THE DEVELOPMENT OF A CONSTRUCTION MATERIAL USING ELECTRIC ARC FURNACE DUST

by

Catherine Grace Barnett

Thesis submitted to the Faculty of the
Virginia Polytechnic Institute and State University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

in

Civil Engineering

APPROVED:

R. E. Weyers, Chairman

R. D. Krebs

T. L. Brandon

DECEMBER, 1988

Blacksburg, Virginia

THE DEVELOPMENT OF A CONSTRUCTION MATERIAL USING ELECTRIC ARC FURNACE DUST

by

Catherine G. Barnett

Committee Chairman: Richard E. Weyers
Civil Engineering

(ABSTRACT)

During the 1970s, the United States passed a series of laws regulating the handling and disposal of hazardous material. The new rules drastically increased the cost of processing toxic wastes. Consequently, many producers began investigating methods that would render toxic material non-hazardous. One solution developed was cement encapsulation, a process that incorporates toxic material into a cement matrix, thus solidifying the waste and reducing the potential for the migration of toxins into the environment. This process can be used to prepare a waste for disposal or can be used to develop a construction material, thus mitigating costs further. This solution was selected by Roanoke Electric Steel as a possible way to dispose of electric arc furnace dust, a by-product which contains a

variety of heavy metals which are classified as hazardous by the United States Environmental Protection Agency.

In this study, the furnace dust was incorporated into mortar as a portion of the fine aggregate. By including a chelating agent and a stabilizing agent, mortar was developed which meets the requirements of ASTM C150 with respect to strength and time of setting. The optimum mixture has a 28 day strength of 4500 psi and passed the EP Toxicity test, as required by the Environmental Protection Agency before a material can be delisted. To further validate the use of furnace dust in masonry products, the mortar was evaluated for its dimensional stability, both physical and chemical, and for its freezing and thawing durability characteristics.

ACKNOWLEDGEMENTS

This study was made possible by the support of Roanoke Electric Steel and the Center for Innovative Technology. The support of these agencies is gratefully acknowledged. The author would also like to thank Dr. Richard Weyers for his insight and encouragement, her parents, Lewis and Charlotte Barnett, for their help with the chemistry, her husband, Jonathan B. Meyers, for his support and understanding, and Mohsen Kashi, whose help in the lab was invaluable.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1: INTRODUCTION

Roanoke Electric Steel Corporation creates about 5600 tons of electric arc furnace dust per year in the production of carbon steel from scrap metal. The factory produces 440,000 tons of carbon steel in the form of angles, flats, rounds, channels, squares, and reinforcing steel. The dust produced is assembled in a baghouse collection system.

The electric arc furnace dust contains 60 percent metals by weight and is classified as hazardous under the Code of Federal Regulations, section 40. The other 40 percent is made-up of oxides or carbonates of those metals. Prior to 1980, the material was disposed of in a nearby private landfill. That fill has been closed, and since that time the dust has been sent to the Horsehead Resource Development Company in Palmerton, Pennsylvania, for zinc reclamation and disposal. Both the transportation and disposal of the dust are expensive, and the reclamation of zinc provides only minor savings and is dependent on the market demand for zinc. The Horsehead Resource Development Company is under no contract with Roanoke Electric Steel and may stop accep-

ting the dust at any time. Continued reclamation is presently not considered an acceptable long term method of disposal (1).

Because of the excessive costs associated with the disposal of the electric arc furnace dust, Roanoke Electric Steel Corporation has elected to explore methods of stabilizing the hazardous material. A preliminary study was performed by Olver, Incorporated, of Blacksburg, Virginia. They determined the constituents of the furnace dust material (see Table 1) and developed a stabilization process which rendered the dust material acceptable within the limits of the EP Toxicity Test (2). This stabilization process uses cement and flyash in conjunction with a stabilizing chemical and a dispersing agent.

Roanoke Electric Steel has already received permission from the Environmental Protection Agency to develop a hazardous waste treatment system. Work has begun on a dust collection system which will homogenize the furnace dust and insure a consistent waste product. This system will be directly connected to the waste stabilization system so that all processing can be accomplished on site. The stabilized waste will be disposed of in a nearby landfill, sanctioned by the Virginia Department of Waste Management.

The purpose of this research is twofold. The first object is to continue the research started by Olver and

TABLE 1: UNTREATED DUST CONSTITUENTS				
Results based on six grab samples				
METAL	MEAN (mg/kg)	MEDIAN (mg/kg)	STANDARD DEVIATION (mg/kg)	COEFFICIENT OF VARIATION (%)
CALCIUM	20767	20480	972	4.7
MAGNESIUM	23648	23805	1037	4.4
IRON	363250	360750	8756	2.4
CADMIUM	554.3	550.5	18.9	3.4
LEAD	33618	33675	2634	7.8
ZINC	159760	160100	7850	4.9

perfect the solidification/stabilization technique which renders the material nonhazardous for disposal in an approved industrial monofill. The second object is to develop a construction material that incorporates the dust material as an aggregate and is economical, environmentally sound, and physically competent.

For a cement-based construction material to be acceptable, it must perform well in a variety of situations. The most basic requirement is compressive strength, which establishes the structural uses of a material. Another fundamental property of a cementing material is setting time. The mixture must set within a reasonable period of time for processing to be economical. If a mixture sets too quickly it may be impossible to place or may ruin construction equipment; if it sets too slowly, it can decrease the rate of processing. These two properties provide the basis for this research in developing both the landfill disposal mixture and the construction material. The strength and set requirements for the landfill were developed for our processing system. The construction material will be governed by the guidelines established by ASTM C150, "Standard Specification for Portland Cement," which requires the compressive strength to reach or exceed 1800 psi and 2800 psi at three and seven days respectively, and which requires the mortar

to set in not less than 45 minutes and not more than eight hours. In addition to these two fundamental tests, the final construction material mixture will be tested for chemical and physical stability and for freeze-thaw durability.

The chemical stability of the construction material was tested using an autoclave. This test indicates if the dust contains any constituents which would react unfavorably with the chemicals in the cement. The physical stability test is similar in purpose to the chemical test. This is a long-term test in two environments, saturated and dry, to insure that the material will not shrink or expand in a way that would be detrimental in construction use. In both of these tests, the dust mixture was compared to a control mortar mixture.

The freeze-thaw durability of the specimens was determined by subjecting the mixture to a number of cycles of freezing and thawing as defined by ASTM C666, "Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing," part A. The dust mixture was air-entrained to determine if an acceptable air void system could be established in the dust samples. The air void system is the key to durability. The results will be compared to those for a control mortar sample.

CHAPTER 2: LITERATURE SEARCH

2.1. THE EFFECT OF HEAVY METALS ON THE HYDRATION OF CEMENT

In the development of any construction material where cement is used as a binding agent, the most important consideration is how an unusual constituent will affect the hydration of the cement. The addition of a foreign substance can affect the behavior of the mortar in a variety of ways, including strength and durability. The electric arc furnace dust is composed of heavy metals and compounds of those metals. These metals include iron (36.3 percent), zinc (16.0 percent), lead (3.4 percent), magnesium (2.4 percent), calcium (2.1 percent), and cadmium (0.1 percent) for a total of approximately 60 percent of the dust. The other 40 percent is made up of carbonates, oxides, and other compounds of the metals (1).

Portland cement is primarily composed of four compounds: tricalcium silicate, dicalcium silicate, tricalcium aluminate, and tetracalcium aluminoferrite. In the chemistry of cement, the oxides involved are abbreviated as follows: CaO=C, SiO_2=S, Al_2O_3=A, and Fe_2O_3=F. Using this

nomenclature, the major constituents are designated C_3S (tricalcium silicate), C_2S (dicalcium silicate), C_3A (tricalcium aluminate), and C_4AF (tetracalcium aluminoferrite). These abbreviations will be used throughout this report.

The hydration of each of these compounds begins with the addition of water, but the different compounds do not hydrate at the same rate. C_3A and C_3S react first. To prevent the flash set of C_3A, gypsum is added to cement. These two compounds combine to form ettringite, which is usually the first crystalline structure to appear, and monosulfates. As the cement structure begins to develop and hydration continues, the ettringite is transformed into monosulfate (3).

The calcium silicates, which represent approximately 70 percent of ordinary portland cement, form calcium silicate hydrates having the approximate chemical formula $C_3S_2H_3$. These crystals compose the bulk of the volume and the strength of the cement paste. This material is sometimes called tobermorite gel, a name which refers to the poorly defined crystalline structure of the stiff gel formed during hydration.

The role of C_4AF is small. Mehta states that Al_2O_3 and Fe_2O_3 are included in cement because these compounds allow calcium silicates to form at reduced temperatures during the clinkering process (3,4). Neville suggested that C_4AF ful-

fills no positive role in the hydration process and stated that when hydrated, $CaOFe_2O_3$ forms as a colloidal gel which surrounds unhydrated particles of cement, actually inhibiting further hydration (5).

This phenomenon might explain the behavior of other metals in the presence of hydrating portland cement. Lead has been recognized for years as a retarder, from experiences using mine tailings as aggregate. Lea noted that the inclusion of as little as 0.001 percent soluble lead oxide could retard the hydration process (6).

This type of behavior was also observed by Thomas et al. in a series of experiments to determine the effect of lead nitrate on the hydration of cement (7). Thomas's experiments included solution analysis, calorimetry, and electron microscopy. He observed the rapid formation of a colloidal gel containing lead around cement particles. This membrane seriously affected the development of early strength gain but did not stop hydration. Despite this decrease in early strength gain, the long-term strength did not seem to be affected. Thomas postulated that other metals such as copper and zinc would also behave in the same manner, and, zinc oxide has, in fact, been used as a retarder (6).

Tashiro et al. performed a variety of experiments with

different heavy metals (8,9,10). Their work confirmed the earlier behavior attributed to lead but also emphasized the unique behavior of each element. The first experiment measured the effects of a variety of heavy metals on the development of mortar strength (8). Each of the metals tested (chromium, copper, zinc, arsenic, cadmium, mercury, and lead) had a negative effect on the compressive strength of mortar. The amount of reduction varied from metal to metal, with the largest decrease shown for mortar containing 5 percent copper or lead by weight.

Tashiro et al. investigated the effect of metals further by determining the effect of chromium, iron, copper, zinc, and lead on ettringite (9). This study included calorimetric analysis and compressive strength tests. The calorimetric study showed that, except in the case of lead, the inclusion of heavy metals caused an increase in the heat of hydration during the first two minutes. The increase was most pronounced for chromium and copper and promoted the growth of ettringite. Along with this increase came an increase in the porosity of the crystalline structure, defined by an increase in the average pore size. This effect was also seen with lead.

Further studies were performed to measure effects on the compressive strength of C_3A paste (10). Chromium, copper, and zinc each retarded the early hydration of C_3A;

copper and zinc retarded the early development to a large degree. Lead hindered the immediate hydration but then actually accelerated crystal growth, yielding a final product with a reduced compressive strength.

2.2. ENCAPSULATION TECHNIQUES

During the 1970s, the United States passed a series of laws concerning the handling and disposal of hazardous material. The most significant of these laws was the Resource Conservation and Recovery Act of 1976. This law defined what would be considered a hazardous material, stipulated handling and transportation requirements, and established disposal restrictions. Materials which had previously been disposed of indiscriminantly now were closely monitored (11).

A variety of problems accompanied these new rules. New regulations drastically increased the cost of disposal. In many cases, the material had to be transported hundreds of miles under strict guidelines to a landfill which was designated safe for that type of waste. Consequently, many producers began investigating methods that would render toxic material nonhazardous and therefore allow disposal in local landfills. One solution was cement encapsulation, a process that incorporates toxic material into a cement matrix, thus solidifying the waste and reducing the poten-

tial for the migration of toxins into the environment.

Due to the variability in toxic materials around the country, a variety of cement stabilization techniques exist (12). Many of these are applicable to only one waste, and many are proprietary, making a complete survey of techniques impossible. Cement encapsulation was first used to bind radioactive material (13) but has evolved to include a variety of both organic and inorganic materials.

Cement stabilization is attractive for a number of reasons. Cement can solidify a previously liquid product, thus facilitating transportation and disposal. By incorporating a waste into a cement binder, the surface-area-to-volume ratio of that waste, the amount of water available to outside influences such as groundwater, is reduced. This yields a material with a reduced permeability and subsequently reduces the solubility of the toxin. The use of cement is especially relevant with heavy metals. The pH of a cementitious material is high (around 12), creating an environment in which heavy metals are naturally less soluble (14).

Cement is not the only material which has been used for encapsulation. Other encapsulators used are polyesters, pozzolans, or cement mixed with another binder such as silicates (15). However, cement has an economic advantage.

The raw materials required are inexpensive, no special processing equipment is required, and no special personnel are needed (15).

Webster and Kukacka (16) studied the effectiveness of a variety of encapsulating techniques on geothermal residues. They studied five separate fluids containing inorganics including arsenic, lead, cadmium, and chromium as well as the radioactive elements radium, thorium, and actinium. They compared cement to a polyester, a methyl methacrylate-based monomer system, sulfur encapsulation, and magnesium polyphosphate cement mortars. They concluded that the portland cement system produced the best results with 28-day compressive strengths comparable to or higher than a control mortar for four out of five residues. In addition to the exceptional strength, the cement based product also had the advantage of using the residue material directly, some processes required washing and drying the geothermal fluids. The cement product passed the EPA toxicity test and was economical.

Further analysis was conducted on the cement fixed material. Webster and Kukacka used seven percent toxic material by weight in their preliminary studies and noted that increasing that percentage to 18 percent yielded much lower compressive strengths. They also noted that the inclusion of the geothermal residue increased the void

volume of the mortar and yielded a reduction (three to 23 percent) in compressive strength for samples which had undergone 100 freeze-thaw cycles. The control mortar exhibited a four percent reduction in strength under the same test.

One important note should be mentioned in consideration of the research performed by Webster and Kukacka. When they received the residues in drums, the solid portion had settled. Before testing any of the residue, the fluid on top was decanted, thus reducing the amount of soluble heavy metals present in the waste. Since this research did not include any compression tests on samples younger than 28 days, it is impossible to determine if the soluble metal ions in the geothermal residues affected the early hydration of the cement or if this problem was diminished by the removal of the aqueous portion of the waste.

Cement encapsulation was also successful in treating sand blasting refuse (17). This refuse consisted of fractured glass beads and paint particles and contained cadmium and lead. Substituting as much as 15 percent by weight as an aggregate in concrete yielded a product acceptable for use as a construction material and environmentally safe.

2.3 CEMENT AS A STABILIZING MEDIUM

The actual mechanism involved in the stabilization of heavy metals in cement can be either chemical or physical (18). Chemical stabilization occurs with some metals, such as cadmium and zinc, which are rendered insoluble by the high alkalinity of the cement media. These metals combine with various ions such as hydroxides or carbonates to form metal salts (19). A shift in the pH of the media towards acidity would cause the metal ion to again become soluble. The pH at which this occurs varies from metal to metal. The alkaline behavior of cement causes cadmium and other metal ions to precipitate out of solution in insoluble compounds. This is the key to the effectiveness of the cement media as an encapsulator but has the drawback of retarding the hydration of cement, as discussed earlier in this chapter. These metal compounds precipitate out of solution and form a layer around the cement particles, inhibiting hydration (18).

Because the timely setting of cement was important for the processing of the dust material in this research, it was imperative to discover some method of preventing this precipitation while maintaining the insolubility of the metal ions. Chelating agents were used to attempt to bind the metals in a form that would not affect the hydration process.

The physical mechanism of stabilization can be used for metals such as mercury where the precipitation discussed above does not happen. For these metals, stabilization is accomplished by providing a physical barrier between the soluble metal and the potential leachate (18). Stabilization is enhanced by a strong, impermeable media.

