Federal Highway Administration Research Project

Task 3- Concrete Mixture Research Related to Pavements

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Principal Investigator:
David W. Fowler, the University of Texas at Austin

Phone: 512/471-4498
Fax: 512/232-0888

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Abstract

Manufactured fine aggregate (MFA) can be used as a replacement for or in conjunction with natural sand in concrete mixtures. MFA does not exhibit ideal shape or texture for fine aggregate, and the production of MFA generates high percentages of microfines, particles that pass the No. 200 sieve. Microfines are washed from the aggregate due to specification limitations, resulting in wasted aggregate and a coarser fine aggregate grading. Three manufactured sands were incorporated into concrete mixtures to determine their effects on fresh and hardened concrete properties. It was found that greater proportions of manufactured sand caused the workability to decrease, the demand for high-range water-reducing admixture to increase, the compressive strength to increase, and the modulus of elasticity to decrease.

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Chapter 1: Introduction

SECTION 1.1: DEFINITION OF MANUFACTURED FINE AGGREGATE (MFA)

Manufactured fine aggregate (MFA) is produced by reducing larger pieces of aggregate into sand-sized aggregate particles. Quarried stone is crushed to a size that will completely pass the 3/8-in. sieve [NCSA, 1976]. Other terms for manufactured fine aggregate include “stone sand”, “crusher sand”, “crushed fine aggregate”, “specification sand”, and “manufactured sand” [NCSA, 1976]. Blended sand is a combination of natural siliceous river sand and MFA.

The National Stone, Sand, and Gravel Association (NSSGA) (2008) offers a description of a typical crushing process. Blasting and drilling remove the rock pieces from their environment. The initial crushing cycle reduces aggregates to approximately 3 to 12 in. The initial crushers are usually jaw, impactor, or gyratory crushers. The material is reduced further in size in the next crushing cycle to approximately 1 to 4 in., and cone and impact crushes are generally used in this round of size-reduction. The tertiary level of crushing employs cone or impact crushers and decreases the aggregate size further to 3/16 to 1 in. The material is sieved to remove aggregate particles larger than 3/16 in., and then smaller, sand-sized aggregate particles are produced by crushing larger pieces in another cone crusher or hammermill.

Manufactured fine aggregate has both advantages and disadvantages over natural sand. MFA can be produced in areas close to construction sites, decreasing the cost of transportation [NSSGA, 2008B]. The use of manufactured fine aggregate also protects delicate fluvial environments from disruption due to sand mining. Environmental limitations have restricted dredging of river beds for sand. The land required for quarrying MFA parent rock can be reclaimed for recreational areas, residential development, commercial development, or wetlands restoration [NSSGA, 2008B].

The main disadvantages of manufactured fine aggregate are related to the shape. Manufactured fine aggregate is more angular and flaky due to the crushing process. Highly angular particles tend to increase the paste content of concrete because additional lubrication is required for particles with sharp corners. Flaky or elongated particles also increase the percentage of voids within the concrete mixture, again requiring additional paste to fill these voids. River sand has a much more ideal shape for use as fine aggregate in concrete. The particles are well-rounded due to weathering and are usually nearly spherical. The rounded shape of the aggregate particle contributes to the workability of the concrete mixture.

The production of MFA increases the proportion of microfines (particles smaller than the No. 200 sieve) included in the sand. Natural sand contains low amounts of microfines when compared with MFA. In some cases microfines can increase the water demand of a concrete mixture because they have such a large surface area. The inclusion of microfines in concrete mixtures is limited by ASTM C 33 "Standard Specification for Concrete Aggregates," and hence microfines are generally removed from manufactured sand before use in concrete. The microfines are usually stockpiled as waste, and the removal of microfines produces a coarser grading of the fine aggregate. If the microfines are well-shaped and have an acceptable particle size distribution, they can help to improve several properties of the concrete, including workability and permeability.

SECTION 1.2: THE USE OF MANUFACTURED FINE AGGREGATE IN INDUSTRY

Manufactured fine aggregate is already used extensively in asphalt paving. It is becoming more common to include MFA in concrete due to the environmental limitations. Unfortunately, standards have not quite caught up to the industry practices [Meininger, 2004]. Most ASTM standards were developed for natural sands, not manufactured sands. Particularly, the grading limits presented in ASTM C 33 present a problem for manufactured fine aggregate. Manufactured sands tend to be coarser with higher percentages of microfines. The International Center for Aggregate Research

(ICAR) has proposed a new grading curve with much higher limits for percent passing of the No. 4, 8, 16, 50, 100, and 200 sieves [Meininger, 2004]. It is proposed that concrete made with aggregate meeting these limits will be equal or superior to concrete made with aggregate meeting current ASTM C 33 limits. As the use of MFA in concrete increases, the standards must also adapt to these new aggregate sources.

SECTION 1.3: RESEARCH SIGNIFICANCE

The negative aspects of manufactured fine aggregate may be overcome by better design and incorporating chemical admixtures. To test how design and the addition of admixtures might impact paving concrete, three kinds of manufactured fine aggregate (representing well-shaped, intermediately-shaped, and poorly-shaped) were sieved to meet various gradings and then substituted for natural sand. The purpose of the experimental program was to determine how fresh and hardened concrete properties might be affected by the type, grading, and amount of manufactured fine aggregate included in a mixture. The ramifications of considering the microfines as part of the paste instead of aggregate and the influence of fly ash as a supplementary cementing material were also examined during the research program. The ultimate goal of the research was to establish a set of guidelines for using manufactured fine aggregate in paving concrete based on grading, blend ratio, and percentage of microfines.

The research was also conducted to determine if suitable concrete could be made with fine aggregate with grading curves outside those presented in ASTM C 33 limits. The merits of current aggregate characterization methods, such as ASTM C 1252 “Standard Test Methods for Uncompacted Void Content of Fine Aggregate (as Influenced by Particle Shape, Surface Texture, and Grading), were also examined to determine if they are relevant for manufactured sands. Aggregate characterization is an important tool for designing concrete and predicting concrete properties. If the tests are only valid for natural sands, they are ineffective when trying to characterize manufactured fine aggregate.

The paper is organized so that a review of relevant publications is presented in Chapter 2. Chapter 3 provides a description of the materials tested in the research program, and Chapter 4 is a description of the experimental program. Chapters 5 and 6 detail the data and results of the experiment. A final summary of the project and conclusions drawn from the data are presented in Chapter 7.

Chapter 2: Literature Review

As manufactured fine aggregate (MFA) becomes more prevalent in concrete mixtures, more information is increasingly available for predicting the behavior of concrete with MFA. Knowing previous problems encountered when using manufactured fine aggregate in concrete will help to avoid these incidences in future concrete mixtures. An extensive review of publications concerning the use of manufactured fine aggregate in concrete has been conducted. Relevant topics of aggregate characterization and methods of mixture proportioning as well as the effects of manufactured fine aggregate on fresh and hardened concrete properties are discussed.

SECTION 2.1: AGGREGATE CHARACTERIZATION

"Aggregate characterization" is blanket term for describing the properties of an aggregate such as its grading, shape, angularity, and texture. The properties of the microfines as well as the properties of the coarse and fine aggregate must be examined to predict how the combined aggregate will behave in a concrete mixture. Multiple tests are available for aggregate characterization, but they may not be suitable for manufactured fine aggregate.

Section 2.1.1: Grading

The grading of an aggregate is determined in accordance with ASTM C 136 "Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates." Aggregates are divided into three categories based on the size of the particle: 1) coarse aggregate, defined as material retained by No. 4 sieve, 2) fine aggregate, defined as material passing the No. 4 sieve and retained on a No. 200 sieve, and 3) microfines, defined as material passing the No. 200 sieve [Quiroga and Fowler, 2004B]. The particle size distribution of microfines cannot be determined by conventional sieving methods; alternative methods laser diffraction, electrical zone sensing, and sedimentation rate [Ferraris et al., 2002].

Coarse aggregate is generally considered to be material retained on the No. 4 sieve and larger [Quiroga and Fowler, 2004B]. An aggregate with an excess or lack of a particular size fraction may decrease workability [Galloway, 1994; Shilstone, 1990]. Intermediate aggregates, those passing the 3/8-in. sieve and retained on the No. 8 sieve, can be combined with coarse aggregate to improve the overall aggregate grading [Quiroga and Fowler, 2004B].

Fine aggregate passes the No. 4 sieve but is retained on the No. 200 sieve [Quiroga and Fowler, 2004B]. Mixtures containing a large proportion of fine aggregate generally require additional paste for workability, resulting in a sticky mixture that may be hard to finish [Shilstone, 1999]. On the other hand, mixtures containing too little sand may be “bony” and also hard to finish [Shilstone, 1990; Mindess, 1981].

Microfines are defined as the particles smaller than the No. 200 sieve. Manufactured sands tend to have a large percentage of microfines due to the crushing process. ASTM C 33 “Standard Specification for Concrete Aggregates” limits the amount of microfines to 3% and 5% for natural sand and 5% and 7% for manufactured sand. The lower limits are for concrete surfaces exposed to abrasive environments.

The grading of one particular aggregate, as well as the combined aggregate (coarse, intermediate, and fine) grading, can impact the workability of the concrete mixture. For example, a fine aggregate that is too coarse will produce harsh mixtures with bleeding and segregation, but fine aggregate with a grading that is too fine will increase water demand [Graves, 2006]. A fine aggregate with values near the minimum requirements for the No. 50 and No. 100 sieves may cause problems with workability, pumpability, or excessive bleeding [ASTM C 33, 2003].

Another issue with grading is that the accepted grading limits are generally intended for natural sands. A particular grading that may be suitable for natural sand could lead to undesirable results when used with manufactured sands [Hudson, 1999; Johansson, 1979]. Also, Clelland (1980) noticed that sands that comply with grading limits may not make suitable concrete because of inherently poor physical characteristics, and sands that do not meet grading limitations have been used successfully in concrete. Further research must examine if manufactured sands do, in fact, require a different grading envelope than natural sands to produce suitable concrete.

Section 2.1.2: Shape, Angularity, and Texture

Shape, angularity, and texture are additional means for defining an aggregate. In fact, the proper grading of an aggregate is actually dependent on the shape and texture of the aggregate [Quiroga and Fowler, 2004B]. Shape, angularity, and texture describe the coarsest, intermediate, and finest surface features of an aggregate, respectively [Koehler and Fowler, 2007].

The shape of an aggregate is related to the sphericity and form of the aggregate [Galloway, 1994]. Sphericity is a measure of the uniformity of the three principal axes of an aggregate, which are length, width, and height [Quiroga and Fowler, 2004B]. The length is the greatest dimension of the aggregate, the thickness or height is the greatest dimension that is perpendicular to the length and width, and the width is the greatest dimension in the plane that is perpendicular to the length [ASTM D 4791, 2005]. The sphericity increases as the three dimensions approach equal values [Brzezicki and Kasperkiewicz, 1999; Graves, 2006]. Completely spherical particles have a sphericity of one [Gonçalves et al., 2007]. The equation for sphericity is provided by Eq. 2.1. The dimensions of the aggregates are defined as long, intermediate, and short (L, I, and S, respectively) [Quiroga and Fowler, 2004B].

$$Sphericity = \sqrt[3]{\frac{SI}{L^2}} \qquad \text{(Eq. 2.1)}$$

Because it is possible for multiple aggregates to have the same numerical sphericity, another shape characteristic, called form, further distinguishes these aggregates [Hudson, 1999]. Form is also referred to as the shape factor [Hudson, 1999].

Two equations for the shape factor or form are presented by Eq. 2.2 and Eq 2.3 [Quiroga and Fowler, 2004B].

$$Form = \frac{S}{\sqrt{LI}} \qquad \text{(Eq. 2.2)}$$

$$Form = \frac{LS}{I^2} \qquad \text{(Eq. 2.3)}$$

The shape can impact mixture proportions, affecting the overall cost of concrete [O'Flynn, 2000]. For example, the coarse aggregate will determine the amount of sand required for a concrete mixture [Quiroga and Fowler, 2004B]. As the coarse aggregate becomes more elongated, flaky, or angular, more sand is required to fill voids [Legg, 1998].

The shape influences fresh concrete properties such as workability and pumpability [O'Flynn, 2000]. Long, thin particles can block bleed water from reaching the surface of the concrete [Kosmatka, 1994]. Aggregate shape also affects hardened concrete properties, such as compressive strength [O'Flynn, 2000]. Shilstone (1990) asserts that well-shaped aggregates exhibit greater compressive strengths than poorly-shaped aggregates. The orientation of a thin, flat particle in hardened concrete can create stress concentrations and weaken the concrete [Graves, 2006].

The shape of natural aggregates depends on the strength, abrasion resistance, and degree of wear they have been subjected to in their depositional environments [Graves, 2006]. The shape of manufactured aggregate depends on the rock type and the crushing equipment [Graves, 2006]. Common rock crusher types include vertical impact crushers, starve-fed cone crushers, and choke-fed cone crushers. Vertical shaft impact crushers fling larger aggregate particles against an anvil or other particle pieces [O'Flynn, 2000; Gonçalves et al., 2007]. The rock-on-rock crushing process helps to smooth the angular faces of manufactured sands [O'Flynn, 2000]. A starve-fed cone crusher will produce irregularly-shaped aggregate of intermediate strength [Gonçalves et al., 2007]. The starve-fed cone crusher reduces particle size by contact with the crusher plates alone [Gonçalves et al., 2007]. A choke-fed cone crusher relies on crusher plates and the interactions between particles to decrease aggregate size [Gonçalves et al., 2007]. A choke-fed cone crusher produces intermediate-shaped aggregate between the poorly-shaped aggregate produced by the starve-fed cone crusher and the more ideally-shaped aggregate produced by the vertical shaft impactor [Gonçalves et al., 2007].

