ASTM classification for fly ashes is based on the type of coal from which the fly ash was produced. The most common types of coals are: anthracite and bituminous coals, found in the eastern and north central United States; and sub-bituminous and lignite coals, found in the western and southwestern United States. ASTM Class F fly ashes are produced from burning anthracite and bituminous coals, and ASTM Class C fly ashes come from the burning of sub-bituminous and lignite coals.

2.7.3 Physical Properties of Fly Ashes

The physical properties of fly ashes (such as particle size and shape, fineness, and density) affect the properties of fresh concrete. The size and shape of the fly ash particles depend on the burning efficiency of the combustion unit and the method of collection. Most fly ash particles are spherical in shape since they were formed floating in air, and they range in size from less than 1 µm to more than 100 µm in diameter, with an average size of 20 µm [38]. The fineness of fly ash depends on the collection method, and affects the amount of pozzolanic activity—the finer the fly ash, the higher the pozzolanic activity. Fly ash density depends on its chemical composition. High density ashes are rich in iron and tend to be tan colored, whereas low density fly ashes are high in alumina, silica, and carbon, which give them a grey or dark color.

2.7.4 Chemical Properties of Fly Ashes

The chemical properties and amount of pozzolanic activity of a fly ash influence the characteristics of hardened concrete, mainly in terms of long-term compressive strength and durability. Pozzolanic reactions involve the combination of silica, alumina, and iron oxides from the fly ash with hydrated lime released during the hydration of cement to form a calcium silicate hydrate gel. This process reduces the amount of calcium hydroxide in the cement pores, thereby reducing permeability and increasing strength.

2.7.5 Advantages and Disadvantages of Fly Ash in Portland Cement Concretes and Mortars

Some of the advantages of using fly ash in portland cement concretes and mortars include:

(a) Improved workability;
(b) Reduced bleeding;
(c) Reduced segregation;
(d) Reduced heat of hydration;
(e) Reduced drying shrinkage;
(f) Increased durability;
(g) Reduced permeability;
(h) Reduced cost; and
(i) Increased ultimate tensile and compressive strength.

Some of the disadvantages of using fly ash in portland cement concretes and mortars include:

(a) Reduced early strength;
(b) Reduced sulfate resistance;
(c) Delayed removal of formwork due to slower strength gain; and
(d) Increased dosage of air entraining admixtures.

These advantages and disadvantages depend on the type of fly ash used, the mix proportions, and the compatibility of the materials.

2.8 SILICA FUME IN PORTLAND CEMENT CONCRETE

2.8.1 General Information

Condensed silica fume (CSF, or microsilica) is a byproduct of the smelting process for producing silicon metal and ferrosilicon alloys. It is created when quartz reacts with coal, coke, and wood chips in an electric arc smelting furnace, producing pure SiO_2. These microsilica particles are spherical and have an average size of 0.1–0.2 µm. The loose bulk specific weight of CSF is around 200 kg/m^3, whereas the compacted specific weight is about 500 kg/m^3. It has a specific gravity of 2.20, and an average specific surface area of approximately 20,000 m^2/kg.

CSF is collected in bag houses, and is stored and transported in either a powder or a slurry form. It is used in portland cement concretes in one of two manners:

(1) As a cement replacement to reduce cement content, usually for economic reasons.

(2) As an addition to cement to improve the properties of both the fresh and hardened concrete.

Condensed silica fume was first used in concrete in the 1950s, and its first use in structural concrete was in 1971 in Norway [48].

2.8.2 Pozzolanic and Filler Effects

The pozzolanic effects of condensed silica fume in concrete can be attributed to the reaction of the CSF with $Ca(OH)_2$ during the hydration process. This reaction produces a C-S-H gel with a lower C/S ratio than during cement hydration alone. This in turn creates a more refined pore structure (i.e., less capillary pore spaces), which leads to lower permeability. CSF accelerates the hydration of cement, but it can also result in lower heat of hydration through lower cement contents.

The filler effects of CSF are directly related to the shape and size of the microsilica particles. Since the CSF particles are spherical and extremely small, they act like millions of tiny ball bearings in the fresh concrete mix, and are able to be thoroughly distributed throughout the mix. It is estimated that for a mix with 10 percent CSF, there are 50,000 CSF particles for each cement grain [52]. This improves the pore particle distribution and aids in distributing the hydration products more homogeneously in the mix. This, in turn, produces denser, stronger, and less permeable concretes and mortars.

2.8.3 In Fresh Concretes/Mortars

The effects of adding CSF to fresh portland cement mixes include:

(a) An increased water demand for the same workability. This is due to the microsilica's high surface area and requires the addition of water-reducing admixtures to achieve the same slump as ordinary portland cement (OPC) mixes.
(b) A more cohesive and stable mix, which causes less bleeding and segregation. The lack of bleeding can be so severe that it can lead to cracking and plastic shrinkage.
(c) Increased C_3S hydration due to high surface area of CSF.
(d) An increased setting time with increased dosages of CSF for equal strength concretes.
(e) A darker concrete color due to the dark color of microsilica.

2.8.4 In Hardening Concretes/Mortars

The effects of CSF in hardening portland cements and mortars include:

(a) An increased sensitivity to curing temperatures compared to OPC mixes.
(b) A slower strength gain than OPC mixes at curing temperatures less than 20 degrees Celsius.
(c) A faster strength gain than OPC mixes at curing temperatures greater than 20 degrees Celsius.
(d) The major contribution of CSF to strength gain is in the first 3 to 28 days at a curing temperature of 20 degrees Celsius.

2.8.5 In Hardened Concretes/Mortars

CSF produces the following effects in hardened concretes and mortars:

(a) Increased strength compared to that of OPC mixes.
(b) Reduced tensile and flexural strengths if not moist-cured, compared to those of OPC mixes.
(c) Increased brittleness.
(d) Increased potential for shrinkage since bleeding is reduced.
(e) Improved bond to aggregates, reinforcement, fibers, or old concrete.
(f) Increased abrasion, erosion, and wear resistance.

2.8.6 Durability

2.8.6.1 Permeability

CSF concrete mixes have very low permeabilities because of the microsilica's pozzolanic and filler effects. The main improvement in the matrix due to the CSF is at the aggregate-paste interface.

2.8.6.2 Frost Resistance

The literature search revealed contradictory test results with respect to the effect of CSF on the frost resistance of concrete. Air entraining admixtures still seem to be the most effective method for improving the freeze-thaw durability of concrete/mortar mixes.

2.8.6.3 Chemical Resistance

CSF mixes tend to have an increased resistance against sulfate attack and alkali aggregate reaction since the refined pore structure of these mixes reduce the mobility of the harmful ions. Also, the reduced C/S ratios in CSF mixes allow more aluminum and/or alkalis to be incorporated into the matrix, essentially isolating them from causing any reactions.

2.9 PORTLAND CEMENT

Portland cement is produced by mixing together clay-and lime-bearing materials and heating them to approximately 1,500° C, producing portland cement clinker. The clinker is then ground to a fine powder and a small amount of gypsum is added. Portland cement is comprised of five major crystalline compounds: tricalcium aluminate (C_3A), tetracalcium aluminoferrite (C_4AF), belite (C_2S), alite (C_3S), and gypsum (CSH_2). When water (H) is added to this mixture, all five of these crystalline components precipitate as hydrated compounds.

The hydrated form of alite and belite, calcium silicate hydrate (C-S-H), is the main binding component of hardened portland cement paste, and will refine itself until no more alite or belite remain in the pore water solution of the concrete. Portland cement hydrates according to the reactions in equations (2.1) and (2.2), where alite reacts at a faster rate than belite and calcium hydroxide (CH) is a soluble byproduct with no cementitious value.

$$2C_3S + 6H \longrightarrow C\text{-}S\text{-}H + 3CH \qquad (2.1)$$

$$2C_2S + 4H \longrightarrow C\text{-}S\text{-}H + CH \qquad (2.2)$$

Secondary binding components form from the hydration of C_3A and gypsum, creating ettringite ($C_6AS_3H_{32}$), monosulfoaluminate (C_4ASH_{12}), and calcium aluminate hydrate (C-A-H) according to equations (2.3) to (2.5).

$$C_3A + 3CSH_{22} + 26H \longrightarrow C_6AS_3H_{32} \qquad (2.3)$$

$$2C_3A + C_6AS_3H_{32} + 4H \longrightarrow C_4ASH_{12} \qquad (2.4)$$

$$C_3A + CH + 18H \longrightarrow C\text{-}A\text{-}H \qquad (2.5)$$

The alumina and silicate hydrates comprise approximately 60-65 percent of the hardened cement paste, the CH occupies about 20 percent, and the remainder is made of water and alumina and ferrite compounds.

The W/C ratio is the most important parameter affecting the hardened paste's strength, durability, and porosity. By removing the water in the capillary pores of the hardened matrix, and replacing it with compatible materials such as fly ash or silica fume, the durability and strength of the paste would increase and the permeability would decrease, thereby reducing the leachability of the matrix [27].

2.10 HIGH-RANGE WATER-REDUCING ADMIXTURES

2.10.1 Background

High-range water reducing admixtures (HRWR), commonly known as superplasticizers, are chemical admixtures that improve the plastic and hardened properties of concretes and mortars. They are capable of reducing the water requirements for a given workability by up to 30 percent, thereby reducing the W/C ratio, increasing strength, and lowering permeability. They are compatible with most other admixtures such as air entraining agents, corrosion inhibitors, retarders, and accelerators.

Superplasticizers greatly improve the workability of fresh concrete without causing undesirable properties in the hardened state. The increased workability is short-lived, however, lasting only about 30 minutes, but redosing is possible and is not detrimental to the concrete. Second-generation superplasticizers have been developed that remain effective for up to two hours, increasing the window of workability.

Dosage requirements for superplasticizers depend on the type and brand of HRWR, mix design, temperature, and time of addition. Common dosages range from 10 to 20 ounces per 100 pounds of cement.

2.10.2 Chemistry

In general, the superplasticizer molecules surround particles of cement, creating a watery shell (Figure 2.1). The molecules attract cement particles on one side and water molecules on the other, creating a lubricating film around the cement particles, thereby reducing the concrete's plastic viscosity. Superplasticizers also disperse large irregular agglomerations of cement particles into smaller particles and create a more complete matrix at six months of age.

2.10.3 Effects of Superplasticizers on Fresh Concrete

Superplasticizers affect the properties of fresh concrete in the following ways:

- Workability is improved, although it is dependent on initial slump, amount of cement, type and dosage of HRWR, time of addition of HRWR, temperature, mixing time and speed, and addition of other admixtures.

- Air Content is reduced due to the lowered viscosity of the mix, which allows the air to escape more easily. It is estimated that 30 to 40 percent of the initial air content is lost through the addition of superplasticizers.

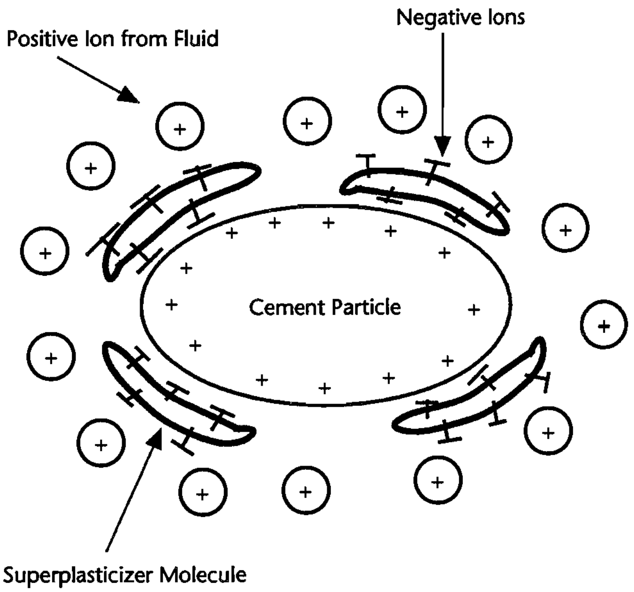

Figure 2.1 *Superplasticizer acting on a cement particle [28]*

- Bleeding is increased compared to that of regular concretes of the same W/C ratio. This is caused by the delayed set time of superplasticized mixes.
- Set Time is increased because superplasticizers delay the hydration of cement. The amount by which the set time is increased depends on the type and dosage of superplasticizer.

2.10.4 Effects of Superplasticizers on Hardened Concrete

Superplasticizers affect the properties of hardened concrete in the following ways:

- Air Void System quality is reduced with the use of HRWR. The spacing factor, as well as the bubble size, is increased, compared to that of non-superplasticized concrete.
- Compressive Strength is equal to or greater than that of concrete mixes made without superplasticizer. This can be explained by the reduction of the W/C ratio and total air content in superplasticized mixes.
- Freeze/Thaw Resistance is reduced in superplasticized mixes since the air void system quality is reduced. With proper air entrainment, however, the resistance is just as effective as that of systems without HRWR.
- Permeability is reduced compared to that of mixes of the same workability without HRWR. However, compared to mixes with the same W/C ratio, superplasticized concretes are more permeable than non-superplasticized ones.

2.11 CALCIUM NITRITE

Calcium nitrite is generally used in reinforced concrete mixtures as a corrosion inhibitor. It is usually in the form of a 30 percent calcium nitrite solution, and can be used in concrete in combination with superplasticizers and air entraining agents with no detrimental effects. Calcium nitrite admixtures meet the requirements of ASTM C494 and are dosed on the basis of gallons per cubic yard of concrete.

It has been found that the service life under severe exposure conditions of reinforced concretes containing calcium nitrite and a water reducing agent is greatly increased. The lower the W/C ratio, the more effective the corrosion protection provided by the calcium nitrite. The use of calcium nitrite in concrete tends to increase the measured values from the AASHTO T-277 Rapid Chloride Ion Permeability Test. However, calcium nitrite is compatible with concretes containing silica fume and/or fly ash, which have reduced chloride permeabilities.

The use of calcium nitrite in concrete has the following effects:

(a) It protects steel and aluminum against chloride-induced corrosion;
(b) Its efficiency is improved as the concrete quality is improved;
(c) It improves the concrete compressive strength; and
(d) It lowers corrosion rates once corrosion begins.

The corrosion of aluminum in concrete is based on the reaction of the aluminum with the alkalies in the cement. The product of the reaction is an aluminum alkali and hydrogen gas. The hydrogen gas can be detrimental to the setting of fresh concrete by creating large amounts of gas bubbles which destroy the integrity of the matrix.

Berke, Shen, and Sundberg [16] used a 30 percent calcium nitrite solution dosed at two and four gallons per cubic yard of concrete to test its anti-corrosive properties on aluminum conduit embedded in the concrete. Aluminum embedded in concrete does not react like steel in concrete with respect to corrosion. Aluminum does not passivate as does steel, and chlorides need not be present for it to corrode. In this study, it was observed that the corrosion inhibitor, when dosed at four gallons per cubic yard, increased the 28-day compressive strength of the concrete by 34 percent and that it effectively delayed and reduced the corrosion of the aluminum [16].

The corrosion of aluminum in concrete takes place whether the aluminum is in the form of a conduit or in the form of spent blasting media contaminated with aluminum-based paints. This study investigated the use of calcium nitrite in portland cement S/S mortars to inhibit the corrosion of the aluminum-based paint chips found in the spent blasting media and to avoid the detrimental effects of the hydrogen gas by-product.

2.12 LEAD IN PORTLAND CEMENT CONCRETE

Lead ions tend to retard the setting of portland cement-based materials and may affect the stability of S/S systems using portland cement as the primary binding mechanism. The lead ions are found well dispersed over the surface of the cement particles and form a gelatinous coating of hydroxides on the outer portions of the C_2S, C_3S, and C_3A particles. Diffusion of water through the coating occurs at a slow rate, which in turn slows the rate of hydration and increases setting times. During the retardation period, no calcium hydroxide is formed and no water is bound, and at the end of retardation, rapid hydration and hydrolysis of C_3S occurs. The retardation process does not affect the initial reactions between ferrites, aluminates, and gypsum during the first few minutes of mixing; thus the first period of rapid sulfate binding to form ettringite is not delayed.

The lead retardation process is cement-dependent. That is, different types of cements react differently to similar lead contents. Cements with high specific surface areas, or very fine cements, tend to have shorter retardation periods than coarse cements. Also, portland cement matrices containing significant amounts of lead may never hydrate fully, resulting in an incomplete internal hydrated structure which lowers the integrity of the matrix.

CHAPTER 3. MATERIALS AND TEST PROCEDURES

3.1 INTRODUCTION

One hundred thirteen different portland cement mortar mixes were tested to investigate the solidification/stabilization capabilities of portland cement concrete/mortar on spent blasting media. The spent material was either blast slag, blast sand, blast dust, or a combination of blast sand and blast dust. Among the main elements of concern found in the spent material were lead, chromium, cadmium, and aluminum.

The variables studied were:

(a) water/cement ratio;
(b) cement content;
(c) amount of fly ash;
(d) amount of silica fume;
(e) dosage of superplasticizer;
(f) spent material type, composition, and amount;
(g) strength gain over time;
(h) leaching of lead, chromium, and cadmium as per the Toxicity Characteristic Leaching Procedure; and
(i) permeability.

This chapter describes the materials, specimens, testing procedure, and testing equipment used in the investigation. Although not considered representative of the expected leaching characteristics in the field, the materials analyses presented in this chapter include those obtained by the Total Constituent Analysis (TCA).

3.2 MATERIALS

Except for the spent blasting materials, all other materials used in this study are commercially available and currently used in the production of portland cement concrete locally in Texas. The materials used include portland cement, silicious river sand, fly ash, silica fume, and high-range water-reducing admixtures.

3.2.1 Portland Cement

The portland cement used in all mixes was LaFarge Type I-II cement conforming to ASTM C150-86, Standard Specification for Portland Cement. Tables 3.1 and 3.2 give the cement's physical and chemical properties, respectively. The composition of the portland cement as determined by Total Constituent Analysis is given in Table 3.3.

Table 3.1 Physical properties of Type I-II portland cement used in the experimental program (ASTM C150-86)

Specific Surface, cm^2/g	Blaine	3,540
	Wagner	1,920
Compressive Strength, psi	1 Day	2,260
	3 Days	3,960
	7 Days	5,300
	28 Days	6,830
Time of Setting, min	Vicat	Gilmore
Initial	100	220
Final	130	230

Table 3.2 Chemical properties of Type I-II portland cement used in the experimental program (ASTM C150-86)

Chemical Composition	Notation	% by Weight
Silicon Dioxide	SiO_2	21.6
Aluminum Dioxide	Al_2O_3	4.4
Ferric Oxide	Fe_2O_3	3.9
Calcium Oxide	CaO	65.1
Magnesium Oxide	MgO	1.2
Sulfur Trioxide	SO_3	2.4
Loss on Ignition	LOI	0.9
Insoluble Residue		0.1
Free Lime		0.6
Tricalcium Silicate	C_3S	59.0
Tricalcium Aluminate	C_3A	5.0
Total Alkali	Na_2O Equivalent	0.6

Table 3.3 Elemental analysis of portland cement from total constituent analysis

Constituent	Value (mg/l)
Lead	0.99
Chromium	2.33
Cadmium	0.66
Aluminum	Not available

3.2.2 Fine Aggregate

The fine aggregate used was a silicious concrete river sand from the Colorado River in Austin, Texas. It had a bulk specific gravity at SSD of 2.58, an absorption capacity of 1.44 percent, and a fineness modulus of 2.82. Table 3.4 shows the results of the sieve analysis.

Table 3.4 Sieve analysis of silicious river sand

Sieve Size	Cum. Percent Retained	ASTM C33-90 Limits
3/8 in.	0.0	
# 4	0.07	0-5
# 8	8.22	0-20
# 16	29.23	15-50
# 30	59.10	40-75
# 50	87.91	70-90
# 100	97.52	90-98
Pan	–	–

3.2.3 Water

The water used in all mixes was tap water conforming with ASTM C94-86b, Standard Specification for Ready-Mixed Concrete.

3.2.4 Spent Blast Slag

The spent blast slag used was obtained from the Texas Department of Transportation's Division of Materials and Tests (D-9) office. The material had been used on the Airport Boulevard Bridge project in Austin, Texas. It had a bulk specific gravity at SSD of 2.55, an absorption capacity of 3.25 percent, and a fineness modulus of 2.67. The composition of the spent blast slag as determined by Total Constituent Analysis is given in Table 3.5. The results of the TCLP on the spent blast slag are given in Table 3.6.

3.2.5 Spent Blast Sand

The spent blast sand used was obtained from the Texas Department of Transportation's Rainbow Bridge project near Beaumont, Texas. It had a bulk specific gravity at SSD of 2.55, an absorption capacity of 2.71 percent, and a fineness modulus of 2.25. The compositions of the two spent blast sand samples as determined by Total Constituent Analysis are given in Tables 3.7 and 3.8. The results of the TCLP on the samples are given in Tables 3.9 and 3.10. No mixes were made with the Sample 2 material.

Table 3.5 Total constituent analysis for the spent blast slag

Constituent	Value (mg/l)
Lead	5.92
Chromium	8.93
Cadmium	0.59
Aluminum	Not available

Table 3.6 TCLP results for the spent blast slag

Constituent	Value (mg/l)
Lead	0.42
Chromium	4.82
Cadmium	0.27
Aluminum	5.44

Table 3.7 Total constituent analysis for the spent blast sand, sample 1

Constituent	Value (mg/l)
Lead	7.34
Chromium	1.09
Cadmium	0.31
Aluminum	3.85

Table 3.8 Total constituent analysis for the spent blast sand, sample 2

Constituent	Value (mg/l)
Lead	Not available
Chromium	Not available
Cadmium	Not available
Aluminum	Not available

3.2.6 Spent Blast Dust

The spent blast dust was collected on site during sandblasting operations and separated from the spent blast sand described in Section 3.2.5 by a vacuum system. The compositions of two samples of the spent blast dust as determined by Total Constituent Analysis are given in Tables 3.11 and 3.12. The results of the TCLP on the samples are given in Tables 3.13 and 3.14. The material's bulk specific gravity was assumed to be 3.15.

Table 3.9 TCLP results for the spent blast sand, sample 1

Constituent	Value (mg/l)
Lead	2.02
Chromium	0.58
Cadmium	0.57
Aluminum	0.54

Table 3.10 TCLP results for the spent blast sand, sample 2

Constituent	Value (mg/l)
Lead	1.13
Chromium	1.42
Cadmium	0.53
Aluminum	1.38

Table 3.11 Total constituent analysis for the spent blast dust, sample 1

Constituent	Value (mg/l)
Lead	57.92
Chromium	14.48
Cadmium	1.36
Aluminum	38.92

Table 3.12 Total constituent analysis for the spent blast dust, sample 2

Constituent	Value (mg/l)
Lead	Not available
Chromium	Not available
Cadmium	Not available
Aluminum	Not available

3.2.7 Unseparated Spent Blast Sand/Dust Mix

An unseparated mixture of spent blast sand and dust was collected on site during sandblasting operations at TxDOT's Rainbow Bridge project. The composition of the blast sand/dust mixture as determined by Total Constituent Analysis is given in Table 3.15. The results of the TCLP on the sample are given in Table 3.16. The material's bulk specific gravity was 2.38.