2.4. CHELATING AGENTS

The term chelating or sequestering agent refers to an organic or inorganic compound which combines with an ion to form a coordination compound (20). This complexing is similar to the reaction discussed above where the metal cations combine with hydroxide anions and precipitate out of solution. The reaction between a metal and a chelating agent is also reversible. With a decrease in the pH of the solution, the metal ion can again become soluble. However, in a environment with a high pH, such as cement, the coordinate bond is extremely stable.

Chelating agents have been used successfully in a variety of commercial applications for years (21). When added to hard water, a chelating agent will prevent the precipation of insoluble calcium or magnesium by bonding with those metals. Sequestering agents are also used to remove trace metals from products such as textiles or natural oils.

Little research has been conducted on how a chelating agent affects the hydration of cement. Yau and Hartt experimented with a chelating agent in concrete to determine if it could be used to reduce the detrimental effects associated with the corrosion of steel bars (22). They found that the chelating agents were effective in increasing the iron ion solubility, thereby decreasing the problems caused by corrosion. They also noted that the chelating agents decreased the compressive strength of the concrete. Although it varied with different compounds, the average decrease in strength was 980 psi, for a control strength of 6000 psi.

CHAPTER 3: PROCEDURES

3.1 SCOPE

The procedures described in this chapter were used to fulfill the objectives stated in Chapter 1. These objectives, briefly noted, were (1) to develop a mixture suitable for disposal in an approved landfill, and (2) to develop a second mixture, competent for use as a construction material. Both mixtures were tested for compressive strength, time of setting, and EP toxicity. Compressive strength and time of setting were used to develop a final optimum mixture for each of the two objectives; minimum requirements were established for each mixture based on these two parameters. The landfill mixture was then tested only for environmental safety with the EP toxicity test, while the construction material was tested for environmental safety, physical and chemical stability, and freeze-thaw behavior.

3.2. COMPRESSIVE STRENGTH

3.2.1 General. The compressive strength of the mortar mixes, both with and without electric arc furnace dust, was determined from two-inch square cubes meeting the require-

ments of ASTM C109, "Standard Test Method for Compressive Strength of Hydraulic Cement Mortars." All testing was conducted on a Forney Compression Machine, Model No. LT-0704, with a maximum system capacity of 400,000 pounds. The specimens were loaded at a rate of approximately 10,000 pounds per minute, a rate at which failure should occur in 20 to 80 seconds. Testing was performed on the cubes at the ages of 24 hours and three, seven, and 28 days. The fine aggregate used for the compressive tests was Ottawa sand conforming to the requirements of ASTM C109. Type I cement was used.

The results obtained for the specimens produced using dust and chemicals were compared to control mixtures containing the same relative amounts of water, cement, and aggregate. These results, for both dust and control mixtures, were compared to the "Standard Physical Requirements" specified in Table 2 of ASTM C150, "Standard Specification for Portland Cement." This section specifies minimum compressive strengths of 1800 psi and 2800 psi at three and seven days respectively.

3.2.2 Mixing. All compressive-strength samples were mixed according to ASTM C305, "Standard Method for Mechanical Mixing of Hydraulic Cement Pastes and Mortars of Plastic Consistency." The procedure was adapted as described below to include the furnace dust. All mixing was accom-

plished using a Hobart Mixer, Model N50.

After weighing out all the ingredients, the chemicals were added to the mixing water. The dust was added to this aqueous mix and stirred by hand to coat the dry particles. The mixture was placed in the electric mixer and mixed at slow speed, approximately 140 rpm, for 60 seconds. The cement was added to the dust and water in two parts, mixing 30 seconds each time at slow speed. Maintaining this speed, the sand was slowly poured in over 30 seconds. Once all the ingredients had been incorporated, the speed was increased to medium, approximately 285 rpm, for 30 seconds. The mortar was then allowed to sit for 90 seconds before mixing a final 60 seconds at medium speed.

3.2.3 Flow. The flow was determined for many mixtures from which compressive strength samples were made. Flow was not a determining factor in mix design but was a way of measuring the effects the various chemical used had on the consistency of the mortar. Flow was determined by the method specified in ASTM C109, as described below, with a Forney Model LA 4225 Flow Table.

Once mixing was completed, the flow mold was placed at the center of the clean, dry flow table and was filled halfway with mortar. Using a 1/2 by one by six-inch rubber tamper, the mortar was compacted with 20 even strokes. This

step was repeated, filling the mold to slightly overflowing. After the second tamping, the excess mortar was cut off the mold by drawing the edge of a trowel across the surface of the mold in a sawing motion. Once filled, the flow mold was lifted from the mortar, and the flow table was dropped 25 times in 15 seconds. The breadth of the mortar mass was then measured in along four different diameters, approximately 45 degrees apart. The flow is the average increase in the diameter of the mortar and is expressed as a percentage of the original diameter.

Once the flow was determined, the mortar was returned to the mixing bowl and remixed into the batch at medium speed for 15 seconds before molding.

3.2.4 Molding Compressive Test Specimens. The test specimens for the compressive strength tests were formed in brass molds in sets of three cubes. The molds were filled approximately half full with mortar and tamped 32 times with the rubber tamper described in section 3.1.3. Tamping was accomplished in four rounds of eight strokes each, turning the tamper 90 degrees between each round. The mold was then filled to overflowing and tamped again in the same manner. The excess mortar was cut off flush with the surface by drawing a trowel across the molds in a sawing motion. This process was completed for each set of three cubes before advancing to the next mold.

The mortar cubes were allowed to remain in the molds for 20 to 24 hours before removal. For some of the preliminary dust mixtures, the strength obtained in 24 hours was not sufficient to successfully remove the cubes without fracturing them. In these cases, only one set of three cubes was removed from the mold; the other cubes were allowed to set in the molds for 48 hours.

3.3. TIME OF SETTING

3.3.1 General. The setting characteristics of mixtures containing different percentages of dust and/or chemicals as well as control mixtures were determined by the procedure established in ASTM C807, "Standard Test Method for Time of Setting of Hydraulic Cement Mortar by Vicat Needle." The vicat needle apparatus consists of a rod mounted in a frame; the rod or plunger is 10 mm thick at one end and contains a needle at the other end. The plunger can be rotated so that either end can be used. To measure consistency or set, the rod was placed at the surface of the mortar and then allowed to move freely under the weight of the plunger. Penetration is defined as the distance the rod or needle moves through the mortar in 30 seconds.

The mortar tested contained 750 grams cement, 375 grams water, and enough sand to produce the consistency described below. For comparison relative to the compressive

strengths, chemicals and dust were added in percentages relative to the weight of cement used. This was necessary to reproduce exactly any effects the dust or chemical would have on the setting time of cement.

3.3.2 Mixing. Mixing was consistent with the procedure described in section 3.1.2.

3.3.3 Molding and Consistency. Once a trial mixture had been prepared, it was placed in the mold to determine if the consistency was acceptable for testing. The mold was first filled half full with mortar, and puddled with the rubber tamper by tapping the small end of the tamper fourteen times around the perimeter of the mold. The rubber tamper was tapped lengthwise four times on the top of the mold, rotated approximately 45 degrees between taps. The mold was then filled to slightly overflowing and puddled as before. Excess mortar was cut off the mold by drawing a trowel across the top surface using a sawing motion. The consistency of the mortar was considered to be acceptable when the rod, with weight attached for a total weight of 400 grams, penetrated the mortar to a depth of 20 plus or minus four mm in 30 seconds. The larger end of the rod was used for this determination. If the rod penetrated further, the mortar was removed to the mixing bowl and more sand was added incrementally until the correct consistency was ob-

tained. The mortar was then remixed and the mold was filled and puddled for the last time for measurement of time of setting.

3.3.4 Time of Setting. The mold containing mortar of the correct consistency was placed in the moisture room. The test for time of setting uses the Vicat Needle apparatus, with a rod weighing 300 grams, and a needle with a diameter of two mm. Penetration was measured at 30 minute intervals after the mortar was placed in the moisture room. Once the cement had begun to set, and penetration was no longer complete, a measurement was taken every 10 minutes. The time of setting is defined as the time at which the two-mm needle penetrates 10 mm. Measurements were taken until penetration was less than 10 mm, and then the time at which penetration was 10 mm was determined graphically.

3.4. CHEMICAL STABILITY

3.4.1 General. The chemical stability of cement is determined by measuring the length change of a specimen after it has been subjected to steam pressure and high temperatures in a Boekel Cement Autoclave, Model No. 25515-016. Specimens made with dust and the optimal amounts of stabilizing chemicals were tested and compared to control cement specimens to make sure that the metals in the dust

material, which include magnesium and calcium, would not cause unsoundness.

3.4.2 Mixing. The specimens were mixed in accordance with section 3.1.2 up to the point where sand was added. No sand is included in autoclave specimens. Each control batch contained 650 grams cement and enough water to produce a normal consistency; dust samples contained 650 grams cement and the relative amounts of dust and chemicals determined for the optimum construction mixture.

3.4.3 Molding. Following mixing, the cement or cement and dust paste was pressed into molds in two layers, using the forefingers. The specimens produced were one x one x 10-inches. Gage studs were set into the samples to facilitate length measurement.

3.4.4 Autoclave Testing. The specimens were allowed to cure in the moisture room for 20 to 23 1/2 hours before removal from the molds. At the age of 24 plus or minus 1/2 hour, the specimens were weighed and measured and placed in the autoclave. The autoclave was then heated and pressurized to achieve 295 psi and 420 degrees fahreinheidt in 45 to 75 minutes. This temperature and pressure was maintained for three hours. The heater was then turned off and the pressure was slowly released to obtain atmospheric pressure in approximately 1 1/2 hours. The specimens were then removed from the autoclave and placed in water at 90 degrees

celsius. The water was cooled to 23 degrees celsius in 15 minutes by adding cool water. After allowing the specimens to remain in the water for 15 additional minutes, the specimens were removed and dried, and the weight and length were measured. The change in length, expressed as a percentage of the original length, indicates any undesirable chemical change. ASTM C150, "Standard Specification for Portland Cement," allows 0.8 percent expansion.

3.5. PHYSICAL STABILITY

3.5.1 General. The physical stability of the construction material containing dust was determined in a procedure adapted from ASTM C157, "Standard Test Method for Length Change of Hardened Cement Mortar and Concrete." Our procedure followed the requirements for water and air storage using only one set of test specimens and transferred them from water storage to air storage at an age of 56 days instead of determining the affects of the different environments on two sets of specimens.

3.5.2 Mixing. The specimens were mixed by the procedure described in section 3.1.2.

3.5.3 Molding. To determine physical stability, specimens were prepared in the same way as for chemical stability testing, as described in section 3.3.3. The specimens for

physical stability, however, contain sand in the proportions determined for the optimum mixture.

3.5.4 Physical Testing. The specimens were removed from the molds after 20 to 24 hours. At the age of 24 plus or minus 1/2 hours, the weight and length of each specimen were measured using a Humboldt Length Comparator, Model H3250. The specimens were then placed in lime-saturated water for 56 days. The length and weight were measured every two weeks, the specimens returned to the water between measurements. After this period, the specimens were transferred to a drying chamber where the humidity was maintained at 50 percent relative humidity by a pan of magnesium nitrate. Evaporation was sustained by a fan installed in the drying chamber. The specimens remained in the chamber for 56 days; weight and length were measure every two weeks.

3.6. FREEZING AND THAWING BEHAVIOR

3.6.1 General. Large specimens, three by four by 16 inches, were prepared to determine how the electric arc furnace dust and the required chemicals would affect the ability of an air-entraining agent to develop an air-void system adequate for resistance to freezing and thawing. The specimens were made using a natural sand instead of the Ottawa sand used in the other testing. Both dust-mortar and control-mortar specimens were prepared and tested.

3.6.2 Mixing. The freeze-thaw samples were prepared in a large mixer in batches larger than 100 pounds. The bowl of the mixer was wiped with a damp rag before mixing to insure that the bowl would not absorb water from the mixture. The water required for the batch was divided in half. One half was mixed with the stabilizing chemicals and one half was mixed with the air-entraining agent. The dust was added to the water containing the chemicals and mixed manually until all the dust particles were coated. The sand was first added to the mixer and blended slightly. The dust, water, and chemical mixture was slowly added to the sand as it mixed, allowing the sand to be thoroughly coated. The cement and the remaining portion of the water were then added alternately to insure consistent mixing. Once all the ingredients were added, mixing continued for three minutes. The mass was then allowed to stand for three minutes and finally mixed for two more minutes.

3.6.3 Batch Testing. Once the mixing process had been completed, the mortar was tested for workability and air content. Workability was determined by measuring the slump and the flow; air content was measured using a pressure meter. The weight of a specified volume of the mixture was also obtained so the unit weight of the batch could be determined.

3.6.4 Molding. For each batch, both freeze-thaw speci-

mens and compressive-strength specimens were prepared. The compressive-strength samples were molded and tested in the manner described in section 3.1. Freeze-thaw specimens were molded in two layers. Each layer was rodded with a 3/8-inch diameter rod 48 times. The excess material was scraped from the top with a trowel. The freeze-thaw specimens were allowed to remain in the mold for 20 to 24 hours before demolding.

3.6.5 Freeze-Thaw Testing. At the age of 24 hours, the freeze-thaw specimens were placed in lime-saturated water where they remained for 14 days. The samples were then weighed, and the initial fundamental frequency was determined by the method described in section 5.6. Once tested, the specimens were placed in stainless steel containers in a Logan Freeze-Thaw Machine, Model H3185. The specimens were subjected to freezing and thawing as specified in ASTM C666, "Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing," procedure A. Each cycle took approximately four hours. Testing was performed at intervals of less than 30 cycles; testing was more frequent during the first week of freezing and thawing. The specimens were rotated through the freeze-thaw apparatus and were turned over after each testing period. Freezing and thawing of the specimens was continued for 300 cycles or until the relative

dynamic modulus of elasticity, determined from the natural frequency, was 60 percent of the initial modulus.

3.6.6 Fundamental Frequency. To determine the relative dynamic modulus of elasticity of the freeze-thaw specimens, they were tested according to ASTM C215, "Standard Test Method for Fundamental Transverse, Longitudinal, and Torsional Frequencies of Concrete Specimens." The specimens were placed on a thick sponge which allowed them to vibrate freely and were subjected to varying frequencies. A driving force was positioned normal to the bottom surface of the specimen at the center of one end, and the frequency was picked up at the opposite end, at the center of the top surface. This yielded the transverse frequency. The fundamental frequency was that which resulted in a maximum peak, which could be observed by a peak in the amplitude seen in the oscilloscope and which was accompanied by a maximum peak in voltage.

3.6.7 Comparison of Freeze-Thaw Systems. In order to determine how the dust material affected the air-void system in mortar, a linear traverse machine was used to measure the air content and the air-bubble size of various samples. During the batching of the freeze-thaw samples containing the dust material, three by six inch cylinders were prepared. These cylinders, and the freeze-thaw specimens that had been subjected to freezing and thawing as described

above, were cut and polished using equipment produced by the Contempo Lapidary Company. These samples were then inspected using a linear transverse machine. The results from this analysis were used to determine how the dust and the chemicals affected the air-void system in the mortar.

3.7. EP TOXICITY TEST

3.7.1 General. To determine if the stabilizing procedure had rendered the dust material nonhazardous, the optimum landfill and construction material mixtures were subjected to an EP Toxicity Test, as defined by 40 CFR, Chapter 1, paragraph 261.24.

3.7.2 Sample Preparation. Samples were prepared in the same manner as compressive-strength specimens, as described in section 3.1. Cube samples were molded and tested for compressive strength at 24 hours. The specimens were then crushed, and 100 grams of dust mortar was weighed out for the EP Toxicity Test. The material was crushed fine enough to pass through a number 10 sieve.