While shape describes the larger surface features of an aggregate, angularity describes the intermediate features of an aggregate. Angularity indicates how sharp edges and corners are [Koehler and Fowler, 2007]. The angularity of an aggregate is the ratio of average radius of curvature of corners and edges to the radius of a maximum inscribed circle [Popovics, 1992]. Aggregates can be categorized as angular, subangular, subrounded, rounded, or well-rounded [Quiroga and Fowler, 2004B; Brzezicki and Kasperkiewicz, 1999; Popovics, 1992]. Angularity and roundness is based on how much wear the aggregate particles have experienced. Well-rounded aggregates do not have any original faces left while angular particles have experienced very little wear [Ahn and Fowler, 2001].

Surface texture measures the finest properties of an aggregate. It is the total sum of the minute surface features of an aggregate [Dolar-Mantuani, 1983]. The texture is dependent on the type of parent rock, the degree of weathering, and the structure of the aggregate [Quiroga and Fowler, 2004B]. The surface texture influences the workability of the mixture, the quantity of cement required for lubrication, and the bond between aggregate and cement. Rougher textures can lead to harsher mixtures, but they can also lead to a better bond between paste and aggregate [O'Flynn, 2000]. However, the fineness and shape of the sand influence workability more than surface texture [Bager et al., 2001].

Section 2.1.3: Test Methods for Aggregate Characterization

While ASTM C 136 is the test method accepted for determining the grading of aggregate, multiple tests are available for determining the shape and angularity of aggregate. ASTM D 4791 and ASTM D 5821 are two common methods for characterizing coarse aggregate, and ASTM C 1252 is a method for characterizing fine aggregate. The methylene blue test and single-drop test are two methods for determining the properties of microfines.

The first method associated with coarse aggregate characterization, ASTM D 4791 "Standard Test Method for Flat Particles, Elongated Particles, or Flat and Elongated Particles in Coarse Aggregate," categorizes flat and elongated particles by their dimension ratios. Aggregates with ratios of length to thickness or width greater than 3:1 or 5:1 are usually undesirable [Graves, 2006]. This test has been championed because is it simple and repeatable, but it has also been criticized because it is time-consuming [Weingart and Prowell 2001; Kandhal and Parker, 1998].

The second method associated with coarse aggregate characterization, ASTM D 5821 "Standard Test Method for Determining the Percentage of Fractured Particles in Coarse Aggregate," assesses the amount of fractured faces of an aggregate particle. The number of fractured faces on a particular aggregate particle is determined by visually examining each aggregate piece [Koehler and Fowler, 2007]. A particle is said to have a fractured face if 25% of the aggregate surface is fractured [Koehler and Fowler, 2007].

A method available for characterizing fine aggregate, ASTM C 1252 "Standard Test Methods for Uncompacted Void Content of Fine Aggregate (as Influenced by Particle Shape, Surface Texture, and Grading)," indirectly tests the shapes of fine aggregates. However, the test is also not able to distinguish between the effects of shape and surface texture [Quiroga and Fowler, 2004B]. Hudson (1999) also faults ASTM C 1252 for giving inaccurate results for coarser fine aggregate. Hudson (1999) proposes that the discharge orifice is too small to allow large particles to pass through it, and the container below the orifice is also too small. Both of these effects will cause some error in the test results.

ASTM D 3398 "Index of Aggregate Particle Shape and Texture" is also utilized to characterize aggregate. The aggregate is sieved, and the size fractions that make up 10% or more of the aggregate are placed in individual cylindrical molds and tamped 10 and 50 times. The voids content of each sieve size is determined for 10 and 50 counts of tamping, and the particle index for each size fraction is then calculated. However, the method is impractical. The test requires separating the aggregate into different size fractions, making the method time-consuming and expensive [Kandhal and Parker, 1998].

A particle image analyzer can be employed to characterize size, shape, and count of an aggregate [Lukkarila, 2006]. The analyzer is able to calculate the elongation, circularity, and convexity of an aggregate particle [Lukkarila, 2006]. Brzezicki and Kasperkiewicz (1999) created a method for measuring all three aggregate dimensions instead of only two dimensions. The grains are placed in a form which is illuminated by several lights. The grains cast shadows onto the spherical form, and the shadows are measured to determine the geometric properties of the aggregate. There are currently no ASTM or AASHTO standards governing the use of image analysis [Quiroga and Fowler, 2004B].

In addition to the characterization of coarse and fine aggregate, it is critical to examine the properties of the microfines contained within the sand. Manufactured sand derived from carbonate rock aggregate, such as limestone or dolomite, can contain insoluble residue composed of clay and fine silica [Hudec and Agistalis, 2000]. The methylene blue test, described in AASHTO TP 57 "Standard Method of Test for The Qualitative Detection of Harmful Clays of the Smectite Group in Aggregates Using Methylene Blue," determines the amount of deleterious material in the aggregate. A small sample of microfines is added to water to form a slurry solution. Methylene blue is then added to the slurry until a light blue halo is seen surrounding a drop of the solution placed on filter paper. The blue halo indicates that no more methylene blue will be adsorbed by the solution.

The method is effective due to the ability of the clay to exchange cations and adsorb the blue dye [Quiroga and Fowler, 2004]. The methylene blue value (MBV) is half of the volume of methylene blue (mL) required for titration. A methylene blue value of 20 or greater generally indicates that the aggregate has high clay content and is not suitable for use in concrete [Norvell et al., 2007]. However, an aggregate with a high MBV should be investigated further before complete rejection [Dumitru et al., 1999].

The water demand of microfines can be determined by conducting the single-drop test [Bigas and Gallias, 2003]. A sample of oven-dried microfines is placed in a container with a large surface area and weighed. A small amount of water (0.2 mL) is added to the surface of the powder, creating an agglomerate of material. After 20 seconds, the glob of powder is removed from the sample, and the sample is reweighed. The ratio of the volume of the water drop to the volume of the agglomerate of fines (*w/f*) is determined. Cement can also be included as part of the fines, and then the *w/(f+c)* is determined. The packing density of the microfines can be determined by dividing the volume of the agglomerate by the sum of the volume of the agglomerate and the volume of the water drop.

SECTION 2.2.: PROPORTIONING METHODS

The negative characteristics of an aggregate can be mitigated by properly proportioning the aggregate. The packing density of an aggregate or aggregate combination is a quantifiable way to determine if the aggregates are suitably graded and in the correct proportions. A greater packing density will decrease the percentage of voids and lower the percentage of paste required in the mixture.

A common concrete proportioning method is ACI 211 Standard Practice for Selecting Proportions for Normal, Heavyweight and Mass Concrete. Other proportioning methods available are the "18-8" Percentage-Retained Size-Distribution Chart and Shilstone's method for proportioning, which considers the 0.45 Power Chart, the Coarseness Chart, and the mortar factor.

Section 2.2.1: Packing Density

The packing density is the volume of solids within a unit volume, and it is equal to one minus the volume of voids [Quiroga and Fowler, 2004]. A higher packing density indicates a lower percentage of voids and vice versa. Packing density is dependent on the shape, texture, and grading of particles within a container [Quiroga and Fowler, 2004B]. Packing density will vary based on the method of compaction (poured, tamped, or vibrated) of the aggregate [Quiroga and Fowler, 2004]. Optimum packing density is not always the same as maximum packing density. The maximum packing density may require gap grading, resulting in segregation, increased bleeding, and decreased finishability of the mixture [Quiroga and Fowler, 2004B].

Graded coarse aggregate, or a uniformly-distributed coarse aggregate, will have a greater packing density as opposed to a single-size aggregate [Graves, 2006]. The smaller aggregates will fill in the voids created by the larger aggregates [Graves, 2006]. Uniformly-distributed aggregates generally require less paste, which will lead to decreased bleeding, creep, and shrinkage [Washa, 1998; Shilstone, 1999].

Section 2.2.2.: ACI 211 Proportioning Method

ACI 211 Standard Practice for Selecting Proportions for Normal, Heavyweight and Mass Concrete is a common method for mixture design. ACI 211 proportions are influenced by the maximum size of the aggregate, desired *w/c*, and slump [Quiroga and Fowler, 2004]. ACI 211 requires only two aggregate sizes (coarse and fine) to be used in the mixture [Quiroga and Fowler, 2004]. ACI 211 may not generate optimum concrete mixtures because it considers only two aggregate sizes; greater packing densities and lower cement contents could be achieved with the addition of another aggregate size. ACI 211 also does not account for shape or texture of the aggregate [Quiroga and Fowler, 2004].

Section 2.2.3: "18-8" Percentage-Retained Size-Distribution Chart

The "18-8" Percentage-Retained Size-Distribution Chart is another method of proportioning. As opposed to ACI 211, this method encourages a uniform distribution of aggregate [Quiroga and Fowler, 2004B]. The minimum percentage retained on sieves No. 30 sieve to 1/2-in. is 8%, and the maximum percentage retained on sieves No. 100 to 1-in. is 18%. This proportioning method may not be ideal for manufactured sands because it is not applicable for aggregates with a high percentage of microfines [Quiroga and Fowler, 2004B].

Section 2.2.4: Shilstone's Method for Proportioning

Shilstone (2002) combines several factors including the 0.45 Power Chart, the Coarseness Chart, and the mortar factor to design an acceptable mixture. The 0.45 Power Chart is a graph of the sieve sizes raised to the 0.45 power versus the percent passing of each sieve. The power curve is presented in Fig. 2.1 for 1 1/4-in. maximum aggregate size. An acceptable grading is very close to the 0.45 line.

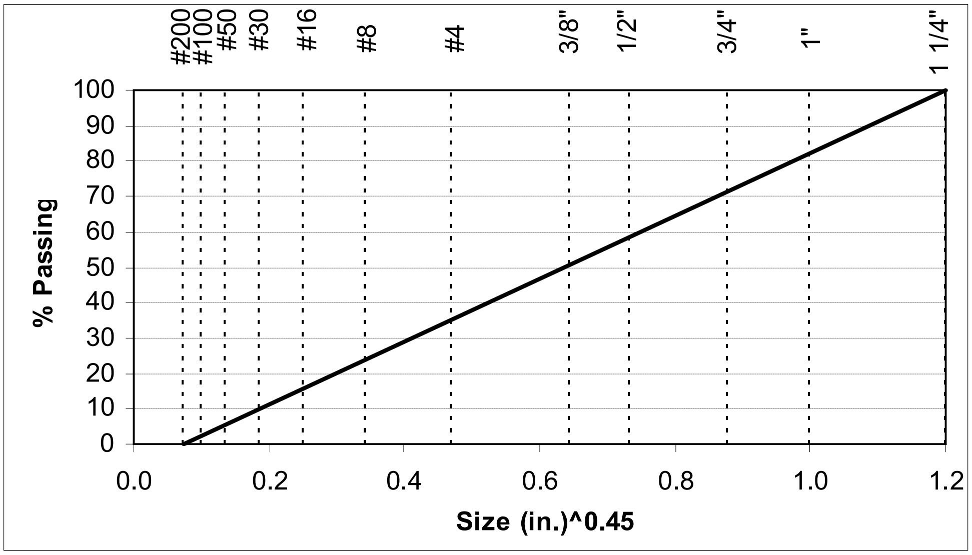

Figure 2.1: 0.45 Power Chart Example

The Coarseness Chart is a graph of the coarseness factor versus the workability factor [Shilstone, 2002]. An example is shown in Fig. 2.2. The coarseness factor is the sum of the percentages retained on sieve sizes 1.5-in. through 3/8-in. divided by the sum of the percentages retained on sieve sizes 1.5-in. through the No. 8 sieve. The workability factor is the percent passing the No. 8 sieve. The Coarseness Chart divides combined aggregate grading into five zones. Zone V delineates rocky mixtures. Mixtures in Zone IV contain a large percentage of fine aggregate and have an increased chance of cracking. Mixtures in Zone II are the most desirable, and mixtures in Zone III are similar to those in Zone II except with a maximum aggregate size of 0.5 in. or less.