Table 3.13 TCLP results for the spent blast dust, sample 1

Constituent	Value (mg/l)
Lead	9.48
Chromium	5.36
Cadmium	1.07
Aluminum	2.54

Table 3.14 TCLP results for the spent blast dust, sample 2

Constituent	Value (mg/l)
Lead	1.14
Chromium	9.51
Cadmium	1.08
Aluminum	4.95

Table 3.15 Total constituent analysis for the spent blast sand/dust mix

Constituent	Value (mg/l)
Lead	19.63
Chromium	7.79
Cadmium	0.68
Aluminum	14.22

Table 3.16 TCLP results for the spent blast sand/dust mix

Constituent	Value (mg/l)
Lead	0.48
Chromium	2.09
Cadmium	0.62
Aluminum	0.56

3.2.8 Fly Ash

One type of Class C fly ash was used in this study. It was produced in Houston, Texas, and had a Bulk Specific Gravity of 2.58. It conformed to ASTM C618-85, Standard Specification for Fly Ash and Raw or Calcined Natural Pozzolan for Use as a Mineral Admixture in Portland Cement Concrete.

Tables 3.17 through 3.19 give the chemical composition and physical properties of the Class C fly ash, as determined by Total Constituent Analysis.

Table 3.17 Chemical properties of Class C fly ash (ASTM C618-85)

Chemical Composition	Notation	% by Weight
Silicon Dioxide	SiO_2	35.59
Aluminum Oxide	Al_2O_3	19.73
Iron Oxide	Fe_2O_3	6.76
Sum of SiO_2,Al_2O_3,& Fe_2O_3		62.08
Magnesium Oxide	MgO	4.70
Sulfur Trioxide	SO_3	1.72
Moisture Content	MC	0.01
Loss on Ignition	LOI	0.21
Available Alkalies as Na_2O	Na_2Oeq	1.33
Calcium Oxide	CaO	25.73

Table 3.18 Physical properties of Class C fly ash (ASTM C618-85)

Physical Properties	Value (%)
Fineness: (amount retained on #325 sieve)	16.52
Water Requirement (percent control)	94
Specific Gravity	2.58
Autoclave Expansion	+0.05
Strength Activity Index with Portland Cement	
7-Day	94
28-Day	100

Table 3.19 TCLP results for the Class C fly ash

Constituent	Value (mg/l)
Lead	1.37
Chromium	2.02
Cadmium	0.72
Aluminum	1,229.60

3.2.9 Silica Fume

The silica fume used was a dry, condensed silica fume with a bulk specific gravity of 2.20, marketed by Master Builders, Inc. Table 3.20 gives the chemical and physical properties of the silica fume, Table 3.21 gives its composition as determined by Total Constituent Analysis, and Table 3.22 gives the results of the TCLP.

3.2.10 Superplasticizer

The superplasticizer used was a napthalene-based admixture marketed by Master Builders under the commercial name Rheobuild 1000. The dosages used ranged from 8 oz/cwt to 34.7 oz/cwt of cementitious material.

3.2.11 Calcium Nitrite

The calcium nitrite used was a liquid admixture marketed by W. R. Grace under the commercial name DCI Corrosion Inhibitor, conforming with an ASTM C-494 Type C admixture. Normal recommended dosages of this admixture, when used for corrosion inhibition, are between 2 and 10 gallons per cubic yard of concrete. The dosages used in this study were 0.75 gal/yd^3, 1.5 gal/yd^3, and 2.25 gal/yd^3 of mortar.

Table 3.20 Chemical and physical properties of silica fume

Property	Notation	Value
Silicon Dioxide, min %	SiO_2	85.0
Chloride Ions, max %	CI	0.25
Sulfur Trioxide, max %	SO_3	1.0
Available Alkalis, max %	Na_2O	1.5
Moisture Content, max %	MC	3.0
Loss on Ignition, max %	LOI	4.0
Specific Surface Area, min m2/gm	BET	20.0
Bulk Density, min lbs/cu ft		
X-Ray Diffraction	Non-crystalline	30.3

Table 3.21 Total constituent analysis of the silica fume

Constituent	Value (mg/l)
Lead	43.733
Chromium	1.518
Cadmium	0.358
Aluminum	42.104

Table 3.22 TCLP results for the silica fume

Constituent	Value (mg/l)
Lead	7.14
Chromium	0.28
Cadmium	0.06
Aluminum	5.09

3.3 SPECIMENS

3.3.1 2-inch Mortar Cubes

Six 2-inch cubes were cast from each batch to be used for the Toxicity Characteristic Leaching Procedure at 7 and/or 28 days after casting.

3.3.2 3-inch by 6-inch Cylinders

Six 3-inch by 6-inch cylinders were cast from each batch for compressive strength testing at 7, 28, and 90 days after casting.

3.3.3 4-inch by 8-inch Cylinders

Two 4-inch by 8-inch cylinders were cast from each batch for permeability testing at 28 or 56 days after casting.

3.4 FORMS AND MOLDS

Three types of molds were used to cast specimens. Solid brass mortar cube molds meeting the specifications of ASTM C109-87, Standard Test Method for Compressive Strength of Hydraulic Cement Mortars, were used to cast the 2-inch cubes used for the Toxicity Characteristic Leaching Procedure. Disposable plastic and cardboard cylinder molds conforming to ASTM C470-87, Standard Specification for Molds for Forming Concrete Test Cylinders Vertically, were used for casting the strength and permeability specimens, respectively.

3.5 MIX PROPORTIONS

Appendices 1 and 4 contain detailed information on the specimen designation and corresponding mix proportions for the mixes studied. When mineral additives were used, fly ash was used as a volumetric replacement for portland cement in the amount of 30 percent, and silica fume was used in addition to the portland cement in the amount of 12 percent of the weight of portland cement.

3.6 MIX PROCEDURE

All batches were mixed using the following procedure:

(a) All raw materials were weighed to the nearest one-tenth of a pound;
(b) the mixer was charged with the dry materials, followed by mixing for ten seconds;
(c) then the water and superplasticizer were added, followed by mixing for three minutes;
(d) the batch was then allowed to rest without mixing for two minutes;
(e) if needed, additional superplasticizer was added to achieve the required workability; and
(f) the batch was then mixed for three more minutes.

3.7 CASTING

Specimen molds were filled in two equal layers each and vibrated on a vibrating table for twenty seconds according to ASTM C192-88, Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory. The specimens were then trowel-finished using aluminum trowels.

3.8 CURING

Curing consisted of placing the specimens under wet burlap and polyethelene for the first 24 hours after casting, as per ASTM C192-88, Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory. The specimens were then placed in a curing room at 23 degrees Celsius and 100 percent relative humidity, conforming to ASTM C511-85, Standard Specification for Moist Cabinets, Moist Rooms, and Water Storage Tanks Used in the Testing of Hydraulic Cements and Concretes, until testing.

3.9 TESTING

3.9.1 Fresh Concrete

3.9.1.1 Flow Test

The workability of the mortar mixes was measured according to ASTM C109-87, Standard Test Method for Compressive Strength of Hydraulic Cement Mortars. The targeted workability was established on the basis of the control mixes, and all subsequent mixes were batched to have similar workability as indicated by the flow table test.

3.9.2 Hardened Concrete

3.9.2.1 Compressive Strength Testing

Compressive strength was determined using 3 inch by 6 inch cylinders tested according to ASTM C39-79, Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens, at 7, 28, and 90 days. The cylinders were capped using unbonded neoprene caps inside steel restraining rings.

3.9.2.2 Permeability Testing

The permeability was determined according to AASHTO T-277, Rapid Chloride Ion Permeability Test, at 7 and/or 28 days, with the following exceptions:

(1) Tests were conducted on 4-inch diameter mortar cylinders instead of 3.75-inch diameter concrete core specimens [62];
(2) Two specimens were cut from the interior of each cylinder instead of using two specimens cut from the ends of a cored specimen [62]; and
(3) Specimens were kept saturated in a sealed vacuum for an hour after evacuation, in lieu of a forced vacuum [62].

3.9.2.3 Toxicity Characteristic Leaching Procedure (TCLP)

The TCLP testing was performed as per EPA 40 CFR Chapter 1 (7-1-90 Edition), Appendix II, at 7 and/or 28 days. Detailed information on the TCLP can be found in Reference 17.

3.10 EQUIPMENT

3.10.1 Mixing Equipment

All mixing was done in a Reynolds 1/3-cubic-foot-capacity mortar mixer, at medium speed.

3.10.2 Curing Equipment

All specimens were cured at 23 degrees Celsius and 100 percent relative humidity in a curing room meeting ASTM C192-88, Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory.

3.10.3 Compressive Strength Testing Equipment

All compressive strength tests were performed on a Forney model LD8606 600-kip testing machine according to ASTM C39-79, Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens.

3.10.4 Permeability Testing Equipment

The permeability specimens were tested according to AASHTO T-277, Rapid Chloride Ion Permeability Test, using a Helios data acquisition system. Figure 3.1 shows the system diagram for the Rapid Chloride Ion Permeability Test.

The test consists of a concrete disk, 4 inches in diameter by 2 inches thick, placed between two conducting cells of ionic solutions. A DC voltage is placed across the system, and the cumulative amount of coulombs, amps• second, passing through the specimen in a six-hour period is measured. This test is a relative measure of the ease with which ions pass through mortar or concrete over a period of time.

3.10.5 TCLP Testing Equipment

For a list of the equipment used to test the specimens under the Toxicity Characteristic Leaching Procedure, please refer to Reference 17.

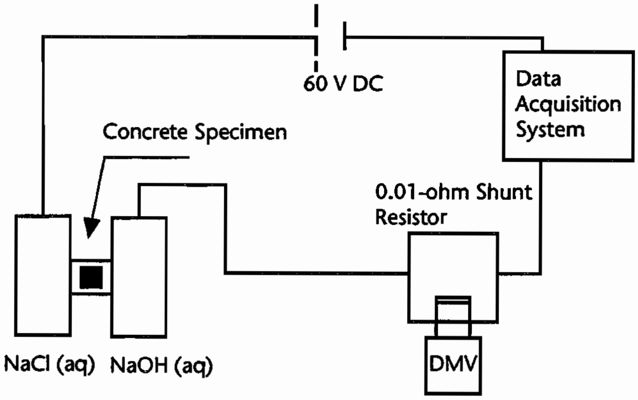

Figure 3.1 System diagram for rapid chloride ion permeability test

CHAPTER 4. EXPERIMENTAL RESULTS

4.1 INTRODUCTION

The compressive strength, chloride ion permeability, and TCLP leaching of portland cement S/S systems were investigated in this study. Typical data are presented in this chapter, while detailed test data are found in Appendices 2, 3, 5, and 6. Detailed information regarding mix proportions and mix designations for all of the mortar batches is presented in Appendices 1 and 4. The results presented herein are analyzed and discussed in Chapter 5.

4.2 FRESH MORTAR PROPERTIES

The various mortar mixes were batched to a constant consistency as measured using a flow table. The air content was assumed to be 2 percent. The ambient temperature during mixing and casting was between 60 and 95° F.

4.3 MIX PROPORTIONS AND DESIGNATIONS

The mix proportions and designations used for S/S of the spent blast sand and dust and for the spent blast slag are presented in Appendices 1 and 4, respectively. A sample of these is given in Tables 4.1 and 4.2.

4.4 COMPRESSIVE STRENGTH RESULTS

The compressive strengths of the S/S mixes containing spent blast sand and spent blast dust are presented in Appendix 2. The compressive strengths for the mixes containing spent blast slag are presented in Appendix 5. Compressive strength is given as the average strength of two cylinders at 7, 28, and 90 days. A sample of these results is shown in Tables 4.3 and 4.4.

4.5 RAPID CHLORIDE ION PERMEABILITY RESULTS

The rapid chloride ion permeability of the S/S mixes is presented in Appendix 2 for the spent blast sand and dust stabilized material and in Appendix 5 for the spent blast slag stabilized material. Permeability was tested at 28 days, and a sample of the results is given in Tables 4.3 and 4.4.

Table 4.1 Typical mix proportions and designations for spent blast sand and dust S/S mixes

1	2	3	4	5	7	10	11	12
Mix	Cement (lbs)	Concrete Sand (lbs)	Blast Sand (lbs)	Blast Dust (lbs)	HRWR (oz/cwt)	Fly Ash (lbs)	Silica Fume (lbs)	W/C by wt
SD1	600	440	660	0	23.5	0	72	0.31
SD1-D	600	440	660	110	18.0	0	72	0.29
SD2	600	0	1,100	0	18.8	0	72	0.28
SD2-D	600	0	1,100	183	26.5	0	72	0.28
SD3	420	440	660	0	20.9	180	72	0.31
SD3-D	420	440	660	110	20.5	180	72	0.31
SD4	420	0	1,100	0	19.2	180	72	0.27
SD4-D	420	0	1,100	183	22.6	180	72	0.35

Table 4.2 Typical mix proportions and designations for spent blast slag S/S mixes

1	2	3	4	5	6	7	8
Mix	Cement (lbs)	Concrete Sand (lbs)	Blast Slag (lbs)	HRWR (oz/cwt)	Fly Ash (lbs)	Silica Fume (lbs)	W/C by wt
SGIII-5	600	800	300	11.6	0	72	0.31
SGIII-6	600	800	300	15.9	0	72	0.29
SGIII-7	600	800	300	20.8	0	72	0.27
SG100	420	825	275	8.0	180	0	0.28
SG101	420	825	275	8.0	180	0	0.27
SG103	420	825	275	17.2	180	0	0.23
SG200	420	550	550	8.0	180	0	0.29
SG201	420	550	550	8.0	180	0	0.27
SG203	420	550	550	19.2	180	0	0.24
SG300	420	275	825	8.0	180	0	0.32
SG301	420	275	825	8.0	180	0	0.29
SG302	420	275	825	12.0	180	0	0.28
SG303	420	275	825	16.0	180	0	0.26

Table 4.3 Compressive strength and permeability results for several spent blast sand and dust S/S mixes

1	2	3	4	5
Mix	7-Day f 'c (psi)	28-Day f 'c (psi)	90-Day f 'c (psi)	Permeability (coulombs)
SD1	3,790	4,050	4,720	110
SD1-D	2,740	3,630	3,620	1,260
SD2	3,710	5,120	4,850	380
SD2-D	1,550	2,450	2,700	1,630
SD3	4,340	5,190	5,270	290
SD3-D	3,510	5,730	5,070	510
SD4	3,370	5,440	4,900	380
SD4-D	2,920	6,620	6,140	260

Table 4.4 Compressive strength and permeability results for several spent blast slag S/S mixes

1	2	3	4	5
Mix	7-Day f 'c (psi)	28-Day f 'c (psi)	90-Day f 'c (psi)	Permeability (coulombs)
SG III-5	7,250	9,240	9,830	N/A
SG III-6	6,970	8,260	9,450	N/A
SG III-7	7,210	8,590	9,300	N/A
SG100	5,870	6,250	7,320	N/A
SG101	6,360	7,210	7,310	N/A
SG103	7,310	8,360	9,910	N/A
SG200	4,160	5,070	6,840	N/A
SG201	4,480	5,585	N/A	N/A
SG203	4,360	5,180	5,010	3,710
SG300	2,990	4,340	5,780	9,770
SG301	3,220	4,540	N/A	6,740
SG302	N/A	4,590	5,600	4,790
SG303	3,160	4,290	5,000	11,190

N/A: Data not available

4.6 TCLP LEACHING RESULTS

The TCLP leaching results of the S/S mixes are presented in Appendix 3 for the spent blast sand and dust stabilized material and in Appendix 6 for the spent blast slag stabilized material. Leachability was tested at 7 and/or 28 days for chromium, cadmium, lead, and aluminum. Tables 4.5 and 4.6 show samples of these results.

4.7 FIELD APPLICATIONS OF S/S MIXES

From the results of the experimental program, one S/S mix was chosen for field use at TxDOT's Rainbow Bridge project in Port Arthur, Texas. It is being used to solidify/stabilize contaminated spent blast sand, blast dust, and blast sand/dust mixtures. By the end of the maintenance project, an estimated 3,000 barrels of spent material will have been generated, all of which is to undergo S/S treatment and be used as backfill for the deadmen near the bridge piers. The stabilized material is being formed into 1-foot-by-1-foot-by-6-inch blocks, and is being cured at the job site under plastic tarps. Approximately 30,000 of these blocks will be cast from the spent material.

The mix design used corresponds with the mix proportions used for the mix designated SDT201 in Appendix 1, which yields approximately 14 cubic feet of stabilized material. It consists of:

(1) 705 lbs of portland cement;
(2) 1,100 lbs of spent blasting material, in the following proportions:
  (a) 1,100 lbs of unseparated spent blast sand/dust, or
  (b) 917 lbs of spent blast sand with 183 lbs of spent blast dust;
(3) 21.8 oz/cwt of superplasticizer;
(4) 84.6 lbs of silica fume; and
(5) a water-to-cement ratio of 0.35 by weight.

Table 4.5 7-day TCLP leaching results for several spent blast sand and dust S/S mixes

1	2	3	4	5
Mix	7-Day TCLP Cr (mg/l)	7-Day TCLP Cd (mg/l)	7-Day TCLP Pb (mg/l)	7-Day TCLP Al (mg/l)
SD1	0.64	0.18	0	36.76
SD1-D	0.96	0.19	0.06	34.81
SD2	0.84	0.2	0	34.11
SD2-D	1.24	0.22	0	33.91

Table 4.6 28-day TCLP leaching results for several spent blast slag S/S mixes

1	2	3	4	5
Mix	28-Day TCLP Cr (mg/l)	28-Day TCLP Cd (mg/l)	28-Day TCLP Pb (mg/l)	28-Day TCLP Al (mg/l)
SG III-5	1.17	0.23	0.06	38.40
SG III-6	0.84	0.49	0.05	38.00
SG III-7	1.12	0.24	0.01	37.89
SG100	1.04	0.17	0.03	32.82
SG101	N/A	N/A	N/A	N/A
SG103	N/A	N/A	N/A	N/A
SG200	1.88	0.15	0.06	31.38
SG201	N/A	N/A	N/A	N/A
SG203	N/A	N/A	N/A	N/A
SG300	2.43	0.19	0.05	34.70
SG301	N/A	N/A	N/A	N/A
SG302	3.42	0.14	0.00	28.53
SG303	1.94	0.16	0.00	32.88

N/A: Data not available

CHAPTER 5. DISCUSSION OF TEST RESULTS

5.1 INTRODUCTION

In this chapter, the test results presented in Chapter 4 are discussed. The discussion will address: the characterization of raw materials; the effect of composition on setting, strength gain, leaching, and permeability; the effect of setting on strength, permeability, and leaching; the effect of strength on permeability and leaching; the effect of permeability on leaching; and, the effect of mixing sequences and times.

5.2 CHARACTERIZATION OF RAW MATERIALS

All raw materials used in this study were characterized both by the TCLP and by Total Constituent Analysis. This information is necessary for determining how much background contamination exists in the portland cement, water, silica fume, etc., and what the contamination level of the spent blasting material is.

The effectiveness of S/S systems is greatly dependent on the materials of which they are made. Since the composition of spent blasting media can vary greatly along the span of a bridge because of the existence of different paint systems, and can also vary between bridges, characterization of the spent media is important in determining the most suitable S/S system for a particular job site.

Likewise, because of the variability of background contamination of portland cement, water, and chemical and mineral admixtures, the characterization of these materials is also necessary. If these materials contain large amounts of contaminants, their use should be questioned, and a similar material with less contamination might have to be used.

5.3 FRESH MORTAR

5.3.1 Effect of Composition on Set Times

5.3.1.1 S/S Mixes Containing Spent Blast Slag

Of the solidified/stabilized mixes containing spent blast slag, the ones that used a mixture of clean sand and spent slag, with and without chemical and mineral admixtures, set within 24 hours. The mixes that contained 100 percent spent blast slag as the fine aggregate content did not set within three days after mixing, after which they were discarded.

5.3.1.2 S/S Mixes Containing Spent Blast Sand

All of the solidified/stabilized mixes containing only spent blast sand set within 24 hours. These mixes included those that had from 0 to 100 percent replacement of the clean fine aggregate with contaminated spent blast sand, some containing chemical and mineral admixtures.

5.3.1.3 S/S Mixes Containing Spent Blast Dust

All of these S/S mixes contained 100 percent clean sand as the fine aggregate content. The mixes with a low portland cement content, 470 lbs/cubic yard equivalent, and no admixtures, set unless spent blast dust was added, in an amount greater than 25 percent of the fine aggregate content, by weight. No mixes with a low cement content and admixtures were made.

The mixes with a high portland cement content, 705 lbs/cubic yard equivalent, no admixtures, and a spent blast dust content less than or equal to 35 percent of the fine aggregate content, by weight, set within 24 hours of mixing. Those with chemical and mineral admixtures and less than 15 percent spent blast dust set within 24 hours, except the ones containing a set retarder, which set within two days of mixing. When a spent blast dust content of 25 percent was used in addition to admixtures, only the mixes containing superplasticizer, fly ash, and silica fume achieved set. The use of admixtures increased the fines content of the S/S mixes and reduced the W/C ratio. This, in turn, reduced the amount of spent blast dust that could be used.

5.3.1.4 S/S Mixes Containing A Mixture of Separated Blast Sand and Blast Dust

The S/S mixes with a low portland cement content, partial replacement of the clean fine aggregate with spent blast sand, and superplasticizer did not set with spent blast dust contents of greater than 5 percent by weight of fine aggregate. For mixes with a high cement content, and partial replacement of the clean fine aggregate with spent blast sand, set was achieved with spent blast dust additions of an amount less than or equal to 15 percent of the fine aggregate content, by weight. No set was attained by any mix with superplasticizer and a W/C ratio of less than 0.45, regardless of the cement content.

5.3.1.5 S/S Mixes Containing Unseparated Blast Sand and Blast Dust

Of the S/S mixes that contained 100 percent replacement of the clean fine aggregate with contaminated spent blasting media, none with a low cement content set, regardless of the addition of chemical and mineral admixtures. Set was also not attained by any of the mixes with a high cement content and superplasticizer or superplasticizer and calcium nitrite corrosion inhibitor. The high cement content mixes with chemical and mineral admixtures did set, however. Of these mixes, the ones containing a retarder had a delayed set of two days.

Both of the mixes that contained only 50 percent replacement of the clean fine aggregate with spent blasting media did set. However, the mix that contained a superplasticizer and a retarder had a delayed set of two days.

5.3.1.6 Summary of Effect of Composition on Set Times

In summary, the effect of composition on set times can be stated as follows:

(1) All S/S mixes containing less than 100 percent replacement of the clean fine aggregate with spent blast slag achieved set within 24 hours of mixing, independently of mix proportions.
(2) All S/S mixes containing spent blast sand set within 24 hours of mixing, regardless of the amount of clean fine aggregate replacement.
(3) For S/S mixes containing spent blast dust: the higher the cement content, the less retardation due to lead; the higher the spent blast dust content, the longer the set time.
(4) For S/S mixes containing separated spent blast sand/dust mix: the higher the cement content, the less retardation due to lead; mixes with low cement contents and with greater than 5 percent spent blast dust do not set, regardless of the amount of clean fine aggregate replacement.
(5) For S/S mixes containing unseparated spent blast sand/dust mix: mixes with 100 percent fine aggregate replacement will set only if they contain high cement contents and admixtures; mixes containing a set retarder have delayed sets of up to 48 hours; and mixes containing calcium nitrite corrosion inhibitor do not set.

5.4 HARDENED MORTAR

5.4.1 Effect of Composition on Compressive Strength

5.4.1.1 S/S Mixes Containing Spent Blast Slag

The S/S mixes containing spent blast slag, fly ash, and HRWR showed decreased strength with an increase in contamination. Variations in W/C ratio and corresponding adjustments to superplasticizer content did not affect the S/S mixes' strength gain. Figure 5.1 shows the typical strength gain versus time for this series of mixes.

