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16. Abstract

The use of abrasive blasting to remove lead-based paint from steel bridges produces contaminated spent blasting abrasives that may be classified as hazardous by the Environmental Protection Agency. If the spent abrasives leach lead, chromium, and cadmium greater than the EPA limits, the spent abrasives are classified as hazardous and must be rendered nonhazardous prior to disposal.

An alternative to disposing of the spent blasting abrasives is to recycle them in an environmentally sound application. This study investigates the feasibility of recycling spent blasting abrasives in portland cement mortars using solidification/stabilization technology to produce a usable construction material. Field application guidelines for recycling spent blasting abrasives in portland cement mortars are established based upon the results of this study.

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Solidification/stabilization technology, lead-based paint removal, recycling spent blasting abrasives, portland concrete mortar mixes

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Research Report Number 1315-3F

Research Project 0-1315
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
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April 1995

IMPLEMENTATION STATEMENT

This study provides field application guidelines for recycling the spent blasting abrasives produced during the removal of lead-based paint from steel bridges. Because these contaminated byproducts must be rendered non-hazardous before disposal, this report outlines a solidification/stabilization technology useful in recycling these hazardous abrasives by integrating them into portland cement mortars and concrete to produce a reusable construction material. The guidelines established by this study have been adopted by the Texas Department of Transportation and used at several sites to manage concerns with the environmental hazards created by abrasive blasting.

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

DISCLAIMERS

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The use of abrasive blasting to remove lead-based paint from steel bridges produces contaminated spent blasting abrasives that may be classified as hazardous by the Environmental Protection Agency. If the spent abrasives leach lead, chromium, and cadmium greater than the EPA limits, the spent abrasives are classified as hazardous and must be rendered nonhazardous prior to disposal.

An alternative to disposing of the spent blasting abrasives is to recycle them in an environmentally sound application. This study investigates the feasibility of recycling spent blasting abrasives in portland cement mortars using solidification/stabilization technology to produce a usable construction material. Field application guidelines for recycling spent blasting abrasives in portland cement mortars are established based upon the results of this study.

CHAPTER 1. INTRODUCTION

1.1 BACKGROUND

Lead-based paints have been used on steel bridges for many years because of their effectiveness against corrosion and their relatively low cost, and because little surface preparation is required before the paint is applied. Over time, the protective paint coating deteriorates and must be removed before repainting. The most common method of removal is abrasive blasting, which is efficient, cost effective, and provides a clean, roughened surface for the new coating. However, the spent blasting abrasives may contain contaminants from the pulverized paint that could pose environmental concerns. Owing to increasing environmental regulation, abrasive blasting of lead-based paints and the disposal of the spent blasting abrasives have become increasingly difficult and costly.

There are several conventional paint removal methods that are used to remove paints and coatings from highway bridges, including mechanical removal with power tools, vacuum blasting, and blasting with enclosures. Abrasive blasting will create material containing lead or other contaminants that could remain airborne or be deposited on land or water, eventually coming into contact with humans. As a result, a major concern is the safe disposal of the spent blasting abrasives that contain paint chips and dust and other debris removed from the steel surface.

The U.S. Environmental Protection Agency (EPA) has imposed regulations on air, water, and soil quality that are applicable to abrasive blasting. In addition, spent blasting abrasives contain lead and other contaminants for which maximum leachable levels have been set by the EPA. As of September 1990, the main test for leaching specified by the EPA is the Toxicity Characteristic Leaching Procedure (TCLP). Materials that have TCLP leaching concentrations greater than the maximum levels set by the EPA are classified as hazardous.

One method of treating the spent blasting abrasives to render them nonhazardous is solidification/stabilization (S/S). Solidification/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, thereby reducing the leachability of any hazardous contaminants.

Several types of solidification/stabilization systems exist. However, portland cement systems are particularly suited for use when dealing with spent blasting abrasives. The mortar or concrete produced with the cement, water, and spent blasting abrasives can be used as a construction material, provided environmental and construction concerns are satisfied. The spent blasting abrasives are effectively treated and recycled in a single step.

1.2 PROBLEM STATEMENT

The use of abrasive blasting to remove lead-based paints results in contaminated spent blasting abrasives that may be classified as hazardous by the EPA. The contaminated spent blasting abrasives are considered hazardous waste if they exhibit a "characteristic of toxicity," as defined in the *Resource Conservation and Recovery Act*. If the TCLP leaching of lead, cadmium, or chromium is in excess of the maximum levels set by the EPA, the material must be treated and rendered nonhazardous prior to land disposal. However, a preferable alternative to land disposal would be recycling the waste material in an environmentally sound way at the construction site.

To produce a usable construction material from spent blasting abrasives, the S/S process must satisfy both environmental and construction concerns. The S/S process must be able to render the spent blasting abrasives nonhazardous by reducing the leaching of the lead, cadmium, and chromium below the maximum levels set by the EPA. At the same time, the S/S process must be able to produce an end product of adequate strength and durability for its intended use.

Contaminants resulting from abrasive blasting of lead-based paints can cause problems with portland cement S/S systems. Lead can act as a retarder on the hydration of cement, causing longer set times and lower strengths. Aluminum, although not considered toxic, is present in many paints. It reacts with the cement to produce hydrogen gas, resulting in lower strength and more permeable mortars.

This study addresses the effectiveness of portland cement mortars in rendering spent blasting abrasives nonhazardous through solidification/stabilization technology, and in recycling the spent blasting abrasives in portland cement mortars for use as a construction material.

1.3 RESEARCH SIGNIFICANCE

This investigation was undertaken to develop information on the feasibility of portland cement S/S systems for recycling spent blasting abrasives. It is estimated that 80 percent of the more than 100,000 existing U.S. steel highway bridges have been painted with lead-based paints, and each year, approximately 1,200 lead-coated bridges are cleaned [1]. A 1987 survey conducted by the Virginia Department of Transportation revealed that 23 of 40 responding states continue to use lead-based paint on steel bridges [2]. Because environmental regulations are becoming more restrictive, and because landfill space is increasingly becoming scarce, it is important to investigate safe alternatives to the disposal of spent blasting abrasives.

1.4 RESEARCH OBJECTIVES

The two main objectives of this research are: (1) to recycle the spent blasting abrasives by producing a mortar having TCLP leaching of lead, cadmium, and chromium well below the maximum levels set by the EPA, and (2) to produce a mortar of adequate compressive strength and durability to be used at the construction jobsite.

Over 180 portland cement mortar batches were made using spent blasting abrasives of various types and contamination levels. Varying chemical and mineral admixtures have also been used. These mixes were evaluated based on their compressive strength, chloride ion permeability, and TCLP leaching to characterize their potential for field use. Guidelines and recommendations for field applications of portland cement mortars using spent blasting abrasives will be established based upon the results of this study. Successful mixes will be characterized by normal set times, high compressive strength, low permeability, and low TCLP leaching.

CHAPTER 2. LITERATURE REVIEW

2.1 INTRODUCTION

This chapter reviews literature related to recycling contaminated spent blasting abrasives in portland cement mortars. Topics discussed include lead-based paint, hazardous waste regulations, solidification/stabilization of hazardous waste, portland cement concrete, and mineral and chemical admixtures.

2.2 DEFINITION OF LEAD-BASED PAINT

There does not exist a legal definition establishing the quantity of total lead in a paint sufficient to categorize it as lead-containing that is strictly applicable to coatings on steel bridges. Other definitions of lead-based paint are as follows [3,4,5]:

- The Department of Housing and Urban Development established in 1990 an action level requiring abatement of paints containing greater than 0.5 percent, or 5000 ppm of lead by weight in public and Indian housing.
- The *Residential Lead-Based Paint Hazard Reduction Act of 1992* defines lead-based paint as "paint or other surface coatings that contain lead in excess of 1.0 milligrams per centimeter squared or 0.5 percent by weight."
- The *Consumer Product Safety Act* states that a "lead-containing paint means paint or other similar surface coating material containing lead or lead compounds and in which the lead content calculated as lead metal is in excess of 0.06 percent by weight of the total nonvolatile content of the paint or the weight of the dried paint film." This act is applicable to paints manufactured for consumer use after 1978.
- House Bill HR 5730 called for an industrial coatings lead limit of 0.06 percent by dry weight. This limit would have been applicable to the manufacturing of new paints and would have no bearing on removal of existing paint. This bill died on the House floor in October 1992. However, in April 1993, legislation amending the *Toxic Substances Control Act* (TOSCA) was introduced to readdress lead in industrial paint and coatings.
- Rhode Island defines lead-based paint as "any surface coating material that contains more than 0.05 percent lead by weight calculated as lead metal in the dried solid." This definition applies to industrial, residential, and commercial paints.
- The Texas Air Control Board uses higher levels for work on water tank exteriors. Vacuum blasting, shrouded wet abrasive blasting, or shrouded hydroblasting are to be used when the amount of lead exceeds 1 percent or 10,000 ppm, while shrouded dry abrasive blasting is permitted when the amount of lead is less than 1 percent.

In summary, there is no well-defined level of lead in paint at which special environmental precautions for spent blasting abrasives should be taken. No correlation has been shown to exist between the total lead in the paint and the leachable lead in the spent blasting abrasives [1, 3, 4, 6]. Possible factors include the condition and type of the paint to be removed, the type of abrasives, and the type of blasting process. These factors contribute to the particle size of the pulverized paint and its concentration in the spent blasting abrasives. Therefore, the spent blasting abrasives should be tested to determine environmental compliance rather than relying upon the lead content of the paint.

2.3 REMOVAL OF LEAD-BASED PAINT FROM STEEL BRIDGES

Lead has been used in paints for more than 100 years. It is relatively inexpensive and is effective in preventing corrosion of steel structures. After about 10 to 20 years, the coatings can become brittle and suffer loss of adhesion. The old coating must usually be completely removed from the steel prior to the application of the new coating. The following is a summary of the environmental and health considerations, removal and containment methods, and abrasive disposal concerns that are involved in removing lead-based paints from steel bridges.

2.3.1 Environmental and Health Considerations

Lead can pose a health hazard to humans and other organisms. It is absorbed by either inhalation or ingestion. It enters the blood stream and is stored in various organs and body tissues. Long-term exposure can lead to damage of the blood, nervous, urinary, and reproduction systems [3].

Lead typically enters the environment through airborne particulates generated from abrasive blast cleaning. When the blasting abrasives hit the steel substrate, the abrasives fracture and remove the paint, producing an airborne mixture of paint and abrasive dust. The two main concerns regarding these airborne particulates are inhalation during paint removal operations and deposition in the surrounding environment. Airborne particles produced by abrasive blasting range in size from 2.5 m to 50 m. Approximately 10 percent of the particulates generated during abrasive blasting have a diameter of less than 15 m and are inhalable [7].

In May of 1993, the Occupational Safety and Health Administration (OSHA) published the *Interim Final Rule on Lead Exposure in Construction* (29 CFR 1926.62). This rule was created to provide a single standard for worker protection from lead for the construction industry. An Action Level (AL) of 30 g/m^3 and a Permissible Exposure Limit (PEL) of 50 g/m^3 were adopted. These two levels refer to the airborne concentration of lead that a worker can be exposed to averaged over an eight-hour workday. Should these levels be exceeded, special precautions must be taken to protect the workers [8].

The *Clean Air Act* adopted in 1970 establishes restrictions on lead and particulate emissions into the atmosphere. The limit for lead emissions was set at a concentration of 1.5 g/m^3 averaged over a calendar quarter. This level has not had a significant impact on bridge paint removal (as it was intended primarily for lead-smelting operations). There have been proposals to decrease both the permissible level and the measurement time period. These reduced levels could have an impact on bridge painting activities. Maximum air concentrations for particulate matter less than 10 m in diameter (PM-10) have been set at 50 g/m^3 averaged over one year, and 150 g/m^3 averaged over 24 hours. Unconfined abrasive blasting could exceed the 24 hour standard [1].

Other particulates can be transported and deposited on nearby streets, sidewalks, buildings, soil, or on water. Lead deposited on soil can have a residence time of several thousand years [7]. Lead deposited on soil can remain in the soil, be resuspended by wind, be carried away by rainfall, or be assimilated by vegetation. The fate of lead deposited on water depends on the size of the lead particle, the turbulence of the water, and the chemical form of the lead particle [7]. The larger the particle and the greater the turbulence, the more quickly the particle will sink. The smaller particles can float, forming a surface scum. Lead compounds associated with bridge painting have very low solubilities in normal water. Therefore, violations of water quality standards during bridge paint removal do not normally occur [7].

2.3.2 Removal and Containment Methods

Many paint removal and surface preparation methods are available. Some of the more common methods include [1, 3, 7]:

- Abrasive Blast Cleaning: Compressed air is used to propel abrasives against the steel surface. The abrasives fracture the paint removing it from the surface. Abrasives typically consist of sand, slag, or metallic grit. Spent abrasives are either collected for disposal or processed for reuse.

- Wet Abrasive Blast Cleaning: This is similar to the above procedure except that water is added to the abrasive air stream. This process reduces the amount of dust produced, but the slurry of water, abrasives, and paint can be difficult to collect.

- High-Pressure Water Jetting: Pressurized water is directed against the steel surface to remove the paint. Containment of the spent water can be difficult. Small amounts of abrasives can be added to the stream to improve efficiency.

- Power Tool Cleaning: Loose paint, rust, and mill scale are removed using power-operated grinding, impact, or brushing tools. While highly labor intensive and low in productivity, this method does generate low amounts of waste.

- Vacuum Blasting: This method consists of an abrasive recovery head surrounding the blast nozzle. Vacuum suction captures the abrasives and paint chips. This method results in good recovery of spent abrasives. However, it is cumbersome and inefficient in areas of difficult accessibility.

Other methods include chemical stripping, sponge jetting, sodium bicarbonate blast cleaning, laser jet cleaning, and carbon dioxide blast cleaning.

Abrasive blast cleaning is the most productive and cost-effective method. It provides an optimum degree of surface preparation. It is also one of only a few methods capable of adequately cleaning areas of difficult accessibility [9]. Unfortunately, it also produces the largest amount of dust and spent abrasive waste.

There are two main methods used for containing spent blasting abrasives [1, 3, 7]:

Free-Hanging Enclosures: These consist of tarps or drapes hanging from the side of the structure. They serve to deflect abrasives away from public areas and towards collection points on the ground.

Total Structural Enclosures: These consist of rigid structures that enclose the work area. They are often assembled in modular units that are moved along the structure as work progresses. Spent abrasives are collected on the floor of the enclosure.

Negative pressure can be used in the enclosures to prevent dust particulates from escaping. Air is continuously pumped into the enclosure through the blast nozzles during removal operations. Removing air from the enclosure at a rate sufficient to counteract the incoming air flow causes the dust particulates to be drawn into the enclosure rather than blown out of it. Removing air from inside the enclosure also results in increased worker visibility and decreased airborne dust concentration in the enclosure [1].

2.3.3 Recovery, Recycling, and Disposal of Spent Abrasives

There are several methods for recovering spent blasting abrasives. The spent abrasives may be collected from the ground or the bottom of the containment structure by vacuuming, sweeping, or shoveling [1]. Some containment structures use funnels or hoppers located in the bottom of the structure. These funnels or hoppers convey the spent abrasives to a central location for recycling or disposal [3].

In the effort to minimize the amount of waste produced, some projects recycle abrasives. The spent abrasives are collected and conveyed to a reclamation unit. The reclamation unit separates the reusable abrasive from the abrasive fines, dust, paint, and other debris. Three common methods for separating the spent abrasives are air-wash separators, cyclone separators, and rotary vibratory screen separators. In an air-wash separator, air blown through a curtain of falling abrasive separates the smaller particles from larger particles. A cyclone separator uses centrifugal action to separate heavier particles from lighter particles. A rotary screen separator uses a rotating screen that is fed by screws in a feed trough. In all three processes, the paint chips, dust, and fine abrasives can be stored for disposal, while the larger particles can be reused for further blasting [1].

In the past, no special precautions were taken with regard to the disposal of spent blasting abrasives — that is, they were placed in landfills or used as fill materials in construction. Today, many environmental regulations exist pertaining to the disposal of spent blasting abrasives as a hazardous waste.

2.4 OVERVIEW OF HAZARDOUS WASTE REGULATIONS

The *Resource Conservation and Recovery Act* (RCRA) was enacted by Congress in 1976 and was amended in 1984 by the *Hazardous and Solid Waste Amendment* (HSWA). These acts regulate the treatment, handling, and disposal of suspected or identified hazardous wastes.

2.4.1 Definition of Hazardous Waste

Hazardous waste has been defined by RCRA legislation as "a solid waste, or combination of solid wastes, which, because of its quantity, concentration, or physical, chemical, or infectious characteristics, may (1) cause, or significantly contribute to, an increase in mortality or an increase in serious irreversible or incapacitating reversible illness or (2) pose a substantial present or potential hazard to human health or the environment when improperly treated, stored, transported or disposed of or otherwise managed" [10].

Under Subtitle C of the Resource Conservation and Recovery Act, the EPA has defined a waste to be hazardous if it meets one or more of the following conditions [10]:

1) It exhibits one of the following characteristics:

   Ignitability —Those wastes that could cause a fire during transport, storage, or disposal.

   Corrosivity — Those wastes with high or low pH that can react dangerously with other wastes or cause toxic contaminants to migrate from certain wastes.

   Reactivity — Those wastes that are unstable and can explode during transport, storage, or disposal.

   Toxicity — Those wastes that are poisonous and capable of killing, injuring, or impairing an organism.

2) It is listed as a specific hazardous waste.
3) It is a combination of a listed hazardous waste and other wastes.
4) It has not been excluded from RCRA regulations as a hazardous waste.
5) It is a by-product from the treatment of any hazardous waste unless specifically excluded from RCRA regulations.

Spent blasting abrasives resulting from the removal of lead-based paint are not a specifically listed waste under RCRA and have not been excluded from RCRA regulations. They may be classified as hazardous if they exhibit toxicity. The EPA has set maximum leaching concentrations for several metals contained in lead-based paint. Should the spent blasting abrasives leach these metals in excess of the EPA regulatory levels, the waste is determined to be hazardous.

2.4.2 Toxicity Characteristic Leaching Procedure

As of September 1990, the official test specified by the EPA for determining whether a waste is hazardous based on toxicity is the Toxicity Characteristic Leaching Procedure (TCLP), which replaced the Extraction Procedure Toxicity test (EPT). Compared with the EPT test, the TCLP is easier and less expensive to run, provides greater reproducibility among labs, and greater repeatability within a given lab [1]. Because the TCLP generally reveals leaching concentrations higher than those revealed through the EPT test, more materials are consequently classified as hazardous through the TCLP test [11]. The TCLP is expected to result in 80 to 90 percent of spent blasting abrasives being classified as hazardous, whereas the EPT test would result in less than 50 percent being classified as hazardous, based on a concentration limit for lead of 5 mg/L [1].

The TCLP is designed to simulate the leaching potential of waste disposed of in a municipal landfill. The waste is subjected to an acetic acid solution to simulate the organic acids produced at a landfill during decomposition of organic material in the refuse [12]. TCLP concentration limits have been set for twenty-five organic compounds, eight metals, and six pesticides. Metals of concern in this study were lead, cadmium, and chromium, since they have been used in the manufacturing of paints and pigments. EPA TCLP concentration limits for these three metals are shown in Table 2.1 [12].

Table 2.1: EPA TCLP Concentration Limits

Metal	Regulatory Level (mg/L)
Lead	5.0
Chromium	5.0
Cadmium	1.0

The 5 mg/L level for lead is based upon a permissible level of 0.05 mg/L set by the EPA for drinking water standards. The EPA uses an attenuation/dilution factor of 100 for solid waste leaching into drinking water. The EPA is considering reducing the permissible level of lead in drinking water to 0.015 mg/L [1], at which time the TCLP concentration limit for lead would most likely be reduced to 1.5 mg/L [3]. In this study, a TCLP concentration limit for lead of 1.5 mg/L rather than 5 mg/L was used in anticipation of the possible future reduction in the regulatory level.

2.4.3 Environmental Regulations

Under the RCRA, the EPA established the "cradle-to-grave" concept of hazardous waste management. It first identified hazardous wastes and then established requirements for the facilities that generate, transport, treat, store, or dispose of such wastes. Some of the more significant portions of the RCRA include [10]:

1) The generator of a waste is required to determine if a waste is hazardous in accordance with the RCRA. If the waste is hazardous, the generator is required to obtain an EPA identification number that helps the EPA monitor and track the waste.
2) The generator must properly package and label the waste and conform to U.S. Department of Transportation regulations if shipping the waste off-site.
3) The waste must be properly manifested. The manifest must contain the name and EPA identification number of the generator, the transporter, and the treatment, storage, and disposal (TSD) facility, as well as a description of the waste.

4) Treatment, storage and disposal (TSD) facilities must be properly permitted. The TSD facility must have an EPA identification number, properly handle and identify their wastes, ensure operations are according to RCRA standards, and employ personnel properly trained in hazardous waste management.

2.5 OVERVIEW OF SOLIDIFICATION/STABILIZATION TECHNOLOGY

The "Third-Third" Land Disposal Restrictions portion of the Hazardous and Solid Waste Amendment became effective in August 1990. In addition to other wastes, these regulations prohibit the land disposal of wastes that are hazardous by characteristic. These regulations are applicable to wastes containing lead, cadmium, and chromium — elements considered hazardous owing to their characteristic of toxicity. The hazardous waste must be treated to render it non-hazardous prior to land disposal. In the case of spent blasting abrasives, treatment would require reducing TCLP leaching concentrations below the maximum levels set by the EPA. One method of accomplishing this is solidification/stabilization (S/S).

2.5.1 Definition of Solidification/Stabilization

Solidification/stabilization processes are designed to: a) improve the handling and physical characteristics of the material; b) decrease the surface area across which the transfer or loss of contaminants can occur; and c) limit the solubility of any hazardous constituents in the material. The following are definitions of solidification/stabilization as used in this report [13]:

- Solidification: This process results in a solid monolith of waste material, one having improved structural integrity. Contaminants within the waste material have not necessarily reacted chemically. Instead, they are mechanically encapsulated within the solidified matrix.

- Stabilization: This process limits the solubility or mobility of the contaminants without changing the physical characteristics of the waste. Stabilization typically involves adding materials to the waste to ensure contaminants are maintained in their least mobile or toxic form.

Solidification/stabilization technology is an ideal treatment process for spent blasting abrasives. The spent blasting abrasives are rendered non-hazardous by reducing TCLP concentrations below regulatory levels. At the same time, an end product of sufficient compressive strength and durability for non-structural purposes is created. The spent blasting abrasives are effectively treated and recycled in a single step.

In addition, solidification/stabilization has been identified by the EPA as a *Best Demonstrated Available Technology* (BDAT) for the treatment of certain wastes. While solidification/stabilization has not been specified as a BDAT for the treatment of spent blasting abrasives, its BDAT status shows that it is a well-accepted treatment process.

2.5.2 Portland Cement Solidification/Stabilization Systems

Portland cement systems were the first to be used in the solidification/stabilization of hazardous wastes [12]. They were first used in the nuclear waste field in the 1950's. Since then, portland cement, alone or in combination with various reagents or pozzolans, has become the most widely used solidification/stabilization system.

Advantages of using portland cement systems are: a) portland cement is widely available, inexpensive, and relatively consistent from source to source; b) setting and hardening properties of portland cement have been extensively studied; c) its natural alkalinity buffers acidic leaching; and, d) leaching of cement-based waste forms have been extensively studied. A disadvantage of using portland cement systems is that many substances found in hazardous wastes have deleterious effects on the set and strength development of portland cement. Some organic compounds, inorganic salts, and metal compounds retard the hydration of portland cement [14].

In a portland cement S/S system, cement, water, and the waste combine to form a mortar. In this study, the waste is spent blasting abrasives consisting of the abrasive, paint chips, dust, and other material. The spent blasting abrasives act as aggregate in the portland cement mortar.

Bishop et al. [15] stabilized wastes containing arsenic, cadmium, chromium, lead, and a mixture of all four using Type II portland cement. The wastes were in the form of metal hydroxide sludges artificially prepared in the laboratory. Type II portland cement was added directly to the sludges. Additional water was added to provide a water/cement (W/C) ratio of 1.0 and 0.5. The lead waste sample had a retarded set time, but compressive strength was not affected after the retardation period had ended. The leaching of the heavy metals was substantially reduced as a result of solidification/stabilization with portland cement. All samples passed the EPA Extraction Procedure Toxicity test and were not classified as hazardous.

In a later paper [16], Bishop stabilized metal hydroxide sludges containing cadmium, chromium, and lead using Type II portland cement. The purpose of these experiments was to develop a leaching test specifically designed for solidified/stabilized waste in the form of a solid monolith, with high alkalinity, and composed of inorganic constituents. He proposed binding mechanisms for lead, cadmium, and chromium. Cadmium was believed to be located in the pores or adsorbed onto the pore walls of the matrix as the paste matrix was formed. Lead and chromium were believed to be present as insoluble silicates bound into the matrix itself.

Bhatty [17] solidified/stabilized metal salt solutions containing cadmium, chromium, lead, mercury, and zinc using pure tricalcium silicate (C_3S). He proposed that such metallic ions as cadmium, chromium, and lead are incorporated into the structure of the calcium silicate hydrate resulting from the hydration of the tricalcium silicate.

There are a variety of reagents that can be added to portland cement systems to improve solidification/stabilization properties. Some reagents particularly suited to solidification/stabilization of cadmium, chromium, and lead include sodium sulfide, ferrous sulfate, and sodium silicate.

2.5.2.1 Sodium Sulfide and Ferrous Sulfate: Hydroxide precipitation is a common mechanism in portland cement S/S systems. As the pH of the waste is raised into the alkaline range, metals in the waste form metal hydroxides. Sulfide precipitation involves the addition of reactive sulfide agents to the waste. The sulfide agents react with the metals in the waste to form metal sulfides. Metal sulfides have much lower solubilities than metal hydroxides. Table 2.2 compares the solubilities of the hydroxide and sulfide forms of the metals of concern in this study. Lead and cadmium can precipitate as both sulfides and hydroxides, but chromium can only precipitate as a hydroxide. Reducing the solubility of the metals by conversion to sulfide form will reduce the potential for leaching.

In this study, sodium sulfide was used. Sodium sulfide is an inorganic soluble sulfide typically added to the waste in the form of a solution. Dosage is typically determined in one of two ways: 1) empirically by trying several dosages and determining the minimum dose that achieves the targeted leaching level; and 2) stoichiometrically based on the amount of metals in the waste. It is necessary to add the sulfide to the waste before adding portland cement because the metals in the portland cement will compete for the sulfide.

Table 2.2: Comparison of Hydroxide and Sulfide Solubilities [a]

Metal	Approximate Solubility (mg/L)		
	Hydroxide	Sulfide	Difference Factor
Lead	2×10	6×10^{-9}	3×10^{8}
Chromium	1×10^{-3}	-	-
Cadmium	3×10^{0}	1×10^{-8}	3×10^{8}

[a]Adapted from [12]

Chromium is typically present in wastes in one of two valence states: trivalent (Cr^{+3}) and hexavalent (Cr^{+6}). The primary environmental problems associated with chromium are with Cr^{+6} compounds. Cr^{+6} compounds are very toxic to aquatic plant and animal life, and have higher solubilities than Cr^{+3} compounds [12]. The most common agent used for reducing Cr^{+6} to Cr^{+3} is ferrous sulfate. Ferrous sulfate is normally used for chromium reduction in acid pH's, but it has been shown to be effective in alkaline pH's when used in combination with sodium sulfide.

Robinson [18] provided a comparison of sulfide precipitation and hydroxide precipitation of heavy metals, including lead, cadmium, and chromium. Robinson agreed that the chief advantage of using a sulfide process was the extremely low solubilities of most metal sulfides. He also claimed that some sulfide processes were capable of removing hexavalent chromium without reduction to its trivalent state.

Higgins and TerMaath [19] reported that sodium sulfide alone was ineffective in reducing hexavalent chromium at alkaline pH. However, when used in combination with ferrous sulfate, sodium sulfide aided in chromium reduction at alkaline pH. The ferrous ion appeared to act as a catalyst for this reduction.

2.5.2.2 Sodium Silicate: Sodium silicate can improve several properties of portland cement S/S systems. Its accelerating effect is the most advantageous with regard to lead-containing waste.

Sodium silicate removes the metals from solution before they can precipitate on the cement grains, causing retardation of the rate of hydration. Sodium silicate also reduces the leachability of metal ions by the formation of low-solubility metal oxide/silicates and by encapsulation of metal ions in silicate- or metal silicate-gel matrix. Sodium silicate also reduces permeability by forming precipitates in the cement matrix that block pores [12].

Tseng [20] investigated the use of portland cement and sodium silicate in solidifying/stabilizing sludges containing heavy metals, including lead, cadmium, and chromium. He found that the combination resulted in rapid set with no retardation from metallic ions. He also found that mixes containing sodium silicate had increased compressive strength and decreased metal leachability.

Poon et al. [21] investigated a solidification/stabilization system using portland cement and sodium silicate. They found that the addition of sodium silicate accelerated the initial setting and strength development but that the water/cement ratio contributed more to the final strength.

2.6 METHODS OF SOLIDIFICATION/STABILIZATION AND RECYCLING SPENT BLASTING ABRASIVES

The following is a summary of some recent work regarding recycling spent blasting abrasives using portland cement S/S systems:

Khosla and Leming [22] investigated the use of lead-contaminated blasting sand in both portland cement and asphalt concrete. Only the portland cement concrete results will be reported here. No problems regarding the effect of lead on the set and strength development of the concrete were reported. Their primary concern was the aluminum particles in the spent blasting abrasives. The aluminum particles corroded rapidly in the moist, alkaline environment of the concrete; the result was hydrogen gas formation, which, because it caused the concrete to expand and become porous, reduced the concrete's strength and durability.

Several solutions to reduce the effect of the aluminum were tried. Blending the spent blasting abrasives with clean sand to dilute the aluminum concentration was determined to be unfeasible owing to the large amount of clean sand required. A rapid set alternative using a Class "C" fly ash was tried so that the concrete would set and harden rapidly (resulting in no expansion). They found that the sensitivity of the process to minor variations in mixing and the potential unpredictability of the end product rendered the rapid set alternative unsuitable for field use. A slow set alternative was tried so that the concrete would set slowly enough that the reaction of the aluminum would be completed while the concrete was still plastic. To accomplish this, the spent blasting sand was premixed with lime to produce a slurry. The slurry was agitated intermittently over a period of four days. This had the effect of allowing the aluminum reaction to complete prior to the addition of the cement. While a stable product with adequate strength was produced with this process, the mixing time of four days did not lend itself to field applications. Samples of the mortar produced were ground and subjected to leaching in an acetic acid solution. It was observed that the high pH of the cement and lime buffered the acetic acid and reduced the leachability of the lead. Leaching concentrations were below EPA limits.

Means et al. [23] investigated a series of treatability tests for chemically stabilizing spent blasting abrasives containing lead and copper. All of the treatments used either a sulfide- or silicate-fixing agent in combination with a silicate-setting agent. Stabilization rather than solidification was the goal of this series of tests. The relatively low cement and pozzolan contents resulted in treated samples having a physical consistency similar to that of the untreated abrasives.

Several series of tests using sulfide-fixing agents were performed. The sulfide mixes used either sodium sulfide hydrate dissolved in water or aqueous sodium hydrosulfide. The sulfide was mixed with the spent blasting abrasives and with relatively small amounts of low-alkalinity portland cement. The mechanism of stabilization was the formation of insoluble metal sulfides. The sulfides were found to effectively stabilize the lead in the spent blasting abrasives. They also found that the physiochemical form of the metals in the pulverized paint had an effect upon their stabilization. The stabilization had to be able to penetrate the polymeric coating on the metals before it could react with and chemically stabilize them. This was allowed for by providing longer mixing times for the spent blasting abrasives and the sulfides.

Garner [24] investigated the effect of concrete mix ingredients and proportions upon the solidification/stabilization of spent blasting abrasives. TCLP analyses were performed for Garner by Brabrand [25]. Variables studied included type of spent abrasives, percentage replacement of clean fine aggregate with spent abrasives, water/cement ratio, cement content, and amount of chemical and mineral admixtures. The most significant conclusions made as a result of this study were:

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 contaminated spent blasting abrasives.
2) The most important factors governing TCLP leaching, compressive strength, and permeability were the water/cement ratio and the cement content. In general, as the water/cement ratio decreased and the cement content increased, the leaching decreased and the compressive strength increased.
3) As the contamination level of the S/S mix increased, the compressive strength decreased.
4) Lower permeability mixes also had lower TCLP leaching concentrations. This was attributed to the effect of water/cement ratio and cement content on the permeability of the cement matrix.
5) Mixing sequence and time were important for the success of the S/S mixes. Best performance was obtained when the dry components were mixed thoroughly prior to the addition of the liquid components. It was necessary to mix the S/S mortar for a longer period than required for ordinary concrete to ensure adequate homogenization of the waste throughout the mix.

The study reported herein is a continuation of the work initiated by Garner. Additional conclusions based on the work of Garner were:

1) Set times and strength development became highly unpredictable as the contamination level of the spent blasting abrasives increased.
2) Contamination level of the spent blasting abrasives was variable. Possible factors include the condition and type of the paint to be removed, the type of abrasives, and the type of blasting process. These factors contribute to the particle size of the pulverized paint and its concentration in the spent blasting abrasives.
3) While all mixes tested by the TCLP had leaching concentrations lower than the EPA regulatory levels, trends in the leaching of the individual metals as a function of mix properties were unpredictable.
4) The mix recommendations provided for use in recycling spent blasting abrasives at the Rainbow Bridge in Port Arthur, Texas were successful. However, the mix design had unpredictable set and strength development qualities, resulting in mix set times of several days.

As a result, the following areas for additional research were identified:

1) The use of accelerators and anti-inhibitors to counteract the effect of the lead on the hydration of cement should be investigated.
2) Spent abrasives should be acquired from several sites to investigate the variability in contamination level upon the mix characteristics.
3) The effect of chemical stabilization of the heavy metals using sulfide and silicate agents upon set, strength, and leaching should be investigated for use in more highly contaminated spent abrasives.
4) New mix recommendations for field applications based on the above results should be made. The new mix recommendations should be less susceptible to low strength and long set times resulting from more highly contaminated spent abrasives.