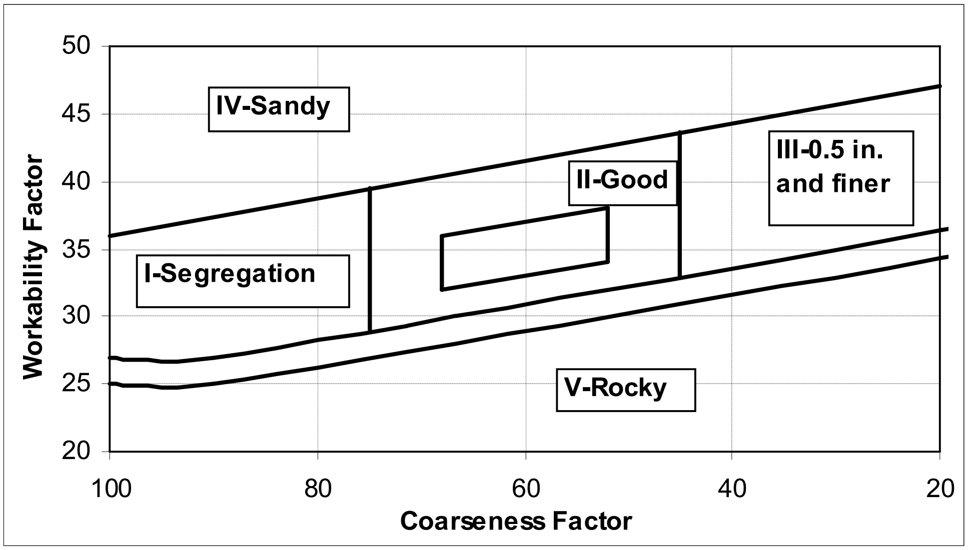

Figure 2.2: Coarseness Chart Example

Shilstone (2002) defines the mortar factor as all material smaller than the No. 8 sieve, including aggregate, cement, water, and air. This mortar factor affects fresh and hardened concrete properties as well as the cost of the mixture [Quiroga and Fowler, 2004B]. The mortar factor also takes the quantity of microfines into consideration. Microfines are treated like mineral fillers and are classified as part of the paste instead of the aggregate [Shilstone, 2002].

SECTION 2.3: THE EFFECTS OF MFA ON FRESH CONCRETE PROPERTIES

The fresh concrete properties of a mixture, such as the workability and finishability, can be greatly impacted by the choice of fine aggregate. Mixtures containing angular sands like manufactured sands tend to have higher paste contents to achieve the same workability as mixtures containing well-shaped sands. The finishability of a concrete surface may be affected by the type and amount of manufactured sand included in a mixture. Other fresh properties that may be impacted by the inclusion of MFA are bleeding, air content, and propensity for segregation.

Section 2.3.1: Workability

The shape of the coarse and fine aggregates as well as the amount of microfines present in the mixture affect the workability of fresh concrete. Wills (1976) found that fine aggregate had a more significant impact on water demand than coarse aggregate. The shape and texture of the fine aggregate influence the properties of the concrete mixture more than the shape and texture of coarse aggregate [Quiroga and Fowler, 2004B]. Grading and shape also affect workability more than the texture of an aggregate [Graves, 2006].

One of the obstacles to using manufactured fine aggregate in concrete is the poor shape of the aggregate. Manufactured sands are typically composed of sharp, angular particles with large numbers of flat and elongated particles [Lukkarila, 2006]. Mixtures containing flaky and elongated particles necessitate higher paste contents to obtain the same workability as mixtures containing cubical or spherical particles [Quiroga and Fowler, 2004B]. Conversely, natural sands tend to have cubical faces due to weathering [Ahn and Fowler, 2001]. Rounded particles also have a smaller surface area and provide greater inherent workability than flaky or elongated particles [Quiroga and Fowler, 2004B]. A mixture incorporating spherical particles has better pumpability and better finishability than a mixture including flaky and elongated aggregates [Shilstone, 1990].

Angular particles create a greater void volume within the aggregate [Quiroga and Fowler, 2004]. Spherical particles result in less than 30% void volume while angular particles can result in greater than 50% void volume [Yzenas, 2006]. Additional water and cement are needed to fill those voids [Quiroga and Fowler, 2004]. Graves (2006) states "a 1% increase in void content, as measured by ASTM C 1252, requires about one additional gallon of water to maintain the same slump, all other things being maintained."

A concrete mixture containing angular sand requires more water to enhance the workability of the mixture, but a superplasticizer can compensate for the additional water demand [Nichols, 1982]. The slump is then dependent not on the shape and texture of the particles but rather the type and dosage of superplastizer utilized in the mixture [Donza et al., 2002B]. The dosage of superplasticizer is increased for concretes with greater percentages of crushed stone sand [Donza et al., 2002B].

The hesitation to use more manufactured fine aggregate in concrete may be due in part to the increased percentage of microfines included in the mixture [Celik and Marar, 1996]. The water demand in a concrete mixture is largely affected by the solid volume percentage of the fine aggregate and the content of microfines [Yamamoto et al., 2005]. Greater microfine content increases the surface area of the fine aggregate and the water demand of the mixture [Celik and Marar, 1996]. As the percentage of microfines increases, the slump correspondingly decreases [Celik, and Marar 1996]. The slump test may inadequate for determining the workability of concrete containing a high percentage of microfines [Quiroga and Fowler, 2004B].

Microfines are viewed warily because they are about the same size as clay particles. Clay-sized aggregate particles, however, are not necessarily deleterious to concrete [Wood and Marek, 1995]. Norvell et al. (2007) concluded that non-clay ultra-fine particles do not negatively impact workability, compressive strength, or drying shrinkage. Hudson (1997) asserted that the dust-of-fracture content could be as high as 15% to 20% without detrimental effects. Forster (1994) also found that crushed fines can be beneficial to concrete. Cubical particles passing the No. 100 can act as a lubricant in concrete, and particles passing the No. 200 can improve strength, workability, and density for lean concrete mixtures [Hudson, 1999; Forster, 1994].

Section 2.3.2: Finishability

There have been claims that the use of manufactured sands may lead to harsh finishing [ACPA, 2003]. However, there was no appreciable difference discovered when finishing hexagonal slabs composed of natural sand and manufactured sand [Nichols, 1982]. As long as the concrete finisher is experienced, there should be no additional difficulty in placing and finishing crushed sand concrete [Nichols, 1982].

Section 2.3.3: Bleeding and Segregation

Crushed fine aggregate increases the water demand, which in turn increases the amount of bleed water in the concrete [Washa, 1998; Kosmatka, 1994]. However, Nichols (1982) contradicts this statement by maintaining that concrete made from angular sands will bleed comparably to concrete made from more cubical sand. Segregation has also been linked with high water contents, but it has been argued that high amounts of microfines can help reduce bleeding and segregation [Hudson, 1999; Kalcheff, 1977]. The Japan Society of Civil Engineers (2002) has also stated that the inclusion of microfines may help to decrease the segregation of concrete.

Section 2.3.4: Air Content

The amount of manufactured sand included in a mixture can affect the air content of the concrete. As the percentage of microfines increases, the entrained air content also increases [Celik and Marar, 1996]. Therefore, crushed aggregate particles with high percentages of microfines can decrease the amount of air-entraining admixture required [Quiroga and Fowler, 2004B].

SECTION 2.4: THE EFFECTS OF MFA ON HARDENED CONCRETE PROPERTIES

Including manufactured fine aggregate in concrete mixtures impacts hardened concrete properties like strength, length change, and durability. Fresh and hardened concrete properties can be influenced by the same variable, such as sand type, grading, or amount of MFA included in the mixture. A particular sand type may be highly angular with a high percentage of microfines, requiring additional water for workability and thereby lowering the compressive strength of the hardened specimens. Fortunately, hardened concrete properties can also be manipulated by proper proportioning and the use of chemical admixtures.

Section 2.4.1: Strength

Concrete made with MFA can have higher compressive and tensile strengths than concrete made with natural sand. Very little data are available concerning the effects of MFA on flexural strength. Concrete made with blended sand has produced higher tensile and compressive strengths for all *w/c* (ranging from 0.4 to 0.6) than natural sand concrete or crushed limestone concrete [Kim et al., 1997]. Crushed limestone concrete by itself has generated compressive and tensile strengths about equal to or larger than natural sand concrete [Kim et al., 1997]. Crushed sand mortars have produced higher compressive strengths than natural sand mortars [Donza et al., 2002]. Crushed granite sand concrete has exhibited higher compressive and tensile strengths at one year than natural sand concrete [Donza et al., 2002B].

The amount of microfines included in the mixture will also influence the concrete strength. Concrete containing up to 7% microfines can reach a compressive strength equal to or better than natural sand concrete with comparable *w/c* [Dukatz and Marek, 1985]. Higher strength concrete has been produced with high percentages of microfines, indicating that the minus No. 200 material is likely non-deleterious and well-shaped [Gonçalves et al., 2007]. Concretes with constant *w/c* of 0.70 have exhibited increasing strengths as the proportions of microfines were increased [Ahmed and El-Kourd, 1989]. Kim et al. (1997) discovered that a concrete mixture with 3% microfines produced the largest compressive and tensile strengths. Celik and Marar (1996) noted that the optimal microfine content to achieve maximum compressive and tensile strengths at 7 and 28 days was 10%.

The compressive strength of mortars made with varying types of manufactured sand decreased when the amount of microfines in the mixture was decreased [Gonçalves et al., 2007]. The strength decrease could be attributed to the lower packing density and greater impact of the interfacial transition zone [Gonçalves et al., 2007]. Conversely, if the cement content is kept constant for each mixture design and the percentage of microfines increases, there simply is not enough paste to coat all of the coarse and fine aggregate particles, decreasing the compressive strength [Celik and Marar, 1996]. For example, the 28-day flexural strength of concretes with 10% dust-of-fracture increased by 10%; the 28-day flexural strength of concretes with 30% dust-of-fracture decreased by 30% [Celik and Marar, 1996]. For concrete of a constant slump, the compressive strength was found to decrease with increasing amounts of microfines [Ahmed and El-Kourd, 1989]. This is due to the addition of water to maintain a constant slump.

Section 2.4.2: Length Change

Shrinkage could be a problem with mixtures containing high microfines. Quiroga and Fowler (2004B) noted that concrete mixtures with about 20% microfines had about 10% greater shrinkage than mixtures with no microfines. The shrinkage of concrete generally increases with an increase in microfines [Ahn and Fowler, 2001].

Section 2.4.3: Durability

Concrete composed of MFA has shown increased resistance to chloride penetration and abrasion [Quiroga et al., 2000]. In concrete with the same *w/c*, strength, and resistance to the carbonation, concrete composed of manufactured fine aggregate or blended sand demonstrate either equal or superior qualities as compared to concrete with sea sand as a fine aggregate [Yamamoto et al., 2005]. The coefficient of permeability decreases as the amount of fines increases [Celik and Marar, 1996]. Microfines fill the capillary voids in the concrete and decrease the permeability of the concrete [Celik and Marar, 1996]. If suitably graded, microfines can result in a higher packing density, denser concrete, and a lower permeability [Hudson, 1997]. However, the durability of the aggregate and the mortar is also dependent upon the amount of insoluble residue [Hudec and Agistalis, 2000]. Clay will adsorb both water and deicing cations, which can expand the aggregate and damage the concrete [Hudec and Agistalis, 2000].

Microfines may cause the surface of the concrete to be more sensitive to environmental damage. Carbonate rock aggregate can increase surface scaling and loss due to freeze-thaw damage [Hudec and Agistalis, 2000]. Concrete pavements made with high percentages of microfines may be more vulnerable to surface polishing. The polishing action smoothes the surface of the concrete, especially where there are pits, gouges, or scratches [Meininger, 2006]. To minimize damage from abrasion, the surface of the concrete must be strong and durable. Unfortunately, little data exist concerning the abrasion resistance of concrete with manufactured fine aggregate.

SECTION 2.5: LITERATURE REVIEW SUMMARY

Coarse and fine aggregate may be characterized by gradation, shape, angularity, and texture. The current methods governing aggregate characterization are not intended for manufactured fine aggregate, and the results may be affected by these flaws in the test methods.

The fresh properties of a concrete mixture can be affected by the type of fine aggregate. Workability decreases if angular, flaky manufactured sands are included in the concrete mixture, but it can be restored with the use of admixtures and proper proportioning. The inclusion of microfines in a mixture may increase or decrease workability; the workability is dependent upon the shape and particle size distribution of the microfines.

Hardened concrete properties may be improved with the addition of manufactured fine aggregate. Compressive strength tends to increase with the addition of MFA. The compressive strength also tends to increase to a certain limit with increasing proportions of microfines. After the limit is reached, the strength decreases because there is not enough paste to coat the aggregate. The permeability of the concrete decreases and durability increases as the percentage of microfines is increased. Voids in the concrete are filled by microfines, lowering permeability. Unfortunately, the addition of microfines to the mixture could exacerbate polishing of the concrete surface.

Chapter 3: Materials

SECTION 3.1: INTRODUCTION

In order to determine the effects of manufactured fine aggregate (MFA) on the fresh and hardened concrete properties of concrete, three different manufactured sands were selected for testing. Two different sizes of crushed limestone were used as coarse aggregate, and siliceous river sand was used as the natural fine aggregate in the sand blends. Portland cement was used in most of the mixtures, but several mixtures incorporated fly ash as a supplementary cementing material. Most mixtures required a high-range water-reducing admixture (HRWRA) to achieve the necessary workability.

SECTION 3.2: AGGREGATES

Section 3.2.1: Coarse Aggregate

Two sizes of coarse aggregate were selected for use in the test program: (1) 1 1/4-in. concrete rock, abbreviated as “CA” for coarse aggregate, and (2) 3/8-in. by No. 10 screen aggregate, abbreviated as “IA” for intermediate aggregate. Both were crushed limestone rock obtained near San Antonio, TX. The 3/8-in. aggregate was included to produce a more uniform distribution of coarse aggregate.