The S/S mixes containing spent blast slag, silica fume, and HRWR showed decreased compressive strength with increased contaminated spent blasting media content. Low W/C ratios with high amounts of superplasticizer provided greater compressive strength than higher W/C ratios with lower superplasticizer dosages. Figures 5.2 and 5.3 show the typical strength gain versus time for this series of mixes.

The S/S mixes with spent blast slag, fly ash, silica fume, and HRWR also provided lower compressive strength as the amount of spent blast slag in the mixes was increased. Low W/C ratios with high dosages of superplasticizer resulted in an increase in compressive strength of nearly 1,000 psi at 7, 28, and 90 days of age. Figure 5.4 shows the typical strength gain versus time for this series of mixes.

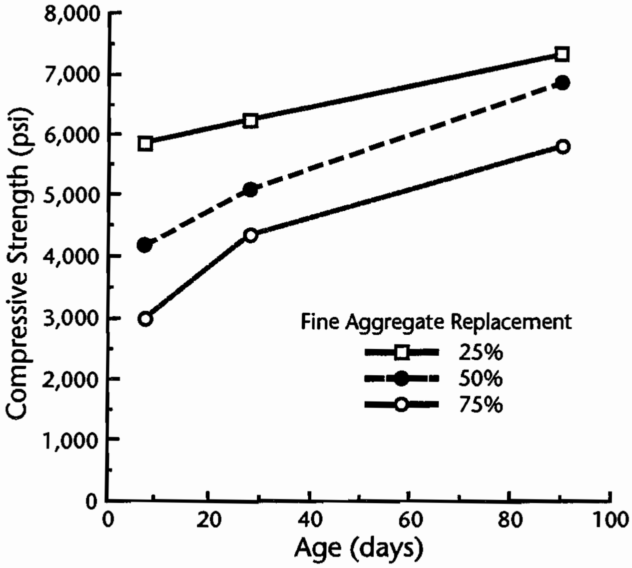

Figure 5.1 *Typical strength gain vs. time for S/S mixes with blast slag, fly ash, and 8 oz/cwt of HRWR*

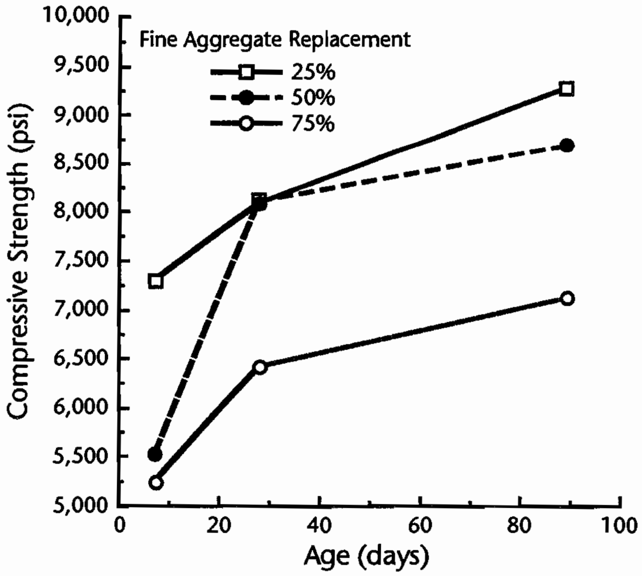

Figure 5.2 *Typical strength gain vs. time for S/S mixes with blast slag, silica fume, and approximately 18 oz/cwt of HRWR*

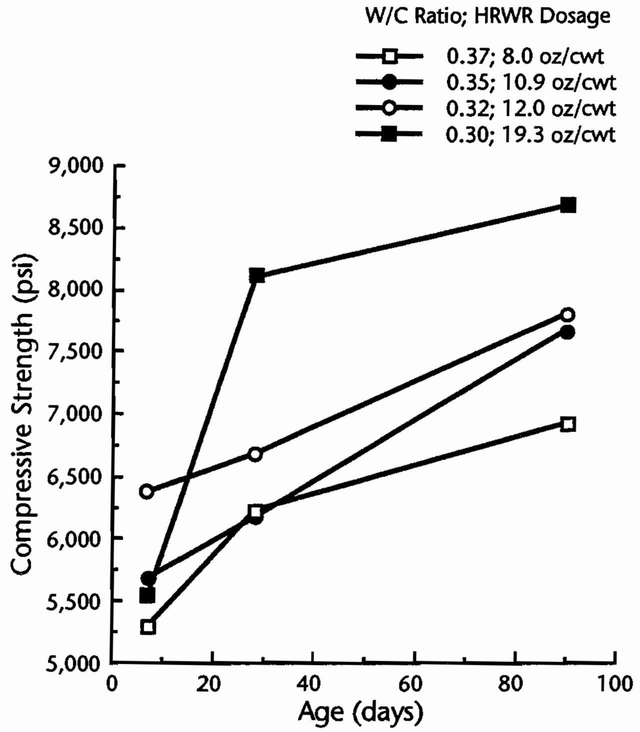

Figure 5.3 *Compressive strength gain vs. time for S/S mixes containing 50% blast slag, silica fume, and varying w/c ratios and HRWR dosages*

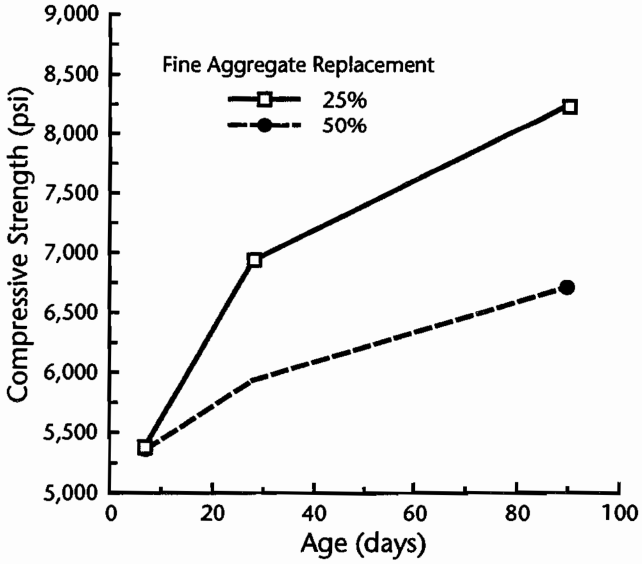

Figure 5.4 *Typical strength gain vs. time for S/S mixes with spent blast slag, fly ash, silica fume, and 8 oz/cwt of HRWR*

5.4.1.2 S/S Mixes Containing Spent Blast Sand

The S/S mixes containing spent blast sand, 600 pounds of portland cement, silica fume, fly ash, and HRWR showed a reduction in 90-day compressive strength when 100 percent of the fine aggregate was replaced with spent blasting material. Figure 5.5 shows the strength gain versus time plot for this series of mixes.

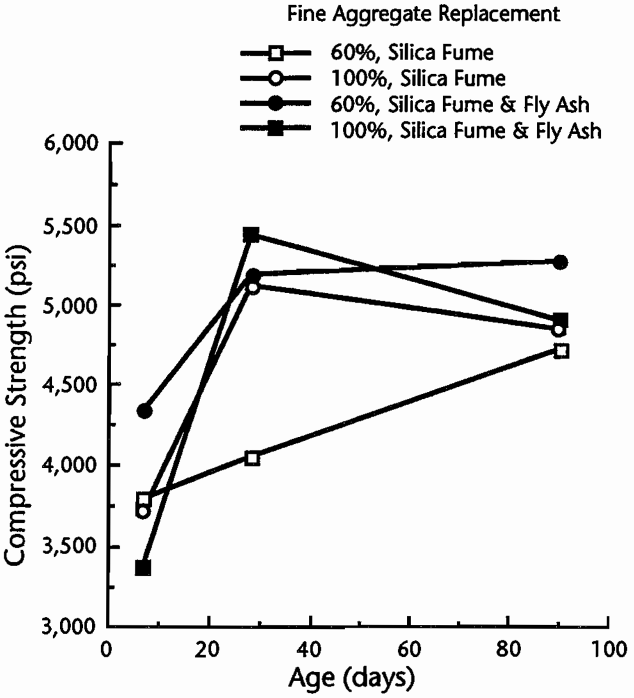

Figure 5.5 ***Strength gain vs. time for S/S mixes with spent blast sand, fly ash, silica fume, and HRWR***

The S/S mixes containing spent blast sand and 470 pounds of portland cement showed decreased strength with increased amounts of fine aggregate replacement. Small strength gains occurred between 28 and 90 days. Figure 5.6 shows the compressive strength gain versus time for this sequence of mixes.

The S/S mixes with spent blast sand and 705 pounds of portland cement showed results similar to those of the mixes with 470 pounds of cement, except that compressive strengths at all ages for the high cement content mixes were higher.

5.4.1.3 S/S Mixes Containing Spent Blast Dust

The S/S mixes with spent blast dust and 470 pounds or 705 pounds of portland cement had decreased strength with increased dust contents. The high cement content mixes showed greater compressive strengths, especially at lower dust contents, than the low cement content mixes did. Figure 5.7 shows the strength gain versus time plot for the high cement content mixes.

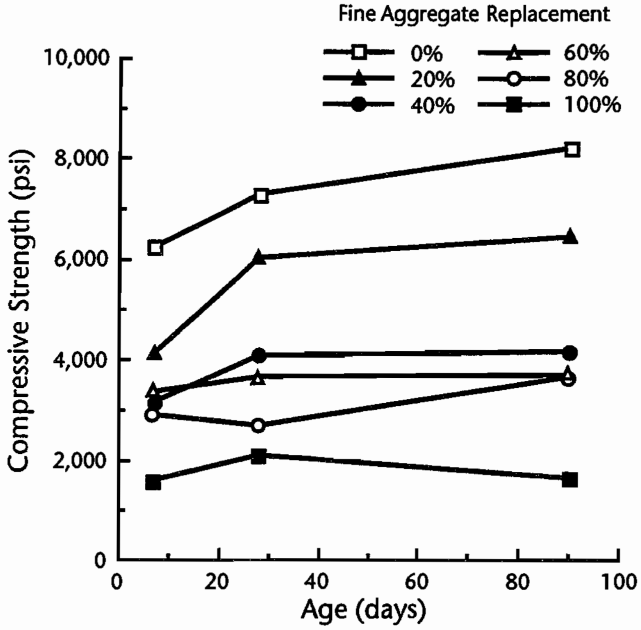

Figure 5.6 ***Strength gain vs. time for S/S mixes with spent blast sand, and 470 lbs portland cement***

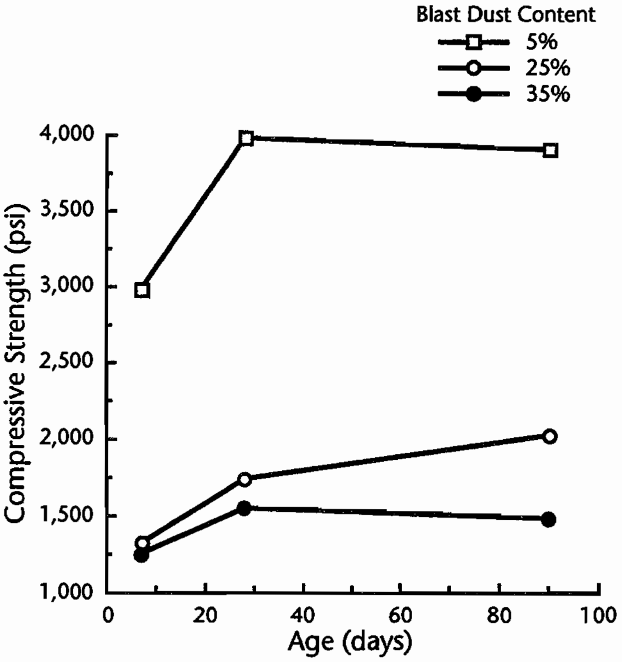

Figure 5.7 ***Strength gain vs. time for S/S mixes with clean sand, spent blast dust, and 705 lbs portland cement***

5.4.1.4 S/S Mixes Containing Separated Spent Blast Sand/ Dust Mix

The S/S mixes containing 17 percent blast dust, 60 percent or 100 percent fine aggregate replacement with spent blast sand, and admixtures, showed lower strength with higher fine aggregate replacement. The mixes containing fly ash, silica fume, and superplasticizer had lower W/C ratios and therefore higher compressive strengths than the mixes with only silica fume and superplasticizer. The mixes with silica fume and fly ash showed a reduction in 90-day strengths that was not apparent in the mixes with only silica fume. Figure 5.8 shows the compressive strength gain versus time for this series of mixes.

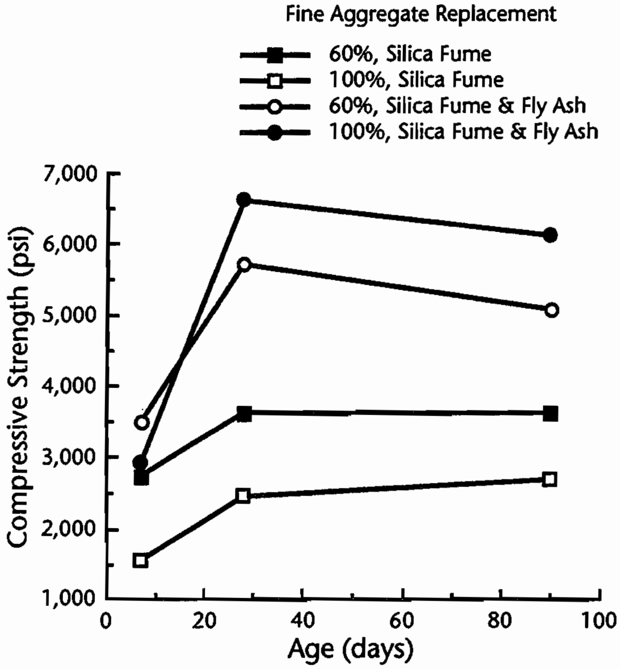

Figure 5.8 ***Compressive strength vs. time for S/S mixes with separated spent blast sand/ dust mix, 600 lbs portland cement, fly ash, silica fume, and HRWR***

The S/S mixes containing 470 pounds portland cement and varying fine aggregate replacements and blast dust contents showed lower strengths with increased fine aggregate replacements for a constant percent of dust added. For the same mixes with 705 pounds of portland cement, amounts of blast dust greater than 15 percent resulted in considerably lower strength, regardless of the amount of fine aggregate replacement. The lowest amount of fine aggregate replacement with the lowest amount of blast dust added provided the highest compressive strength. Figure 5.9 shows the compressive strength gain versus time for the high cement content mixes.

5.4.1.5 S/S Mixes Containing Unseparated Spent Blast Sand/ Dust Mix

For the S/S mixes containing 50 percent replacement of the fine aggregate with unseparated blast sand/dust mix and chemical additives, the mix with the superplasticizer alone gave higher compressive strengths than the mixes with superplasticizer and retarder combined. The retarder was used to allow any hydrogen gas that may have been formed by the reaction of the alkalies in the portland cement with aluminum in the spent blasting material to escape before the S/S matrix set.

The S/S mixes with 100 percent fine aggregate replacement with unseparated spent blast sand/ dust and additives gave the greatest strength when only silica fume and superplasticizer were used. Mixes with silica fume and fly ash did not provide compressive strengths as high as those of mixes with silica fume alone. Mixes with retarders delayed set by two days and had very low 7-day strengths, but had 28-day strengths comparable to those of mixes without retarders. Figure 5.10 shows the compressive strength gain for these mixes.

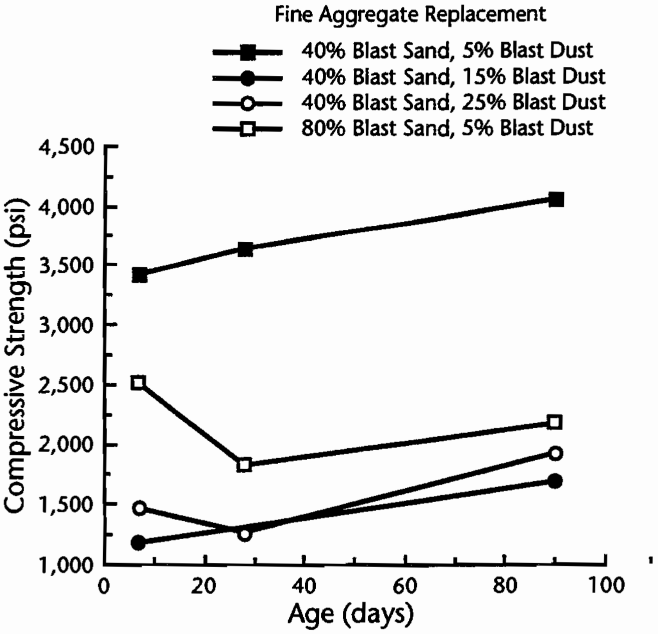

Figure 5.9 ***Strength gain vs. time for S/S mixes with separated blast sand/dust mix, and 705 lbs portland cement***

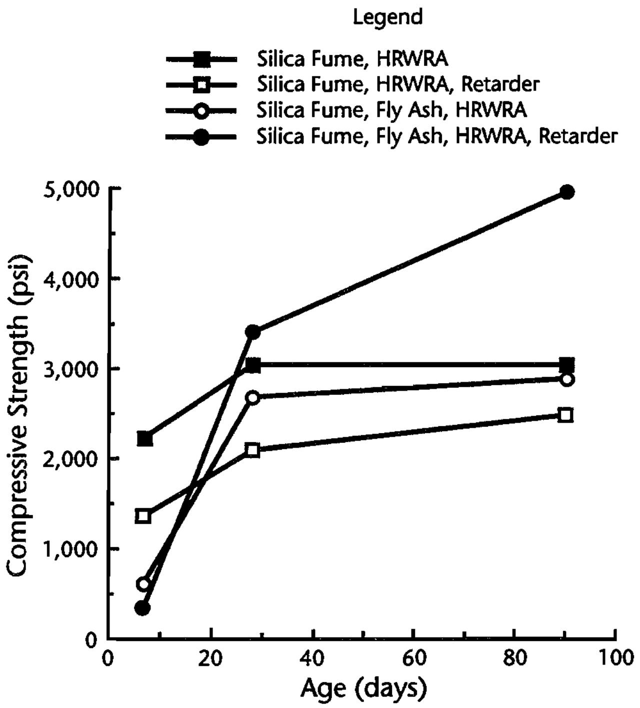

Figure 5.10 ***Strength gain vs. time for S/S mixes with unseparated blast sand/dust mix, 100 percent fine aggregate replacement, and 705 lbs portland cement***

5.4.1.6 Summary of Effect of Composition on Compressive Strength

In summary,

(1) For S/S mixes containing spent blast slag: the higher the amount of spent blast slag used, the higher the W/C ratio and therefore the lower the compressive strength; and the lower the W/C ratio, the higher the compressive strength.

(2) For S/S mixes containing spent blast sand: mixes without admixtures exhibited lower compressive strength with higher clean fine aggregate replacement; the compressive strength of mixes with admixtures was not affected by changes in the clean fine aggregate replacement; and mixes with increased cement contents had increased compressive strengths.

(3) For S/S mixes containing spent blast dust: the higher the spent blast dust content, the lower the compressive strength; the higher the cement content, the higher the compressive strength.

(4) For S/S mixes with separated spent blast sand/dust mix: the higher the fine aggregate replacement and spent blast dust content, the lower the compressive strength. Mixes with silica fume and HRWR had lower compressive strengths than mixes with silica fume, fly ash, and HRWR.

(5) For S/S mixes with unseparated spent blast sand/dust mix: the ones containing silica fume and HRWR exhibited higher compressive strengths than the ones containing silica fume, fly ash, and HRWR.

5.4.2 Effect of Composition on Permeability

5.4.2.1 S/S Mixes Containing Spent Blast Slag

The S/S mixes containing spent blast slag, silica fume, and HRWR showed that the addition of contaminated spent blasting media did not affect the chloride ion permeability. The mixes with the highest W/C ratio and the lowest superplasticizer content showed the highest permeability. Compared to S/S mixes with fly ash and fly ash/silica fume combinations, the mixes with silica fume alone had the lowest permeability. Figure 5.11 shows the changes in permeability as the percent of fine aggregate replacement and the W/C ratio are increased for S/S mixes with equal cement and silica fume contents. The mixes with a W/C ratio of 0.31 showed the lowest permeability when compared to mixes with higher or lower W/C ratios.

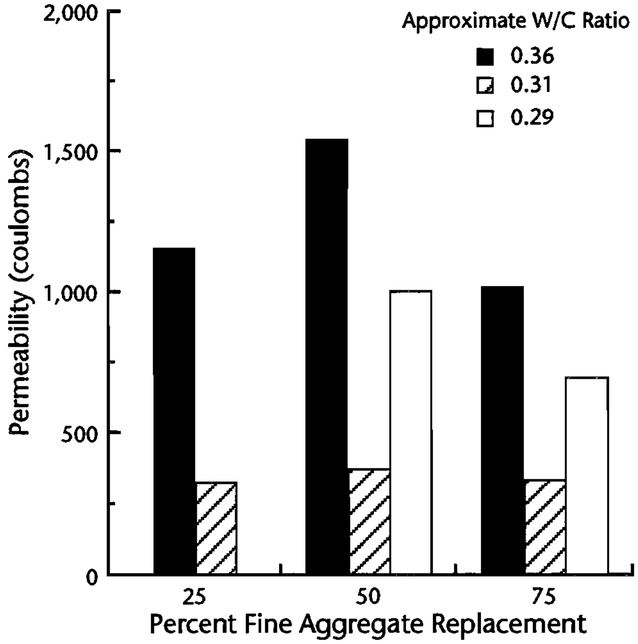

Figure 5.11 ***Permeability of S/S mixes containing spent blast slag, silica fume, and HRWR***

The S/S mixes containing spent blast slag, 600 pounds of portland cement, fly ash, silica fume, and HRWR also showed no effect on permeability with increased fine aggregate replacement. Of these mixes, the ones with high W/C ratios and low superplasticizer dosages had the highest permeabilities. The mixes with intermediate W/C ratios and superplasticizer dosages had the lowest permeabilities. Figure 5.12 shows the change in permeability of these mixes as the percent of fine aggregate replacement and W/C ratios were varied.

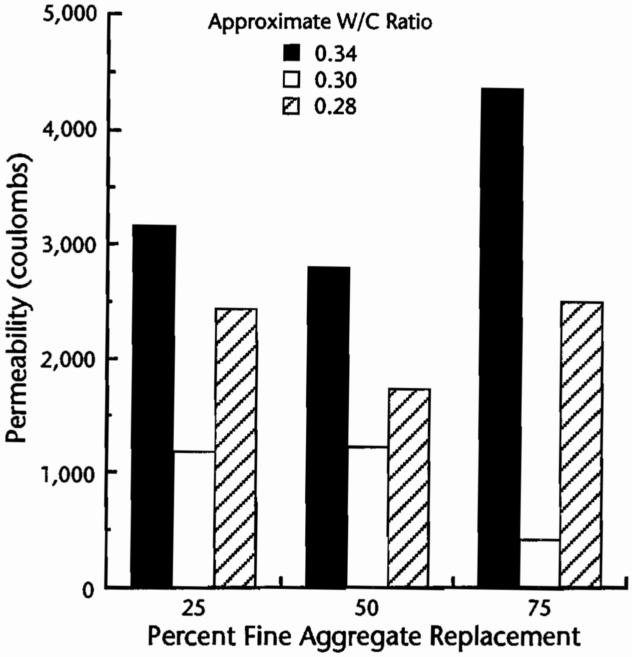

Figure 5.12 ***Permeability of S/S mixes containing spent blast slag, fly ash, silica fume, and HRWR***

The S/S mixes with with spent blast slag, fly ash, and HRWR had the highest permeability of the blast slag series mixes. The permeabilities of these mixes were in the 5,000 to 11,000 coulomb range, compared to permeabilities in the 300 to 4,500 coulomb range for mixes containing silica fume. The permeability-reducing capability of silica fume is an important factor in reducing the permeability of S/S mixes containing spent blast slag. Regardless of the admixtures used, the S/S mixes with intermediate W/C ratios and superplasticizer dosages provided the lowest permeability of all the mixes. This may be an indication of the dependence of the permeability of S/S mixes on W/C ratio.