3.7.3 Extraction. The crushed samples were placed in a beaker with 1600 ml of deionized water and were agitated by a Phipps and Bird Six Paddle Stirrer, Model no. 300, at a rate in excess of 100 rpm. The solution was stirred for a total of 24 hours; during the first period of mixing, the pH

was monitored. If the pH was greater than five, 0.5 normal acetic acid was added to the solution until a pH of five plus or minus 0.2 was attained. The pH was checked every 15 minutes until the pH stabilized and then every 30 minutes during the first six hours of agitation. No more than four ml of acid could be added for each gram of sample; once 400 ml of acetic acid had been added, the pH was no longer monitored. After the extraction period, the liquid-to-solid ratio was 20 to one.

3.7.3 Filtration. After the sample was stirred for 24 hours, the solution was allowed to settle, and the top portion was decanted. This step was taken to facilitate filtration. The aqueous portion was filtered using a vacuum filter apparatus and a 0.45 um membrane. A 100 ml portion of filtrate was collected for the acid digestion process.

3.7.4 Digestion. In order to insure that the samples would yield the correct amounts of metals, and to remove any other constituents which could impair measurement, the samples were digested. The 100 ml sample of filtrate was placed in a beaker along with three ml of concentrated nitric acid. The beaker was then covered and slowly heated until the solution evaporated to near dryness. At this point, an additional three ml of nitric acid was added, and the beaker was again heated until a gentle reflux action oc-

curred. This process continued, with additional acid when necessary, until the digestate was clear. The sample was again allowed to evaporate to near dryness. A final aliquot of nitric acid was added to yield a concentration of 0.5 percent of the total volume. The beaker was heated slightly to dissolve any residue, and deionized water was added to attain a sample size equal to the original 100 ml.

3.7.5 Metal Concentrations. The metal concentrations resulting from the extraction procedure were determined by testing the digested sample using a Perkin-Elmer Atomic Absorption Spectrophotometer, Model 703. The results were directly compared to the maximum concentrations allowed by the Environmental Protection Agency to determine if the material would be considered hazardous.

CHAPTER 4: DEVELOPMENT OF OPTIMUM MIXTURES

4.1 CHARACTERISTICS OF ELECTRIC ARC FURNACE DUST

The electric arc furnace dust is a fine brown powder that appears to be homogeneous in size and content. Periodic testing by Olver, Inc., confirmed that the material was consistent in composition (1). The dust passes through a number 200 sieve (0.074 mm); hydrometer analysis showed that approximately 70 percent of the dust was larger than 0.02 mm, so the dust particles are slightly larger, on average, in size than cement particles. The specific gravity of the dust is 4.45.

4.2 DEVELOPMENT OF OPTIMUM CONSTRUCTION MATERIAL

The research performed by Olver was designed to transform the electric arc furnace dust into a solid mass which would be environmentally sound and disposable. They arrived at a mixture which used a combination of cement and flyash to solidify the dust, a stabilizing agent to chemically stabilize the dust, and a dispersing agent to facilitate coating of the dust particles. They performed a series of environmental tests on the resulting solid and confirmed its

environmental acceptability.

Our research stemmed from this original study. Mortar cubes were prepared using the mixture developed by Olver. The cubes formed did not exhibit a measurable compressive strength until the seven-day test, when a strength of 54 psi was attained; at 28 days, the mixture had a strength of 61 psi. These results demonstrated that the mixture was not suitable for use as a construction material and indicated that it would not be satisfactory as a landfill mixture, because the slow gain in strength would inhibit processing.

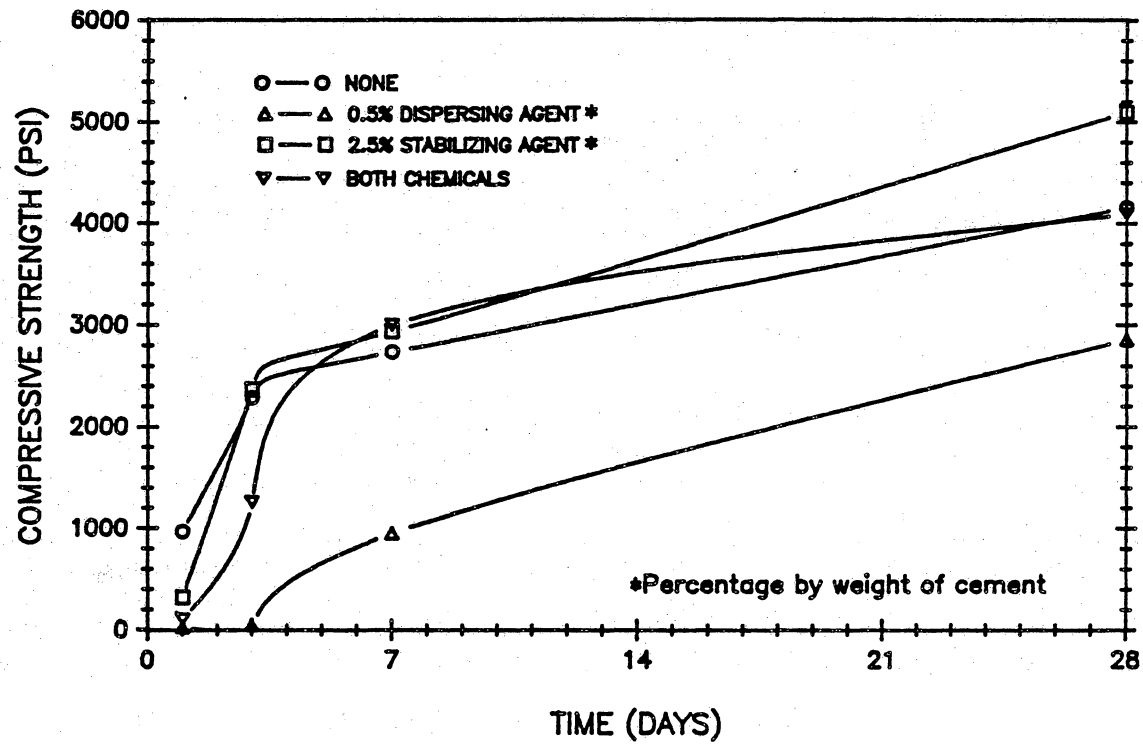
A cursory review of the Olver mixture suggests why its compressive strength increased so slowly. The water-to-cementitious-material ratio was greater than one, and half of the cementitious portion was flyash, which would not contribute to the early strength. While these relationships could yield an environmentally safe mixture, they are not conducive to material strength.

An adjusted mix design was developed from the proportions described in ASTM C109, "Standard Test Method for Compressive Strength of Hydraulic Cement Mortars." This yielded a water-to-cement ratio of 0.48 and a fine aggregate-to-cement ratio of 2.75; the cementitious portion was adjusted to 75 percent cement and 25 percent flyash by weight. The stabilizing agent and dispersing agent were

maintained in the same proportions as the original because the Olver mixture had yielded an environmentally acceptable product. The results were encouraging. The mixture had a one-day strength of 200 psi. The research then shifted to exploring what effects the individual ingredients of the mixture had on the hydration of the cement, and how these effects could be adjusted to develop a better product.

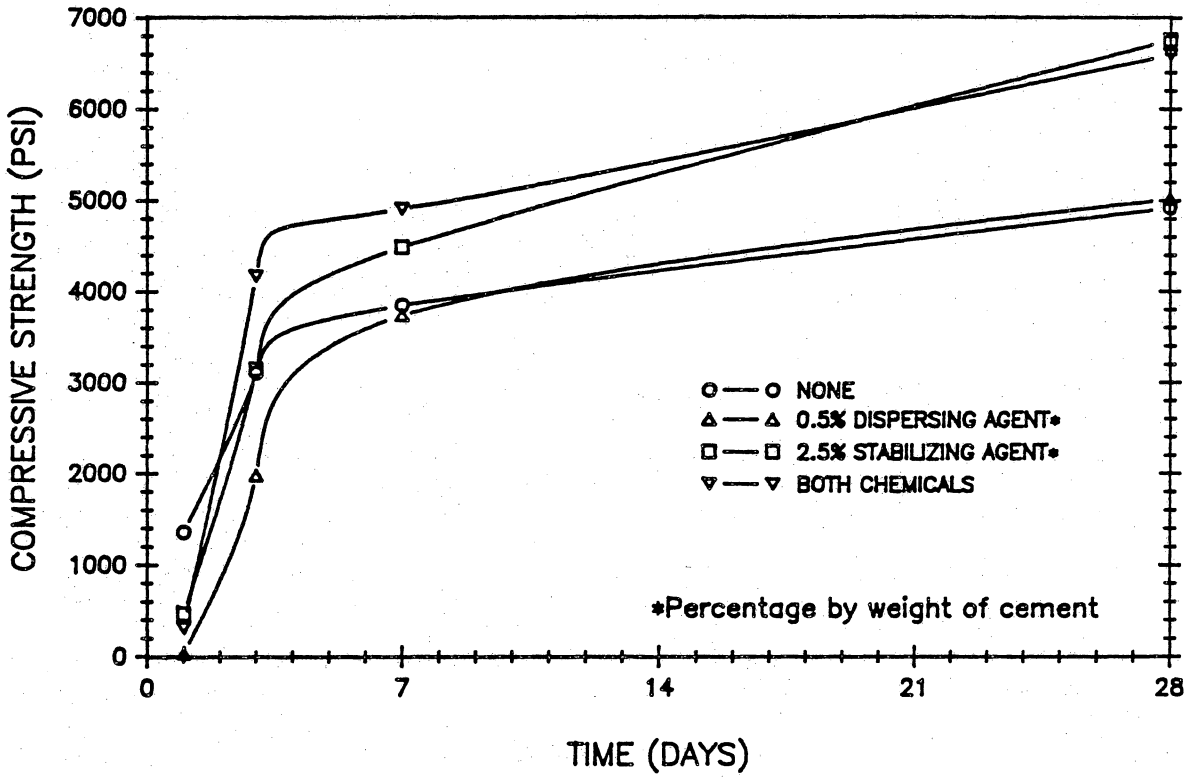
A mortar mixture was made without the stabilizing and dispersing agents. The cubes attained no strength until seven days, when they reached a strength of 42 psi, but at 28 days the compressive strength was 2900 psi. This dramatic gain in strength demonstrated that the dust itself was inhibiting the early hydration of the cement and is consistent with the literature discussed in Chapter 2. Our original adjusted mixture, described above, never reached the same strength as this mixture but showed strength at earlier ages. This suggests that the chemicals were also affecting the hardening of cement.

To explore these effects further, a series of control mixtures was tested. A comparison of the effects of the stabilizing agent, the dispersing agent, and both together is shown in Figure 1, for control mixtures with flyash, and in Figure 2, for control mixtures without flyash. In all cases, the additives decreased the early gain of strength. The dispersing agent alone seemed to have the largest affect



THE EFFECT OF CHEMICALS ON THE CONTROL MIX WITH FLYASH

FIGURE 1



THE EFFECT OF CHEMICALS ON THE CONTROL MIX WITHOUT FLYASH

FIGURE 2

on the gain of strength of the mixture, and caused a decrease in the strength for the duration of testing for the sample with flyash. At later stages, the other combinations of chemicals seemed to have little detrimental effect. In fact, the control mixtures containing the stabilizing agent exhibited greater strength than those without the chemical.

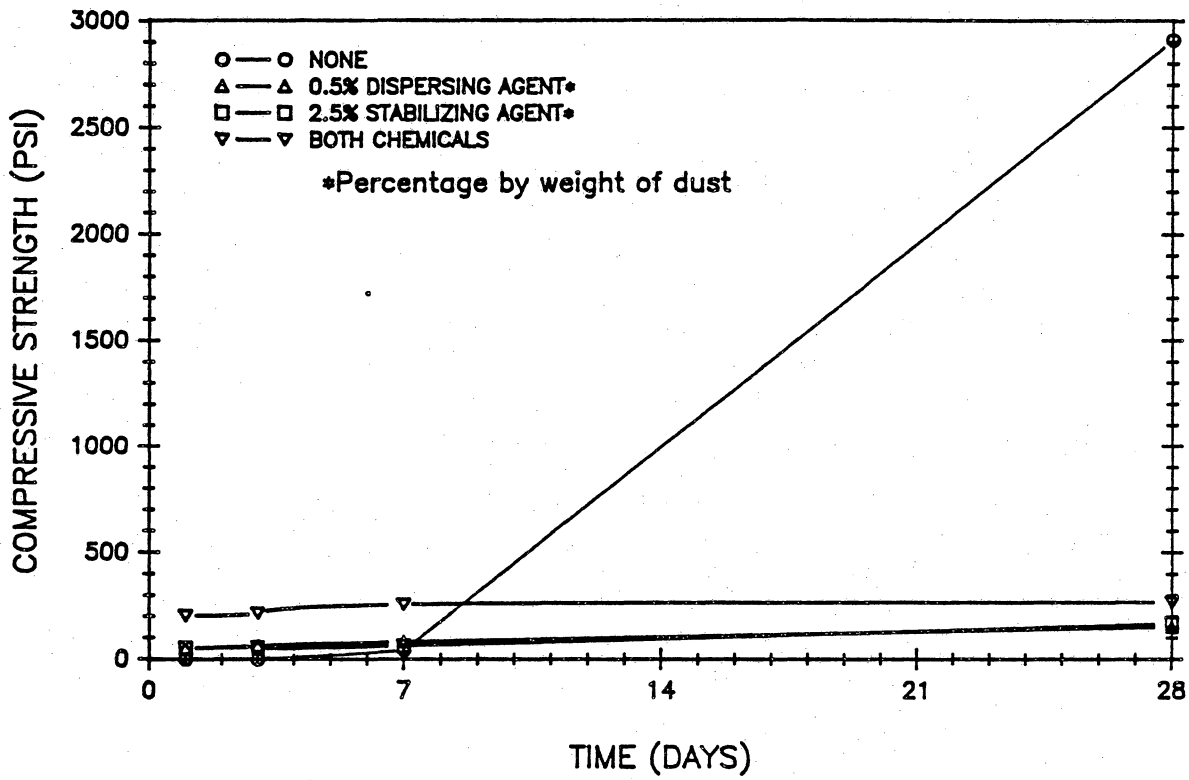
A study of the chemicals was continued by determining the effect on time of setting, as measured using the Vicat needle. These tests were performed on a control mix, adding the chemicals in the same proportion by weight of cement as in the Olver design mixture. The control mix with no additives set in 160 minutes. The addition of the stabilizing agent caused the setting time to increase slightly, time of setting to 192 minutes; the dispersing agent caused a large increase in time of setting, to 485 minutes. However, when both chemicals were added to the control mix, the mortar set in less than 30 minutes. This test was performed several times with the same conclusion. This contradicted the results seen when the furnace dust was included. When both chemicals were added to the dust mixture, setting was delayed. The low strength at one day is an extension of the slow early hydration.

These results were not definitive in showing if the chemicals could be responsible for the delay in strength

gain of the dust mixture. The behavior of the chemicals is inextricably linked to the behavior of the dust. A parallel series of tests was performed using the dust and comparing the effects of the chemicals alone and together. The results of this analysis is shown in Figure 3. By comparing these results with the results from the control mixtures, it is obvious that the dust and chemical mixtures never came close to the strength shown in the control mixtures. Figures 4 through 7 show this comparison.