2.7 PORTLAND CEMENT

Materials used in the manufacturing of portland cement must have appropriate proportions of calcium oxide, silica, alumina, and iron oxide. Limestone rock is the most common source of calcium oxide. Iron-bearing aluminosilicates, such as clays, silts, or shales, are used as the primary source for the other components. The raw materials are ground and blended. The raw mix is then fed into a kiln passing through at a rate controlled by the slope and rotational speed of the kiln. The heating process to which the raw mix is subjected is referred to as clinkering. During clinkering, partial melting takes place, with approximately one-quarter of the mix in a liquid state at a given time. It is while the mix is in this liquid condition that the chemical reactions occur. When the material exits the kiln, it is in the form of cement clinker: grayish-black pebbles approximately 1.27 cm (0.5 inch) in diameter. The cement clinker is cooled and ground to a fine powder. A small amount of gypsum is then added to regulate the setting time of the cement. The end product is known as portland cement [26, 27].

Portland cement is primarily made up of five different compounds [26]:

a. Tricalcium silicate (C_3S) hydrates and hardens rapidly (it is largely responsible for initial set and early strength).
b. Dicalcium silicate (C_2S) hydrates and hardens more slowly (it is largely responsible for strength at later ages).
c. Tricalcium aluminate (C_3A) liberates a large amount of heat during the early stages of hydration and hardening and contributes slightly to early-strength development.
d. Tetracalcium aluminoferrite (C_4AF) acts as a fluxing agent lowering the fusion temperature during clinkering. It hydrates rapidly (thus, contributing very little to strength) and also gives portland cement its color.
e. Calcium sulfate dihydrate (gypsum) slows down the hydration rate of tricalcium aluminate. Without gypsum, tricalcium aluminate can cause portland cement to flash set.

The reaction of portland cement with water is termed hydration. The hydration reactions of primary importance in portland cement belong to the two calcium silicate compounds. These reactions are given in equations (2-1) and (2-2):

$$2C_3S + 6H \rightarrow C_3S_2H_3 + 3CH \qquad (2\text{-}1)$$

$$2C_2S + 4H \rightarrow C_3S_2H_3 + CH \qquad (2\text{-}2)$$

where $C_3S_2H_3$ is calcium silicate hydrate (C-S-H) and CH is calcium hydroxide [27].

C-S-H composes approximately one-half to two-thirds the volume of the hydrated cement paste. As hydration proceeds, the C-S-H layer on the surface of each cement grain grows thicker effectively increasing the cement grain in size. The spines of the C-S-H begin to intermesh, forming a solid bond between cement grains [27].

The most important parameter affecting the strength, durability, and permeability of hardened cement paste is the water/cement ratio. The lower the water/cement ratio is, the higher the strength and durability and the lower the permeability will be. This relationship is due to the fact that reducing the amount of water will reduce the capillary porosity causing a denser, stronger matrix [27].

2.8 EFFECT OF LEAD ON THE HYDRATION OF PORTLAND CEMENT

Lead compounds retard the rate of hydration of portland cement. Lieber [28] found that amounts of lead oxide as small as 0.1 percent retard the setting time of portland cement. He also found that once the retarding period had finished, pastes with lead achieved final compressive strengths comparable to pastes without lead. Thomas et al. [29] proposed that the retardation of the hydration of cement by lead compounds is the result of a very rapid precipitation of lead hydroxide. The lead hydroxide precipitates onto the cement grains forming a gelatinous surface coating. The lead hydroxide coating forms a diffusional barrier to water, reducing the rate at which it contacts the cement grains. Portland cement solidification/stabilization systems will encounter this effect when used in recycling lead-contaminated spent blasting abrasives. Compared with lead, cadmium and chromium have a negligible effect on the hardening properties of portland cement [44, 45].

2.9 PERMEABILITY OF CONCRETE

2.9.1 Background

Permeability of concrete refers to the ability of concrete to resist the penetration of liquids, gases, or ions [26]. In general, the durability of concrete increases as the permeability decreases. Decreasing the permeability of the concrete restricts the penetration by liquids or other aggressive agents. This property is particularly important to the success of portland cement S/S systems. Making the concrete more resistant to penetration should decrease the potential for leaching.

The factor having the largest influence on permeability is the water/cement ratio. Decreasing the amount of water for a given amount of cement decreases the porosity of the paste. Permeability also decreases with age and moist curing. Well-hydrated pastes with low water/cement ratios have permeabilities that may be three orders of magnitude or more lower than a paste with a high water/cement ratio. By reducing the water content, the larger pores become more isolated, making water movement more difficult.

2.9.2 Measurement of Permeability

The Rapid Chloride Permeability Test was developed for use in determining the permeability of bridge decks to chloride ions. The predominant mechanism for transport of chloride ions is ionic diffusion. Ionic diffusion occurs when an electric potential is applied across an electrolytic solution within a porous material. The ions are then transported toward the electrodes of the opposing sign [30].

The Rapid Chloride Permeability Test, designated AASHTO T 277, consists of monitoring the amount of electrical current passed through a 51-mm (2-inch) thick by 95- or 102-mm (3.75- or 4.00-inch) diameter concrete specimen. One end of the specimen is immersed in a sodium chloride solution and the other is immersed in a sodium hydroxide solution. A potential difference of 60 volts is maintained across the specimen for 6 hours. The total charge in coulombs passed is related to chloride permeability.

The above test procedure does not directly measure the permeability of concrete to chloride ions. However, the total charge passed in the test has been correlated to long-term diffusion experiments. Also, the above test procedure does not directly measure the flow of liquid through concrete. However, it is a quick, reproducible test method that is useful in comparing the relative permeabilities of concrete specimens and can therefore provide an indicator of permeability to liquids.

2.10 SILICA FUME

2.10.1 Background

Silica fume is a by-product resulting from the reduction of high-purity quartz with coal in an electric arc furnace in the production of silicon and ferrosilicon alloys. The fume rises with the gases in the furnace, where it cools and condenses to form very fine amorphous silicon dioxide spheres. The silica fume is collected by huge cloth bags and then processed to remove impurities and to control particle size [26].

Silica fume is commercially available as both a powder and as a water-based slurry. It is used either as: a) a replacement for portland cement to reduce the cement content, usually for economic reasons; or b) an addition to portland cement to improve concrete properties in both the fresh and hardened states [31].

Silica fume varies from light to dark gray in color. Its specific gravity is about 2.2 but can be as high as 2.5. Its bulk density is approximately 250 to 300 kg/m^3 (16 to 19 pcf), about 25 percent that of portland cement. It is an extremely fine material, with most particles less than 1 m and with an average diameter of about 0.1 m, approximately 100 times smaller than the average cement particle [26, 32]. Table 2.3 compares the surface areas of some typical fine materials found in concrete.

Table 2.3: Comparison of Surface Areas of Fine Concrete Materials

Material	Surface Area (m^2/kg)	Test Method
Silica Fume	≈ 20,000	Nitrogen Adsorption
Fly Ash	400 to 700	Blaine
Type I Portland Cement	300 to 400	Blaine
Type III Portland Cement	500 to 600	Blaine

[a] Adapted from [26] and [32]

2.10.2 Pozzolanic and Filler Effects

The extreme fineness and high silica content of silica fume make it a highly effective pozzolanic material. Silica fume possesses no inherent cementitious qualities. However, in the presence of water, it will chemically react with the calcium hydroxide formed by the hydration of portland cement. This reaction forms the cementitious compound calcium silicate hydrate (C-S-H). The calcium silicate hydrate formed by the reaction of silica fume typically has a lower density and lower permeability than that of the hydrates normally formed with hydration of portland cement. In a concrete mix containing 10 percent silica fume, there will be approximately 50,000 silica fume particles for each grain of cement [33]. This ratio results in an improved distribution of pore particles and hydration products. The extreme fineness of silica fume causes it to physically fill voids between the cement grains. The combined pozzolanic and filler effects result in refining the pore structure when silica fume is added to cement mixes. The refined pore structure results in a stronger, denser, less permeable concrete.

2.10.3 Effects on Fresh Concrete

Silica fume has the following effects on fresh concrete [26, 31, 32]:

- Silica fume concrete is normally a darker gray than ordinary concrete.
- Owing to the high surface area of silica fume, water demand is increased. High-range water reducers are normally required for adequate workability at lower water/cementitious material ratios.
- Increased mixing time is required for adequate dispersion of silica fume particles.
- The dosage of air-entraining admixture to produce a required volume of air is increased, owing to the high surface area of silica fume.
- Fresh concrete incorporating silica fume is more cohesive and less prone to segregation, though the mix can become sticky as a result of the high content of fine particles.
- Bleeding is reduced to the point that care should be taken to prevent plastic shrinkage cracking.

2.10.4 Effects on Hardened Concrete

Silica fume has the following effects on hardened concrete [26,31,32]:

- The main contribution to increasing strength development takes place from about 3 to 38 days.
- Silica fume concrete has an increased sensitivity to curing temperature. Silica fume concretes have an increased strength gain at higher temperatures and a decreased strength gain at lower temperatures, compared with ordinary concrete.
- Bond to aggregates, reinforcing steel, reinforcing fibers, and old concrete are improved.
- In general, silica fume concrete has increased durability compared with ordinary concrete.

2.10.5 Effects on Durability of Concrete

Silica fume has the following effects on the durability of concrete [26, 31, 32]:

- Permeability of silica fume concrete is markedly decreased owing to pozzolanic and filler effects.

- Because of its low permeability, silica fume concrete is resistant to chemical attack (e.g., by chloride ions).
- Silica fume helps in preventing expansion caused by alkali-silica reactions.
- Sulfate resistance is increased.
- The effect upon freeze/thaw resistance is inconclusive. Air-entraining agents are more effective in increasing freeze/thaw resistance than silica fume.

2.10.6 Use in Portland Cement Solidification/Stabilization Systems

Fuessle and Taylor [34] investigated the use of silica fume in solidification/stabilization of a hazardous waste containing such heavy metals as lead, cadmium, and chromium. They performed TCLP analyses on waste samples solidified/stabilized using Type I portland cement with silica fume content ranging from 0 to 30 percent by weight replacement of portland cement. In general, they found that S/S mixes containing silica fume were more effective at reducing TCLP leaching than S/S mixes without silica fume. While the mix with 15 percent silica fume had lower lead leaching than the mix without silica fume, there was no significant difference in leaching of lead between mixes with 15 percent and 30 percent silica fume.

2.11 CALCIUM CHLORIDE AND CALCIUM NITRITE

2.11.1 Background

Calcium chloride is the most commonly used accelerating admixture for concrete. However, a significant disadvantage of calcium chloride is that chloride ions can contribute to the corrosion of reinforcing steel. Calcium nitrite was developed as a noncorrosive, nonchloride containing accelerator. Calcium nitrite also inhibits the corrosion of steel and other metals in concrete.

Calcium salts accelerate the set and strength development of concrete by increasing the rate of hydration of tricalcium silicate (C_3S). Tricalcium silicate is the compound in portland cement that is largely responsible for initial set and early strength of concrete. The mechanism by which calcium salts increase the rate of hydration of C_3S is a subject of debate, but some possible mechanisms are discussed by investigators in [35, 36, 37].

2.11.2 Accelerating Properties of Calcium Chloride

Calcium chloride is a more effective accelerator than calcium nitrite in that it accelerates more at a particular dose than a corresponding dose of calcium nitrite. However, calcium chloride has been used less in recent practice owing to concerns of chloride-induced corrosion of steel reinforcement and aluminum in concrete [27]. Calcium chloride was not used extensively in this study because of concerns with the high aluminum content of the spent blasting abrasives.

2.11.3 Accelerating Properties of Calcium Nitrite

Chin [38] investigated the effect of calcium nitrite dosage and ambient temperature upon the initial set and early strength development of concrete made with four different Type I portland cements. In general, increasing dosages of calcium nitrite corresponded with decreasing set times and increasing compressive strength. The degree to which set times decreased and compressive strength increased varied with the fineness and tricalcium silicate content of the cements. Accelerating effects were observed at ambient temperatures of 22° C (72° F) and 10° C (50° F). The average percent acceleration over the reference mix containing no calcium nitrite was found to be greater for the 10° C (50° F) mix than for the 22° C (72° F) mix.

2.11.4 Corrosion-Inhibiting Properties of Calcium Nitrite

Calcium nitrite's effect of inhibiting the chloride-induced corrosion of reinforcing steel has been extensively studied [39]. Calcium nitrite blocks the corrosion reaction of chloride ions by chemically reinforcing and stabilizing the passive film on the surface of the reinforcing steel. Calcium nitrite has also been found to be effective at delaying and reducing the corrosion of aluminum in concrete [40]. This quality can be beneficial in the solidification/stabilization of spent blasting abrasives using portland cement. Spent blasting abrasives typically have a high content of aluminum as a result of the common use of aluminum in many paints and pigments. Calcium nitrite could be helpful in preventing reactions of the aluminum particles in the abrasives when used in portland cement mortars.

2.12 HIGH-RANGE WATER REDUCERS

2.12.1 Background

High-range water reducers (HRWR), also known as superplasticizers, are typically used in concrete for one of three purposes: 1) to increase workability; 2) to increase strength and decrease permeability by decreasing water content and water/cement ratio; and 3) to reduce temperature rise and volume change by decreasing water and cement content [41].

HRWR's are able to reduce water requirements by 12 to 30 percent. Early HRWR's increased workability for approximately 30 to 60 minutes, after which a rapid loss in workability occurred. More recent HRWR's impart a longer working life to the concrete. Dosage of HRWR's is a function of the type of HRWR, cement fineness, mix proportions and application, temperature, and the time of addition [27].

In a cement paste, cement particles with opposite charge will attract each other and flocculate. A considerable amount of water is used in these cement particle agglomerations. This leaves less water available for reducing the viscosity of the cement paste. HRWR's will either neutralize the cement particle surface charge or cause all surface charges to be of uniform sign. This causes the particles to repel each other and disperse fully in the paste. This enables most of the water to be available for reducing the viscosity of the paste [27].

2.12.2 Effects on Concrete Properties

The most noticeable effect that HRWR's have on fresh concrete is an increase in workability. The increase in workability is a function of the type and dose of HRWR, the initial workability, the cement content, temperature, and time of addition. Bleeding is increased for mixes of equal water/cement ratio but is decreased for mixes of equal workability. Set times are sometimes increased owing to the retarding effects of some HRWR's. Shrinkage is decreased for mixes of equal workability owing to decreased water content. Air content is reduced as a result of the lower viscosity of the mix, which allows the air to escape more easily.

Lower water/cement ratios and the cement dispersing effect cause the compressive strength of hardened HRWR concretes to be higher. The use of lower water/cement ratios also decreases the permeability of concrete. Freeze/thaw resistance is reduced owing to the reduction in the quality of the air void system if air entraining admixtures are not used.

The high surface area of silica fume can cause a large increase in water demand when it is used in concrete. To maximize the full potential of silica fume concrete, HRWR's are normally necessary. The dosage of the HRWR will depend upon the amount of silica fume and the type of HRWR [32].

CHAPTER 3. MATERIALS AND TEST PROCEDURES

3.1 INTRODUCTION

Over 180 different mix designs have been tested to investigate the feasibility of recycling contaminated spent blasting abrasives in portland cement mortars using solidification/stabilization technology. The spent blasting abrasives consisted of spent blasting slag, separated spent blasting sand, separated spent blasting dust, and unseparated spent blasting sand/dust. Metals of concern in the spent blasting abrasives include lead, chromium, cadmium, and aluminum. Variables studied were:

a) water/cement ratio;
b) cement content;
c) dosage of accelerating admixtures including calcium chloride, calcium nitrite, and sodium silicate;
d) amount of silica fume;
e) dosage of superplasticizer;
f) type, contamination level, and amount of spent blasting abrasive;
g) initial set times;
h) compressive strength gain over time;
i) TCLP leaching of lead, chromium, cadmium, and aluminum; and
j) chloride ion permeability.

This chapter describes the materials, specimens, testing procedures, and testing equipment used in this study.

3.2 MATERIALS

Except for the spent blasting abrasives, all materials used in this study are commercially available and currently used in Texas either in the production of portland cement concrete or in the solidification/stabilization of hazardous waste. Materials used in portland cement concrete include portland cement, siliceous river sand, silica fume, calcium nitrite, and superplasticizer. Sodium silicate is commonly used in portland cement solidification/stabilization systems.

3.2.1 Portland Cement

The portland cement used was a Type I/II cement conforming to ASTM C 150, "Standard Specification for Portland Cement." The cement was obtained from LaFarge Corporation in New Braunfels, Texas. Tables 3.1 and 3.2 give the cement's chemical composition and physical data, respectively. The composition of the portland cement as determined by Total Constituent Analysis for lead, cadmium, chromium, and aluminum is given in Table 3.3.

Table 3.1: Chemical Composition for Type I/II Portland Cement (ASTM C 150)

Chemical Composition	Notation	Percent by Weight
Silicon Dioxide	SiO_2	21.5
Aluminum Dioxide	Al_2O_3	4.4
Ferric Oxide	Fe_2O_3	3.9
Calcium Oxide	CaO	64.1
Magnesium Oxide	MgO	1.5
Sulfur Trioxide	SO_3	2.6
Loss on Ignition	LOI	1.3
Insoluble Residue	-	0.1
Free Lime	-	0.7
Tricalcium Silicate	C_3S	55.0
Tricalcium Aluminate	C_3A	5.1
Total Alkali	Na_2O Equivalent	0.60

Table 3.2: Physical Data for Type I/II Portland Cement (ASTM C 150)

Specific Surface	Blaine	3540 cm^2/g
	Wagner	1900 cm^2/g
Compressive Strength	1 Day	2020 psi
	3 Day	3530 psi
	7 Day	4670 psi
	28 Day	6290 psi
Time of Setting	Vicat - Initial	110 min.
	Vicat - Final	200 min.
	Gilmore - Initial	130 min.
	Gilmore - Final	220 min.

1000 psi = 6.895 MPa

Table 3.3: Total Constituent Analysis for Type I/II Portland Cement

Metal	Total Content, mg/kg	Percent by Weight
Lead	33	0.003
Chromium	92	0.009
Cadmium	47	0.005

3.2.2 Concrete Sand

The concrete sand used was from the portion of the Colorado River running through Austin, Texas. It had a saturated surface dry (SSD) bulk specific gravity of 2.55, an absorption capacity of 1.02 percent, and a fineness modulus of 2.79. Table 3.4 gives the gradation of the concrete sand and gradation limits from ASTM C 33, "Standard Specification for Concrete Aggregates."

Table 3.4: Gradation of Concrete Sand

Sieve Size	Percent Passing by Weight	ASTM C 33 Limits
3/8 in.	100.0	100
No. 4	99.9	95 to 100
No. 8	90.5	80 to 100
No. 16	69.3	50 to 85
No. 30	42.8	25 to 60
No. 50	14.1	10 to 30
No. 100	4.1	2 to 10
Pan	-	-

3.2.3 Water

The water used in all mixes was tap water conforming to ASTM C 94, "Standard Specification for Ready-Mixed Concrete."

3.2.4 Spent Blasting Slag

The spent blasting slag used in this study is commonly known as "Black Beauty." It was obtained from blasting operations at the Montopolis Bridge on U.S. 183 over the Colorado River in Austin, Texas. It had a SSD bulk specific gravity of 2.63, an absorption capacity of 0.75 percent, and a fineness modulus of 1.93. The composition of the spent blasting slag, as determined by Total Constituent Analysis, is given in Table 3.5. TCLP leaching concentrations are given in Table 3.6.

Table 3.5: Total Constituent Analysis for Spent Blasting Slag

Metal	Total Content, mg/kg	Percent by Weight
Lead	1941	0.194
Chromium	564	0.056
Cadmium	61	0.006
Aluminum	2064	0.206

Table 3.6: TCLP Leaching Concentrations for Spent Blasting Slag

Metal	Concentration, mg/L
Lead	3.58
Chromium	2.34
Cadmium	0.47
Aluminum	4.74

3.2.5 Separated Spent Blasting Sand

The majority of the S/S mixes were made with spent blasting sand. The blasting sand had been processed in several forms. "Separated spent blasting sand" and "separated spent blasting dust" resulted from spent blasting sand that had been run through a particle separator after blasting. The particle separator separates the larger sand particles to be reused for further blasting and separates the dust and paint chips and stores them in waste barrels. The separated spent blasting sand and spent blasting dust can be combined in the desired proportions for recycling in concrete. "Unseparated spent blasting sand/dust" is spent blasting sand that has not been run through a particle separator before being stored in waste barrels.

The separated spent blasting sand was obtained from the Texas Department of Transportation's Rainbow Bridge Project site near Port Arthur, Texas. It had a SSD bulk specific gravity of 2.55, an absorption capacity of 2.71 percent, and a fineness modulus of 2.25. A sample was taken from two different waste barrels. The compositions of the separated spent blasting sand for the two different samples, as determined by Total Constituent Analysis, are given in Table 3.7. TCLP leaching concentrations for the two different samples are given in Table 3.8.

Table 3.7: Total Constituent Analysis for Separated Spent Blasting Sand

Metal	Total Content, mg/kg		Percent by Weight	
	Sample 1	Sample 2	Sample 1	Sample 2
Lead	367	1580	0.037	0.158
Chromium	55	462	0.006	0.046
Cadmium	16	27	0.002	0.003
Aluminum	193	816	0.019	0.082

Table 3.8: TCLP Leaching Concentrations for Separated Spent Blasting Sand

Metal	Concentration, mg/L	
	Sample 1	Sample 2
Lead	2.20	7.22
Chromium	0.58	1.04
Cadmium	0.57	0.80
Aluminum	0.54	0.74

3.2.6 Separated Spent Blasting Dust

The separated spent blasting dust was obtained from the Texas Department of Transportation's Rainbow Bridge Project site near Port Arthur, Texas. The bulk specific gravity of the separated spent blasting dust was assumed to be 3.15. The fineness and density of the separated spent blasting dust is similar to that of portland cement. A sample was taken from two different waste barrels. The compositions of the separated spent blasting dust for the two different samples, as determined by Total Constituent Analysis, are given in Table 3.9. TCLP leaching concentrations for the two different samples are given in Table 3.10.

Table 3.9: Total Constituent Analysis for Separated Spent Blasting Dust

Metal	Total Content, mg/kg		Percent by Weight	
	Sample 1	Sample 2	Sample 1	Sample 2
Lead	2896	6610	0.290	0.661
Chromium	725	968	0.072	0.097
Cadmium	68	85	0.007	0.009
Aluminum	1946	2560	0.195	0.256

Table 3.10: TCLP Leaching Concentrations for Separated Spent Blasting Dust

Metal	Concentration, mg/L	
	Sample 1	Sample 2
Lead	9.48	4.91
Chromium	5.36	3.76
Cadmium	1.07	1.01
Aluminum	2.54	3.04

3.2.7 Unseparated Spent Blasting Sand/Dust

The unseparated spent blasting sand/dust was obtained from a Texas Department of Transportation project site on I-20 near Odessa, Texas. Two barrels were obtained. Barrel 2 had a slightly different appearance from Barrel 1, as it had some soil in it resulting from the spent abrasive collection process. Sample 1 from Barrel 1 had a SSD bulk specific gravity of 2.62, an absorption capacity of 0.42 percent, and a fineness modulus of 2.02. Sample 2 from Barrel 2 had a SSD bulk specific gravity of 2.51, an absorption capacity of 0.40 percent, and a fineness modulus of 2.39. The compositions of the unseparated spent blasting sand/dust for the two different samples, as determined by Total Constituent Analysis, are given in Table 3.11. TCLP leaching concentrations for the two different samples are given in Table 3.12.

Table 3.11: Total Constituent Analysis for Unseparated Spent Blasting Sand/Dust

Metal	Total Content, mg/kg		Percent by Weight	
	Sample 1	Sample 2	Sample 1	Sample 2
Lead	246	184	0.025	0.018
Chromium	53	80	0.005	0.008
Cadmium	11	7	0.001	0.001
Aluminum	930	440	0.093	0.044

Table 3.12: TCLP Leaching Concentrations for Unseparated Spent Blasting Sand/Dust

Metal	Concentration, mg/L	
	Sample 1	Sample 2
Lead	1.33	2.78
Chromium	0.56	0.45
Cadmium	0.29	0.10
Aluminum	0.65	2.77

3.2.8 Silica Fume

The silica fume used was a dry, condensed silica fume marketed by Master Builders, Inc., under the product name MB-SF. It has a bulk specific gravity of 2.20. Table 3.13 gives the chemical and physical properties of the silica fume, Table 3.14 gives its composition as determined by Total Constituent Analysis, and Table 3.15 gives the TCLP leaching concentrations.

Table 3.13: Chemical and Physical Properties of Silica Fume

Chemical Composition	Notation	Quantity
Silicon Dioxide, min, %	SiO_2	85.0
Chloride Ions, max, %	Cl	0.25
Sulfur Trioxide, max %	SO_3	1.0
Available Alkalies, max, %	Na_2O Equivalent	1.5
Moisture Content, max, %	-	3.0
Loss on Ignition, max, %	LOI	4.0
Specific Surface Area, min, m^2/gm	BET	20.0
Bulk Density, min, lb/ft^3	-	30.0
X-Ray Diffraction	Non-crystalline	

Table 3.14: Total Constituent Analysis for Silica Fume

Metal	Total Content, mg/kg	Percent by Weight
Lead	68	0.007
Chromium	22	0.002
Cadmium	18	0.002
Aluminum	232	0.023

3.2.9 Superplasticizer

The superplasticizer used was a naphthalene-based high-range water-reducing admixture marketed by Master Builders, Inc., under the product name Rheobuild 1000. The superplasticizer was a Type F chemical admixture conforming to ASTM C 494, "Standard Specification for Chemical Admixtures for Concrete."

3.2.10 Calcium Chloride

The calcium chloride admixture used was a combination accelerator and water reducer marketed by Master Builders, Inc., under the product name Pozzolith 122-HE. The calcium chloride admixture was a Type C and Type E chemical admixture conforming to ASTM C 494, "Standard Specification for Chemical Admixtures for Concrete." Typical recommended dosages range from 10 to 42 mL per kg (16 to 64 fluid ounces) per 100 pounds of cement. This study used dosages of 23 to 47 mL per kg (36 and 72 fluid ounces) per 100 pounds of cement.

3.2.11 Calcium Nitrite

The calcium nitrite admixture used was a corrosion inhibitor marketed by W.R. Grace & Co. under the product name DCI Corrosion Inhibitor. The calcium nitrite admixture was a Type C chemical admixture conforming to ASTM C 494, "Standard Specification for Chemical Admixtures for Concrete." Recommended dosages range from 7.6 to 22.7 liters (2.0 to 6.0 gallons) per cubic yard of concrete based upon use as a corrosion inhibitor. This study used dosages of 7.6 L (2.0 gallons) and 15.2 L (4.0 gallons) in combination with cement contents of 213 kg (470 lb) and 320 kg (705 lb). These mix proportions were reduced to a 9440-cm^3 (1/3-cubic foot) batch volume for used in the laboratory.

3.2.12 Sodium Silicate

Sodium silicate was obtained from Spectrum Chemical Mfg. Corp. It was in a 40° Bé solution form also known as "water glass." Sodium silicate was dosed on the basis of sodium silicate/cement ratios of 0.02 and 0.04 by weight. The sodium silicate was added to the mix water prior to the addition of the mix water to the mortar batch.

3.2.13 Sodium Sulfide and Ferrous Sulfate

The use of sodium sulfide and ferrous sulfate was determined to be an unviable option for the spent blasting abrasives used in this study for the following reasons:

1) Based on the literature review, sodium sulfide and ferrous sulfate are normally used in the stabilization rather than in the solidification of wastes. The reduced surface area of the monolithic solidified waste forms used in this study as compared to a stabilized waste causes reduction in metal solubilities to be unwarranted.
2) The recycling of the spent blasting abrasives in this study caused the TCLP leaching of lead and cadmium to be lowered to method detection limits (MDL). Further reduction of TCLP leaching of lead and cadmium due to the formation of metal sulfides would not have been detectable.
3) TCLP leaching of chromium was above method detection limits and further lowering of chromium leaching would have been detectable. However, chromium will not react with sodium sulfide to form chromium sulfide. Chromium leaching might be further lowered through reduction from hexavalent form to trivalent form by using ferrous sulfate. However, the addition of sodium sulfide to ferrous sulfate is necessary for chromium reduction at neutral to alkaline pH.
4) All other chemical admixtures used in this study, including calcium nitrite, calcium chloride, superplasticizer, and sodium silicate, are commercially available in solutions of standard concentration and grade. They are obtainable in quantities ranging from 19-L (5-gallon) buckets to 208-L (55-gallon) barrels. Sodium sulfide and ferrous sulfate are available in granular, flake, and pelletized forms of varying chemical purity, causing them to be less feasible for field use.

3.3 SPECIMENS

3.3.1 TCLP Specimens

Two 76-mm-by-76-mm (3-inch by 3-inch) diameter long cylinders were cast from each batch for TCLP testing at 7 and 28 days after casting [25, 43].

3.3.2 Compressive Strength Specimens

Six 76-mm-by-152-mm (3-inch-by-6-inch) diameter long cylinders were cast from each batch for compressive strength testing at 7, 28, and 90 days after casting.

3.3.3 Permeability Specimens

Two 102-mm-by-204-mm (4-inch-by-8-inch) diameter long cylinders were cast from each batch for permeability testing at 28 days after casting.

3.4 FORMS AND MOLDS

Molds for all three types of specimens were disposable plastic cylinder molds conforming to ASTM C 470, "Standard Specification for Molds for Forming Concrete Test Cylinders Vertically."

3.5 MIX PROPORTIONS

Appendix 1 contains detailed information on the specimen designations and corresponding mix proportions for the mixes studied. Silica fume was used as a 12 percent by weight addition to the portland cement. To maintain a constant water/cement ratio, 3.2 kg (7 lb) of mix water was removed for each 3.785 liters (gallon) of calcium chloride and calcium nitrite used. Sodium silicate was considered as part of the mixing water in determining the total water/cement ratio. For example, a water/cement ratio of 0.33 plus a sodium silicate/cement ratio of 0.02 would result in a total water/cement ratio of 0.35.

3.6 MIXING PROCEDURE

Trial batches were made in 9440-cm^3 (1/3-cubic foot) volumes for use in the laboratory. All batches were mixed using the following procedure:

a) All 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) the water and superplasticizer were added followed by mixing for three minutes;
d) the batch was 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 mixed for three additional minutes.

Mixes with high contents of fines, such as silica fume or separated spent blasting dust, typically required mixing for a period of time approximately twice as long as a mix with a lower content of fines. These longer mixing times were necessary to ensure adequate dispersion of the fine particles throughout the mortar.

3.7 CASTING

Specimen molds were filled in two equal layers, with each layer vibrated on a vibrating table for twenty seconds according to ASTM C 192, "Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory." The specimens were then trowel finished.

3.8 CURING

Curing consisted of placing the specimens under wet burlap and polyethylene for the first 24 hours after casting per ASTM C 192, "Standard Specification for Making and Curing Concrete Test Specimens in the Laboratory." They were then removed from the molds and placed in a moist curing room. Mixes taking longer than 24 hours to set (owing to lead retardation) were kept under the wet burlap and polyethylene until they set, at which time they were removed from the molds and placed in a moist curing room. Mixes that had not set within 7 days after casting were discarded. The moist curing room was kept at 23° C and 100 percent relative humidity, conforming with ASTM C 511, "Standard Specification for Moist Cabinets, Moist Rooms, and Water Storage Tanks Used in the Testing of Hydraulic Cements and Concretes."

3.9 TESTING

3.9.1 Fresh Concrete

The workability of the mortar mixes was measured according to ASTM C 109, "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. Trial batches were mixed to produce a flow of 110 ± 5.

3.9.2 Hardened Concrete

3.9.2.1 Compressive Strength Testing: Compressive strength was determined using 76-mm-by-152-mm (3-inch-by 6-inch) diameter long cylinders tested according to ASTM C 39, "Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens," at 7, 28, and 90 days after casting. Two companion specimens were tested at each test age. The cylinders were capped using unbonded neoprene caps inside steel restraining rings.

3.9.2.2 Permeability Testing: Permeability was determined according to AASHTO T 277, "Rapid Determination of the Chloride Permeability of Concrete," at 28 days after casting, with the following exceptions:

1) Tests were conducted on 102-mm (4-inch) diameter mortar cylinders, instead of on 95-mm (3.75-inch) diameter concrete core specimens [42];

2) Two specimens were cut from the interior of each cylinder, instead of using two specimens cut from the ends of a cored specimen [42]; and,
3) Specimens were kept saturated in a sealed vacuum for an hour after evacuation, in lieu of a forced vacuum [42].

3.9.2.3 Toxicity Characteristic Leaching Procedure: The Toxicity Characteristic Leaching Procedure testing was performed as per 40 CFR 261, Appendix II - Method 1311 (7-1-90 Edition), at 7 and 28 days after casting [25, 43].

3.10 CORING

Cores were taken from several 305-mm square by 152-mm thick (12-inch square by 6-inch thick) concrete blocks made with spent blasting abrasives at the Rainbow Bridge in Port Arthur, Texas. Cores were made using a 102-mm (4-inch) inside diameter drilling bit. These cores were used for compressive strength, permeability, and TCLP testing. Coring was performed conforming with ASTM C 42, "Standard Test Method for Obtaining and Testing Drilled Cores and Sawed Beams of Concrete." Four cores were taken from each block. Two cores were used for compressive strength testing, while the other two cores were sawed into 51-mm (2-inch) thick specimens for permeability testing. The remaining portion of the block was crushed and homogenized for TCLP testing.

3.11 EQUIPMENT AND TESTING APPARATUS

3.11.1 Mixing Equipment

All mixing was done in a Reynolds 9440-cm^3 (1/3-cubic foot) capacity mortar mixer at medium speed.

3.11.2 Curing Equipment

All specimens were cured at 23° C and 100 percent relative humidity in a curing room meeting ASTM C 192, "Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory."

3.11.3 Compressive Strength Testing Apparatus

All compressive strength tests were performed on a Forney Model LD8606 2,669 kN (600 kip) capacity testing machine according to ASTM C 39, "Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens."