5.4.2.2 S/S Mixes Containing Spent Blast Sand

The S/S mixes containing spent blast sand, silica fume, fly ash and HRWR displayed increased permeability with increased fine aggregate replacement. The mixes with silica fume alone and those with silica fume and fly ash had similar permeabilities, and the permeabilities of all mixes were very low, in the 125 to 400 coulomb range. Figure 5.13 shows the permeabilities of these mixes with increasing fine aggregate replacement.

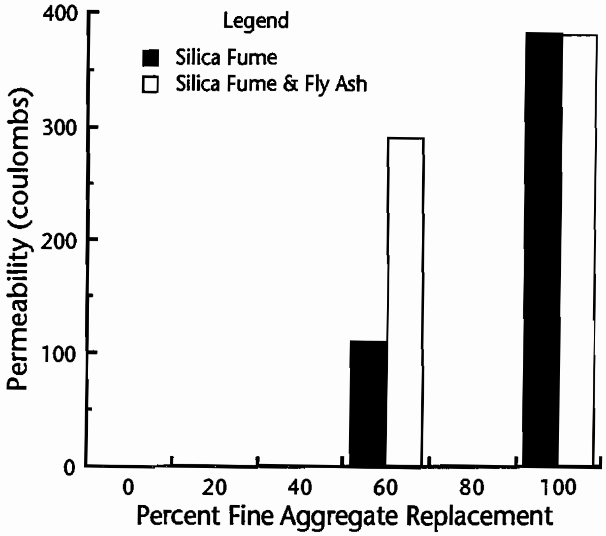

Figure 5.13 ***Permeability of S/S mixes containing spent blast sand, fly ash, silica fume, and HRWR***

The S/S mixes containing spent blast sand and 470 pounds of portland cement had higher W/C ratios with increased fine aggregate content, and therefore greater permeabilities. All the mixes in this series had relatively high permeabilities, between 7,000 and 12,000 coulombs. Figure 5.14 presents permeability versus fine aggregate replacement for this series of mixes.

The S/S mixes with spent blast sand and 705 pounds of portland cement also had higher W/C ratios with increased fine aggregate replacement and displayed higher permeabilities. Permeability values were in the same range as those for the mixes with 470 pounds of cement. Figure 5.15 gives permeability versus fine aggregate replacement for this series of mixes.

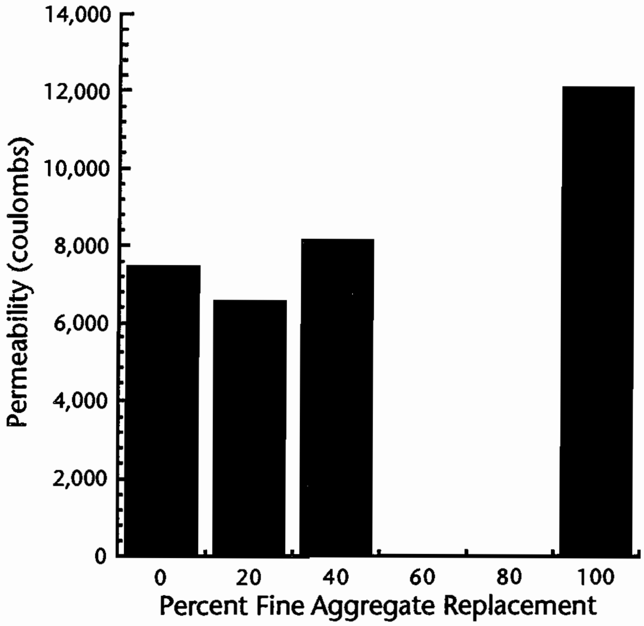

Figure 5.14 ***Permeability of S/S mixes containing spent blast sand and 470 lbs portland cement***

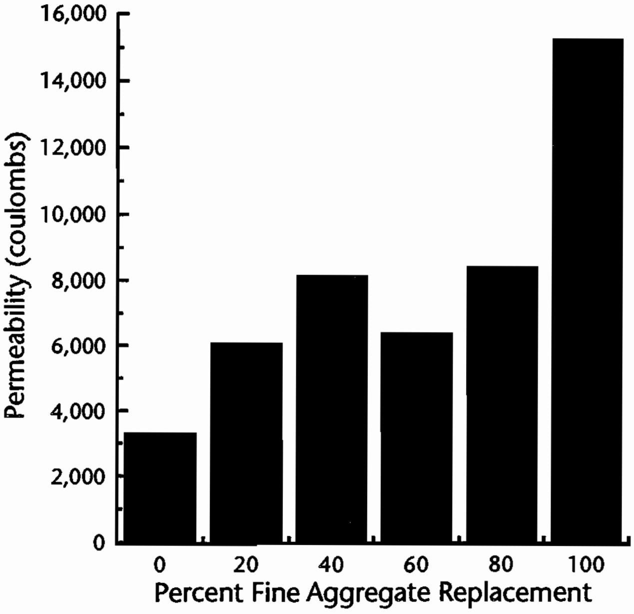

Figure 5.15 ***Permeability of S/S mixes containing spent blast sand and 705 lbs portland cement***

5.4.2.3 S/S Mixes Containing Spent Blast Dust

The S/S mixes containing clean fine aggregate, spent blast sand, and portland cement displayed increasing W/C ratios with increasing amounts of contaminated dust, causing increased permeabilities. Permeability values were in the same range as those for mixes with spent blast sand. Figure 5.16 shows the permeabilities of mixes containing 705 pounds of portland cement and increasing amounts of spent blast dust.

5.4.2.4 S/S Mixes Containing Separated Spent Blast Sand/ Dust Mix

The S/S mixes containing 17 percent spent blast dust, varying amounts of spent blast sand, silica fume, fly ash, and HRWR had permeabilities in the 250 to 1,750 coulomb range. The mixes with silica fume and fly ash had lower permeabilities than the mixes with silica fume alone.

The mixes with separated spent blast sand/dust mix and 705 pounds of portland cement showed increasing permeability with increased fine aggregate replacement and increased contaminated dust content. This was due to higher W/C ratios as the dust content was increased. Dust contents of 15 percent resulted in extremely permeable S/S matrices with permeability values between 11,000 to 15,000 coulombs. Figure 5.17 shows the permeability of these mixes.

5.4.2.5 S/S Mixes Containing Unseparated Spent Blast Sand/ Dust Mix

The S/S mixes containing 50 percent replacement of the fine aggregate with unseparated spent blasting media and chemical additives had higher

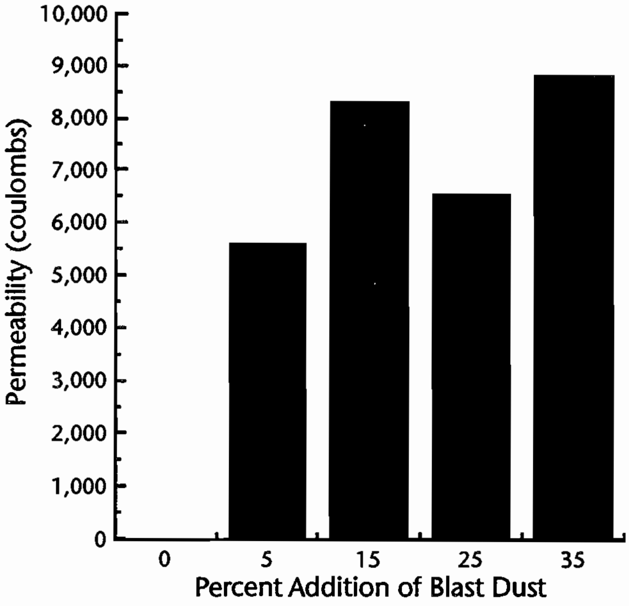

Figure 5.16 ***Permeability of S/S mixes containing spent blast dust, clean sand, and 705 lbs portland cement***

permeabilities than those of mixes containing 100 percent fine aggregate replacement and chemical and mineral additives. Permeability values for all mixes containing unseparated spent material were in the 5,000 to 12,000 coulomb range. Figure 5.18 displays the permeability of these mixes.

5.4.2.6 Summary of the Effect of Composition on Permeability

In summary, the effects of composition on permeability can be stated as follows:

(1) In general, the lower the W/C ratio and the higher the cement content, the lower the permeability.
(2) For S/S mixes containing spent blast slag: the permeability of the S/S matrices was not affected by increased clean fine aggregate replacement.
(3) For S/S mixes containing spent blast sand: the W/C ratios of the S/S matrices increased as the clean fine aggregate replacement was increased, causing increased permeabilities; and the permeabilities of S/S mixes with silica fume and/or fly ash with a HRWR were lower than the permeabilities of mixes without admixtures.
(4) For S/S mixes containing spent blast dust: as the amount of spent blast dust increased, the W/C ratio also increased, thereby increasing permeability.
(5) For S/S mixes containing separated spent blast sand/dust mix: the W/C ratios increased with increased clean fine aggregate replacement and increased spent blast dust content. This resulted in higher permeabilities.
(6) The permeabilities of S/S mixes with unseparated spent blast sand/dust mix were extremely high, regardless of the mix proportions or of the admixtures used.

5.4.3 Effect of Composition on TCLP Leaching

5.4.3.1 General Information

Some of the contaminated spent blasting material had TCLP leaching values less than the EPA limit values for a hazardous material. However, none of the S/S mixes, even those with hazardous spent blasting media, yielded TCLP leaching results greater than the EPA limits (see Table 2.1). Consequently, all of the S/S mixes in this study were considered nonhazardous.

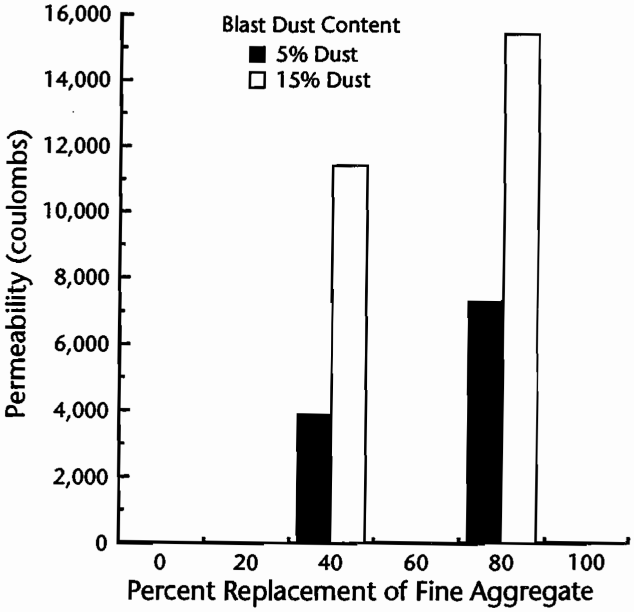

Figure 5.17 *Permeability of S/S mixes containing separated blast sand/dust mix and 705 lbs portland cement*

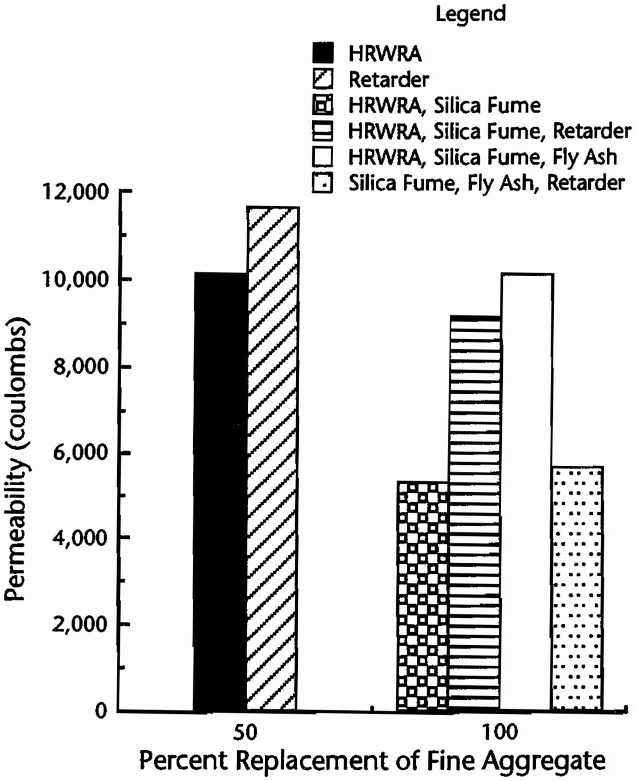

Figure 5.18 *Permeability of S/S mixes containing unseparated spent blast sand/dust mix, 705 lbs portland cement, and additives*

For more discussion on the results of the TCLP leaching tests, please refer to Reference 17.

5.4.3.2 S/S Mixes Containing Blast Slag

The S/S mixes containing spent blast slag, silica fume, and HRWR showed no change in lead or cadmium leaching with increased fine aggregate replacement or with changing W/C ratio. Lead and cadmium leaching values were extremely small, and changes in these values from mix to mix were on the order of the TCLP detection limits. However, chromium leaching increased with greater fine aggregate replacement, but showed no change with variations in W/C ratio/superplasticizer dosage. Figures 5.19 through 5.21 show the TCLP leaching results for this series of mixes.

The S/S mixes containing spent blast slag, fly ash, and low dosage of HRWR had lead leaching levels below 0.1 mg/L. These values did not increase with higher fine aggregate replacement. Cadmium and chromium leaching increased with increased spent blasting material levels. Figures 5.22 through 5.24 show the TCLP leaching trends for these mixes with low superplasticizer dosages.

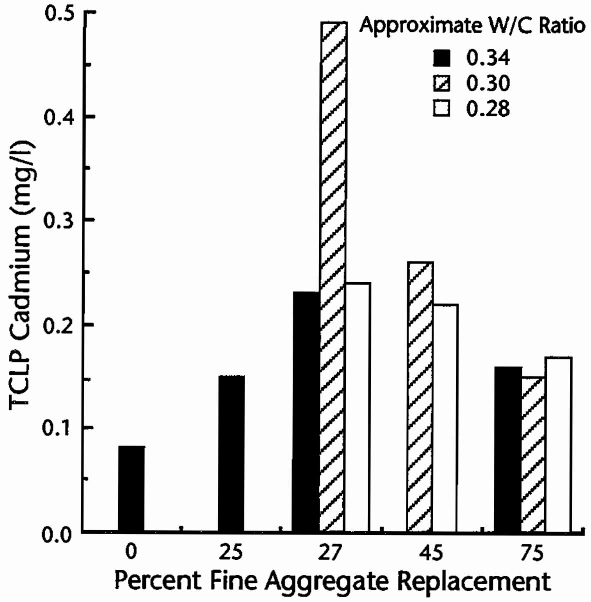

Figure 5.20 ***Cadmium TCLP leaching for S/S mixes with spent blast slag, 600 lbs portland cement, silica fume, and HRWR***

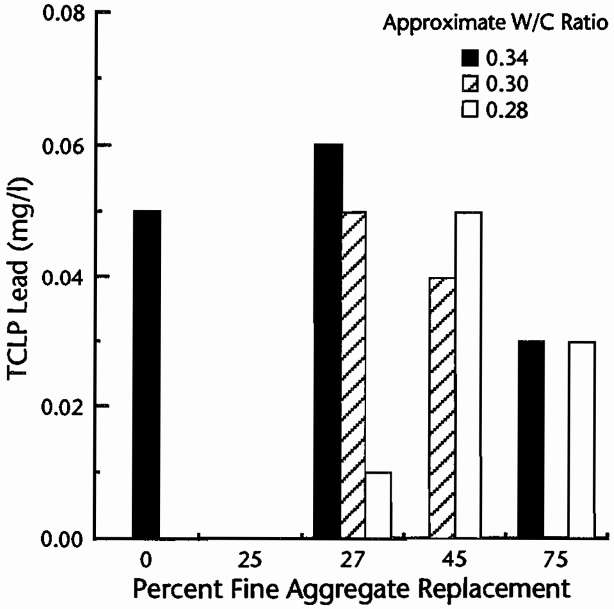

Figure 5.19 ***Lead TCLP leaching for S/S mixes with spent blast slag, 600 lbs portland cement, silica fume, and HRWR***

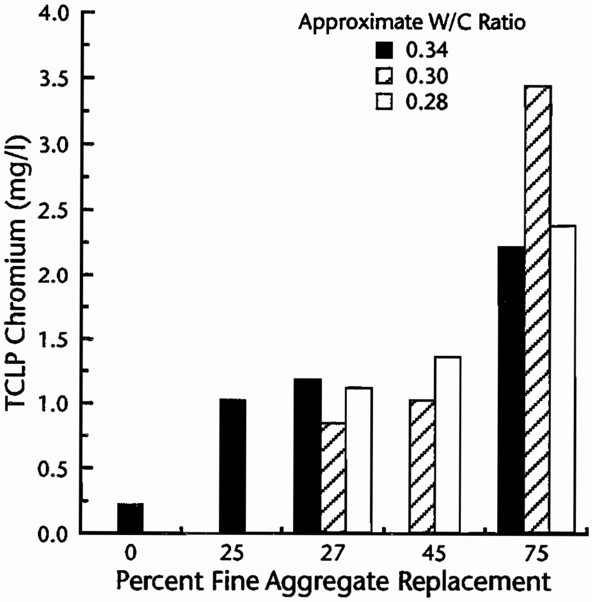

Figure 5.21 ***Chromium TCLP leaching for S/S mixes with spent blast slag, 600 lbs portland cement, silica fume, and HRWR***

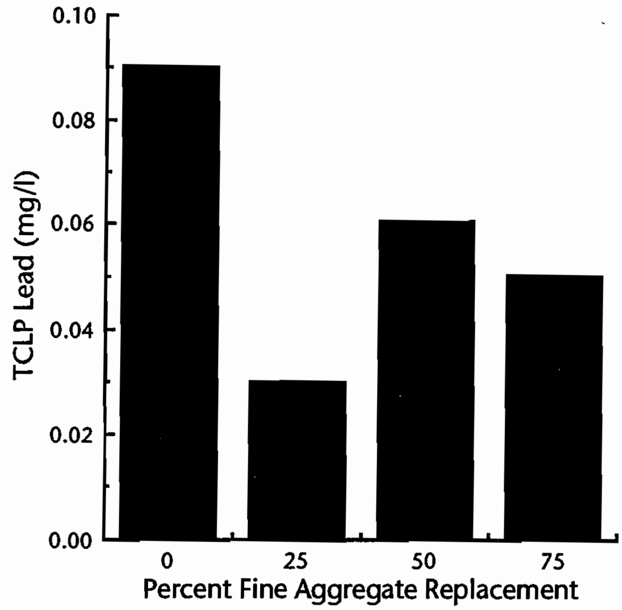

Figure 5.22 ***Lead TCLP leaching for S/S mixes with spent blast slag, 600 lbs portland cement, fly ash, and 8 oz/cwt HRWR***

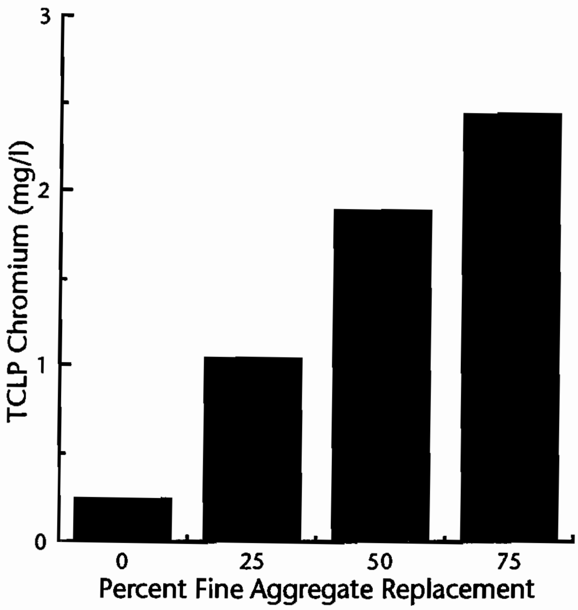

Figure 5.24 ***Chromium TCLP leaching for S/S mixes with spent blast slag, 600 lbs portland cement, fly ash, and 8 oz/cwt HRWR***

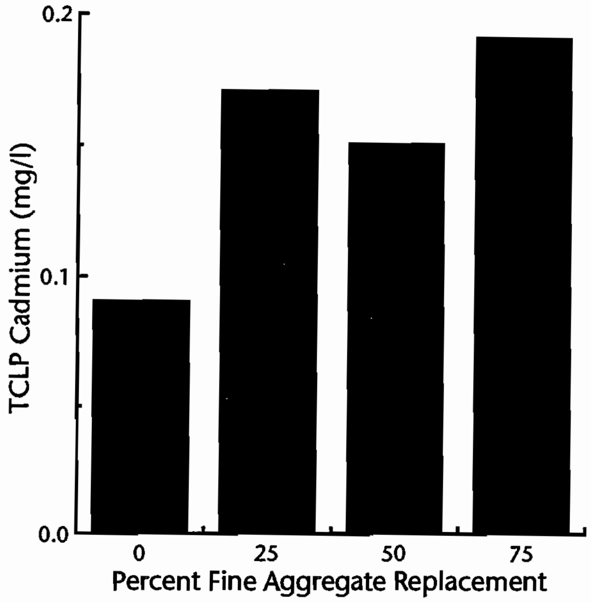

Figure 5.23 ***Cadmium TCLP leaching for S/S mixes with spent blast slag, 600 lbs portland cement, fly ash, and 8 oz/cwt HRWR***

The S/S mixes containing spent blast slag, silica fume, fly ash, and low HRWR dosage showed the same trends as did the mixes with only silica fume or fly ash. Lead leaching was not dependent on the amount of fine aggregate replacement, whereas cadmium and chromium leaching increased with increased contaminated material addition. Figures 5.25 and 5.26 show the cadmium and chromium leaching results for these mixes with low superplasticizer dosages.

Lead, cadmium, and chromium TCLP leaching levels were not affected by varying cement contents in any of the S/S mixes containing spent blast slag. The leaching levels were also not affected by varying W/C ratios in any of these mixes. Figures 5.27 and 5.28 show cement content and W/C ratio versus lead TCLP leaching as an example of this phenomenon.

Overall, the leaching levels for lead, cadmium, and chromium were unchanged by the addition of different combinations of mineral admixtures in the three series of mixes containing spent blast slag.