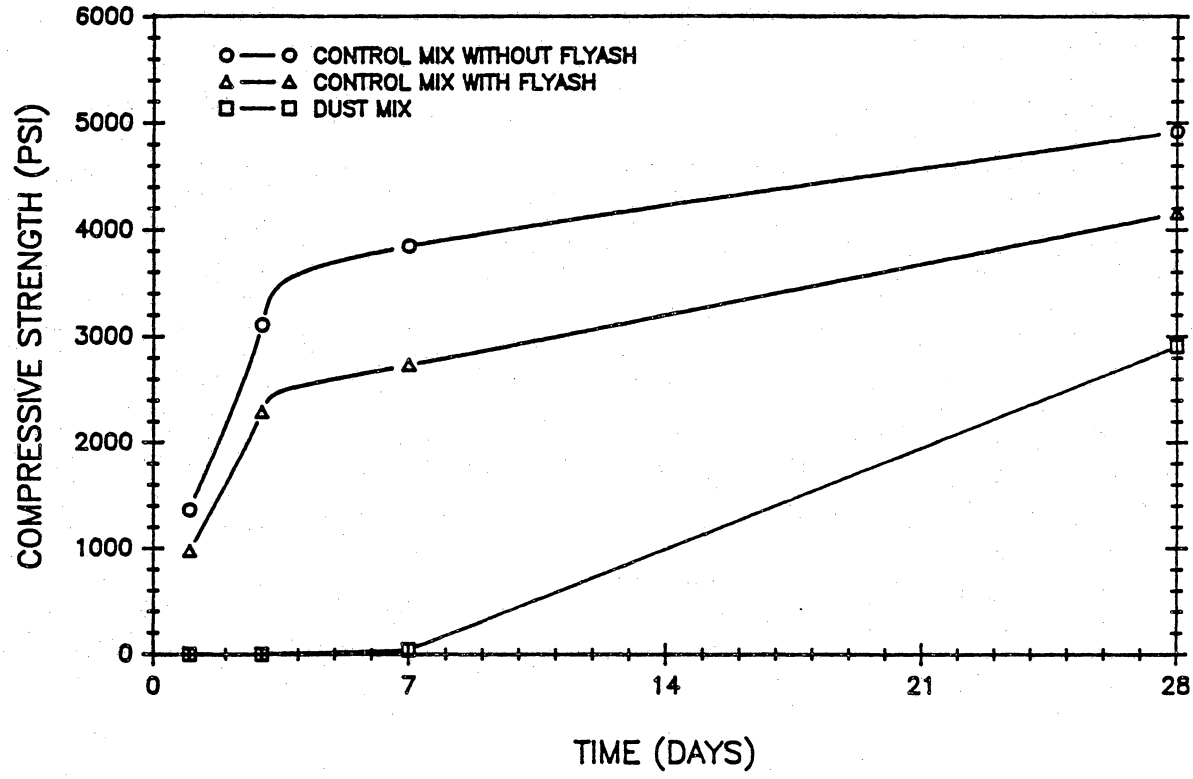
Since Olver had documented the need for the stabilizing agent for environmental safety, the dispersing agent was adjusted. The percentage, which was originally based on the volume of water, was increased as a percentage of the dust by weight. Flyash was removed from all mixtures to reduce the number of variables. The results were encouraging. A comparison of the various amounts is shown in Figure 8. Each increase of the dispersing agent increased the compressive strength of the mortar, even at early ages. The strength peaked in the mixture with 3.8 percent dispersing agent by weight of dust; larger percentages of the dispersing agent reduced the compressive strength.

The original dispersing agent was a commercially available product containing two primary ingredients. A study of the ingredients, by preparing compressive strength specimens containing each of the ingredients, showed that one of the



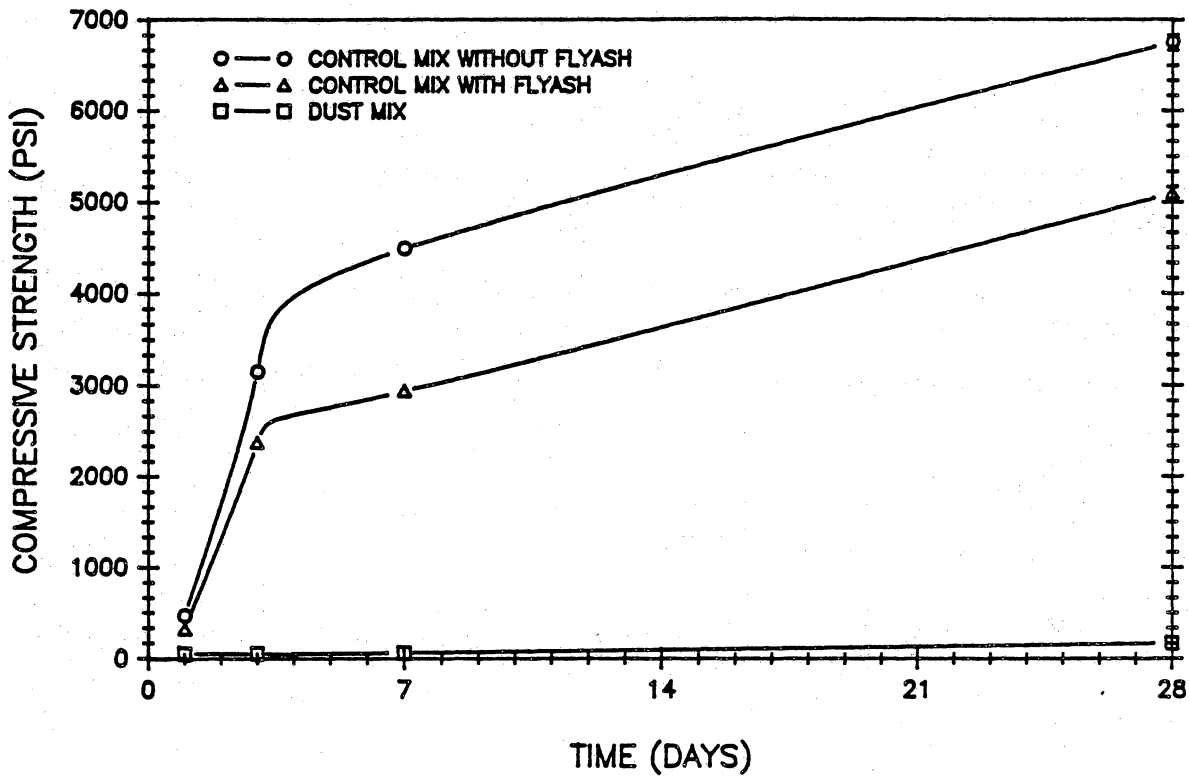
THE EFFECT OF CHEMICALS ON THE DUST MIXTURE