3.11.4 Permeability Testing Apparatus

The permeability specimens were tested according to AASHTO T 277, "Rapid Determination of the Chloride Permeability of Concrete," using a Helios automatic data acquisition system.

The test consists of monitoring the amount of electrical current passed through a 102-mm (4-inch) diameter by 51-mm (2-inch) thick concrete specimen. One end of the specimens is immersed in a sodium chloride solution, while the other is immersed in a sodium hydroxide solution. A potential difference of 60 volts is maintained across the specimen for 6 hours. The total charge in coulombs passed during the 6 hour test period is related to chloride permeability.

3.11.5 TCLP Testing Apparatus

A detailed description of the TCLP testing apparatus is described by Brabrand and Webster [25, 43].

CHAPTER 4. EXPERIMENTAL RESULTS

4.1 INTRODUCTION

The compressive strength, chloride ion permeability, and TCLP leaching of portland cement mortars containing recycled spent blasting abrasives were investigated in this study. Mix proportions and test results for selected mixes are presented in this chapter. Complete information regarding proportions and designations for all of the mortar batches is presented in Appendix 1. Complete test results can be found in Appendices 2 and 3. The experimental results presented herein and in the Appendices are analyzed and discussed in Chapter 5.

4.2 FRESH MORTAR PROPERTIES

The various mortar batches were mixed to produce a flow of 110 ± 5 as determined by the flow table test. The air content of the mortar was assumed to be approximately 2 percent. The ambient air temperature during mixing and casting was between 16° C and 32° C (60° F and 90° F).

4.3 MIX PROPORTIONS AND DESIGNATIONS

Complete information regarding proportions and designations for all of the mortar batches produced in this study is presented in Appendix 1. Additional information regarding mix proportions can be found in a report by Garner [24]. Proportions for selected mixes are given in Tables 4.1 to 4.4.

Table 4.1: Mix Proportions for Selected Mixes Containing Separated Spent Blasting Sand and Separated Spent Blasting Dust

Mix	Cement lbs	Blast Sand lbs	Blast Dust lbs	HRWR oz/cwt	Calcium Nitrite gallons	Silica Fume lbs	W/C Ratio by weight
SDT205D3	470	1100	165	21.3	0.0	0	0.35
SDT205D4	470	1100	275	41.0	0.0	0	0.35
SDT207D1	705	1100	0	0.0	2.0	0	0.35
SDT207D2	705	1100	55	2.6	2.0	0	0.35
SDT209D1	705	1100	0	3.7	0.0	84.6	0.35
SDT209D2	705	1100	55	9.7	0.0	84.6	0.35

lb = 0.45 kg
1 oz/cwt = 0.65 mL per kg of cement
1 gal = 3.785 L

Table 4.2: Mix Proportions for Selected Mixes Containing Unseparated Spent Blasting Sand/Dust

Mix	Cement lbs	Blast Sand/Dust lbs	HRWR oz/cwt	Calcium Nitrite gallons	Silica Fume lbs	W/C Ratio by weight
SDT304	470	1100	23.2	2.00	0.0	0.35
SDT400	705	1100	12.0	0.00	0.0	0.35
SDT401	705	1100	16.5	0.00	84.6	0.35
SDT405	705	1100	12.0	4.00	0.0	0.35

1 lb = 0.45 kg
1 oz/cwt = 0.65 mL per kg of cement
1 gal = 3.785 L

Table 4.3: Mix Proportions for Selected Mixes Containing Concrete Sand and Separated Spent Blasting Dust

Mix	Cement lbs	Concrete Sand lbs	Blast Dust lbs	HRWR oz/cwt	Sodium Silicate lbs	W/C Ratio by weight
CM # 2	705	1100	55	5.4	0.00	0.35
SILI 1A	705	1100	0	1.8	14.10	0.35
SILI 2D	705	1100	275	35.7	28.20	0.35

1 lb = 0.45 kg
1 oz/cwt = 0.65 mL per kg of cement

Table 4.4: Mix Proportions for Selected Mixes Containing Spent Blasting Slag

Mix	Cement lbs	Blast Slag lbs	HRWR oz/cwt	Silica Fume lbs	Calcium Chloride oz/cwt	Calcium Nitrite gallons	Sodium Silicate lbs	W/C Ratio by weight
MONT 1	705	1100	2.9	0.0	0.0	0.00	0.00	0.35
MONT 2	705	1100	2.9	0.0	0.0	2.00	0.00	0.35
MONT 3	705	1100	12.0	84.6	0.0	0.00	0.00	0.35
MONT 4	705	1100	5.3	0.0	0.0	0.00	14.10	0.35

1 lb = 0.45 kg
1 oz/cwt = 0.65 mL per kg of cement
1 gal = 3.785 L

4.4 COMPRESSIVE STRENGTH RESULTS

Complete results for compressive strength testing of all mortar batches is presented in Appendix 2. Compressive strength testing results for selected mixes are given in Tables 4.5 to 4.8. Compressive strength is given as the average strength of two companion 76-mm (3-inch) diameter by 152-mm (6-inch) long cylinders tested at 7, 28, and 90 days after casting.

4.5 CHLORIDE ION PERMEABILITY RESULTS

Complete results for chloride ion permeability testing of all mortar batches is presented in Appendix 2. Chloride ion permeability testing results for selected mixes are given in Tables 4.5 to 4.8. Chloride ion permeability is given as the average of four companion 102-mm (4-inch) diameter by 51-mm (2-inch) thick concrete specimens tested at 28 days after casting.

Table 4.5: Compressive Strength and Permeability Results for Selected Mixes Containing Separated Spent Blasting Sand and Separated Spent Blasting Dust

Mix	Compressive Strength			Permeability
	7-Day psi	28-Day psi	90-Day psi	coulombs
SDT205D3	-	-	-	-
SDT205D4	-	-	-	-
SDT207D1	3210	3930	4800	21110
SDT207D2	2330	3340	3230	18260
SDT209D1	1690	2450	2420	4450
SDT209D2	1980	2820	2570	6990

1000 psi = 6.895 MPa
- Not tested due to no set

Table 4.6: Compressive Strength and Permeability Results for Selected Mixes Containing Unseparated Spent Blasting Sand/Dust

Mix	Compressive Strength			Permeability
	7-Day psi	28-Day psi	90-Day psi	coulombs
SDT304	5170	6480	7250	6410
SDT400	1720	2370	2230	12800
SDT401	2020	2330	2660	2450
SDT405	6520	8250	8710	7290

1000 psi = 6.895 MPa

Table 4.7: Compressive Strength and Permeability Results for Selected Mixes Containing Concrete Sand and Separated Spent Blasting Dust

Mix	Compressive Strength			Permeability
	7-Day psi	28-Day psi	90-Day psi	coulombs
CM # 2	3190	3510	4660	5770
SILI 1A	6380	7550	-	13030
SILI 2D	5520	5250	-	11660

1000 psi = 6.895 MPa
- Not tested due to no set

Table 4.8: Compressive Strength and Permeability Results for Selected Mixes Containing Spent Blasting Slag

Mix	Compressive Strength			Permeability
	7-Day psi	28-Day psi	90-Day psi	coulombs
MONT 1	-	-	-	-
MONT 2	-	-	-	-
MONT 3	2870	3640	-	3870
MONT 4	2260	2710	-	8750

1000 psi = 6.895 MPa
- Not tested

4.6 TOXICITY CHARACTERISTIC LEACHING PROCEDURE RESULTS

Complete results for TCLP testing of all mortar batches is presented in Appendix 3. TCLP testing results for selected mixes are given in Tables 4.9 to 4.12. TCLP results are given as the average of three 50 mg samples tested at 7 and/or 28 days after casting.

Method detection limits (MDL) were determined for the TCLP analyses performed in this study. The method detection limit is defined as the lowest concentration that an analysis procedure can reliably detect with 99 percent confidence that the concentration is greater than zero. Method detection limits for the metals in this study are shown in Table 4.13. Further discussion of the procedure involved in determining the method detection limits for this study can be found in Webster [43].

Table 4.9: TCLP Results for Selected Mixes Containing Separated Spent Blasting Sand and Separated Spent Blasting Dust

Mix	7-Day TCLP, mg/L			28-Day TCLP, mg/L		
	Pb	Cr	Cd	Pb	Cr	Cd
SDT205D3	-	-	-	-	-	-
SDT205D4	-	-	-	-	-	-
SDT207D1	0.18	1.72	0.15	0.10	1.71	0.08
SDT207D2	0.19	1.92	0.19	0.07	2.00	0.07
SDT209D1	0.08	1.87	0.06	0.08	1.84	0.09
SDT209D2	0.07	1.92	0.09	0.15	1.99	0.09

- Not tested due to no set

Table 4.10: TCLP Results for Selected Mixes Containing Unseparated Spent Blasting Sand/Dust

Mix	7-Day TCLP, mg/L			28-Day TCLP, mg/L		
	Pb	Cr	Cd	Pb	Cr	Cd
SDT 304	0.02	0.71	0.03	0.14	0.61	0.15
SDT 400	0.17	0.67	0.11	0.12	0.45	0.14
SDT 401	0.07	0.79	0.03	0.09	0.68	0.11
SDT 405	0.00	0.49	0.05	0.07	0.49	0.14

Table 4.11: TCLP Results for Selected Mixes Containing Concrete Sand and Separated Spent Blasting Dust

Mix	7-Day TCLP, mg/L			28-Day TCLP, mg/L		
	Pb	Cr	Cd	Pb	Cr	Cd
CM # 2	< 0.07	0.47	0.16	< 0.07	0.44	0.17
SILI 1A	< 0.07	0.20	0.13	-	-	-
SILI 2D	< 0.07	0.73	0.14	-	-	-

- Not tested

Table 4.12: TCLP Results for Selected Mixes Containing Spent Blasting Slag

Mix	7-Day TCLP, mg/L			28-Day TCLP, mg/L		
	Pb	Cr	Cd	Pb	Cr	Cd
MONT 1	-	-	-	-	-	-
MONT 2	-	-	-	-	-	-
MONT 3	< 0.07	2.38	0.17	-	-	-
MONT 4	< 0.07	1.60	0.17	-	-	-

- Not tested

Table 4.13: TCLP Method Detection Limits

Metal	Detection Limit, mg/L
Lead	0.07
Chromium	0.07
Cadmium	0.02
Aluminum	0.26

4.7 FIELD APPLICATIONS OF RECYCLING SPENT BLASTING ABRASIVES IN PORTLAND CEMENT MORTARS

From the results of the experimental program initiated by Garner [24], one portland cement mortar mix design was chosen for field use at the Rainbow Bridge in Port Arthur, Texas. It was used to recycle sand blasting abrasives processed in three forms: separated spent blasting sand, separated spent blasting dust, and unseparated spent blasting sand/dust. The mix design was used to produce approximately 50,000 30.5-cm square by 15.2-cm thick (12-inch square by 6-inch thick) blocks to be used as filler material in dolphins around the bridge piers. The dolphins are used to protect the bridge piers from damage due to ship collisions.

The mortar mix proportions are given in Table 4.14. The mix proportions given yield approximately 0.40 cubic meters (14 cubic feet) of mortar.

Table 4.14: Rainbow Bridge Mortar Mix Design

Ingredient	Proportion
Portland Cement	705 lbs
Spent Blasting Abrasives [a]	1100 lbs
Superplasticizer	21.8 oz/cwt
Silica Fume	84.6 lbs
Water/Cement Ratio	0.35

[a] 1100 lbs of unseparated spent blasting sand/dust or 917 lbs of separated spent blasting sand combined with 183 lbs of separated spent blasting dust

1 lb = 0.45 kg; 1 oz/cwt = 0.65 mL/kg of cement

Approximately one year after casting, three blocks made at the Rainbow Bridge were cored and tested for compressive strength, chloride ion permeability, and TCLP leaching. Table 4.15 gives the results for compressive strength and permeability, while Table 4.16 gives the results for TCLP leaching. Compressive strength is given as the average of two 102-mm(4-inch) diameter by 152-mm (6-inch) long cylinders corrected for length/diameter ratios in conformance with ASTM C 39. Chloride ion permeability is given as the average of four 102-mm (4-inch) diameter by 51-mm (2-inch) thick concrete specimens. TCLP leaching concentrations are given for each of three 50 mg samples.

Table 4.15: Compressive Strength and Chloride Ion Permeability for Rainbow Bridge Mortar Blocks

Sample	Compressive Strength, psi	Permeability, coulombs
Block 1	360	12320
Block 2	5970	360
Block 3	2320	1740

1000 psi = 6.895 MPa

Table 4.16: TCLP Leaching Concentrations for Rainbow Bridge Mortar Blocks

Sample		Concentration, mg/L			
		Lead	Cadmium	Chromium	Aluminum
Block 1	Average	< 0.07	0.20	2.27	25.2
	Sample 1	0.05	0.20	2.35	25.4
	Sample 2	0.07	0.19	2.26	24.5
	Sample 3	0.05	0.21	2.19	25.7
Block 2	Average	0.07	0.21	0.70	25.5
	Sample 1	0.07	0.20	0.72	25.1
	Sample 2	0.08	0.21	0.66	25.6
	Sample 3	0.07	0.21	0.72	25.8
Block 3	Average	0.07	0.20	0.49	24.2
	Sample 1	0.07	0.19	0.48	23.7
	Sample 2	0.07	0.20	0.49	23.9
	Sample 3	0.06	0.21	0.49	25.1

CHAPTER 5. DISCUSSION OF EXPERIMENTAL RESULTS

5.1 INTRODUCTION

In this chapter, the test results presented in Chapter 4 and Appendices 1-3 are analyzed and discussed. Topics addressed include the effect of mix composition on set times, strength development, permeability, TCLP leaching, and field applications of recycling spent blasting abrasives in portland cement mortars.

5.2 EFFECT OF MIX COMPOSITION ON SET TIMES

5.2.1 Mixes Containing Separated Spent Blasting Sand and Separated Spent Blasting Dust

The purpose of these mixes was to study the effect of increasing contamination level upon mix characteristics including set times, compressive strength, permeability, and TCLP leaching. The mixes contained a constant amount of 499 kg (1100 lb) of separated spent blasting sand with varying additional amounts of separated spent blasting dust. By increasing the amount of separated spent blasting dust, the contamination level of the mix was increased above that resulting from the separated spent blasting sand alone.

Figures 5.1 and 5.2 show the set times for this series of mixes as a function of separated spent blasting dust content, and therefore, contamination level. Figure 5.1 shows the set times for mixes with a cement content of 213 kg (470 lb) per batch. Figure 5.2 shows the set times for mixes with a higher cement content of 320 kg (705 lb) per batch. Four control mixes with increasing spent blasting dust contents and no accelerating admixtures were made for each cement content. Corresponding mixes containing 7.57 L (2 gallons) of calcium nitrite and silica fume in the amount of 12 percent by weight addition to portland cement were also made. These two admixtures were used in an effort to achieve earlier set times of the mixes.

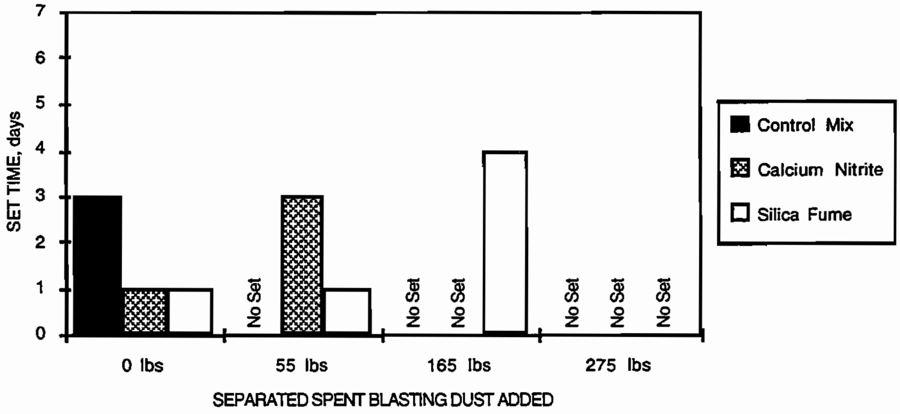

Figure 5.1: Set Times for Separated Spent Sand/Separated Spent Dust Mixes with 213 kg (470 lb) Cement Content With No Admixtures, With Calcium Nitrite, and With Silica Fume

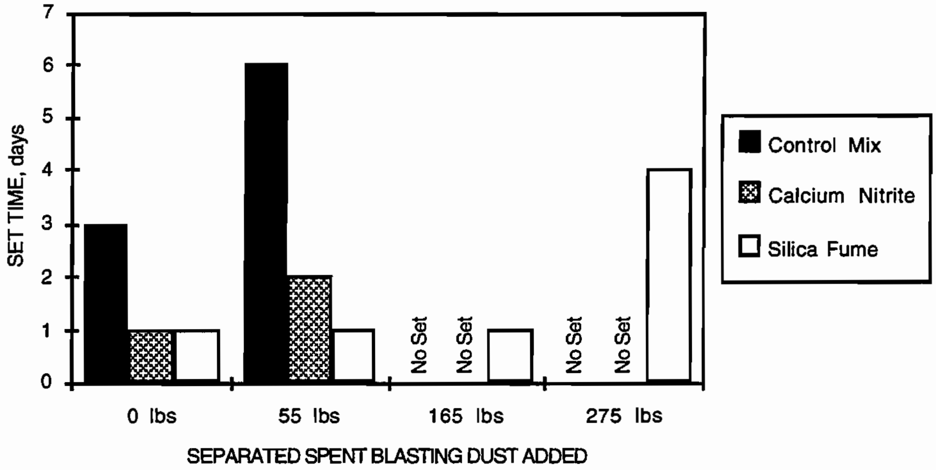

Figure 5.2: Set Times for Separated Spent Sand/Separated Spent Dust Mixes with 320 kg (705 lb) Cement Content With No Admixtures, With Calcium Nitrite, and With Silica Fume

As can be seen in Figures 5.1 and 5.2, set times increased with increasing spent blasting dust content. Set times were shorter for the higher cement content mixes than for their corresponding lower cement content mixes. Both calcium nitrite and silica fume were effective in shortening set times, as compared with their corresponding control mixes. However, silica fume was more effective than calcium nitrite in shortening set times, particularly in the mixes containing the highest amounts of spent blasting dust, and therefore, contamination level. The only mix made with a spent blasting dust content of 125 kg (275 lb) that set within 7 days after casting contained silica fume and a high cement content.

5.2.2 Mixes Containing Unseparated Spent Blasting Sand/Dust

All mixes containing unseparated spent blasting sand/dust set within 24 hours of mixing, regardless of whether accelerating admixtures were used. Mixes were made with medium and high cement contents as well as with calcium nitrite and silica fume in similar proportions to the separated spent blasting sand/separated spent blasting dust mixes. Owing to the low contamination level of the unseparated spent blasting sand/dust, no significant differences in set times as a function of amount of portland cement, silica fume, or calcium nitrite were observed.

5.2.3 Mixes Containing Concrete Sand and Separated Spent Blasting Dust

This purpose of these mixes was to study the effect of sodium silicate additions upon mix characteristics including set time, compressive strength, permeability, and TCLP leaching. Similar to the mixes containing separated spent blasting sand and separated spent blasting dust, these mixes contained a constant amount of 499 kg (1100 lbs) of concrete sand with varying additional amounts of separated spent blasting dust. By increasing the amount of separated spent blasting dust, the contamination level of the mix was increased. Four control mixes with increasing spent blasting dust contents, no accelerating admixtures, and a high cement content of 320 kg (705 lb), superplasticizer, and a water/cement ratio by weight of 0.35 were made. Corresponding mixes containing sodium silicate as an accelerating admixture were also made. Sodium silicate/cement ratios of 2 percent and 4 percent by weight were used. Figure 5.3 shows the set times for this series of mixes.

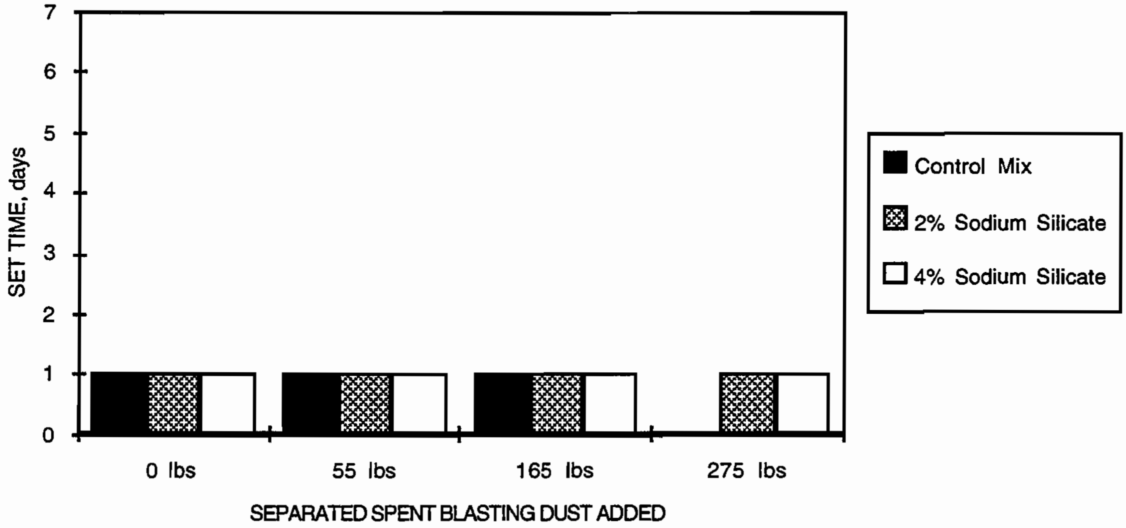

Figure 5.3: Set Times for Concrete Sand/Separated Spent Blasting Dust Mixes With Sodium Silicate

As can be seen in Figure 5.3, all of the control mixes except for the 124.7 kg (275 lb) spent dust content mix set within 24 hours. However, the 124.7 kg (275 lb) spent dust content control mix did not set within 7 days after casting. Sodium silicate in both the 2 percent and the 4 percent by weight amount was effective in reducing the set time for this mix to within 24 hours after casting.

5.2.4 Mixes Containing Spent Blasting Slag

The spent blasting slag used in this study was produced at the Montopolis Bridge maintenance job in Austin, Texas. The spent blasting slag was to be recycled in a portland cement mortar at the construction site for use as rip-rap. The purpose of this series of mixes was to determine mix proportions to be used for this field application. A control mix consisting of 499 kg (1100 lb) of spent blasting slag, a cement content of 320 kg (705 lb), superplasticizer, and a water/cement ratio by weight of 0.35 was made. Corresponding mixes containing four different accelerating admixtures in two different dosages each were also made. Accelerating admixtures used were calcium nitrite, silica fume, calcium chloride, and sodium silicate. Calcium nitrite was used in doses of 7.57 L (2 gallons) and 15.14 L (4 gallons) equivalent to 23.4 mL per kg of cement (36 oz/cwt) and 46.8 mL per kg of cement (72 oz/cwt), respectively. Calcium chloride was also used in doses of 23.5 mL per kg of cement (36 oz/cwt) and 46.8 mL per kg of cement (72 oz/cwt). Silica fume was used as an addition in the amount of 6 and 12 percent by weight of portland cement. Sodium silicate/cement ratios of 2 percent and 4 percent by weight were used. Figure 5.4 shows the set times for these mixes.

As can be seen in Figure 5.4, the only mixes to set within 24 hours of casting were those containing sodium silicate. Mixes containing 12 percent by weight silica fume or 46.8 mL per kg of cement (72 oz/cwt) of calcium chloride set in two days. Mixes containing 6 percent by weight silica fume, 46.8 mL per kg of cement (72 oz/cwt) of calcium nitrite, or 23.4 mL per kg of cement (36 oz/cwt) calcium chloride set in five days. The control mix containing no accelerating admixtures and the mix containing 23.4 mL per kg of cement (36 oz/cwt) calcium nitrite did not set within 7 days after casting.

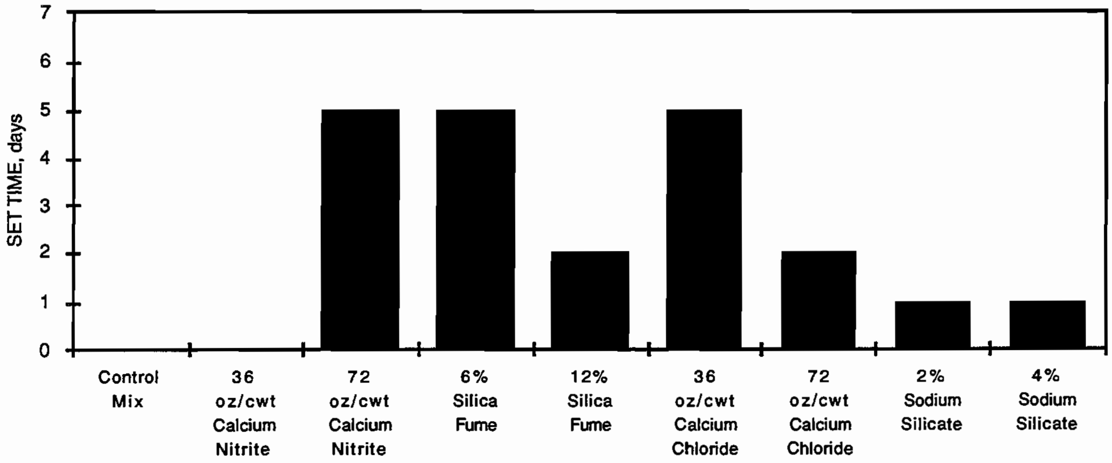

Figure 5.4: Set Times for Spent Blasting Slag Mixes With Four Different Accelerating Admixtures

Based upon the results of these nine mixes, four additional mixes were identified for trial batching for field use. These four mixes contained accelerating admixtures in the combinations of 4 percent sodium silicate with 8 percent silica fume, 4 percent sodium silicate with 12 percent silica fume, 6 percent sodium silicate with 8 percent silica fume, and 6 percent sodium silicate with 12 percent silica fume. All four of these mixes set within 24 hours after casting.

5.2.5 Summary of the Effect of Mix Composition on Set Times

The effect of mix composition on set times investigated in this study can be stated as follows:

1) For the separated spent blasting sand/separated spent blasting dust mixes, set times were reduced as the cement content increased.
2) For the separated spent blasting sand/separated spent blasting dust mixes as well as for the concrete sand/separated spent blasting dust mixes, increasing the contamination level increased the set times.

3) For the separated spent blasting sand/separated spent blasting dust mixes, silica fume was a more effective accelerating admixture than calcium nitrite.
4) In the unseparated spent blasting sand/dust used in this study, no significant effects upon set times were observed with the use of calcium nitrite or silica fume (apparently due to the low contamination level of these mixes).
5) For the concrete sand/separated spent blasting dust mixes, sodium silicate was very effective in reducing the set times of the most highly contaminated mixes.
6) For the spent blasting slag mixes, sodium silicate was the most effective accelerating admixture used in reducing set times to within 24 hours. Mixes containing no accelerating admixtures did not set within 7 days after casting.
7) Based upon the above observations, sodium silicate was the most effective accelerating admixture used in this study. For the dosages used in this study, silica fume and calcium chloride were approximately equivalent, and they were the next most effective accelerating admixtures compared to sodium silicate. Calcium nitrite was effective in reducing the set times of lesser contaminated mixes but was ineffective in highly contaminated mixes.

5.3 EFFECT OF MIX COMPOSITION ON COMPRESSIVE STRENGTH

5.3.1 Mixes Containing Separated Spent Blasting Sand and Separated Spent Blasting Dust

Figures 5.5 to 5.10 show the compressive strength gain versus contamination level for mixes containing separated spent blasting sand and separated spent blasting dust. Each figure contains one compressive strength curve for each amount of separated spent blasting dust added. In instances where a curve is not shown for a particular amount of separated spent blasting dust, the corresponding mix did not set within 7 days of casting and was not tested for compressive strength.

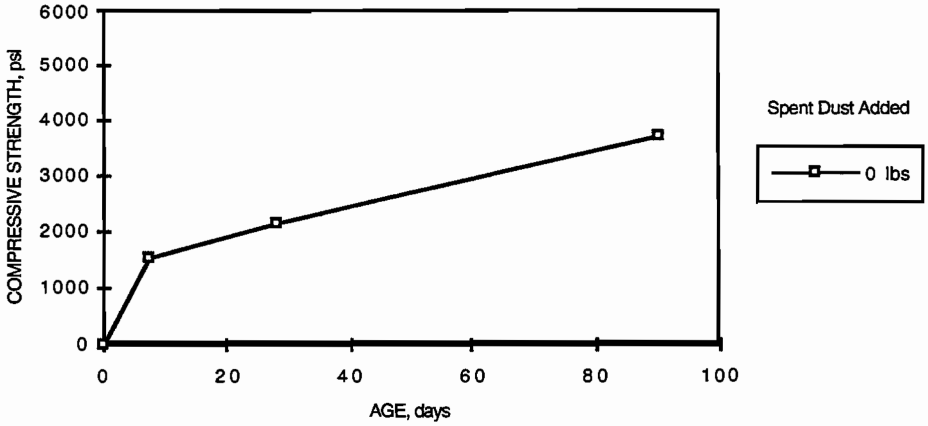

Figure 5.5: Compressive Strength for Separated Spent Sand/Separated Spent Dust Control Mixes with 470 lbs (213 kg) Cement Content

Figure 5.5 shows the compressive strength gain for the medium cement content control mixes. These mixes contained 499 kg (1100 lb) of separated spent blasting sand, 213 kg (470 lb) of portland cement, superplasticizer, a water/cement ratio by weight of 0.35, and no accelerating admixtures. As seen in Figure 5.5, the only medium cement content mix to set within 7 days after casting was the mix containing no separated spent blasting dust.

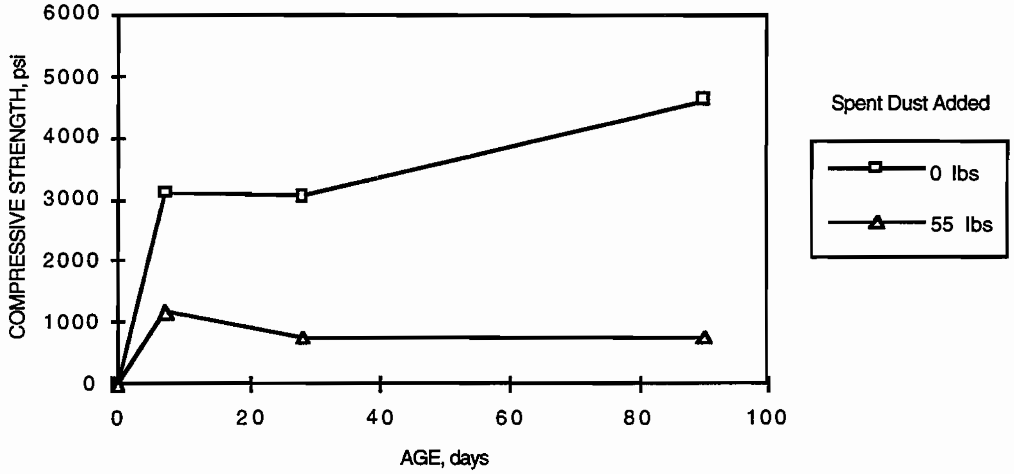

Figure 5.6: Compressive Strength for Separated Spent Sand/Separated Spent Dust Control Mixes with 320 kg (705 lb) Cement Content

Figure 5.6 shows the compressive strength gain for the high cement content control mixes. These mixes contained 499 kg (1100 lb) of separated spent blasting sand, 320 kg (705 lb) of portland cement, superplasticizer, a water/cement ratio by weight of 0.35, and no accelerating admixtures. As seen in Figure 5.6, the mixes containing 0 kg (0 lb) and 24.9 kg (55 lb) separated spent dust set while the two higher spent dust concentration mixes did not set within 7 days after casting. The mix containing no separated spent dust had a higher compressive strength than the mix containing 24.9 kg(55 lb) separated spent dust.

Comparing Figures 5.5 and 5.6, the increase in cement content caused the 24.9 kg (55 lb) separated spent dust mix to set within 7 days after casting and increased the compressive strength of the mix containing no separated spent dust. In both figures, the general shape of the compressive strength curves were somewhat erratic, illustrating the unpredictability of gain in compressive strength when no accelerating admixtures were used.

Figure 5.7 shows the compressive strength gain for the medium cement content mixes containing calcium nitrite. These mixes contained 499 kg (1100 lb) of separated spent blasting sand, 213 kg (470 lb) of portland cement, superplasticizer, a water/cement ratio by weight of 0.35, and 7.57 L (2 gallons) of calcium nitrite. As seen in Figure 5.7, both the 0 kg (0 lb) and the 24.9 kg (55 lb) separated spent dust mixes set, while the two higher spent dust concentration mixes did not set within 7 days after casting. The mix containing no separated spent dust had a higher compressive strength than the mix containing 24.9 kg(55 lb) separated spent dust.

