BENEFICIAL REUSE OF NYE CHROMITE ORE SAND IN CONSTRUCTION APPLICATIONS

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FINAL REPORT

Prepared for

Shieldalloy Metallurgical Corporation

by

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ABSTRACT

Shieldalloy Metallurgical Corporation has a major stockpile of a mineral product that requires assessment for beneficial use in the construction industry. The mineral product is chromite ore sand, a non–toxic material derived from a mining process. Since the material is not a standard material of construction, there exists the need to properly evaluate the characteristics of the material and compare these characteristics to those of construction materials. There exists the possibility that the material will offer characteristics beneficial to specific applications in commercial or highway construction, precast product, or mine land reclamation. The purpose of this research is to identify applications that are improved or optimized by the use of this material.

The two main applications studied are controlled low strength material (CLSM) and high density concrete. Both these applications have been considered because the chromite ore sand characteristics may be suitable to the products. CLSM mixtures were tested for flow consistency, density, hardening time, strength gain and permeability. High density concrete mixtures were designed so as to have maximum possible density of concrete. Two types of mixtures were designed, one using chromite ore sand as the only aggregate material in the mixture and the other with hematite coarse aggregate and chromite ore sand as fine aggregate. High density of the concrete was the controlling property, as it was to be tested for concrete shielding purposes.

Test results for the chromite ore sand CLSM have shown that all properties of the mixtures are comparable to CLSM mixtures produced with regular silica sand; therefore, chromite ore sand can be successfully used to produce CLSM mixtures. By the selection of proper components and proportioning, CLSM mixtures can be designed to achieve the strength requirements necessary for their purposes. Results for the chromite ore sand high density mixtures showed that the mixtures that included this sand alone provided a marginal increase in nuclear shielding capabilities. High density coarse aggregates along with chromite ore sand as fine aggregate can be used to produce high density concrete for ballast, nuclear shielding, and other high density concrete applications.

The objective of this study was to identify construction applications for the stockpiled chromite ore sand. The approach pursued the properties of the sand, identified potential applications, and evaluated the suitability of the sand to the proposed applications.

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CHAPTER 1 INTRODUCTION

This research documents a laboratory investigation performed to evaluate the beneficial use of a chromite ore sand, mined for use as a metallurgical alloying resource, in the construction industry. Finding a beneficial use for this sand will prevent the disposal of a nearly 200,000-ton stockpile of it.

1.1 Problem Statement

Shieldalloy Metallurgical Corporation (SMC) has a major stockpile of the ore-derived sand and seeks its assessment for beneficial use in the construction industry. The mineral sand is a non–toxic material derived from the crushing of naturally occurring chromite ore. Since the material is not a standard material of construction, there exists a need to properly evaluate the characteristics of the material and compare these characteristics to those of standard construction materials. There also exists the possibility that the material will offer characteristics beneficial to applications in commercial or highway construction, precast product, or mine land reclamation. The purpose of this research is to identify applications that are improved or optimized by the use of this material.

1.2 Origin of the Chromite Ore

Of the numerous minerals essential to manufacturing in the United States, four are considered particularly important: the chromium, cobalt, manganese and platinum group of metals. Interest in these four materials is high because the United States lacks reserves of these minerals and must rely on imports from politically volatile regions (Davidson, 2000). The fact that minerals are not evenly distributed in the Earth's crust has generated further concerns. Heavy reliance on imports has been considered a major disadvantage for a country's economic, political and military independence. During the cold war period, a large national defense stockpile was created in the United States, consisting of almost every mineral raw material that was not available in adequate quantities in the country. The Strategic and Critical Materials Stockpiling Act grants the Department of Defense the authority to maintain a stockpile of so-called strategic and critical materials to supply the military, industrial and civilian needs of the United States for the country's defense (Davidson, 2000). The chromite ore at SMC was potentially a valuable source of chromium and was therefore stockpiled as a possible source of a strategic mineral.

1.3 Current Status

With the end of the cold war, the importance of some of these material stockpiles has decreased. Moreover, since the process of extraction of chromium from the ore is no longer economical, there is a need to assess the ore for other purposes. SMC also has a lease on the land where the material is stored and wants to terminate the lease.

1.4 Objective

The objective of this investigation is to identify construction or industrial applications for the stockpiled sand. The use of the stockpiled sand will not only help

SMC to clear the land under lease but also to free landfill space that would have to be used for disposal of the chromite sand.

1.5 Approach

1) Characterize the engineering properties of the material, which must be known before its use as a construction material.
2) Identify potential applications in which the chromite sand can be used as construction material.
3) Study the suitability of this sand to the proposed applications.

CHAPTER 2 BACKGROUND AND LITERATURE REVIEW

The Shieldalloy Metallurgical Corporation (SMC) owns a stockpile of Nye ore in Columbus, Montana. The stockpile is a granular chromite ore. This chapter provides a description of the material properties, characteristics and composition of the chromite ore sand. It relates the significance of the components and their properties to possible applications. An overview of the possible applications, properties of the applications, and earlier study conducted on the applications is also presented.

2.1 Nye Ore

The Nye ore is an impure form of chromite ore. It is composed primarily of aluminum, chromium, iron and silica. There are other minor metals in the ore; however, the ore was mined for its chromium content. The chromium content of the ore is between 20 and 30 percent. The ore was mined in Nye, Montana, and later transported to Columbus, Montana. The stockpile in Columbus is approximately 200,000 tons and 95,000 cubic yards. While the ore is not an environmental concern, there remains a need to remove the ore from Columbus, hence the need to find a use for it.

The chromite ore has a few distinguishing features that provide advantages and limitations to its use as a construction material. The size and gradation of the material may not make it suitable for exclusive use as aggregate for either portland cement concrete or bituminous asphalt concrete. However, its density and hardness may be sufficient to allow its use as an aggregate addition for abrasion resistance, nuclear shielding, and energy absorption in portland cement concrete or bituminous asphalt concrete. The high density is a highly sought after quality in certain sectors of the concrete and precast concrete market. There is the potential to demonstrate that the material provides higher moduli concrete structures and has applications in ballast or shielding structures.

However, transportation costs from the remote location of the stockpile may limit demand for the material.

2.2 Physical Properties

The physical properties data sheet of the chromite ore sand, as obtained from SMC, is presented in Table 1. The main property of interest is the high specific gravity. The specific gravity of regular silica sand used as fine aggregate in concrete mixture design is in the range of 2.4 to 2.8. The specific gravity of 5.2 of the chromite ore sand classifies the material as a high density aggregate.

Property	***Nye Ore****
Appearance	Black Granular Powder
Odor	Odorless
Melting Point	2300° C
Specific Gravity	5.2
Solubility (Water)	Insoluble

*Source: Shieldalloy Metallurgical Corporation (2001)

Table 1: Physical Data of Nye, Montana, Chromite Ore

The other property of interest to this study, which is not presented in the table, is the particle size distribution of the chromite ore sand. The fineness and gradation properties describe the particle size distribution. Fineness is a measure of the particle size, often used to describe the aggregates. Fineness modulus is a numerical factor, obtained by adding the total percentages of material in the sample that are coarser than each of the particular set of sieves (cumulative percentages retained), and dividing the sum by 100 (American Concrete Institute [ACI], 2003, 116R). Fine aggregates or silica sand generally used in construction have a fineness modulus value in the range of 2.4 to 3.0 (ACI, 2003, 211). The larger the fineness modulus value, the coarser the material, and vice versa. The gradation is the distribution of aggregate particles among various sizes. The size distribution of the aggregate particles affects the relative proportions, cementing materials and water requirements, workability, pumpability, economy, porosity, shrinkage, and durability of concrete. The size distribution of the aggregate particles should be a combination of sizes that results in a minimum of void spaces.

It was observed that the chromite ore sand is a finely graded sand. The gradation analysis and fineness modulus value are presented in the next chapter. In an aggregate for a concrete mixture or other application, high density and fineness will affect the properties of the product. The suitability of chromite ore sand for use in construction applications is discussed with respect to the material properties of the particular application.

2.3 Chemical Composition

To understand the suitability of the material to various applications, tests were conducted to determine the chemical composition and structure of the sand. These included:

1) X-ray diffraction test
2) Spectrochemical analysis
3) Toxicity characteristic leachate procedure (TCLP) test

The description and background of these tests is presented in the following sections. The results obtained from these tests are presented in the next chapter.

2.3.1 X-ray Diffraction Test

X-ray diffraction (XRD) is generally a reliable method for the identification and quantification of crystalline materials. The technique utilizes the diffraction (reflection) of X-rays from the unique arrangement of atoms in a crystal structure. The technique is particularly useful for materials with grain sizes too small for microscopic identification (i.e., clay minerals, soil minerals, dusts, etc.). The experimental results provide direct information on the atomic-level spacing of crystal planes within the lattice of the sample. This information is used to identify the crystal structure of the phases found in the specimen. The XRD can even distinguish between identical crystal structures, with different compositions.

2.3.2 Spectrochemical Analysis

Spectrochemical analysis is one of the major tools of analytical chemistry (Ingle and Crouch, 1988). The four major classes of spectrochemical methods are based on the phenomena responsible, such as emission, absorption, luminescence or scattering. The spectrochemical methods are further classified depending upon the source used to generate these phenomena. For the spectrochemical analysis of the chromite ore sand, inductively coupled plasma (ICP) emission and atomic absorption methods were used.

2.3.3 TCLP Test

The Environmental Protection Agency (EPA) promulgated the toxicity characteristic leachate procedure (TCLP) test. The TCLP determination is part of the toxicity characteristic (TC) rule. Toxicity is one of four characteristics used to determine if a solid waste, excluding listed hazardous wastes, is classified as a hazardous waste. The other three characteristics are ignitability, corrosivity, and reactivity. The TCLP is described in *Test Methods for Evaluating Solid Wastes,* SW-846 Method 1311, U.S. Environmental Protection Agency (EPA) (July 1992).

TCLP is a laboratory test that is designed to simulate what would occur if the material were disposed of in a landfill where rainfall percolates through the soil and waste and eventually ends up in the groundwater. A representative sample of the material is placed in a container with a buffered extraction fluid (acetic acid) and is tumbled for 18 to 24 hours. After the tumbling is complete, the concentration of specific target contaminants is measured in the extraction fluid. If the concentration of any target contaminant exceeds the maximum allowable concentration limit for that contaminant, then the material is said to exhibit the toxicity characteristic for that contaminant (EPA). As the material is a chromite ore and chromium is one of the target contaminants listed by EPA, a brief description of chromium is presented in the next section.

2.3.3.1 Chromium

Chromium is a naturally occurring element found in rocks, animals, plants and soils. Chromium does not occur free in nature; in bound form it makes up 0.1 to 0.3 parts per million of the Earth's crust. Chromium is present in the environment in several different oxidation states ranging from Cr^{2-} to Cr^{6+}. The most common forms are chromium (Cr^{0}), trivalent chromium (Cr^{3+}), and hexavalent chromium (Cr^{6+}). Naturally occurring chromium compounds are generally in trivalent state, while hexavalent chromium compounds are produced industrially by the oxidation of trivalent chromium compounds. Chromium is an essential trace element for human health. However, some chromium compounds are acutely toxic, chronically toxic, and/or carcinogenic. The EPA regards all chromium compounds as toxic, even though in general, toxicity of chromium is mainly caused by hexavalent compounds. The EPA regulates chromium releases into the environment by setting regulatory limits.

2.3.4 Bulk Chemical Analysis

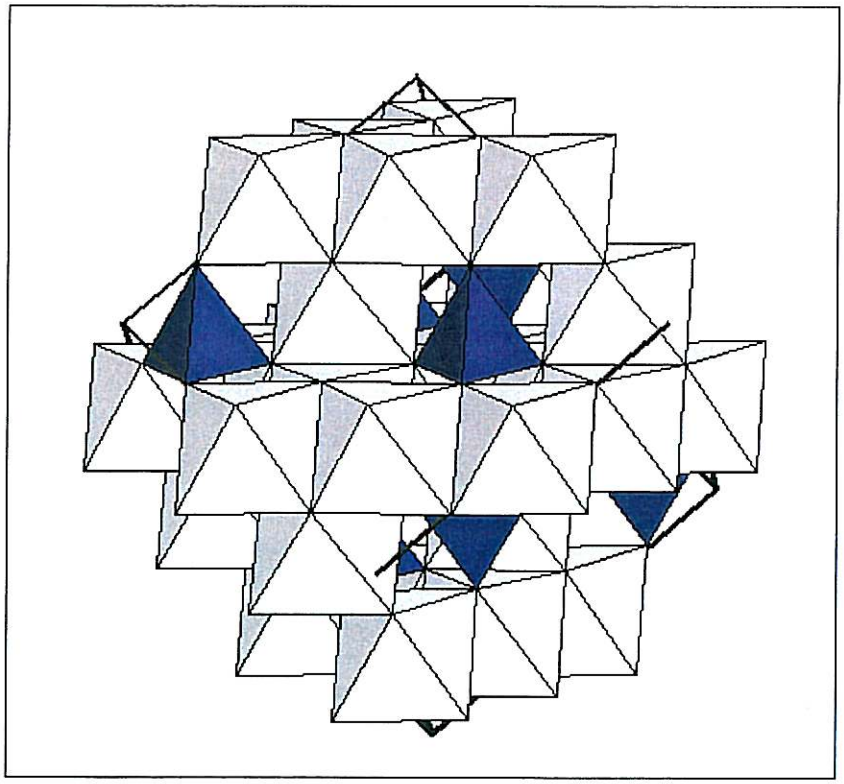
The data obtained from the X-ray diffraction and spectrochemical analysis were used to determine the bulk formula for the chromite ore sand. It was found that the ore is a member of the spinel group and is a solid solution.

2.3.4.1 Spinel Group Minerals

The spinels are a group of oxides that have very similar structures. The spinel group contains over twenty members, but only a few are considered common. Named after their sole gemstone representative, spinel ($MgAl_2O_4$), the minerals form an important group. The group includes one of the most important ores of iron, magnetite; an important ore of chromium, chromite; an important ore of lead, minium; a once important ore of manganese, iron and zinc, franklinite; and others. The general formula of the spinel group is **AB_2O_4**. The ***A*** represents a divalent metal ion such as magnesium, iron, nickel, manganese and/or zinc. The ***B*** represents trivalent metal ions such as aluminum, iron, chromium and/or manganese. Examples of spinel group minerals are chromite $FeCr_2O_4$ and spinel $MgAl_2O_4$. Solid solutions are common in this group of minerals, meaning that they may contain varying amounts of different ions in any particular specimen.

2.3.4.2 Spinel Structure

Spinel structure is made up of tetrahedrally and octahedrally coordinated ions. The structure needs eight AB_2O_4 molecules to define the unit cell. The spinel structure is represented in Figure 1. The dark colored ions represent the tetrahedral ions, which here are also the divalent metal ions such as Fe^{2+}, Mg^{2+}. The light colored ions represent the octahedral ions, which here are also the trivalent metal ions such as Al^{3+}, Cr^{3+}.



Source: http://ruby.colorado.edu/~smyth/min/spinel.html

Figure 1: Spinel Structure

2.3.4.3 Solid Solution Compounds

Generally, minerals are not pure substances, and there is extensive variation in chemical composition, which is a result of substitution. In a solid solution, specific atomic sites of the mineral structure are occupied in variable proportions by different ions. The substitution is controlled by the 1) size of the ions (<15 percent in size difference) and 2) valence of the substituting ions (electric charge must be balanced).

2.4 Possible Applications

With this background of physical and chemical characteristics of the chromite ore sand, this section will discuss the possible applications. The purpose of this research is to find the potential engineering applications of the Nye chromite ore sand. The tests carried out using the sand were aimed primarily to study its use in two main civil engineering applications, namely:

1) Controlled low strength material
2) High density concrete

2.4.1 Controlled Low Strength Material (CLSM)

CLSM is a self-compacted, cementitious material primarily used as a backfill in place of compacted fill. Several terms are currently used to describe this material including flowable fill, control density fill, flowable mortar, plastic soil-cement, soil-cement slurry, K-krete, and other names (ACI Committee 229, 1994). CLSM defined by "Cement and Concrete Terminology" of the American Concrete Institute (ACI, 2003, 116R) as a cementitious material that is in a flowable state at the time of placement and has a specified compressive strength of 1200 psi or less at 28 days.