FIGURE 3

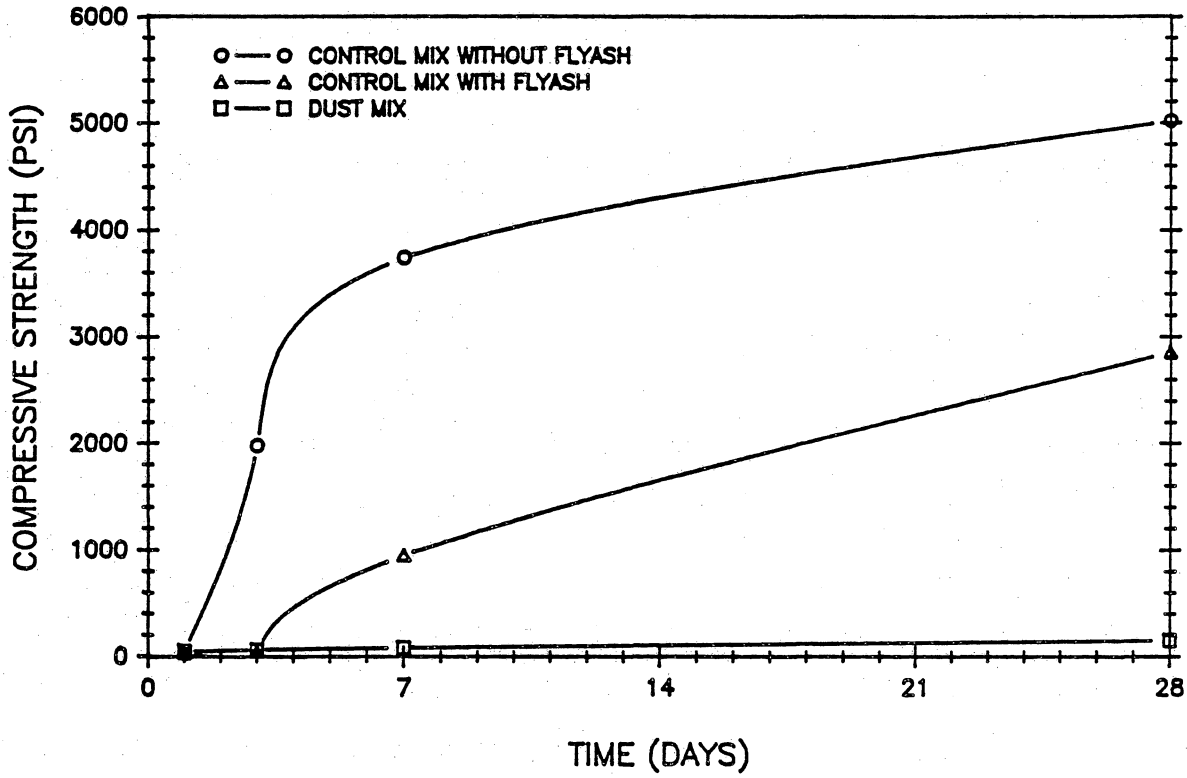


COMPARISON OF MIX TYPES: NO CHEMICALS ADDED

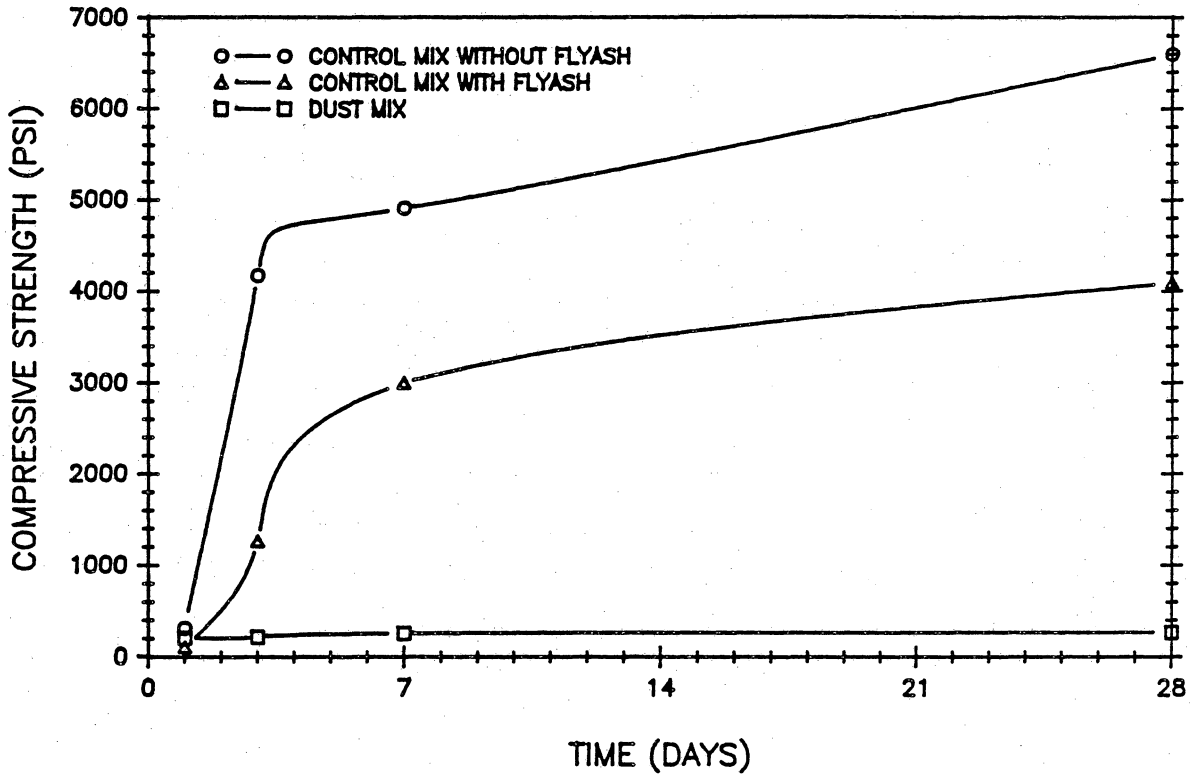
FIGURE 4



COMPARISON OF MIX TYPES
WITH 2.5% STABILIZING AGENT BY WEIGHT OF DUST OR CEMENT
FIGURE 5

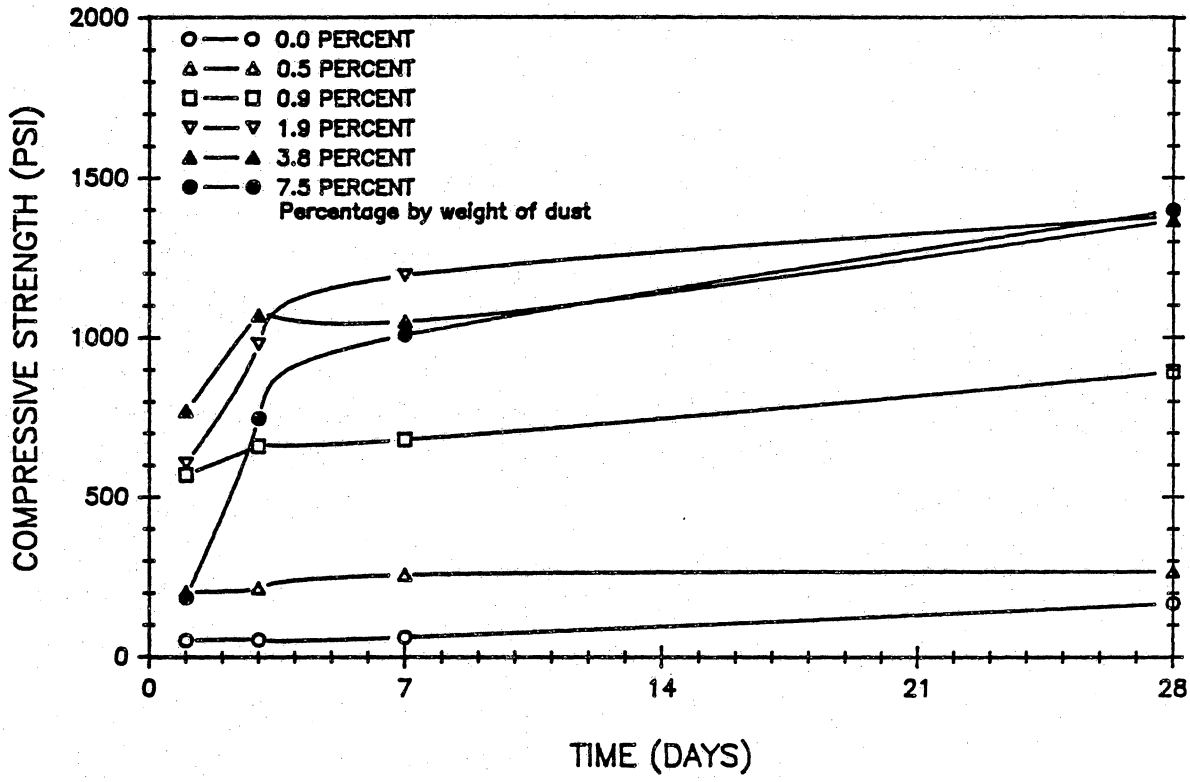


COMPARISON OF MIX TYPES
WITH 0.5% DISPERSING AGENT BY WEIGHT OF DUST OR CEMENT
FIGURE 6



COMPARISON OF MIX TYPES
WITH 0.5% DISPERSING AGENT AND 2.5% STABILIZING AGENT BY WEIGHT OF DUST OR CEMENT

FIGURE 7



THE EFFECT OF THE DISPERSING AGENT ON DUST MIXTURES

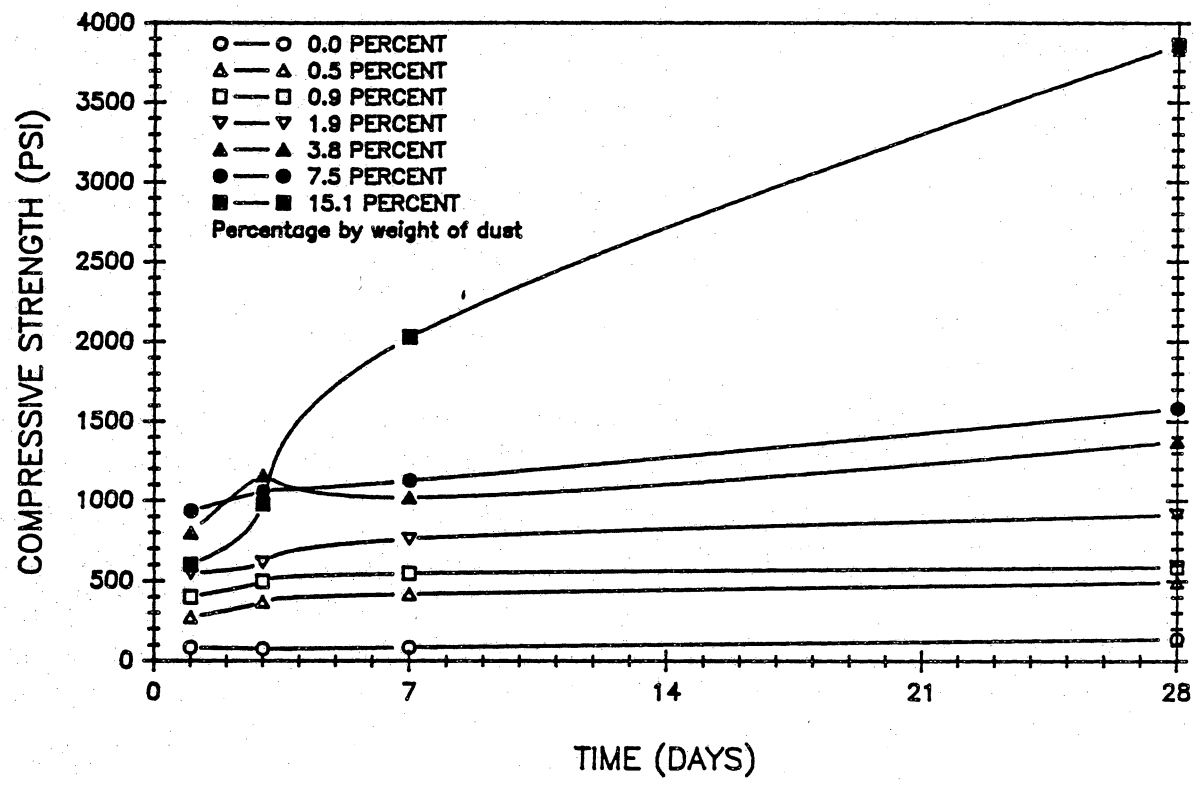
FIGURE 8

ingredients, a chelating agent, was responsible for the increase in strength. Two chelating agents were selected for further study and use of the original dispersing agent was suspended.

The results for chelating agent A are shown in Figure 9. Each increasing increment produced a gain in strength at all ages tested. This increase was consistent for each addition until the amount was increased to 15.1 percent. At this stage, the early strength was reduced but the seven- and 28-day strengths increased dramatically. At 28 days, the 7.5 percent sample had a compressive strength of 1580 psi while the 15.1 percent mixture measured 3900 psi.

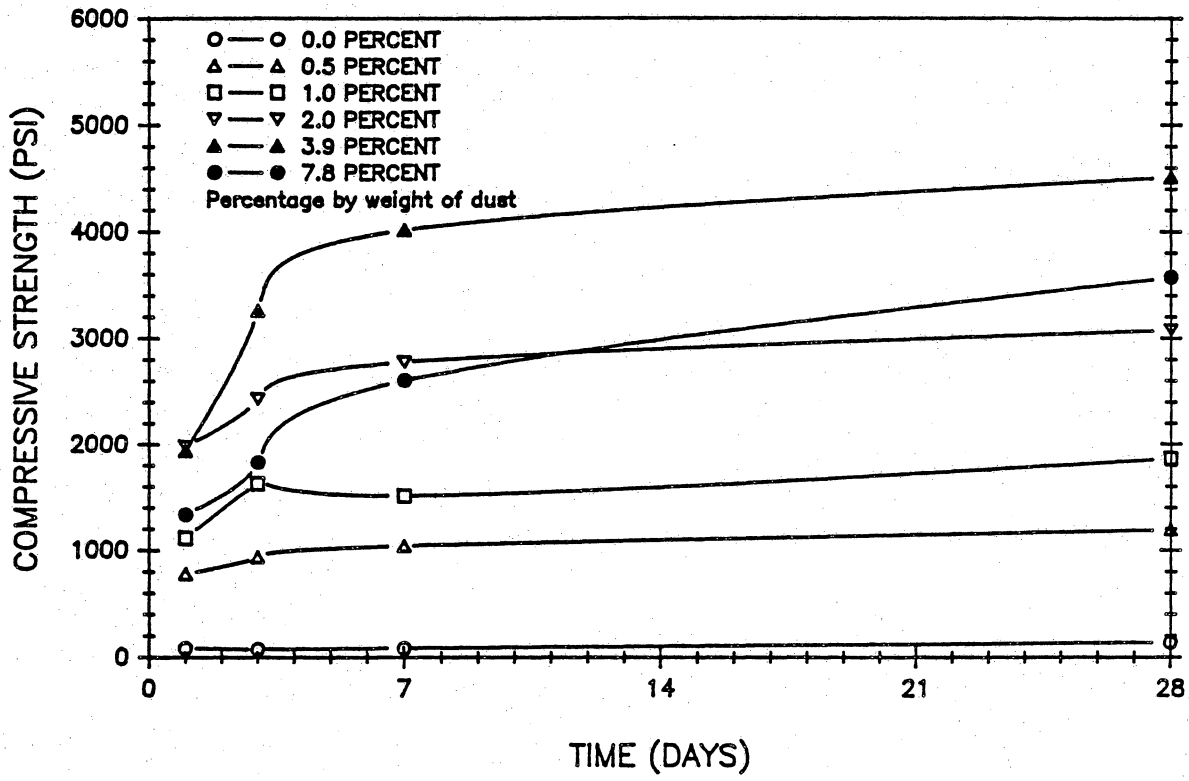
Chelating agent B behaved in a similar manner (see Figure 10). The strength gradually increased with each addition up to 3.9 percent. At this point, the strength reached a peak. A further increase did not yield an increase in compressive strength. The 28 day compressive strength of the mixture containing 3.9 percent was 4500 psi.

Chelating agent B was selected for use in the optimal mix. The testing performed indicated that the optimum percentage of the chelating agent had been reached and that this optimum percentage provided an acceptable strength for a construction material. Chelating agent A might have ulti-



THE EFFECT OF CHELATING AGENT A ON DUST MIXTURES

FIGURE 9



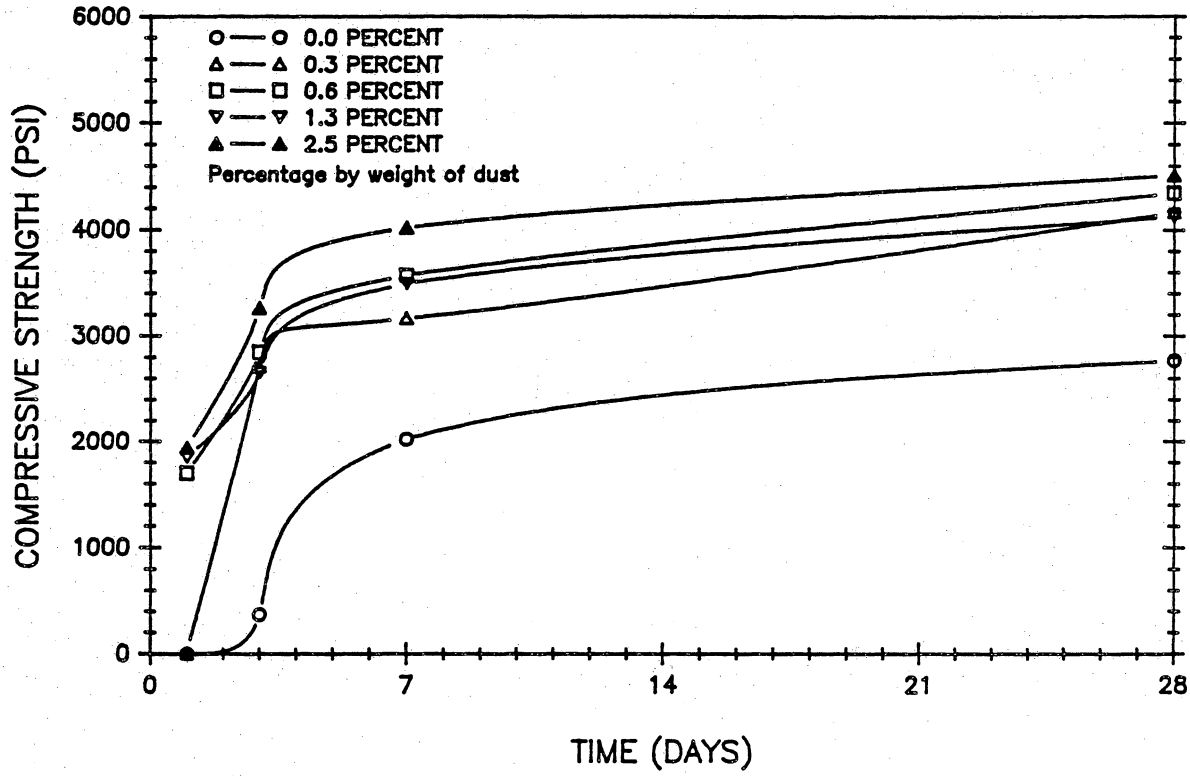
THE EFFECT OF CHELATING AGENT B ON DUST MIXTURES

FIGURE 10

mately produced a comparable strength at a larger percentage, but the amount needed was already almost four times that required of chelating agent B and was not economical.

The research up to this point had been conducted assuming that the stabilizing agent was necessary to provide environmental safety. The results using the chelating agent showed that this chemical was responsible for binding the soluble metals. This can be documented by the fact that the early hydration of cement was no longer disrupted. If the soluble metals were still in solution, they would have continued to inhibit the hydration as discussed in Chapter 2, and as evidenced in the compressive strength of the cubes containing no chemicals.

The research continued by altering the amount of stabilizing agent to see if a more economical mixture could be achieved using less of this chemical. These tests were performed using the optimum amount of chelating agent B, 3.9 percent by weight of dust. The amount of stabilizing agent prescribed in the Olver report was 2.5 percent by weight of dust. When both of these amounts were included, the mortar attained a one-day strength of 1900 psi and a 28-day strength of 4500 psi. When no stabilizing agent was added, the mortar showed no strength at one day and only 2800 psi at 28 days. Various percentages between zero and 2.5 were also tested, and the results are shown in Figure 11. The



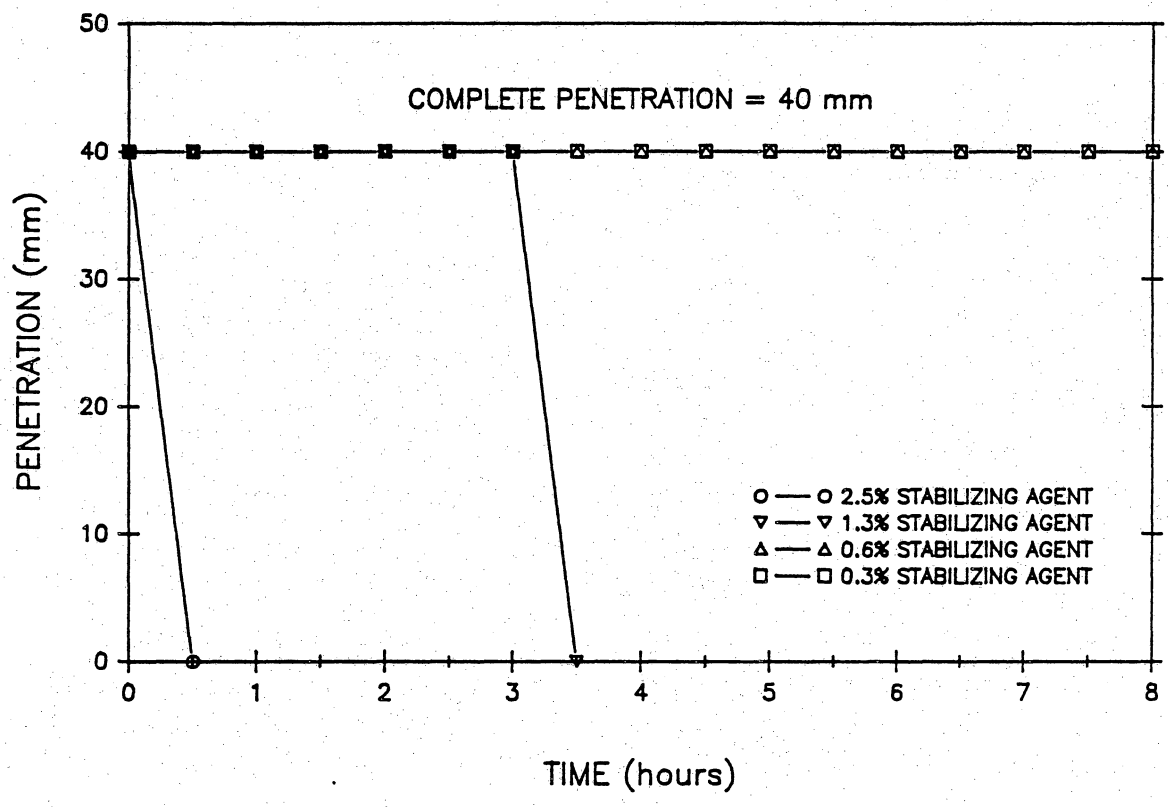
THE EFFECT OF THE STABILIZING AGENT ON DUST MIXTURES

FIGURE 11

strengths achieved from 0.6 percent through 2.5 percent were essentially the same, therefore a smaller percentage of stabilizing agent could be used without sacrificing strength.

To make a final determination of the amount of stabilizing agent required, the time of setting of the different mixtures was determined. Visual observations during the mortar preparation indicated that the stabilizing agent did have an effect on the rate of setting. The mortar containing 2.5 percent stabilizing agent set very quickly, in less than 30 minutes. With each decrease in stabilizing agent, the time of setting increased. ASTM specifies that the time of setting should be not less than 45 minutes and not more than 8 hours. A comparison of the time of setting for the different percentages is shown in Figure 12. An acceptable time of setting, 140 minutes, was observed with the mixture containing 1.3 percent stabilizing agent, a percentage at which an acceptable strength had also been achieved.

The optimum mixture for use as a construction material and for further study in this research had been determined. The constituents, expressed as a percentage of the weight of the dust, are as follows: cement, 98 percent; sand, 216 percent; water, 48 percent; chelating agent B, 3.9 percent;



THE EFFECT OF THE STABILIZING AGENT ON TIME OF SETTING

FIGURE 12

and stabilizing agent, 1.3 percent.