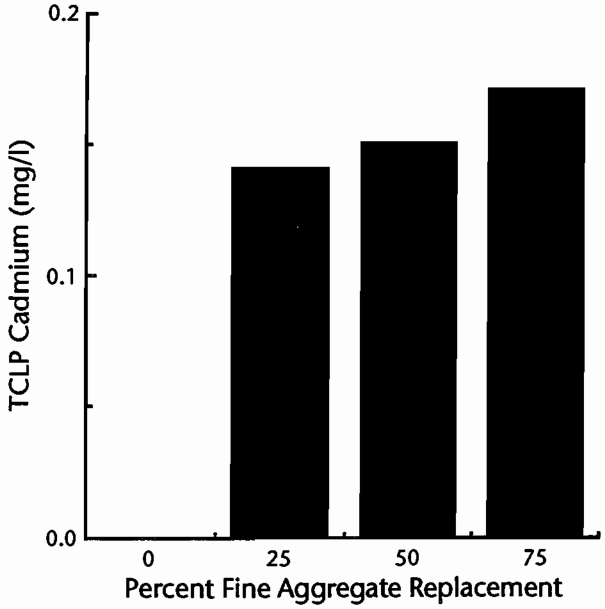

Figure 5.25 ***Cadmium TCLP leaching for S/S mixes with spent blast slag, 600 lbs portland cement, fly ash, silica fume, and 8 oz/cwt HRWR***

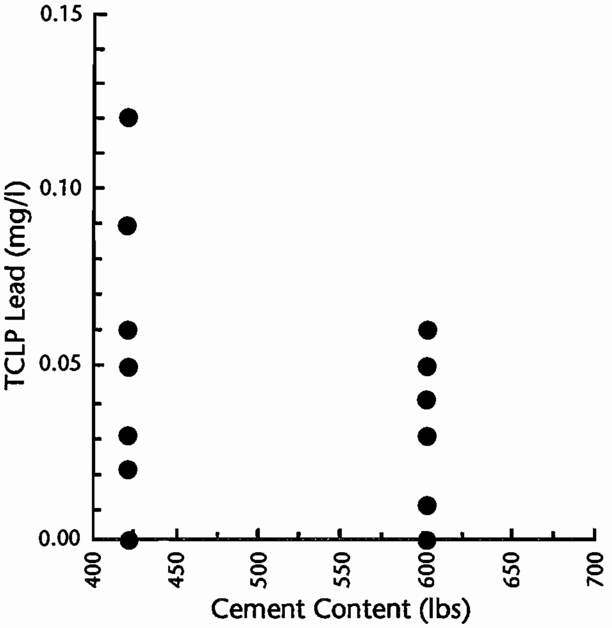

Figure 5.27 ***TCLP lead vs. cement content for S/S mixes containing spent blast slag and admixtures***

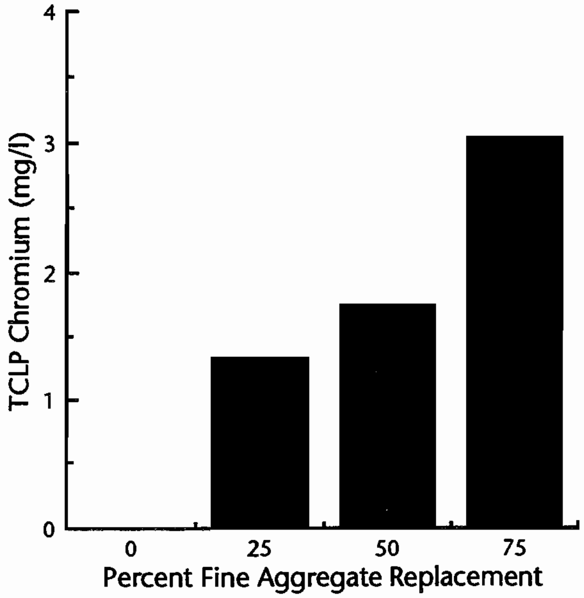

Figure 5.26 ***Chromium TCLP leaching for S/S mixes with spent blast slag, 600 lbs portland cement, fly ash, silica fume, and 8 oz/cwt HRWR***

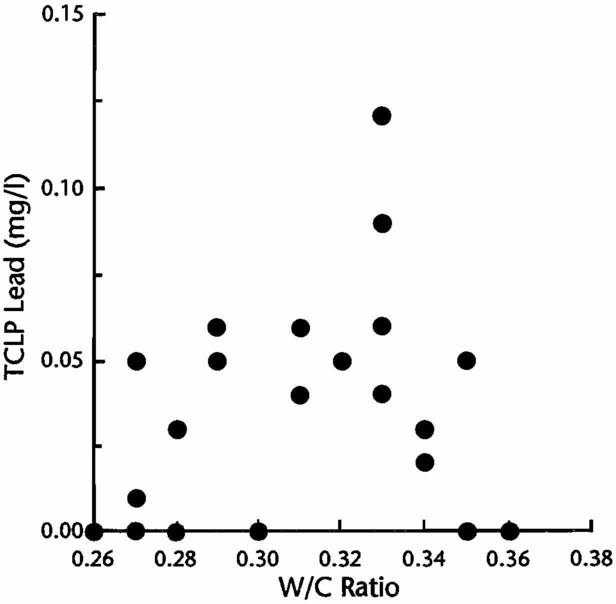

Figure 5.28 ***TCLP lead vs. W/C ratio for S/S mixes containing spent blast slag and admixtures***

5.4.3.3 S/S Mixes Containing Spent Blast Sand

The S/S mixes containing spent blast sand and 470 pounds of portland cement showed increased lead leaching and no change in cadmium or chromium leaching with increased clean fine aggregate replacement. The mixes with 705 pounds of cement showed no significant change in lead, cadmium, or chromium leaching with increased fine aggregate replacement. Also, the high cement content mixes did not have lead and cadmium leaching levels significantly different from the levels of the low cement content mixes. The high cement mixes did, however, reduce the chromium leaching levels. Figures 5.29 through 5.31 display the TCLP leaching for the low and high cement content mixes.

Lead and cadmium TCLP leaching were not affected by changes in the W/C ratio of the S/S mixes. Chromium leaching, however, increased as the W/C ratio increased. Figure 5.32 shows lead TCLP leaching versus W/C ratio, and Figure 5.33 shows the same plot for chromium TCLP leaching.

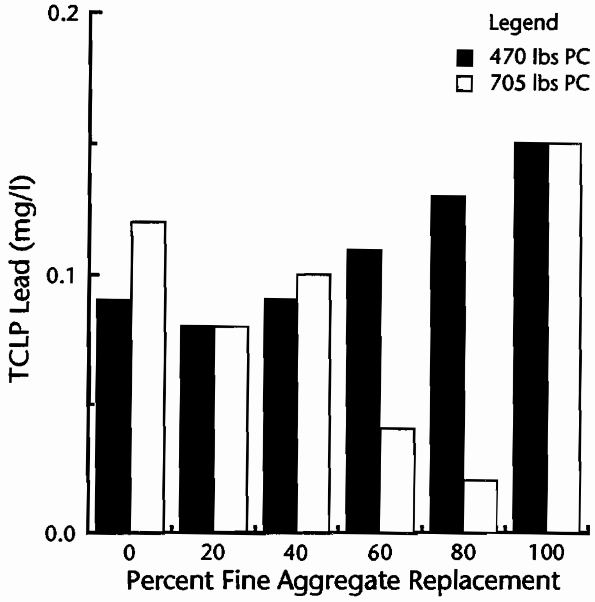

Figure 5.29 ***Lead TCLP leaching for S/S mixes with spent blast sand and low and high portland cement contents***

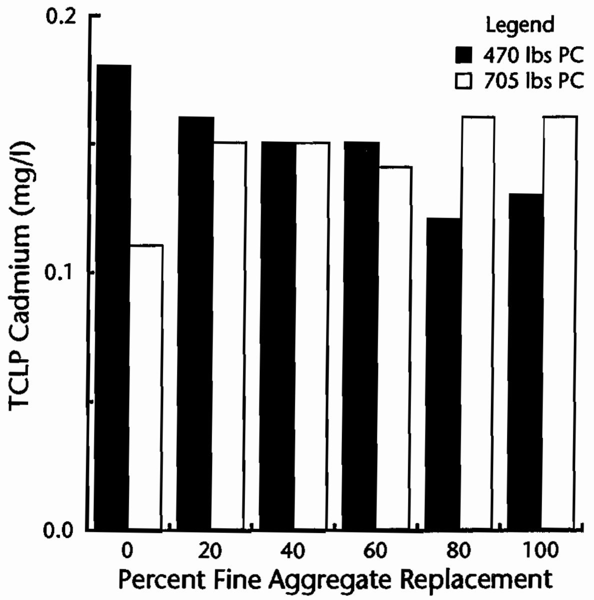

Figure 5.30 ***Cadmium TCLP leaching for S/S mixes with spent blast sand and low and high portland cement contents***

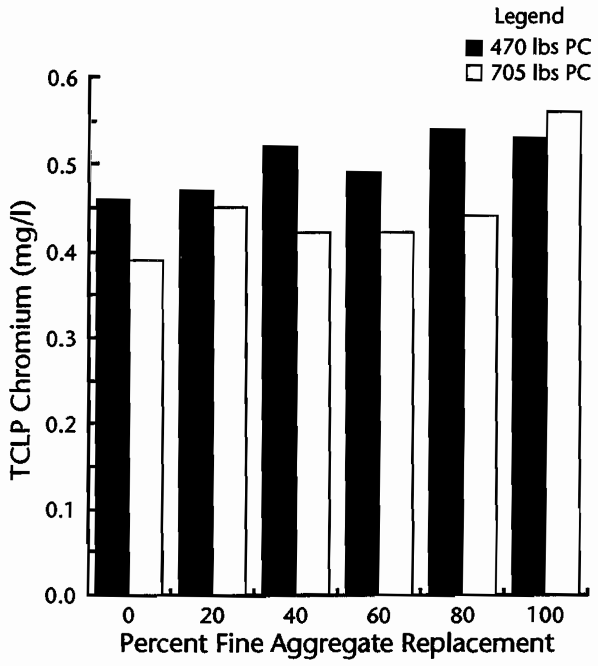

Figure 5.31 ***Chromium TCLP leaching for S/S mixes with spent blast sand and low and high portland cement contents***

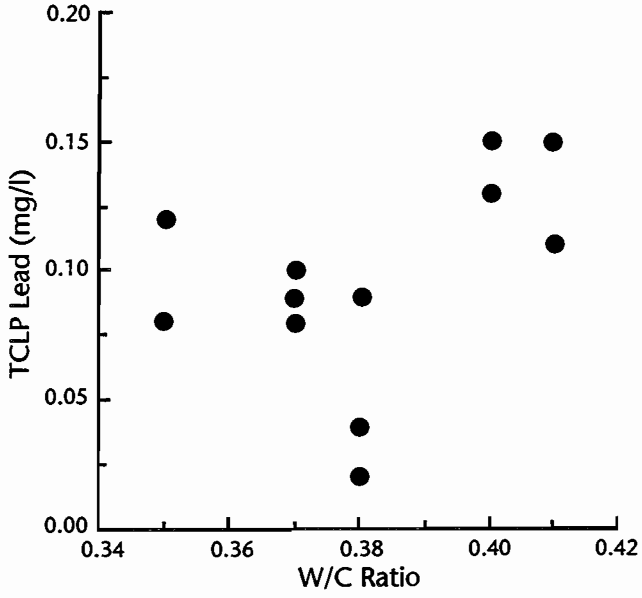

Figure 5.32 ***Lead TCLP leaching vs. W/C ratio for S/S mixes containing spent blast sand***

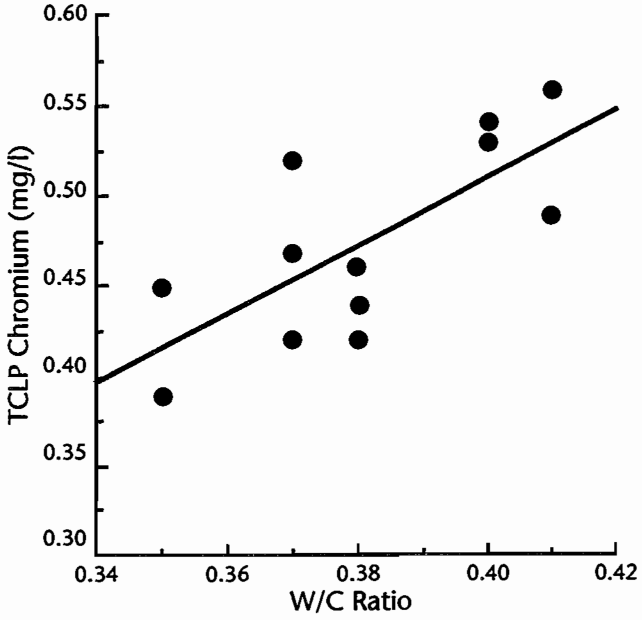

Figure 5.33 ***Chromium TCLP leaching vs. W/C ratio for S/S mixes containing spent blast sand***

5.4.3.4 S/S Mixes Containing Spent Blast Dust

The S/S mixes containing spent blast dust and 470 pounds of portland cement had increased lead and chromium leaching with increased dust content. Cadmium leaching remained constant as the dust content was changed.

Changes in lead and cadmium leaching in the mixes with 705 pounds of cement were negligible compared to the detection limits of the TCLP. Chromium leaching, however, did increase as the spent blast dust content was raised.

The high cement content mixes showed lower leaching levels for lead and chromium than the low cement content mixes did. Cadmium leaching was similar in both types of mixes. Changes in lead, cadmium, and chromium TCLP leaching due to changes in W/C ratio were not apparent. Figures 5.34 through 5.37 show the leaching trends of this series of mixes.

5.4.3.5 S/S Mixes Containing Separated Spent Blast Sand/ Dust Mix

The S/S mixes containing separated spent blast sand/dust mix and 705 pounds of portland cement showed decreased leaching of lead and chromium as fine aggregate replacement was increased and greater leaching at low fine aggregate replacement levels as the spent blast dust content was raised. Cadmium leaching increased as the fine aggregate replacement increased but remained constant as the spent dust content was changed.

In general, lead and chromium TCLP leaching increased as the W/C ratio increased, whereas cadmium leaching was not affected by changes in the W/C ratio. Lead TCLP leaching also increased with decreased cement content, whereas cadmium and chromium leaching were not affected. Figures 5.38 through 5.43 show the TCLP leaching of this series of mixes.

5.4.3.6 S/S Mixes Containing Unseparated Spent Blast Sand/ Dust Mix

The S/S mixes with unseparated spent blast sand/dust, 705 pounds of portland cement, and additives showed little change in lead and cadmium leaching as the percent of fine aggregate leaching was increased. Chromium leaching, however, was increased with higher fine aggregate replacement.

The mix with silica fume and superplasticizer had less leaching than did the mix with silica fume, fly ash, and superplasticizer for both lead and chromium. Figures 5.44 through 5.46 show the TCLP leaching of these mixes.

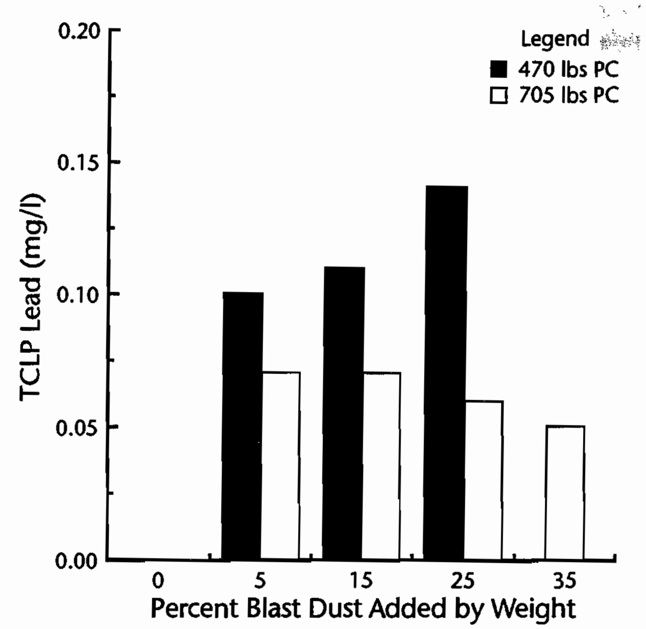

Figure 5.34 *Lead TCLP leaching for S/S with spent blast dust, clean sand, and low and high portland cement concrete mixes tents*

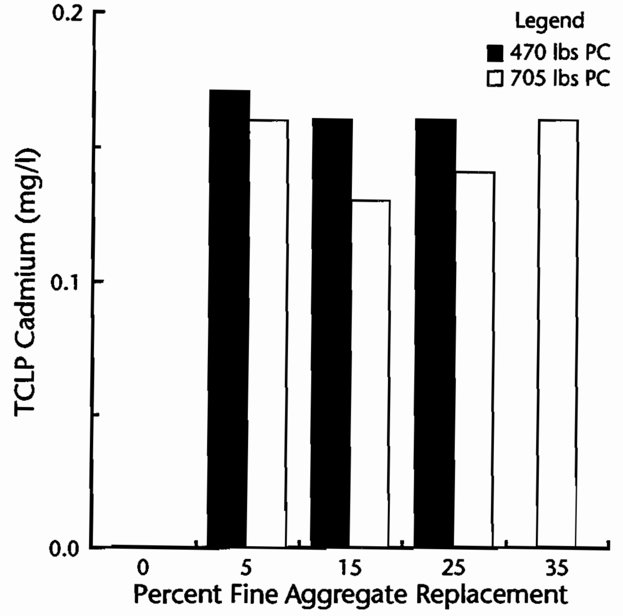

Figure 5.35 *Cadmium TCLP leaching for S/S mixes with spent blast dust, clean sand, and low and high portland cement contents*

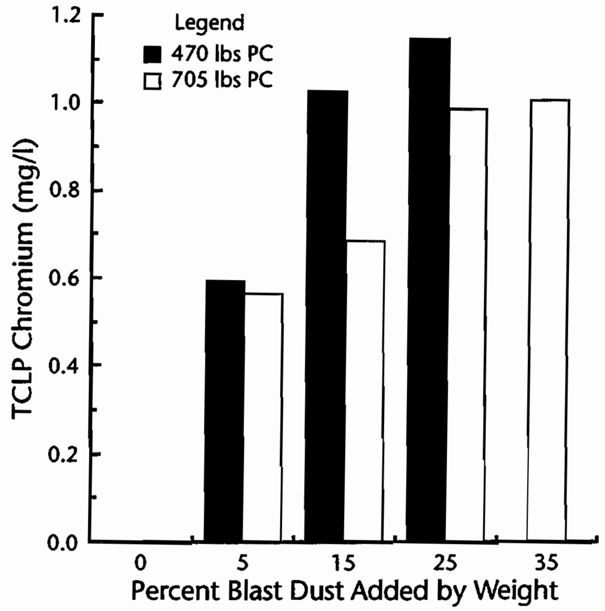

Figure 5.36 *Chromium TCLP leaching for S/S mixes with spent blast dust, clean sand, and low and high portland cement contents*

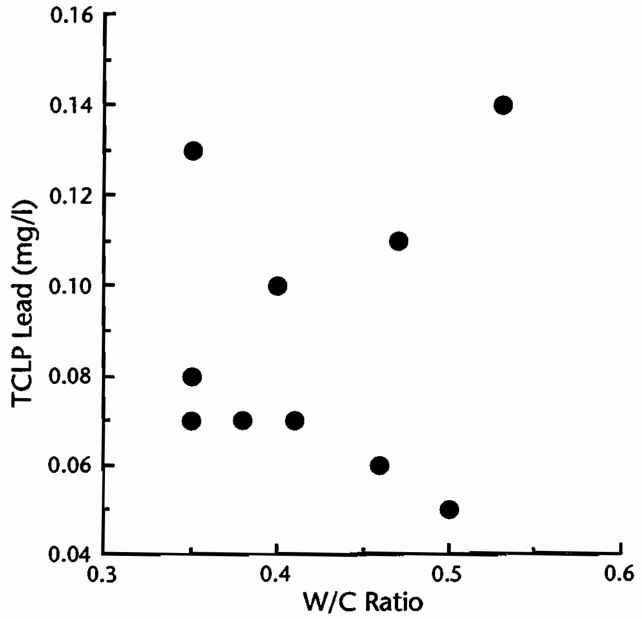

Figure 5.37 *Lead TCLP leaching vs. W/C ratio for S/S mixes containing spent blast dust*

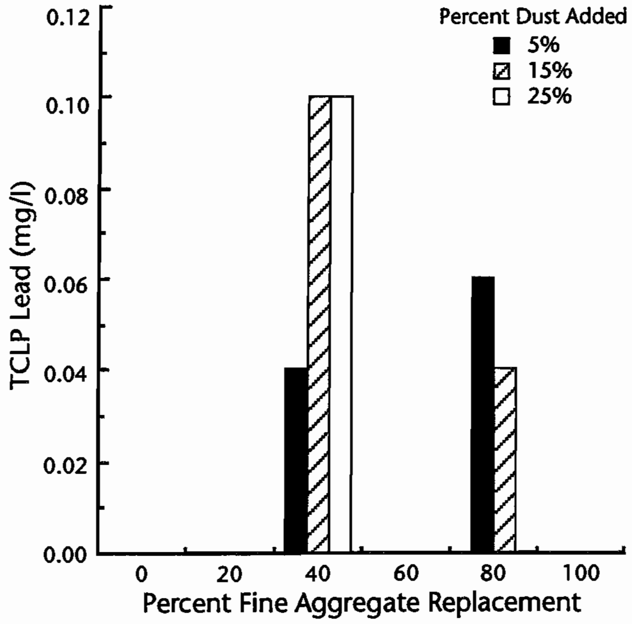

Figure 5.38 ***Lead TCLP leaching for S/S mixes with separated spent blast sand/dust mix and 705 lbs portland cement***

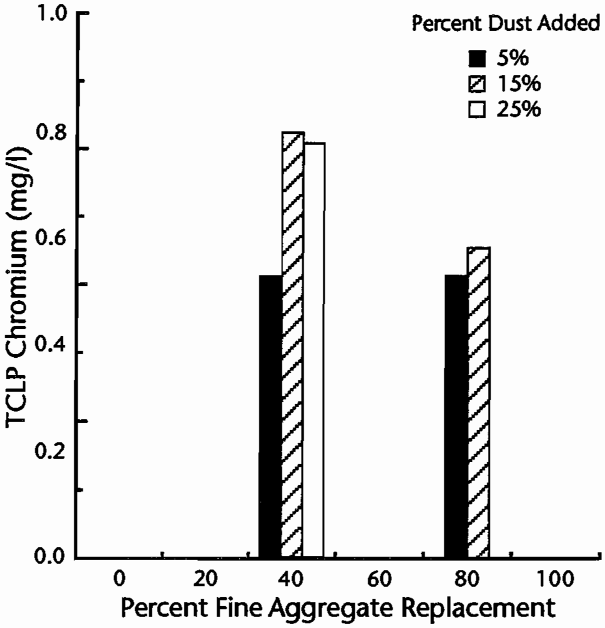

Figure 5.40 ***Chromium TCLP leaching for S/S mixes with separated spent blast sand/dust mix and 705 lbs portland cement***

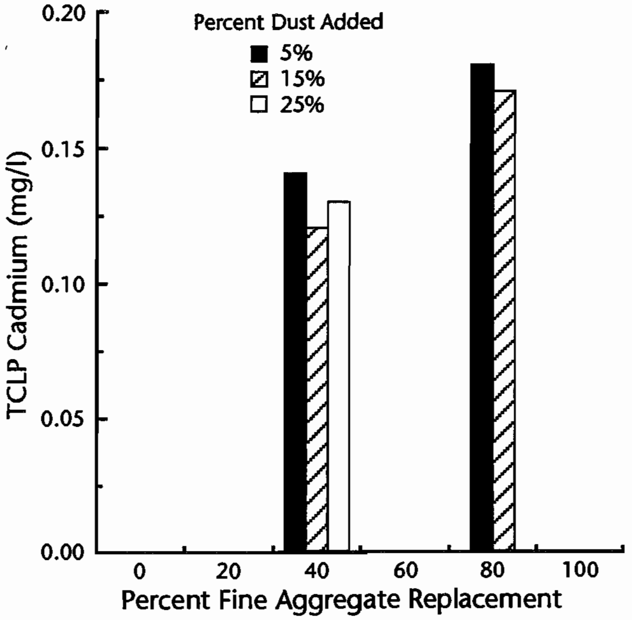

Figure 5.39 ***Cadmium TCLP leaching for S/S mixes with separated spent blast sand/dust mix and 705 lbs portland cement***