The properties of CA and IA are listed in Table 3.1. The characteristics of CA and IA are nearly identical because they are from the same parent source and aggregate producer. The aggregates were tested in accordance with ASTM C 136 “Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates,” ASTM C 117 “Standard Test Method for Materials Finer than 75-µm (No. 200) Sieve in Mineral Aggregates by Washing,” ASTM C 127 “Standard Test Method for Density, Relative Density (Specific Gravity), and Absorption of Coarse Aggregate,” and ASTM C 29 “Standard Test Method for Bulk Density (Unit Weight) and Voids in Aggregate.”

Table 3.1: Properties of CA and IA

		CA	**IA**
Density (OD)	lb/ft^3	158.0	159.5
Density (SSD)	lb/ft^3	160.5	162.0
Density (Apparent)	lb/ft^3	165.0	165.5
Specific Gravity (OD)	-	2.54	2.56
Specific Gravity (SSD)	-	2.58	2.60
Specific Gravity (Apparent)	-	2.65	2.66
Absorption	%	1.6	1.4
Bulk Density (Dry, Rodding)	lb/ft^3	98	91
Voids Content (Dry, Rodding)	%	38	43
Shape Factor	-	5	5

The aggregates were also subjected to a visual examination of shape, angularity and texture. The shape factor is a qualitative, visual grading of the aggregate. A value of 1 indicates that the aggregate is well-shaped, and a value of 5 indicates that an aggregate is poorly-shaped. The shape factor was high for CA and IA because they were crushed limestone. They contained elongated particles, had rough surfaces, and were angular. The shape factor for a particular aggregate combination in a concrete mixture is a weighted averaged of the shape factors of the coarse, intermediate, and fine aggregates based on their relative proportions of the total aggregate.

The as-received gradings of the aggregates are presented in Table 3.2. IA provided a large amount material on the No. 4 sieve. IA made up 25% of the total volume of coarse aggregate. The increased proportion of smaller aggregate kept the combined aggregate grading of each mixture close to the 0.45 power curve and placed it in the "good" section of the coarseness chart.

Table 3.2: As-Received CA and IA Gradings

US Sieve	Size	CA		IA	
No.	(in.)	% Ret.	% Pass.	% Ret.	% Pass.
1.5-in.	1.500	0	100	0	-
1-in.	1.000	20	80	0	-
3/4-in.	0.750	25	55	0	-
1/2-in.	0.500	28	28	0	-
3/8-in.	0.375	18	10	28	72
4	0.187	8	2	70	2
8	0.093	-	-	1	1
16	0.046	-	-	0	1
30	0.024	-	-	0	1
50	0.012	-	-	0	1
100	0.006	-	-	0	1
200	0.003	-	-	1	1
Pan	-	1	-	0	-
Total	-	99	-	100	-

Section 3.2.2: Fine Aggregate

The fine aggregates included in mixtures were composed of three manufactured sands and one natural, siliceous river sand. The river sand was from the Colorado River near Austin, Texas, and the manufactured sands were limestone concrete sand from near San Antonio, Texas, dolomitic limestone concrete sand from Illinois, and granite screenings from South Carolina. The granite sand was considered to be poorly-shaped, the dolomitic limestone sand was considered to be intermediate-shaped, and the limestone sand was considered to be well shaped. The natural sand is abbreviated as “NS”, the limestone sand as “LS”, the dolomitic limestone sand as “DL”, and the granite sand as “GR”.

The properties of the fine aggregates are listed in Table 3.3. All sands except the dolomitic limestone sand had been previously tested as part of another research program [Koehler and Fowler, 2007]. The dolomitic limestone sand was subjected to the same tests except at a later date. The sands were tested in accordance with ASTM C 136 "Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates," ASTM C 117 "Standard Test Method for Materials Finer than 75-µm (No. 200) Sieve in Mineral Aggregates by Washing," ASTM C 128 "Standard Test Method for Density, Relative Density (Specific Gravity), and Absorption of Fine Aggregate," ASTM C 29 "Standard Test Method for Bulk Density (Unit Weight) and Voids in Aggregate," and ASTM C 1252 "Standard Test Methods for Uncompacted Void Content of Fine Aggregate (as Influenced by Particle Shape, Surface Texture, and Grading) - Test Method A Standard Graded Sample." The fine aggregates were rated from 1 to 5 based on a visual examination of shape.

Table 3.3: Fine Aggregate Properties

		NS	**LS**	**DL**	**GR**
Location	-	Austin, TX	Garden Ridge, TX	Manteno, IL	Liberty, SC
Density (OD)	lb/ft^3	161.5	160.0	167.1	166.9
Density (SSD)	lb/ft^3	162.0	162.5	170.1	167.9
Specific Gravity (OD)	-	2.59	2.57	2.68	2.68
Specific Gravity (SSD)	-	2.60	2.61	2.73	2.69
Absorption	%	0.56	1.62	1.82	0.56
Uncompacted Voids	%	41.0	44.1	48.0	48.3
Bulk Density (Dry, Rodding)	lb/ft^3	109	107	112	105
Voids Content (Dry Rodding)	%	32.4	33.4	32.9	37.1
Fineness Modulus	-	2.6	2.8	3.1	2.1
Shape Factor	-	1	1	3	5

The as-received gradings of the fine aggregates are presented in Table 3.4. GR and DL had very high percentages of microfines. These sands would typically be rejected because they do not meet ASTM C 33 limitations. LS had a much lower percentage of microfines but could still be eliminated from use if the concrete was to be placed in an abrasive environment.

Table 3.4: As-Received Fine Aggregate Gradings

US Sieve	**Size**	**NS**		**LS**		**DL**		**GR**	
No.	**in.**	**% Ret.**	**% Pass.**	**% Ret.**	**% Pass.**	**% Ret.**	**% Pass.**	**% Ret.**	**% Pass.**
4	0.187	1.5	98.5	0.0	100.0	3.5	96.5	0.1	99.9
8	0.093	11.6	86.9	4.5	95.5	26.5	70.0	11.1	88.8
16	0.046	11.8	75.1	33.7	61.8	23.7	46.3	15.0	73.9
30	0.024	21.7	53.4	24.2	37.6	14.6	31.8	14.1	59.8
50	0.012	32.5	20.9	17.4	20.2	9.2	22.5	17.7	42.1
100	0.006	14.2	6.8	11.1	9.1	4.9	17.7	17.6	24.5
200	0.003	5.0	1.8	3.7	5.4	3.4	14.3	11.0	13.5
Pan	-	1.8	-	5.3	-	14.2	-	13.5	-
Total	-	100.0	-	99.9	-	99.9	-	100.0	-

Section 3.2.3: Microfines

The microfines contained within the manufactured sands were also analyzed. The shape and water-to-fines (*w/f*) ratio of the microfines were determined with the single-drop test [Bigas and Gallias, 2003]. Laser diffraction size analysis had been previously performed on the microfines by the National Institute of Standards and Technology (NIST) [Koehler and Fowler, 2007]. AASHTO TP 57 Standard Method of Test for The Qualitative Detection of Harmful Clays of the Smectite Group in Aggregates Using Methylene Blue was performed to evaluate the clay content of the microfines. The properties of the microfines are listed in Table 3.5.

Table 3.5: Microfine Properties

		Single-Drop Test		**Laser Diffraction**	
Sand	**MBV (mg/g)**	**w/f**	**Packing Density**	**Span**	**SSA (1/µm)**
LS	1.63	0.401	0.714	6.673	1.394
DL	1.25	0.427	0.702	2.651	0.394
GR	0.63	0.559	0.642	2.192	0.467

SECTION 3.3 CEMENTING MATERIALS

Section 3.3.1: Cement

The cement used in the experimental procedure was a portland cement meeting ASTM C 150 "Standard Specification for Portland Cement Type I/II." It was obtained from New Braunfels, TX. The properties of the cement provided by the manufacturer are presented in Table 3.6. The cement was manufactured with a processing addition meeting ASTM C 465 "Standard Specification for Processing Additions for Use in the Manufacture of Hydraulic Cements." The cement composition was determined by the Bogue equations given in ASTM C 150, but the phase proportions were corrected for the processing addition by an equation provided by the manufacturer of the processing addition.

Table 3.6: Cement Properties

Property	**Value**
Blaine Fineness (m^2/kg)	395
Na_2Oeq (%)	0.44
SO_3 (%)	2.9
C_3S (%)	58
C_2S (%)	14
C_3A (%)	7
C_4AF (%)	9

Section 3.3.2: Fly Ash

The fly ash was an ASTM C 618 "Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete" Type Class F fly ash obtained from Jewett, TX. The properties of the fly ash, determined in another research program and obtained from the supplier, are listed in Table 3.7 [Koehler and Fowler, 2007].

Table 3.7: Fly Ash Properties

Property	Value
Loss-on-Ignition	0.11
SG	2.39
CaO	9.90
$SiO_2+Al_2O_3+Fe_2O_3$	83.71

SECTION 3.4: CHEMICAL ADMIXTURES

Section 3.4.1: Water-Reducing Admixture (WRA)

Masterpave (BASF) is a water-reducing admixture used for concrete paving mixtures. Masterpave meets ASTM C 494/C 494M “Standard Specification for Chemical Admixtures for Concrete” requirements for Type A, water-reducing, Type B, retarding, and Type D, water-reducing and retarding admixtures. When used in large dosages, it can have a negative effect on setting times.

For the trial mixtures containing high percentages of microfines, the dosage of Masterpave required to reach an acceptable slump was greater than the recommended dosage. The highest recommended dosage of Masterpave is 5 oz/cwt, yet the trial mixture required a dosage of 20 oz/cwt. It was decided that a polycarboxylate-based high-range water-reducing admixture would be utilized for the majority of the concrete mixtures in the research program.

Section 3.4.2: High-Range Water-Reducing Admixture (HRWRA)

Glenium 7101 (BASF) is a polycarboxylate high-range water-reducing admixture. The admixture meets ASTM C 494/C 494M “Standard Specification for Chemical Admixtures for Concrete” provisional compliance requirements for Type A, water-reducing, and Type F, high-range water-reducing, admixtures. The recommended dosage range for Glenium 7101 is 3 to 12 oz/cwt. As compared to WRA, HRWRA generates the necessary workability for concrete mixtures containing high percentages of microfines with only minor increases in setting times.

SECTION 3.5: MATERIALS SUMMARY

Three manufactured sands composed of limestone, dolomitic limestone, and granite were selected for testing during the research program. The coarse aggregate was composed of two sizes of crushed limestone, and the natural sand was siliceous river sand. The cementing materials used in the concrete mixtures were portland cement and Class F fly ash. High-range water-reducing admixture (HRWRA) and water-reducing admixture (WRA) were incorporated into the mixtures to reach the required workability.

Chapter 4: Experimental Program

SECTION 4.1: INTRODUCTION

The materials described in Chapter 3 were tested during an experimental program that was divided into two distinct parts. The first portion of the experimental program was devoted to examining the effects of fine aggregate type, grading, and blend ratio on fresh and hardened concrete properties. The second part of the experimental program focused on the optimization of selected mixtures. The two phases of the project are referred to as the "Sand Blends Study" and the "Optimization Study," respectively.

SECTION 4.2: AGGREGATE GRADINGS

Section 4.2.1: Manufactured Fine Aggregate Gradings

Three sand gradings were examined during the laboratory program. The first grading consisted of the as-received gradings of limestone (LS), dolomitic limestone (DL), and granite (GR) sands with the microfines removed. The manufactured sands were washed over the No. 200 sieve to mimic the process used in industry. Microfines are typically washed from manufactured sands before use in concrete because they are limited by ASTM C 33. Washing the sand may not be necessary if suitable concrete could be made with the microfines included. This grading was abbreviated as "WARG" for washed, as-received grading. The gradings are different for each sand type, as seen in Fig. 4.1.

The second grading was selected so as to meet the grading limits set forth in ASTM C 33. In order for a blended sand to be used in concrete, the sands to be blended must meet ASTM C 33 limits, and the final blended sand must also meet ASTM C 33 limits. Suitable manufactured sands may not be allowed in concrete because of this postulation. ASTM C 33 has historically been aimed at natural sands, but, as the use of manufactured sands increases, the grading limits must be re-examined to determine their relevance for manufactured sands. This grading was abbreviated as "C33," and it was the same for all three manufactured sands, as seen in Fig. 4.1.

The third grading had high microfines content with 18% passing the No. 200 sieve. This grading represented typical manufactured sands after it has been crushed and before the microfines have been removed. If a higher percentage of microfines were allowed in concrete, the cost and energy required to process the crushed sand would be significantly reduced in many cases. This grading is abbreviated as "HMF" for high microfines, and it is the same for all three manufactured sands, as seen in Fig. 4.1.