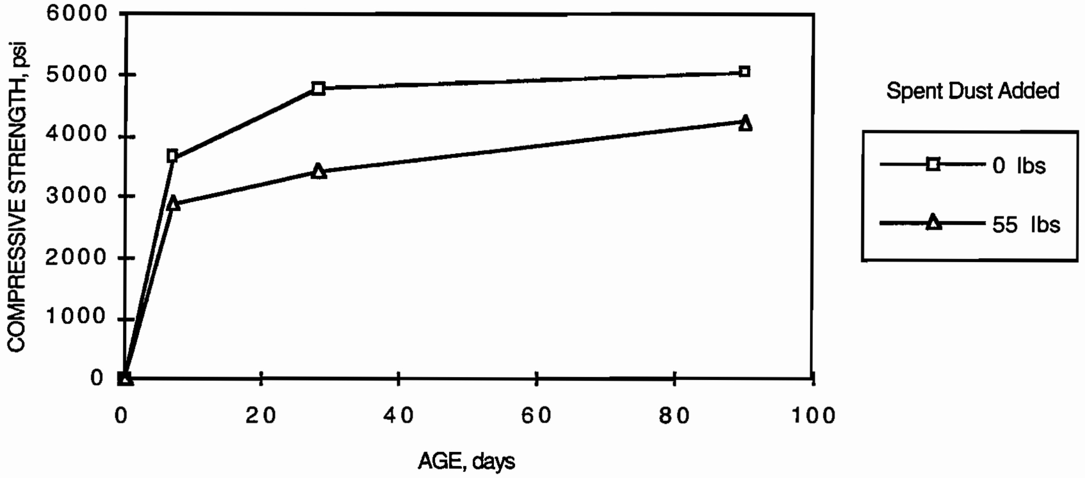

Figure 5.7: Compressive Strength for Separated Spent Sand/Separated Spent Dust Mixes with 213 kg (470 lb) Cement Content and Calcium Nitrite

Figure 5.8 shows the compressive strength gain for the high cement content mixes containing calcium nitrite. These mixes contained 499 kg (1100 lb) of separated spent blasting sand, 320 kg (705 lb) of portland cement, superplasticizer, a water/cement ratio by weight of 0.35, and 7.57 L (2 gallons) of calcium nitrite. As seen in Figure 5.8, both the 0 kg (0 lb) and the 24.9 kg (55 lb) separated spent dust mixes set, while the two higher spent dust concentration mixes did not set within 7 days after casting. The mix containing no separated spent dust had a higher compressive strength than the mix containing 24.9 kg (55 lb) separated spent dust.

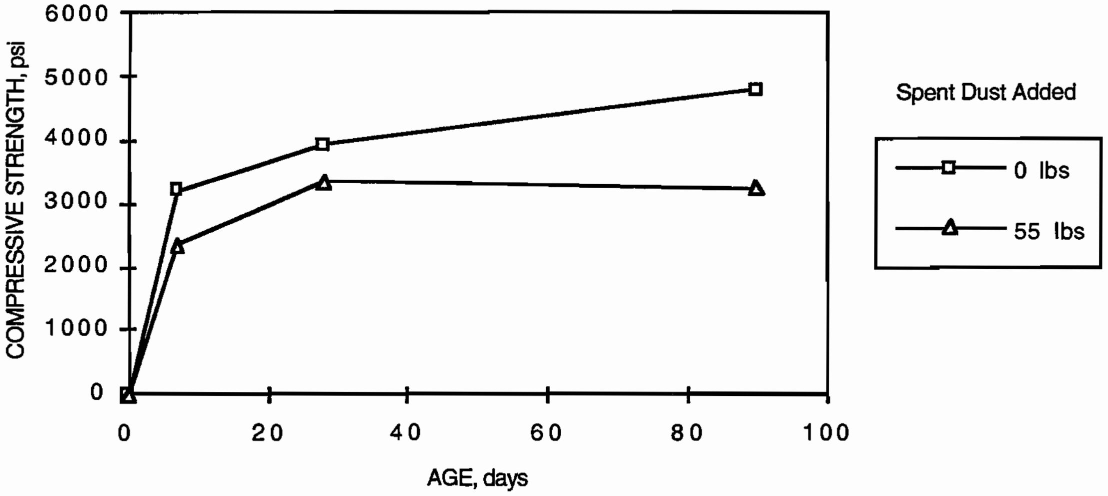

Figure 5.8: Compressive Strength for Separated Spent Sand/Separated Spent Dust Mixes with 320 kg (705 lb) Cement Content and Calcium Nitrite

Comparing Figures 5.7 and 5.8, increasing the cement content above 213 kg (470 lb) did not affect the set of the mix. In fact, the medium cement content mixes had a higher compressive strength than the high cement content mixes. This is attributed to the use of a constant amount of calcium nitrite in each batch rather than a constant ratio of calcium nitrite to cement. When the cement content was increased and the amount of calcium nitrite was held constant, the lower calcium nitrite/cement ratio caused the accelerating effects to be reduced. This resulted in lower compressive strengths at all test ages.

Figure 5.9 shows the compressive strength gain for the medium cement content mixes containing silica fume. These mixes contained 499 kg (1100 lb) of separated spent blasting sand, 213 kg (470 lb) of portland cement, superplasticizer, a water/cement ratio by weight of 0.35, and silica fume in the amount of 12 percent by weight addition to portland cement. As seen in Figure 5.9, the 0 kg (0 lb), 24.9 kg (55 lb), and 74.8 kg (165 lb) separated spent dust mixes set, while the 124.7 kg (275 lb) separated spent dust mix did not set within 7 days after casting. The mix containing no separated spent dust had a higher compressive strength than the mix containing 24.9 kg (55 lb) separated spent dust. However, the mix containing 74.8 kg (165 lb) separated spent dust had the highest compressive strength at 90 days after casting.

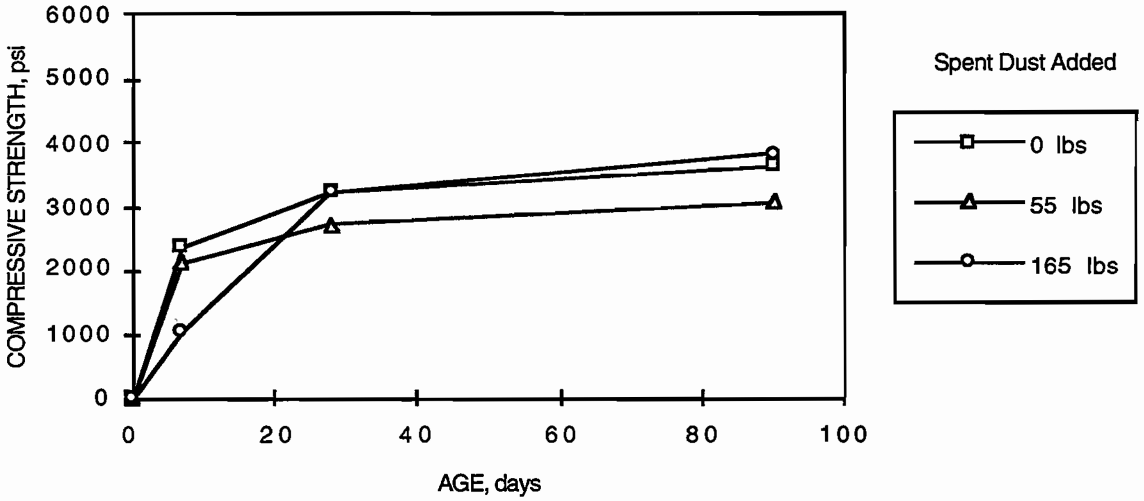

Figure 5.9: Compressive Strength for Separated Spent Sand/Separated Spent Dust Mixes with 213 kg (470 lb) Cement Content and Silica Fume

Figure 5.10 shows the compressive strength gain for the high cement content mixes containing silica fume. These mixes contained 499 kg(1100 lb) of separated spent blasting sand, 320 kg (705 lb) of portland cement, superplasticizer, a water/cement ratio by weight of 0.35, and silica fume in the amount of 12 percent by weight addition to portland cement. As seen in Figure

5.10, all four spent dust concentrations set within 7 days after casting. The highest compressive strength was obtained in the mix containing 74.8 kg (165 lb) separated spent dust followed in order of decreasing compressive strength by the mixes containing 24.9 kg (55 lb), 0 kg (0 lb), and 124.7 kg (275 lb) separated spent dust.

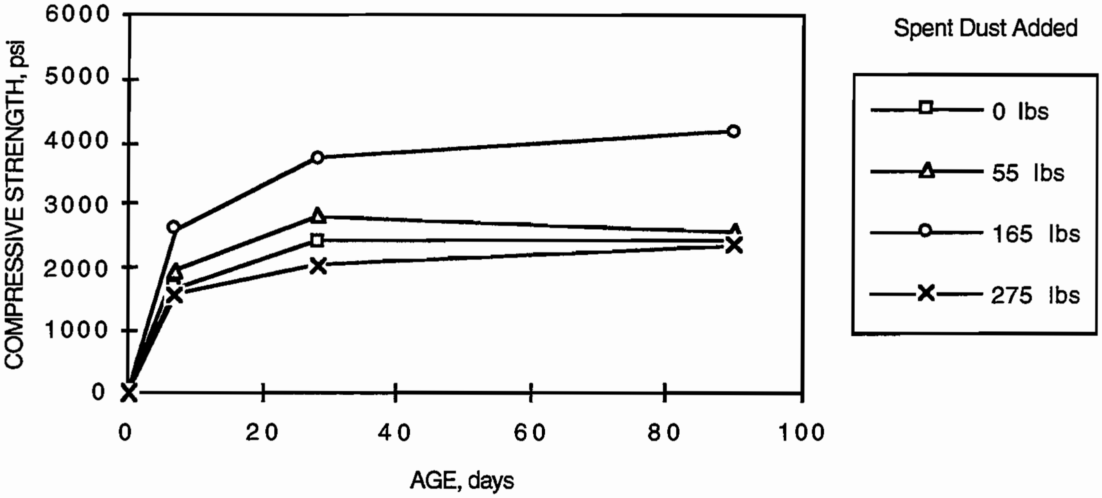

Figure 5.10: Compressive Strength for Separated Spent Sand/Separated Spent Dust Mixes with 320 kg (705 lb) Cement Content and Silica Fume

As illustrated in Figures 5.9 and 5.10, an increase in cement content caused the highest spent dust concentration mix to set which had not set with a medium cement content. There was also no clear trend in this series of mixes as to the effect of cement content or contamination level on compressive strength. For several of the spent dust concentrations, the high cement content mixes had a higher compressive strength than the medium cement content mixes. However, for other spent dust concentrations, the medium cement content mixes had a higher compressive strength than the high cement content mixes. This discrepancy is attributed to the difficulty in consolidating the mortar to a constant degree from mix to mix in this series. The high fines content of mixes containing silica fume resulted in "sticky" mixes that were difficult to consolidate in the cylinder molds even with external vibration.

Figures 5.11 to 5.18 show the compressive strength gain versus accelerating admixture for mixes containing separated spent blasting sand and a constant amount of separated spent blasting dust. Each figure contains one compressive strength curve for each accelerating admixture used. In instances where a curve is not shown for a particular accelerating admixture, the corresponding mix did not set within 7 days after casting and was not tested for compressive strength.

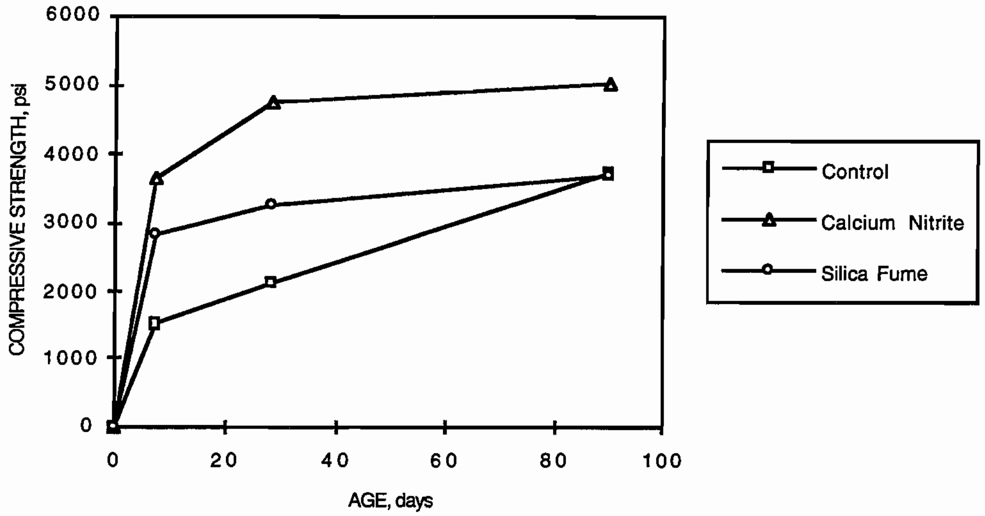

Figure 5.11: Compressive Strength for 213 kg (470 lbs) Cement Content Mixes Containing No Separated Spent Blasting Dust With No Admixtures, With Calcium Nitrite, and With Silica Fume

Figure 5.11 shows the compressive strength gain for medium cement content mixes containing no separated spent blasting dust. A curve is shown for a control mix containing no accelerating admixtures, a mix containing 7.57 L (2 gallons) of calcium nitrite, and a silica fume mix containing 12 percent by weight addition to the cement. The calcium nitrite mix had the highest compressive strength at 7, 28, and 90 days after casting. The next highest compressive strength was obtained in the silica fume mix with the lowest compressive strength belonging to the control mix.

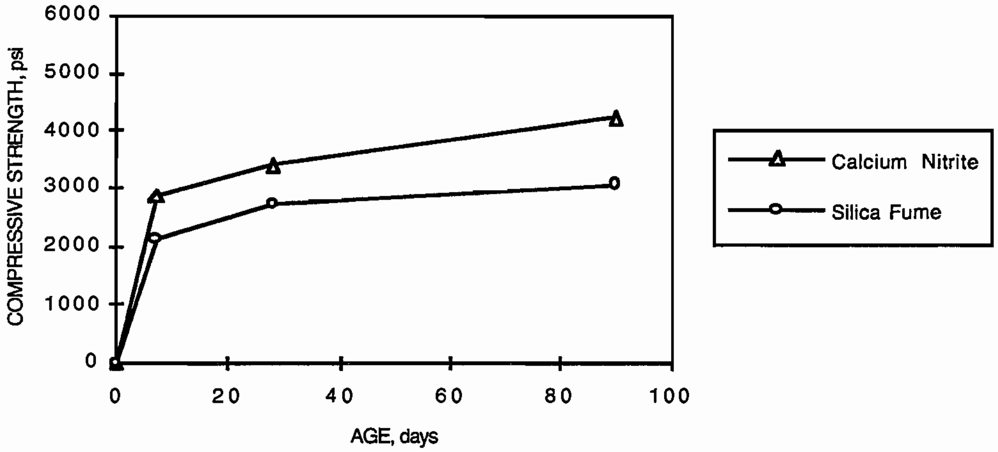

Figure 5.12: Compressive Strength for 213 kg (470 lb) Cement Content Mixes Containing 24.9 kg (55 lb) Separated Spent Blasting Dust With No Admixtures, With Calcium Nitrite, and With Silica Fume

Figure 5.12 shows the compressive strength gain for medium cement content mixes containing 24.9 kg (55 lb) separated spent blasting dust. A curve is shown for a mix containing 7.57 L (2 gallons) of calcium nitrite and a silica fume mix containing 12 percent by weight addition to the cement. The calcium nitrite mix had the highest compressive strength at 7, 28, and 90 days after casting followed by the silica fume mix. The control mix which contained no accelerating admixtures did not set within 7 days after casting.

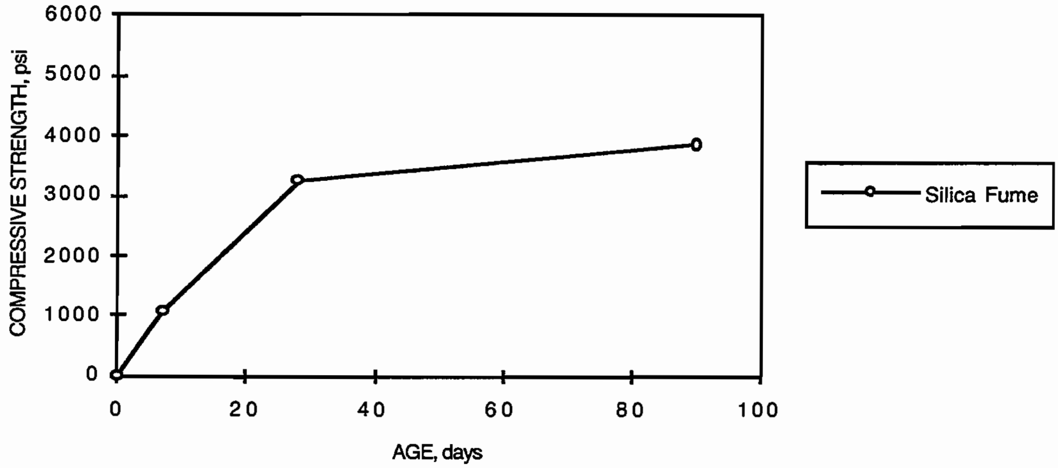

Figure 5.13: Compressive Strength for 213 kg (470 lb) Cement Content Mixes Containing 74.8 kg (165 lb) Separated Spent Blasting Dust With No Admixtures, With Calcium Nitrite, and With Silica Fume

Figure 5.13 shows the compressive strength gain for medium cement content mixes containing 74.8 kg (165 lb) separated spent blasting dust. A curve is shown for a silica fume mix containing 12 percent by weight addition to the cement. The silica fume mix was the only one of the three mixes to set within 7 days after casting.

No figure is shown for the compressive strength gain for medium cement content mixes containing 124.7 kg (275 lb) separated spent blasting dust. These mixes consisted of a control mix containing no accelerating admixtures, a mix containing 7.57 L (2 gallons) of calcium nitrite, and a silica fume mix containing 12 percent by weight addition to the cement. None of the three mixes set within 7 days after casting and were therefore not tested for compressive strength.

Figure 5.14 shows the compressive strength gain for high cement content mixes containing 0 kg (0 lb) separated spent blasting dust. A curve is shown for a control mix containing no accelerating admixtures, a mix containing 7.57 L (2 gallons) of calcium nitrite, and a silica fume mix containing 12 percent by weight addition to the cement. The calcium nitrite mix had the highest compressive strength at 7, 28, and 90 days after casting. The next highest compressive strength was obtained in the control mix with the lowest compressive strength being obtained in the silica fume mix.

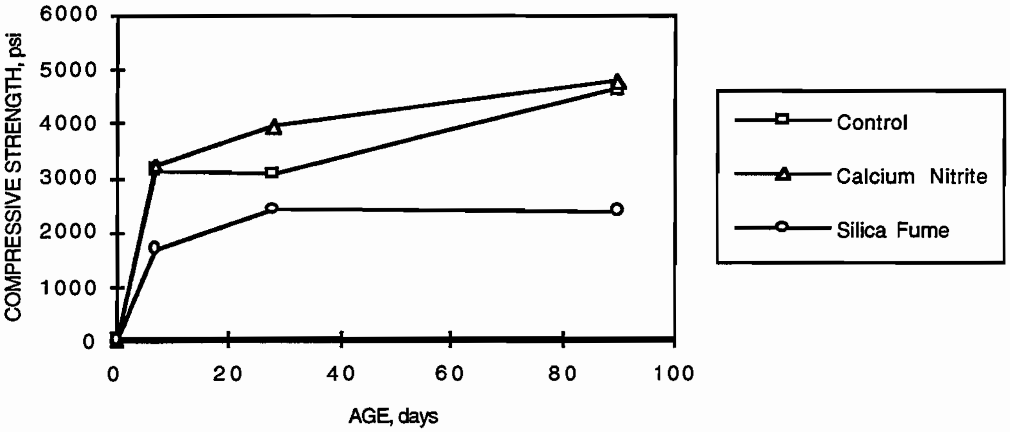

Figure 5.14: Compressive Strength for 320 kg (705 lb) Cement Content Mixes Containing No Separated Spent Blasting Dust With No Admixtures, With Calcium Nitrite, and With Silica Fume

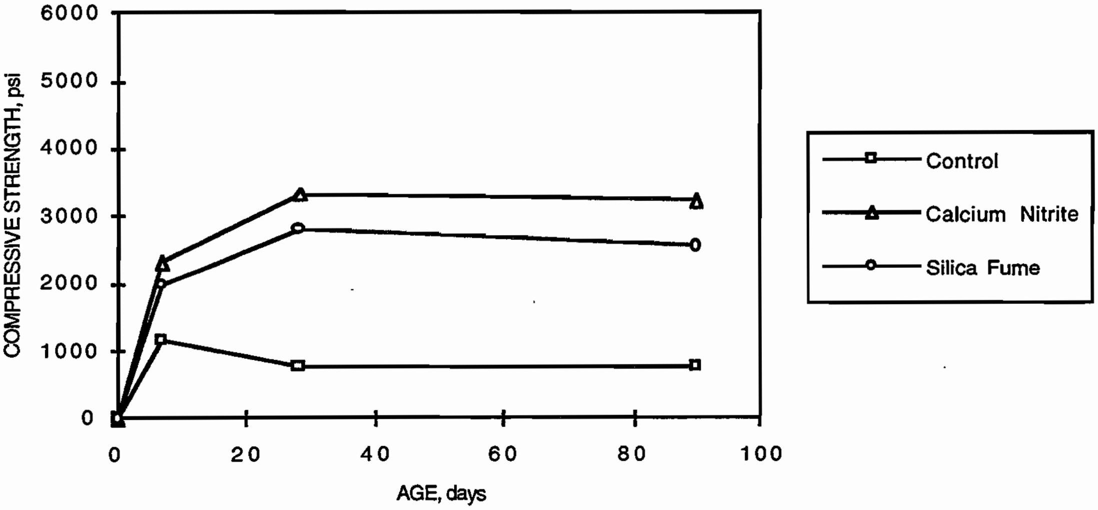

Figure 5.15: Compressive Strength for 320 kg (705 lb) Cement Content Mixes Containing 24.9 kg (55 lb) Separated Spent Blasting Dust With No Admixtures, With Calcium Nitrite, and With Silica Fume

Figure 5.15 shows the compressive strength gain for high cement content mixes containing 24.9 kg (55 lb) separated spent blasting dust. A curve is shown for a control mix containing no accelerating admixtures, a mix containing 7.57 L (2 gallons) of calcium nitrite, and a silica fume mix containing 12 percent by weight addition to the cement. The calcium nitrite mix had the highest compressive strength at 7, 28, and 90 days after casting, followed by the silica fume mix. The control mix with no accelerating admixtures had the lowest compressive strength.

Figure 5.16 shows the compressive strength gain for high cement content mixes containing 74.8 kg (165 lb) separated spent blasting dust. A curve is shown for a silica fume mix containing 12 percent by weight addition to the cement. The silica fume mix was the only one of the three mixes to set within 7 days after casting.

Figure 5.17 shows the compressive strength gain for high cement content mixes containing 124.7 kg (275 lb) separated spent blasting dust. A curve is shown for a silica fume mix containing 12 percent by weight addition to the cement. The silica fume mix was the only one of the three mixes to set within 7 days after casting.

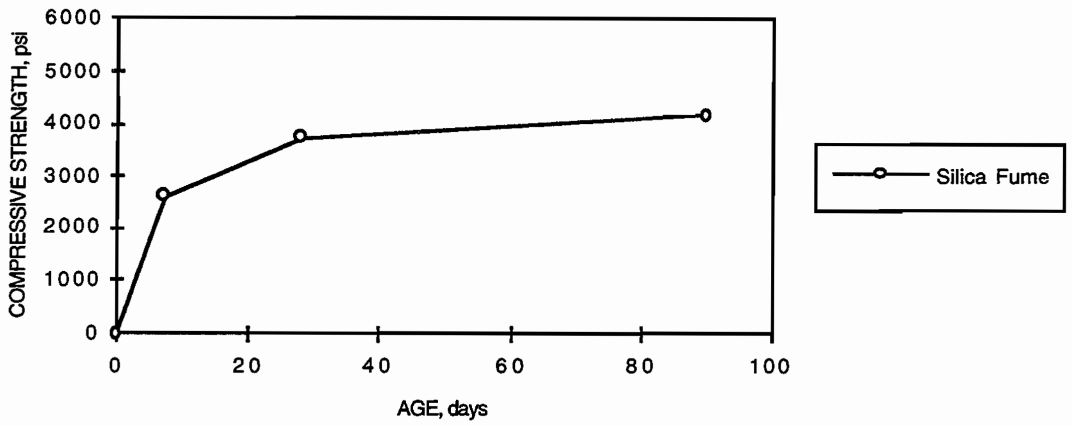

Figure 5.16: Compressive Strength for 320 kg (705 lb) Cement Content Mixes Containing 74.8 kg (165 lb) Separated Spent Blasting Dust With No Admixtures, With Calcium Nitrite, and With Silica Fume

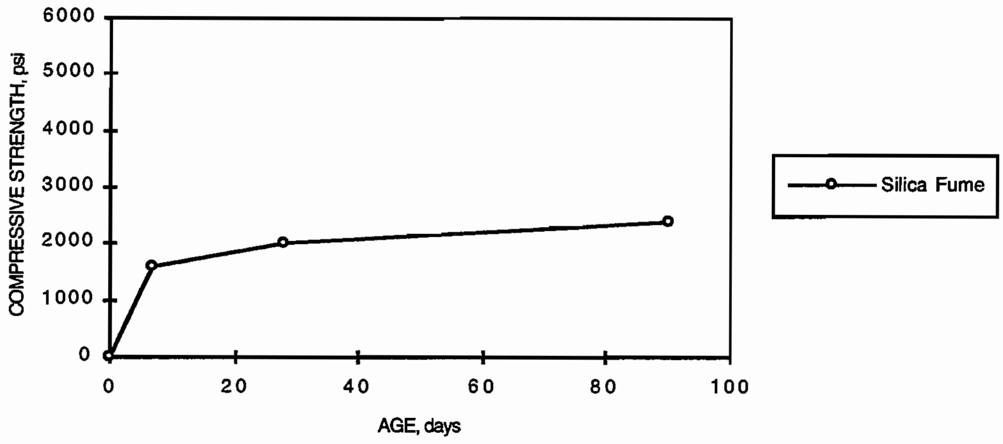

Figure 5.17: Compressive Strength for 320 kg (705 lb) Cement Content Mixes Containing 124.7 kg (275 lb) Separated Spent Blasting Dust With No Admixtures, With Calcium Nitrite, and With Silica Fume

5.3.2 Mixes Containing Unseparated Spent Blasting Sand/Dust

Figures 5.18 and 5.19 show the compressive strength gain versus accelerating admixture for mixes containing unseparated spent blasting sand/dust. Each figure contains one compressive strength curve for each type and amount of accelerating admixture used. All mixes containing unseparated spent blasting sand/dust set within 24 hours after casting. Accelerating admixtures were used in this series of mixes to increase the rate of compressive strength gain at early ages.

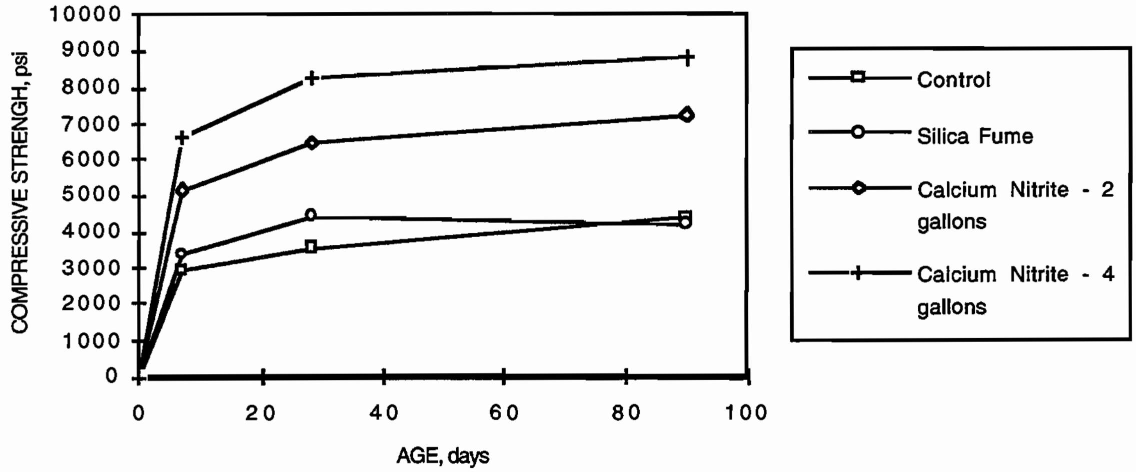

Figure 5.18: Compressive Strength for Unseparated Spent Sand/Dust Mixes with 213 kg (470 lb) Cement Content With No Admixtures, With Calcium Nitrite, and With Silica Fume

Figure 5.18 shows the compressive strength gain versus accelerating admixture for unseparated spent blasting sand/dust mixes with a medium cement content. These mixes contained 499 kg (1100 lb) of unseparated spent blasting sand/dust, 213 kg (470 lb) of portland cement, superplasticizer, and a water/cement ratio by weight of 0.35. A curve is shown for a control mix containing no accelerating admixtures, a silica fume mix containing 12 percent by weight addition to the cement, a mix containing 7.57 L (2 gallons) of calcium nitrite, and a mix containing 15.14 L (4 gallons) of calcium nitrite. The highest compressive strength was obtained in the mix containing 15.14 L (4 gallons) of calcium nitrite followed by the mix containing 7.57 L (2 gallons) of calcium nitrite. The mix containing silica fume had only a slightly higher compressive strength than the control mix containing no accelerating admixtures.

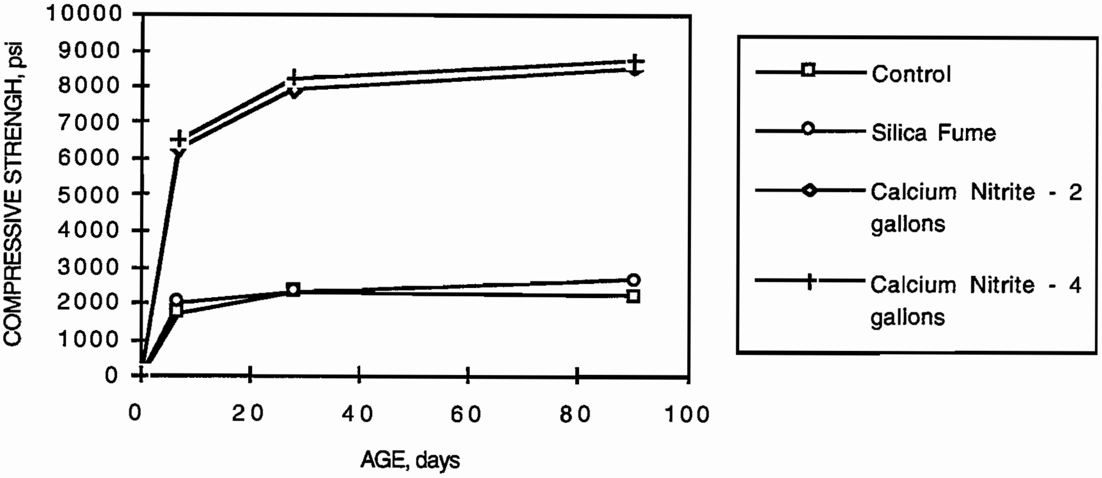

Figure 5.19: Compressive Strength for Unseparated Spent Sand/Dust Mixes with 320 kg (705 lb) Cement Content With No Admixtures, With Calcium Nitrite, and With Silica Fume

Figure 5.19 shows the compressive strength gain versus accelerating admixture for unseparated spent blasting sand/dust mixes with a high cement content. These mixes contained 499 kg (1100 lb) of unseparated spent blasting sand/dust, 320 kg (705 lb) of portland cement, superplasticizer, and a water/cement ratio by weight of 0.35. A curve is shown for a control mix containing no accelerating admixtures, a silica fume mix containing 12 percent by weight addition to the cement, a mix containing 7.57 L (2 gallons) of calcium nitrite, and a mix containing 15.14 L (4 gallons) of calcium nitrite. The highest compressive strengths were obtained in the mixes containing 7.57 L (2 gallons) and 15.14 L (4 gallons) of calcium nitrite. Unlike the 213 kg (470 lb) cement content mixes, the 15.14 L (4 gallon) calcium nitrite mix had a compressive strength only slightly higher than the 7.57 L (2 gallon) calcium nitrite mix. This can most likely be attributed to the use of a constant amount of calcium nitrite in each batch, rather than a constant ratio of calcium nitrite to cement. When the cement content was increased and the amount of calcium nitrite was held constant, the lower calcium nitrite/cement ratio in the higher cement content mixes resulted in a decrease in the accelerating effects. Similar to the medium cement content mixes, the mix containing silica fume had only a slightly higher compressive strength than the control mix containing no accelerating admixtures.

Comparing Figures 5.18 and 5.19, there was no significant difference in compressive strength between the medium and high cement content mixes containing 15.14 L (4 gallons) of calcium nitrite. However, the compressive strength for the high cement content mix containing 7.57 L (2 gallons) of calcium nitrite was higher than the corresponding medium cement content mix. The compressive strengths for the high cement content mix containing no accelerating admixtures and the high cement content mix containing silica fume were lower than those for the corresponding medium cement content mixes.

5.3.3 Mixes Containing Concrete Sand and Separated Spent Blasting Dust

Figure 5.20 to 5.22 show the compressive strength versus contamination level for mixes containing concrete sand and separated spent blasting dust. Similar to the mixes containing separated spent blasting sand and separated spent blasting dust, these mixes contained a constant amount of 499 kg (1100 lb) of concrete sand with varying amounts of separated spent blasting dust. Four control mixes with increasing spent blasting dust contents, no accelerating admixtures, a high cement content of 320 kg (705 lb), superplasticizer, and a water/cement ratio by weight of 0.35 were made. Corresponding mixes containing sodium silicate as an accelerating admixture were made. Sodium silicate/cement ratios of 2 percent and 4 percent by weight were used.

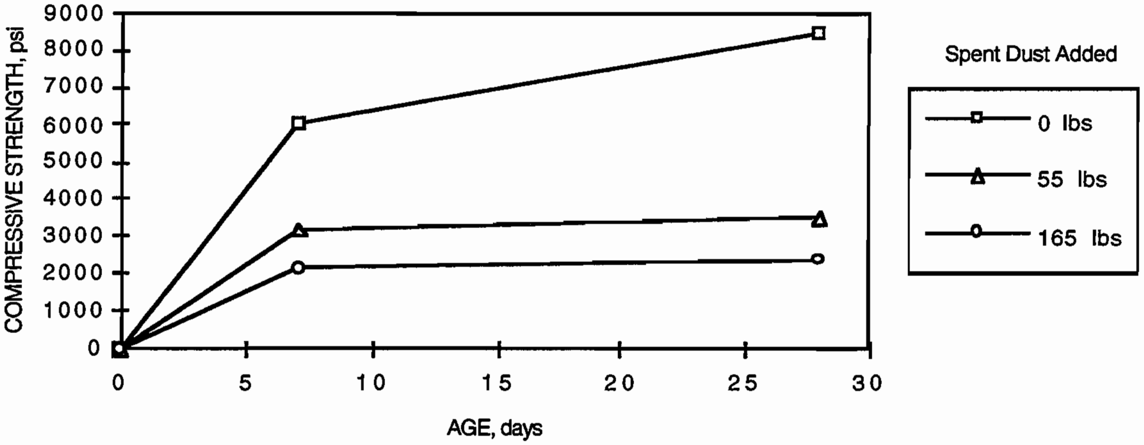

Figure 5.20: Compressive Strength for Concrete Sand/Separated Spent Dust Control Mixes

Figure 5.20 shows the compressive strength gain versus contamination level for concrete sand/separated spent dust mixes with a high cement content and no sodium silicate. The compressive strength for the mix containing no separated spent dust was very high as the mix contained no contamination from spent blasting abrasives. However, the mixes containing 24.9 kg (55 lb) and 74.8 kg (165 lb) of separated spent dust had decreasing compressive strength with increasing separated spent dust content. The mix containing 124.7 kg (275 lb) of separated spent dust did not set within 7 days after casting.