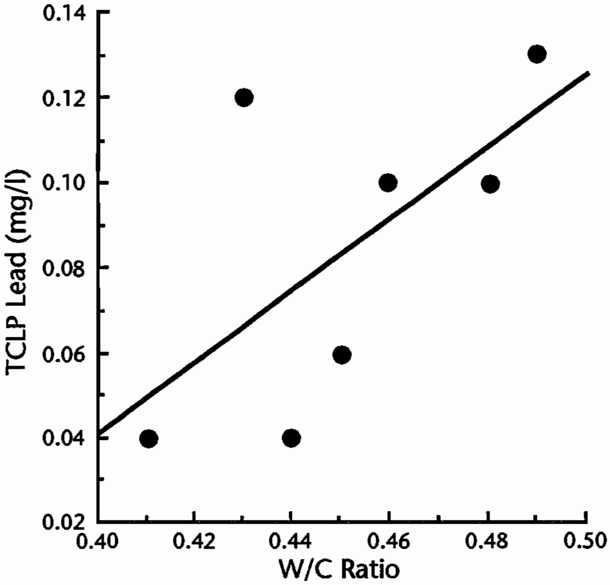

Figure 5.41 ***Lead TCLP leaching vs. W/C ratio for S/S mixes containing separated spent blast sand/dust mix***

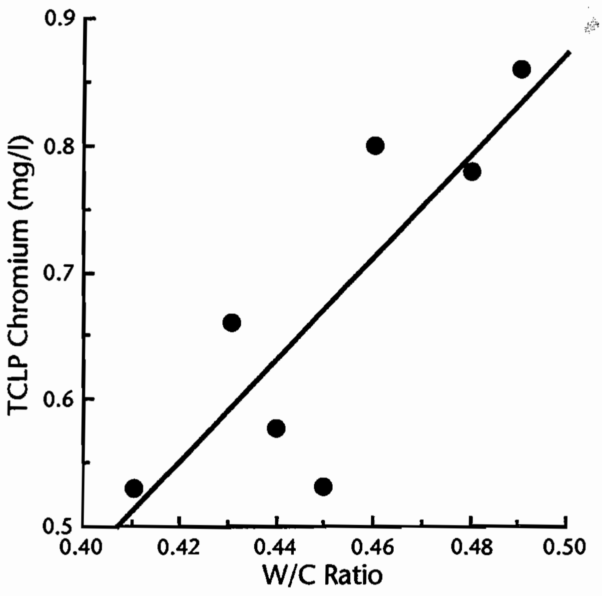

Figure 5.42 *Chromium TCLP leaching vs. W/C ratio for S/S mixes containing separated spent blast sand/dust mix*

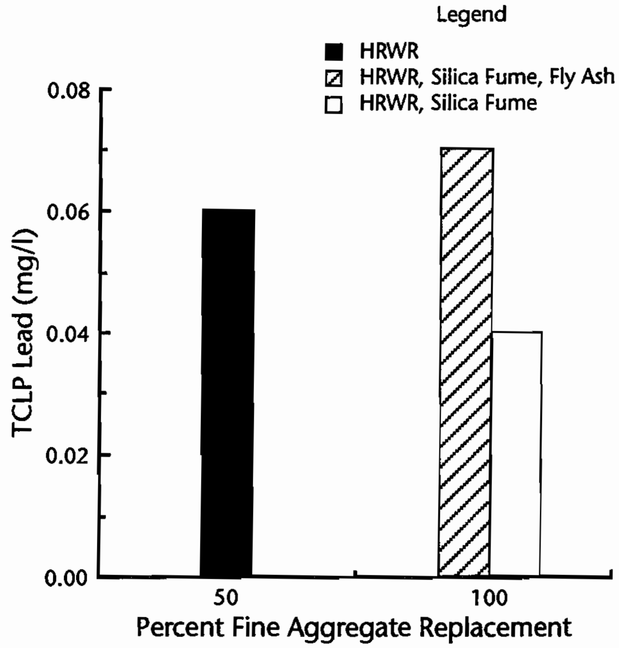

Figure 5.44 *Lead TCLP leaching for S/S mixes with unseparated spent blast sand/dust, 705 lbs portland cement, and additives*

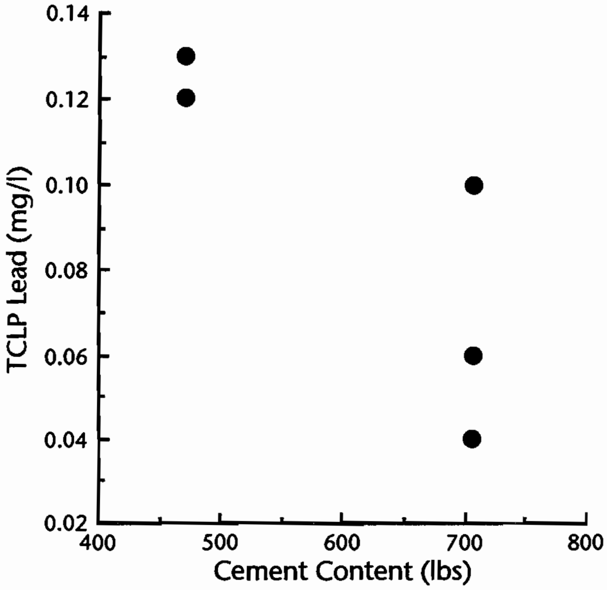

Figure 5.43 *Lead TCLP leaching vs. cement content for S/S mixes containing separated spent blast sand/dust mix*

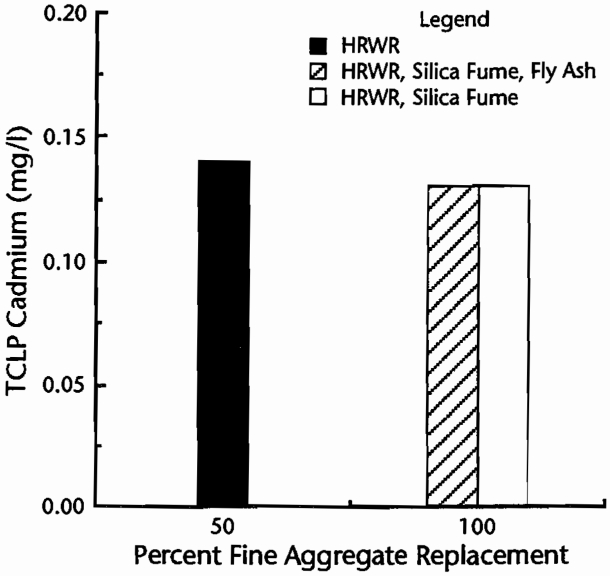

Figure 5.45 *Cadmium TCLP leaching for S/S mixes with unseparated spent blast sand/dust, 705 lbs portland cement, and additives*

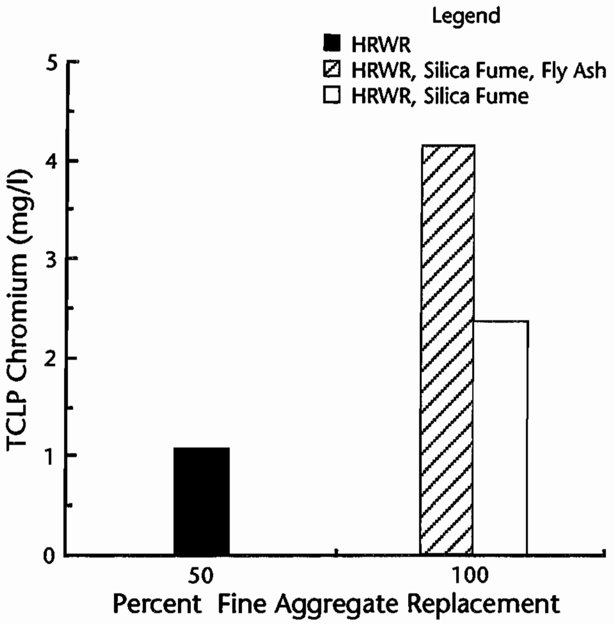

Figure 5.46 ***Chromium TCLP leaching for S/S mixes with unseparated spent blast sand/dust, 705 lbs portland cement, and additives***

5.4.3.7 Summary of the effect of composition on TCLP leaching

In summary, the effect of composition on TCLP leaching can be stated as follows:

1. In general, the higher the W/C ratio, the higher the leaching.
2. In general, the higher the cement content, the lower the leaching.
3. For S/S mixes containing spent blast slag, the TCLP leaching of chromium and cadmium increased with increased amounts of clean fine aggregate replacement, whereas the TCLP leaching of lead did not.
4. For S/S mixes containing spent blast sand, the TCLP leaching of chromium increased with increased spent blast dust content, whereas the TCLP leaching of lead and cadmium did not.
5. For S/S mixes containing spent blast dust: the higher the cement content, the lower the TCLP leaching of lead, cadmium, and chromium; the TCLP leaching of chromium increased with increased spent blast dust content, whereas the TCLP leaching of lead and cadmium did not.
6. For S/S mixes containing separated spent blast sand/dust mix, the TCLP leaching for lead, cadmium, and chromium was not significantly affected by increased clean fine aggregate replacement and/or increased spent blast dust content.
7. For S/S mixes containing unseparated spent blast sand/dust mix, the TCLP leaching of chromium increased with increased replacement of the clean fine aggregate, regardless of the addition of HRWR and silica fume and/or fly ash, whereas the TCLP leaching of lead and cadmium was not affected.
8. In terms of finding an equivalent contamination per volume of spent blasting material, no trends were observed. Regardless of the amount of contamination incorporated into the S/S matrix, nearly all of the TCLP results are equal. This is due to the fact that everything involved in the S/S process is dependent on the composition of the spent blasting media.

5.4.4 Effect of Permeability on TCLP Leaching

5.4.4.1 General Information

For all S/S mixes investigated, TCLP leaching tests were performed on a crushed S/S material sample, whereas permeability tests were run on monolithic material. Once the S/S material was crushed, the integrity of the matrix was destroyed and its permeability was no longer the same as the permeability of the monolithic structure.

5.4.4.2 S/S Mixes Containing Spent Blast Slag

The S/S mixes containing spent blast slag and chemical and mineral additives showed no correlation between permeability and TCLP leaching. Figure 5.47 displays the permeability versus chromium TCLP leaching results from mixes containing spent blast slag as a typical example.

5.4.4.3 S/S Mixes Containing Spent Blast Sand, Blast Dust, and Combinations of These Materials

The S/S mixes with spent blast sand, blast dust, and separated or unseparated blast sand/dust mix showed no correlation between chloride ion permeability and TCLP leaching. Figure 5.48 shows a typical permeability versus TCLP leaching for the S/S mixes with spent blast sand, blast dust, or a combination of the two.

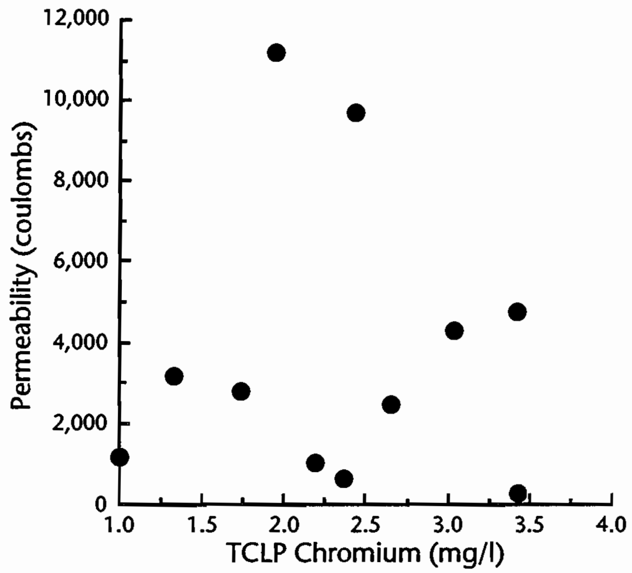

Figure 5.47 *Chromium TCLP leaching for S/S mixes with spent blast slag and additives*

5.4.4.4 Summary of the Effect of Permeability on TCLP Leaching

In summary, the effect of permeability on TCLP leaching can be stated as follows:

1. No direct correlation between permeability and TCLP leaching was observed in any of the series of mixes investigated in this study. However, permeability can be used as a tool for identifying S/S matrices with lower TCLP leaching properties. Two factors that affect permeability, W/C ratio and cement content, also are important to TCLP leaching of S/S matrices. The lower the W/C ratio and the higher the cement content, the lower the permeability and the lower the leaching.
2. The TCLP was performed on samples of crushed S/S material, whereas the rapid chloride ion permeability test was conducted on monolithic S/S matrices.

5.4.5 Effect of Compressive Strength on TCLP Leaching

5.4.5.1 S/S Mixes Containing Spent Blast Slag

The S/S mixes containing spent blast slag and additives showed no relationship between lead and cadmium TCLP leaching and compressive strength. The leaching levels for these elements were small, less than 0.15 mg/L for lead and less than 0.5 mg/L for cadmium, and may not have presented a large enough range of values for any trends to be apparent. Chromium leaching, however, was related to compressive strength; as compressive strength increased, TCLP leaching was reduced. Figures 5.49 and 5.50 show lead and chromium leaching, respectively, versus 28-day compressive strength.

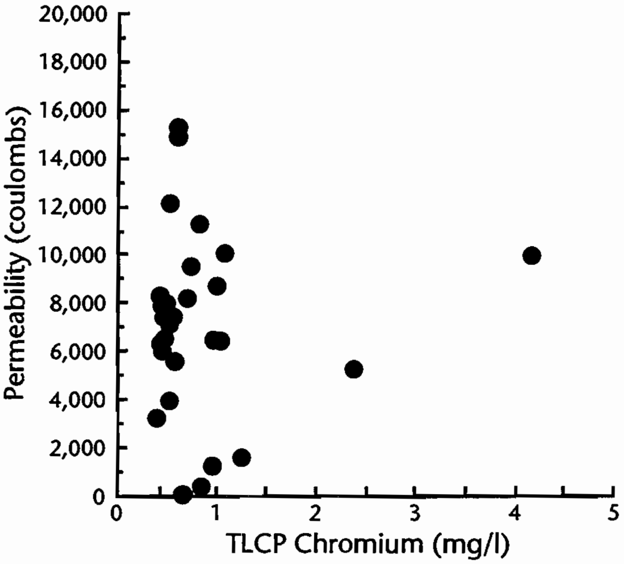

Figure 5.48 *Chromium TCLP leaching vs. permeability for S/S mixes with spent blast sand, blast dust, or a combination of these materials*

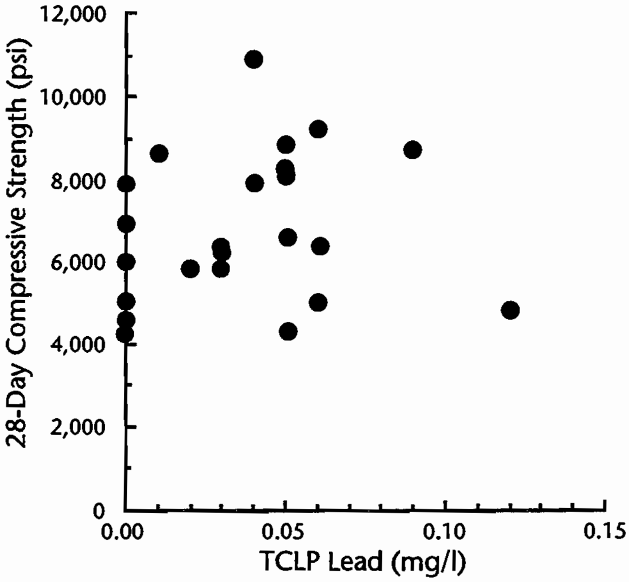

Figure 5.49 *Lead TCLP leaching vs. compressive strength for S/S mixes with spent blast slag and additives*

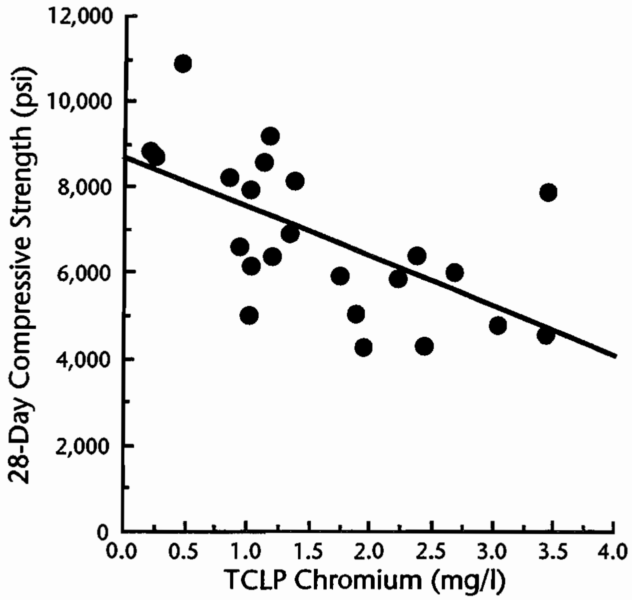

Figure 5.50 ***Chromium TCLP leaching vs. compressive strength for S/S mixes with spent blast slag and additives***

5.4.5.2 S/S Mixes Containing Spent Blast Sand, Blast Dust, and Combinations of These Materials

The S/S mixes containing spent blast sand, blast dust, and separated or unseparated blast sand/dust mix showed decreased lead leaching with increasing strength at a low cement content, and no variation in leaching at a high cement content. Figures 5.51 and 5.52 display lead TCLP leaching versus compressive strength, both at 7 days.

Cadmium leaching was not related to compressive strength in either low or high cement content S/S mixes. Figures 5.53 and 5.54 show cadmium TCLP leaching versus compressive strength, both at 7 days.

The S/S mixes containing a low cement content showed decreased chromium leaching with increased compressive strength, whereas the TCLP leaching of chromium in mixes with a high cement content was not affected by compressive strength. Figures 5.55 and 5.56 show these trends.

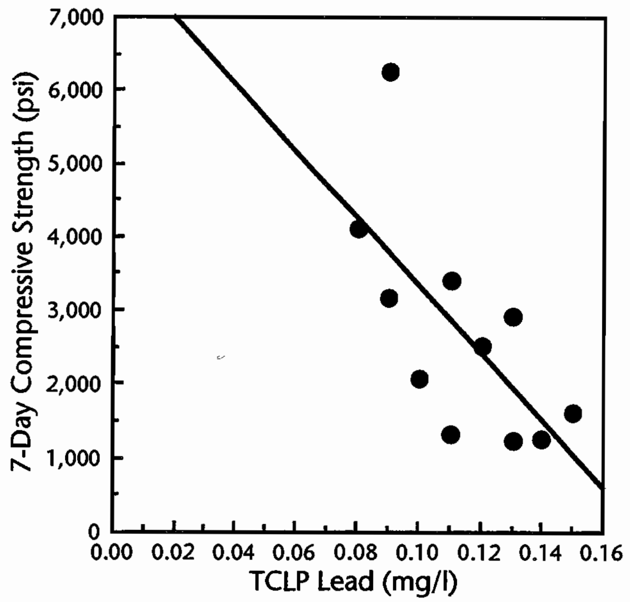

Figure 5.51 ***Lead TCLP leaching vs. compressive strength for S/S mixes with spent blast sand, blast dust, or a combination of these materials, and 470 lbs cement***

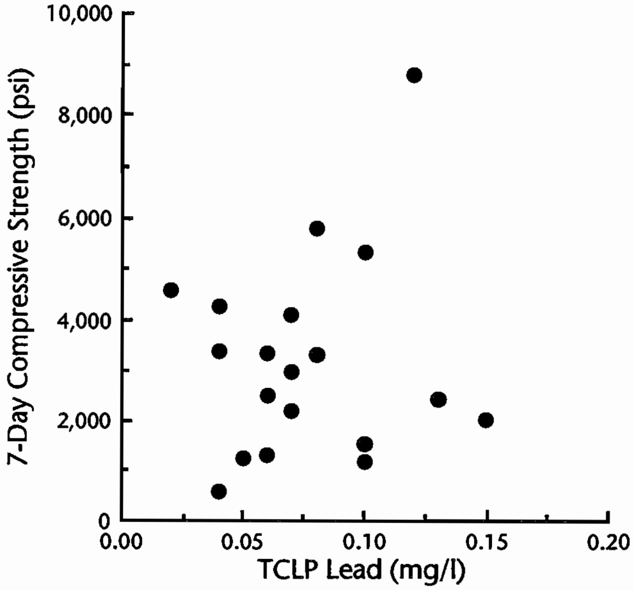

Figure 5.52 ***Lead TCLP seaching vs. compressive strength for S/S mixes with spent blast sand, blast dust, or a combination of these materials, and 705 lbs cement***

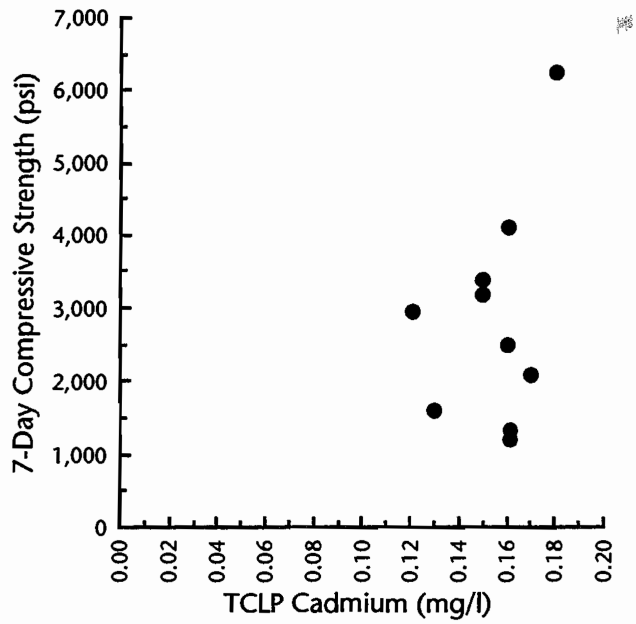

Figure 5.53 *Cadmium TCLP leaching vs. compressive strength for S/S mixes with spent blast sand, blast dust, or a combination of these materials, and 470 lbs cement*

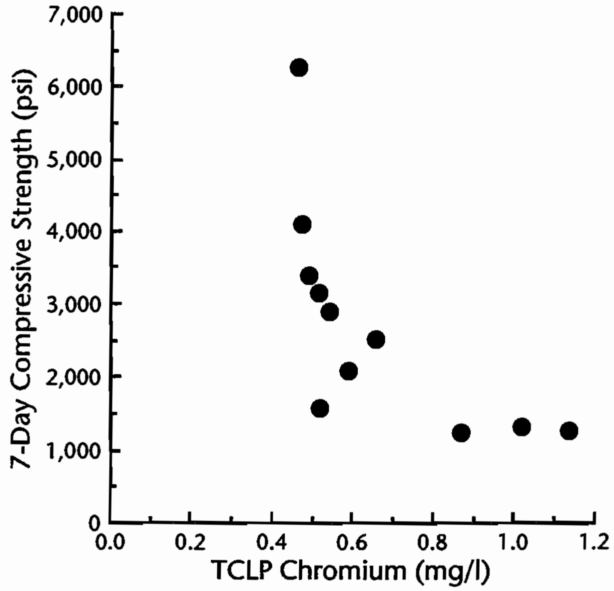

Figure 5.55 *Chromium TCLP leaching vs. compressive strength for S/S mixes with spent blast sand, blast dust, or a combination of these materials, and 470 lbs cement*

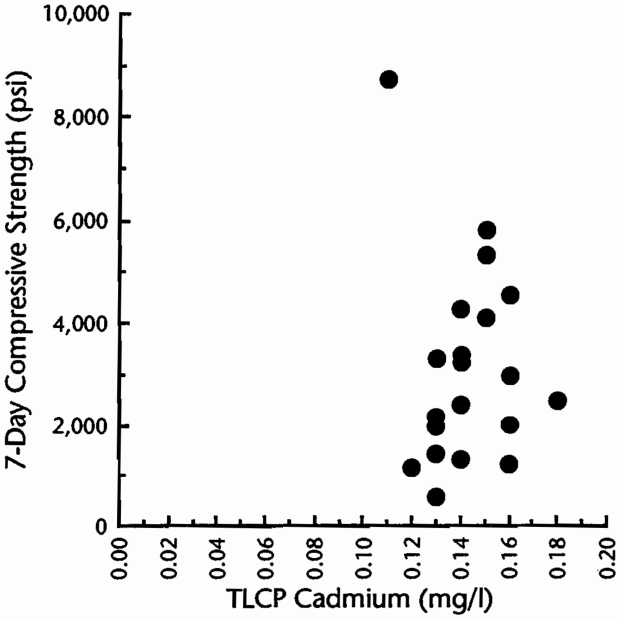

Figure 5.54 *Cadmium TCLP leaching vs. compressive strength for S/S mixes with spent blast sand, blast dust, or a combination of these materials, and 705 lbs cement*

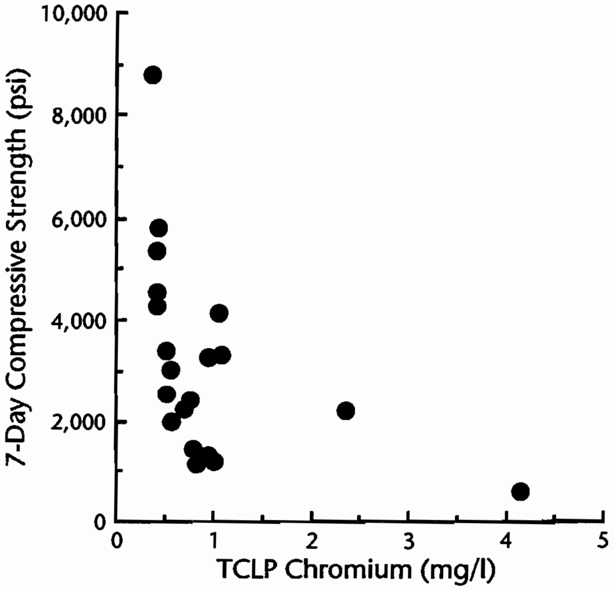

Figure 5.56 *Chromium TCLP leaching vs. compressive strength for S/S mixes with spent blast sand, blast dust, or a combination of these materials, and 750 lbs cement*

5.4.5.3 Summary of the Effect of Compressive Strength on TCLP Leaching

In summary, there is a trend towards decreased leaching with increased compressive strength; however, in many mixes, no correlation was observed. Two variables that affect compressive strength, W/C ratio and cement content, are the most important factors affecting TCLP leaching. Lower W/C ratios and higher cement contents produce mixes with higher compressive strengths and lower leaching.