The term CLSM can be used to describe a family of mixtures for a variety of applications. A lower strength requirement of 200 psi or less is necessary to allow for future excavation of CLSM (ACI Committee 229, 1994). Higher strengths may be used where future excavation is unlikely, such as for structural fill under buildings. CLSM should not be considered as a type of low strength concrete, but rather a self-compacted backfill material that is used in place of compacted fill. Generally CLSM mixtures are not designed to resist freezing and thawing, abrasive or erosive forces, or aggressive chemicals. Non-standard materials may be used to produce CLSM as long as the materials have been tested and found to satisfy the intended application (ACI 229, 1994). Examples of non-standard materials that may be suitable as aggregates for CLSM include bottom ash produced in the coal combustion process, blast furnace slag, discarded foundry sand, and reclaimed crushed concrete.

Flowable mixtures make up a class of engineering materials having characteristics and uses that overlap those of a broad range of traditional materials, including compacted soil, soil cement, and concrete. Flowable mixtures consist of sand, water, cement and sometimes fly ash. The mixtures are proportioned, mixed and delivered in a very fluid consistency to facilitate placement; they provide an in-place product that is equivalent to a high-quality compacted soil, but without the expensive compaction equipment, vibration and related labor.

Flowable fills have been used as backfill for bridge structures, including abutments, culverts, and trenches. They have been used for embankments, bases, and subbases. They are commonly used as bedding for slabs and pipes. They have also been used to economically fill caissons and piles, abandoned storage tanks, sinkholes, shafts and tunnels.

Flowable fill materials usually offer an economic advantage over the cost of placing and compacting earthen backfill materials. Depending on the job conditions and costs involved, significant savings are possible. The closer the project location to the source of the flowable fill, the greater the potential cost savings.

Virtually any sand can be used in flowable fill mixtures if the mixture is proportioned accordingly (FIRST, 2002). The mineralogy is not as important as the physical properties and stability of the material for CLSM. Sand for flowable fill can be used in a dry or moisture-conditioned form.

2.4.2 CLSM Advantages

Advantages of CLSM as described in the ACI Committee 229 Report (1994) are summarized as follows:

1) Readily available – Local concrete suppliers can produce CSLM to meet most project specifications utilizing locally available material.
2) Easy to deliver – Mixed and delivered in concrete mixing trucks.
3) Easy to place – CLSM can typically be placed by chute, conveyor, pump or bucket. Additionally, CLSM is self-compacting and self-leveling, speeding construction and reducing labor requirements.
4) Versatile – CLSM mixtures can be designed to meet specific requirements.
5) Strong and durable – CLSM load carrying capacities are typically higher than compacted fills.
6) Excavatable – Lower strength CLSM (50 to 100 psi) are excavatable by hand or with conventional excavation equipment.
7) Reduced inspection – The extensive field compaction testing required with conventional fill material is not required of CLSM.

8) Rapid hardening – Hardens within several hours, permitting construction to proceed.
9) No settlement – CLSM does not form voids during placement, eliminating settlement.
10) Reduces excavation costs – CLSM permits narrower trench excavation for utility excavations.
11) Worker safety – CLSM is placed without requiring workers in the trench.
12) All-weather construction – CLSM will displace standing water and can be placed in cold weather like traditional concrete.
13) Reduced equipment needs – CLSM can be placed without loaders, rollers and/or tamping equipment.
14) No storage requirements – CLSM is delivered at the time of placement, eliminating the need for soil stockpiling.
15) By-product recycling – CSLM utilizes fly ash and possibly other residual products.

2.4.3 Plastic Properties of CLSM

Plastic properties of CLSM include flowability, segregation, subsidence, hardening time and plastic density. These properties define the performance during the construction process.

2.4.3.1 Flowability

Flowability allows CLSM to be self-leveling and self-compacting. These effects provide major advantages over conventional backfill. Flowability can be determined using the standard concrete slump cone, American Association of State Highway and Transportation Officials (AASHTO) (2000) T 119; flow cone, American Society for Testing and Materials (ASTM) (2003) C 939; or open-ended cylinder modified flow test, ASTM (2003) D 6103. ASTM (2003) C 939 is used to determine the flowability of grout and is successful when testing mixtures with aggregates less than 6.3 mm. For ASTM (2003) D 6103, the diameter of the spread should be at least 8 inches. The open-ended cylinder is placed on a level surface and filled with CLSM. The cylinder is lifted vertically within a 10 second interval, and the resulting spread is measured. CLSM proportioning must adequately fill the voids in the mixture to ensure flowability and pumpability. To achieve the desired flowability, it is recommended to increase the water content by 5 to 10 percent increments (Naik et al., 1990).

The chromite ore sand is finer than regular silica sand, which suggests that it can achieve better flowability as compared to silica sands. On the other hand, the high specific gravity of the chromite ore sand will make it difficult to flow in the CLSM mixture. The high specific gravity and fineness together mean that there is need for a component in the CLSM mixture that is finer and lighter than the sand to carry the sand in the mixture and make the mixture flowable. A possible material for such use may be fly ash.

2.4.3.2 Segregation

Segregation commonly occurs in mixtures with high flow. With proper mixture proportioning, high flow mixtures can be cast without segregation. To achieve flow without segregation, adequate fines are needed in the mixture to provide cohesion. For instance, fly ash provides cohesion in CLSM mixtures. Air-entrainment may be utilized in CLSM, but air contents exceeding 6 percent can increase segregation (Van Tassel, 1999). If segregation occurs, the CLSM will not be pumpable, because of line blockage and interrupted flow.

Due to the high specific gravity of the chromite ore sand, the possibility of segregation in chromite ore sand CSLM mixtures is high. To avoid this, proper proportioning and use of an appropriate quantity of fly ash for cohesion would be necessary. The cohesive forces formed in the CLSM mixture will prevent segregation.

2.4.3.3 Subsidence

Subsidence occurs after the placed CLSM reduces in volume as it releases water and entrapped air while consolidating (ACI Committee 229, 1994). Excess water is often absorbed by surrounding soils or is seen as bleed water at the CLSM surface. Most subsidence occurs during consolidation and is a direct result of this excess or free water. Reports show that CLSM subsides approximately 10 to 20 mm per meter of depth. As expected, mixtures with lower water contents have less subsidence.

For the chromite ore sand CLSM mixtures, excess water quantities could be reduced by proper proportioning of the components. This reduces subsidence.

2.4.3.4 Hardening Time

Hardening time is defined as the time from placement to the time that the CLSM can hold the weight of a person. Hardening time is influenced by the quantities of water and cementitious materials. The permeability and the degree of saturation of surrounding soils, humidity, ambient and CLSM temperatures, and the depth of fill also affect hardening time. Hardening generally occurs in 3 to 5 hours and is determined by a penetration resistance test, AASHTO (2000) T 197. Penetration numbers of 3.5 to 10.4 MPa are typically required to assure adequate bearing strength (ACI Committee 229, 1994). Hardening time is also increased with the use of high early strength cement. (Van Tassel, 1999)

Most of the factors affecting hardening time are external factors, associated with the surrounding soil where the CLSM is placed, and cannot be controlled for chromite ore sand CLSM mixtures. The factors affecting hardening time of chromite ore sand CLSM mixtures that can be controlled are water content and cementitious material. Proper proportioning of the components so that just enough water is added to satisfy the flow requirements can control water content. The appropriate use of cement or other cementitious material can decrease the hardening time.

2.4.4 Hardened Properties of CLSM

Hardened properties of CLSM include strength, density, settlement, thermal insulation, corrosivity, permeability, shrinkage and excavatability. These properties define the engineering performance properties. Some of these properties are briefly discussed.

2.4.4.1 Strength

Well-compacted soil has compressive strengths from 0.35 to 0.7 MPa (ACI Committee 229, 1994). To be considered excavatable, CLSM must not exceed long-term strengths of 2.1 MPa. For standard backfills, compressive strengths of 0.7 MPa or less are recommended (Brewer and Hurd, 1993). For structural fills, CLSM bearing strengths range from 0.7 to 8.3 MPa for foundation support.

Different materials, types and sources affect the compressive strength of the CLSM, so laboratory tests should be performed on initial mixtures to ensure that strength requirements are met (Brewer and Hurd, 1993). CLSM obtains 75 to 80 percent of its final strength in approximately one month.

Good soil backfill has an unconfined compressive strength 0.14 to 0.35 MPa (Amon, 1990). This level of strength is similar to that of undisturbed or recompacted soils, making the CLSM suitable for use in utility trenches containing ducts, pipes and manholes; excavations in streets and around foundations; and as fill for abandoned tunnels, sewers, and other underground cavities (Naik et al., 1990).

The chromite ore sand CLSM mixtures can be proportioned to have low or high strengths, depending upon the intended use of the mixture. By varying the use of cementitious material, strength can be varied. The angular nature of the chromite ore sand will aid bonding between particles and increase strength as compared to rounded particles. The fineness and gradation of the chromite ore sand particles suggest that the homogeneity of the CLSM mixture can be well developed as compared to a CLSM mixture of poorly graded, coarse and fine aggregate. This suggests better comparative strength development.

2.4.4.2 Density

CLSM has densities from 1840 to 2320 kg/m^3, which are greater than those of conventional backfills. The plastic density of CLSM ranges from 2000 to 2500 kg/m^3, so this must be accounted for when CLSM is used in such applications such as retaining walls, where the lateral pressure of the CLSM is of interest (Amon, 1990).

The chromite ore sand has a very high specific gravity. Therefore, the density of chromite ore sand CLSM mixtures will be much higher compared to other CLSM mixtures. An increase in density of 20 to 30 percent can be expected. The effects of the lateral pressure exerted by these high density mixtures should be considered and accounted for in design for the intended application.

2.4.4.3 Settlement

Compacted fills may have a tendency for settlement, if the compaction process is not undertaken properly. CLSM flows into the void when in flowable form and then hardens. However, no appreciable settlement occurs after hardening of CLSM. In one project located in Seattle, Washington, 600 m^3 of CLSM was used to fill a 3.7-meter-deep shaft. Total settlement reported for this project was approximately 1.4 mm (Fox, 1989).

The properties of chromite ore sand CLSM would be similar to other CLSM mixtures with respect to the settlement criteria; hence, no appreciable settlement can be expected for these mixtures as well.

2.4.4.4 Permeability

From literature review, the permeability of CLSM is approximately 5×10^{-6} cm/sec (Naik et al., 1990). Backfills consisting of sand typically have permeabilities ranging from 10^{-1} to 10^{-3} cm/sec (Naik et al., 1990). With increased fines and higher strength, lower permeabilities can be achieved. The use of materials such as bentonite clay and diatomaceous earth may also decrease permeability, but their effects on the CLSM properties must be determined through testing (ACI Committee 229, 1994). Permeability is increased with a decrease in cementitious materials and an increase in fine aggregate content.

Chromite ore sand being very fine, the CLSM mixtures produced using this sand will tend to have lower permeabilities, mainly due to increased percentage of fines. On the other hand, the uniform fly ash particle size causes higher permeability. The use of chromite ore sand and fly ash in proper proportions will help achieve acceptable permeability values.

2.4.4.5 Excavatability

The difficulty of CLSM excavation is directly related to its compressive strength. CLSM with compressive strengths under 0.35 MPa can be excavated manually, while CLSM with compressive strengths ranging from 0.7 to 1.4 MPa must be excavated mechanically (ACI Committee 229, 1994). To ensure removability, the compressive strength should not exceed 0.7 MPa (Brewer and Hurd, 1993). Mixtures with high coarse aggregate content are more difficult to excavate than those with high fine aggregate and fly ash content. Limiting cement contents in mixtures is necessary where future excavation is anticipated. By increasing the air content of a mixture, long-term compressive strengths can be decreased (Van Tassel, 1999).

The chromite ore sand CLSM mixtures can be designed to have excavatable or non-excavatable characteristics. The compressive strengths can be controlled by mixture design and use of relevant components. As mentioned earlier, a mixture of high fine aggregate and fly ash content will aid excavation, as compared to other mixtures of similar strengths. Therefore, chromite ore sand mixtures with lower strengths would be easily excavatable.

2.4.5 Earlier CLSM Research at Penn State

Earlier research (Van Tassel, 1999) looked at integrating recycled and co-product materials into CLSM. The materials evaluated in that research included fly ash, spent foundry sand, glass cullet, and reclaimed portland cement concrete. CLSM mixtures were tested for flow consistency, density, hardening time, strength gain, and permeability. It was shown that CLSM could incorporate locally available recycled or co-product material, provided the CLSM met certain performance standards of the particular use and the materials met certain minimum material standards consistent with the performance standards.

2.5 High Density Concrete

The chromite ore sand has high density, making it a heavy aggregate. High density or heavy aggregate is used primarily to make high density concrete. High density concrete has various applications. The most widely used application is in shielding. This research study includes developing high density concrete using chromite ore sand as an aggregate. Though the research looks at the suitability of using the high density concrete for shielding purposes, it must be noted that high density concrete can also be used for various other applications. While the quality control specifications for high density concrete for shielding are stringent and difficult to achieve, the specifications for high density concrete for other applications are easily achievable. Hence, the use of chromite ore sand for high density concrete in other applications must also be considered. Some applications for high density concrete are:

1) Floor tiles, paving stones and bricks

2) Roof ballast

3) Retaining wall units

4) Dams and offshore structures

5) Armor elements for breakwaters and scour protection

6) Pipe coatings in swampy areas or river crossings

7) Burial vaults

8) Storm shelters

9) Renewable-energy houses

10) Blocks, hollow blocks, guides and railway ties

11) Bridge decks, parking structures, highways

12) Structures in marine environments

2.5.1 Shielding

High density concrete is widely used in shielding (Kaplan, 1989). It is worthwhile to list the various applications of concrete shielding to aid understanding of the factors involved in its design and manufacture:

1) Nuclear reactors

2) Radiation barriers in hospitals (X-ray rooms, cancer treatment)

3) Military facilities

4) Chemical decontamination cell

5) Storage facilities for biohazardous material

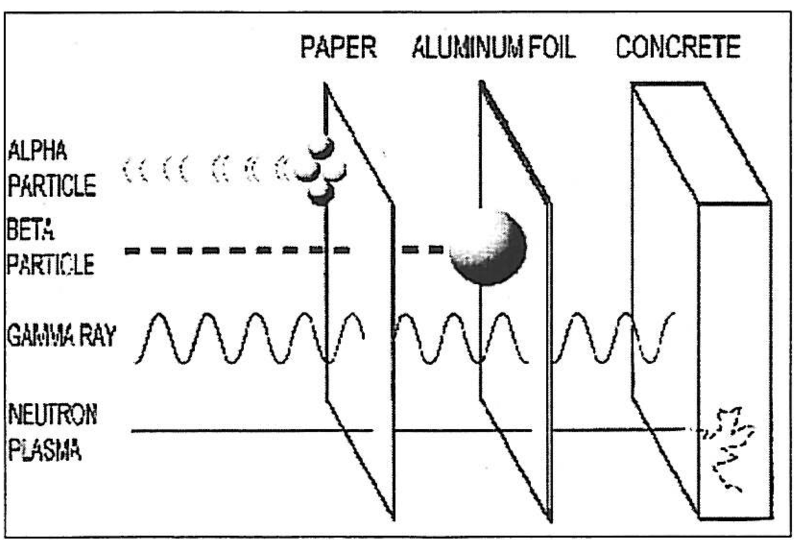
6) Nuclear waste containment structures and casks

7) Noise/sound barriers

This study focuses on developing high density concrete for radiation shielding.