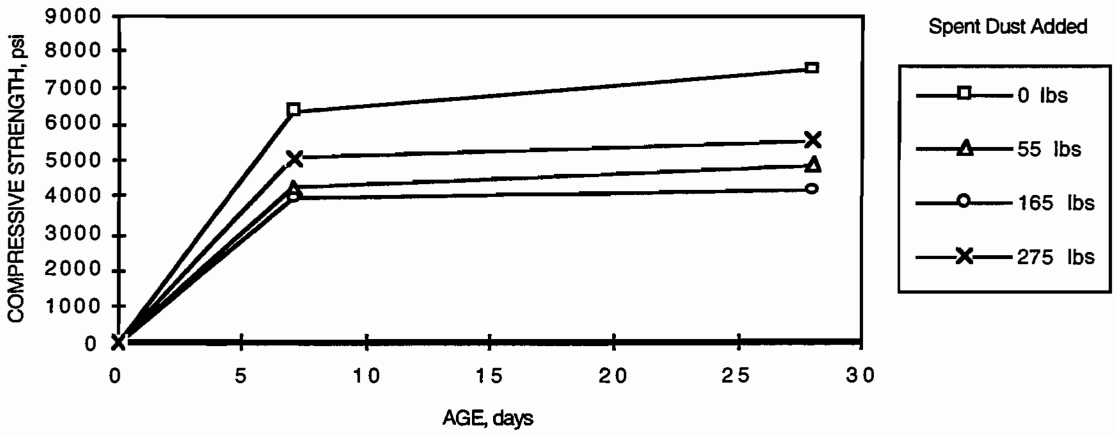

Figure 5.21: Compressive Strength for Concrete Sand/Separated Spent Dust Mixes Containing 2 Percent Sodium Silicate

Figure 5.21 shows the compressive strength gain versus contamination level for concrete sand/separated spent dust mixes with a high cement content and a 2 percent by weight sodium silicate/cement ratio. Similar to the control mix, the compressive strength for the mix containing no separated spent dust was high as the mix contained no contamination from spent blasting abrasives. The mix containing 124.7 kg (275 lb) of separated spent dust had slightly higher compressive strength than the mixes containing 24.9 kg (55 lb) and 74.8 kg (165 lb) of separated spent dust.

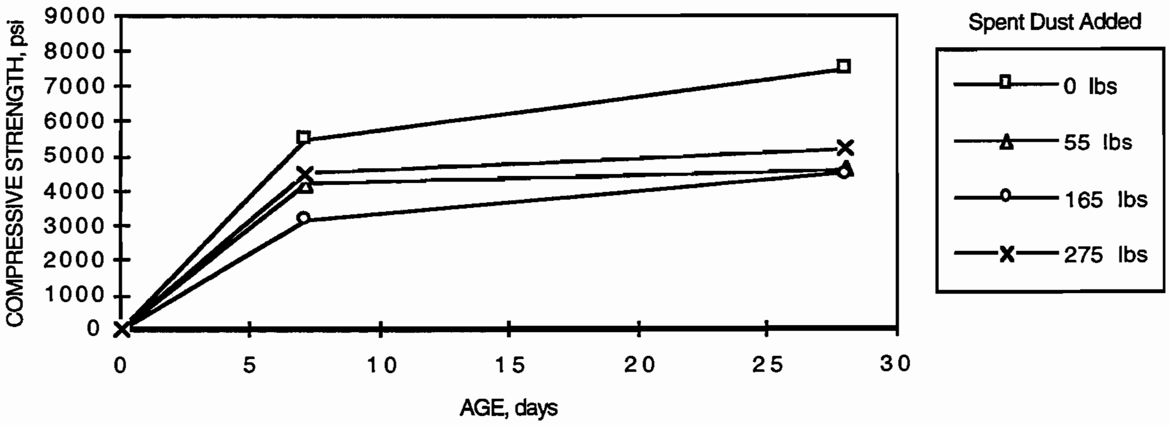

Figure 5.22: Compressive Strength for Concrete Sand/Separated Spent Dust Mixes Containing 4 Percent Sodium Silicate

Figure 5.22 shows the compressive strength gain versus contamination level for concrete sand/separated spent dust mixes with a high cement content and a 4 percent by weight sodium silicate/cement ratio. Similar to the control mix, the compressive strength for the mix containing no separated spent dust was also high as the mix contained no contamination from spent blasting abrasives. Similar to the 2 percent by weight sodium silicate mix, the mix containing 124.7 kg (275 lb) of separated spent dust had slightly higher compressive strength than the mixes containing 24.9 kg (55 lb) and 74.8 kg (165 lb) of separated spent dust.

Figure 5.23 shows the compressive strength gain versus dosage of sodium silicate for concrete sand/separated spent dust mixes containing no separated spent dust. Compressive strengths were high, as the mixes contained no spent blasting abrasives. The control mix containing no sodium silicate had the highest compressive strength at 28 days after casting. The 2 percent and 4 percent by weight sodium silicate mixes had no significant difference in compressive strength at 28 days after casting.

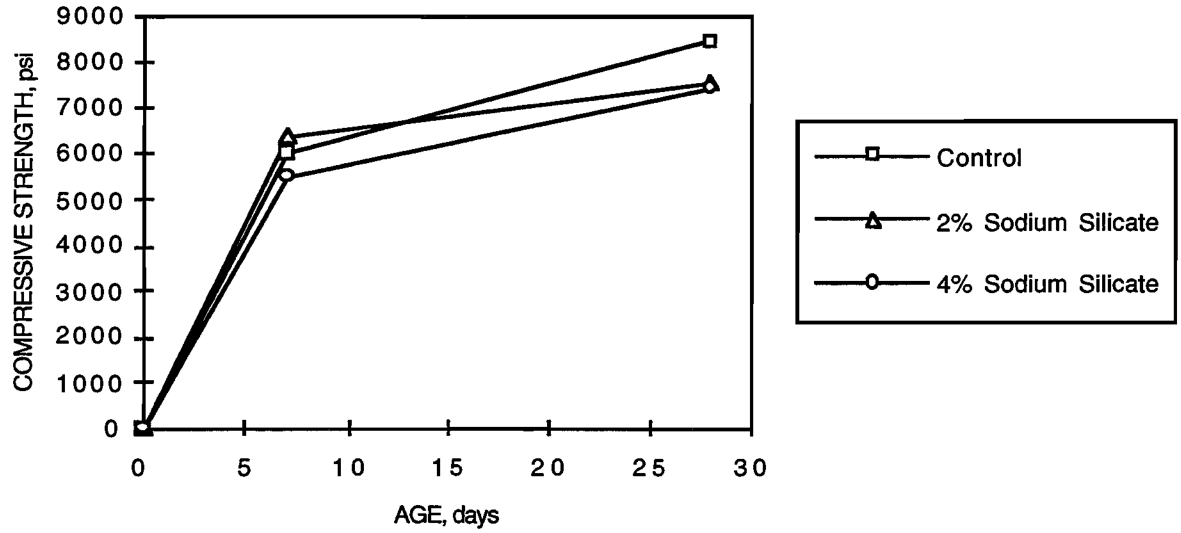

Figure 5.23: Compressive Strength for Concrete Sand/Separated Spent Dust Mixes Containing No Separated Spent Dust and Sodium Silicate

Figure 5.24 shows the compressive strength gain versus dosage of sodium silicate for concrete sand/separated spent dust mixes containing 24.9 kg (55 lb) separated spent dust. The 2 percent by weight sodium silicate mix had a compressive strength only slightly higher than the 4 percent by weight sodium silicate mix at both 7 and 28 days after casting. However, the compressive strength of both the sodium silicate mixes were higher than the control mix containing no sodium silicate.

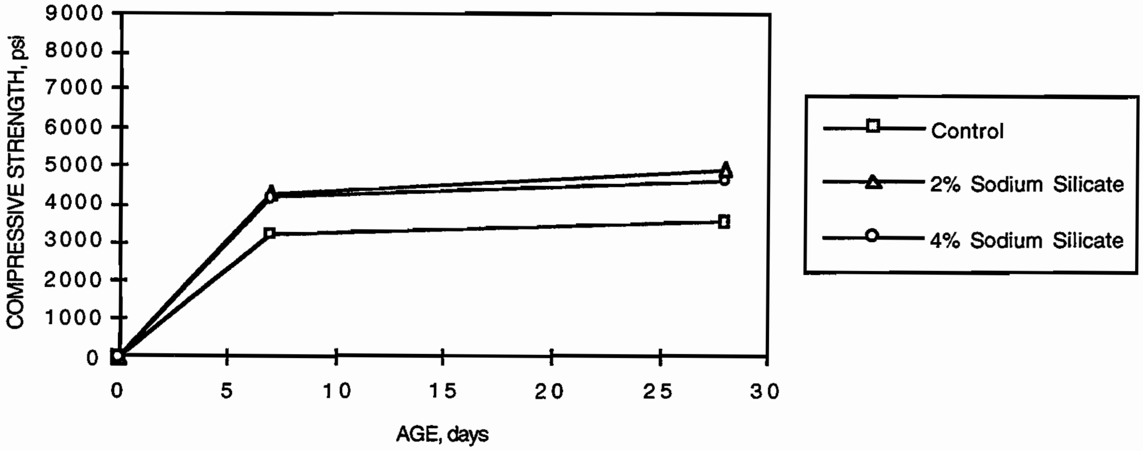

Figure 5.24: Compressive Strength for Concrete Sand/Separated Spent Dust Mixes Containing 24.9 kg (55 lb) Separated Spent Dust and Sodium Silicate

Figure 5.25 shows the compressive strength gain versus dosage of sodium silicate for concrete sand/separated spent dust mixes containing 74.8 kg (165 lb) separated spent dust. The 2 percent by weight sodium silicate mix had a compressive strength only slightly higher than the 4 percent by weight sodium silicate mix at 7 days after casting. However, the 4 percent by weight sodium silicate mix had a higher compressive strength than the 2 percent by weight sodium silicate mix at 28 days after casting. The compressive strength of both the sodium silicate mixes were higher than the control mix containing no sodium silicate.

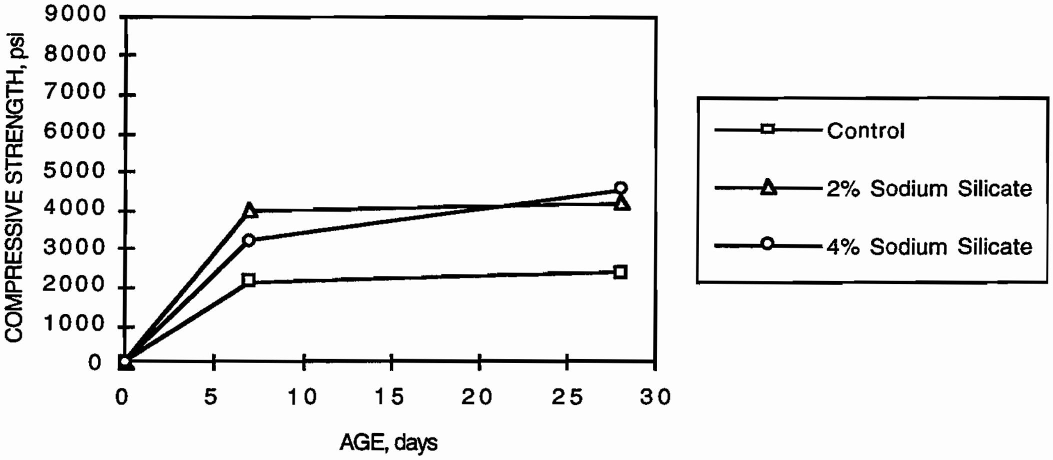

Figure 5.25: Compressive Strength for Concrete Sand/Separated Spent Dust Mixes Containing 74.8 kg (165 lb) Separated Spent Dust and Sodium Silicate

Figure 5.26 shows the compressive strength gain versus dosage of sodium silicate for concrete sand/separated spent dust mixes containing 124.7 kg (275 lb) separated spent dust. The 2 percent by weight sodium silicate mix had a compressive strength slightly higher than the 4 percent by weight sodium silicate mix at both 7 and 28 days after casting. The corresponding control mix containing no sodium silicate did not set within 7 days after casting.

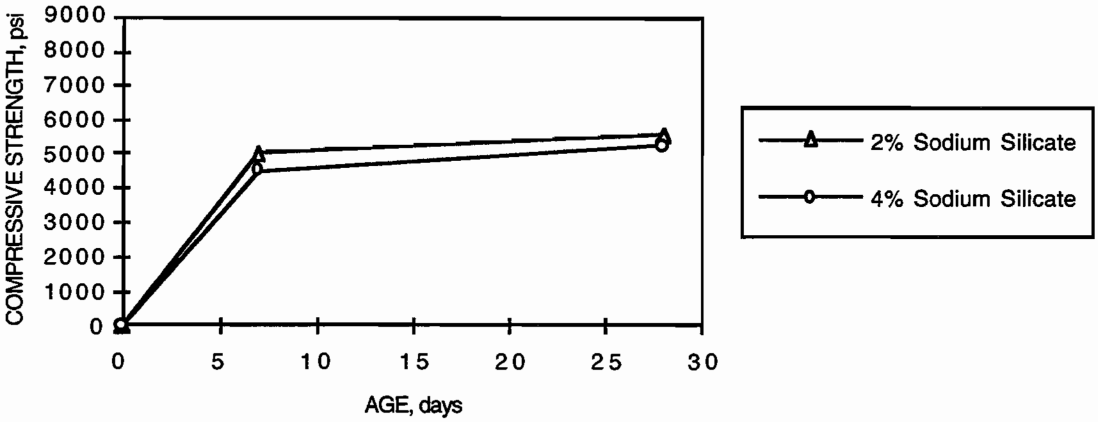

Figure 5.26: Compressive Strength for Concrete Sand/Separated Spent Dust Mixes Containing 124.7 kg (275 lb) Separated Spent Dust and Sodium Silicate

5.3.4 Mixes Containing Spent Blasting Slag

Figures 5.27 and 5.28 show the 7-day and 28-day compressive strength versus accelerating admixture for mixes containing spent blasting slag, respectively. A control mix consisting of 499 kg (1100 lb) of spent blasting slag and a high cement content of 320 kg (705 lb) was made. Corresponding mixes containing four different accelerating admixtures in two different dosages each were also made. Accelerating admixtures used were calcium nitrite, silica fume, calcium chloride, and sodium silicate.

As can be seen in Figure 5.27, the highest 7-day compressive strengths were achieved by the high dose calcium nitrite mix and both the low and high dose calcium chloride mixes. There was a considerable increase in 7-day compressive strength by increasing the amount of silica fume from 6 percent to 12 percent by weight addition to cement. However, there was only a slight increase in compressive strength by increasing the sodium silicate/cement ratio from 2 percent to 4 percent by weight.

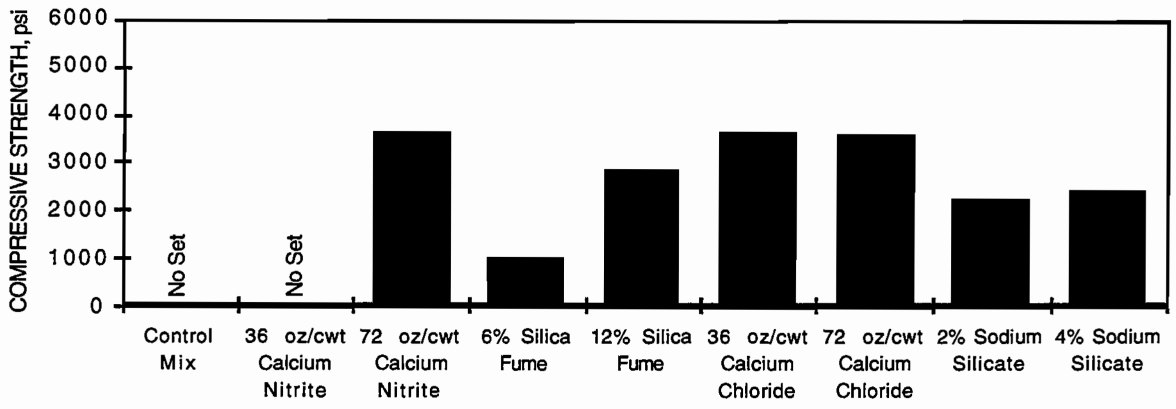

Figure 5.27: Seven-Day Compressive Strength for Spent Blasting Slag Mixes With Four Different Accelerating Admixtures

Figure 5.28 is similar to Figure 5.27 in that the highest 28-day compressive strengths were achieved by the high dose calcium nitrite mix and both the low and high dose calcium chloride mixes. However, there was a larger difference between the high dose calcium nitrite mix and the two calcium chloride mixes at 28 days after casting. The low dose calcium chloride had a slightly higher compressive strength than the high dose calcium chloride mix.

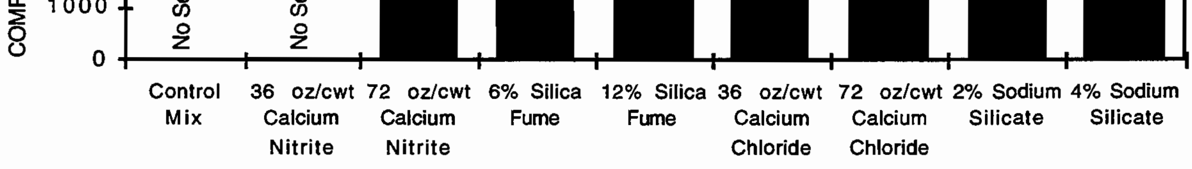

Figure 5.28: Twenty-eight-Day Compressive Strength for Spent Blasting Slag Mixes With Four Different Accelerating Admixtures

Based upon the results of these nine mixes, four additional mixes were identified for trial batching for field use. These four mixes contained accelerating admixtures in the combinations of 4 percent sodium silicate with 8 percent silica fume, 4 percent sodium silicate with 12 percent silica fume, 6 percent sodium silicate with 8 percent silica fume, and 6 percent sodium silicate with 12 percent silica fume. Figure 5.29 shows the 7-day compressive strength for these four mixes. The mix containing 4 percent sodium silicate and 12 percent silica fume had the highest compressive strength. There was no significant difference in compressive strength between the 4 percent sodium silicate/12 percent silica fume mix and the 6 percent sodium silicate/12 percent silica fume mix. However, the mix containing 6 percent sodium silicate/8 percent silica fume had a higher compressive strength than the 4 percent sodium silicate/8 percent silica fume mix.

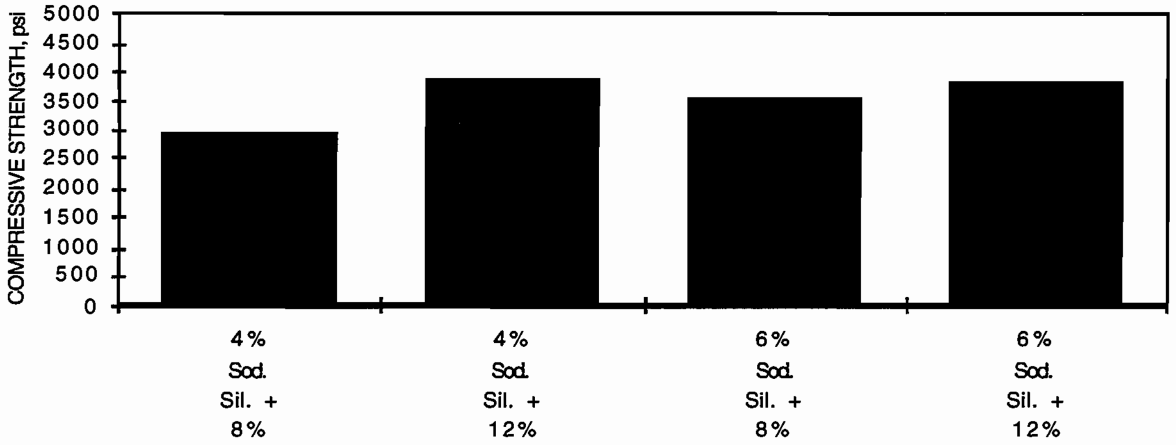

Figure 5.29: Seven-Day Compressive Strength for Spent Blasting Slag Mixes With Sodium Silicate and Silica Fume for Field Use

5.3.5 Summary of the Effect of Mix Composition on Compressive Strength

The effect of mix composition on compressive strength as investigated in this study can be stated as follows:

1) For both the separated spent blasting sand/separated spent blasting dust mixes and the unseparated spent blasting sand/dust mixes, compressive strength increased as the cement content increased.
2) For the separated spent blasting sand/separated spent blasting dust mixes, as well as for the concrete sand/separated spent blasting dust mixes, increasing the contamination level decreased the compressive strength.
3) For both the separated spent blasting sand/separated spent blasting dust mixes and the unseparated spent blasting sand/dust mixes, calcium nitrite was a more effective strength-accelerating admixture than silica fume for lesser contaminated mixes. However, for the case of the separated spent blasting sand/separated spent blasting dust

mixes, the more highly contaminated mixes that did not set with calcium nitrite did set when silica fume was used.

4) In the case of the concrete sand/separated spent blasting dust mixes, compressive strength of mixes with no contaminated spent blasting abrasives was decreased when sodium silicate was used. However, compressive strength of mixes with contaminated spent blasting abrasives was increased when sodium silicate was used.
5) In the case of the spent blasting slag mixes, silica fume, calcium nitrite, and calcium chloride provided higher compressive strength but longer set times than sodium silicate when the accelerating admixtures were used alone. However, adding silica fume to the sodium silicate mixes increased the compressive strength while still providing a short set time.

5.4 EFFECT OF MIX COMPOSITION ON PERMEABILITY

5.4.1 Mixes Containing Separated Spent Blasting Sand and Separated Spent Blasting Dust

Figures 5.30 and 5.31 show the permeability versus contamination level for mixes containing separated spent blasting sand and separated spent blasting dust. Each figure contains a permeability value for each combination of amount of separated spent blasting dust added and accelerating admixture. In instances where a value is not shown for a particular accelerating admixture and amount of separated spent blasting dust, the corresponding mix did not set within 7 days after casting and was not tested for permeability.

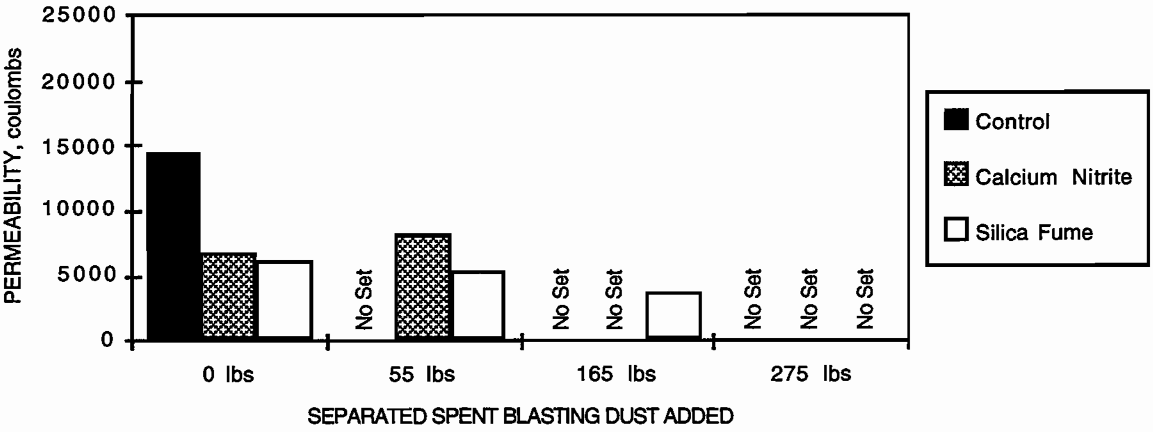

Figure 5.30: Permeability for Separated Spent Sand/Separated Spent Dust Mixes with 213 kg (470 lb) Cement Content With No Admixtures, With Calcium Nitrite, and With Silica Fume

Figure 5.30 shows the permeability of the separated spent sand/separated spent dust mixes with a medium cement content. These mixes contained 499 kg (1100 lb) of separated spent blasting sand, 213 kg (470 lb) of portland cement, superplasticizer, and a water/cement ratio by weight of 0.35. A permeability value is shown for a control mix containing no accelerating admixtures, a mix containing 7.57 L (2 gallons) of calcium nitrite, and a silica fume mix containing 12 percent by weight addition to the cement. Owing to only 50 percent of the mixes in this series setting, no clear trends were able to be seen as to the effect of contamination level on permeability for this particular series. However, Figure 5.30 does show that the permeability of the silica fume mixes was lower than either the control mixes or the calcium nitrite mixes.

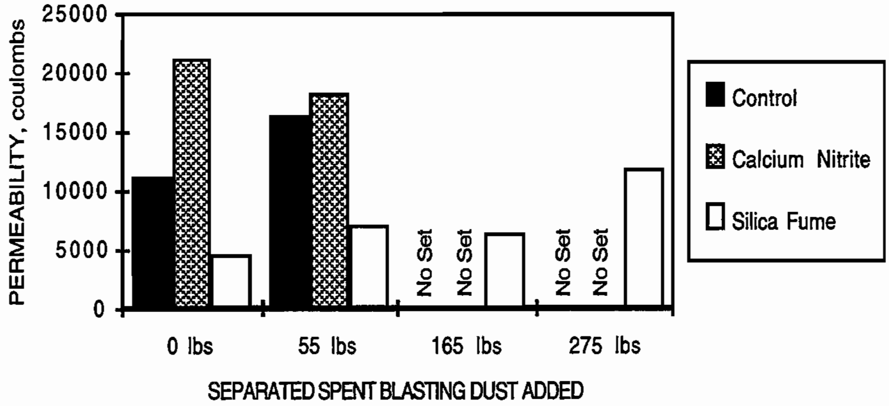

Figure 5.31: Permeability for Separated Spent Sand/Separated Spent Dust Mixes with 320 kg (705 lb) Cement Content With No Admixtures, With Calcium Nitrite, and With Silica Fume

Figure 5.31 shows the permeability of the separated spent sand/separated spent dust mixes with a high cement content. These mixes contained 499 kg (1100 lb) of separated spent blasting sand, 320 kg (705 lb) of portland cement, superplasticizer, and a water/cement ratio by weight of 0.35. A permeability value is shown for a control mix containing no accelerating admixtures, a mix containing 7.57 L (2 gallons) of calcium nitrite, and a silica fume mix containing 12 percent by weight addition to the cement. Figure 5.31 does show that the permeability of the control mixes and the silica fume mixes increased with contamination level. However, the calcium nitrite mixes did not follow this trend. As in Figure 5.30, the permeability of the silica fume mixes was lower than the control mixes and the calcium nitrite mixes.

Comparing Figures 5.30 and 5.31, the permeability of the calcium nitrite mixes and the silica fume mixes increased as the cement content increased. However, the permeability of the control mix containing no separated spent dust decreased as the cement content increased. Of the three types of mixes performed, the silica fume mixes had the lowest permeability.

According to ASTM C 1202, “Standard Test Method for Electrical Indication of Concrete’s Ability to Resist Chloride Ion Penetration,” a specification which is similar to AASHTO T 277, “Rapid Determination of the Chloride Permeability of Concrete,” misleading permeability results can be obtained for concretes containing calcium nitrite. Concretes containing calcium nitrite typically indicate higher permeabilities than identical concretes without calcium nitrite. However, ponding tests have indicated that concretes containing calcium nitrite were at least as resistant to chloride ion penetration as the concretes without calcium nitrite.

5.4.2 Mixes Containing Unseparated Spent Blasting Sand/Dust

Figure 5.32 shows the permeability versus accelerating admixture for unseparated spent blasting sand/dust mixes with a medium cement content. These mixes contained 499 kg (1100 lb) of unseparated spent blasting sand/dust, 213 kg (470 lb) of portland cement, superplasticizer, and a water/cement ratio by weight of 0.35. The permeability is shown for a control mix containing no accelerating admixtures, a silica fume mix containing 12 percent by weight addition to the cement, a mix containing 7.57 L (2 gallons) of calcium nitrite, and a mix containing 15.14 L (4 gallons) of calcium nitrite. The permeability of the portland cement mortar was very low for the mix containing silica fume. The mixes containing calcium nitrite had a lower permeability than the control mix, but the permeability increased slightly with an increase in the calcium nitrite dosage.

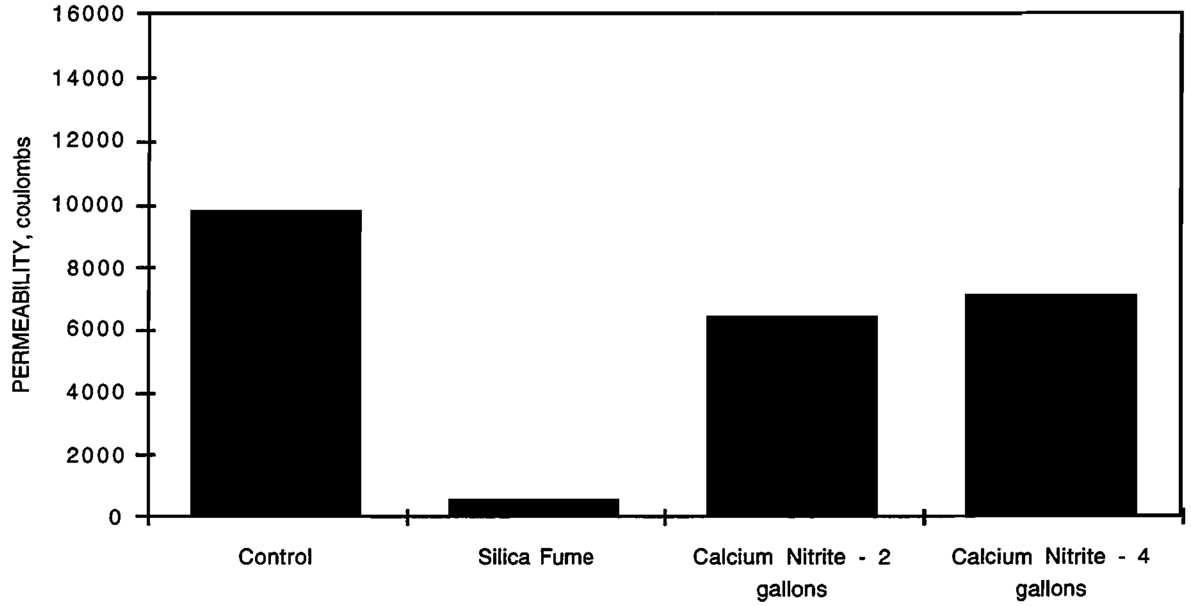

Figure 5.32: Permeability for Unseparated Spent Sand/Dust Mixes with 213 kg (470 lb) Cement Content With No Admixtures, With Calcium Nitrite, and With Silica Fume

Figure 5.33 shows the permeability versus accelerating admixture for unseparated spent blasting sand/dust mixes with a high cement content. These mixes contained 499 kg (1100 lb) of unseparated spent blasting sand/dust, 320 kg (705 lb) of portland cement, superplasticizer, and a water/cement ratio by weight of 0.35. Similar to the medium cement content mixes, the permeability is shown for a control mix containing no accelerating admixtures, a silica fume mix containing 12 percent by weight addition to the cement, a mix containing 7.57 L (2 gallons) of calcium nitrite, and a mix containing 15.14 L (4 gallons) of calcium nitrite. Similar to the medium cement content mixes, the permeability of the portland cement mortar was lowest for the mix containing silica fume. The mixes containing calcium nitrite also had a lower permeability than the control mix, but the permeability increased slightly with an increase in the calcium nitrite dosage.

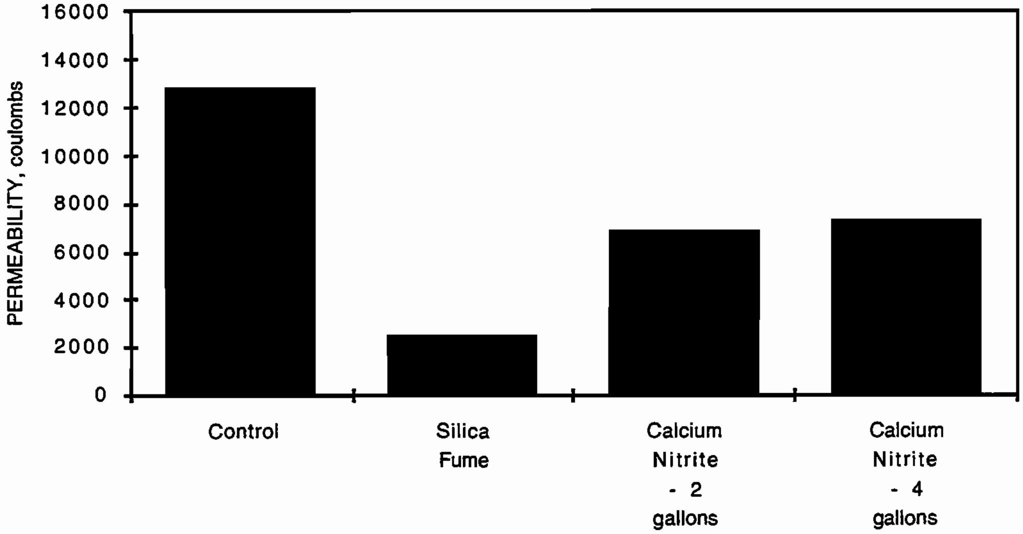

Figure 5.33: Permeability for Unseparated Spent Sand/Dust Mixes with 320 kg (705 lb) Cement Content With No Admixtures, With Calcium Nitrite, and With Silica Fume

Comparing Figures 5.32 and 5.33, similar trends in permeability were observed. The silica fume mixes provided the lowest permeability followed by the 7.57 L (2 gallon) calcium nitrite, 15.14 L (4 gallon) calcium nitrite, and control mixes, in order of increasing permeability. However, the permeability was increased for the four types of mixes as the cement content was increased from 213 kg (470 lb) to 320 kg (705 lb).