5.4.6 Effect of Permeability on Compressive Strength

5.4.6.1 S/S Mixes Containing Spent Blast Slag

The S/S mixes containing spent blast slag and additives showed an increase in compressive strength with decreased permeability. Compressive strength at 28 days ranged from 1,500 to 10,000 psi and chloride ion permeability at 28 days ranged from 500 to 12,100 coulombs. Figure 5.57 presents these data.

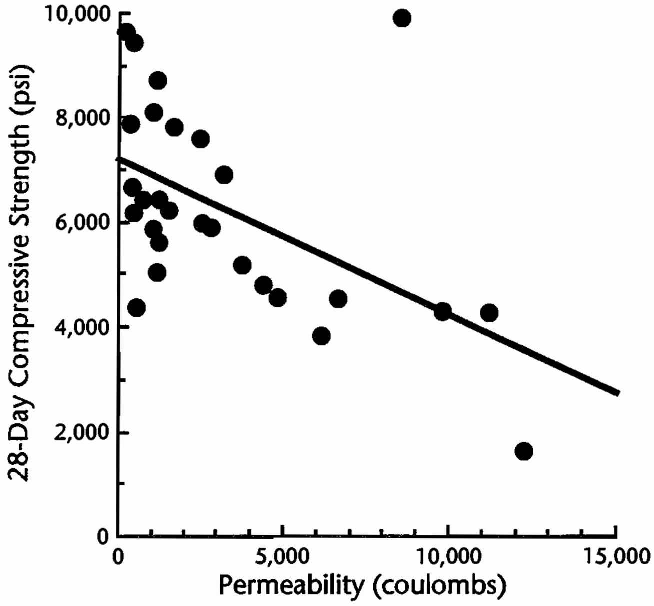

Figure 5.57 ***Permeability vs. compressive strength for S/S mixes with spent blast slag and additives***

5.4.6.2 S/S Mixes Containing Spent Blast Sand, Blast Dust, and Combinations of These Materials

The S/S mixes containing spent blast sand, blast dust, and separated or unseparated blast sand/dust mix also showed an increase in compressive strength with lower permeability. Compressive strengths at 28 days ranged from 1,000 to 10,000 psi, and chloride ion permeability ranged from 400 to 15,200 coulombs. Figure 5.58 presents permeability versus compressive strength for these mixes.

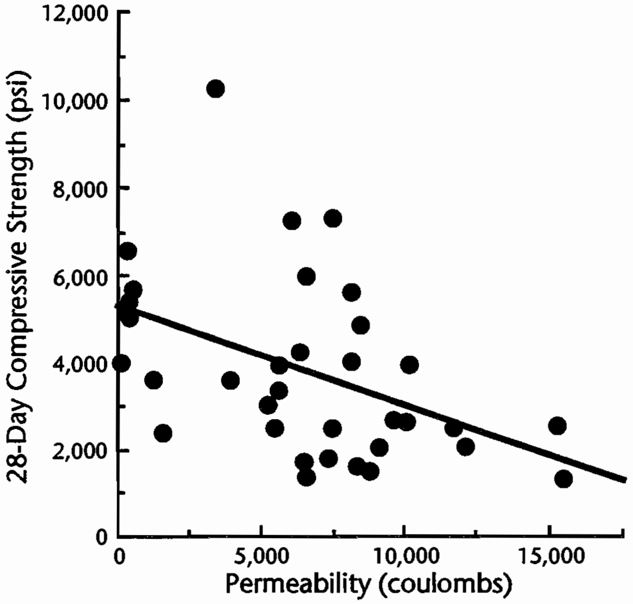

Figure 5.58 ***Permeability vs. compressive strength for S/S mixes with spent blast sand, blast dust, or a combination of these materials***

5.4.6.3 Summary of the Effect of Permeability on Compressive Strength

In general, the compressive strength of the S/S matrices decreases as the permeability of the matrices increases, regardless of the type of spent blasting media or whether chemical and/or mineral admixtures were used.

5.5 EFFECT OF MIXING SEQUENCES AND TIMES

The importance of mixing sequences and times was determined from laboratory observations. The stabilized mortar mixes that were batched using the following mixing procedure were the most uniform and gave the most predictable results.

- Mix the majority of the dry materials first: This has the effect of spreading the contaminants uniformly throughout the mix and avoids segregation, creating a more uniform product. If condensed silica fume is used, mixing the dry material first aids in breaking up the condensed particles and distributes the microsilica evenly in the mix.
- Add the water and chemical admixtures next: This should be done while the mixer is running, if possible. If a low W/C ratio is used and the mix has a high fines content, care should be used to ensure that all dry material is coated with water. If a HRWR is used, it may be combined with the mix water to ensure that it reaches all parts of the mix.
- Add the remaining dry material: This can be done with the mixer running or at a standstill.
- Continued mixing: To ensure the uniformity and quality of the final S/S product, it is very important that once the mixer is fully charged, all of the materials should be thoroughly mixed. This allows the binding mechanism and chemical reactions necessary for the stabilization process to occur in all locations within the mix. As a rule of thumb, S/S mixes should be mixed approximately two to three times as long as ordinary concrete mixes.

Several other mixing sequences were investigated but did not produce uniform, consistent S/S matrices. These methods did not allow for adequate mixing of all the dry material, but, instead, mixed part of the dry material with part of the water as the first step in the mixing sequence. This did not allow the contaminated material to be uniformly distributed throughout the mix and created pockets of high contamination. S/S mixes with a W/C ratio less than 0.35 in which a superplasticizer was added at the end of mixing did not allow for the thorough wetting of all the dry material and did not disperse the chemical admixture evenly in the mix, thereby reducing the effectiveness of the HRWR. S/S mixes that were mixed for short periods of time were not uniform and had pockets of unmixed material. Depending on the mix constituents in these areas of concentration, the pockets had either an accelerated or a delayed set.

CHAPTER 6. SUMMARY, CONCLUSIONS, RECOMMENDATIONS AND GUIDELINES

6.1 SUMMARY

Lead-based paints have been used on structural steel buildings and bridges for many years because of their effectiveness against corrosion and because little surface preparation is required before the paint system is applied. With time, this protective coating deteriorates and must be removed before repainting. The most common method of removal is by abrasive blasting. Some of the advantages of abrasive blasting are that it is efficient, is cost effective, and provides a clean, roughened surface for the new coating. However, as a result of blasting, byproducts are produced that may contain contaminants such as lead, chromium, and cadmium, which could pose environmental concerns if disposed of in a landfill. As a result of recent environmental regulations [34], abrasive blasting of lead-based paints, along with the disposal of the blasting by-products, has become increasingly difficult and costly.

This study investigated the use of solidification/stabilization (S/S) technology using a portland cement binder to recycle contaminated spent blasting abrasives into a usable construction material. The topics investigated included:

(1) characterization of spent blasting material;
(2) development of construction-oriented and environmentally sound S/S methods;
(3) strength testing of S/S matrices;
(4) permeability testing of S/S matrices; and
(5) leachability testing of S/S matrices.

6.2 CONCLUSIONS

Based on the results of the investigation presented herein, the following conclusions can be drawn:

6.2.1 For S/S Mixes in General

(1) A portland cement-based S/S system having adequate compressive strength and permeability properties and meeting the EPA's environmental guidelines can be produced using the contaminated spent blasting abrasives investigated in this study.
(2) It is essential to the successful formulation of a S/S system to know the composition of all raw materials. Both the Toxicity Characteristic Leaching Procedure and Total Constituent Analysis should be performed on the spent blasting media, the binding material, the mix water, and any chemical and mineral admixtures.
(3) In general, the most important factors governing TCLP leaching, compressive strength, and permeability are W/C ratio and cement content. The lower the W/C ratio and the higher the cement content, the lower the leaching and the higher the compressive strength, regardless of the admixtures used.
(4) In general, the higher the contamination in a S/S mix, the lower the compressive strength.
(5) In general, it was found that S/S matrices exhibiting lower permeability also had lower TCLP leaching properties. This was attributed not to the permeability of the matrix, but to the fact that the factors that affect leaching the most, W/C ratio and cement content, also affect permeability. The lower the W/C ratio and the higher the cement content, the lower the permeability and the lower the leaching.
(6) In general, there is a trend towards decreased leaching with increased compressive strength; however, in many mixes, no correlation was observed.
(7) In general, setting times do not affect TCLP leaching or compressive strength. S/S mixes with delayed set due to lead retardation exhibited adequate strength and leaching characteristics once the temporary retardation period had ended.
(8) Mixing sequence and times are important for the success of S/S systems. Best performance was obtained when the majority of the dry components were mixed thoroughly prior to the addition of any liquid components.

6.2.2 S/S Mixes Containing Spent Blast Slag

(1) All mixes containing less than 100 percent replacement of the clean fine aggregate achieved set within 24 hours of mixing, independently of mix proportions.
(2) The higher the replacement of clean fine aggregate with contaminated spent blast slag, the lower the compressive strength of the S/S matrix.
(3) The lower the water-to-cement ratio of the S/S matrix, the higher the compressive strength.
(4) Increased fine aggregate replacement had no effect on W/C ratios and corresponding HRWR dosages.
(5) The TCLP leaching of chromium and cadmium increased with increasing amounts of clean fine aggregate replacement. The TCLP leaching of lead did not.
(6) As the W/C ratios of the mixes decreased, compressive strength of the S/S matrices increased, and the TCLP leaching of chromium decreased. The TCLP leaching of lead and cadmium was not affected by changes in W/C ratio.

6.2.3 S/S Mixes Containing Spent Blast Sand

(1) All S/S mixes, regardless of the amount of fine aggregate replacement or cement content, achieved set within 24 hours of mixing.
(2) S/S mixes that did not contain chemical and/or mineral admixtures showed increased W/C ratios with increased clean fine aggregate replacement. This resulted in decreased compressive strengths, increased chromium TCLP leaching, and higher permeabilities.
(3) S/S mixes that contained chemical and/or mineral admixtures had similar W/C ratios and compressive strengths regardless of the amount of clean fine aggregate replaced.
(4) S/S mixes with higher cement contents produced higher compressive strengths.
(5) The W/C ratios of S/S matrices without admixtures increased as the fine aggregate replacement was increased. This resulted in increased permeabilities.
(6) For the same workability, S/S matrices containing silica fume and/or fly ash with a HRWR had lower W/C ratios than S/S mixes without admixtures. This resulted in permeabilities that were lower than the permeabilities of S/S matrices without admixtures.
(7) The TCLP leaching of lead increased as the replacement of clean fine aggregate increased. The TCLP leaching of chromium and cadmium did not.
(8) The higher the cement content, the lower the TCLP leaching of lead, chromium, and cadmium.
(9) The lower the W/C ratio, the lower the TCLP leaching of chromium. TCLP leaching of lead and cadmium were not affected by changes in W/C ratio.

6.2.4 S/S Mixes Containing Spent Blast Dust

(1) The higher the spent blast dust content of a S/S matrix, the longer the set time.
(2) The higher the cement content of a S/S matrix, the less retardation due to lead.
(3) The use of silica fume, fly ash, and HRWR increased the fines content of the S/S mix and reduced the W/C ratio. This, in turn, reduced the amount of spent blast dust that could be utilized in a S/S mix while still achieving set.
(4) The compressive strength of S/S matrices decreased with increased spent blast dust content.
(5) The greater the cement content of a S/S matrix, the higher the compressive strength for a given workability.
(6) As the amount of spent blast dust in the S/S matrices increased, the W/C ratio also increased, thereby increasing permeability.
(7) The higher the cement content, the lower the TCLP leaching of lead, chromium, and cadmium.
(8) The TCLP leaching of chromium increased with increased spent blast dust content, whereas the TCLP leaching of lead and cadmium were not affected.

6.2.5 S/S Mixes Containing Separated Spent Blast Sand/Dust Mix

(1) The higher the spent blast media content of a S/S matrix, the longer the set time for a given cement content.
(2) The higher the cement content of a S/S matrix, the less retardation caused by lead.
(3) S/S mixes with a low cement content and greater than 5 percent spent blast dust did not set, regardless of the amount of clean fine aggregate replacement.
(4) S/S matrices with increased clean fine aggregate replacement and/or increased spent blast dust content had decreased compressive strengths. Therefore, the higher the contamination in a S/S mix, the lower the compressive strength.

(5) S/S matrices containing silica fume and HRWR had higher W/C ratios and therefore lower compressive strengths than S/S matrices with silica fume, fly ash, and HRWR.
(6) The W/C ratios of S/S matrices increased with increased clean fine aggregate replacement and increased spent blast dust content. This resulted in higher permeabilities.
(7) For S/S mixes with high cement contents, the TCLP leaching for lead, chromium, and cadmium was not significantly affected by increased clean fine aggregate replacement and/or increased spent blast dust content.

6.2.6 S/S Mixes Containing Unseparated Spent Blast Sand/Dust Mix

(1) For S/S mixes containing 100 percent replacement of the clean fine aggregate and a constant W/C ratio, only the ones with a high cement content and chemical and mineral admixtures achieved set.
(2) The S/S mixes containing a set retarder had a delayed set of up to 48 hours. Once these mixes set, they performed as well as mixes without retarders.
(3) The use of calcium nitrite in S/S mixes was not found to be effective in preventing excessive retardation.
(4) The permeabilities of S/S mixes with this spent blasting material were very high.
(5) The TCLP leaching of chromium increased with increased replacement of the clean fine aggregate, regardless of the addition of HRWR, and silica fume and/or fly ash. The TCLP leaching of lead and cadmium was not affected.

6.3 RECOMMENDATIONS FOR FURTHER RESEARCH

Based on the findings of this study, the following topics for further investigation are suggested:

(1) Study the effect of a spent blasting material with different levels of contamination on S/S processes using portland cement as the primary binding mechanism.
(2) Study the effect of calcium chloride and sodium silicate on preventing excessive retardation of set of portland cement-based S/S systems.
(3) Study the effect of using polymer concretes and latex-modified cements as the primary binding mechanism on the effectiveness of S/S systems.

6.4 GUIDELINES FOR THE S/S OF SPENT BLASTING ABRASIVES WITH PORTLAND CEMENT CONCRETES AND MORTARS

The following are suggested guidelines for using portland cement-based S/S systems in construction to recycle contaminated spent abrasive blasting media:

(1) Establish the job requirements and environmental limits to be met by the solidified/stabilized material in terms of compressive strength, setting time, and TCLP leaching.
(2) Characterize all raw materials using the TCLP and Total Constituent Analysis.
(3) Determine trial mix proportions. This includes determining the binding mechanism to be used and which, if any, chemical and/or mineral admixtures will be utilized. This may be accomplished with the aid of the mix proportions and corresponding results from this study.
(4) Make a trial batch. Ensure that the proper mixing sequence is used and that adequate mixing is achieved.
(5) Test the trial batch for compressive strength and TCLP leachability.
(6) Determine whether the trial batch meets the requirements of the specific application.
(7) If needed, adjust the mix design to adjust for strength, setting, and leaching requirements.
(8) Repeat steps 5 through 8 until a successful S/S system is attained.
(9) Ensure that the same materials and job conditions are used in both the trial batches and in the field applications.
(10) Ensure that the proper mixing sequence is used and that adequate mixing is achieved during the field application of the S/S system.

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APPENDIX 1

The following tables present the mix designations and mix proportions used for the blast sand, blast dust, and blast sand/dust S/S mixtures. The nomenclature used in the tables is given below.

NOMENCLATURE:

Column 1: mix designation.
Column 2: amount of portland cement used, in pounds.
Column 3: amount of clean sand used, in pounds.
Column 4: amount of blast sand used, in pounds.
Column 5: amount of blast dust used, in pounds.
Column 6: amount of blast sand/dust mixture used, in pounds.
Column 7: dosage of superplasticizer used, in ounces per hundred weight of cement.
Column 8: dosage of retarder used, in ounces per hundred weight of cement.
Column 9: dosage of corrosion inhibitor used, in ounces per hundred weight of cement.
Column 10: amount of fly ash used, in pounds, and as a percent replacement of portland cement.
Column 11: amount of silica fume used, in pounds, and as a percent addition of portland cement.
Column 12: W/C ratio used.

it mix proportions and designations

1	2	3	4	5	6	7	8	9	10	11	12
MIX	CEMENT lbs	CONCRETE SAND lbs	BLAST SAND lbs	BLAST DUST lbs	BLAST SAND/DUST lbs	HRWR oz/cwt	RETARDER oz/cwt	DCI oz/cwt	FLY ASH lbs	SILICA FUME lbs	W/C BY WT
SD1	600	440	660	0	0	23.5	0.0	0.0	0	72	0.31
SD1-D	600	440	660	110	0	18.0	0.0	0.0	0	72	0.29
SD2	600	0	1100	0	0	18.8	0.0	0.0	0	72	0.28
SD2-D	600	0	1100	183	0	26.5	0.0	0.0	0	72	0.28
SD3	420	440	660	0	0	20.9	0.0	0.0	180	72	0.31
SD3-D	420	440	660	110	0	20.5	0.0	0.0	180	72	0.31
SD4	420	0	1100	0	0	19.2	0.0	0.0	180	72	0.27
SD4-D	420	0	1100	183	0	22.6	0.0	0.0	180	72	0.35
SD10	470	1100	0	0	0	0.0	0.0	0.0	0	0	0.38
SD11	470	880	220	0	0	0.0	0.0	0.0	0	0	0.37
SD12	470	660	440	0	0	0.0	0.0	0.0	0	0	0.37
SD13	470	440	660	0	0	0.0	0.0	0.0	0	0	0.41
SD14	470	220	880	0	0	0.0	0.0	0.0	0	0	0.40
SD15	470	0	1100	0	0	0.0	0.0	0.0	0	0	0.40
SD20	705	1100	0	0	0	0.0	0.0	0.0	0	0	0.35
SD21	705	880	220	0	0	0.0	0.0	0.0	0	0	0.35
SD22	705	660	440	0	0	0.0	0.0	0.0	0	0	0.37
SD23	705	440	660	0	0	0.0	0.0	0.0	0	0	0.38
SD24	705	220	880	0	0	0.0	0.0	0.0	0	0	0.38
SD25	705	0	1100	0	0	0.0	0.0	0.0	0	0	0.41
DT10	470	1100	0	55	0	0.0	0.0	0.0	0	0	0.40
DT11	470	1100	0	165	0	0.0	0.0	0.0	0	0	0.47

Blast sand and blast dust mix proportions and designations

1	2	3	4	5	6	7	8	9	10	11	12
MIX	CEMENT lbs	CONCRETE SAND lbs	BLAST SAND lbs	BLAST DUST lbs	BLAST SAND/DUST lbs	HRWR oz/cwt	RETARDER oz/cwt	DCI oz/cwt	FLY ASH lbs	SILICA FUME lbs	W/C BY WT
DT12	470	1100	0	275	0	0.0	0.0	0.0	0	0	0.53
DT13	470	1100	0	385	0	0.0	0.0	0.0	0	0	0.57
DT20	705	1100	0	55	0	0.0	0.0	0.0	0	0	0.38
DT21	705	1100	0	165	0	0.0	0.0	0.0	0	0	0.41
DT21S	705	1100	0	165	0	17.9	0.0	0.0	0	0	0.35
DT21M	705	1100	0	165	0	24.6	0.0	0.0	212	84.6	0.35
DT21R	705	1100	0	165	0	13.2	4.0	0.0	0	0	0.35
DT22	705	1100	0	275	0	0.0	0.0	0.0	0	0	0.46
DT22S	705	1100	0	275	0	26.5	0.0	0.0	0	0	0.35
DT22M	705	1100	0	275	0	24.9	0.0	0.0	212	84.6	0.35
DT22R	705	1100	0	275	0	25.4	4.0	0.0	0	0	0.35
DT23	705	1100	0	385	0	0.0	0.0	0.0	0	0	0.50
SDT12A	470	660	440	55	0	0.0	0.0	0.0	0	0	0.43
SDT12B	470	660	440	165	0	0.0	0.0	0.0	0	0	0.47
SDT12C	470	660	440	275	0	0.0	0.0	0.0	0	0	0.54
SDT14A	470	220	880	55	0	0.0	0.0	0.0	0	0	0.49
SDT14B	470	220	880	165	0	0.0	0.0	0.0	0	0	0.54
SDT14C	470	220	880	275	0	0.0	0.0	0.0	0	0	0.60
SDT14Cs	470	220	880	275	0	34.7	0.0	0.0	0	0	0.45
SDT22A	705	660	440	55	0	0.0	0.0	0.0	0	0	0.41
SDT22B	705	660	440	165	0	0.0	0.0	0.0	0	0	0.46
SDT22Bs	705	660	440	165	0	23.9	0.0	0.0	0	0	0.35

Blast sand and blast dust mix proportions and designations

1	2	3	4	5	6	7	8	9	10	11	12
MIX	CEMENT lbs	CONCRETE SAND lbs	BLAST SAND lbs	BLAST DUST lbs	BLAST SAND/DUST lbs	HRWR oz/cwt	RETARDER oz/cwt	DCI oz/cwt	FLY ASH lbs	SILICA FUME lbs	W/C BY WT
SDT22C	705	660	440	275	0	0.0	0.0	0.0	0	0	0.48
SDT24A	705	220	880	55	0	0.0	0.0	0.0	0	0	0.45
SDT24B	705	220	880	165	0	0.0	0.0	0.0	0	0	0.44
SDT100	470	0	0	0	1100	24.3	0.0	0.0	0	0	0.35
SDT100B	470	0	0	0	1100	14.4	0.0	0.0	0	0	0.35
SDT100B1	470	0	0	0	1100	18.9	0.0	10.2	0	0	0.35
SDT100B2	470	0	0	0	1100	16.0	0.0	20.4	0	0	0.35
SDT100B3	470	0	0	0	1100	15.4	0.0	30.6	0	0	0.35
SDT100R	470	0	0	0	1100	7.9	4.0	0.0	0	0	0.35
SDT200	705	0	0	0	1100	12.0	0.0	0.0	0	0	0.35
SDT200B	705	0	0	0	1100	9.5	0.0	0.0	0	0	0.35
SDT200B1	705	0	0	0	1100	10.0	0.0	6.8	0	0	0.35
SDT200B2	705	0	0	0	1100	10.0	0.0	13.6	0	0	0.35
SDT200B3	705	0	0	0	1100	10.0	0.0	20.4	0	0	0.35
SDT200R	705	0	0	0	1100	2.4	4.0	0.0	0	0	0.35
SDT201	705	0	0	0	1100	21.8	0.0	0.0	0	84.6	0.35
SDT201R	705	0	0	0	1100	6.0	4.0	0.0	0	84.6	0.35
SDT202	705	0	0	0	1100	12.0	0.0	0.0	212	84.6	0.35
SDT202R	705	0	0	0	1100	0.0	4.0	0.0	212	84.6	0.35
SDT203	705	550	0	0	550	12.0	0.0	0.0	0	0	0.35
SDT203R	705	550	0	0	550	0.0	4.0	0.0	0	0	0.34

APPENDIX 2

The following tables present the 7-, 28-, and 90-day compressive strengths as well as the 28-day rapid chloride ion permeability for the blast sand, blast dust, and blast sand/dust S/S mixtures. The nomenclature used in the tables is given below.