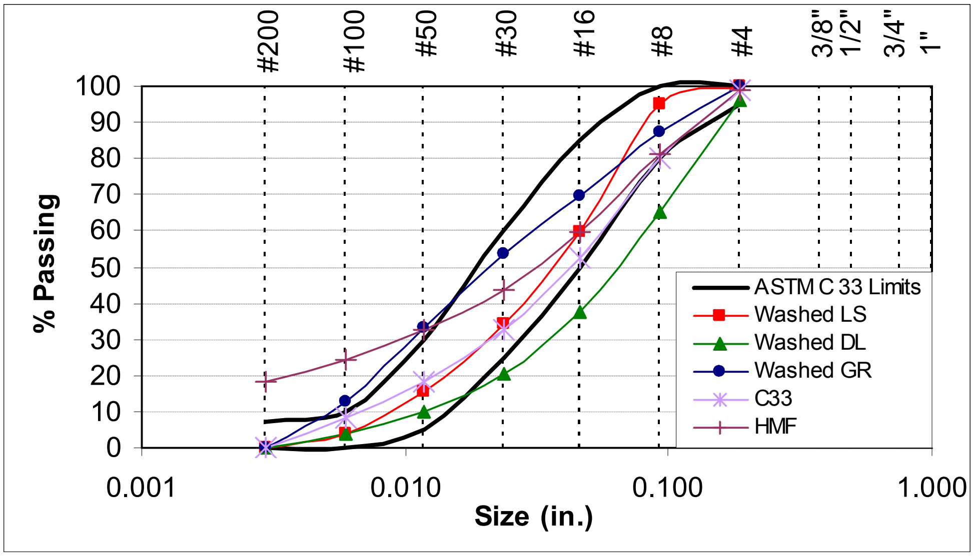

Figure 4.1: Percent Passing of MFA Gradings

Section 4.2.2: Blended Fine Aggregate Gradings

Manufactured sand may be used by itself or in combination with natural sand. For the "Sand Blends Study," natural river sand (NS) was replaced with varying amounts of LS, DL, or GR with WARG, C33, or HMF grading. For each type of sand with the WARG grading, the following two mixtures were tested: (1) a mixture with 50% sand with WARG grading and 50% NS and (2) a mixture with 100% sand with WARG grading. For each type of sand with the C33 grading, the following four mixtures were tested: (1) a mixture with 30% manufactured sand with C33 grading and 70% NS, (2) a mixture with 50% manufactured sand with C33 grading and 50% NS, (3) a mixture with 70% manufactured sand with C33 grading and 30% NS, and (4) a mixture with 100% manufactured sand with C33 grading. For each type of sand with HMF grading, the following two mixtures were tested: (1) a mixture with 50% sand with HMF grading and 50% NS, and (2) a mixture with 100% sand with HMF grading. A mixture with the fine aggregate composed of 100% NS was considered to be the control mixture. The sand blends and descriptions are presented in Appendix A.

The grading curves of the blended sand combinations are presented in Fig. 4.2. For simplicity, only LS is shown on the graphs of C33 and HMF grading, but the percent passing values are the exact same for DL and GR.

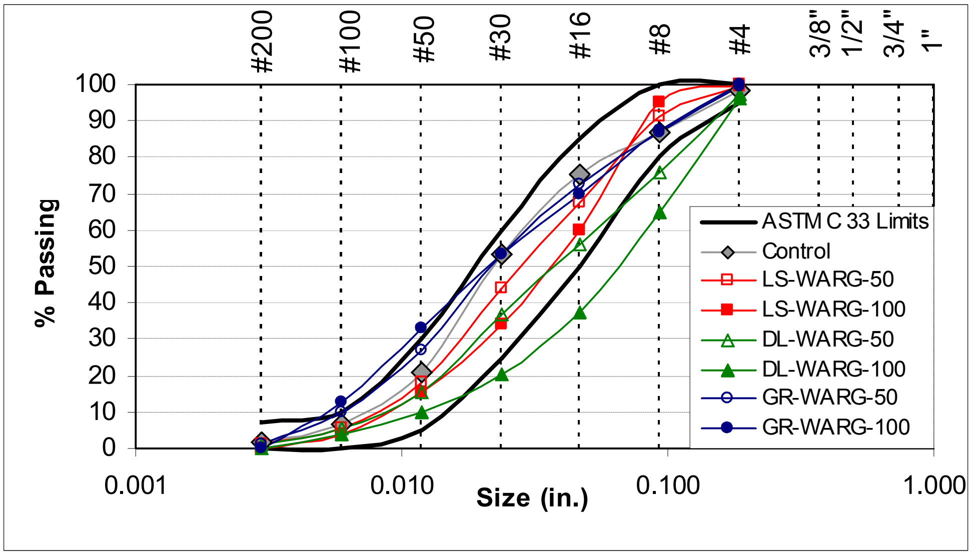

Figure 4.2(a) Percent Passing of Blended Sands with WARG Grading

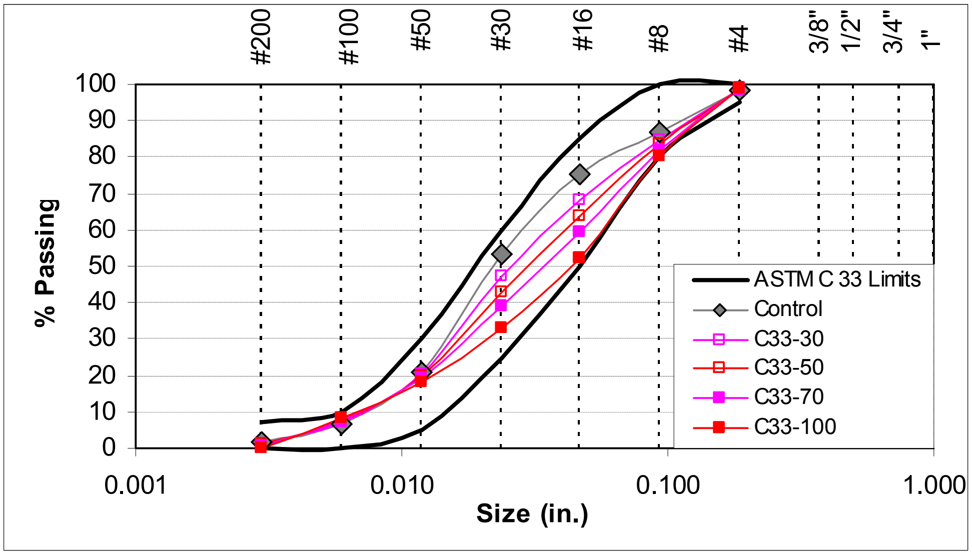

Figure 4.2(b): Percent Passing of Blended Sands with C33 Grading

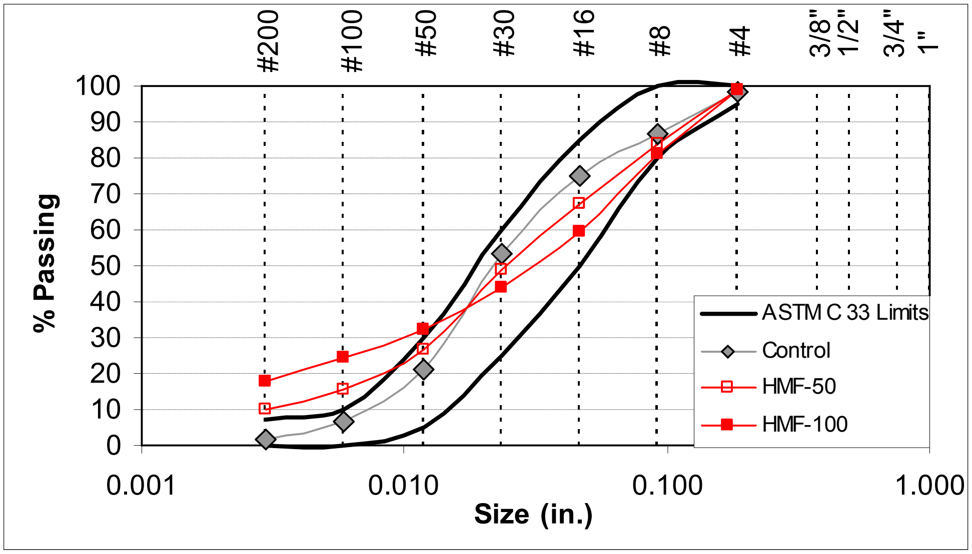

Figure 4.2(c): Percent Passing of Blended Sands with HMF Grading

The ASTM C33 limits are provided in each graph for comparison. The sand blends containing DL with WARG grading did not fall within the allowable grading band stipulated by ASTM C 33. DL was coarse sand; the fineness modulus was 3.1, just within the limits given in ASTM C 33. The sand blends containing GR with WARG grading also fell slightly outside of the ASTM C 33 limits. GR, however, was graded more finely than DL. It had a fineness modulus of 2.1, less than the value of 2.3 stipulated by ASTM C 33.

All of the blends containing manufactured sand with C33 grading fell in the acceptable grading band. The individual manufactured sands were within the grading band, and the as-received grading of NS was also within the ASTM C 33 grading limits. The gradings of the sand blends with C33 grading were the same for all three sand types.

The blends with HMF grading did not fit the grading limits given by ASTM C 33 as the aggregate size decreased. This particular grading was composed of 18% by weight of particles smaller than the No. 200 sieve. The sand blend composed of only 50% manufactured sand with HMF grading had a smaller deviation from ASTM C 33 limits than the sand blend composed of 100% manufactured sand with HMF grading. The gradings of the sand blends containing manufactured sand with HMF grading were the same for all three sand types.

Section 4.2.3: Combined Coarse, Intermediate, and Fine Aggregate Gradings

The aggregate in each test concrete mixture consisted of 45% coarse aggregate (CA), 15% intermediate aggregate (IA), and 40% fine aggregate. The coarse aggregate, intermediate aggregate and blended fine aggregate combinations are shown on the 0.45 Power Chart, Coarseness Chart, and "18-8" Percentage-Retained Size-Distribution Chart for comparison in Figs. 4.3 through 4.5. For simplicity, only LS is shown on the graphs of C33 and HMF grading, but the aggregate combinations shown are the same for all three sand types. The percent passing values of the combined sand blends are available in Appendix B.

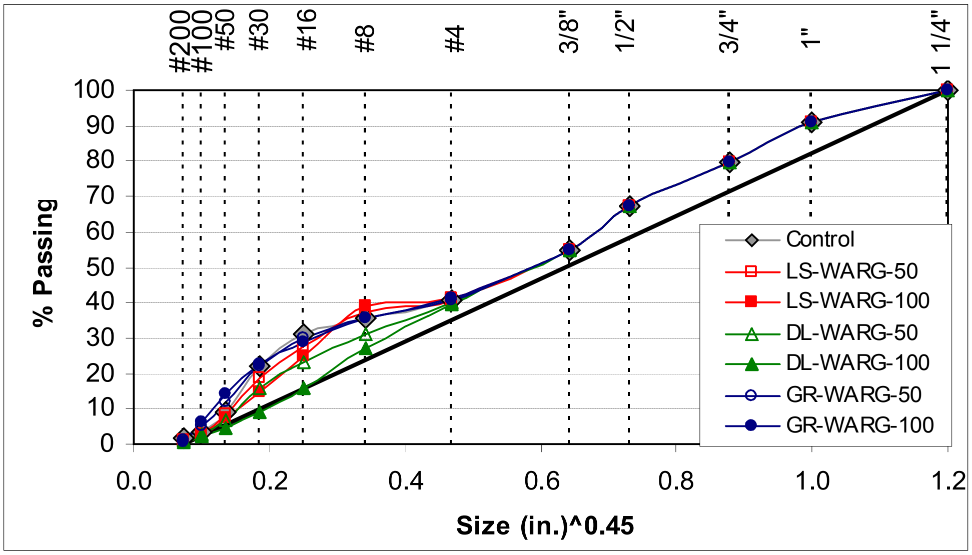

Figure 4.3(a): 0.45 Power Chart of WARG Grading

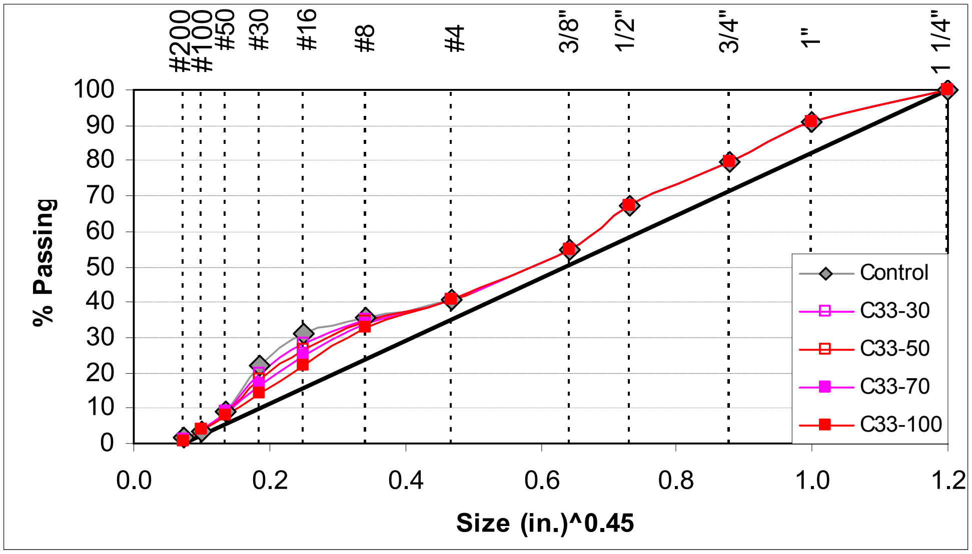

Figure 4.3(b): 0.45 Power Chart of C33 Grading

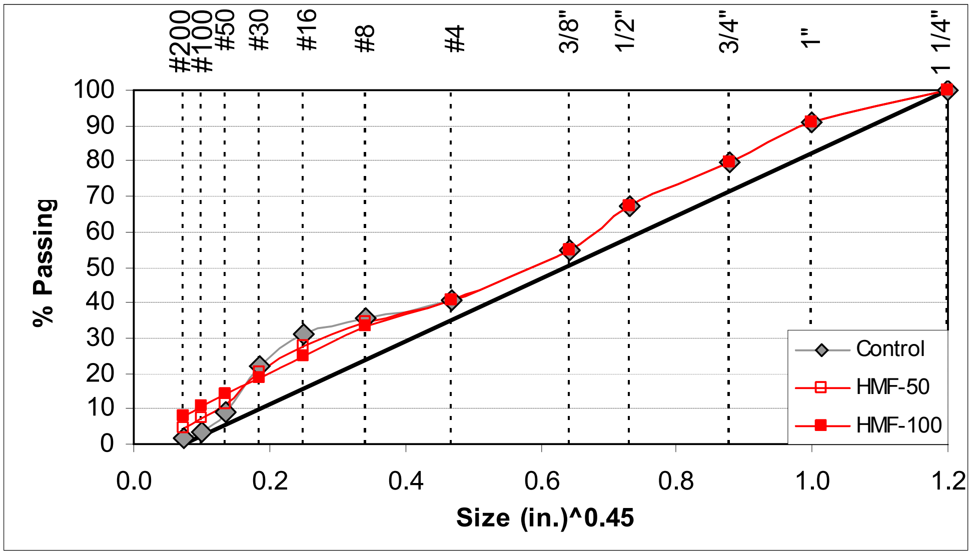

Figure 4.3(c): 0.45 Power Chart of HMF Grading

Each combined aggregate grading fell above the 0.45 line, including the combination with 100% NS. No grading met the curve exactly, including the combination with 100% NS and the combinations with C33 grading. The combination with 100% DL with WARG grading was closest to the 0.45 line.