2.5.2 Radiation

Radiation, when properly shielded, provides energy and medical treatments. Just as there are several types and levels of radiation, there are also several materials that can be used in radiation shielding. Figure 2 shows types of radiation and some materials that can be used to shield them. As energy levels increase, the complexity of the required shield also increases. High-energy neutrons and gamma radiation require a shield that consists of both heavy and light elements. In high density concrete, hydrogen serves as the light element while extremely dense aggregates provide the heavy element.



Source: Nuclear Shielding Supplies and Service, Inc. [NSSS] website, www.nulcearshielding.com

Figure 2: Radiation Types and Some Shielding Materials

2.5.3 The Light and Heavy Element Components in Concrete

Neutrons emanating from the core region of a reaction must be slowed down to thermal energies and then captured in the nucleus of a shield atom. Hydrogen is the most effective element in slowing down neutrons over the entire fission spectrum. An elastic scattering reaction occurs because of the favorable mass ratio between the neutron and the hydrogen nucleus (proton). In the collision, the neutron is able to impart a large fraction of its energy to the proton. Further, the thermal neutron cross section of hydrogen is reasonably high, resulting in gamma release energy of only about 2.2 MeV as compared to 8 MeV for most other nuclei. While hydrogen alone is a poor gamma ray shield and would be inadequate in attenuating primary and secondary gamma fields, as a natural ingredient in concrete it contributes its neutron shielding capabilities and becomes an integral contributor to the effectiveness of the high density concrete shield (Nuclear Shielding Supplies and Service, Inc., [NSSS] website, www.nuclearshielding.com).

The high density of a shield and its thickness are the key components in gamma or X-ray shielding. High density aggregates serve as the main ingredients in high density concrete for this purpose. Aggregates make up about 75 percent of finished concrete by volume. The heavy element component in high density concrete is thus made up of the high density aggregates. The high density aggregates are commercially available, natural, heavy minerals like hematite, ilmenite, and magnetite or artificial materials like steel punchings.

2.5.4 High Density Concrete for Radiation Shielding

As discussed earlier, the high density concrete acts as a composite shield. It has both heavy (high density aggregate) and light (hydrogen nuclei) components for radiation shielding. High density concrete is effective in thermalizing and removing neutrons from the entire fission energy range, while also attenuating primary and secondary gamma radiation. It can be poured in place, preplaced, made into transportable blocks and slabs, or grouted around a framework. A variety of admixtures can be used to customize the concrete for individual job requirements, such as high strength or protection against harsh weather.

2.5.5 High Density Concrete vs. Regular Concrete

High density concrete and regular concrete are equally good in their extreme flexibility and workability in construction applications. Therefore comparing the two requires evaluating the benefits associated with high density concrete's ability to place required weight in a fraction of the space required by regular concrete. While the per ton cost of high density aggregate is higher than that of common aggregate, further analysis of the monetary and spatial savings afforded by the use of high density concrete demonstrates why its popularity in shielding applications is so broad. The maximization of space is becoming an important factor in construction and more so in hospitals, where space can be a sought-after commodity.

2.5.6 High Density Concrete for Hospital Shields

The demand for high density concrete shielding in hospitals and cancer clinics continues to grow for protection from radiation sources such as linear accelerators and cyclotrons. Hospitals are steering clear of the environmental and health issues associated with lead, and are using high density concrete (NSSS website, www.nuclearshielding.com). Table 2 shows a comparison of the two materials.

HIGH DENSITY CONCRETE VS. LEAD	HIGH DENSITY CONCRETE	LEAD
STOPS GAMMA RADIATION	✓	✓
STOPS NEUTRON RADIATION	✓	
STRUCTURAL VALUE IN CONSTRUCTION	✓	
ENVIRONMENTALLY FRIENDLY	✓	
NON-TOXIC	✓	
SEVERAL TIMES MORE EXPENSIVE		✓

Source: NSSS website, www.nuclearshielding.com

Table 2: High Density Concrete vs. Lead

2.5.7 High Density Concrete Bricks, Blocks and Grout

Many cancer centers and hospitals are replacing older, linear accelerators with new, high power machines. This presents problems, as the current shield may not be adequate and space may be limited for additional shielding. Access to these rooms may be a problem, and it may be difficult to install poured-in-place high density concrete. To solve these problems, high density concrete bricks and blocks are being used. Grout of equivalent high density is also provided to cement the bricks or blocks and prevent radiation streaming.

2.5.8 Miscellaneous Factors Affecting Concrete Shielding

The primary factor involved in radiation shielding is the reduction of the intensity of the radiation to the acceptable level. Secondary to this are economic and mechanical factors, which are interrelated to a considerable extent. Accomplishment of the reduction in radiation intensity is relatively simple. Almost any material will serve for shielding purposes if sufficient thickness is used. However, the use of materials requiring excessive thicknesses may be precluded on an economic basis, while other materials requiring moderate thicknesses may not be practical for economic or mechanical reasons. Fortunately, concrete can prove to be a good shielding material. The other factors involved in concrete shielding are briefly discussed.

Assuming that the required thickness of the shield has been obtained in the design, the major requirement for shielding effectiveness is homogeneity of the concrete (ACI, 1962). This is necessary because portions of the shield may not actually be composed of the material upon which the design thickness is based, and such portions may prove inadequate. A radiation shield is only as good as its weakest point. If pockets are formed in the concrete during placing, or segregation occurs, the effective concrete thickness is lessened and the intensity of radiation passing these sections is greater than anticipated (ACI, 1962). Similarly, if joints are not keyed in properly, or cracks develop, the intensity of radiation transmitted through these weak planes may easily be much greater than permissible.

The construction of most large concrete shields involves a variety of mechanical problems. Such shields are complicated by the presence of numerous openings required for operational or experimental purposes, such as the tubes used in charging reactors (ACI, 1962). These openings are of many sizes, are widely scattered, and are required in large numbers. This requires accurate placement of formwork and skillful placement of concrete to avoid segregation. Additional thickness is required to compensate for these openings, and careful design is necessary (ACI, 1962).

Space requirement is often a factor of considerable importance. If the shield is too thick, valuable space is lost. The difference between the use of heavy and ordinary concrete for shielding a reactor may be as much as 6 ft in thickness, or 12 ft in each direction (ACI, 1962).

All of these factors must be considered in determining the economics of concrete shielding. Due to the important differences between heavy and ordinary concrete, careful consideration of the cost factors involved is required. The increased costs of heavy concrete, due both to the need for obtaining and transporting heavy aggregates and the relative unfamiliarity of contractors with regard to their concreting properties, are often compensated by the reductions in shielding thickness and space requirements (ACI, 1962).

2.5.9 Physical Properties of Concrete Used for Shielding

Structural requirements of concrete shields are usually quite low due to the tremendous area of the thick shield sections. Generally, any major loads are due to the thermal stresses (ACI 1962). As with ordinary concretes, the properties of dense concretes can be varied over a wide range to meet the particular requirements by the proper selection of materials and proportioning of the mixture. Dense mixtures proportioned on a volume basis can be expected to have structural properties similar to those of the same mixture made with ordinary aggregates. Where a hard aggregate such as magnetite iron ore is used, the concrete strength increases.

Thermal properties such as specific heat and thermal conductivity are important where thermal stress problems are encountered. These properties are similar in magnetite concrete and ordinary concrete. They are 25 to 50 percent lower for barite concretes, whereas the conductivity is considerably higher for concretes containing refined metallic aggregates (ACI, 1962).

Workability of dense concrete mixtures is in general much poorer than that of ordinary concretes. This is primarily due to:

1) The dense aggregates generally crushing into sharp, angular, and elongated particles.
2) The tendency to decrease the amounts of air entraining agents, cement, and free water to increase the density.
3) The dense materials simply require more effort to move.

2.5.10 Optimum Density and Composition

The optimum density and composition for a concrete shield are influenced by (ACI, 1962):

1) Type and intensity of radiation
2) Limitations on shield dimensions or space restriction
3) Complexity of placing conditions and shape of forms
4) Number and proximity of through-tubes and embedded items
5) Proposed construction methods
6) Temperatures and operating conditions
7) External and dead loads
8) Available aggregates
9) Economy

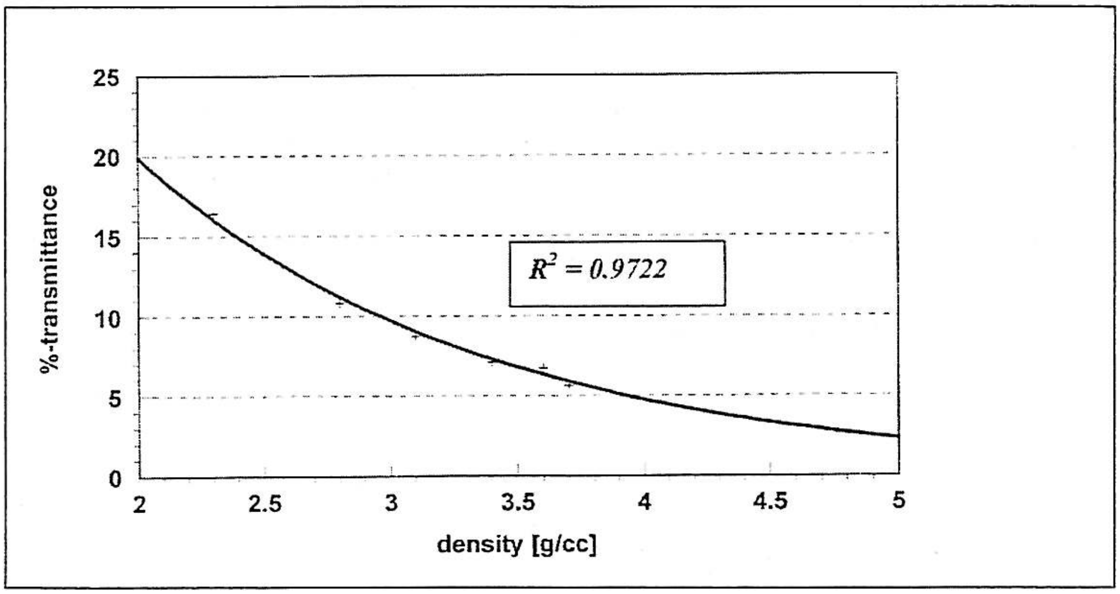
In general, proportioning mixtures of high density concrete does not differ radically from conventional concrete; that is, the mixture which produces the given quality of the hardened concrete at the least cost is usually the most desirable mixture. It must be noted, however, that the design must be modified so as to allow for increased density, the need for uniformity, and the fact that heavy aggregates may cost several times as much as cement (ACI, 1962).

2.5.11 Other High Density Concrete Research at Penn State

Earlier research (Dunkelberger, 2002) looked at developing high density concrete for radiation shielding in dry cask storage application. From the data collected in that study, an exponential relation between the calculated density of the concrete to the percent transmission of a 0.662-MeV gamma ray was calculated that gave the relation as follows:

$$\textbf{\%-Gamma Transmission} = 4.7063 \times e^{-0.0441 \times \text{density}}$$

Figure 3 summarizes this relationship.



Source: Dunkelberger (2002)

Figure 3: Percent Gamma Transmission vs. Density of Shielding Concrete

The simplest interpretation of the results of this series of experiments is that the effectiveness of the shielding can be judged by a mass-volume calculation to determine density.

This relationship can be used to judge the effectiveness of the chromite ore sand high density concrete, by calculating the density of the concrete without the need for actually conducting the more involved gamma transmittance tests.

CHAPTER 3 METHODOLOGY & PROCEDURE

This chapter describes the materials, mixture designs, sample preparation procedures, and test procedures used in this research. Standardized test procedures and modifications to those procedures are presented.

3.1 Materials

The CLSM mixtures evaluated in this research consisted of cement, fly ash, ground granulated blast furnace slag, water, regular sand and chromite ore sand. Control mixtures were developed using the silica sand meeting ASTM (2003) C 33. By using the control mixtures, the chromite ore sand mixtures are compared to similar mixtures used in standard construction applications. The high-density concrete mixtures consisted of cement, admixture, water, chromite ore sand and hematite coarse aggregate. The properties, characteristics, and sources of each material are discussed in the subsequent subsections of this chapter.

3.1.1 Cementitious Material

Spectrochemical analysis data of all cementitious materials, that is, cement, fly ash and slag, to be used in the project were obtained from the respective producers and are presented in Table 3. The moisture content and loss on ignition (LOI) values for these materials are also presented.

Composition	Keystone Cement	Masterbuilders Fly Ash	Grancem GGBFS
		Mass (Percent)	
Al_2O_3	6.68	19.1	10.8
B_2O_3	0.01	0.02	0.01
BaO	0.03	0.05	0.1
CaO	64	0.66	38
Co_2O_3	0.01	0.01	<0.005
Cr_2O_3	0.01	0.02	<0.005
Fe_2O_3	2.26	3.07	0.3
K_2O	0.9	2.6	0.53
MgO	2.76	0.45	11.4
MnO_2	0.11	0.02	0.8
MoO_3	<0.005	<0.005	<0.005
Na_2O	0.54	0.39	0.4
NiO_2	<0.005	<0.005	<0.005
SiO_2	21.1	71	37
SrO	0.36	0.01	0.06
TiO_2	0.28	0.38	0.64
V_2O_5	<0.005	0.01	<0.005
ZnO	0.01	0.01	0.01
F	<0.005	<0.005	<0.005
Cl	0.01	<0.005	0.01
NO_2	<0.005	<0.005	<0.005
NO_3	<0.005	<0.005	<0.005
PO_4	<0.005	0.01	<0.005
SO_4	1.67	0.08	0.09
Total	100.01	98.87	100.15
Other properties			
Moisture (%)	0.1	0.02	0.05
LOI (1000)	0.95	0.98	(+1.22)

Table 3: Chemical Compositions of Cement, Fly Ash and Slag

3.1.2 High Range Water Reducing Admixture

The high range water reducing admixture was used for making high density concrete. The admixture used was Rheobuild® 1000. Rheobuild® 1000 is a chloride free, high range water reducing admixture. It contains a sulphonated polymer, and is specially formulated to impart rheoplastic qualities to concrete. A rheoplastic concrete is a fluid concrete with a slump value of at least 200 mm or higher, that flows easily but at the same time is free from segregation, and has the same water/cement ratio as that of a no-slump concrete without additive. Rheobuild® 1000 meets the requirements of ASTM (2003) C494 type A and F for high range water reducing admixtures. Using the water reducer allowed for a high solids content without compromising the workability.

3.1.3 Water

Potable tap water was used for mixing, and the water temperature was approximately room temperature (23°C) for all mixtures. For CLSM mixtures water was added so that the flow requirements were satisfied, allowing for addition of extra water if needed. For the high-density concrete mixtures, water was added so that it satisfied the workability requirements.

3.1.4 Silica Sand

Control mixtures were developed using the silica sand meeting ASTM (2003) C 33. The sand was river sand with a specific gravity of 2.60 and absorption of 1.73 percent. The grain size distribution is presented in Figure 4.