4.3 DEVELOPMENT OF OPTIMUM LANDFILL MIXTURE

Once the construction material had been developed, the ingredients were adjusted for a landfill mixture. The chelating agent, believed responsible for binding the metals, was not altered, but the amount of stabilizing agent was reduced. The earlier compression tests had indicated that reasonable strength could be achieved with as little as 0.6 percent stabilizing agent by weight of dust. The time of setting, which was governed by ASTM C109 for the construction material, was not as important for processing the landfill material. Therefore, the smaller amount of stabilizing agent was sufficient.

A major portion of the cost associated with disposal of a toxic material hinges on the volume. In order to reduce the volume, all sand was eliminated. To further reduce costs, the amount of cement was cut in half. When all these variables were adjusted, the resulting landfill mixture had a one-day strength of 157 psi, a 28-day strength of 595 psi, and a time of setting of 975 minutes. These results are acceptable.

4.4 EP TOXICITY TESTS

The most critical element in this study is attaining a product which would be acceptable to the Environmental Pro-

tection Agency. Once the two optimum mixtures had been developed and found to be acceptable with respect to strength and time of setting, they were subjected to an EP Toxicity test. The results are shown in Table 2. Both mixtures were found to be nonhazardous.

4.5 STATISTICAL VARIATION

Once the optimum mixtures were developed and found to be suitable with respect to strength, time of setting, and environmental safety, a series of compressive tests was performed to evaluate the repeatability of the mixtures. Three batches each of the control mixture, the construction material mixture, and the landfill mixture (nine batches in all), were prepared and tested at one, three, seven and 28 days. The standard deviation and coefficient of variation, both between batch and within batch, were computed for each. The results are shown in detail in Appendix A. The 95 percent confidence limits for the compressive strength, defined as the average strength plus or minus twice the standard deviation between batch, are shown in Table 3.

TABLE 2: EP TOXICITY TEST RESULTS			
METAL TESTED	MAXIMUM ALLOWED (mg/L)	CONSTRUCTION MATERIAL (mg/L)	LANDFILL MATERIAL (mg/L)
BARIUM	6.3	0.8	1.3
CADMIUM	0.063	0.055	0.040
CHROMIUM	0.315	0.095	0.090
NICKEL	2.20	0.13	0.13
SILVER	0.315	0.180	0.245
LEAD	0.315	0.200	0.250
MERCURY	0.0126	0.0002	0.0005

TABLE 3: 95 PERCENT CONFIDENCE LIMITS FOR COMPRESSIVE STRENGTH			
AGE (DAYS)	COMPRESSIVE STRENGTH (PSI)		
	CONTROL MIXTURE	CONSTRUCTION MATERIAL	LANDFILL MATERIAL
1	2139 to 2377	1761 to 1801	176 to 188
3	3605 to 3877	2671 to 2859	314 to 342
7	4355 to 4993	3019 to 3389	389 to 473
28	5650 to 5858	3764 to 4016	500 to 668

CHAPTER 5: CONSTRUCTION REQUIREMENTS

5.1 SCOPE

The qualities of a material able to function in a practical situation extend beyond workability and developed strength. The various segments of any structure must maintain their form in order to perform correctly, and they must be able to withstand severe environmental changes to have an acceptable service life. This section addresses the ability of the construction material mixture to perform with regard to these two concerns.

5.2 CHEMICAL STABILITY

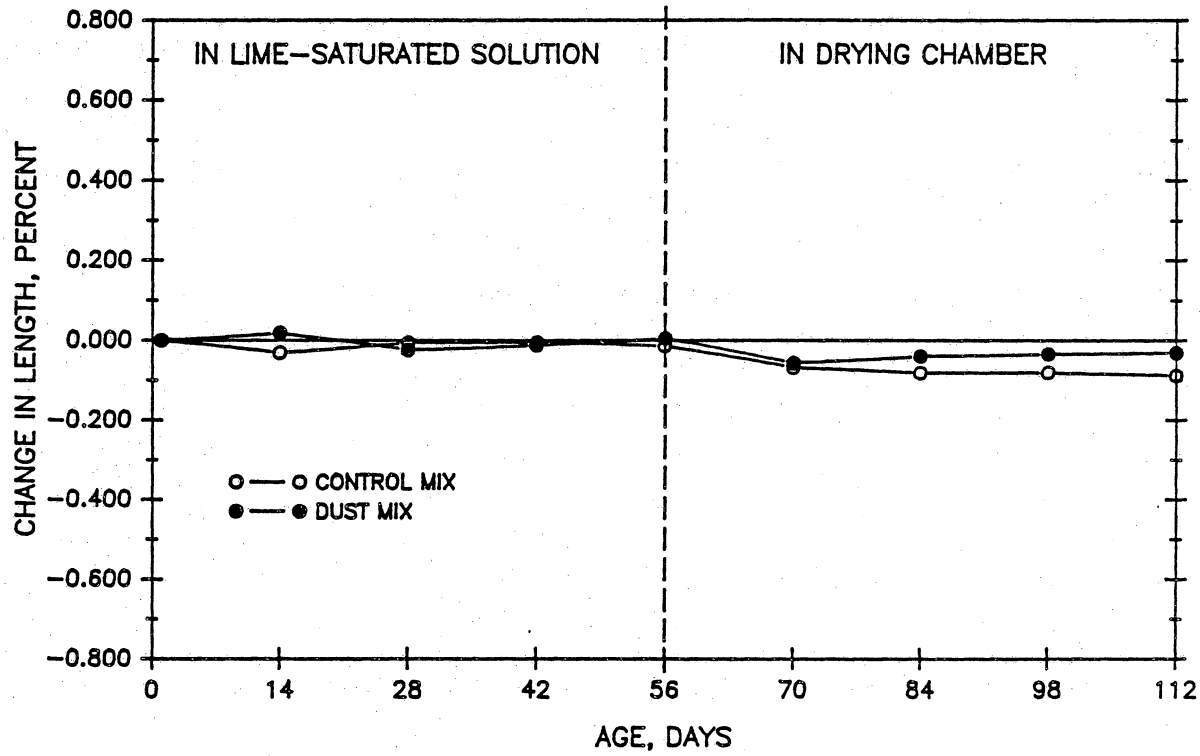
The dimensional stability of a cement product can be affected by chemical reactions within the paste. The research conducted on the strength of the mortar showed that the dust and the cement did react. Consequently, one-day-old specimens were subjected to steam curing to accelerate any potentially detrimental chemical reaction. Three batches of two specimens each were prepared for both a control cement mixture and a dust-chemical-cement mixture as described in Chapter 3. The results are shown in Table 4.

TABLE 4: CHEMICAL STABILITY				
CONTROL MIXTURE				
BATCH NUMBER	SPECIMEN NUMBER	ORIGINAL LENGTH (IN)	FINAL LENGTH (IN)	PERCENT CHANGE
1	1 2	11.2987 11.2854	11.3129 11.3012	+0.126 +0.140
2	1 2	11.2872 11.2636	11.3018 11.2786	+0.129 +0.133
3	1 2	11.2776 11.2927	11.2950 11.3086	+0.154 +0.141
DUST MIXTURE				
1	1 2	11.2689 11.2237	11.2616 11.2156	-0.065 -0.072
2	1 2	11.2875 11.2775	11.2793 11.2685	-0.073 -0.080
3	1 2	11.2734 11.2865	11.2639 11.3220	-0.084 -0.315

Both mixtures performed well within the requirements of ASTM C150, "Standard Specification for Portland Cement," which allows 0.8 percent change in length.

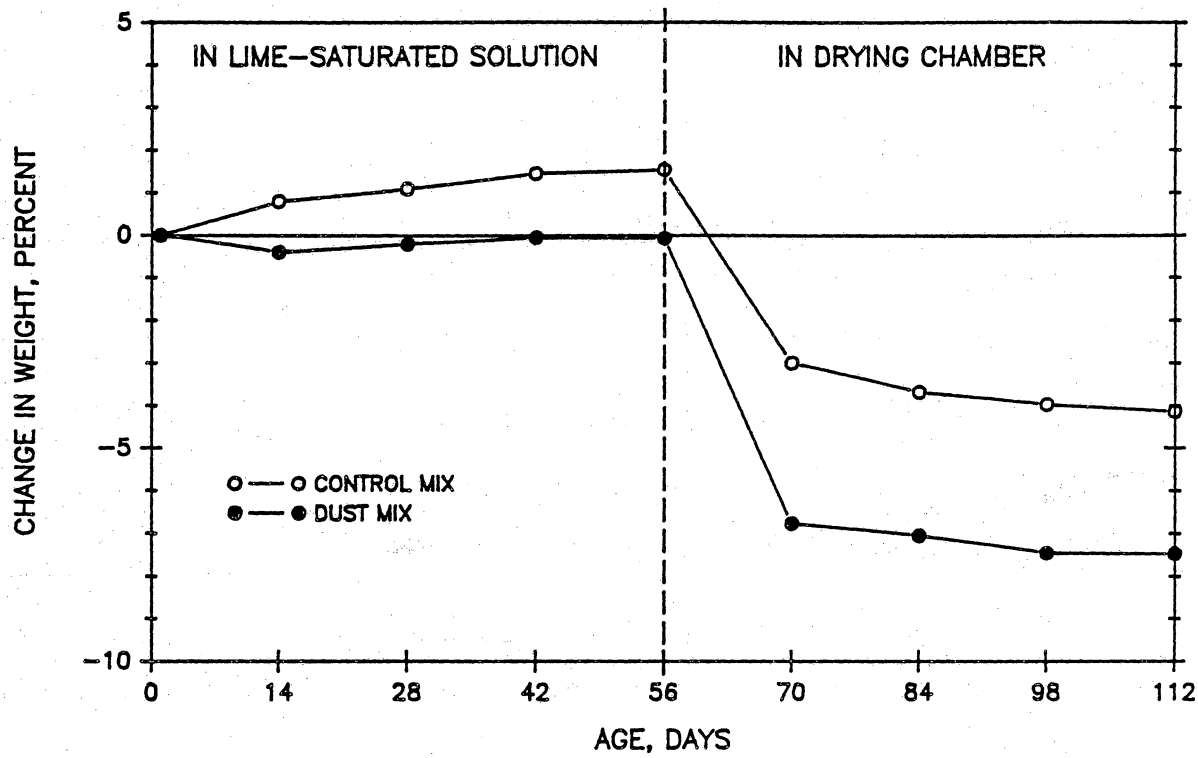
5.3 PHYSICAL STABILITY

The physical stability of a construction material can be estimated by subjecting a specimen to extremes in humidity. The control mortar and the optimum dust-mortar were each subjected to 56 days in a lime-saturated solution, followed by 56 days in an environment with the relative humidity maintained at 50 percent. Four batches of each mortar were prepared; three control mixture specimens and two dust mixture specimens were made from each batch. The resulting changes in length, for the average of the two types of specimens, are shown in Figure 13, and the resulting changes in weight are shown in Figure 14. The results are detailed in Appendix B. The most dramatic change occurred when the specimens were transferred from the lime-saturated solution to the drying chamber and was most notable in the change in the weight of the specimens. The dust mixture exhibited a larger decrease in weight at this junction, more than two times the weight loss of the control specimens. This indicates that the dust specimens are more permeable. A more open, porous media allows the water



CHANGE IN LENGTH DURING PHYSICAL STABILITY TESTING

FIGURE 13



CHANGE IN WEIGHT DURING PHYSICAL STABILITY TESTING

FIGURE 14

within the mortar to be drawn out more easily. After the specimens had adjusted to the new environment, little change in length or weight was observed. The change in length never approached the maximum allowed by ASTM C150, 0.8 percent.

5.4 FREEZE-THAW DURABILITY

An adequate air-void system is generally required for a mortar or concrete to withstand numerous cycles of freezing and thawing. Water contained within the cement matrix must have room in which to freeze, because the volume of ice is greater than that of water. Consequently, the mortar tested for freeze-thaw durability included an air-entraining agent, Master Builder VR. The first three batches prepared included the manufacturer's recommended amount of air-entraining agent: 1.5 ounces per 100 pounds of cement. These three batches included a control mixture and two dust mixtures, one with a water-to-cement ratio of 0.50 (the same as the control), and one with a water-to-cement ratio of 0.40. The details of these and the other mixtures tested are shown in Appendix C. Six control-mixture specimens, six dust specimens with a water-to-cement ratio of 0.50, and four dust specimens with a water-to-cement ratio of 0.40 were prepared.

These first three batches were placed in the freeze-

thaw cabinet and subjected to alternating cycles of freezing and thawing. Both dust mixtures failed quickly; the control mixtures survived 300 cycles without failure. Failure was defined as the point at which the relative dynamic modulus of elasticity was reduced to 60 percent of the original. The relative dynamic modulus, according to ASTM C666, is defined by the following equation:

$$P_c = (n_c^2/n_i^2) * 100$$

where: P_c = relative dynamic modulus, after c cycles, percent
n_i = initial fundamental transverse frequency, hertz
n_c = fundamental transverse frequency, after c cycles, hertz

The durability factor, DF, is defined as:

$$DF = PN/M$$

where: P = relative dynamic modulus, P_c, for c = N
N = number of cycles to failure
M = specified number of cycles to acceptance = 300

The results of the first three batches are shown in Table 5. The early failure of these first specimens showed that the air-entraining agent did not work effectively in the mortar containing the furnace dust. Samples of the dust mixture with a water-to-cement ratio of 0.50 and the control mixture were inspected using the linear traverse machine. This study confirmed that the amount of air entrained in the

TABLE 5: FREEZE-THAW TEST RESULTS FOR MIXTURES CONTAINING 1.5 OUNCES OF AIR-ENTRAINING AGENT PER 100 LBS OF CEMENT

	MIXTURE 1	MIXTURE 2	MIXTURE 3
TYPE	CONTROL	DUST	DUST
WATER/CEMENT	0.50	0.50	0.40
CYCLES TO FAILURE	DID NOT FAIL	37	45
INITIAL FREQUENCY	1892	1634	1718
FREQUENCY AT FAILURE	--	1265	1330
$P_{FAILURE}$	100	60	60
DURABILITY FACTOR	100	7.4	9.0

dust-mortar, only 1.9 percent, was insufficient for durability, while the control mortar had enough air entrained, with 9.4 percent. The details of the linear traverse study are shown in Appendix D.

Additional freeze-thaw specimens containing the dust mortar were prepared using an increased amount of the air-entraining agent to determine if an acceptable air-void system could be developed. The details of the mixes are shown in Appendix B. Each increase yielded an increase in the durability. The mixture containing 2.5 ounces of air-entraining agent per 100 pounds of cement had a durability factor of 10, failing after 50 cycles, and the mixture containing 5 ounces of air-entraining agent per 100 pounds of cement had a durability factor of 29, failing after 146 cycles.

These two batches were also studied using the linear traverse. The air-void system for each increasing increment of air-entraining agent approached the requirements specified by the ACI. The final batch, containing the largest percentage of air, had parameters comparable to the control mix that did not fail through 300 cycles (see Table 6). The early failure of these specimens suggests that the dust mortar was failing for reasons apart from the air-void system. One cause for this early failure may have been the

TABLE 6: COMPARISON OF AIR-VOID SYSTEMS		
	CONTROL MIX	DUST MIX
WATER/CEMENT	0.50	0.40
AEA (OZ PER 100 LBS CEMENT)	1.5	5.0
AVERAGE CHORD INTERCEPT	0.010	0.009
VOIDS PER INCH	9.7	9.2
SPECIFIC SURFACE (in^2/in^3)	415	458
PASTE/AIR	5.0	5.9
AIR CONTENT (%)	9.4	8.1
SPACING FACTOR	0.0112	0.0110

high permeability of the specimens, observed in the analysis of the physical stability.