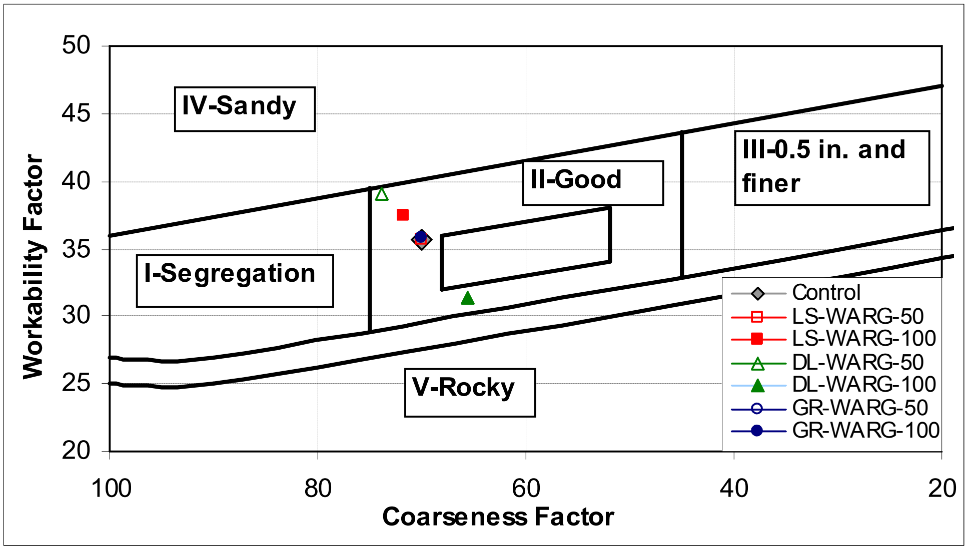

Figure 4.4(a): Coarseness Chart of WARG Grading

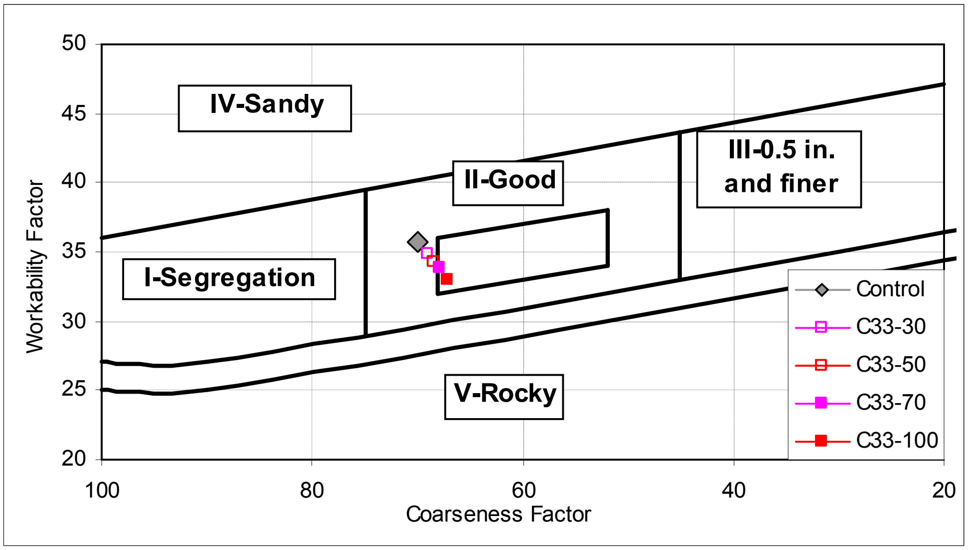

Figure 4.4(b): Coarseness Chart of C33 Grading

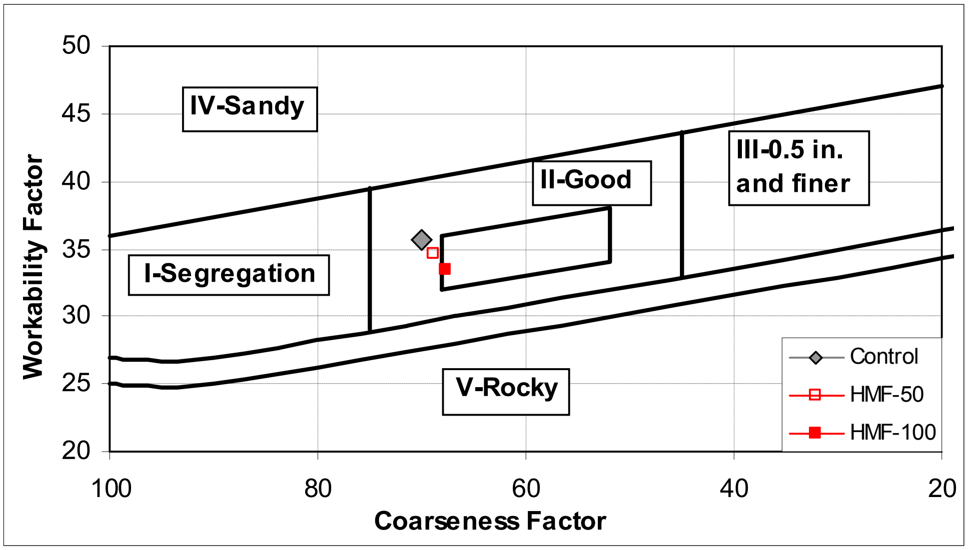

Figure 4.4(c): Coarseness Chart of HMF Grading

All of the sand blends fell within the “good” portion of the coarseness chart. The aggregate blend containing 50% DL with WARG grading was close to the “sandy” portion of the coarseness chart but still fell within the zone of “good” grading. The mixture containing 100% DL with WARG grading was near the “rocky” portion of the coarseness chart, but it remained in the “good” section. All of the combined aggregate gradings were deemed appropriate by this proportioning method.

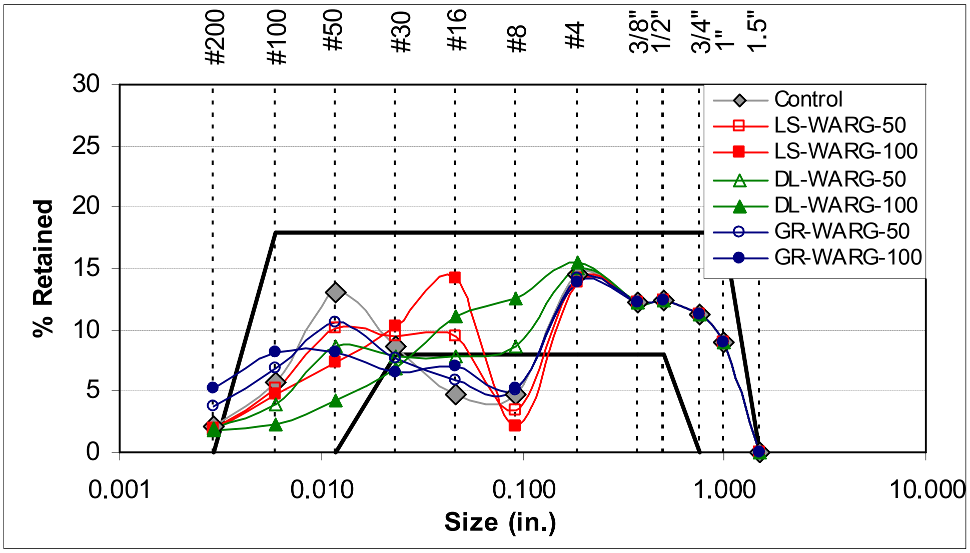

Figure 4.5(a): "18-8" Chart of WARG Grading

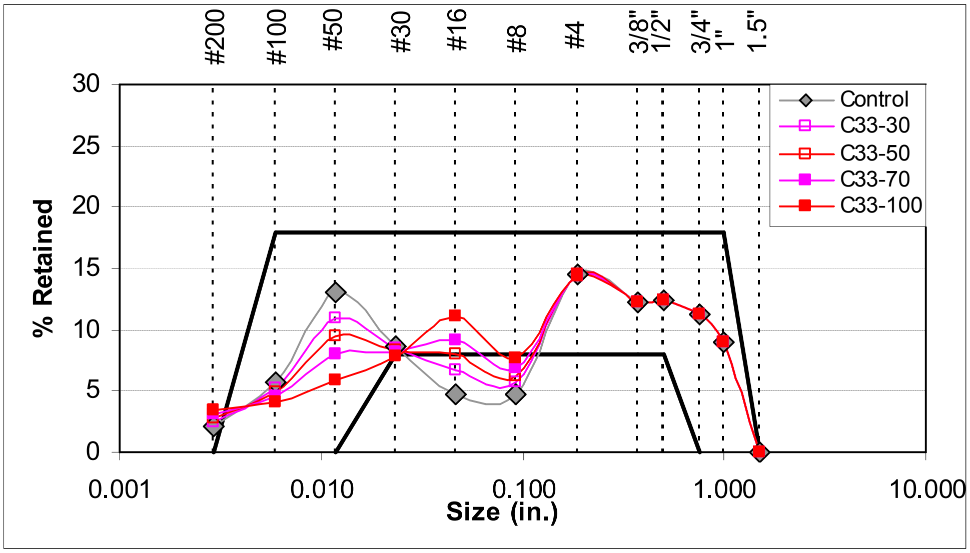

Figure 4.5(b): "18-8" Chart of C33 Grading

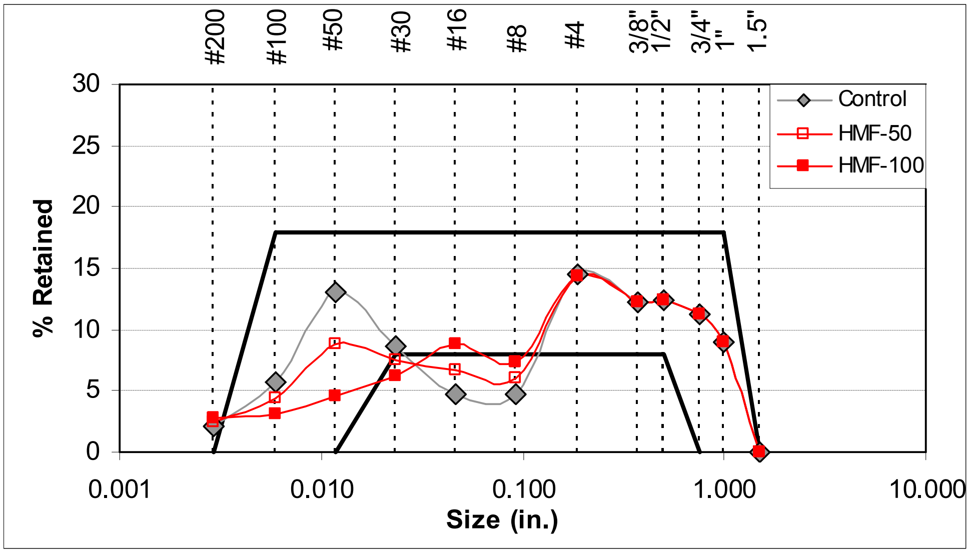

Figure 4.5(c): “18-8” Chart of HMF Grading

None of combined aggregate gradings fell within the limits of the “18-8” proportioning guidelines. All of the sand blends had too little material on the No. 16 and No. 8 sieves to meet the “18-8” limits. The uniform distribution of aggregate recommended by this method would not be suitable for the blends with HMF grading.

SECTION 4.3: MIXTURE PROPORTIONING

Section 4.3.1: Control Mixture

For comparison, the concrete mixtures were based on a single, universal mixture called the control mixture. The control mixture was expected to achieve the target workability for paving concrete (a slump of 2 in.), accommodate a wide range of aggregate (well-shaped natural sand to poorly-shaped manufactured sand), and reach the appropriate compressive strength for pavement concrete. The control mixture was established through several trial mixtures.