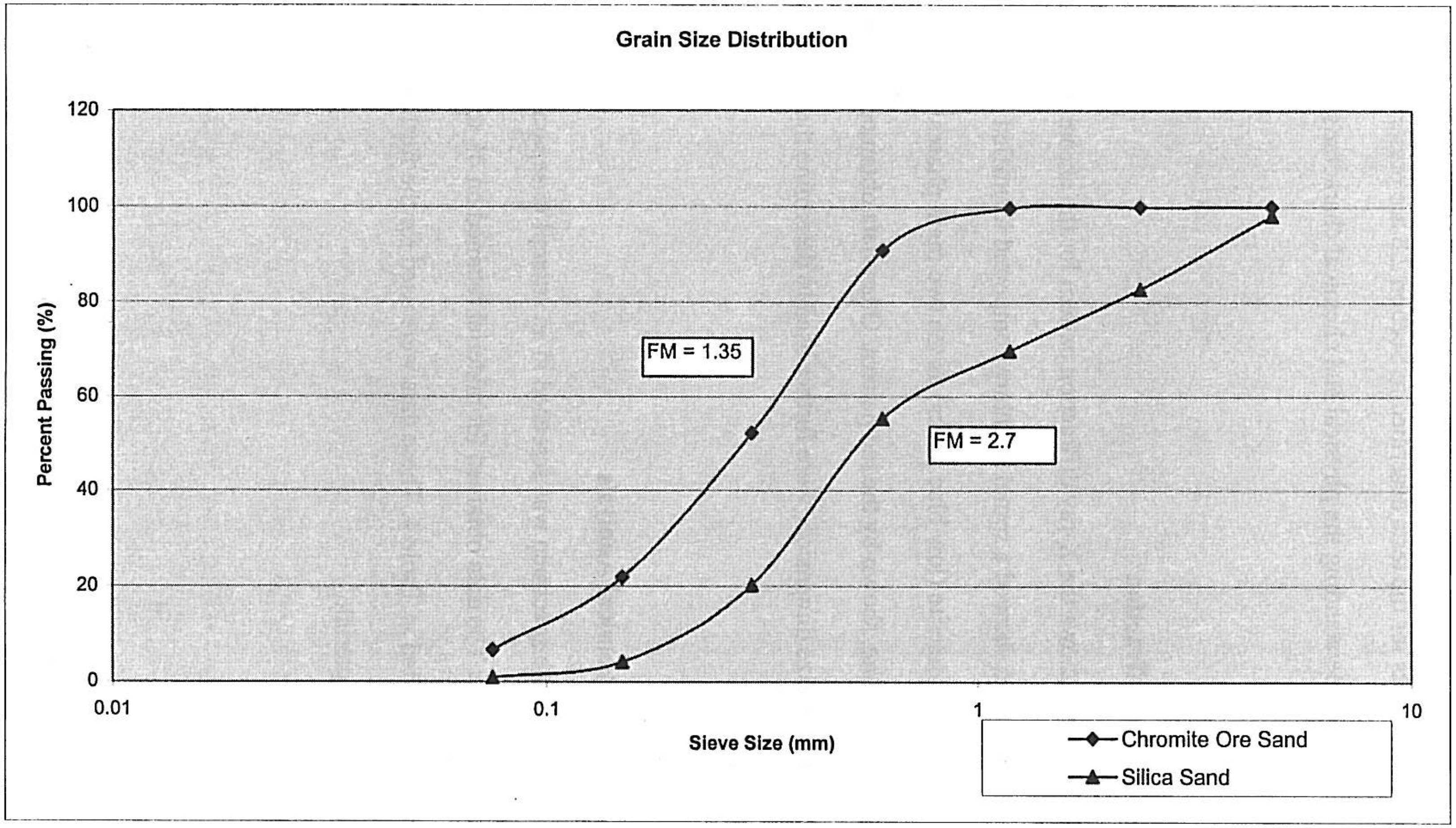


Figure 4: Grain Size Distribution for Chromite Ore Sand and Silica Sand

3.1.5 Chromite Ore Sand

The results for the tests described in Section 2.3 are presented. These results help in better understanding the physical and chemical characteristics of the chromite ore sand.

3.1.5.1 X-ray Diffraction

Figure 5 shows the X-ray diffraction pattern for the chromite ore sand. The diffraction pattern showed a spinel structure compound identified as chromite (higher blue peaks) and fosterite (low blue peaks) as the two main phases. A search match for magnetite was done, shown by the red pattern. Other data obtained from this test, such as the cell size dimension, were further used to determine the chemical composition.

3.1.5.2 Spectrochemical Analysis

The sample specimen was screened in an attempt to separate the chromite from the fosterite. The data obtained for material retained on 45 screen and 200 screen are presented in Table 4. These data were used for the further chemical analysis of the material.

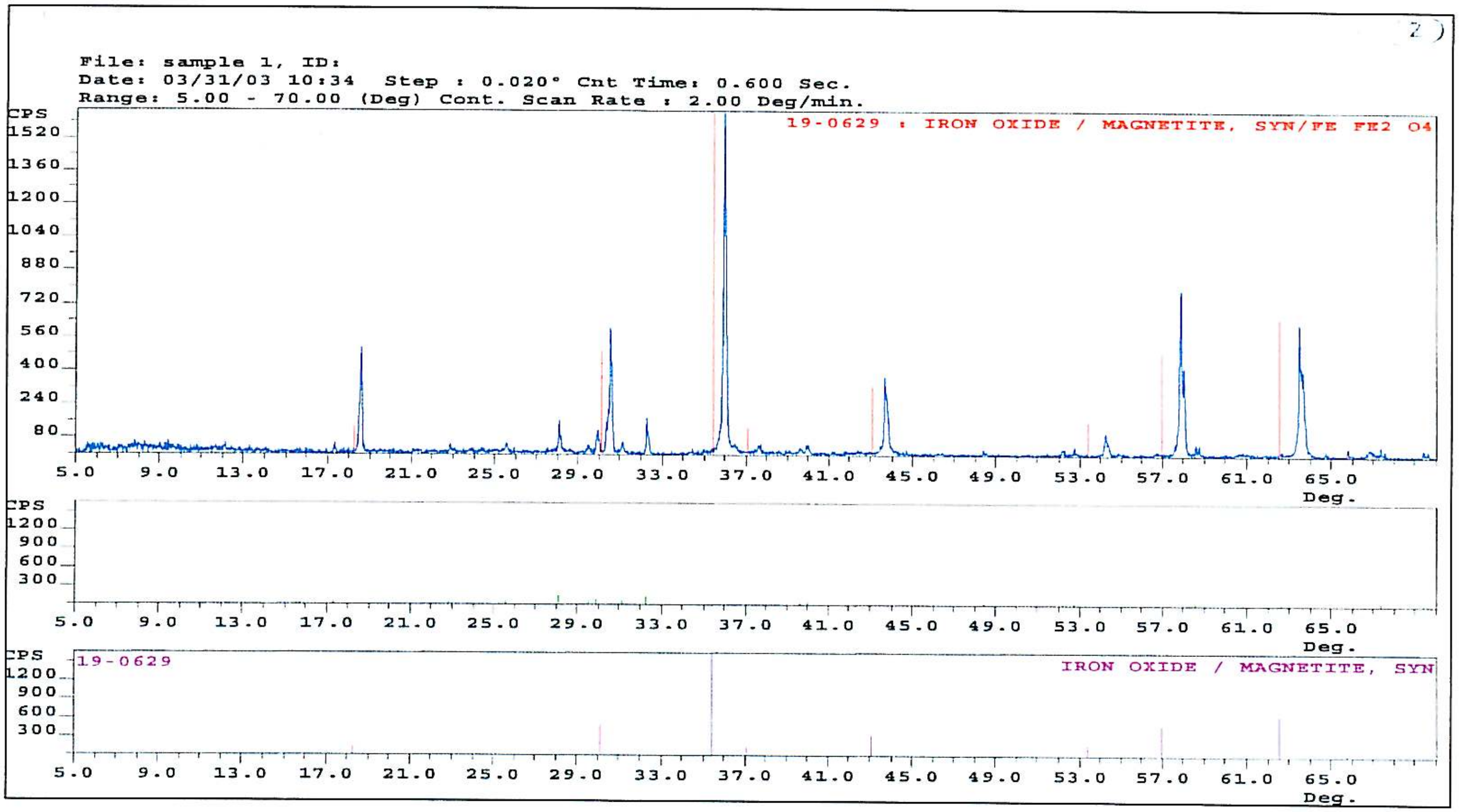


Figure 5: X-Ray Diffraction for the Chromite Ore Sand

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Weight (%)	Retained on 45 BES-45-1	Retained on 200 BES-200-1
Al_2O_3	17.2	11.5
BaO	<0.005	<0.005
CaO	0.75	1.24
Co_2O_3	0.07	0.06
Cr_2O_3	40.0	30.0
FeO	21.1	19.6
K_2O	0.03	0.07
MgO	14.5	19.8
MnO	0.32	0.34
MoO_3	0.01	0.01
Na_2O	0.11	0.12
NiO	0.16	0.22
SiO_2	4.63	16.1
SrO	<0.005	<0.005
TiO_2	0.69	0.56
V_2O_5	0.23	0.19
ZnO	0.10	0.08
Total	99.9	99.9

Table 4: Spectrochemical Analysis of the Nye Chromite Ore Using the +45 and +200 Sieve Fraction

3.1.5.3 TCLP Test

The TCLP test results and the EPA regulatory limits for the relevant components are presented in Table 5. From the TCLP results it was found that the chromium levels in the sand are just at the threshold level. The chromium content levels may limit the use of the sand in the various possible applications.

3.1.5.4 Bulk Chemical Analysis

It was found from the bulk chemical analysis that the chromite ore sand is a solid solution. The general bulk chemical formula for the ore is $(Fe,Mg)(Cr,Al)_2O_4$, where Chromite $FeCr_2O_4$ and Spinel $MgAl_2O_4$ are the end products of the series. From the data obtained from earlier tests and other bulk chemical analysis calculations, it was found that the chemical formula best representing the chromite ore sand was given by:

$\mathbf{(Fe_{0.59}, Mg_{0.41})(Cr_{0.61}, Al_{0.39})_2O_4}$

Another approximation of the chemical composition was made using the principle of Vegard's Law. According to this principle, the unit cell dimensions of a mixed crystal vary linearly with composition. Using the cell size data from the X-ray diffraction test for the chromite ore sand, and cell size data for the end products of the series, Chromite $FeCr_2O_4$ and Spinel $MgAl_2O_4$, from the literature, an approximate composition for the material was obtained. Figure 6 represents the composition determination process.

Component	Content mg/L	EPA Reg. Limit mg/L
Ag	<0.02	
Al	1.6	
As	<0.005	5.0
B	1.5	
Ba	0.3	100
Be	<0.02	
Ca	51.0	
Cd	<0.005	1
Co	<0.02	
Cr	**4.9**	**5.0**
Cu	0.1	
Fe	0.5	
Hg	<0.001	0.2
K	8.5	
Mg	47.0	
Mn	1.5	
Mo	0.1	
Ni	0.5	
Pb	<0.005	5.0
Sb	<0.005	
Se	<0.005	1.0
Si	4.3	
Sr	0.1	
Ti	<0.02	
Tl	<0.005	
V	0.1	
Zn	0.1	
NO_3	0.2	
PO_4	<0.1	
SO_4	6.0	

Table 5: TCLP Test Result of the Nye Chromite Ore

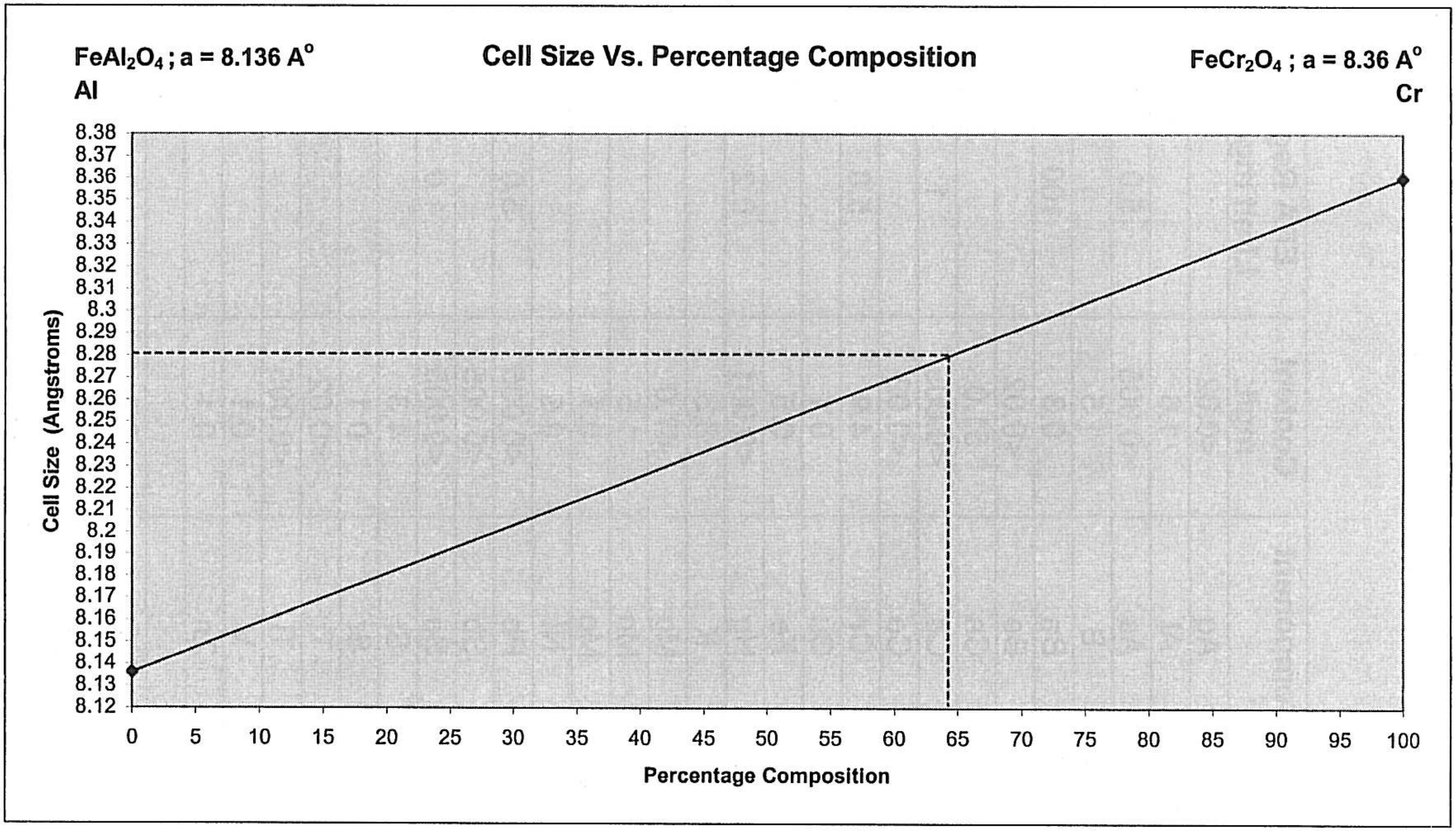

Figure 6: Chemical Composition Determination Using Vegard's Principle for the Chromite Ore Sand

3.1.5.5 Grain Size Distribution

While the other properties of the chromite ore sand have been discussed earlier, the comparative grain size distribution for regular silica sand and chromite ore sand is presented in Figure 4. The chromite ore sand was much finer than the regular silica sand as seen from the figure. The fineness modulus for chromite ore sand was 1.35, as compared to 2.7 for regular silica sand.

3.1.6 Hematite Coarse Aggregate

The hematite coarse aggregate was specially obtained from NSSS (www.nuclearshielding.com) for use in high density concrete. The hematite aggregate is a commercially available aggregate with a high specific gravity. It is mainly used for high density concrete applications. The hematite aggregate was obtained so as to develop high density concrete using hematite as the coarse aggregate and chromite ore sand as the fine aggregate. The high density concrete mixture design was formulated so as to obtain maximum achievable density. The relevant data are presented in Table 6, and grain size distribution is presented in Fig. 7.