5.4.3 Mixes Containing Concrete Sand and Separated Spent Blasting Dust

Figure 5.34 shows the permeability versus contamination level for mixes containing concrete sand and separated spent blasting dust. These mixes contained a constant amount of 499 kg (1100 lb) of concrete sand, a high cement content of 320 kg (705 lb), superplasticizer, and a water/cement ratio by weight of 0.35. Four control mixes with increasing spent blasting dust contents and no accelerating admixtures were made. Corresponding mixes containing sodium silicate/cement ratios of 2 percent and 4 percent by weight were also made.

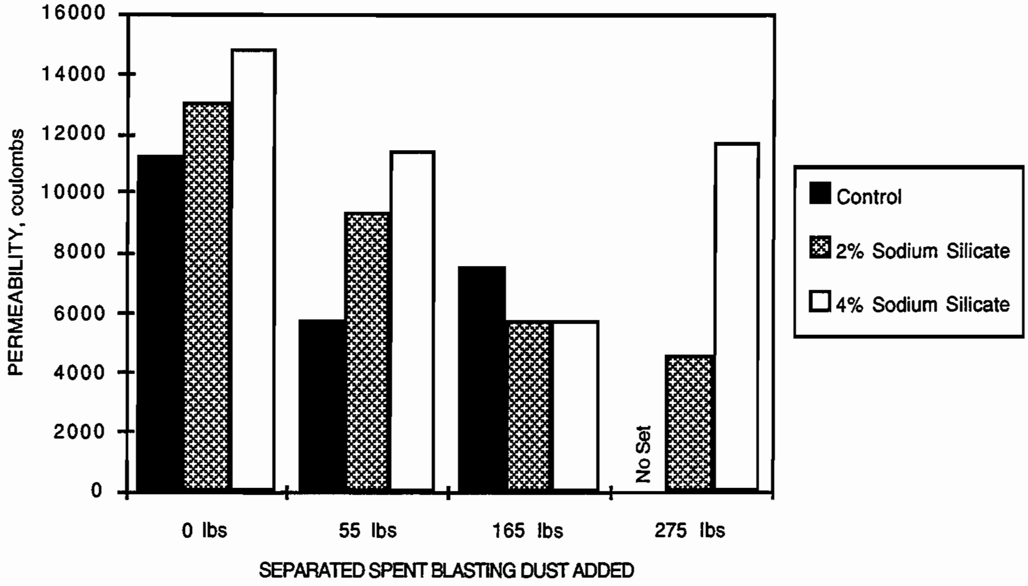

Figure 5.34: Permeability for Concrete Sand/Separated Spent Dust Mixes With Sodium Silicate

Sodium silicate was not effective in reducing the permeability of the portland cement mortars. In general, permeability increased with increasing dosage of sodium silicate. Permeability of the 2 percent by weight sodium silicate mixes decreased with increasing amounts of spent blasting dust added. A similar trend was observed in the 4 percent by weight sodium silicate mixes except for an increase in permeability for the 124.7 kg (275 lb) separated spent dust mix. No clear trend as a function of contamination level was seen for the control mixes. or for the 4 percent by weight sodium silicate mixes.

5.4.4 Mixes Containing Spent Blasting Slag

Figure 5.35 shows the permeability results versus accelerating admixture for mixes containing spent blasting slag. A control mix consisting of 499 kg (1100 lb) of spent blasting slag, a high cement content of 320 kg (705 lb), superplasticizer, and a water/cement ratio by weight of 0.35 was made. Corresponding mixes containing four different accelerating admixtures in two different dosages each were also made. Accelerating admixtures used were calcium nitrite, silica fume, calcium chloride, and sodium silicate.

As can be seen in Figure 5.35, the mix containing 12 percent by weight silica fume had a permeability much lower than the rest of the accelerating admixtures. However, silica fume added in the 6 percent by weight amount was not effective in reducing permeability. The mixes with the next lowest permeability were the 2 percent and 4 percent by weight sodium silicate mixes, with the 4 percent mix having a slightly higher permeability than the 2 percent mix. Calcium chloride and calcium nitrite were also found to be not effective in reducing the permeability of the spent blasting slag mixes.

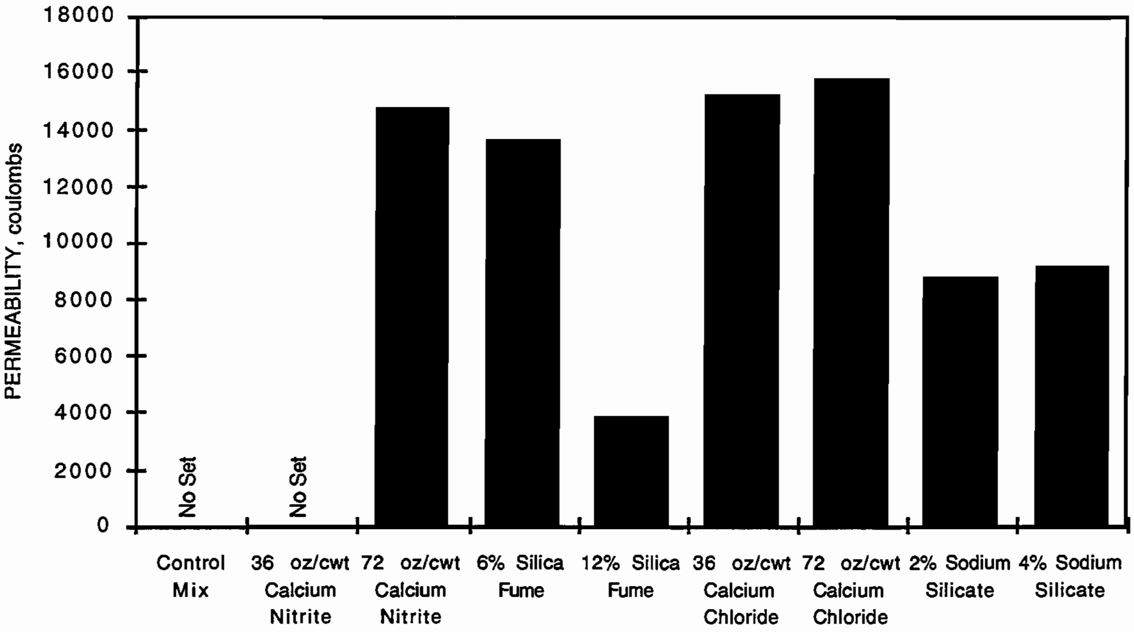

Figure 5.35: Permeability for Spent Blasting Slag Mixes With Four Different Accelerating Admixtures

Based upon the results of these nine mixes, four additional mixes were trial batched for field use. These four mixes contained accelerating admixtures in the combinations of 4 percent sodium silicate with 8 percent silica fume, 4 percent sodium silicate with 12 percent silica fume, 6 percent sodium silicate with 8 percent silica fume, and 6 percent sodium silicate with 12 percent silica fume.

As shown in Figure 5.36, the mix with the lowest permeability was the mix containing 4 percent sodium silicate and 12 percent silica fume. There was a slight decrease in permeability for the 8 percent silica fume mixes as the amount of sodium silicate was increased from 4 percent of 6 percent. However, there was a slight increase in permeability for the 12 percent silica fume mixes as the amount of sodium silicate was increased from 4 percent to 6 percent.

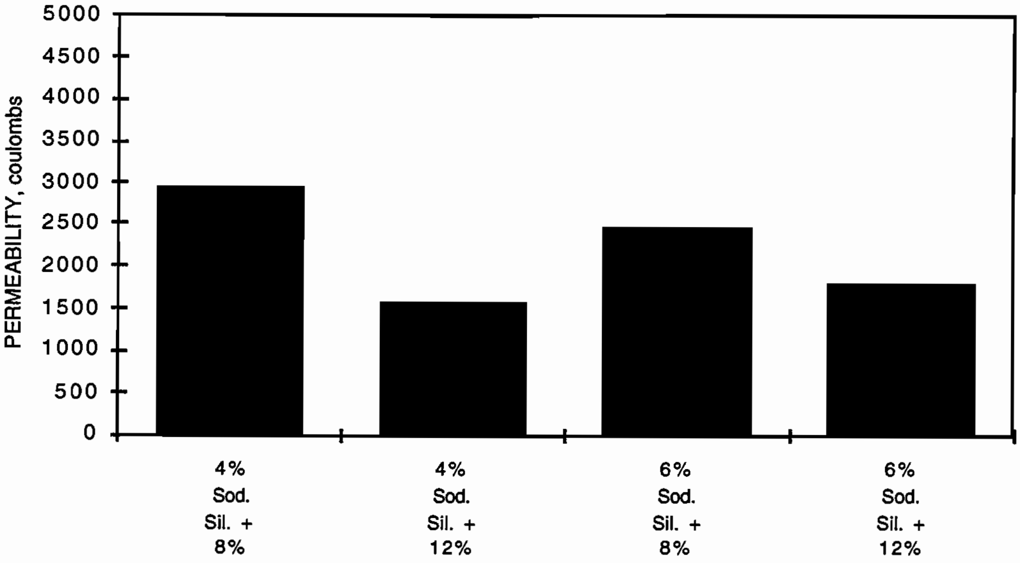

Figure 5.36: Seven-Day Permeability for Spent Blasting Slag Mixes With Sodium Silicate and Silica Fume for Field Use

5.4.5 Summary of the Effect of Mix Composition on Permeability

The effect of mix composition on permeability investigated in this study can be stated as follows:

1) For the separated spent sand/separated spent dust mixes, permeability increased with increasing cement content and contamination level. The lowest permeabilities were obtained from the mixes containing silica fume.
2) For the unseparated spent sand/dust mixes, permeability increased with increasing cement content. Similar to the separated spent sand/separated spent dust mixes, the lowest permeabilities were obtained from the mixes containing silica fume.
3) For the concrete sand/separated spent dust mixes, permeability increased with increasing amounts of sodium silicate for mixes with equal amounts of separated spent blast dust.
4) For the spent blasting slag mixes, only the mix containing 12 percent by weight silica fume was found to have its permeability lowered to reasonable levels. Calcium chloride, calcium nitrite, and sodium silicate mixes had very high permeabilities that would not be suitable for field use. However, the addition of sodium silicate to the mix containing 12 percent by weight silica fume was found to lower the permeability as compared to the 12 percent by weight silica fume mix.

5) For the spent blasting abrasives in this study, silica fume was the most effective admixture in reducing the permeability of the portland cement mortars.

5.5 EFFECT OF MIX COMPOSITION ON TCLP LEACHING

5.5.1 Mixes Containing Separated Spent Blasting Sand and Separated Spent Blasting Dust

Figures 5.37 to 5.42 show the TCLP leaching versus contamination level for mixes containing separated spent blasting sand and separated spent blasting dust. Each figure contains a TCLP leaching concentration for each metal studied and for each amount of separated spent blasting dust. Figures 5.37 to 5.42 are organized by cement content and accelerating admixture. In instances where a TCLP leaching concentration is not shown for a particular amount of separated spent blasting dust, the corresponding mix did not set within 7 days after casting and was not tested for leaching. TCLP leaching tests were performed at both 7 and 28 days after casting.

Figure 5.37 shows the TCLP leaching for separated spent sand/separated spent dust mixes with a medium cement content and no accelerating admixtures. These mixes contained 499 kg (1100 lb) of separated spent blasting sand, 213 kg (470 lb) of portland cement, superplasticizer, and a water/cement ratio by weight of 0.35. Only the mix with no separated spent dust added set within 7 days after casting.

Leaching of both the lead and cadmium was lowered substantially below the limits of 1.5 mg/L and 1.0 mg/L, respectively. While the leaching of chromium was lowered below the limit of 5.0 mg/L, it was not reduced to the same degree as the leaching of lead and cadmium. The leaching of the lead and cadmium was so low that there was no significant difference between the 7-day and 28-day TCLP leaching. However, the 28-day TCLP leaching of chromium was noticeably lower than the 7-day results.

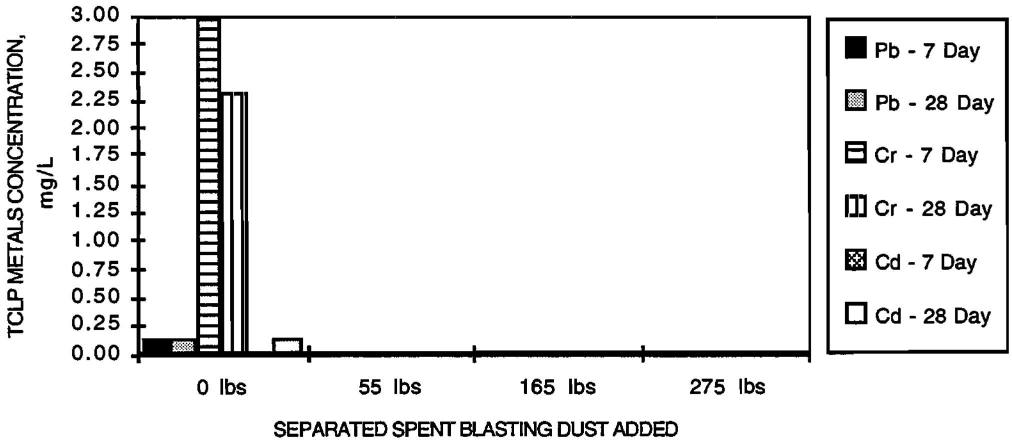

Figure 5.37: TCLP Leaching for Separated Spent Sand/Separated Spent Dust Control Mixes with 213 kg (470 lb) Cement Content

Figure 5.38 shows the TCLP leaching for separated spent sand/separated spent dust mixes with a high cement content and no accelerating admixtures. These mixes contained 499 kg (1100 lb) of separated spent blasting sand, 320 kg (705 lb) of portland cement, superplasticizer, and a water/cement ratio by weight of 0.35. Only the lesser contaminated mixes with 0 kg (0 lb) and 24.9 kg (55 lb) of separated spent dust added set within 7 days after casting.

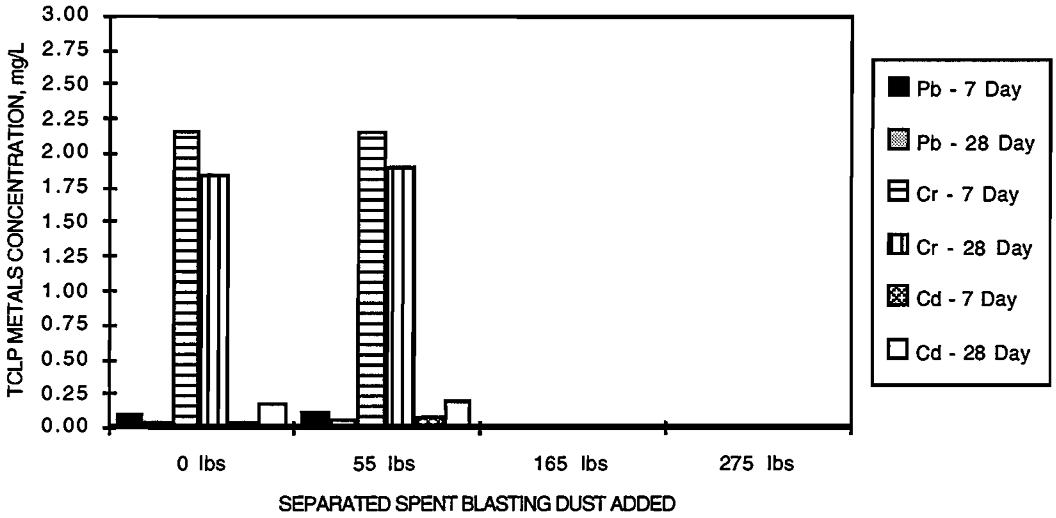

Figure 5.38: TCLP Leaching for Separated Spent Sand/Separated Spent Dust Control Mixes with 320 kg (705 lb) Cement Content

Similar to the medium cement content mixes, leaching of both the lead and cadmium was lowered substantially below the limits of 1.5 mg/L and 1.0 mg/L, respectively. While the leaching of chromium was lowered below the limit of 5.0 mg/L, it was also not reduced to the same degree as the lead and cadmium. The leaching of the lead and cadmium were so low that there was no significant difference between the 7-day and 28-day TCLP leaching. However, the 28-day TCLP leaching of chromium was lower than the 7-day results. There was also no significant difference in the leaching of lead, cadmium, or chromium between the two amounts of separated spent dust.

No significant difference was observed in the lead and cadmium leaching for the medium and high cement content mixes. However, the chromium leaching for the mix containing 0 kg (0 lb) separated spent dust was lower for the high cement content mix than for the medium cement content mix.

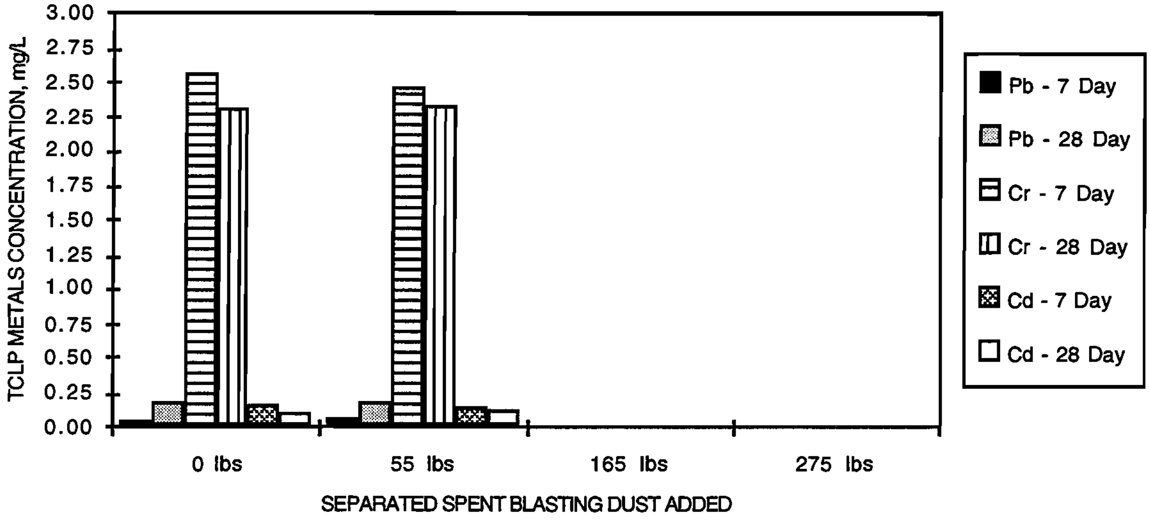

Figure 5.39: TCLP Leaching for Separated Spent Sand/Separated Spent Dust Mixes with 213 kg (470 lb) Cement Content and Calcium Nitrite

Figure 5.39 shows the TCLP leaching for separated spent sand/separated spent dust mixes with a medium cement content and calcium nitrite. These mixes contained 499 kg (1100 lb) of separated spent blasting sand, 213 kg (470 lb) of portland cement, superplasticizer, a water/cement ratio by weight of 0.35, and 7.57 L (2 gallons) of calcium nitrite. Only the lesser contaminated mixes with 0 kg (0 lb) and 24.9 kg (55 lb) of separated spent dust added set within 7 days after casting.

Similar to the control mixes, leaching of both the lead and cadmium was lowered substantially below the limits of 1.5 mg/L and 1.0 mg/L, respectively. While the leaching of chromium was lowered below the limit of 5.0 mg/L, it was also not reduced to the same degree as the lead and cadmium. The leaching of the lead and cadmium was so low that there was no significant difference between the 7-day and 28-day TCLP leaching. However, the 28-day TCLP leaching of chromium was slightly lower than the 7-day results. There was also no significant difference in the leaching of lead, cadmium, or chromium between the two amounts of separated spent dust.

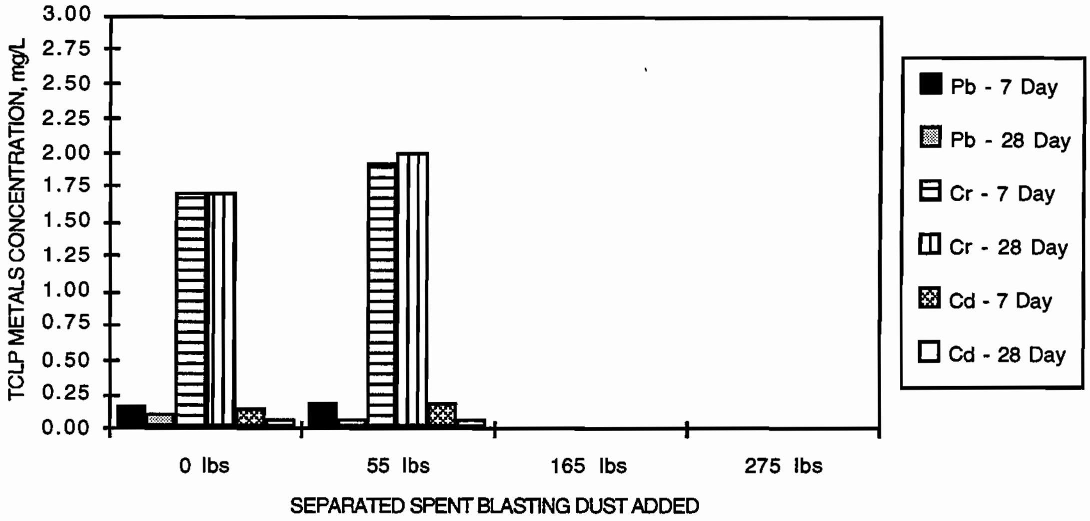

Figure 5.40: TCLP Leaching for Separated Spent Sand/Separated Spent Dust Mixes with 320 kg (705 lb) Cement Content and Calcium Nitrite

Figure 5.40 shows the TCLP leaching for separated spent sand/separated spent dust mixes with a high cement content and calcium nitrite. These mixes contained 499 kg (1100 lb) of separated spent blasting sand, 320 kg (705 lb) of portland cement, superplasticizer, a water/cement ratio by weight of 0.35, and 7.57 L (2 gallons) of calcium nitrite. Only the lesser contaminated mixes with 0 kg (0 lb) and 24.9 kg (55 lb) of separated spent dust added set within 7 days after casting.

Similar to the control mixes, leaching of both the lead and cadmium was lowered substantially below the limits of 1.5 mg/L and 1.0 mg/L, respectively. While the leaching of chromium was lowered below the limit of 5.0 mg/L, it was also not reduced to the same degree as the lead and cadmium. The leaching of the lead and cadmium were so low that there was no significant difference between the 7-day and 28-day TCLP leaching. Unlike the control mixes, there was not as large of a difference between the 7-day and 28-day TCLP leaching of chromium. There was no significant difference in the leaching of lead and cadmium between the two amounts of separated spent dust. However, the leaching of the chromium increased slightly with the increase in the amount of separated spent blasting dust.

No significant difference was observed in the lead and cadmium leaching for the medium and high cement content mixes. However, the chromium leaching for the mixes containing both 0 kg (0 lb) and 24.9 kg (55 lb) separated spent dust was lower for the high cement content mixes than for the medium cement content mixes.

Figure 5.41 shows the TCLP leaching for separated spent sand/separated spent dust mixes with a medium cement content and silica fume. These mixes contained 499 kg (1100 lb) of separated spent blasting sand, 213 kg (470 lb) of portland cement, superplasticizer, a water/cement ratio by weight of 0.35, and silica fume in the amount of 12 percent by weight addition to cement. The mix with 124.7 kg (275 lb) of separated spent dust added did not set within 7 days after casting.

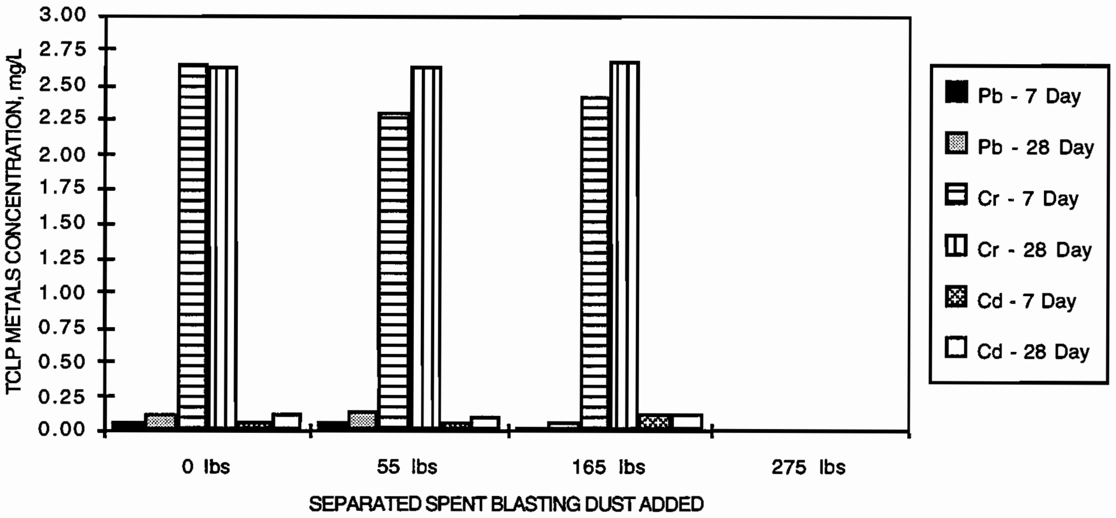

Figure 5.41: TCLP Leaching for Separated Spent Sand/Separated Spent Dust Mixes with 213 kg (470 lb) Cement Content and Silica Fume

Similar to the control and calcium nitrite mixes, leaching of both the lead and cadmium was lowered substantially below the limits of 1.5 mg/L and 1.0 mg/L, respectively. While the leaching of chromium was lowered below the limit of 5.0 mg/L, it was approximately at the same levels as observed in the control and calcium nitrite mixes. The leaching of the lead and cadmium were so low that there was no significant difference between the 7-day and 28-day TCLP leaching. The 28-day TCLP leaching of chromium for the mix containing 0 kg (0 lb) of separated spent dust was approximately the same as the 7-day results. However, the 28-day TCLP leaching of chromium for the mixes containing 24.9 kg (55 lb) and 74.8 kg (165 lb) of separated spent dust were higher than the 7-day results. There was also no significant difference in the leaching of lead, cadmium, or chromium between the three amounts of separated spent dust.

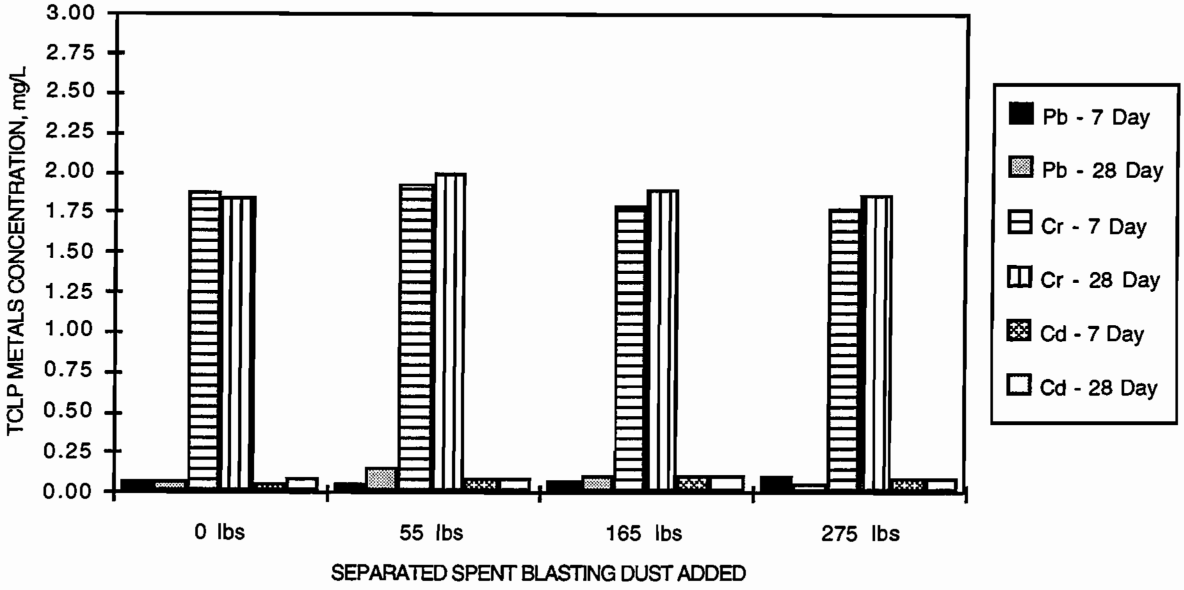

Figure 5.42: TCLP Leaching for Separated Spent Sand/Separated Spent Dust Mixes with 320 kg (705 lb) Cement Content and Silica Fume

Figure 5.42 shows the TCLP leaching for separated spent sand/separated spent dust mixes with a high cement content and silica fume. These mixes contained 499 kg (1100 lb) of separated spent blasting sand, 320 kg (705 lb) of portland cement, superplasticizer, a water/cement ratio by weight of 0.35, and silica fume in the amount of 12 percent by weight addition to cement.

Similar to the control and calcium nitrite mixes, leaching of both the lead and cadmium was lowered substantially below the limits of 1.5 mg/L and 1.0 mg/L, respectively. While the leaching of chromium was lowered below the limit of 5.0 mg/L, it was approximately at the same levels as observed in the control and calcium nitrite mixes. The leaching of the lead and cadmium were so low that there was no significant difference between the 7-day and 28-day TCLP leaching. The 28-day TCLP leaching of chromium for the mix containing 0 lbs (0 kg) of separated spent dust was approximately the same as the 7-day results. However, the 28-day TCLP leaching of chromium for the mixes containing 24.9 kg (55 lb), 74.8 kg (165 lb), and 124.7 kg (275 lb) of separated spent dust were slightly higher than the 7-day results. There was also no significant difference in the leaching of lead, cadmium, or chromium between the four amounts of separated spent dust.

Figures 5.43 to 5.46 compare the TCLP leaching of lead and cadmium versus contamination level and accelerating admixture for separated spent sand/separated spent dust mixes. Fluctuations in the leaching of these two metals appear to be somewhat random in nature. No correlation is apparent between TCLP leaching of lead and cadmium as a function of parameters such as contamination level, cement content, or type of accelerating admixture. TCLP leaching of lead and cadmium are lowered significantly below the limits of 1.5 mg/L and 1.0

mg/L, respectively, regardless of the type of mix used. Also, the TCLP leaching of lead and cadmium are either below or very close to the test method detection limits of 0.07 mg/L and 0.02 mg/L, respectively. Therefore, the differences between individual leaching values may be within the error that can be subscribed to slight differences in mixing the mortars or performing the TCLP test.