The paste contents for the trial mixtures were based on the void contents of the combinations of coarse, intermediate, and blended fine aggregate. The void contents of the aggregate combinations were determined in accordance with ASTM C 29 “Standard

Test Method for Bulk Density ("Unit Weight") and Voids in Aggregate" and are shown in Fig. 4.6. Each mixture needed enough paste to fill the voids between the aggregate and to provide adequate lubrication of the aggregate particles. None of the void contents exceeded 30%, even for the worst-shaped aggregate. The aggregate combination containing 100% DL with WARG grading had the greatest void content. As expected, the mixture containing 100% NS had the lowest void content. The bulk density and void contents of the sand blends are available in Appendix B.

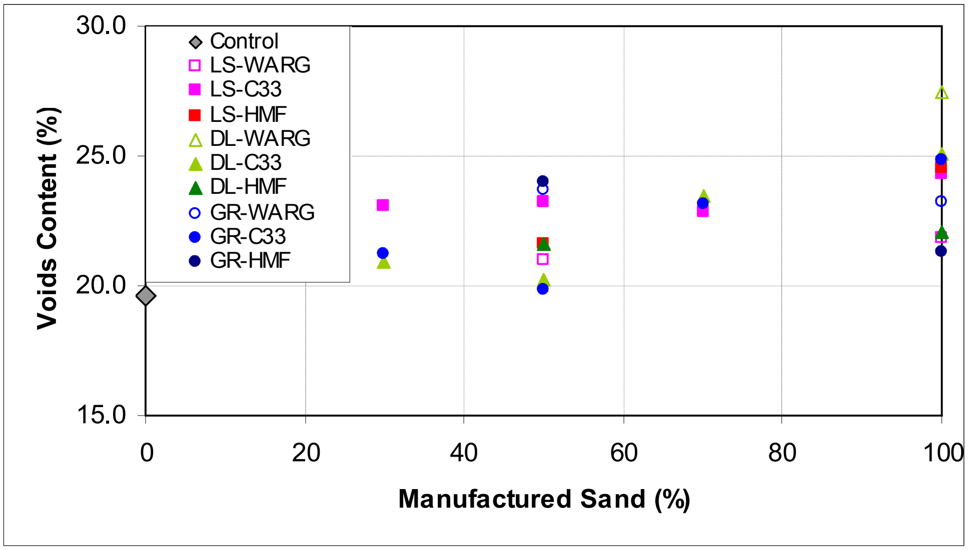

Figure 4.6: Void Contents of Coarse, Intermediate, and Blended Fine Aggregate Combinations

Four trial mixtures were tested in order to establish a suitable control mixture. Water-reducing admixture was added to the trial mixtures as needed to increase workability without increasing water content. The mixture proportions of the trial mixtures are listed in Table 4.1.

The first two trial mixtures both contained 100% GR in its as-received condition. The first trial mixture was dry and much too lean. The coarse aggregate only had a thin coating of paste surrounding it. The second mixture was slightly more robust than the initial mixture, but the mixture was still too lean. The third and fourth trial mixtures, composed of 100% NS and 100% GR, were designed with higher paste contents. The mixture containing 100% NS required less water than calculated to reach a 2-in. slump. The fourth mixture was robust and achieved the necessary slump, so a paste content of 30% was selected for the experimental program.

Table 4.1: Trial Mixture Proportions

Trial Mixture Number	**w/c**	**Paste (%)**	**Cement (lbs/yd^3)**	**CA (lbs/yd^3)**	**IA (lbs/yd^3)**	**FA (lbs/yd^3)**	**Water (lbs/yd^3)**
1	0.45	25	504.9	1467.0	492.8	1359.6	227.2
2	0.45	27	548.8	1427.9	479.7	1323.4	247.0
3	0.45	30	614.7	1369.2	460.0	1226.5	276.6
4	0.45	30	614.7	1369.2	460.0	1269.0	276.6

Based on these trial mixtures, the control mixture had *w/c* of 0.45. It contained only cement (no SCMs), and 100% NS. It had 30% paste volume, and it contained 614.7 lbs/yd^3 of cement. The air content was assumed to be 2% for every mixture. The aggregate consisted of 45% by volume coarse aggregate (1369.2 lbs/yd^3), 15% by volume intermediate aggregate (460.0 lbs/yd^3), and 40% by volume fine aggregate (approximately 1250 lbs/yd^3) for every mixture.

Section 4.3.2: Mixtures for the "Sand Blends Study"

The control mixture served as the basis for comparison of the test mixtures in both parts of the experimental program. The first part of experimental program, the "Sand Blends Study," was devoted to examining the how fresh and hardened concrete properties varied when sand type, grading, and blend ratio were changed. All other parameters (paste content, *w/c*, amount of coarse and intermediate aggregate, etc.) were held constant throughout the study. The fine aggregate in the mixtures was composed of the sand blends previously described. Including the control mixture, twenty-five mixtures were tested in this study. The mixture proportions, based on those of the control mixture described above, are listed in Table 4.2. The mixture names are abbreviated by the type of aggregate (LS, DL, or GR), followed by the grading (WARG, C33, or HMF), and then by the percentage of manufactured sand included in the mixture.

Table 4.2: “Sand Blends Study” Mixture Proportions

Mixture Name	**Cement** (lb/yd^3)	**MF** (lb/yd^3)	**CA** (lb/yd^3)	**IA** (lb/yd^3)	**NS** (lb/yd^3)	**MFA** (lb/yd^3)	**Water** (lb/yd^3)
CONTROL	614.7	0.0	1369.2	460.0	1226.5	0.0	276.6
LS-WARG-50	614.7	0.0	1369.2	460.0	613.3	615.6	276.6
LS-WARG-100	614.7	0.0	1369.2	460.0	0.0	1231.2	276.6
LS-C33-30	614.7	0.0	1369.2	460.0	858.6	369.3	276.6
LS-C33-50	614.7	0.0	1369.2	460.0	613.3	615.6	276.6
LS-C33-70	614.7	0.0	1369.2	460.0	368.0	861.8	276.6
LS-C33-100	614.7	0.0	1369.2	460.0	0.0	1231.2	276.6
LS-HMF-50	614.7	110.8	1369.2	460.0	613.3	504.8	276.6
LS-HMF-100	614.7	221.6	1369.2	460.0	0.0	1009.6	276.6
DL-WARG-50	614.7	0.0	1369.2	460.0	613.3	643.9	276.6
DL-WARG-100	614.7	0.0	1369.2	460.0	0.0	1287.9	276.6
DL-C33-30	614.7	0.0	1369.2	460.0	858.6	386.4	276.6
DL-C33-50	614.7	0.0	1369.2	460.0	613.3	643.9	276.6
DL-C33-70	614.7	0.0	1369.2	460.0	368.0	901.5	276.6
DL-C33-100	614.7	0.0	1369.2	460.0	0.0	1287.9	276.6
DL-HMF-50	614.7	115.9	1369.2	460.0	613.3	528.0	276.6
DL-HMF-100	614.7	231.8	1369.2	460.0	0.0	1056.0	276.6
GR-WARG-50	614.7	0.0	1369.2	460.0	613.3	634.5	276.6
GR-WARG-100	614.7	0.0	1369.2	460.0	0.0	1269.0	276.6
GR-C33-30	614.7	0.0	1369.2	460.0	858.6	380.7	276.6
GR-C33-50	614.7	0.0	1369.2	460.0	613.3	634.5	276.6
GR-C33-70	614.7	0.0	1369.2	460.0	368.0	888.3	276.6
GR-C33-100	614.7	0.0	1369.2	460.0	0.0	1269.0	276.6
GR-HMF-50	614.7	114.2	1369.2	460.0	613.3	520.3	276.6
GR-HMF-100	614.7	228.4	1369.2	460.0	0.0	1040.6	276.6

Section 4.3.3: Mixtures for the “Optimization Study”

The mixtures tested in the “Sand Blends Study” were based on a single mixture designed to accommodate every sand blend. However, the ideal mixture for a particular sand blend may not match the mixture proportions of the universal mixture design. The latter portion of the research project was devoted to the optimization of concrete mixtures. The goal of optimization was to make the system as effective as possible [Quiroga and Fowler, 2004B]. The mixtures tested in the “Optimization Study” were redesigned by holding the paste content constant and considering the microfines as powder instead of aggregate, substituting cement for microfines, substituting fly ash for cement, and lowering the *w/cm*.

The simplest optimization mixtures involved the substitution of fly ash for cement and the decrease of the *w/cm*. Of the mixtures tested in the "Sand Blends Study," the mixture containing LS-C33-30 demonstrated the best workability from the mixtures containing manufactured sand. It was theorized that if the cement was replaced with fly ash, the *w/cm* could be decreased to improve hardened concrete properties without harming the workability. LS-C33-30 was redesigned with 25% of the cement by volume replaced with Class F fly ash. This mixture is denoted by "25%FA" at the end of the mixture name. LS-C33-30-25%FA was then redesigned with a lower *w/cm* and this mixture is denoted by "0.40W/CM" at the end of the mixture name (LS-C33-30-25%FA-0.40W/CM). The *w/cm* decreased from 0.48 to 0.43, slightly below the target values of 0.45 and 0.40 because the cement was replaced by fly ash by volume instead of mass. The fly ash had a lower specific gravity than portland cement. The mixture proportions for LS-C33-30-25%FA and LS-C33-30-25%FA-0.40W/CM are listed in Table 4.3.

The second portion of the "Optimization Study" involved counting microfines as powder instead of aggregate. When using microfines in concrete mixtures, the microfines may be considered to be part of the aggregate or part of the powder [Koehler and Fowler, 2007]. Powder is composed of cement, supplementary cementing materials, and microfines or mineral filler. If the microfines are considered to be part of the aggregate (e.g. the microfines replace a portion of the sand volume), the water demand is generally increased because the amount of powder is increased [Koehler and Fowler, 2007]. If the microfines are considered to be powder (e.g. the microfines replace a portion of the cement or SCM volume), the amount of water required to reach certain workability may be reduced depending on the properties of the microfines [Koehler and Fowler, 2007]. Keeping the *w/c* the same as additional microfines are incorporated into the concrete mixture may result in greater compressive strengths because packing density is increased [Koehler and Fowler, 2007].

The mixtures containing 50% MFA with HMF grading were redesigned with the microfines considered to be powder instead of aggregate and are denoted by the letter "P" included at the end of the mixture name. The amount of coarse and intermediate aggregate remained the same, but the total amounts of fine aggregate included in the mixtures increased. The amount of microfines increased proportionally with the amount of fine aggregate so as to keep the same grading of 18% passing the No. 200 sieve. The paste content was held to 30% and the *w/c* was kept at 0.45, so the amount of water and cement decreased.

In the "Sand Blends Study," the microfines were all considered to be part of the aggregate. If the microfines had been considered to be powder, the paste volume of LS-HMF-50, DL-HMF-50, and GR-HMF-50 would have actually been 32.5% instead of 30%, and the paste volume of LS-HMF-100, DL-HMF-100, and GR-HMF-50 would have actually been 35% instead of 30%. The decrease in paste content from 32.5% to 30% was expected to decrease the workability of the mixtures. The compressive strength could decrease from the mixtures in the "Sand Blends Study" because there was less cement included in the mixtures. The compressive strength could also increase because additional microfines were incorporated into the mixtures that resulted in increased packing density and filling of capillary voids.

Two optimized mixtures were selected for additional modifications. The first mixture, DL-HMF-50-P, was redesigned with 25% of the cement by volume replaced with Class F fly ash. This mixture has "25%FA" at the end of the mixture name to designate the inclusion of 25% fly ash. The addition of fly ash was expected to improved workability, and the workability of this mixture was controlled by water-reducing admixture instead of high-range water-reducing admixture.

The second mixture modified was LS-HMF-100 from the "Sand Blends Study." It was redesigned with all of the microfines replaced by an equal volume of cement. This mixture is denoted by the word "CEMENT" at the end of the mixture abbreviation. The paste content was kept at 35% for this mixture. The goal of LS-HMF-100-CEMENT was to demonstrate that if a large amount of poorly-shaped powder is included in a concrete mixture, regardless if it is composed of cement or microfines, the workability will be reduced. All of the mixture proportions for the mixtures tested in the "Optimization Study" are presented in Table 4.3.

SECTION 4.4: CONCRETE MIXING PROCEDURE

Concrete mixtures ranged in size from 2.7 ft^3 to 3.7 ft^3 and were mixed in a 9-ft^3 drum mixer. The aggregate was added first and mixed for a short period of time before adding the cementing materials. The cementing materials were then added and mixed again until the dry mixture appeared uniform. The mixing water was then added while the mixer was rotating. The concrete was mixed for a period of 3 min., left to rest for 3 min., and then mixed again for 2 min. The mixture was visually examined, and, if necessary, high-range water-reducing admixture was added toward the end of the rest period. A slump test was made after the last 2-min. mixing period. If the ideal slump had not been met, additional high-range water-reducing admixture was added to the concrete, and the concrete was mixed again for a short period of time. Another slump test was made, and the procedure was repeated until the target slump was achieved.