Property	***Value***
Specific Gravity	**5.06**
Absorption (%)	**0.6**
Dry Unit Weight	**185 pcf**
Moisture (%)	**2.5**

Source: NSSS data sheet, www.nuclearshielding.com

Table 6: Data for Hematite Coarse Aggregate

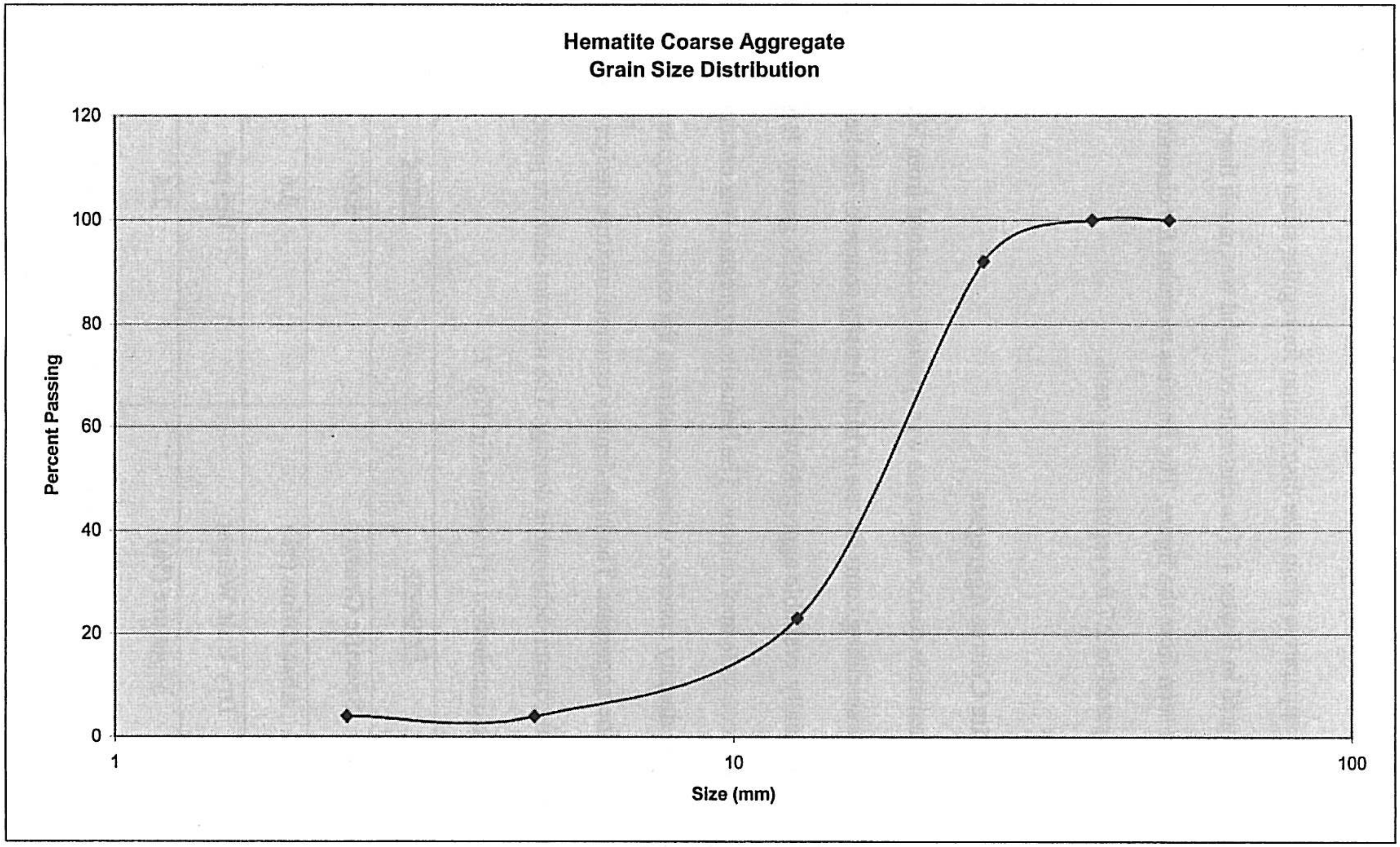

Figure 7: Grain Size Distribution for Hematite Coarse Aggregate

3.2 Mixture Design Considerations for CLSM

Considering all the factors discussed earlier, the mixture designs were formulated. The chromite ore sand obtained has a much higher specific gravity compared with normal sand. The higher density of the sand affected the flowability of the mix. Flowability of the mixture would play a major role in deciding the proportions of the mixture. It was decided to design the mixture so that it had a 28-day strength above the minimum required 50 psi value.

A number of trial mixtures of smaller quantity were formulated to get the approximate proportions of the components so that the mixture would satisfy its flowability requirements. The components used were chromite ore sand, cement, fly ash, blast furnace slag and water. Cement, fly ash and blast furnace slag were used as the binding or cementitious material. It was found that fly ash not only acted as a good binder but also helped in considerably increasing the flowability of the mixture. Increase in cement or blast furnace slag quantities to improve the flowability by improving binder quality increased the strengths to levels which were much greater than those required for CLSM. Thus it became clear through initial trials that fly ash would have to be incorporated in all the mixtures to achieve the desired flowability without exceeding the strength limits for CLSM.

3.3 Mixture Design Groups

Critical parameters of interest include density, flow consistency, compressive strength and permeability. The mixture designs were formulated so as to vary the mixture composition and proportions to evaluate these parameters for different mixtures. The mixtures are divided into three groups, designated herein as Group I, Group II and Group III. The mixtures are divided into groups based on the cementitious components used in the mixture. Each group has one control mixture with regular silica sand and two mixtures with chromite ore sand, while the other components in the mixture remain same. This will help in comparing the properties of the chromite ore sand mixtures with the regular silica sand mixtures. The cementitious components, which differentiate each group from the other, are listed below.

Group I Components – Cement and fly ash

Group II Components – Fly ash

Group III Components – Slag and fly ash

3.4 Mixing Procedure and Sample Preparation

After establishing a mixture design matrix to evaluate the suitability of chromite ore sand in CSLM, batch mixing and sample preparation were performed using the following process.

Step I: Proportioning and Blending Dry Materials.

The dry materials (cement, fly ash, slag, silica sand and chromite ore sand) were weighed according to batch weights for each mixture. All weight measurements were performed on an electronic balance with the capacity of 180 kg and an accuracy of +/- 0.1 kg. The dry materials were then blended together prior to the addition of water. Blending consisted of mixing all dry materials in a steel concrete mixer.

Step II: Measuring and Water Addition

After proportioning and blending the dry materials, the quantity of water that was proposed in the mixture design was measured and divided into four equal parts. One portion was added to the mixture at a time, and the consistency of the CLSM was monitored. Once the consistency reached that of pancake batter, the flow consistency was measured according to ASTM (1996) D 6103. Water was added in small increments, followed by additional flow consistency measurements, until a reading greater than 20 cm was achieved. Once this point was reached, the remaining water was weighed on the electronic balance and subtracted from the original amount, to determine the amount of water used. Throughout this process, the mixer was used to continually blend the components.

Step III: Filling Molds and Tests Performed

After thorough mixing, tests were performed on each mixture to determine other properties relevant to CSLM in addition to ***flow consistency***. Once the flow requirement was satisfied the tests for finding ***plastic density*** and ***setting time*** were carried out. The mixture was cast into 4-in-diameter and 8-in-high cardboard cylinders for ***compressive strength*** determination at 7, 14 and 28 days. Cardboard cylinders were used because they helped in easy demolding. The plastic molds used earlier were difficult to demold, and they invariably damaged the cylinder specimens beyond acceptable limits. To determine ***permeability*** at 28 days, the mixture was cast into a Proctor mold. At 28 days the ***dry density*** and ***oven dry density*** were also determined. All these tests were carried out according to ASTM specifications.

3.5 CLSM Controlling Properties

To characterize the basic material properties, several tests were performed on the CLSM mixtures. CLSM tests include plastic density, flow consistency, setting time, compressive strength, oven dry density and permeability.

3.5.1 Plastic CLSM Density

The plastic concrete density was measured in accordance with ASTM (1996) D 6023, *Standard Test Method for Unit Weight, Yield, Cement Content, and Air Content of Controlled Low Strength Material.* The measurement utilized a unit weight container and a scale with a capacity of 20 +/- 0.01 kg.

3.5.2 Flow Consistency of Plastic CLSM

The workability of the CLSM was determined by its flow consistency in accordance with ASTM (1997) D 6103, *Standard Test Method for Flow Consistency of Controlled Low Strength Material.* This procedure involved a bottomless, plastic, cylindrical mold resting on a smooth, non-absorbent, steel surface. The mold was filled with CLSM and vertically removed over a 10-second interval. The diameter of the resulting spread was measured to determine the flow consistency. Water was added to each mixture until the spread diameter was greater than 20 cm to ensure that the mixture was self-leveling and void-filling.

3.5.3 Setting Time

The setting time, also referred to as hardening time, was evaluated according to AASHTO (2000) T 197, *Time of Setting of Concrete Mixtures by Penetration Resistance.* For this procedure, a rectangular steel mold was filled with fresh CLSM. After two hours elapsed from the time of mixing, the CLSM penetration resistance was measured with either a 19.35 cm^2 or 6.45 cm^2 steel penetration needle. Thereafter the penetration resistance was measured at half-hour intervals for at least six, non-zero readings.

3.5.4 Compressive Strength

For all compressive strength measurements, ASTM (1995) Standard D 4832, *Standard Test Method for Preparation and Testing of Controlled Low Strength Material Test Cylinders,* was used. Compressive strength was measured using three, 4-in-by-8-in cylinders. For all mixtures, compressive strengths were evaluated at 7, 14 and 28 days. Typically, strength measurements are taken at 1 and 3 days, but because the cylinders are easily damaged at early ages, these measurements were foregone. The cylinder molds consisted of waxed cardboard, and the cylinders were demolded at 4 days after casting. The cylinder strength was measured using a screw-type testing machine with a 5 kN load ring.

3.5.5 Oven Dry Density

The oven dry density of the CLSM mixtures was determined following the procedure outlined in ASTM (1986) C 495, *Standard Test Method for Compressive*

Strength of Lightweight Insulating Concrete. The cylinders used had dimensions of 10.16 cm by 20.32 cm and a volume of 1647 cm^3. Cylinders were dried until a constant weight change (<1%) was achieved in a 24-hour time period.

3.5.6 Permeability

CLSM permeability was evaluated according to AASHTO (2000) T 215, *Permeability of Granular Soils (Constant Head).* This test method was developed to evaluate the permeability of compacted soil or soil/cement mixtures.

For this method, CLSM was cast into a 10.16-diameter Proctor compaction mold. The sample was then cured for 28 days. At the 28^{th} day, the sample was removed from the curing chamber and placed in the permeameter. Due to time constraints with the testing apparatus, the permeameter was not run until the 29^{th} day to avoid leakage. On the 29^{th} day, a constant head of 122 cm of water was applied. After a constant flow was reached, water was collected over a specified time, and flow was calculated using Darcy's Law,

$$k = \frac{QL}{Aht}$$

where k is the coefficient of permeability (cm/sec), Q is the flow (cm^3), L is the specimen length (cm), A is the specimen area (cm^2), h is the head difference (cm) and t is the elapsed time (sec).

3.6 High Density Concrete

The second application was to develop high density concrete using chromite ore sand. Initially, it was decided to formulate high density mixtures using chromite ore sand as the only aggregate material. The high density of the chromite ore sand would be used to achieve high density mixture that could be used for grouting or sealing joints for high density concrete blocks. By varying proportions of the components, the mixture design aimed at developing maximum density for the chromite ore sand mixture.

The mixture designs for high density concrete used chromite ore sand as the fine aggregate and hematite aggregate as the coarse aggregate. The hematite aggregate is a commercially available, high density aggregate used in the manufacture of high density concrete.

3.6.1 Controlling Property

As discussed in Section 2.5.11, from other research (Dunkelburger, 2002), it has been shown that there exists a correlation between the density of the material and its shielding capabilities. In simple terms, the higher the density, the higher is the shielding capability of the material for a given thickness. Using this as a basis for the mixture design, the concrete mixtures were designed so as to achieve maximum possible density with the materials available. The material density could then be used to determine the possible shielding ability of the material. Thus the density of the material was the most controlling property.

3.6.2 Dense Mixtures with Chromite Ore Sand as Only Aggregate

The primary factor influencing the mixture proportions was attaining maximum possible density of concrete It was evident that out of the three constituents, chromite ore sand, cement and water, increasing the quantity of sand in the mix would increase the density, as it was the heaviest constituent. At the same time minimizing the water content meant reducing the workability. To achieve this, high range water reducer was also used. Cement was also proportioned so that it just satisfied the binding requirements.

To test its density, the dense mixture produced was cast into plastic cubes that measured 2 inches on a side. To ensure uniform compaction of the cubes, the cube molds were placed on a vibratory table and tamped with a plastic tamper. If density of the mixture using only chromite ore sand were enough to meet the density requirements, then it would mean maximum utilization of chromite ore sand in the mixture.

The cubes were demolded on the next day after casting. The dimensions of the cubes were measured to the nearest millimeter, and their volumes were computed. The weight of the cubes was recorded using a balance with an accuracy of +/- 1 gm. The density was calculated for each of the cubes, and then the average density of the cubes was determined.

3.6.3 High Density Concrete with Hematite Aggregate

Standard Practice for Selecting Proportions for Normal, Heavyweight, and Mass Concrete (ACI, 2003, 211.1 – 91) was used for mixture design. Achieving maximum density was again the main design consideration. Workability was reduced to minimum required. High range water reducing admixture was used to reduce the water content. The concrete was cast into step molds made of wood with approximate volume of $0.05m^3$. Vibrator was used to enhance the compaction effort and improve density of the block. The step blocks so produced could be stacked one on top of the other to form a barrier suitable for shielding purposes. Figure 8 shows a set of step blocks stacked one on top of the other to form a shielding barrier. The joints between the blocks can be sealed with grout of equal or higher density. The actual mixture design proportions are presented in the next chapter with other results.

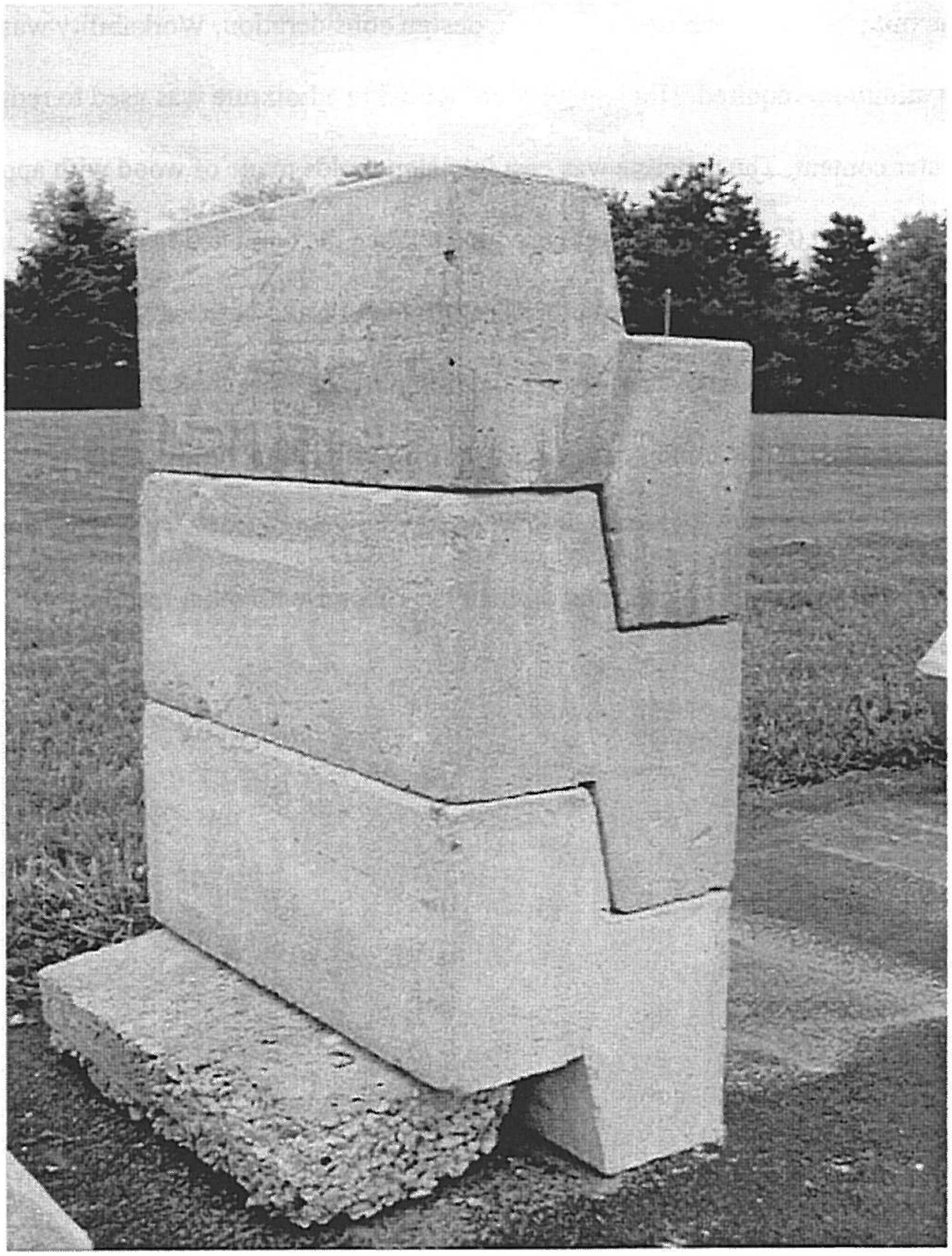

Figure 8: Set of Blocks Stacked to Form Shielding Barrier

CHAPTER 4 RESULTS AND DISCUSSION

This chapter presents the mixture proportions, results obtained from the various tests performed, and discussion thereof for CLSM and High Density Concrete mixtures.