The freeze-thaw testing is performed on specimens that have been cured for two weeks in lime-saturated water. During the time of testing in the freeze-thaw apparatus, the specimens are immersed in water. However, the impermeable nature of mortar does not allow fast, complete saturation of the matrix. The time that it takes for failure to occur is partially dependent on how long it takes for all the air voids within the specimens to be filled with water. Once this state is reached, the specimens must respond to the pressure caused by freezing water, and microfractures will appear within the cement matrix regardless of the air-void system. In the case of the dust-mortars, the higher permeability allows the air-voids to become filled more quickly, leading to a faster failure.

Another problem surfaced during the preparation of the freeze-thaw specimens. Unlike the dust-mixture specimens prepared for earlier studies, these specimens were mixed in large batches in a two-cubic-foot mixer. The change in mixing caused a change in the behavior of the batch. The resulting mortar was more workable and set more quickly than the previous mortar. The change in workability should not affect the rate of processing and was not considered a problem. The change in time of setting was extreme. The

second batch of dust-mortar set in less than 20 minutes. When the final two batches containing dust were mixed, a retarding agent, Sika Plastocrete 161R, in the amount of four ounces per 100 pounds of cement, was included. This increased the time of setting to approximately 90 minutes, within the guidelines specified by ASTM C150. The compressive strength of these batches was tested in conjunction with each freeze-thaw batch and showed that the retarding agent did not have a deleterious effect on the mortar. These results are included with the mix data in Appendix C.

CHAPTER 6: CONCLUSIONS

6.1 CONCLUSIONS

This research showed that the electric arc furnace dust produced by Roanoke Electric Steel can be successfully incorporated into mortar for either disposal or construction purposes and that this product will be acceptable to the U.S. Environmental Protection Agency. The following conclusions about including this foreign material containing metals in mortar were reached:

(1) The electric arc furnace dust does effect the hydration of cement. These effects include a decrease in early compressive strength, an increase in the time of setting, and an increase in permeability.

(2) The effect of the dust with respect to strength and time of setting can be controlled by the inclusion of a chelating agent and a stabilizing agent.

(3) These chemicals also serve to stabilize the heavy metals in the dust and render them nonhazardous, as determined by the EP Toxicity test.

(4) The construction material, including the two

chemical agents, satisfies the requirements established by the ASTM for compressive strength, time of setting, and dimensional stability.

(5) The dust reduces the effectiveness of the air-entraining agent. This reduction can be partially counter-balanced by increasing the amount of agent, but the higher permeability of the mortar yields a material with a low freeze-thaw durability.

6.2 SUGGESTIONS FOR FURTHER STUDY

The following list contains some suggestions for further research which may produce a more economical and more durable construction material:

(1) Increase the percentage of dust included as portion of the fine aggregate. The tests performed for the landfill mixture where no sand was included suggest that an acceptable construction product could be developed with a larger percentage of dust.

(2) Experiment with more chelating agents. Hundreds of different types of chelating agents exist, and one of these may provide a more economical mixture.

(3) Complete the research using flyash. A pozzolan may decrease the permeability of the mortar and thus provide a more durable product.

(4) Continue the study of the freeze-thaw durability

by using different air-entraining agents. A different chemical may be more efficient in developing an acceptable air-void system.

(5) Study the effects of preparing the dust mortar in large batches. The increase in time of setting observed during the preparation of the freeze-thaw specimens may be controlled by alterations in the chemicals added.

REFERENCES

1. Olver Incorporated, Roanoke Electric Steel Corporation Delisting Petition, Emission Control Dust (K061), Supplement No. 1, March, 1987.

2. Olver Incorporated, Roanoke Electric Steel Corporation, Delisting Petition, Emission Control Dust (K061), March, 1987.

3. P. Kumar Mehta, Concrete: Structure, Properties, and Materials, Prentice-Hall, Inc., Englewood Cliffs, New Jersey, copyright 1986.

4. Portland Cement Association, Design and Control of Concrete Mixtures, Twelth Edition, PCA, Skokie, Illinois, copyright 1979.

5. A.M. Neville, Properties of Concrete, Third Edition, Pitman Publishing Inc., Marshfield, Massachusetts, copyright 1981.

6. F.M. Lea, The Chemistry of Cement and Concrete, Third Edition, Edward Arnold Ltd., copyright 1970.

7. N.L. Thomas, D.A. Jameson, and D.D. Double, "The Effect of Lead Nitrate on the Early Hydration of Portland Cement," Cement and Concrete Research, vol. 11, copyright 1981, pp. 143-153.

8. C. Tashiro et al., "Hardening Property of Cement Mortar Adding Heavy Metal Compound and Solubility of Heavy Metal from Hardened Mortar," Cement and Concrete Research, vol. 7, copyright 1977, pp. 283-290.

9. C. Tashiro, J. Oba, and K. Akama, "The Effects of Several Heavy Metal Oxides on the Formation of Ettringite and the Microstructure of Hardened Ettringite," Cement and Concrete Research, vol. 9, copyright 1979, pp. 303-308.

10. C. Tashiro and J. Oba, "The Effects of Cr_2O_3, $Cu(OH)_2$, ZnO and PbO on the Compressive Strength and the Hydrates of the Hardened C_3A Paste," Cement and Concrete Research, vol. 9, copyright 1979, pp. 253-258.

11. Congress of the United States, Congressional Budget Office, Hazardous Waste Management: Recent Changes and Policy Alternatives, Washington, Government Printing Office, May, 1985.

12. U.S. Environmental Protection Agency, Survey of Solidification/Stabilization Technology for Hazardous Industrial Wastes, Environmental Laboratory, Vicksburg, Mississippi, July, 1979.

13. Douglas W. Thompson, Philip G. Malone, and Larry W. Jones, "Survey of Available Stabilization Technology," R. Pojasek, editor, Toxic and Hazardous Waste Disposal, vol. 1, Ann Arbor Science Publishers, copyright 1979, pp. 9-22.

14. U.S. Environmental Protection Agency, Guide to the Disposal of Chemically Stabilized and Solidified Waste, SW-872, Environmental Laboratory, Vicksburg, Mississippi, September, 1980.

15. C.S. Poon, C.J. Peters, and R. Perry, "Use of Stabilization Processes in the Control of Toxic Wastes," Effluent and Water Treatment Journal, November, 1980, pp. 451-459.

16. R.P. Webster and L.E. Kukacka, Stabilization of Geothermal Residues by Encapsulation, Brookhaven National Laboratory Associated Universities, Inc., September, 1987.

17. Ronald E. Benson, Jr., Henry W. Chandler, and Kenneth A. Chacey, "Hazardous Waste Disposal as Concrete Admixture," ASCE, Journal of Environmental Engineering, vol. 111, no. 4, August, 1985.

18. U.S. Department of Commerce, Critical Review of Cement Base Stabilization/Solidification Techniques for the Disposal of Hazardous Wastes, U.S. Army Construction Engineering Research Laboratory, Champaign, Illinois, National Technical Information Service, 1986.

19. PEI Associates, Inc., Electromembrane Process for Recovery of Lead from Contaminated Soils, National Science Foundation, Washington, July, 1986.

20. Charles F. Baes, Jr., and Robert E. Mesmer, The Hydrolysis of Cations, Robert E. Krieger Publishing Company, Malabar, Florida, copyright 1986.

21. Colin F. Bell, Principles and Applications of Metal Chelation, Clarendon Press, Oxford, copyright, 1977.

22. Stanley Chaberek and Arthur E. Martell, Organic Sequestering Agents, John Wiley & Sons, Inc., New York, copyright 1959.

23. S.S. Yau and W. H. Hartt, "Influence of Selected Chelating Admixtures upon Concrete Cracking Due to Embedded Metal Corrosion," Corrosion of Reinforcing Steel in Concrete: A Symposium, ASTM STP 713, D.E. Tonini and J.M. Gaidis, Eds., American Society for Testing and Materials, 1980, pp. 51-63.

APPENDIX A

STATISTICAL ANALYSIS OF MIX DESIGNS

EQUATIONS USED:

WITHIN BATCH
For each batch, given the compressive strength, x:
Average Compressive strength, $\bar{x}$

$$\bar{x} = \frac{\Sigma\, x}{n} \qquad n = \text{number of specimens}$$

Standard Deviation, σ

$$\sigma = \left[\sum_{i=1}^{n} (x_i - \bar{x})^2 \,/\, n \right]^{1/2}$$

Coefficient of Variation, v

$$v = \left[\frac{\sigma}{\bar{x}} \right] * 100\ \%$$

Grand Average Compressive Strength, $\bar{\bar{x}}$

$$\bar{\bar{x}} = \frac{\Sigma\, \bar{x}}{N} \qquad N = \text{number of batches}$$

BETWEEN BATCH
Standard Deviation, σ'

$$\sigma' = \left(\left[(\Sigma \bar{x}^2) - (\Sigma \bar{x})^2 / N \right] \div (N - 1) \right)^{1/2}$$

Coefficient of Variation, v'

$$v' = \left(\frac{\sigma'}{\bar{\bar{x}}} \right) * 100\ \%$$

95% Confidence Limits, L_{95} to U_{95}

$$L_{95} = \bar{\bar{x}} - 1.96\, \sigma' / N^{1/2}$$

$$U_{95} = \bar{\bar{x}} - 1.96\, \sigma' / N^{1/2}$$

APPENDIX A
STATISTICAL ANALYSIS OF MIX DESIGNS

CONTROL MIXTURE

ONE DAY COMPRESSIVE STRENGTH

BATCH NUMBER	COMPRESSIVE STRENGTH (PSI)	AVERAGE COMPRESSIVE STRENGTH (PSI)	STANDARD DEVIATION (PSI)	COEFFICIENT OF VARIATION (%)
1	2205 2274 2250	2243	35	2
2	2170 2086 2230	2162	72	3
3	2442 2294 2373	2370	74	3
BETWEEN BATCH	STANDARD DEVIATION: 105 COEFFICIENT OF VARIATION: 5 95% CONFIDENCE LIMITS: 2139 TO 2377			

THREE DAY COMPRESSIVE STRENGTH

BATCH NUMBER	COMPRESSIVE STRENGTH (PSI)	AVERAGE COMPRESSIVE STRENGTH (PSI)	STANDARD DEVIATION (PSI)	COEFFICIENT OF VARIATION (%)
1	3777 3955 3906	3879	92	2
2	3787 3658 3584	3676	103	3
3	3446 3841 3713	3667	202	6
BETWEEN BATCH	STANDARD DEVIATION: 120 COEFFICIENT OF VARIATION: 3 95% CONFIDENCE LIMITS: 3605 TO 3877			

APPENDIX A
STATISTICAL ANALYSIS OF MIX DESIGNS

CONTROL MIXTURE

SEVEN DAY COMPRESSIVE STRENGTH

BATCH NUMBER	COMPRESSIVE STRENGTH (PSI)	AVERAGE COMPRESSIVE STRENGTH (PSI)	STANDARD DEVIATION (PSI)	COEFFICIENT OF VARIATION (%)
1	4445 4494 4504	4481	32	1
2	4459 4805 4365	4543	232	5
3	5335 4776 4880	4997	297	6

BETWEEN BATCH
STANDARD DEVIATION: 282
COEFFICIENT OF VARIATION: 6
95% CONFIDENCE LIMITS: 4355 TO 4993

28 DAY COMPRESSIVE STRENGTH

BATCH NUMBER	COMPRESSIVE STRENGTH (PSI)	AVERAGE COMPRESSIVE STRENGTH (PSI)	STANDARD DEVIATION (PSI)	COEFFICIENT OF VARIATION (%)
1	6007 6056 5349	5804	395	7
2	5849 5829 5750	5809	523	1
3	5423 5844 5676	5648	212	4

BETWEEN BATCH
STANDARD DEVIATION: 92
COEFFICIENT OF VARIATION: 2
95% CONFIDENCE LIMITS: 5650 TO 5858

APPENDIX A
STATISTICAL ANALYSIS OF MIX DESIGNS

CONSTRUCTION MATERIAL

ONE-DAY COMPRESSIVE STRENGTH

BATCH NUMBER	COMPRESSIVE STRENGTH (PSI)	AVERAGE COMPRESSIVE STRENGTH (PSI)	STANDARD DEVIATION (PSI)	COEFFICIENT OF VARIATION (%)
1	1898 1785 1666	1783	116	7
2	1775 1760 1859	1798	53	3
3	1696 1765 1829	1763	67	4

BETWEEN BATCH STANDARD DEVIATION: 18
COEFFICIENT OF VARIATION: 1
95% CONFIDENCE LIMITS: 1761 TO 1801

THREE DAY COMPRESSIVE STRENGTH

BATCH NUMBER	COMPRESSIVE STRENGTH (PSI)	AVERAGE COMPRESSIVE STRENGTH (PSI)	STANDARD DEVIATION (PSI)	COEFFICIENT OF VARIATION (%)
1	2685 2833	2798	101 2877	4
2	2862 2739 2877	2826	763	3
3	2596 2694 2724	2671	67	3

BETWEEN BATCH STANDARD DEVIATION: 83
COEFFICIENT OF VARIATION: 3
95% CONFIDENCE LIMITS: 2671 TO 2859

APPENDIX A
STATISTICAL ANALYSIS OF MIX DESIGNS

CONSTRUCTION MATERIAL

SEVEN DAY COMPRESSIVE STRENGTH

BATCH NUMBER	COMPRESSIVE STRENGTH (PSI)	AVERAGE COMPRESSIVE STRENGTH (PSI)	STANDARD DEVIATION (PSI)	COEFFICIENT OF VARIATION (%)
1	3332	3298	82	2
	3357			
	3204			
2	3505	3299	179	5
	3209			
	3184			
3	3184	3016	212	7
	2778			
	3085			

BETWEEN BATCH
STANDARD DEVIATION: 163
COEFFICIENT OF VARIATION: 5
95% CONFIDENCE LIMITS: 3019 TO 3389

28 DAY COMPRESSIVE STRENGTH

BATCH NUMBER	COMPRESSIVE STRENGTH (PSI)	AVERAGE COMPRESSIVE STRENGTH (PSI)	STANDARD DEVIATION (PSI)	COEFFICIENT OF VARIATION (%)
1	3792	3835	148	4
	3713			
	4000			
2	3876	4018	124	3
	4108			
	4069			
3	3945	3818	111	3
	3767			
	3742			

BETWEEN BATCH
STANDARD DEVIATION: 111
COEFFICIENT OF VARIATION: 3
95% CONFIDENCE LIMITS: 3764 TO 4016

APPENDIX A
STATISTICAL ANALYSIS OF MIX DESIGNS

LANDFILL MATERIAL

ONE DAY COMPRESSIVE STRENGTH

BATCH NUMBER	COMPRESSIVE STRENGTH (PSI)	AVERAGE COMPRESSIVE STRENGTH (PSI)	STANDARD DEVIATION (PSI)	COEFFICIENT OF VARIATION (%)
1	178 168 188	178	10	6
2	148 188 203	180	28	16
3	198 178	188	14	7

BETWEEN BATCH STANDARD DEVIATION: 5
COEFFICIENT OF VARIATION: 3
95% CONFIDENCE LIMITS: 176 TO 188

THREE DAY COMPRESSIVE STRENGTH

BATCH NUMBER	COMPRESSIVE STRENGTH (PSI)	AVERAGE COMPRESSIVE STRENGTH (PSI)	STANDARD DEVIATION (PSI)	COEFFICIENT OF VARIATION (%)
1	277 346 326	316	36	11
2	331 316 341	329	13	4
3	331 341 346	339	8	2

BETWEEN BATCH STANDARD DEVIATION: 12
COEFFICIENT OF VARIATION: 4
95% CONFIDENCE LIMITS: 314 TO 342

APPENDIX A
STATISTICAL ANALYSIS OF MIX DESIGNS

LANDFILL MATERIAL

SEVEN DAY COMPRESSIVE STRENGTH

BATCH NUMBER	COMPRESSIVE STRENGTH (PSI)	AVERAGE COMPRESSIVE STRENGTH (PSI)	STANDARD DEVIATION (PSI)	COEFFICIENT OF VARIATION (%)
1	376 455	416	56	13
2	465 440 514	473	38	8
3	420 386 406	404	17	4