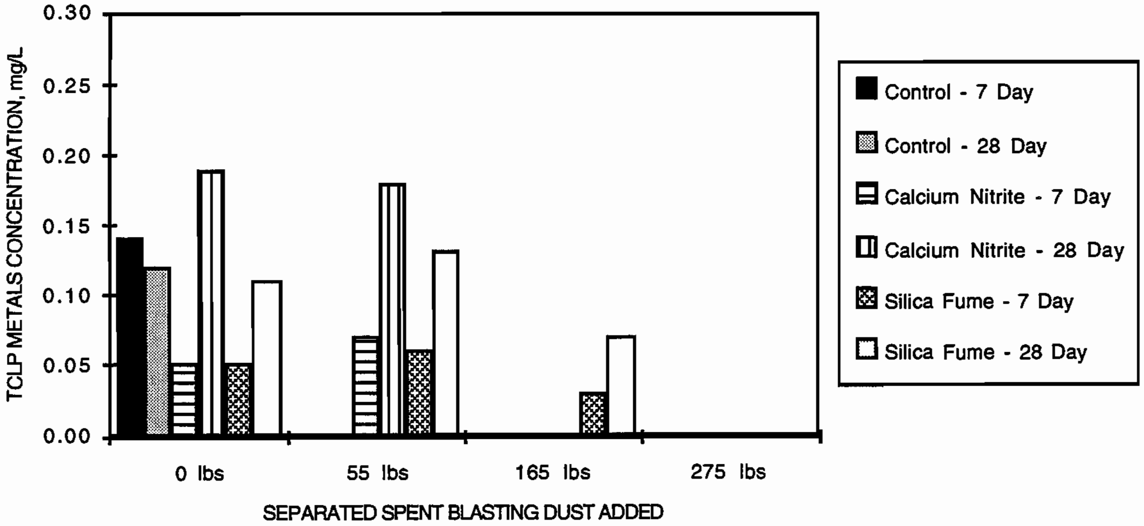

Figure 5.43: TCLP Lead Leaching for Separated Spent Sand/Separated Spent Dust Mixes with 213 kg (470 lb) Cement Content With No Admixtures, With Calcium Nitrite, and With Silica Fume

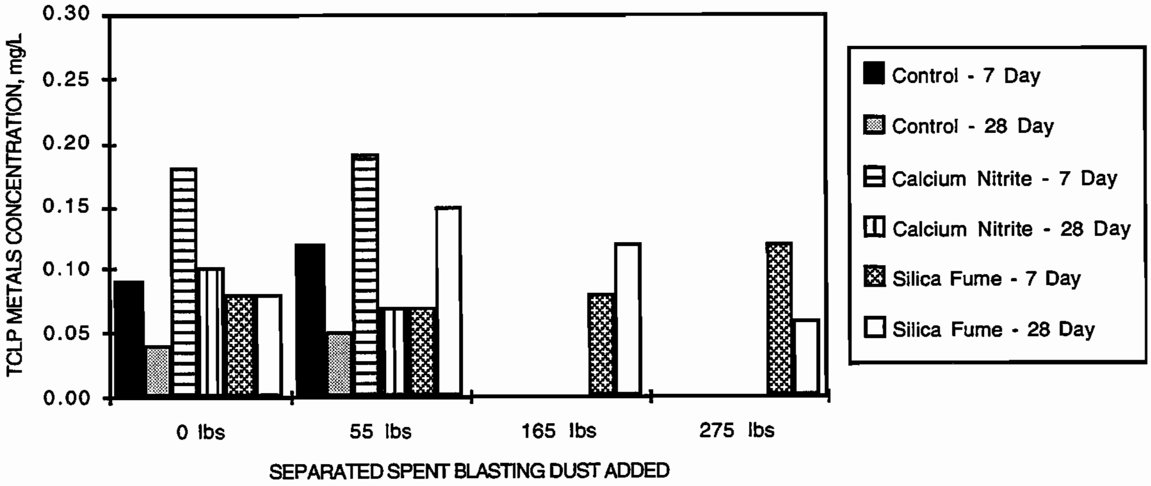

Figure 5.44 TCLP Lead Leaching for Separated Spent Sand/Separated Spent Dust Mixes with 320 kg (705 lb) Cement Content With No Admixtures, With Calcium Nitrite, and With Silica Fume

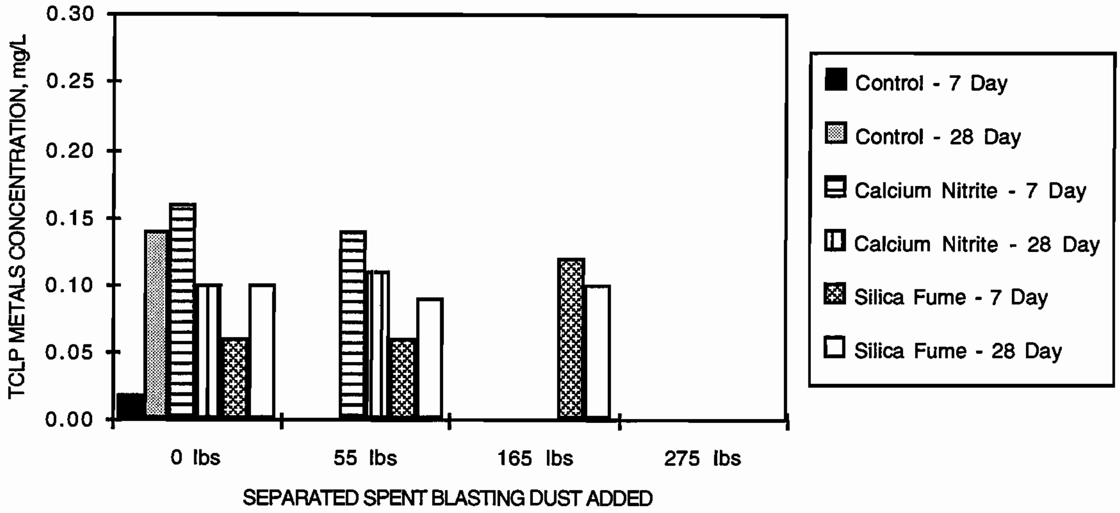

Figure 5.45: TCLP Cadmium Leaching for Separated Spent Sand/Separated Spent Dust Mixes with 213 kg (470 lb) Cement Content With No Admixtures, With Calcium Nitrite, and With Silica Fume

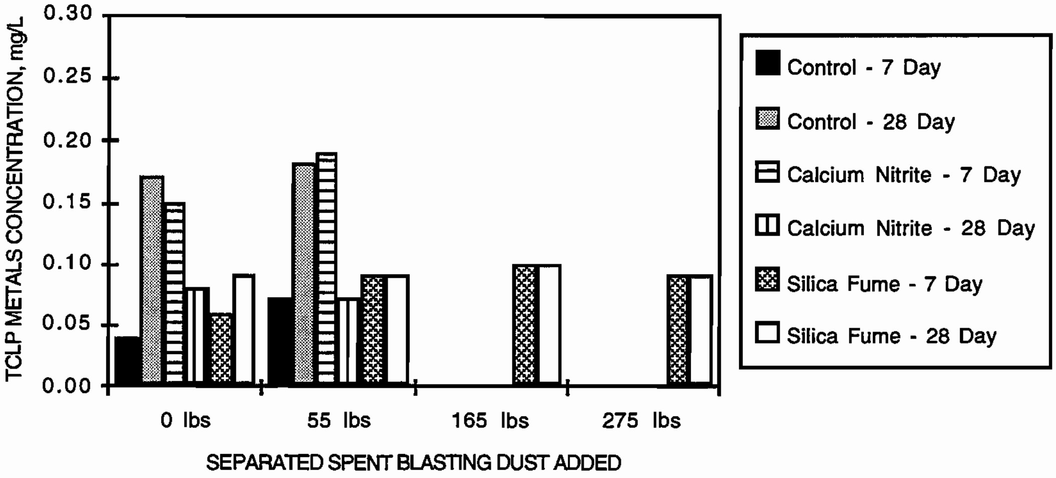

Figure 5.46: TCLP Cadmium Leaching for Separated Spent Sand/Separated Spent Dust Mixes with 320 kg (705 lb) Cement Content With No Admixtures, With Calcium Nitrite, and With Silica Fume

Figures 5.47 to 5.48 compare the TCLP leaching of chromium versus contamination level and accelerating admixture for separated spent sand/separated spent dust mixes. Unlike the TCLP leaching of lead and cadmium, TCLP leaching of chromium appears to be independent of the amount of separated spent blasting dust added or the type of accelerating admixture used for a constant amount of cement. However, the TCLP leaching of chromium was lowered as the amount of cement increased.

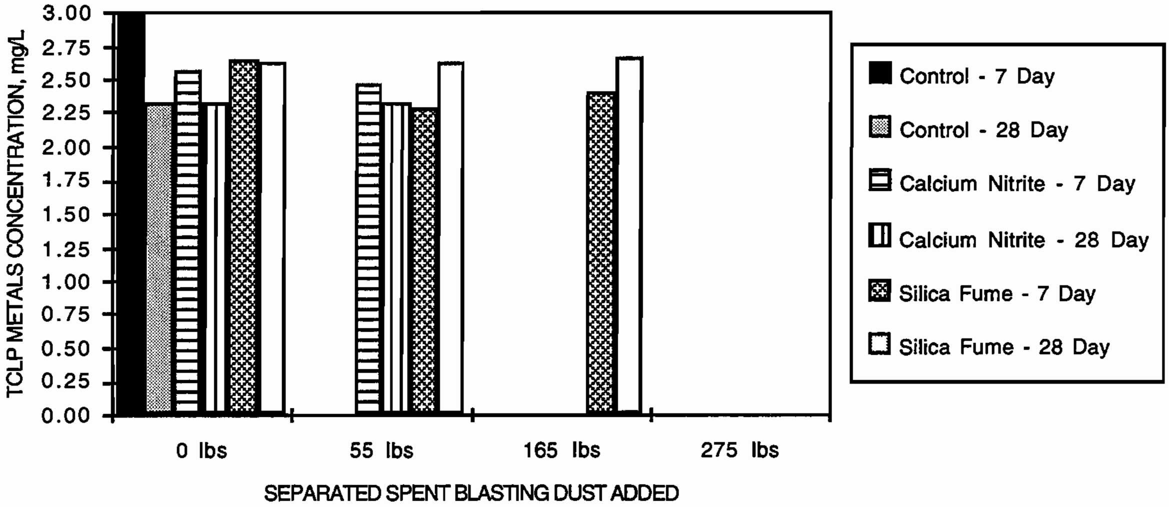

Figure 5.47: TCLP Chromium Leaching for Separated Spent Sand/Separated Spent Dust Mixes with 213 kg (470 lb) Cement Content With No Admixtures, With Calcium Nitrite, and With Silica Fume

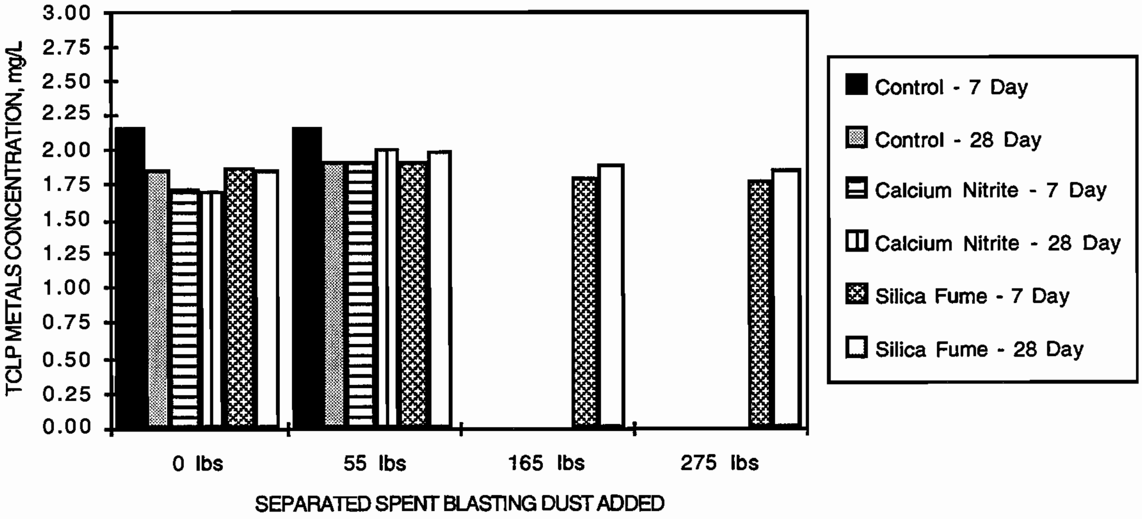

Figure 5.48: TCLP Chromium Leaching for Separated Spent Sand/Separated Spent Dust Mixes with 320 kg (705 lb) Cement Content With No Admixtures, With Calcium Nitrite, and With Silica Fume

5.5.2 Mixes Containing Unseparated Spent Blasting Sand/Dust

Figures 5.49 to 5.52 show the TCLP leaching versus accelerating admixture for mixes containing unseparated spent blasting sand/dust with medium and high cement contents. Each figure contains a TCLP leaching concentration for each metal studied and for each accelerating admixture. TCLP leaching tests were performed at both 7 and 28 days after casting.

Figure 5.49 shows the 7-day TCLP leaching for the unseparated spent sand/dust mixes with a medium cement content of 213 kg (470 lb). Leaching of both lead and cadmium were lowest for the two calcium nitrite mixes. Leaching of chromium was slightly higher for the mix containing silica fume than for the calcium nitrite mixes with the control mix having the lowest chromium leaching.

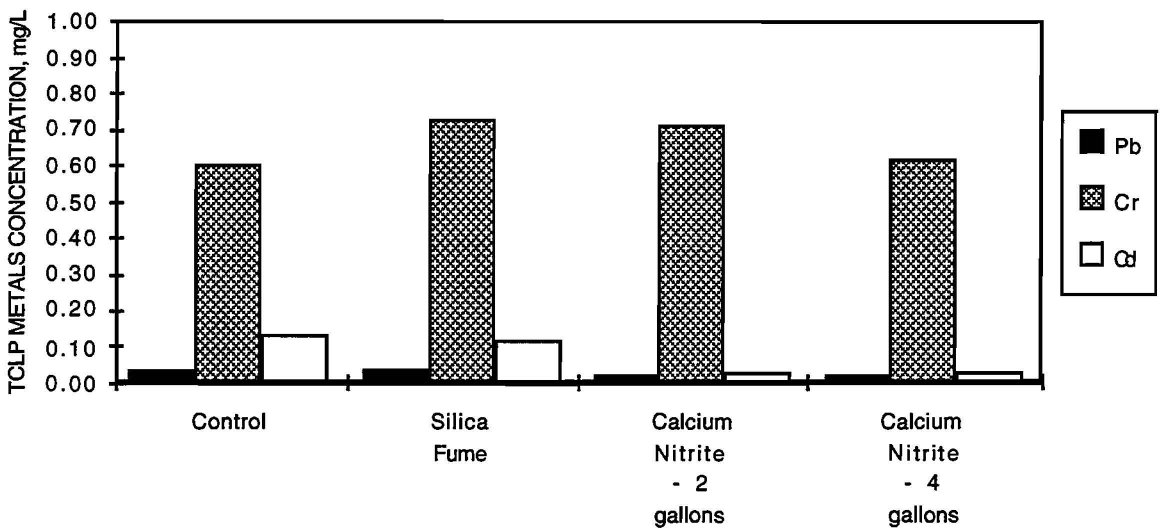

Figure 5.49: Seven-Day TCLP Leaching for Unseparated Spent Sand/Dust Mixes with 213 kg (470 lb) Cement Content With No Admixtures, With Calcium Nitrite, and With Silica Fume

Figure 5.50 shows the 7-day TCLP leaching for the unseparated spent sand/dust mixes with a high cement content of 320 kg (705 lb). Leaching of chromium was largest for the mix containing silica fume while the calcium nitrite mixes had the lowest chromium leaching. Leaching of lead and cadmium was highest for the control mix. There was no significant difference in lead and cadmium leaching between the silica fume mix and the two calcium nitrite mixes.

Comparing Figures 5.49 and 5.50, leaching of lead and cadmium increased with an increase in the cement content for all four mixes. The leaching of chromium decreased with an increase in the cement content for both of the calcium nitrite mixes but increased with an increase in the cement content for the control and silica fume mixes.

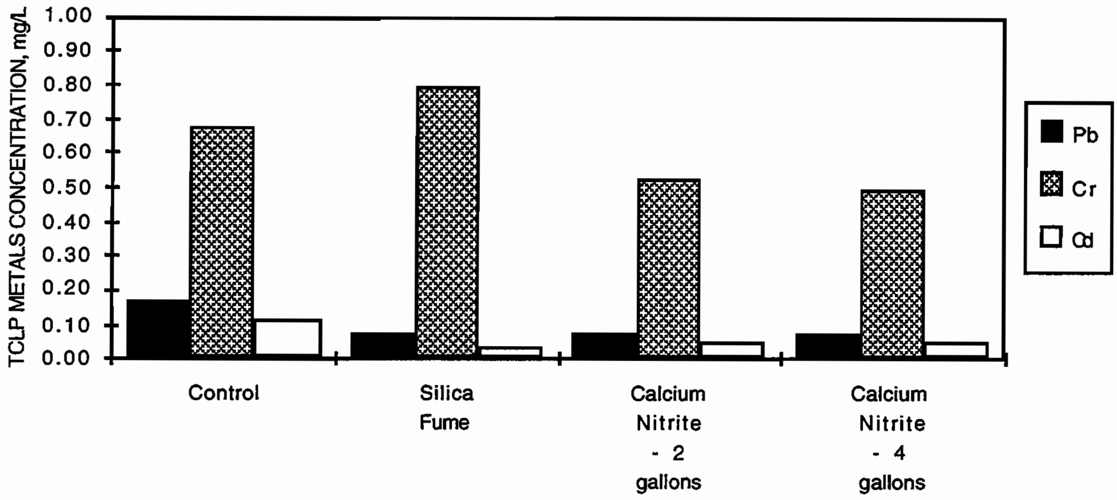

Figure 5.50: 7-Day TCLP Leaching for Unseparated Spent Sand/Dust Mixes with 320 kg (705 lb) Cement Content With No Admixtures, With Calcium Nitrite, and With Silica Fume

Figure 5.51 shows the 28-day TCLP leaching for the unseparated spent sand/dust mixes with a medium cement content of 213 kg (470 lb). A significant variation in lead or cadmium leaching between the accelerating admixtures was not observed. Leaching of chromium was higher for the mix containing silica fume than for the calcium nitrite mixes with the control mix having the lowest chromium leaching.

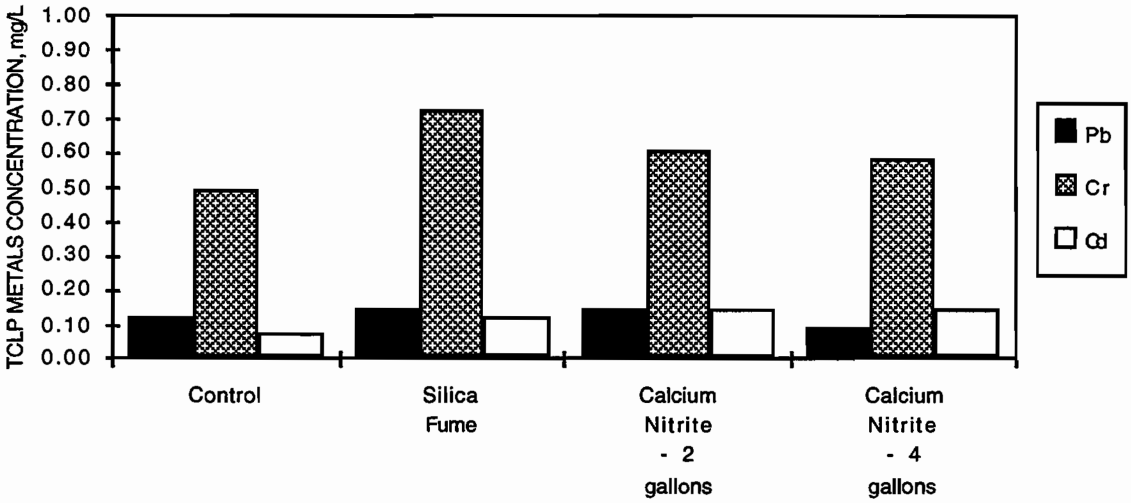

Figure 5.51: 28-Day TCLP Leaching for Unseparated Spent Sand/Dust Mixes with 213 kg (470 lb) Cement Content With No Admixtures, With Calcium Nitrite, and With Silica Fume

Figure 5.52 shows the 28-day TCLP leaching for the unseparated spent sand/dust mixes with a high cement content of 320 kg (705 lb). A significant variation in lead or cadmium leaching between the accelerating admixtures was not observed. Similar to the medium cement content mixes, leaching of chromium was slightly higher for the mix containing silica fume than for the calcium nitrite mixes with the control mix having the lowest chromium leaching.

Comparing Figures 5.51 and 5.52, leaching of lead and cadmium were approximately the same for both the medium and high cement contents. However, the leaching of chromium slightly decreased with an increase in cement content.

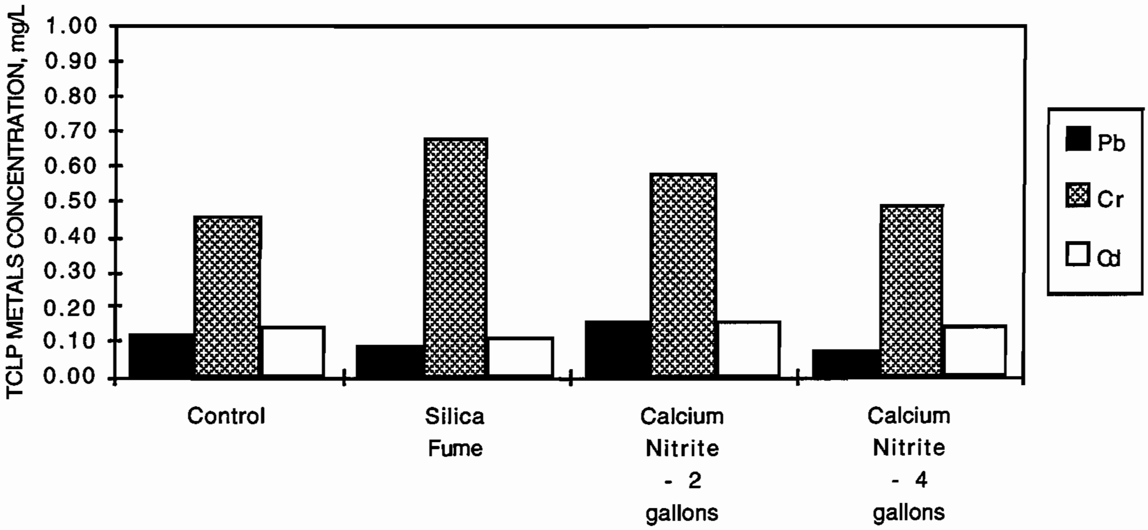

Figure 5.52: 28-Day TCLP Leaching for Unseparated Spent Sand/Dust Mixes with 320 kg (705 lb) Cement Content With No Admixtures, With Calcium Nitrite, and With Silica Fume

5.5.3 Mixes Containing Concrete Sand and Separated Spent Blasting Dust

Figure 5.53 to 5.55 shows the TCLP leaching versus contamination level for mixes containing concrete sand and separated spent blasting dust. These mixes contained a constant amount of 499 kg (1100 lb) of concrete sand, a high cement content of 320 kg (705 lb), superplasticizer, and a water/cement ratio by weight of 0.35. Four control mixes with increasing spent blasting dust contents and no accelerating admixtures were made. Corresponding mixes containing sodium silicate/cement ratios of 2 percent and 4 percent by weight were also made.

Figure 5.53 shows the TCLP results for lead leaching. All mixes that set had leaching concentrations below the test method detection limit of 0.07 mg/L regardless of the amount of sodium silicate used. The control mix containing 124.7 kg (275 lb) of separated spent dust did not set within 7 days after casting and was not tested for leaching.

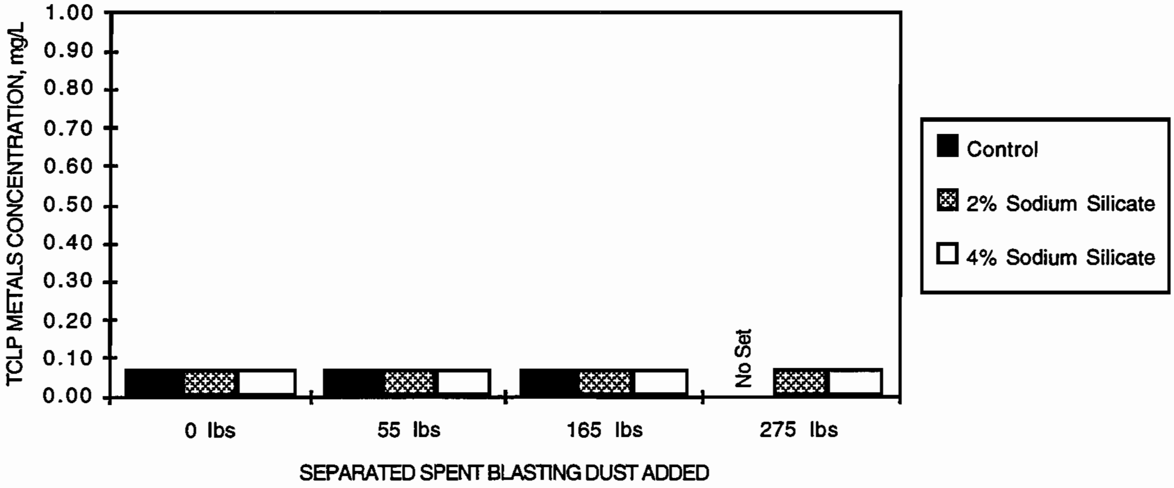

Figure 5.53: Seven-Day TCLP Lead Leaching for Concrete Sand/Separated Spent Dust Mixes With Sodium Silicate

Figure 5.54 shows the TCLP results for chromium leaching. All mixes that set had leaching concentrations well below the EPA limit of 5.0 mg/L. The control mix containing 124.7 kg (275 lb) of separated spent dust did not set within 7 days after casting and was not tested for leaching. The leaching of the chromium increased with increasing separated spent dust content. A clear trend in chromium leaching between the control mixes and sodium silicate mixes for a constant separated spent dust content was not observed.

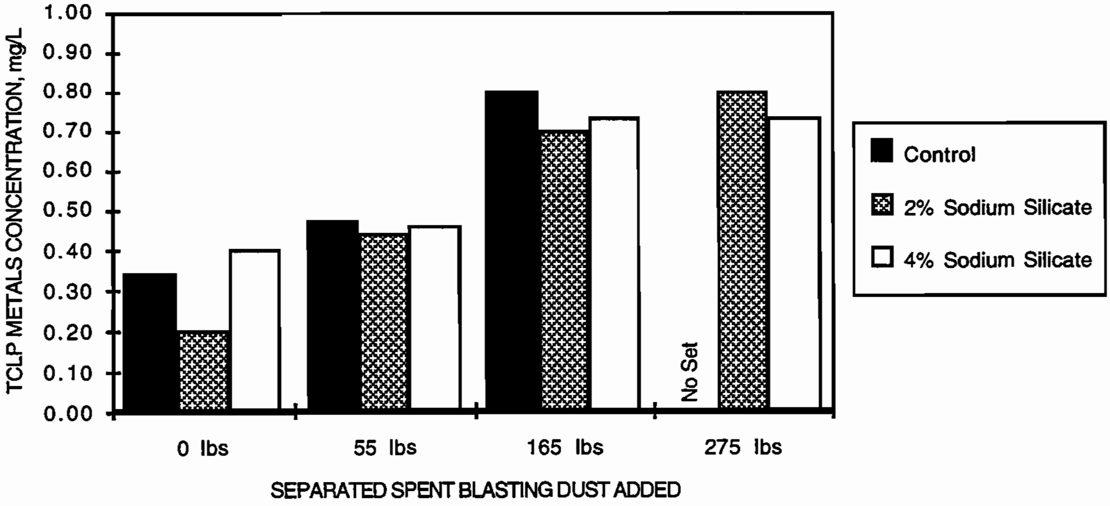

Figure 5.54: Seven-Day TCLP Chromium Leaching for Concrete Sand/Separated Spent Dust Mixes With Sodium Silicate

Figure 5.54 shows the TCLP results for cadmium leaching. All mixes that set had leaching concentrations well below the EPA limit of 1.0 mg/L. The control mix containing 124.7 kg (275 lb) of separated spent dust did not set within 7 days after casting and was not tested for leaching. The leaching of the cadmium did not increase with increasing separated spent dust content. A significant difference in cadmium leaching between the control mixes and sodium silicate mixes for a constant separated spent dust content was not observed.

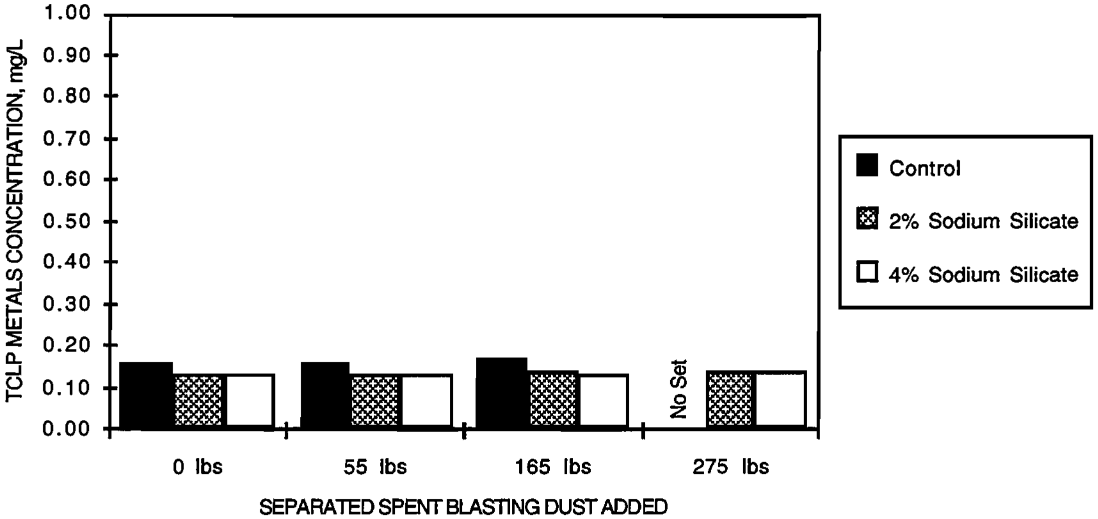

Figure 5.55: Seven-Day TCLP Cadmium Leaching for Concrete Sand/Separated Spent Dust Mixes With Sodium Silicate

5.5.4 Mixes Containing Spent Blasting Slag

Based upon the results for set times, compressive strength, and permeability, a mix containing a high cement content of 320 kg (705 lb), a water/cement ratio by weight of 0.35, superplasticizer, 499 kg (1100 lb) of spent blasting slag, a sodium silicate/cement ratio of 2 percent by weight, and silica fume in the amount of 12 percent by weight addition to cement was chosen for field use at the Montopolis Bridge in Austin, Texas. To verify compliance with environmental regulations, this mortar mix was tested for TCLP leaching at 7 days after casting. Table 5.1 shows the results for the 7-day TCLP leaching for the Montopolis Bridge field mix.

Table 5.1: Seven-Day TCLP Leaching for the Montopolis Bridge Field Mix

Metal	TCLP Metals Concentration, mg/L
Lead	< 0.07
Chromium	1.42
Cadmium	0.14

5.5.5 Summary of the Effect of Mix Composition on TCLP Leaching

The effect of mix composition on TCLP leaching investigated in this study can be stated as follows:

1) For the separated spent sand/separated spent dust mixes, lead and cadmium leaching were very low and no trends were seen as a function of the cement content, the amount of spent dust added, or the type of accelerating admixture. Chromium leaching was relatively constant and independent of the amount of spent dust added and the type of accelerating admixture, but was lower for mixes with a higher cement content.
2) For the unseparated spent sand/dust mixes, those mixes containing silica fume had the highest chromium leaching, regardless of test age or cement content. For a given mix, there was only a slight difference in leaching of lead, chromium, and cadmium for different test ages and cement contents. This was most likely due to the low contamination level of these mixes.
3) For the concrete sand/separated spent dust mixes, lead leaching was lowered below test method detection limits for all the mixes tested regardless of whether sodium silicate was used or not. Cadmium leaching was lowered to just above test method detection limits. Cadmium leaching did not vary with contamination level but was slightly lower for mixes containing sodium silicate. Chromium leaching increased with contamination level. However, no trend was observed when comparing the control mixes with the sodium silicate mixes.
4) The portland cement mortar chosen for recycling spent blasting slag at the Montopolis Bridge was found to have TCLP leaching concentrations for lead, chromium, and cadmium well below the EPA limits.
5) All the portland cement mortars tested in this study had TCLP leaching concentrations below the EPA limits. Trends in the leaching of individual metals as a function of mix composition were variable. Therefore, the TCLP test should not be used as a means for determining mix proportions but rather as a means for verifying the environmental compliance of a mix chosen by other performance criteria such as set time, compressive strength, and permeability.

5.6 FIELD APPLICATIONS OF RECYCLING SPENT BLASTING ABRASIVES

5.6.1 Rainbow Bridge, Port Arthur, Texas

Approximately one year after casting, three portland cement mortar blocks made at the Rainbow Bridge were cored and tested for compressive strength, chloride ion permeability, and TCLP leaching. The mortar mix proportions used in recycling the spent blasting abrasives in the portland cement mortar blocks are shown in Table 5.2. Figures 5.56, 5.57, and 5.58 show the compressive strength, permeability, and TCLP results, respectively, for the cores taken from these three blocks.

Table 5.2: Rainbow Bridge Mortar Mix Proportions

Constituent	Proportion
Type I/II Portland Cement	705 lb
Water	247 lb
Superplasticizer	154 fl. oz.
Spent Blasting Abrasives	1100 lb
Silica Fume	84.6 lb

1 lb = 0.45 kg
1 fl. oz. = 29.6 mL

Figures 5.56 and 5.57 show a large range in compressive strength and permeability for the three blocks tested. This illustrates the sensitivity of the mortar mix to the highly variable contamination level of the spent blasting abrasives. A high porosity was observed in Block 1, the lowest in compressive strength and highest in permeability. This was most likely due to a very high aluminum content in the spent blasting abrasives used in that particular batch.

Comparing Figures 5.56 and 5.57, a good correlation is shown between the compressive strength and permeability. The block that was highest in compressive strength had the lowest permeability, while the block that had the lowest compressive strength had the highest permeability.

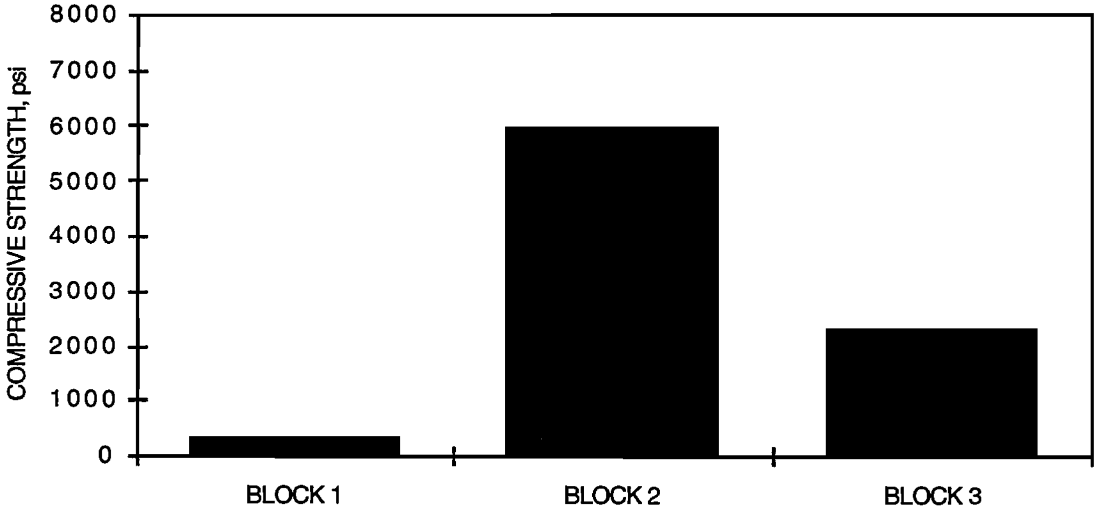

Figure 5.56: Compressive Strength Results for Rainbow Bridge Mortar Blocks

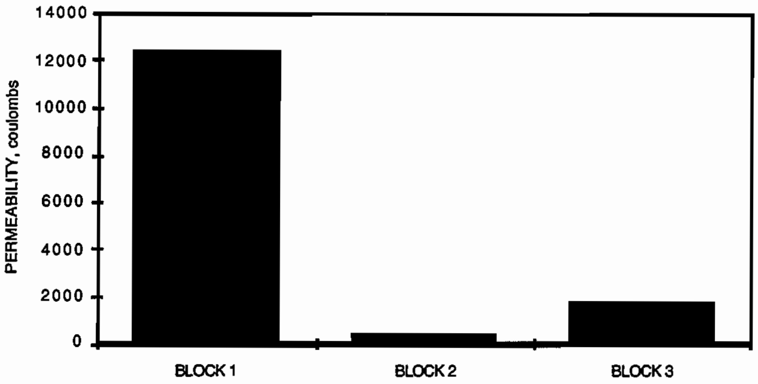

Figure 5.57: Permeability Results for Rainbow Bridge Mortar Blocks

As this project involved recycling approximately 3,000 barrels of spent abrasives, variations in the contamination level of the spent abrasives should be expected. Variability in the contamination level could be the result of the condition and type of paint to be removed and the amount of spent abrasives used in cleaning a unit area of the structure. These factors contribute to the particle size of the pulverized paint and its concentration in the spent blasting abrasives.