4.1 CLSM

All mixtures were formulated according to the procedures described in chapter 3. The final mixture proportions and other properties for mixtures of groups I, II and III are presented in tabular form in Tables 7 to 15. The Figures 9 to 11 thereafter show the plot of comparative compressive strength development of each mixture at 7, 14 and 28 days within a group. All of the mixtures in groups I, II and III were flowable and showed no signs of segregation. A brief description of the range of results obtained for the properties tested for CLSM is presented in the subsections following the tables and figures.

CLSM Group I Control		
Mixture Proportion Details		
Material	***kg / m³***	***Batch Size 0.04 m³ kg***
Cement	**20**	**0.8**
Fly Ash	**270**	**10.8**
Normal Sand	**990**	**39.6**
Water	**210**	**8.052**
Properties		
Plastic Density=	**2203**	**kg/m³**
Weight=	**4.706**	**kg**
Volume=	**$2.136*10^{-3}$**	**m³**
Flow =	**8**	**inches**
Contact with Water	**3.30 p.m.**	
Setting Time=	**4 hours**	
Dry density =	**2187**	**kg/m³**
Oven Dry	**2125**	**kg/m³**
Density =		
Permeability =	**4.007×10^{-6}**	**cm/sec**
Day	***Avg. Comp. Strength***	***Unit***
7	**40**	**psi**
14	**55**	**psi**
28	**105**	**psi**

Table 7: CLSM Group I Control Mixture Proportions and Properties

CLSM Group I A		
Mix Proportion Details		
Material	*kg / m³*	*Batch Size 0.04 m³ kg*
Cement	30	1.2
Fly Ash	320	12.8
Chromite Sand	1500	60
Water	210	8.736
Properties		
Plastic Density=	2900	kg/ m^3
Weight=	6.195	kg
Volume=	$2.136*10^{-3}$	m^3
Flow =	8	inches
Contact with Water	10.30 a.m.	
Setting Time=	4 hours	
Dry density =	2850	kg/ m^3
Oven Dry	2802	kg/ m^3
Density =		
Permeability =	3.45×10^{-6}	cm/sec
Day	*Avg. Comp. Strength*	*Unit*
7	30	psi
14	40	psi
28	50	psi

Table 8: CLSM Group I A Mixture Proportions and Properties

CLSM Group I B		
Mix Proportion Details		
Material	*kg / m³*	*Batch Size 0.04 m³ kg*
Cement	20	0.8
Fly Ash	270	10.8
Chromite Sand	1500	60
Water	210	8.502
Properties		
Plastic Density=	2899	kg/ m^3
Weight=	6.193	kg
Volume=	$2.136*10^{-3}$	m^3
Flow =	8	inches
Contact with Water	11.45 a.m.	
Setting Time=	5 hours	
Dry density =	2807	kg/ m^3
Oven Dry Density =	2758	kg/ m^3
Permeability =	3.25×10^{-6}	cm/sec
Day	*Avg. Comp. Strength*	*Unit*
7	30	psi
14	58	psi
28	65	psi

Table 9: CLSM Group I B Mixture Proportions and Properties

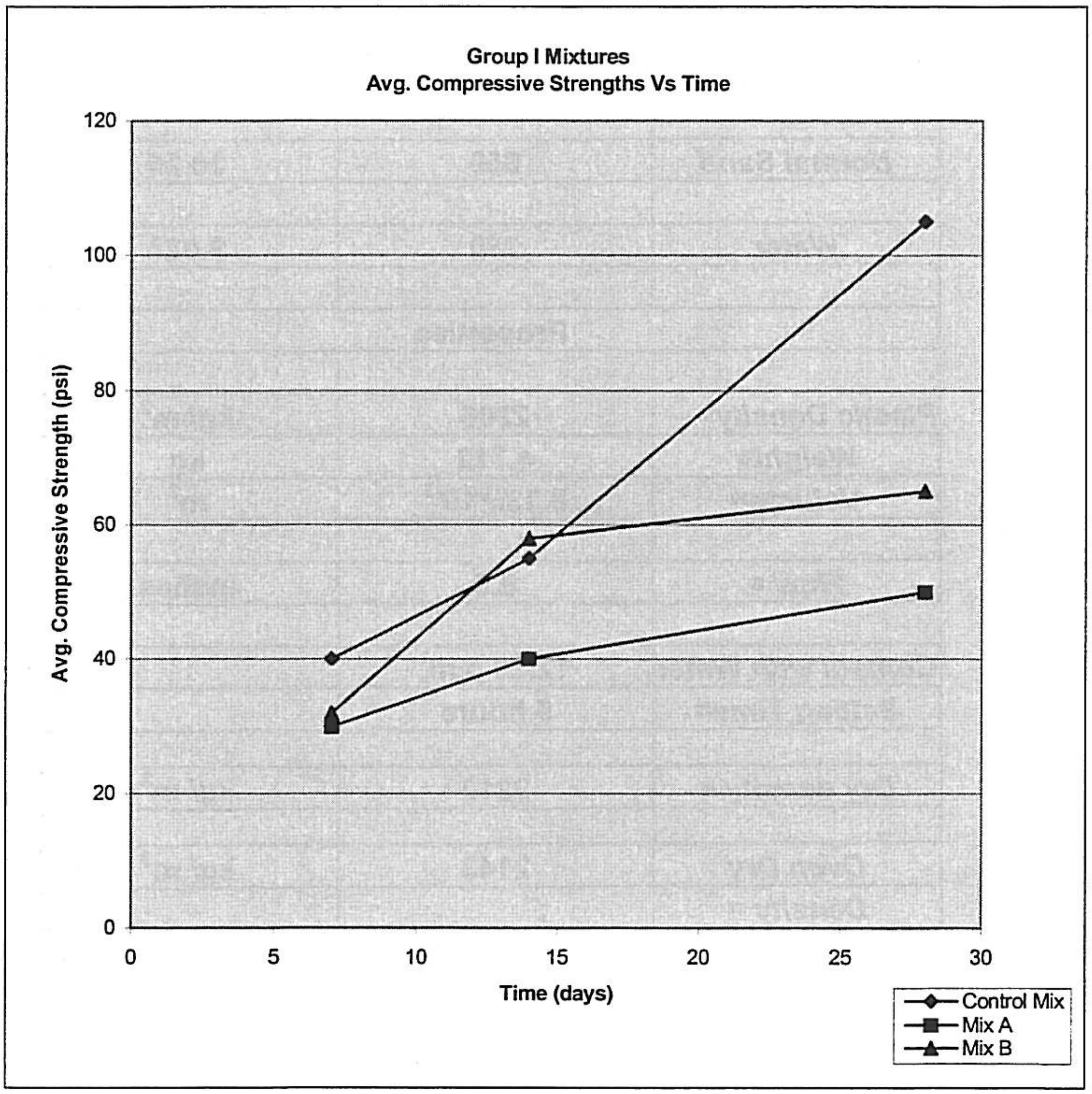

Figure 9: CLSM Group I Mixtures Compressive Strength Development at 7, 14 and 28 Days

CLSM Group II Control		
Mix Proportion Details		
Material	*kg / m^3*	*Batch Size 0.045 m^3 kg*
Fly Ash	500	22.5
Normal Sand	850	38.25
Water	210	9.028
Properties		
Plastic Density=	2206	kg/ m^3
Weight=	4.712	kg
Volume=	$2.136*10^{-3}$	m^3
Flow =	8.5	inches
Contact with Water	12.30 p.m.	
Setting Time=	5 hours	
Dry density =	2210	kg/ m^3
Oven Dry	2143	kg/ m^3
Density =		
Permeability =	3.11×10^{-5}	cm/sec
Day	*Avg. Comp. Strength*	*Unit*
7	26	psi
14	43	psi
28	55	psi

Table 10: CLSM Group II Control Mixture Proportions and Properties

CLSM Group II A		
Mix Proportion Details		
Material	*kg / m^3*	*Batch Size 0.045 m^3 kg*
Fly Ash	500	22.5
Chromite Sand	1290	58.05
Water	210	9.343
Properties		
Plastic Density=	2801	kg/ m^3
Weight=	5.9832	kg
Volume=	2.136*10^{-3}	m^3
Flow =	8	inches
Contact with Water	11.00 a.m.	
Setting Time=	3 hours	
Dry density =	2810	kg/ m^3
Oven Dry	2775	kg/ m^3
Density =		
Permeability	3.411 x 10^{-5}	cm/sec
Day	*Avg. Comp. Strength*	*Unit*
7	22	psi
14	42	psi
28	70	psi

Table 11: CLSM Group II A Mixture Proportions and Properties

CLSM Group II B		
Mix Proportion Details		
Material	*kg / m^3*	*Batch Size 0.045 m^3 kg*
Fly Ash	600	27
Chromite Sand	1140	51.3
Water	210	9.45
Properties		
Plastic Density=	2755	kg/ m^3
Weight=	5.8846	kg
Volume=	2.136*10^{-3}	m^3
Flow =	8	inches
Contact with Water	11.30 a.m.	
Setting Time=	3 hours 15 minutes	
Dry density =	2727	kg/ m^3
Oven Dry	2654	kg/ m^3
Density =		
Permeability =	2.788 x 10^{-5}	cm/sec
Day	*Avg. Comp. Strength*	*Unit*
7	40	psi
14	55	psi
28	85	psi

Table 12: CLSM Group II B Mixture Proportions and Properties

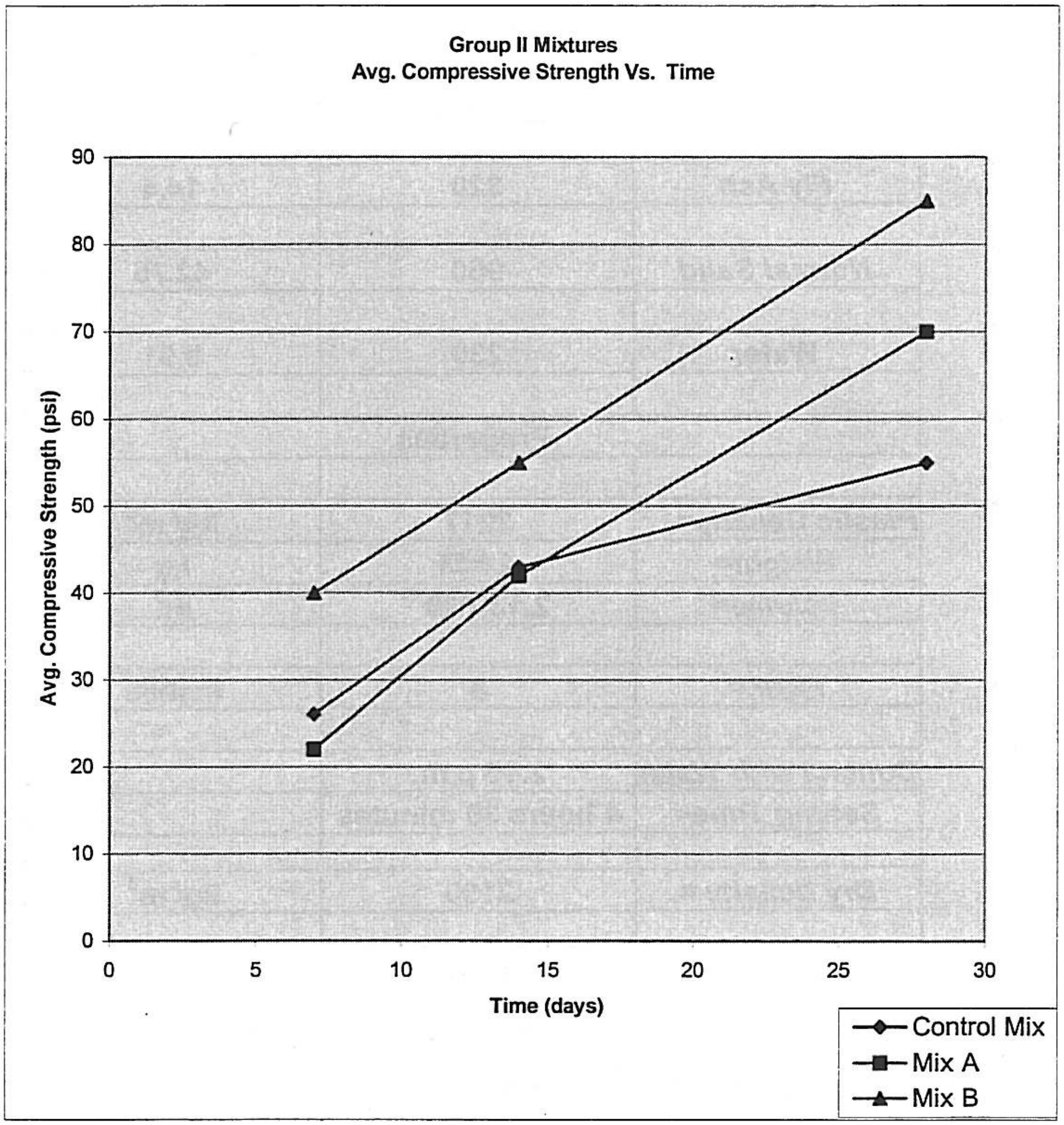

Figure 10: CLSM Group II Mixtures Compressive Strength Development at 7, 14 and 28 Days

CLSM Group III Control		
Mix Proportion Details		
Material	*kg / m³*	*Batch Size 0.045 m³ kg*
Slag	75	3.375
Fly Ash	320	14.4
Normal Sand	950	42.75
Water	230	9.51
Properties		
Plastic Density=	2217	kg/ m³
Weight=	4.543	kg
Volume=	$2.136*10^{-3}$	m³
Flow =	8	inches
Contact with Water	2.15 p.m.	
Setting Time=	4 hours 30 minutes	
Dry density =	2190	kg/ m³
Oven Dry	2156	kg/ m³
Density =		
Permeability =	3.054×10^{-6}	cm/sec
Day	*Avg. Comp. Strength*	*Unit*
7	50	psi
14	110	psi
28	240	psi