NOMENCLATURE:

Column 1: mix designation.
Column 2: 7-day compressive strength in psi.
Column 3: 28-day compressive strength in psi.
Column 4: 90-day compressive strength in psi.
Column 5: rapid chloride ion permeability in coulombs.
Column 6: indicates when the mix achieved final set. If the cell is blank, final set was reached within the first 24 hours. No set indicates that final set was not reached within three days of mixing.

NOTE: N/A indicates that data are not available.

Strength and permeability results for mixes with blast sand and blast dust

1	2	3	4	5	6
MIX	7-Day f'c psi	28-Day f'c psi	90-Day f'c psi	PERMEABILITY Coulombs	NOTES
SD1	3790	4050	4720	110	
SD1-D	2740	3630	3620	1260	
SD2	3710	5120	4850	380	
SD2-D	1550	2450	2700	1630	
SD3	4340	5190	5270	290	
SD3-D	3510	5730	5070	510	
SD4	3370	5440	4900	380	
SD4-D	2920	6620	6140	260	
SD10	6260	7320	8230	7460	
SD11	4120	6030	6440	6550	
SD12	3160	4090	4180	8110	
SD13	3390	3690	3730	N/A	
SD14	2930	2710	3670	N/A	
SD15	1620	2110	1650	12100	
SD20	8790	10230	11180	3300	
SD21	5820	7270	6120	6050	
SD22	5360	5660	6890	8100	
SD23	4310	4270	4260	6380	
SD24	4560	4910	4290	8410	
SD25	2030	2590	1710	15220	
DT10	2060	2545	2870	7460	
DT11	1330	1400	1700	6550	
DT12	1270	1650	1200	N/A	
DT13	0	0	0	N/A	NO SET
DT20	2990	3990	3900	5620	
DT21	2200	1670	3120	8320	
DT21S	2430	2740	2090	9620	
DT21M	3330	N/A	N/A	N/A	
DT21R	2180	2550	3050	5480	SET DAY 2
DT22	1320	1740	2020	6530	
DT22S	0	0	0	N/A	NO SET
DT22M	4120	N/A	N/A	N/A	
DT22R	0	0	0	N/A	NO SET
DT23	1260	1560	1490	8810	
SDT12A	2520	2650	2670	N/A	

Strength and permeability results for mixes with blast sand and blast dust

1	2	3	4	5	6
MIX	7-Day f'c psi	28-Day f'c psi	90-Day f'c psi	PERMEABILITY Coulombs	NOTES
SDT12B	0	0	0	N/A	NO SET
SDT12C	0	0	0	N/A	NO SET
SDT14A	1240	1430	1150	N/A	
SDT14B	0	0	0	N/A	NO SET
SDT14C	0	0	0	N/A	NO SET
SDT14Cs	0	0	0	N/A	NO SET
SDT22A	3420	3640	4070	3900	
SDT22B	1190	N/A	1690	11420	
SDT22Bs	0	0	0	N/A	NO SET
SDT22C	1470	1270	1930	N/A	SET DAY 2
SDT24A	2520	1830	2180	7310	
SDT24B	N/A	1360	N/A	15400	SET DAY 2
SDT100	0	0	0	N/A	NO SET
SDT100B	0	0	0	N/A	NO SET
SDT100B1	0	0	0	N/A	NO SET
SDT100B2	0	0	0	N/A	NO SET
SDT100B3	0	0	0	N/A	NO SET
SDT100R	0	0	0	N/A	NO SET
SDT200	0	0	0	N/A	NO SET
SDT200B	0	0	0	N/A	NO SET
SDT200B1	0	0	0	N/A	NO SET
SDT200B2	0	0	0	N/A	NO SET
SDT200B3	0	0	0	N/A	NO SET
SDT200R	0	0	0	N/A	NO SET
SDT201	2230	3040	3040	5270	
SDT201R	1370	2100	2480	9090	SET DAY 2
SDT202	620	2690	2890	10070	
SDT202R	350	3415	4970	5620	SET DAY 2
SDT203	3350	4000	4700	10080	
SDT203R	2120	2530	2620	11630	SET DAY 2

APPENDIX 3

The following tables present the mix designations and the 7- and 28-day TCLP leaching results for the blast sand, blast dust, and blast sand/dust S/S mixtures. The nomenclature used in the tables is given below.

NOMENCLATURE:

Column 1: mix designation.
Column 2: 7-day TCLP leaching for chromium in mg/L.
Column 3: 7-day TCLP leaching for cadmium in mg/L.
Column 4: 7-day TCLP leaching for lead in mg/L.
Column 5: 7-day TCLP leaching for aluminum in mg/L.
Column 6: 28-day TCLP leaching for chromium in mg/L.
Column 7: 28-day TCLP leaching for cadmium in mg/L.
Column 8: 28-day TCLP leaching for lead in mg/L.
Column 9: 28-day TCLP leaching for aluminum in mg/L.

NOTE: N/A indicates that data are not available.

7-day TCLP leaching results for mixes with blast sand and blast dust

1	2	3	4	5
MIX	7-Day TCLP Cr (mg/L)	7-Day TCLP Cd (mg/L)	7-Day TCLP Pb (mg/L)	7-Day TCLP Al (mg/L)
SD1	0.64	0.18	0	36.76
SD1-D	0.96	0.19	0.06	34.81
SD2	0.84	0.2	0	34.11
SD2-D	1.24	0.22	0	33.91
SD3	N/A	N/A	N/A	N/A
SD3-D	N/A	N/A	N/A	N/A
SD4	N/A	N/A	N/A	N/A
SD4-D	N/A	N/A	N/A	N/A
SD10	0.46	0.18	0.09	27.67
SD11	0.47	0.16	0.08	27.39
SD12	0.52	0.15	0.09	26.84
SD13	0.49	0.15	0.11	22.44
SD14	0.54	0.12	0.13	21.26
SD15	0.53	0.13	0.15	21.11
SD20	0.39	0.11	0.12	20.39
SD21	0.45	0.15	0.08	26.48
SD22	0.42	0.15	0.1	25.68
SD23	0.42	0.14	0.04	24.92
SD24	0.44	0.16	0.02	25.56
SD25	0.56	0.16	0.15	26.29
DT10	0.59	0.17	0.1	21.92
DT11	1.02	0.16	0.11	21.43
DT12	1.14	0.16	0.14	21.21
DT13	N/A	N/A	N/A	N/A
DT20	0.56	0.16	0.07	25.71
DT21	0.68	0.13	0.07	22.17
DT21S	0.73	0.14	0.13	24.97
DT21M	0.95	0.13	0.08	22.13
DT21R	N/A	N/A	N/A	N/A
DT22	0.98	0.14	0.06	22.23
DT22S	N/A	N/A	N/A	N/A
DT22M	1.05	0.15	0.07	21.76
DT22R	N/A	N/A	N/A	N/A
DT23	1	0.16	0.05	25.2
SDT12A	0.66	0.16	0.12	25.3
SDT12B	N/A	N/A	N/A	N/A

7-day TCLP leaching results for mixes with blast sand and blast dust

1	2	3	4	5
MIX	7-Day TCLP Cr (mg/L)	7-Day TCLP Cd (mg/L)	7-Day TCLP Pb (mg/L)	7-Day TCLP Al (mg/L)
SDT12C	N/A	N/A	N/A	N/A
SDT14A	0.86	0.16	0.13	24.95
SDT14B	N/A	N/A	N/A	N/A
SDT14C	N/A	N/A	N/A	N/A
SDT14Cs	N/A	N/A	N/A	N/A
SDT22A	0.53	0.14	0.04	20.55
SDT22B	0.8	0.12	0.1	19.8
SDT22Bs	N/A	N/A	N/A	N/A
SDT22C	0.78	0.13	0.1	19.62
SDT24A	0.53	0.18	0.06	25.54
SDT24B	0.58	0.17	0.04	25.56
SDT100	N/A	N/A	N/A	N/A
SDT100B	N/A	N/A	N/A	N/A
SDT100B1	N/A	N/A	N/A	N/A
SDT100B2	N/A	N/A	N/A	N/A
SDT100B3	N/A	N/A	N/A	N/A
SDT100R	N/A	N/A	N/A	N/A
SDT200	N/A	N/A	N/A	N/A
SDT200B	N/A	N/A	N/A	N/A
SDT200B1	N/A	N/A	N/A	N/A
SDT200B2	N/A	N/A	N/A	N/A
SDT200B3	N/A	N/A	N/A	N/A
SDT200R	N/A	N/A	N/A	N/A
SDT201	2.36	0.13	0.07	23.39
SDT201R	N/A	N/A	N/A	N/A
SDT202	4.15	0.13	0.04	23.05
SDT202R	N/A	N/A	N/A	N/A
SDT203	1.07	0.14	0.06	22.61
SDT203R	N/A	N/A	N/A	N/A

7- and 28-day TCLP leaching results for mixes with blast sand and blast dust in addition to fly ash and silica fume

1	2	3	4	5	6	7	8	9
MIX	**7-Day TCLP Cr (mg/L)**	**7-Day TCLP Cd (mg/L)**	**7-Day TCLP Pb (mg/L)**	**7-Day TCLP Al (mg/L)**	**28-Day TCLP Cr (mg/L)**	**28-Day TCLP Cd (mg/L)**	**28-Day TCLP Pb (mg/L)**	**28-Day TCLP Al (mg/L)**
SD1	0.64	0.18	0	36.76	0.91	0.34	0.11	27.26
SD1-D	0.96	0.19	0.06	34.81	1.19	0.35	0.07	25.80
SD2	0.84	0.2	0	34.11	0.86	0.30	0.12	24.69
SD2-D	1.24	0.22	0	33.91	1.05	0.14	0.10	23.35
SD3	N/A	N/A	N/A	N/A	0.53	0.16	0.07	22.68
SD3-D	N/A	N/A	N/A	N/A	0.78	0.13	0.15	22.51
SD4	N/A	N/A	N/A	N/A	0.65	0.14	0.11	22.13
SD4-D	N/A	N/A	N/A	N/A	0.77	0.14	0.11	22.32

APPENDIX 4

The following tables present the mix designations and mix proportions used for the spent blast slag S/S mixtures. The nomenclature used in the tables is given below.

NOMENCLATURE:

Column 1: mix designation.
Column 2: amount of portland cement used, in pounds.
Column 3: amount of clean sand used, in pounds.
Column 4: amount of blast slag used, in pounds.
Column 5: dosage of superplasticizer used, in ounces per hundred weight of cement.
Column 6: amount of fly ash used, in pounds, and as a percent replacement of portland cement.
Column 7: amount of silica fume used, in pounds, and as a percent addition to portland cement.
Column 8: W/C ratio used.

Blast slag mix proportions and designations

1	2	3	4	5	6	7	8
MIX	CEMENT lbs	CONCRETE SAND lbs	BLAST SLAG lbs	HRWRA oz/cwt	FLY ASH lbs	SILICA FUME lbs	W/C BY WT
CM I	600	1100	0	8.0	0	0	0.33
CM II	420	1100	0	8.0	180	0	0.33
CM III	600	1100	0	8.0	0	72	0.35
CM IIIB	600	1100	0	8.0	0	72	0.33
CSG CM	600	600	500	8.0	0	0	0.33
SG III-1	600	600	500	8.0	0	72	0.40
SG III-2	600	600	500	14.7	0	72	0.31
SG III-3	600	600	500	21.4	0	72	0.29
SG III-4	600	600	500	30.8	0	72	0.27
SG III-5	600	800	300	11.6	0	72	0.31
SG III-6	600	800	300	15.9	0	72	0.29
SG III-7	600	800	300	20.8	0	72	0.27
SG100	420	825	275	8.0	180	0	0.28
SG101	420	825	275	8.0	180	0	0.27
SG103	420	825	275	17.2	180	0	0.23
SG200	420	550	550	8.0	180	0	0.29
SG201	420	550	550	8.0	180	0	0.27
SG203	420	550	550	19.2	180	0	0.24
SG300	420	275	825	8.0	180	0	0.32
SG301	420	275	825	8.0	180	0	0.29
SG302	420	275	825	12.0	180	0	0.28
SG303	420	275	825	16.0	180	0	0.26
SG400	600	825	275	8.0	0	72	0.36
SG401	600	825	275	8.0	0	72	0.33
SG402	600	825	275	13.0	0	72	0.31
SG403	600	825	275	18.5	0	72	0.30
SG500	600	550	550	8.0	0	72	0.37
SG501	600	550	550	10.9	0	72	0.35
SG502	600	550	550	12.0	0	72	0.32
SG503	600	550	550	19.3	0	72	0.30
SG600	600	275	825	8.0	0	72	0.34
SG601	600	275	825	10.6	0	72	0.32
SG602	600	275	825	14.5	0	72	0.30
SG603	600	275	825	18.0	0	72	0.28
SG700	420	825	275	8.0	180	72	0.35

Blast slag mix proportions and designations

1	2	3	4	5	6	7	8
MIX	CEMENT lbs	CONCRETE SAND lbs	BLAST SLAG lbs	HRWRA oz/cwt	FLY ASH lbs	SILICA FUME lbs	W/C BY WT
SG702	420	825	275	12.0	180	72	0.31
SG703	420	825	275	18.3	180	72	0.29
SG800	420	550	550	8.0	180	72	0.34
SG802	420	550	550	12.8	180	72	0.30
SG803	420	550	550	18.3	180	72	0.29
SG900	420	275	825	8.0	180	72	0.33
SG901	420	275	825	10.1	180	72	0.30
SG902	420	275	825	13.3	180	72	0.29
SG903	420	275	825	17.8	180	72	0.27
SG903B	420	275	825	19.9	180	72	0.27
SGL1	300	275	825	20.3	100	0	0.27
SGL2	100	0	1100	0.0	0	0	1.53
SGL3	300	0	1100	0.0	0	0	0.54
SGL4	300	0	1100	0.0	0	0	0.57

APPENDIX 5

The following tables present the 7-, 28-, and 90-day compressive strengths as well as the 28-day rapid chloride ion permeability for the blast slag S/S mixtures. The nomenclature used in the tables is given below.

NOMENCLATURE:

Column 1: mix designation.
Column 2: 7-day compressive strength in psi.
Column 3: 28-day compressive strength in psi.
Column 4: 90-day compressive strength in psi.
Column 5: rapid chloride ion permeability in Coulombs.
Column 6: indicates when the mix achieved final set. If the cell is blank, final set was reached within the first 24 hours. No set indicates that final set was not reached within three days of mixing.

NOTE: N/A indicates that data are not available.

Strength and permeability results for mixes with spent blast slag

1	2	3	4	5	6
MIX	**7-Day f'c psi**	**28-Day f'c psi**	**90-Day f'c psi**	**PERMEABILITY Coulombs**	**NOTES**
CM I	7620	9910	10120	8550	
CM II	6360	8750	10140	N/A	
CM III	6820	8840	11840	N/A	
CM IIIB	8350	10910	11900	N/A	
CSG CM	5480	6420	7420	N/A	
SG III-1	4410	5460	5960	N/A	
SG III-2	6490	7970	8920	N/A	
SG III-3	5990	6630	7340	N/A	
SG III-4	6550	8140	8520	N/A	
SG III-5	7250	9240	9830	N/A	
SG III-6	6970	8260	9450	N/A	
SG III-7	7210	8590	9300	N/A	
SG100	5870	6250	7320	N/A	
SG101	6360	7210	7310	N/A	
SG103	7310	8360	9910	N/A	
SG200	4160	5070	6840	N/A	
SG201	4480	5585	N/A	N/A	
SG203	4360	5180	5010	3710	
SG300	2990	4340	5780	9770	
SG301	3220	4540	N/A	6740	
SG302	N/A	4590	5600	4790	
SG303	3160	4290	5000	11190	
SG400	5170	5070	7790	1150	
SG401	7120	9070	9670	N/A	
SG402	7410	9610	9760	320	
SG403	7300	8100	9270	N/A	
SG500	5290	6230	6930	1540	
SG501	5700	6170	7680	N/A	
SG502	6390	6680	7810	370	
SG503	5540	8110	8680	1000	
SG600	4390	5890	7800	1020	
SG601	3100	4360	3515	510	
SG602	N/A	7910	8430	330	
SG603	5260	6420	7120	690	
SG700	5390	6930	8230	3160	

Strength and permeability results for mixes with spent blast slag

1 MIX	2 7-Day f'c psi	3 28-Day f'c psi	4 90-Day f'c psi	5 PERMEABILITY Coulombs	6 NOTES
SG702	6030	8720	9530	1190	
SG703	6560	7610	8820	2440	
SG800	5350	5930	6710	2800	
SG802	5360	6450	8540	1220	
SG803	6110	7830	8490	1730	
SG900	3340	4830	4180	4360	
SG901	4080	5620	6460	1200	
SG902	N/A	6200	7430	420	
SG903	4760	6000	N/A	2500	
SG903B	6470	9690	12475	200	
SGL1	1600	3855	5100	6190	
SGL2	N/A	N/A	N/A	N/A	NO SET
SGL3	1140	1670	2210	12250	
SGL4	N/A	N/A	N/A	N/A	NO SET

APPENDIX 6

The following tables present the mix designations and the 28-day TCLP leaching results for the blast slag S/S mixtures. The nomenclature used in the tables is given below.

NOMENCLATURE:

Column 1: mix designation.
Column 2: 28-day TCLP leaching for chromium in mg/L.
Column 3: 28-day TCLP leaching for cadmium in mg/L.
Column 4: 28-day TCLP leaching for lead in mg/L.
Column 5: 28-day TCLP leaching for aluminum in mg/L.

NOTE: N/A indicates that data are not available.

28-day TCLP leaching results for mixes with spent blast slag

1	2	3	4	5
MIX	28-Day TCLP Cr (mg/L)	28-Day TCLP Cd (mg/L)	28-Day TCLP Pb (mg/L)	28-Day TCLP Al (mg/L)
CM I	N/A	N/A	N/A	N/A
CM II	0.24	0.09	0.09	35.33
CM III	0.21	0.08	0.05	35.47
CM IIIB	0.45	0.22	0.04	38.34
CSG CM	1.18	0.21	0.06	38.69
SG III-1	N/A	N/A	N/A	N/A
SG III-2	1.01	0.26	0.04	43.44
SG III-3	0.92	0.24	0.05	40.35
SG III-4	1.36	0.22	0.05	39.30
SG III-5	1.17	0.23	0.06	38.40
SG III-6	0.84	0.49	0.05	38.00
SG III-7	1.12	0.24	0.01	37.89
SG100	1.04	0.17	0.03	32.82
SG101	N/A	N/A	N/A	N/A
SG103	N/A	N/A	N/A	N/A
SG200	1.88	0.15	0.06	31.38
SG201	N/A	N/A	N/A	N/A
SG203	N/A	N/A	N/A	N/A
SG300	2.43	0.19	0.05	34.70
SG301	N/A	N/A	N/A	N/A
SG302	3.42	0.14	0.00	28.53
SG303	1.94	0.16	0.00	32.88
SG400	1.01	0.15	0.00	30.98
SG401	N/A	N/A	N/A	N/A
SG402	N/A	N/A	N/A	N/A
SG403	N/A	N/A	N/A	N/A
SG500	N/A	N/A	N/A	N/A
SG501	N/A	N/A	N/A	N/A
SG502	N/A	N/A	N/A	N/A
SG503	N/A	N/A	N/A	N/A
SG600	2.21	0.16	0.03	32.62
SG601	N/A	N/A	N/A	N/A
SG602	3.43	0.15	0.00	27.29
SG603	2.37	0.17	0.03	32.55
SG700	1.33	0.14	0.00	26.39
SG702	N/A	N/A	N/A	N/A

28-day TCLP leaching results for mixes with spent blast slag

1	2	3	4	5
MIX	**28-Day TCLP Cr (mg/L)**	**28-Day TCLP Cd (mg/L)**	**28-Day TCLP Pb (mg/L)**	**28-Day TCLP Al (mg/L)**
SG703	N/A	N/A	N/A	N/A
SG800	1.74	0.15	0.02	26.12
SG802	N/A	N/A	N/A	N/A
SG803	N/A	N/A	N/A	N/A
SG900	3.03	0.17	0.12	32.15
SG901	N/A	N/A	N/A	N/A
SG902	N/A	N/A	N/A	N/A
SG903	2.66	0.17	0.00	32.03
SG903B	N/A	N/A	N/A	N/A
SGL1	N/A	N/A	N/A	N/A
SGL2	N/A	N/A	N/A	N/A
SGL3	N/A	N/A	N/A	N/A
SGL4	N/A	N/A	N/A	N/A