BETWEEN BATCH
STANDARD DEVIATION: 37
COEFFICIENT OF VARIATION: 9
95% CONFIDENCE LIMITS: 389 TO 473

28 DAY COMPRESSIVE STRENGTH

BATCH NUMBER	COMPRESSIVE STRENGTH (PSI)	AVERAGE COMPRESSIVE STRENGTH (PSI)	STANDARD DEVIATION (PSI)	COEFFICIENT OF VARIATION (%)
1	396 623 489	503	114	23
2	618 658 534	603	63	10
3	653 633 653	646	12	2

BETWEEN BATCH
STANDARD DEVIATION: 74
COEFFICIENT OF VARIATION: 13
95% CONFIDENCE LIMITS: 500 TO 668

APPENDIX B
PHYSICAL STABILITY

BATCH NO.	SPEC. NO.	1-DAY WEIGHT	1-DAY LENGTH	14-DAY WEIGHT	14-DAY LENGTH	28-DAY WEIGHT	28-DAY LENGTH
		CONTROL MIXTURE					
1	1	432.9	11.2760	436.4	11.2742	437.8	11.2754
	2	431.6	11.2849	435.0	11.2822	436.5	11.2829
	3	429.0	11.2467	432.5	11.2444	433.5	11.2480
2	1	426.5	11.2386	429.8	11.2284	431.4	11.2316
	2	429.7	11.2437	432.1	11.2400	434.7	11.2427
	3	434.8	11.2673	438.5	11.2639	440.0	11.2665
3	1	433.1	11.2922	436.5	11.2887	438.2	11.2914
	2	437.2	11.2985	440.6	11.2950	442.3	11.2975
	3	436.1	11.2962	439.5	11.2928	441.3	11.2956
4	1	437.0	11.2932	440.6	11.2926	442.4	11.2952
	2	434.4	11.2797	438.5	11.2763	440.1	11.2790
	3	440.3	11.2922	444.3	11.2887	445.8	11.2916
		DUST MIXTURE					
1	1	473.0	11.2861	471.4	11.2865	471.8	11.2837
	2	470.2	11.2654	468.7	11.2700	469.1	11.2628
2	1	480.1	11.2927	478.1	11.2955	478.4	11.2905
	2	487.0	11.2821	484.9	11.2839	485.2	11.2799
3	1	475.1	11.2784	473.1	11.2795	473.9	11.2761
	2	472.7	11.2609	470.8	11.2644	471.2	11.2586
4	1	481.5	11.3003	479.7	11.3010	480.3	11.2985
	2	478.8	11.2220	476.5	11.2233	476.7	11.2211

APPENDIX B
PHYSICAL STABILITY

BATCH NO.	SPEC. NO.	42-DAY WEIGHT	42-DAY LENGTH	56-DAY WEIGHT	56-DAY LENGTH	70-DAY WEIGHT	70-DAY LENGTH
CONTROL MIXTURE							
1	1	438.8	11.2771	439.6	11.2760	419.4	11.2684
	2	437.4	11.2874	438.0	11.2837	418.6	11.2764
	3	434.8	11.2472	435.3	11.2465	416.4	11.2396
2	1	432.4	11.2337	433.4	11.2283	412.9	11.2358
	2	435.8	11.2442	436.4	11.2435	416.2	11.2358
	3	441.0	11.2680	441.6	11.2670	421.4	11.2599
3	1	439.8	11.2932	440.2	11.2925	420.2	11.2848
	2	444.1	11.2994	444.3	11.2985	424.4	11.2914
	3	442.5	11.2977	443.0	11.2970	423.6	11.2893
4	1	443.7	11.2968	444.3	11.2964	423.9	11.2887
	2	441.6	11.2808	442.3	11.2801	421.7	11.2726
	3	447.2	11.2936	447.9	11.2935	427.7	11.2858
DUST MIXTURE							
1	1	473.1	11.2946	473.7	11.2869	438.2	11.2821
	2	470.0	11.2636	471.0	11.2657	436.0	11.2613
2	1	479.2	11.2917	490.1	11.2934	445.8	11.2891
	2	486.1	11.2806	486.8	11.2789	451.8	11.2786
3	1	475.2	11.2766	475.7	11.2789	440.5	11.2751
	2	472.5	11.2591	473.0	11.2612	438.3	11.2572
4	1	481.8	11.2988	482.1	11.3015	447.1	11.2969
	2	478.2	11.2118	478.7	11.2447	444.2	11.2187

APPENDIX B
PHYSICAL STABILITY

BATCH NO.	SPEC. NO.	84-DAY WEIGHT	84-DAY LENGTH	98-DAY WEIGHT	98-DAY LENGTH	112-DAY WEIGHT	112-DAY LENGTH
CONTROL MIXTURE							
1	1	416.4	11.2672	415.3	11.2671	414.6	11.2669
	2	415.6	11.2753	414.6	11.2751	413.8	11.2748
	3	413.7	11.2382	412.5	11.2380	411.8	11.2376
2	1	410.1	11.2197	408.9	11.2194	408.2	11.2190
	2	413.3	11.2346	412.1	11.2345	411.3	11.2339
	3	418.5	11.2586	417.2	11.2584	416.4	11.2579
3	1	417.3	11.2836	415.8	11.2834	415.1	11.2829
	2	421.4	11.2900	420.1	11.2896	419.3	11.2893
	3	420.6	11.2882	419.4	11.2874	418.7	11.2875
4	1	420.9	11.2875	419.7	11.2874	418.9	11.2870
	2	418.5	11.2711	417.3	11.2711	416.6	11.2702
	3	424.5	11.2846	423.3	11.2847	422.4	11.2831
DUST MIXTURE							
1	1	437.4	11.2888	437.3	11.2819	437.1	11.2820
	2	435.2	11.2615	435.1	11.2610	435.0	11.2612
2	1	444.8	11.2890	444.7	11.2881	444.6	11.2784
	2	450.9	11.2787	450.8	11.2780	450.8	11.2784
3	1	439.8	11.2754	439.7	11.2746	439.5	11.2748
	2	437.4	11.2573	437.1	11.2571	437.1	11.2570
4	1	446.2	11.2972	445.9	11.2971	445.8	11.2968
	2	443.4	11.2200	443.2	11.2186	443.2	11.2210

APPENDIX C
FREEZE-THAW SPECIMENS

MIXTURE 1: CONTROL WITH WATER/CEMENT = 0.50
1.5 OUNCES AEA PER 100 LB CEMENT

INGREDIENT	AMOUNT
CEMENT	26.34 LB
WATER	14.68 LB
SAND	69.56 LB
AEA	11.71 ML

CHARACTERISTICS OF FRESH CONCRETE

BATCH NUMBER	SLUMP (in)	AIR CONTENT (%)	FLOW (%)	UNIT WEIGHT (PCF)
1	2.5	14	80	142
2	4.5	15	102	143
3	4.5	11	92	146

COMPRESSIVE STRENGTH

AGE (DAYS)	BATCH 1 EACH	BATCH 1 AVG	BATCH 2 EACH	BATCH 2 AVG	BATCH 3 EACH	BATCH 3 AVG
7	3560	3634	3075	3130	3535	3551
	3738		3105		3639	
	3604		3209		3480	
28	4281	4563	4661	4522	4568	4728
	4623		4430		4662	
	4786		4805		4954	

APPENDIX C
FREEZE-THAW SPECIMENS

MIXTURE 2: DUST WITH WATER/CEMENT = 0.50
1.5 OUNCES AEA PER 100 LB CEMENT

INGREDIENT	AMOUNT
CEMENT	23.74 LB
WATER	12.60 LB
SAND	55.20 LB
DUST	13.46 LB
AEA	10.5 ML
CHELATING AGENT	244.2 G
STABILIZING AGENT	145.3 G

CHARACTERISTICS OF FRESH CONCRETE

BATCH NUMBER	SLUMP (in)	AIR CONTENT (%)	FLOW (%)	UNIT WEIGHT (PCF)
1	9.5	4	128	167
2	9.0	4.2	133	166
3	9.0	4	130	167

COMPRESSIVE STRENGTH

AGE (DAYS)	BATCH 1 EACH	BATCH 1 AVG	BATCH 2 EACH	BATCH 2 AVG	BATCH 3 EACH	BATCH 3 AVG
1	1290	1281	1142	1239	1246	1303
	1271		1335		1360	
7	2235	2243	2304	2292	2230	2233
	2250		2279		2235	
28	3520	3627	3446	3263	3742	3728
	3733		3080		3713	

APPENDIX C
FREEZE-THAW SPECIMENS

MIXTURE 3: DUST WITH WATER/CEMENT = 0.40
1.5 OUNCES AEA PER 100 LB CEMENT

INGREDIENT	AMOUNT
CEMENT	24.30 LB
WATER	10.50 LB
SAND	56.46 LB
DUST	13.78 LB
AEA	10.8 ML
CHELATING AGENT	250.0 G
STABILIZING AGENT	148.8 F

CHARACTERISTICS OF FRESH CONCRETE

BATCH NUMBER	SLUMP (in)	AIR CONTENT (%)	FLOW (%)	UNIT WEIGHT (PCF)
1	5.5	5.5	--	166
2	4.5	5.13	--	168

COMPRESSIVE STRENGTH

AGE (DAYS)	BATCH 1 EACH	BATCH 1 AVG	BATCH 2 EACH	BATCH 2 AVG
1	1963	2040	2022	2037
	2116		2052	
7	3105	3187	3189	3155
	3268		3120	
28	4825	4531	3021	3071
	4237		3120	

APPENDIX C
FREEZE-THAW SPECIMENS

MIXTURE 4: DUST WITH WATER/CEMENT = 0.40
2.5 OUNCES AEA PER 100 LB CEMENT

INGREDIENT	AMOUNT
CEMENT	36.45 LB
WATER	16.91 LB
SAND	84.94 LB
DUST	20.67 LB
AEA	11.71 ML
CHELATING AGENT	361.55 G
STABILIZING AGENT	214.29 G

CHARACTERISTICS OF FRESH CONCRETE

BATCH NUMBER	SLUMP (in)	AIR CONTENT (%)	FLOW (%)	UNIT WEIGHT (PCF)
1	9.0	6	108	167

COMPRESSIVE STRENGTH

AGE (DAYS)	BATCH 1 EACH	AVG
1	1350	1370
	1389	
3	1730	1772
	1814	
7	1997	1997
	1997	
28	2225	2248
	2373	
	2146	

APPENDIX C
FREEZE-THAW SPECIMENS

MIXTURE 5: DUST WITH WATER/CEMENT = 0.40
5.0 OUNCES AEA PER 100 LB CEMENT

INGREDIENT	AMOUNT
CEMENT	25.52 LB
WATER	10.97 LB
SAND	59.84 LB
DUST	14.48 LB
AEA	38.00 ML
CHELATING AGENT	262.7 G
STABILIZING AGENT	156.3 G

CHARACTERISTICS OF FRESH CONCRETE

BATCH NUMBER	SLUMP (in)	AIR CONTENT (%)	FLOW (%)	UNIT WEIGHT (PCF)
1	--	11.5	--	158

COMPRESSIVE STRENGTH

AGE (DAYS)	BATCH 1 EACH	AVG
1	1837	1823
	1809	
3	2235	2307
	2378	
7	2828	2769
	2709	

APPENDIX D
LINEAR TRAVERSE

CONTROL MIXTURE: WATER/CEMENT = 0.50
1.5 OUNCES AEA PER 100 LBS OF CEMENT

TOTAL TRAVEL EXECUTED: 55 INCHES
TOTAL VOID LENGTH: 5.14992 INCHES
TOTAL NUMBER OF VOIDS: 534

VOIDS SMALLER THAN 25µm:	186
26µm TO 50µm:	0
51µm TO 75µm:	7
76µm TO 100µm:	17
101µm TO 125µm:	36
126µm TO 150µm:	29
151µm TO 175µm:	30
176µm TO 200µm:	28
201µm TO 225µm:	16
226µm TO 250µm:	20
VOIDS GREATER THAN 250µm:	165

AVERAGE CHORD INTERCEPT: 0.010
VOIDS PER INCH: 9.7
SPECIFIC SURFACE (IN2/IN3): 415
PASTE-TO-AIR RATIO: 5.0
AIR CONTENT (PERCENT): 9.4
SPACING FACTOR: 0.0112

APPENDIX D
LINEAR TRAVERSE

DUST MIXTURE: WATER/CEMENT = 0.50
1.5 OUNCES AEA PER 100 LBS OF CEMENT

TOTAL TRAVEL EXECUTED: 55 INCHES
TOTAL VOID LENGTH: 1.03196 INCHES
TOTAL NUMBER OF VOIDS: 164

VOIDS SMALLER THAN 25µm:	118
26µm TO 50µm:	0
51µm TO 75µm:	0
76µm TO 100µm:	0
101µm TO 125µm:	0
126µm TO 150µm:	1
151µm TO 175µm:	1
176µm TO 200µm:	0
201µm TO 225µm:	0
226µm TO 250µm:	1
VOIDS GREATER THAN 250µm:	43

AVERAGE CHORD INTERCEPT: 0.006
VOIDS PER INCH: 3.0
SPECIFIC SURFACE (IN2/IN3): 636
PASTE-TO-AIR RATIO: 27.2
AIR CONTENT (PERCENT): 1.9
SPACING FACTOR: 0.0154

APPENDIX D
LINEAR TRAVERSE

DUST MIXTURE: WATER/CEMENT = 0.40
2.5 OUNCES AEA PER 100 LBS OF CEMENT

TOTAL TRAVEL EXECUTED: 55 INCHES
TOTAL VOID LENGTH: 3.93556 INCHES
TOTAL NUMBER OF VOIDS: 335

VOIDS SMALLER THAN 25µm:	74
26µm TO 50µm:	0
51µm TO 75µm:	1
76µm TO 100µm:	8
101µm TO 125µm:	17
126µm TO 150µm:	23
151µm TO 175µm:	15
176µm TO 200µm:	23
201µm TO 225µm:	19
226µm TO 250µm:	13
VOIDS GREATER THAN 250µm:	142

AVERAGE CHORD INTERCEPT: 0.012
VOIDS PER INCH: 6.1
SPECIFIC SURFACE (IN2/IN3): 340
PASTE-TO-AIR RATIO: 7.1
AIR CONTENT (PERCENT): 7.2
SPACING FACTOR: 0.0160

APPENDIX D
LINEAR TRAVERSE

DUST MIXTURE: WATER/CEMENT = 0.40
5.0 OUNCES AEA PER 100 LBS OF CEMENT

TOTAL TRAVEL EXECUTED: 55 INCHES
TOTAL VOID LENGTH: 4.4386 INCHES
TOTAL NUMBER OF VOIDS: 508

VOIDS SMALLER THAN 25µm:	150
26µm TO 50µm:	0
51µm TO 75µm:	3
76µm TO 100µm:	7
101µm TO 125µm:	28
126µm TO 150µm:	28
151µm TO 175µm:	39
176µm TO 200µm:	33
201µm TO 225µm:	38
226µm TO 250µm:	15
VOIDS GREATER THAN 250µm:	167

AVERAGE CHORD INTERCEPT: 0.009
VOIDS PER INCH: 9.2
SPECIFIC SURFACE (IN2/IN3): 458
PASTE-TO-AIR RATIO: 5.9
AIR CONTENT (PERCENT): 8.1
SPACING FACTOR: 0.0110

The vita has been removed from the scanned document