Table 13: CLSM Group III Control Mixture Proportions and Properties

CLSM Group III A		
Mix Proportion Details		
Material	*kg / m³*	*Batch Size 0.03 m³ kg*
Slag	75	2.25
Fly Ash	320	9.6
Chromite Sand	1450	43.5
Water	232	6.543
Properties		
Plastic Density=	2922	kg/ m^3
Weight=	6.242	kg
Volume=	$2.136*10^{-3}$	m^3
Flow =	8	inches
Contact with water	11.00 a.m.	
Setting Time=	5 hours	
Dry density =	2725	kg/ m^3
Oven Dry	2654	kg/ m^3
Density =		
Permeability =	2.356×10^{-6}	cm/sec
Day	*Avg. Comp. Strength*	*Unit*
7	185	psi
14	360	psi
28	550	psi

Table 14: CLSM Group III A Mixture Proportions and Properties

CLSM Group III B		
Mix Proportion Details		
Material	*kg / m³*	*Batch Size 0.04 m³ kg*
Slag	100	4
Fly Ash	320	12.8
Chromite Sand	1450	57.2
Water	210	8.4
Properties		
Plastic Density=	2906	kg/ m^3
Weight=	6.207	kg
Volume=	$2.136*10^{-3}$	m^3
Flow =	8	inches
Contact with Water	12.00 p.m.	
Setting Time=	4 hrs 30 mins	
Dry density =	2755	kg/ m^3
Oven Dry Density =	2685	kg/ m^3
Permeability =	2.024×10^{-6}	cm/sec
Day	*Avg. Comp. Strength*	*Unit*
7	225	psi
14	410	psi
28	600	psi

Table 15: CLSM Group III B Mixture Proportions and Properties

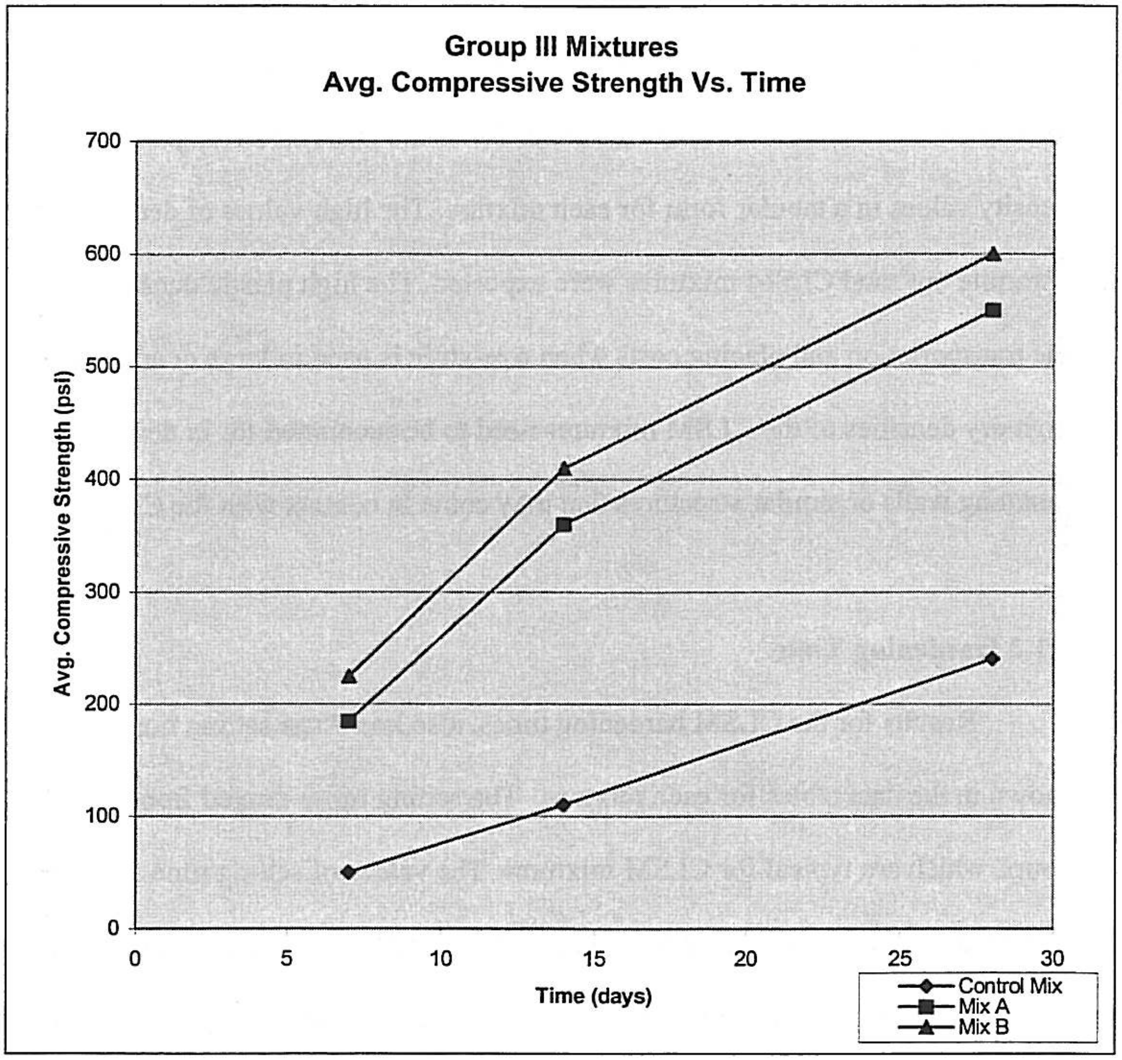

Figure 11: CLSM Group III Mixtures Compressive Strength Development at 7, 14 and 28 Days

4.1.1 Unit Weight

Both the plastic and dry densities were determined. The plastic density values ranged from 2755 kg/m^3 to 2922 kg/m^3 for chromite ore mixtures. The plastic densities for silica sand mixtures were lower by about 25 percent, and values ranged from 2180 kg/m^3 to 2217 kg/m^3. The dry densities also showed a similar range difference for silica and chromite ore sand. These are presented along with oven dry density values in a tabular form for each mixture. The high values of densities of the chromite ore sand CLSM mixtures were expected. The high plastic density can affect the transportation and placing costs when a mixture is used in large quantities. The high dry densities of the CLSM mixtures need to be accounted for in design of retaining walls or similar structures that may come in contact with the CLSM fill.

4.1.2 Hardening Time

Results for the CLSM hardening times, also known as setting times, are shown in the data tables for each mixture. The setting times ranged from 3 to 6 hours, which are typical for CLSM mixtures. The values of setting time are presented in the data table for each mixture. There was no significant difference in setting times observed between chromite ore sand CLSM mixtures and silica sand CLSM mixtures. Also, there was no distinguishing pattern that could be observed between mixtures of the same group and mixtures of different groups. Thus, it can be said that, for the given mixtures, the use of chromite ore sand in CLSM mixtures did not adversely affect the CLSM setting properties. Since the setting times for chromite ore sand

CLSM mixtures are similar to regular silica sand, the chromite sand can be used as aggregate material for producing CLSM.

4.1.3 Compressive Strength

The 7-, 14-, and 28-day average compressive strengths are presented in the data table of each mixture. Figures 9 to 11 show the plot of comparative compressive strength development of each mixture at 7, 14 and 28 days within a group. The compressive strengths for Group I are approximately in the range of 50 to 100 psi. Group II showed similar strengths, ranging from 50 to 75 psi. Group III showed much higher strengths compared to Group I and II. The presence of slag in the mixtures increased the CLSM strength. The compressive strength for Group III ranged from approximately 250 to 550 psi. The higher strengths of CSLM imply that these mixtures can be used for non-excavatable fills such as structural fills. The compressive strength criterion is further considered in the discussion about suitability of using chromite ore sand for CLSM.

4.1.4 Permeability

Permeability evaluation by the constant head permeability test was done for all the mixtures. The values for permeability ranged from 2.024×10^{-6} cm/sec to 4.0×10^{-6} cm/sec for Groups I and III. Group II mixtures showed higher permeability values in the range of 2.788×10^{-5} cm/sec to 3.411×10^{-5} cm/sec. The permeability values were slightly on the higher side compared to the value of 5×10^{-6} cm/sec generally accepted for CLSM (Naik et al., 1990). It is important to note that CLSM is not designed for freeze-thaw resistance. Freeze-thaw action may cause cracking in hardened CLSM, which alters the permeability of the material; however, if the material is placed below the frost line, freeze-thaw action is unlikely. The permeability values for chromite ore sand CLSM mixtures are similar to those obtained for other CLSM mixtures, which suggests that these mixtures can be used for CLSM applications.

4.2 Suitability as CLSM

This section considers the suitability of using chromite ore sand to produce CLSM. The suitability with respect to the main properties of flowability, hardening time and compressive strength is discussed.

4.2.1 Flowability

All the mixtures were designed so as to achieve the desired flowability. The chromite ore sand being much heavier than silica sand, the need to produce the required flowability in the mixture was critical. The desired flowability was achieved by selecting the right components and their proportions. It was necessary to use fly ash in all the mixtures to produce the needed flowability. The use of fly ash helped to produce the desired flowability in the mixture without having to change the cement quantities, which in turn would have affected the strength requirements for CLSM. Thus, these test results show that the chromite ore sand can be used in the CLSM mixtures.

4.2.2 Hardening Time

Hardening time is the approximate period of time required for CLSM to go from the plastic state to the hardened state with sufficient strength to support the weight of a person. Expected hardening time for CLSM as suggested by ACI Committee 229 (1994) is about 3 to 5 hours. From the test results obtained on the chromite ore sand CLSM mixtures, it was found that these mixtures took about 3 to 6 hours. This shows that these mixtures satisfy the hardening time requirements for CLSM.

4.2.3 Compressive Strength

The CLSM mixtures were initially designed to achieve lower 28-day strengths in the range of 50 to 200 psi. Most of the mixtures achieved this targeted range of compressive strengths. However, the mixtures that used slag as a binder in place of cement produced high strengths. The proportion of slag in the mixtures can be altered to achieve the desired lower strength requirements.

Mixture proportions can be adjusted to suit the strength requirements of the application. By changing the proportion and type of binder that is the cementitious material content, the strength can be increased or decreased. The high strength mixtures can be used in applications where the fill is permanent and does not need to be excavated later, such as structural fill. CLSM may be used for foundation support. Compressive strengths may vary from 100 to 1200 psi (ACI Committee 229, 1994). Low strength mixtures can be used where excavation may later be necessary, such as in filling utility pipe trenches. The test results showed that chromite ore sand can be successfully used to produce both high and low strength flowable material by proper material selection and proportioning.

These test results show that the chromite ore sand CLSM mixtures satisfy all the general CLSM requirements. Hence, the chromite ore sand can be successfully used to produce CLSM

4.3 Dense Mortars Using Only Chromite Ore Sand as Aggregate

Mortars primarily consist of sand, cement and other additives, and are used in masonry construction. Their primary uses are to join and seal concrete masonry units, strengthen masonry structures by bonding with steel reinforcing, and provide architectural quality. Approximately one cubic foot of sand is used to make one cubic foot of mortar. The cement paste occupies the space between the sand particles and makes it workable. Adequate gradation reduces mortar segregation and bleeding, and improves mortar water retention and workability. Chromite ore sand is finer than the ASTM (2003) C33 gradation requirements, but it can be blended with coarser sands to meet the specification.

As discussed earlier, the primary objective of the mixture design was to produce the mixture with maximum possible density from the available component materials. Therefore, the only property of interest was the density of the mixture. The compressive strength of the cubes was always expected to be much more than is necessary for a mortar or grout material, and therefore would not have been of much consequence during testing. Each mixture design was accomplished with the need to increase the density of the material kept in mind. The mixture proportions and the densities obtained for all the mixtures are presented in tabular form in Tables 16 through 19.

DENSE MIXTURE M - 1		
MIXTURE PROPORTIONS		
Material	*kg / m³*	*Batch Size 0.0013 m³ (10 cubes) kg*
Chromite Sand	2460	3.204
Water	245	0.32
Cement	400	0.521
Water Cement Ratio = 0.61		
Percent of Sand By Weight In Mix = 79.2		
Bulk Density =		2769 kg/ m³
		2.769 g/cc

Table 16: Dense Mixture M - 1 Mixture Proportions and Bulk Density

DENSE MIXTURE M - 2		
MIX PROPORTIONS		
Material	*kg / m^3*	*Batch Size 0.0013 m^3 (10cubes) kg*
Chromite Sand	2208	2.875
Water	275	0.357
Cement	575	0.748
Water Cement Ratio = 0.47		
Percent of Sand By Weight In Mix = 72.2		
Bulk Density		2902.5 kg/ m^3
		2.902 g/cc

Table 17: Dense Mixture M - 2 Mixture Proportions and Bulk Density

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DENSE MIXTURE M - 3		
MIX PROPORTIONS		
Material	*kg / m³*	*Batch Size 0.0013 m³ (10 cubes) kg*
Chromite Sand	2900	3.77
Water	200	0.26
Cement	410	0.535
Water Reducer	Dosage of 10 ounces per 100 pound cement	
Water Cement Ratio = 0.48		
Percent of Sand By Weight In Mix = 82.6		
Bulk Density		2865 kg/ m³
		2.865 g/cc

Table 18: Dense Mixture M - 3 Mixture Proportions and Bulk Density

DENSE MIXTURE M - 4		
MIX PROPORTIONS		
Material	*kg / m^3*	*Batch Size 0.0013 m^3 (10cubes) kg*
Chromite Sand	2950	3.842
Water	150	0.195
Cement	410	0.535
Water Reducer	Dosage of 10 ounces per 100 pound cement	
Water Cement Ratio = 0.36		
Percent of Sand By Weight In Mix = 84		
Bulk Density =	2921 kg/ m^3	
	2.921g/cc	

Table 19: Dense Mixture M - 4 Mixture Proportions and Bulk Density

4.4 Suitability of Chromite Ore Sand Dense Mixtures

The high density mixtures produced using the chromite ore sand were designed so as to have maximum possible density value. The mixtures resulted in density values just less than 3 g/cc. It must be noted that the mixture was designed using the chromite ore sand as the only aggregate material. The use of other dense coarser aggregate may have yielded higher density, but that would not lead to the maximum use of the chromite ore sand, which is the primary goal of this study.

The density values of the high density mixtures produced using the chromite ore sand are in the range of 2.75 g/cc to 2.92 g/cc. These values give a corresponding gamma transmittance value of 13 to 10 percent from Figure 3 (Dunkelberger, 2002). It shows that chromite ore sand, in spite of having high density, would not be useful by itself for producing high density mixtures capable of shielding. However, it may be used as a supplement to other components in the mixture to form high density mixtures for shielding applications.

4.5 High Density Concrete

High density concrete mixtures were formulated with hematite coarse aggregate and chromite ore sand fine aggregate. The use of hematite coarse aggregate enhanced the density of the concrete. Two mixtures were formulated using slightly variable proportions of the same components. The high range water reducer was used for both mixtures, which helped in reducing the water quantity, and hence the water-cement ratio. The water-cement ratios had values of 0.30 and 0.33, which are less than those for regular concrete, which have values approximately ranging from 0.4 to 0.5.

Another criterion for mixture design was to maximize the use of chromite ore sand within the mixture, without compromising on the concrete density values. The first mixture had 25 percent chromite ore sand by weight of aggregates. The percentage was improved to 36 percent by weight of aggregates in the second mixture by reducing the coarse aggregate content and increasing the sand content. The density for both concrete mixtures was slightly above 4 g/cc, compared to regular concrete densities of 2.0 g/cc to 2.2 g/cc. The mixture proportions and other data are presented in Tables 20 and 21. The suitability of the high density concretes for the shielding purpose is discussed in a further subsection.