Figure 5.58 shows the TCLP results for lead, chromium, and cadmium leaching for the three blocks. Despite the large variation in compressive strength and permeability, all three blocks were below the EPA leaching limits. Leaching of lead for all three blocks was at the test method detection limit of 0.07 mg/L. Leaching of cadmium was also at approximately the same level for all three blocks. While the leaching of cadmium was above the method detection limit of 0.02 mg/L, it was well below the EPA leaching limit of 1.0 mg/L. The only variation among the three blocks was in chromium leaching. Block 1, the lowest strength and most permeable block, had the highest chromium leaching equal to 2.27 mg/L. However, this was still below the EPA limit of 5.0 mg/L.

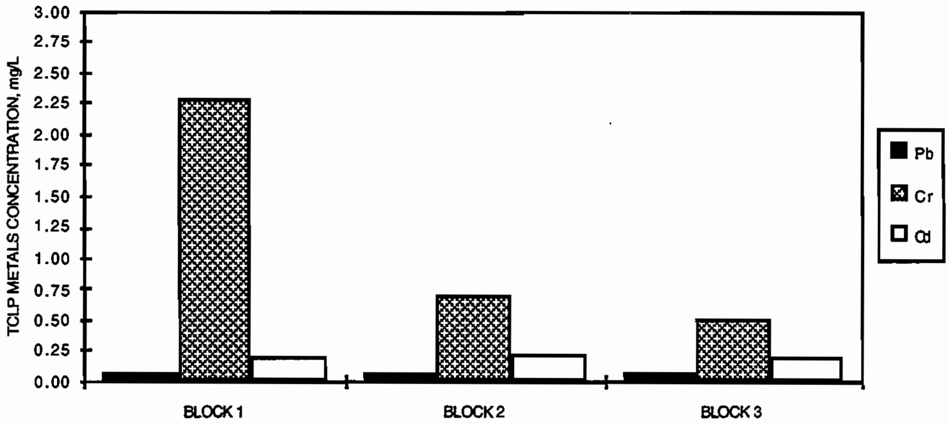

Figure 5.58: TCLP Results for Rainbow Bridge Mortar Blocks

5.6.2 Montopolis Bridge, Austin, Texas

Based upon the results for set times, compressive strength, and permeability for all the spent blasting slag mixes that were trial batched, the mix proportions shown in Table 5.3 were recommended for field use in recycling the spent blasting slag at the Montopolis Bridge. These mix proportions yielded approximately 0.42 to 0.45 m^3 (15 to 16 cubic feet) of mortar.

Table 5.3: Montopolis Bridge Mortar Mix Proportions

Constituent	Proportion
Type I/II Portland Cement	705 lb
Water	220 lb
Superplasticizer	120 fl. oz.
Spent Blasting Abrasives	1100 lb
Silica Fume	84.6 lb
Sodium Silicate	28.2 lb

1 lb = 0.45 kg
1 fl. oz. = 29.6 mL

The mortar described in Table 5.3 was tested for set time, compressive strength, permeability, and TCLP leaching. Table 5.4 gives the set time, compressive strength, permeability results and Table 5.5 gives the TCLP leaching results for the mortar produced with this particular barrel of spent blasting abrasives in the laboratory.

Table 5.4: Montopolis Bridge Mortar Performance Results

Test	Results
Set Time	Less than 24 hours
7-Day Compressive Strength	3900 psi
7-Day AASHTO T 277 Permeability	1600 coulombs (Low)

Table 5.5: Montopolis Bridge Mortar TCLP Leaching Results

Metal	7-Day TCLP Metals Concentration, mg/L
Lead	< 0.07
Chromium	1.42
Cadmium	0.14

CHAPTER 6. CONCLUSIONS AND RECOMMENDATIONS

6.1 SUMMARY

Lead-based paints have been used on steel bridges for many years because of their effectiveness against corrosion and relatively low cost, and because little surface preparation is required before the paint is applied. Over time, the protective paint coating deteriorates and must be removed before repainting. The most common method of removal is abrasive blasting because it is efficient, cost effective, and provides a clean, roughened surface for the new coating. Spent blasting abrasives contain lead and other contaminants for which maximum leachable levels have been set by the EPA. Materials that have TCLP leaching concentrations larger than the maximum levels set by the EPA are classified as hazardous.

One method of treating the spent blasting abrasives to render them nonhazardous is solidification/stabilization (S/S). Portland cement systems are particularly suited for use when dealing with spent blasting abrasives. The mortar or concrete produced with the cement, water, and spent blasting abrasives can be used as a construction material provided environmental and construction concerns are satisfied. The spent blasting abrasives are effectively treated and recycled in a single step.

This study addresses the effectiveness of portland cement mortars in rendering spent blasting abrasives nonhazardous through solidification/stabilization technology and in recycling the spent blasting abrasives in portland cement mortars for use as a construction material. Guidelines and recommendations for field applications of portland cement mortars using spent blasting abrasives will be established based upon the results of this study.

6.2 CONCLUSIONS

As described in Chapter 2, the following areas for additional research were identified based upon the work initiated by Garner [24]:

1) The use of accelerators and anti-inhibitors to counteract the effect of the lead on the hydration of cement should be investigated.
2) Spent abrasives should be acquired from several sites to investigate the variability in contamination level upon the mix characteristics.
3) The effect of chemical stabilization of the heavy metals using sulfide and silicate agents upon set, strength, and leaching should be investigated for use in more highly contaminated spent abrasives.
4) New mix recommendations for field applications based upon the above results should be made. The new mix recommendations should be less susceptible to low strength and long set times resulting from more highly contaminated spent abrasives.

As a result of this study, the following conclusions regarding these areas of research were made:

1) Of the four accelerating admixtures used in this study, sodium silicate was the most effective in reducing the set times of the most highly contaminated mixes. For the dosages used in this study, silica fume and calcium chloride were approximately equivalent, and they were the next most effective accelerating admixtures compared to sodium silicate. Calcium nitrite was effective in reducing the set times of lesser contaminated mixes but was ineffective in highly contaminated mixes.
2) While providing shorter set times than the other accelerating admixtures, sodium silicate also provided lower compressive strengths than the other accelerating admixtures as well. However, the compressive strength of a mix containing sodium silicate was higher than a control mix containing no accelerating admixtures.
3) The combination of sodium silicate and silica fume provided higher compressive strengths and lower permeabilities when used together than when used individually.
4) The lead/portland cement ratio was important in determining set times and compressive strength. By either decreasing the spent abrasive content or increasing the portland cement, the lead retardation effects were decreased.
5) The effect of variations in the contamination level of the spent blasting abrasives was found to be most apparent in differences in mortar set times. In general, if a mix set, it would also have a reasonable compressive strength that could be increased by adjusting mix proportions. However, accelerating admixtures were required in achieving set for the most highly contaminated mixes.
6) Based upon the literature review, sodium sulfide and ferrous sulfate were determined to be unviable admixtures for recycling spent blasting abrasives. This was due to the use of a monolithic waste form with a low surface area for leaching as well as the low levels of TCLP leaching accomplished without the use of sodium sulfide and ferrous sulfate.
7) All the portland cement mortars tested in this study had TCLP leaching concentrations below the EPA limits. Trends in the leaching of individual metals as a function of mix composition were variable. Therefore, the TCLP test should not be used as a means for determining mix proportions but rather as a means for verifying the environmental compliance of a mix chosen by other criteria such as set time, compressive strength, and permeability.
8) Based upon the above observations, it was determined that a set-time oriented procedure for trial batching was necessary for recycling highly contaminated spent blasting abrasives in portland cement mortars. Once reasonable set times are achieved, the mix proportions can be optimized to increase compressive strength and decrease permeability. Guidelines for this set-time oriented trial batching procedure are described in Section 6.3.
9) The use of this set-time oriented trial batching procedure was found to be effective in determining mortar mix proportions to be used in recycling spent blasting slag at the Montopolis Bridge in Austin, Texas.

6.3 GUIDELINES FOR RECYCLING CONTAMINATED SPENT BLASTING ABRASIVES IN PORTLAND CEMENT MORTARS

The following are recommended guidelines for recycling contaminated spent blasting abrasives in portland cement mortars:

Step 1) Characterize the spent blasting abrasives using the Toxicity Characteristic Leaching Procedure and Total Constituent Analysis. This will determine the contamination level of the spent blasting abrasives.

Step 2) Characterize the portland cement, mineral admixtures, and chemical admixtures using the Toxicity Characteristic Leaching Procedure and Total Constituent Analysis. Some of these materials contain lead, cadmium, or chromium and could contribute to the TCLP leaching of the portland cement mortar.

Step 3) Establish desired mortar properties including set time, compressive strength, and permeability. These will typically be based upon the application for which the spent abrasives are being recycled.

Step 4) Establish additional job requirements that would contribute to selection of materials and mix proportions. These would include whether additional clean aggregate will be used, the type of batching procedure and equipment to be used at the site, and the availability of certain chemical and mineral admixtures.

Step 5) Determine trial mix proportions. The following procedure has been found to be the most efficient process for determining optimum mix proportions for recycling spent blasting abrasives:

a. Trial batch to reduce set times: Long set times of portland cement mortars due to lead retardation have been found to be the most troublesome aspect in determination of mix proportions for field applications. Ways to reduce set times of the portland cement mortars include:

   i. Increase the cement content. This has the effect of decreasing the lead to cement ratio, and therefore, reducing the retardation effects.
   ii. Decrease the amount of spent blasting abrasives. This will lower the contamination level of the mix. Addition of clean aggregate will also help lower the contamination level.
   iii. Add or increase the dosage of accelerating agents. Sodium silicate has been found to be the most effective accelerator used in this study followed by silica fume, calcium chloride, and calcium nitrite. In general, increasing the accelerator dosages for a given amount of cement and spent abrasives will shorten the set times.

b. Optimize mix proportions to increase compressive strength. After proportions for a mix with an adequate set time have been determined, the proportions can be adjusted to increase the compressive strength. Ways to increase the compressive strength of the portland cement mortars are similar to the procedures used for reducing set times including:

    i. Increase the cement content.
    ii. Decrease the amount of spent blasting abrasives. This will lower the contamination level of the mix. Addition of clean aggregate will also help lower the contamination level.
    iii. Add or increase the dosage of accelerating agents. In general, increasing the accelerator dosages for a given amount of cement and spent abrasives will result in higher strengths.
    iv. Lower the water/cement ratio. This reduces the porosity of the portland cement matrix increasing the compressive strength. High-range water reducers can be used to provide required workability at low water/cement ratios. The high-range water reducers will also aid in increasing compressive strength by dispersing and deflocculating the cement particles.
    v. Improve curing procedures. Properly moist-cured concretes will attain higher compressive strengths than poorly cured concretes.

c. Adjust the mix proportions to decrease permeability. This can be done concurrently while adjusting the mix proportions to increase the compressive strength. The following are several trends observed for reducing permeability:

    i. Decrease the cement content. This has the effect of decreasing the paste content of the mortar. However, in the case of spent abrasives high in aluminum content, increasing the cement content has been observed to be beneficial in reducing the permeability.
    ii. Decrease the amount of spent blasting abrasives. This will lower the contamination level of the mix. Addition of clean aggregate will also help lower the contamination level.
    iii. Lower the water/cement ratio. This reduces the porosity of the portland cement matrix decreasing the permeability.
    iv. Improve curing procedures. Properly moist-cured concretes will have lower permeabilities than poorly cured concretes.
    v. Add or increase the amount of mineral admixtures. The pozzolanic and filler effects of mineral admixtures aid in reducing the permeability of the portland cement matrix. Silica fume was found to be extremely effective in reducing the permeability of portland cement mortars containing spent blasting abrasives.

d. Test portland cement mortar using the Toxicity Characteristic Leaching Procedure. Choose the mortar mix with the best performance in the areas of set times, compressive strength, and permeability and test according to the TCLP test. No portland cement mortars investigated in this study failed the EPA limits for the TCLP test. The TCLP test needs to be performed upon the chosen mortar to ensure and document compliance with environmental regulations.

Step 6) Obtain multiple samples of the spent blasting abrasives. The mortar mix chosen for field use in the trial batching process should be batched using samples from several barrels at the job site. This would aid in assessing the possible range in contamination level of the spent blasting abrasives and the sensitivity of the mortar to the variation in contamination level.

Step 7) Coordinate with the contractor in determining mixing and placing procedures. Portland cement mortars containing spent blasting abrasives require some additional attention for field use. The use of mineral admixtures such as silica fume can result in "sticky" mixes that require longer mixing times and increased effort for adequate consolidation. The high fineness of spent abrasives in general can result in a loss of workability due to absorption of water. Highly efficient accelerators such as sodium silicate can cause a rapid loss of workability or can even cause the cement to flash set if dosages are too high.

Step 8) Establish a field testing program. The portland cement mortars produced in the field can be tested similar to concrete on a normal construction project. This will enable monitoring of the set times, compressive strength, permeability, and environmental compliance throughout the duration of the project. If necessary, further adjustments in mix proportions or field mixing procedures can be made.

6.4 AREAS FOR FURTHER RESEARCH

The combination of the work of this author and the work initiated by Garner [24] provides guidelines for determining mix proportions for recycling spent blasting abrasives in portland cement mortars. A trial-batching procedure that is applicable to spent blasting abrasives of low to high contamination level was established. However, the following are areas for further investigation:

1) A study of the long-term durability and environmental compliance of field-produced portland cement mortars containing spent blasting abrasives.
2) A field testing program that monitors the consistency in production of portland cement mortars containing spent blasting abrasives at the construction jobsite.

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APPENDIX 1:

MIX PROPORTIONS

Table A1.1: Proportions for Mixes Containing Separated Spent Blasting Sand and Separated Spent Blasting Dust

MIX I.D. #	CEMENT lbs	SAND lbs	DUST lbs	HRWR oz/cwt	CALC NITR gallons	SIL FUME lbs	W/C RATIO
SDT204D1	705	1100	0	0.0	0.0	0	0.35
SDT204D2	705	1100	55	18.9	0.0	0	0.35
SDT204D3	705	1100	165	39.1	0.0	0	0.35
SDT204D4	705	1100	275	60.7	0.0	0	0.35
SDT205D1	470	1100	0	12.0	0.0	0	0.35
SDT205D2	470	1100	55	12.0	0.0	0	0.35
SDT205D3	470	1100	165	21.3	0.0	0	0.35
SDT205D4	470	1100	275	41.0	0.0	0	0.35
SDT206D1	470	1100	0	3.2	2.0	0	0.35
SDT206D2	470	1100	55	12.0	2.0	0	0.35
SDT206D3	470	1100	165	30.6	2.0	0	0.35
SDT206D4	470	1100	275	44.3	2.0	0	0.35
SDT207D1	705	1100	0	0.0	2.0	0	0.35
SDT207D2	705	1100	55	2.6	2.0	0	0.35
SDT207D3	705	1100	165	8.4	2.0	0	0.35
SDT207D4	705	1100	275	17.1	2.0	0	0.35
SDT208D1	470	1100	0	20.7	0.0	56.4	0.35
SDT208D2	470	1100	55	23.9	0.0	56.4	0.35
SDT208D3	470	1100	165	30.6	0.0	56.4	0.51
SDT208D4	470	1100	275	34.6	0.0	56.4	0.48
SDT209D1	705	1100	0	3.7	0.0	84.6	0.35
SDT209D2	705	1100	55	9.7	0.0	84.6	0.35
SDT209D3	705	1100	165	26.7	0.0	84.6	0.35
SDT209D4	705	1100	275	32.3	0.0	84.6	0.35

1 lb = 0.45 kg
1 oz/cwt = 0.65 mL/kg of cement
1 gallon = 3.785 L

Table A1.2: Proportions for Mixes Containing Unseparated Spent Blasting Sand/Dust

MIX	CEMENT	SAND/	HRWR	CALC	CALC	FLY	SIL	W/C
I.D. #		DUST		NITR	CHLOR	ASH*	FUME	RATIO
	lbs	lbs	oz/cwt	gallons	oz/cwt	lbs	lbs	
SDT200CC1	705	1100	12.0	0.00	16.0	0.0	0.0	0.35
SDT200CC2	705	1100	12.0	0.00	32.0	0.0	0.0	0.35
SDT200CC3	705	1100	13.7	0.00	64.0	0.0	0.0	0.35
SDT200CN1	705	1100	12.0	0.38	0.0	0.0	0.0	0.35
SDT200CN3	705	1100	12.0	1.13	0.0	0.0	0.0	0.35
SDT300	470	1100	12.0	0.00	0.0	0.0	0.0	0.35
SDT301	470	1100	16.2	0.00	0.0	0.0	56.4	0.35
SDT302	470	1100	12.0	0.00	0.0	141.0	0.0	0.35
SDT303	470	1100	17.7	0.00	0.0	141.0	56.4	0.35
SDT304	470	1100	23.2	2.00	0.0	0.0	0.0	0.35
SDT305	470	1100	28.9	4.00	0.0	0.0	0.0	0.35
SDT400	705	1100	12.0	0.00	0.0	0.0	0.0	0.35
SDT401	705	1100	16.5	0.00	0.0	0.0	84.6	0.35
SDT402	705	1100	5.2	0.00	0.0	211.5	0.0	0.35
SDT403	705	1100	12.0	0.00	0.0	211.5	84.6	0.35
SDT404	705	1100	12.0	2.00	0.0	0.0	0.0	0.35
SDT405	705	1100	12.0	4.00	0.0	0.0	0.0	0.35
SDT500	470	1100	17.7	0.00	0.0	0.0	0.0	0.35
SDT501	470	1100	23.4	0.00	0.0	0.0	56.4	0.35
SDT502	470	1100	6.9	0.00	0.0	141.0	0.0	0.35
SDT503	470	1100	17.7	0.00	0.0	141.0	56.4	0.35
SDT600	705	1100	5.2	0.00	0.0	0.0	0.0	0.35
SDT601	705	1100	14.2	0.00	0.0	0.0	84.6	0.35
SDT602	705	1100	5.1	0.00	0.0	211.5	0.0	0.35
SDT603	705	1100	8.6	0.00	0.0	211.5	84.6	0.35

* Used as a replacement for portland cement

1 lb = 0.45 kg

1 oz/cwt = 0.65 mL/kg of cement

1 gallon = 3.785 L

Table A1.3: Proportions for Mixes Containing Concrete Sand and Separated Spent Blasting Dust

MIX I.D. #	CEMENT lbs	SAND lbs	DUST lbs	HRWR oz/cwt	W/C RATIO	SOD. SILI lbs
CM # 1	705	1100	0	3.2	0.35	0.00
CM # 2	705	1100	55	5.4	0.35	0.00
CM # 3	705	1100	165	7.5	0.35	0.00
CM # 4	705	1100	275	17.0	0.35	0.00
SILI 1A	705	1100	0	1.8	0.35	14.10
SILI 1B	705	1100	55	3.0	0.35	14.10
SILI 1C	705	1100	165	12.0	0.35	14.10
SILI 1D	705	1100	275	26.7	0.35	14.10
SILI 2A	705	1100	0	2.2	0.35	28.20
SILI 2B	705	1100	55	5.5	0.35	28.20
SILI 2C	705	1100	165	14.3	0.35	28.20
SILI 2D	705	1100	275	35.7	0.35	28.20

1 lb = 0.45 kg
1 oz/cwt = 0.65 mL/kg of cement

Table A1.4: Proportions for Mixes Containing Spent Blasting Slag

MIX I.D. #	CEMENT lbs	SLAG lbs	HRWR oz/cwt	SIL FUME lbs	CALC CHLOR oz/cwt	CALC NITR gallons	SOD. SILI. lbs	W/C RATIO
MONT 1	705	1100	2.9	0.0	0.0	0.0	0.00	0.35
MONT 2	705	1100	2.9	0.0	0.0	2.0	0.00	0.35
MONT 3	705	1100	12.0	84.6	0.0	0.0	0.00	0.35
MONT 4	705	1100	5.3	0.0	0.0	0.0	14.10	0.35
MONT 5	705	1100	3.1	42.3	0.0	0.0	0.00	0.35
MONT 6	705	1100	1.8	0.0	0.0	4.0	0.00	0.35
MONT 7	705	1100	5.2	0.0	0.0	0.0	28.20	0.35
MONT 8	705	1100	0.0	0.0	36.0	0.0	0.00	0.35
MONT 9	705	1100	0.0	0.0	72.0	0.0	0.00	0.35
MONT 10	705	1100	12.0	56.4	0.0	0.0	28.20	0.35
MONT 11	705	1100	16.6	84.6	0.0	0.0	28.20	0.35
MONT 12	705	1100	16.6	56.4	0.0	0.0	42.30	0.35
MONT 13	705	1100	21.0	84.6	0.0	0.0	42.30	0.35

1 lb = 0.45 kg
1 oz/cwt = 0.65 mL/kg of cement

APPENDIX 2:

COMPRESSIVE STRENGTH AND PERMEABILITY RESULTS

Table A2.1: Compressive Strength and Permeability Results for Mixes Containing Separated Spent Blasting Sand and Separated Spent Blasting Dust

MIX I.D. #	SET TIME	COMPRESSIVE STRENGTH, psi 7-Day	28-Day	90-Day	PERMEABILITY coulombs
SDT204D1	3 Day	3120	3050	4640	11130
SDT204D2	6 Day	1160	770	750	16460
SDT204D3	No Set	0	0	0	N/A
SDT204D4	No Set	0	0	0	N/A
SDT205D1	3 Day	1510	2120	3700	14519
SDT205D2	No Set	0	0	0	N/A
SDT205D3	No Set	0	0	0	N/A
SDT205D4	No Set	0	0	0	N/A
SDT206D1	1 Day	3650	4760	5030	6880
SDT206D2	3 Day	2880	3410	4220	8240
SDT206D3	No Set	0	0	0	N/A
SDT206D4	No Set	0	0	0	N/A
SDT207D1	1 Day	3210	3930	4800	21110
SDT207D2	2 Day	2330	3340	3230	18260
SDT207D3	No Set	0	0	0	N/A
SDT207D4	No Set	0	0	0	N/A
SDT208D1	1 Day	2380	3260	3680	6210
SDT208D2	1 Day	2131	2720	3060	5340
SDT208D3	4 Day	1060	3260	3830	3780
SDT208D4	No Set	0	0	0	N/A
SDT209D1	1 Day	1690	2450	2420	4450
SDT209D2	1 Day	1980	2820	2570	6990
SDT209D3	1 Day	2610	3750	4160	6450
SDT209D4	4 Day	1580	2040	2370	11790

1000 psi = 6.895 MPa

Table A2.2: Compressive Strength and Permeability Results for Mixes Containing Unseparated Spent Blasting Sand/Dust

MIX I.D. #	SET TIME	COMPRESSIVE STRENGTH, psi 7-Day	28-Day	90-Day	PERMEABILITY coulombs
SDT200CC1	No Set	0	0	0	N/A
SDT200CC2	6 Day	1990	2330	3240	15220
SDT200CC3	No Set	0	0	0	N/A
SDT200CN1	No Set	0	0	0	N/A
SDT200CN3	No Set	0	0	0	N/A
SDT300	1 Day	2910	3540	4370	9750
SDT301	1 Day	3390	4420	4230	550
SDT302	1 Day	840	1100	980	12800
SDT303	1 Day	1210	1500	1900	2670
SDT304	1 Day	5170	6480	7250	6410
SDT305	1 Day	6650	8240	8830	7130
SDT400	1 Day	1720	2370	2230	12800
SDT401	1 Day	2020	2330	2660	2450
SDT402	1 Day	1790	2150	2450	11650
SDT403	1 Day	2320	3820	3770	3400
SDT404	1 Day	6270	7910	8520	6880
SDT405	1 Day	6520	8250	8710	7290
SDT500	1 Day	3450	4770	4930	6290
SDT501	1 Day	5080	5850	6260	760
SDT502	1 Day	3280	3920	3330	5890
SDT503	1 Day	4060	5260	6140	650
SDT600	1 Day	4700	5250	5540	8050
SDT601	1 Day	4920	6520	6200	1000
SDT602	1 Day	3260	4690	4370	7110
SDT603	1 Day	4870	4750	7090	1150

1000 psi = 6.895 MPa

Table A2.3: Compressive Strength and Permeability Results for Mixes Containing Concrete Sand and Separated Spent Blasting Dust

MIX I.D. #	SET TIME	COMPRESSIVE STRENGTH, psi 7-Day	28-Day	90-Day	PERMEABILITY coulombs
CM # 1	1 Day	6010	8450	9190	11230
CM # 2	1 Day	3190	3510	4660	5770
CM # 3	1 Day	2130	2340	2600	7530
CM # 4	No Set	0	0	0	N/A
SILI 1A	1 Day	6380	7550	-	13030
SILI 1B	1 Day	4240	4900	-	9390
SILI 1C	1 Day	3990	4180	-	4680
SILI 1D	1 Day	5040	5560	-	4570
SILI 2A	1 Day	5520	7470	-	14840
SILI 2B	1 Day	4170	4600	-	11434
SILI 2C	1 Day	3190	4510	-	5670
SILI 2D	1 Day	4530	5250	-	11660

- Not Tested
1000 psi = 6.895 MPa

Table A2.4: Compressive Strength and Permeability Results for Mixes Containing Spent Blasting Slag

MIX I.D. #	SET TIME	COMPRESSIVE STRENGTH, psi 7-Day	28-Day	90-Day	PERMEABILITY coulombs
MONT 1	No Set	0	0	0	N/A
MONT 2	No Set	0	0	0	N/A
MONT 3	1.5 Day	2870	3640	-	3870
MONT 4	< 1 Day	2260	2710	-	8750
MONT 5	5 Day	1000	1730	-	13560
MONT 6	5 Day	3640	5170	-	14740
MONT 7	< 1 Day	2410	3010	-	9110
MONT 8	5 Day	3630	4600	-	15200
MONT 9	2 Day	3600	4150	-	15780
MONT 10	< 1 Day	2980	3600	-	2950*
MONT 11	< 1 Day	3870	4620	-	1570*
MONT 12	< 1 Day	3540	4300	-	2460*
MONT 13	< 1 Day	3830	4560	-	1800*

- Not Tested
* 7-Day Test Age
1000 psi = 6.895 MPa

APPENDIX 3:

TOXICITY CHARACTERISTIC LEACHING PROCEDURE RESULTS

Table A3.1: TCLP Results for Mixes Containing Separated Spent Blasting Sand and Separated Spent Blasting Dust

MIX I.D. #	7-DAY TCLP, mg/L				28-DAY TCLP, mg/L			
	Pb	Cr	Cd	Al	Pb	Cr	Cd	Al
SDT204D1	0.09	2.17	0.04	37.76	0.04	1.86	0.17	35.56
SDT204D2	0.12	2.16	0.07	40.17	0.05	1.90	0.18	36.17
SDT204D3	-	-	-	-	-	-	-	-
SDT204D4	-	-	-	-	-	-	-	-
SDT205D1	0.14	2.97	0.02	68.30	0.12	2.31	0.14	63.11
SDT205D2	-	-	-	-	-	-	-	-
SDT205D3	-	-	-	-	-	-	-	-
SDT205D4	-	-	-	-	-	-	-	-
SDT206D1	0.05	2.56	0.16	70.60	0.19	2.32	0.10	62.58
SDT206D2	0.07	2.47	0.14	68.91	0.18	2.33	0.11	62.04
SDT206D3	-	-	-	-	-	-	-	-
SDT206D4	-	-	-	-	-	-	-	-
SDT207D1	0.18	1.72	0.15	67.51	0.10	1.71	0.08	35.33
SDT207D2	0.19	1.92	0.19	72.53	0.07	2.00	0.07	32.85
SDT207D3	-	-	-	-	-	-	-	-
SDT207D4	-	-	-	-	-	-	-	-
SDT208D1	0.05	2.65	0.06	35.81	0.11	2.62	0.10	36.96
SDT208D2	0.06	2.29	0.06	37.09	0.13	2.63	0.09	36.45
SDT208D3	0.03	2.41	0.12	38.55	0.07	2.66	0.10	37.57
SDT208D4	-	-	-	-	-	-	-	-
SDT209D1	0.08	1.87	0.06	36.13	0.08	1.84	0.09	36.73
SDT209D2	0.07	1.92	0.09	38.00	0.15	1.99	0.09	36.28
SDT209D3	0.08	1.79	0.10	37.51	0.12	1.89	0.10	36.05
SDT209D4	0.12	1.77	0.09	35.58	0.06	1.86	0.09	35.76

- Not Tested

Table A3.2: TCLP Results for Mixes Containing Unseparated Spent Blasting Sand/Dust

MIX	7-DAY TCLP, mg/L				28-DAY TCLP, mg/L			
I.D. #	Pb	Cr	Cd	Al	Pb	Cr	Cd	Al
SDT200CC1	0.23	23.21	1.23	120.73	-	-	-	-
SDT200CC2	0.14	3.64	0.44	62.63	0.08	1.94	0.07	40.38
SDT200CC3	0.36	7.91	0.90	85.98	-	-	-	-
SDT200CN1	-	-	-	-	-	-	-	-
SDT200CN3	-	-	-	-	-	-	-	-
SDT300	0.04	0.60	0.13	33.60	0.12	0.49	0.08	59.04
SDT301	0.04	0.73	0.12	32.05	0.14	0.72	0.12	67.49
SDT302	0.03	0.98	0.12	31.33	0.10	0.91	0.11	61.27
SDT303	0.07	1.01	0.14	32.52	0.10	0.99	0.17	71.95
SDT304	0.02	0.71	0.03	31.21	0.14	0.61	0.15	62.15
SDT305	0.02	0.62	0.03	30.30	0.09	0.58	0.14	63.41
SDT400	0.17	0.67	0.11	39.92	0.12	0.45	0.14	72.22
SDT401	0.07	0.79	0.03	33.32	0.09	0.68	0.11	61.43
SDT402	0.12	0.46	0.02	32.42	0.11	0.55	0.14	64.32
SDT403	0.19	0.62	0.02	31.95	0.04	0.57	0.13	70.72
SDT404	0.00	0.53	0.05	30.83	0.16	0.58	0.16	63.99
SDT405	0.00	0.49	0.05	30.78	0.07	0.49	0.14	63.74
SDT500	0.07	0.81	0.15	36.39	0.05	0.93	0.16	31.97
SDT501	0.11	1.10	0.15	42.58	0.07	1.09	0.24	36.84
SDT502	0.09	0.93	0.14	40.57	0.04	1.06	0.18	32.56
SDT503	0.08	0.77	0.15	34.73	0.04	0.85	0.29	39.83
SDT600	0.06	0.67	0.15	24.83	0.03	0.59	0.15	31.15
SDT601	0.04	0.61	0.14	24.54	0.04	0.68	0.15	30.43
SDT602	0.04	0.73	0.15	24.88	0.04	0.74	0.15	30.24
SDT603	0.05	0.71	0.34	25.59	0.06	0.63	0.14	29.94

- Not Tested

Table A3.3: TCLP Results for Mixes Containing Concrete Sand and Separated Spent Blasting Dust

MIX	7-DAY TCLP, mg/L				28-DAY TCLP, mg/L			
I.D. #	Pb	Cr	Cd	Al	Pb	Cr	Cd	Al
CM # 1	< 0.07	0.34	0.16	30.76	< 0.07	0.33	0.17	33.32
CM # 2	< 0.07	0.47	0.16	30.36	< 0.07	0.44	0.17	34.36
CM # 3	< 0.07	0.80	0.17	31.05	< 0.07	0.73	0.18	34.58
CM # 4	-	-	-	-	-	-	-	-
SILI 1A	< 0.07	0.20	0.13	30.01	-	-	-	-
SILI 1B	< 0.07	0.44	0.13	29.86	-	-	-	-
SILI 1C	< 0.07	0.70	0.14	30.30	-	-	-	-
SILI 1D	< 0.07	0.80	0.14	30.52	-	-	-	-
SILI 2A	< 0.07	0.40	0.13	29.11	-	-	-	-
SILI 2B	< 0.07	0.46	0.13	29.40	-	-	-	-
SILI 2C	< 0.07	0.73	0.13	29.76	-	-	-	-
SILI 2D	< 0.07	0.73	0.14	29.73	-	-	-	-

- Not Tested

Table A3.4: TCLP Results for Mixes Containing Spent Blasting Slag

MIX	7-DAY TCLP, mg/L				28-DAY TCLP, mg/L			
I.D. #	Pb	Cr	Cd	Al	Pb	Cr	Cd	Al
MONT 1	-	-	-	-	-	-	-	-
MONT 2	-	-	-	-	-	-	-	-
MONT 3	< 0.07	2.38	0.17	33.28	-	-	-	-
MONT 4	< 0.07	1.60	0.17	33.49	-	-	-	-
MONT 5	-	-	-	-	-	-	-	-
MONT 6	-	-	-	-	-	-	-	-
MONT 7	-	-	-	-	-	-	-	-
MONT 8	-	-	-	-	-	-	-	-
MONT 9	-	-	-	-	-	-	-	-
MONT 10	-	-	-	-	-	-	-	-
MONT 11	< 0.07	1.42	0.14	-	-	-	-	-
MONT 12	-	-	-	-	-	-	-	-
MONT 13	-	-	-	-	-	-	-	-

- Not Tested