HIGH DENSITY CONCRETE HDC-1		
MIXTURE PROPORTIONS		
Material	kg/ m^3	Batch Size 0.052 m^3 kg
Hematite Coarse Aggregate	2567	133.5
Chromite Ore Sand	860	44.71
Cement	505	26.25
Water	151	7.87
Admixture	850ml/100kg cement	225 ml
Water Cement Ratio = 0.30		
Percent of Chromite Ore Sand By Weight of Aggregates = 25		
Bulk Density =		4083 kg/m^3
		4.08 g/cc

Table 20: High Density Concrete Mixture HDC-1
Using Hematite Coarse Aggregate and Chromite Ore Sand Fine Aggregate

HIGH DENSITY CONCRETE HDC-2		
MIXTURE PROPORTIONS		
Material	kg/ m^3	Batch Size 0.052 m^3 kg
Hematite Coarse Aggregate	2160	136.11
Chromite Ore Sand	1233	77.73
Cement	511	32.19
Water	169	10.65
Admixture	950ml/100kg	345 ml
Water Cement Ratio = 0.33		
Percent of Chromite Ore Sand By Weight of Aggregates = 36		
Bulk Density =		4074 kg/m^3
		4.07 g/cc

Table 21: High Density Concrete Mixture HDC-2
Using Hematite Coarse Aggregate and Chromite Ore Sand Fine Aggregate

4.6 Suitability as High Density Concrete

The chromite ore sand along with hematite coarse aggregate was used to produce high density concrete for shielding applications. The density value of the produced concrete was found to be approximately 4 g/cc, which is comparable to those listed in "Table 2 - Typical Proportions of Heavyweight Concrete" in ACI (2003) 304.3R –99 for heavyweight concrete. The listed densities range from 3.04 g/cc to 4.81 g/cc. This indicates that the chromite ore sand can be used in conjunction with other aggregates to produce high density concrete. The high density concrete has various applications as listed in section 2.5. Most of these applications do not have strict specifications; therefore, the chromite ore sand can be used for concrete for these applications.

Suitability of the produced high density concrete for shielding applications is discussed herein. As mentioned in section 2.5.11, a correlation between the density and shielding capabilities was developed (Dunkelberger, 2002), and is presented in the form of Figure 3. From the figure, for a concrete with density 4 g/cc, the percent transmittance value for a 0.662 MeV gamma ray is 5 percent. This is a reduction of 50 percent in the transmittance value for high density chromite sand mixture with density 3 g/cc. The low transmittance value suggests that the chromite ore sand is to be used to produce high density concrete suitable for shielding applications. It must be understood that if the chromite ore sand is to be used to produce any special product like high density concrete for shielding, it must overcome the initial transportation and associated costs.

4.7 Other Possible Applications for Chromite Ore Sand

Chromite ore sand has a high density compared with regular fine aggregate, such as silica sand, which classifies it is as a heavy aggregate. Chromite ore sand as a fine aggregate may have applications where it could be used to partially or fully replace regular silica sand in construction applications.

Chromite Ore Sand in Structural Fills and Embankments

Chromite ore sand may be used effectively in normal embankment construction with and without permeability and leachate control. It could be used in conjunction with geogrid systems and with reinforced earth retaining walls that use straps or grids as horizontal tiebacks. Standard construction procedures can be adjusted to account for using chromite ore sand. Many procedures have been developed as the result of the experience gained using foundry sand in trial embankment and construction projects. This experience may be useful and applicable to using other sands as well such as the chromite ore sand.

Chromite Ore Sand in Road Bases

A road base is a foundation layer underlying a flexible or rigid pavement and overlying a subgrade of natural soil or embankment fill material. It can be composed of crushed stone, crushed slag, or some other stabilized material. It protects the underlying soil from the detrimental effects of environment and from the stresses and strains induced by traffic loads. To meet specifications for road bases, blending the chromite ore sand with another aggregate may be necessary. The gradation of the road base materials influences base stability, drainage, and frost susceptibility. Likewise, the aggregate must be sound and able to resist environmental deterioration. Being fine and heavy, the chromite ore sand can be blended with other aggregates to produce a stable and durable road base.

Chromite Ore Sand in Hot Mix Asphalt

Asphalt concrete is the most popular paving material for highways and roadways in the United States. Over 94 percent of all pavements are asphalt. This translates to over 2,030,000 miles. The most prevalent type of asphalt paving material is hot mix asphalt (HMA). It includes a combination of plant-dried coarse and fine aggregates. They are coated with hot asphalt cement, which acts as a binder. Foundry sand has been used successfully to replace a portion of the fine aggregate used in HMA. Studies have shown that foundry sand can be used to replace between 8 and 25 percent of the fine aggregate content. Similarly, chromite ore sand could be used in HMA. When the mixes are properly designed using Superpave, Marshall, or Hveem techniques, so as to incorporate the properties of chromite ore sand in the design, it may prove that chromite ore sand is an effective fine aggregate alternative. Use of this sand can be cost effective for the HMA industry. Highway agencies and contractors could switch to the material when it is geographically and economically competitive.

Chromite Ore Sand as Heavy Aggregate

Chromite ore sand is a heavy or high density aggregate. High density aggregates have applications of their own beside being used in high density concrete. Some of these applications are listed below:

1) Refractory lining
2) Fluidized bed bioreactors
3) Blast furnace troughs
4) Marine ballast
5) Hard wearing surface

CHAPTER 5 CONCLUSIONS

This chapter presents a summary of significant results for CLSM and high density concrete that use chromite ore sand. It also presents the conclusions derived from these results.

5.1 Summary of Results

The objective of this study was to identify potential construction applications for the stockpiled chromite ore sand. The approach pursued was to study the properties of the sand, identify potential applications and then study the suitability of the sand to the proposed applications. All these tasks were successfully completed.

The engineering properties of the sand were characterized. It was found that the fineness and high specific gravity were the main properties that would influence the use of this material in various applications. CLSM and high density concrete were identified as the main potential applications. The chromite ore sand was then used to produce CLSM, high density mixtures and high density concrete to check the suitability of the sand in these applications. It was found that chromite ore sand could be successfully used in these applications.

The results for the CLSM mixtures are summarized in Table 22, so as to give a comparative matrix of the results. The results for high density chromite ore mixtures and high density concrete are summarized in Tables 23 and 24, respectively.

Mixture	Flow	Plastic Density	Oven Dry Density	Setting Time	Permeability	Compressive Strength
	(inches)	(kg/m^3)	(kg/m^3)	(Hours)	cm/sec	28 - Day (psi)
Group I - Cement and Fly Ash						
Control	8	2180	2125	4	4.00×10^{-6}	105
A	8	2900	2802	4	3.45×10^{-6}	50
B	8	2899	2758	5	3.25×10^{-6}	65
Group II - Fly Ash						
Control	8.5	2206	2143	5	3.11×10^{-5}	55
A	8	2801	2775	3	3.41×10^{-5}	70
B	8	2755	2654	3.25	2.78×10^{-5}	85
Group III – Slag and Fly Ash						
Control	8	2237	2156	4.5	3.05×10^{-6}	240
A	8	2925	2654	5	2.35×10^{-6}	550
B	8	2906	2685	4.5	2.02×10^{-6}	600

Table 22: Summary of Results for Chromite Ore Sand CLSM Mixture

5.2 Conclusions for CLSM

Based on the test results and observations during testing, the following conclusions can be made for the CLSM:

- Chromite ore sand can be successfully used to produce CLSM to meet excavatable or structural application requirements.
- CLSM mixtures can be designed so as to achieve the desired compressive strengths by standard CLSM mixture proportioning procedures.
- Higher strength CLSM mixtures can be designed for structural fills or foundation material where future excavation is not required. Lower strength mixtures can be designed where future excavation is necessary.
- High mass CLSM produced using chromite ore sand can be designed and used for counterweight geotechnical applications.
- Chromite ore sand has no direct effect on the hardening times and permeability of CLSM.
- For the mixture designs formulated, fly ash had to be used in all chromite ore sand CLSM mixtures to satisfy the flowability requirements. Use of fly ash helped satisfy the flowability requirements without adversely affecting the strength requirements.

Dense Mixture	*W/C Ratio*	*Percent Sand By Weight*	*Bulk Density g/cc*
M1	0.61	79.2	2.769
M2	0.47	72.2	2.902
M3	0.48	82.6	2.865
M4	0.36	84	2.921

Table 23: Summary of Results for High Density Chromite Ore Sand Mixtures

5.3 Conclusions for High Density Mixtures Using Chromite Ore Sand

Based on the test results and observations during testing, the following conclusions can be made for the high density mixtures:

- Chromite ore sand can be successfully used to produce high density mortar or grout mixtures.
- The chromite ore sand percent by weight in the high density mixtures is as much as 80 percent, indicating that this application can lead to maximum utilization of the sand.
- High-density mixtures made using chromite ore sand as the only aggregate material provided a marginal increase in nuclear shielding capabilities.
- Reduction in water quantity increases the density of the mixture.
- With reduction in water content and increase in chromite ore sand content, more compactive effort is needed to achieve the desired density.

HDC Mixture	*HDC-1*	*HDC-2*
Water Cement Ratio	0.3	0.33
Percent Sand By Weight of Aggregates	25	36
Bulk Density g/cc	4.07	4.08

Table 24: Summary of Results for High Density Concrete Using Chromite Ore Sand and Hematite Coarse Aggregate

5.4 Conclusions for High Density Concrete

Based on the test results and observations during testing, the following conclusions can be made for the high density concrete mixtures:

- The use of high density coarse aggregates along with chromite ore sand as fine aggregate can produce high density concrete for ballast applications, nuclear shielding applications and other high density concrete applications.
- The shielding capabilities of the high density concrete were satisfactory and comparable to other high density concrete mixtures.
- Chromite ore sand occupied about 35 percent by weight of the aggregates, suggesting that large quantities of sand can be used in concrete applications.
- The use of water reducing admixture helped reduce the water content and increase the density of the concrete mixture. The use of vibration equipment helped in compaction of concrete in the mold and helped improve the density.

5.5 General Conclusions

- The fineness and high density are the two main technical properties of the chromite ore sand that will influence its suitability and use in various applications.
- The main criteria for marketing the chromite ore sand for any application will be the beneficial technical properties and the costs associated with transporting the sand to the place of interest.
- For the user of the sand, either the transportation costs must be competitive or the sand must be a value-added component.
- The study showed that the chromite ore sand can be successfully used to produce Controlled Low Strength Material (CLSM), high density mortars and high density concrete.
- The chromite ore sand can be used in CLSM applications locally or within the state, which will minimize the costs of transportation and handling.
- Application in high density mortars and grouts or high density concrete for nuclear shielding applications can offset the costs associated with transportation.
- Though this study specifically dealt with the beneficial reuse of chromite ore sand, the results obtained and mixture proportions developed can be used to study the beneficial reuse of other materials with similar technical properties.

5.6 Recommendations

- Tests conducted on the chromite ore sand have shown that it does not have harmful environmental effects and can be marketed for use as a fine aggregate for construction applications.
- Potential nuclear shielding applications using chromite ore sand should be pursued.
- Additional tests should be conducted to document the suitability of the chromite ore sand with respect to other properties required for shielding applications.
- Precast tanks and casks may be products that could be manufactured on site to eliminate material transportation costs.
- High density concrete product suppliers and producers should be contacted, and potential buyers for the material should be sought.
- Another option is to offer the sand to a local contractor or concrete supplier at low cost for use in local concrete applications, from driveways to backfill for underground cavities, sinkholes and mines.

BIBLIOGRAPHY

American Association of State Highway and Transportation Officials (AASHTO). *Standard Specifications for Transportation Materials and Methods of Sampling and Testing,* 20th ed., sections as indicated in text references, Washington, D.C., 2000.

American Concrete Institute (ACI). *Manual of Concrete Practice,* Volumes 1-6, sections as indicated in text references, Farmington Hills, Michigan, 2003.

American Concrete Institute (ACI) Committee 229. *Controlled Low Strength Materials (CLSM).* ACI Committee 229 Report, Farmington Hills, Michigan, 1994.

American Concrete Institute (ACI) Committee 232. *Use of Fly Ash in Concrete.* ACI 232.2R. *Manual of Concrete Practice,* Part 1, Materials and General Properties of Concrete, Farmington Hill, Michigan, 1996.

American Concrete Institute (ACI). *Concrete for Radiation Shielding.* Compilation No. 1, 2nd ed., Detroit, 1962.

American Society for Testing and Materials (ASTM). *Annual Book of ASTM Standards,* standards as indicated in text references, ASTM International: West Conshohocken, Pennsylvania, 2003.

American Society for Testing and Materials (ASTM). *Annual Book of ASTM Standards,* Volume 04.02, Concrete and Aggregates, ASTM C 495, *Standard Test*

Method for Compressive Strength of Lightweight Insulating Concrete, Easton, Maryland, 1986.

American Society for Testing and Materials (ASTM). *Annual Book of ASTM Standards,* Volume 04.08, Soil and Rock (I), ASTM D 4832, *Standard Test Method for Preparation and Testing of Controlled Low Strength Material Test Cylinders,* Easton, Maryland, 1995.

American Society for Testing and Materials (ASTM). *Annual Book of ASTM Standards,* Volume 04.09, Soil and Rock (II) ASTM D 6023, *Standard Test Method for Unit Weight, Yield, Cement Content and Air Content (Gravimetric) of Controlled Low Strength Material,,* Easton, Maryland, 1996.

American Society for Testing and Materials (ASTM). *Annual Book of ASTM Standards,* Volume 04.09, Soil and Rock (II), ASTM D 6103, *Standard Test Method for Flow Consistency of CLSM,* Easton, Maryland, 1997.

Amon, Joseph A. *Controlled Low-Strength Material.* The Construction Specifier, December 1990.

Blackburn, W. H. and Dennen, W. H. *Principles of Mineralogy.* Wm. C. Brown Publishers, Dubuque, Iowa, 1988.

Brewer, W.E. and John O. Hurd, *Economic Considerations When Using Controlled Low-Strength Material (CLSM-CDF) as Backfill.* Transportation Research Record 1315, 1993.

Chilton, A. B., Shutlis, J. K. and Faw, R. E. *Principles of Radiation Shielding.* Prentice-Hall, Inc., New Jersey, 1984.

Davidson D., *Critical and Strategic Mineral*, Environmental Science in Action, Biosphere 2000 Project, Internet Resource, 2000.

Dunkelburger II, R. O. *Enhanced Design of Dry Cask Storage Using Magpel Sand Bearing Concrete.* Thesis in environmental pollution control, The Pennsylvania State University, 2002.

Foundry Industry Recycling Starts Today (FIRST), *Foundry Sand Facts For Civil Engineers*, 2002.

Fox, T. A., *Use of Coarse Aggregate in Controlled Low Strength Material,* Transportation Research record 1234, 1989.

Gaffney, M. V. *Beneficial Use of Excess Foundry System Sand As Fine Aggregate In Controlled Low Strength Material: A Laboratory Investigation.* Thesis in Environmental Engineering, The Pennsylvania State University, 1997.

Ingle, J. D. and S. R. Crouch. *Spectrochemical Analysis.* Prentice-Hall, Inc., New Jersey, 1988.

Irwin, R. J., M. Van Mouwerik, L. Stevens, M. D. Seese, and W. Basham. *Environmental Contaminants Encyclopedia*, National Park Service, Water Resources Division, Fort Collins, Colorado, 1997.

Kaplan, M. F. *Concrete Radiation Shielding,* Longman Group, UK, Limited, 1989.

Komarovskii, A. N. *Design of Nuclear Plants.* 2nd. ed., Israel Program for Scientific Translations, Jerusalem, 1968.

Nuclear Shielding Supplies and Service, Inc., Tucson, Arizona, www.nuclearshielding.com.

Naik, T. R., B. W. Ramme, and H. Kolveck. *Filling Abandoned Underground Facilities with CLSM Fly Ash Slurry.* Concrete International, July 1990.

U.S. Environmental Protection Agency. Methods for Chemical Analysis of Water and Wastes, SW-846 Method 1311, *Test Methods for Evaluating Solid Wastes,* Office of Research and Development, Washington, DC, July 1992.

Van Tassel, E. L. *Integration of Recycled and Co-Product Materials in Controlled Low-Strength Material.* Thesis in Environmental Engineering, The Pennsylvania State University, 1999.