Table 4.3: "Optimization Study" Mixture Proportions

Mixture Name	**w/cm**	**Cement** (lb/yd^3)	**FA** (lb/yd^3)	**MF** (lb/yd^3)	**CA** (lb/yd^3)	**IA** (lb/yd^3)	**NS** (lb/yd^3)	**MFA** (lb/yd^3)	**Water** (lb/yd^3)
LS-C33-30-25%FA	0.48	461.0	114.2	0.0	1369.2	460.0	858.6	368.4	276.6
LS-C33-30-25%FA-0.40W/CM	0.43	493.1	122.1	0.0	1369.2	460.0	858.6	370.8	263.0
LS-HMF-50-P	0.45	547.2	0.0	135.1	1369.2	460.0	613.3	614.8	246.3
LS-HMF-100-P	0.45	614.7	0.0	221.6	1369.2	460.0	0.0	1009.6	276.6
LS-HMF-100- CEMENT	0.31	882.2	0.0	0.0	1369.2	460.0	0.0	1009.6	276.6
DL-HMF-50-P	0.45	547.2	0.0	141.4	1369.2	460.0	613.3	643.1	246.2
DL-HMF-100-P	0.45	614.7	0.0	231.8	1369.2	460.0	0.0	1056.0	276.6
DL-HMF-50-P-25%FA	0.48	410.4	101.6	141.4	1369.2	460.0	613.3	643.1	246.2
DL-HMF-100-P-25%FA	0.48	461.0	114.2	231.8	1369.2	460.0	0.0	1056.0	276.6
GR-HMF-50-P	0.45	547.2	0.0	139.3	1369.2	460.0	613.3	633.7	246.2
GR-HMF-100-P	0.45	614.7	0.0	228.4	1369.2	460.0	0.0	1040.5	276.6

SECTION 4.5: FRESH CONCRETE TESTING PROCEDURE

Section 4.5.1: Workability

To achieve a slip-form paving mixture, the target slump of all concrete mixtures was 2 in, and acceptable slumps were between 1 and 3 in. The slump was achieved by adding high-range water-reducing admixture to the concrete mixture and performing a slump test. The slump tests were performed in accordance with ASTM C 143/C 143M "Standard Test Method for Slump of Hydraulic-Cement Concrete."

The slump test, however, is not useful for extremely stiff or extremely fluid concretes. The test is valid mainly for concrete with "medium plastic" to "highly plastic" consistency [Popovics, 1994]. It is unable to differentiate between mixtures with low slumps, such as paving concretes [Quiroga and Fowler, 2004B]. It can also be argued that two mixtures with the same slump may have completely different properties. For example, one mixture may lose all cohesiveness upon vibration [Quiroga and Fowler, 2004B]. Other means must be established for comparing the workability of low-slump mixtures. Tests that have been proposed to replace or supplement the slump test all have one defining characteristic: the concrete must be in a dynamic state while it is tested [Quiroga and Fowler, 2004B]. Tattersall (1973) suggested that workability tests should focus on flowability, compactability, stability, finishability, pumpability, and extrudability.

The flow table test was used to assess the workability of concrete in addition to the traditional slump test [Quiroga and Fowler, 2004]. The test was conducted in accordance with ASTM C 109/C 109M "Standard Test Method for Compressive Strength of Hydraulic Cement Mortars" and ASTM C 230/C 230M "Standard Specification for Flow Table for Use in Tests of Hydraulic Cement." A slump cone was placed on a vibrating table and filled in three layers. The cone was removed, and the sample was vibrated for 5 seconds. The diameter of the resulting circle was measured in two directions and averaged.

The water-reducing admixture demand can also be an indicator of workability. High HRWRA demand indicates a stiffer mixture, and low HRWRA demand indicates a more fluid mixture.

Section 4.5.2: Air Content

The air content of the mixtures was recorded for every concrete mixture. It was measured with two methods, ASTM C 231 “Standard Test Method for Air Content of Freshly Mixed Concrete by the Pressure Method” and ASTM C 138/C 138M “Standard Test Method for Density (Unit Weight), Yield, and Air Content (Gravimetric) of Concrete.”

Section 4.5.3: Time of Set

The set times of several concrete mixtures were taken in accordance with ASTM C 403/C 403M “Standard Test Method for Time of Setting of Concrete Mixtures by Penetration Resistance.” The set times were measured for the control mixture and all of the mixtures in the “Optimization Study” except for LS-C33-30-25%FA-0.40W/CM.

SECTION 4.6: HARDENED CONCRETE TESTING PROCEDURE

Section 4.6.1: Compressive Strength

The compressive strength of every mixture was measured according to ASTM C 39 “Standard Test Method for Compressive Strength of Cylindrical Specimens.” Cylinders with a 6-in. diameter and a length of 12 in. were tested in a Forney compression machine at a rate of approximately 60,000 lb/min. The specimens were tested after moist-curing for 28 days in accordance with ASTM C 192/C 192M

"Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory." The target compressive strength was 4,400 psi or greater at 28 days [TX DOT, 2004].

Section 4.6.2: Flexural Strength

The flexural strength of every mixture was measured according to ASTM C 78 "Standard Test Method for Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading)." Beams with a 6-in. x 6-in. cross-section with a span of 18 in. were tested in a Tinius Olsen screw-type compression machine at a load rate of approximately 0.01 in./min. The specimens were tested after moist-curing for 28 days in accordance with ASTM C 192/C 192M "Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory." The target flexural strength was 680 psi at 28-days [TX DOT, 2004].

Section 4.6.3: Modulus of Elasticity

The modulus of elasticity of every mixture was measured according to ASTM C 469 "Standard Test Method for Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression." Cylinders with a 6-in. diameter and a length of 12 in. tested in a Forney compression machine at a rate of approximately 60,000 lb/min. The specimens were tested after moist-curing for 28 days in accordance with ASTM C 192/C 192M "Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory."

Section 4.6.4: Length Change

The changes in length of the control mixture, the mixtures containing 50% and 100% manufactured sand with C33 grading, and all of the mixtures from the "Optimization Study" were measured in accordance with ASTM C 157 "Standard Test Method for Length Change of Hardened Hydraulic-Cement Mortar and Concrete." The specimens were demolded after 24 hours and placed in a saturated solution of limewater for approximately 30 min. The initial shrinkage reading was taken after the beams had soaked in the limewater for at least 30 min. The specimens remained in the limewater for 7 days after mixing and were then placed in a drying shrinkage room with an average temperature of 73°F and 50% relative humidity for a period of 56 days. Length measurements were taken at 1, 7, 28, and 56 days.

Section 4.6.5: Abrasion

ASTM C 944 "Standard Test Method for Abrasion Resistance of Concrete or Mortar Surfaces by the Rotating-Cutter Method" was performed on the mixtures with 50% and 100% MFA with HMF grading and all of the mixtures in the "Optimization Study." The specimens were obtained from previously-tested flexural beams, and the sample sizes ranged from 6 to 8 in. in length. The beams were cut in half length-wise to decrease the weight of the specimens, making the specimens approximately 3-in. thick. The samples were subjected to a double-load of 44 lbs and three testing periods of 2 min. One test was performed on the finished surface of the concrete, and the other two tests were performed on the formed sides of the concrete. The specimens were moist-cured for 84 days in accordance with ASTM C 192/C 192M "Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory." They were then removed from the fog room and placed in an oven for one week. The specimens were approximately 91 days old at the time of testing.

Section 4.6.6: Density, Absorption, and Voids

The density, absorption, and voids of the control mixture and all of the mixtures in the "Optimization Study" except LS-C33-30-25%FA-0.40W/CM were determined in accordance with ASTM C 642 "Standard Test Method for Density, Absorption, and

Voids in Hardened Concrete." The specimens were approximately 1-1/2 in. thick disks cut from 6-in. diameter cylinders. Two disks were tested for each mixture, and the results were averaged. The specimens were tested after moist-curing for 28 days in accordance with ASTM C 192/C 192M "Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory."

Section 4.6.7: Coefficient of Thermal Expansion

The coefficients of thermal expansion (CTE) of the control mixture and all of the mixtures in the "Optimization Study" except LS-C33-30-25%FA-0.40W/CM were determined in accordance with AASHTO TP 60 "Coefficient of Thermal Expansion of Hydraulic Cement Concrete." The specimens were formed by casting a 4-in. diameter cylinder and cutting the specimen to a length of 7 in. The specimens were tested after moist-curing for 28 days in accordance with ASTM C 192/C 192M "Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory."

SECTION 4.7: SUMMARY OF EXPERIMENTAL PROCEDURE

The experimental procedure was divided into two distinct programs, the "Sand Blends Study" and the "Optimization Study." The goal of the "Sand Blends Study" was to observe general trends in concrete properties when the aggregate type is changed, the grading is switched, or the amount of MFA included in the mixture is increased or decreased. The purpose of the "Optimization Study" was to determine how concrete properties varied when the paste content was held constant and the microfines were considered to be powder instead of aggregate. Other goals of the "Optimization Study" were to see how a mixture would behave if microfines were replaced by a material with a similar particle size distribution and non-ideal shape, such as cement, and how a mixture would behave if cement was replaced with fly ash.

Chapter 5: "Sand Blends Study" Results

SECTION 5.1: INTRODUCTION

The purpose of the "Sand Blends Study" was to determine how sand type, grading, and blend ratio affect fresh and hardened concrete properties. Limestone (LS), dolomitic limestone (DL), and granite (GR) sands with washed, as-received gradings (WARG), gradings meeting ASTM C 33 limits (C33), or gradings with high microfines (HMF) were combined with natural river sand (NS) in proportions ranging from 30% to 100%. Including the control mixture, 25 concrete mixtures were tested during this phase of the experimental procedure. The mixture proportions of the mixtures tested in the "Sand Blends Study" were presented in Table 4.2.

SECTION 5.2: RESULTS OF FRESH CONCRETE TESTS

Section 5.2.1: Workability

Section 5.2.1.1: Slump

The slumps for the mixtures tested in the "Sand Blends Study" are listed in Table 5.1. The slumps recorded during the research program reached a minimum value of 1.0 in. and a maximum value of 4.5 in. The average slump was 2.6 in., slightly above the selected target value of 2 in. The slump was highly dependent on the amount of high-range water-reducing admixture (HRWRA) added to the mixture.

Lower slumps were associated with mixtures containing poorly-shaped sand with and without microfines. The angularity of the sands decreased the slump, and higher paste contents may be necessary for these mixtures. Without increasing the paste content, the mixtures required higher dosages of high-range water-reducing admixture to produce slumps within the acceptable range of 1 to 3 in.

The maximum slump was achieved by LS-C33-30. This mixture required no addition of high-range water-reducing admixture to reach a slump of 4.5 in., 1.25 in. greater than that of the control mixture containing 100% river sand. LS is well-shaped sand, which helped to improve workability.

Table 5.1: "Sand Blends Study" Slump Results

Mixture	**Slump (in.)**
CONTROL	3.25
LS-WARG-50	3.00
LS-WARG-100	4.00
LS-C33-30	4.50
LS-C33-50	3.00
LS-C33-70	3.50
LS-C33-100	1.50
LS-HMF-50	4.00
LS-HMF-100	1.50
DL-WARG-50	3.50
DL-WARG-100	1.75
DL-C33-30	1.00
DL-C33-50	1.50
DL-C33-70	1.75
DL-C33-100	1.00
DL-HMF-50	1.50
DL-HMF-100	3.00
GR-WARG-50	2.00
GR-WARG-100	2.75
GR-C33-30	2.00
GR-C33-50	1.75
GR-C33-70	4.00
GR-C33-100	3.00
GR-HMF-50	3.00
GR-HMF-100	2.75

Section 5.2.1.2: Flow Table Values

The flow table results for the mixtures in the "Sand Blends Study" are presented in Table 5.2. The minimum flow table value was 12.5 in., and the maximum flow table value was 22.3 in. The average flow table value was 17.4 in. The flow table value recorded for the control mixture was 12.6 in., barely above the minimum flow table value. The greatest flow table value was recorded for DL-WARG-100. This mixture achieved a high flow table value because the mixture segregated during vibration.

Table 5.2: “Sand Blends Study” Flow Table Results

Mixture	Flow Table (in.)
CONTROL	12.6
LS-WARG-50	17.8
LS-WARG-100	21.6
LS-C33-30	14.8
LS-C33-50	17.5
LS-C33-70	17.9
LS-C33-100	16.0
LS-HMF-50	17.5
LS-HMF-100	15.3
DL-WARG-50	21.5
DL-WARG-100	22.3
DL-C33-30	15.4
DL-C33-50	12.5
DL-C33-70	15.3
DL-C33-100	17.4
DL-HMF-50	15.1
DL-HMF-100	18.8
GR-WARG-50	15.0
GR-WARG-100	18.6
GR-C33-30	19.4
GR-C33-50	17.5
GR-C33-70	20.4
GR-C33-100	18.8
GR-HMF-50	16.8
GR-HMF-100	18.6

There was little correlation between slump and flow table test results, as seen in Fig. 5.1. The R^2 value was 0.11, but this low correlation was expected because the slump test is a poor indication of workability for mixtures with high microfines. The slump values ranged from only about 1 to 3 in. while the flow table results varied widely. Mixtures with lower slump values produced large flow table test results and vice versa.

There were no definite trends of flow table results versus slump based on aggregate type or grading. Some mixtures were more cohesive than other mixes, and several mixtures segregated upon being vibrated. Overall, the flow table test gave better relative indications of the cohesiveness and the quality of mixture than the slump test.

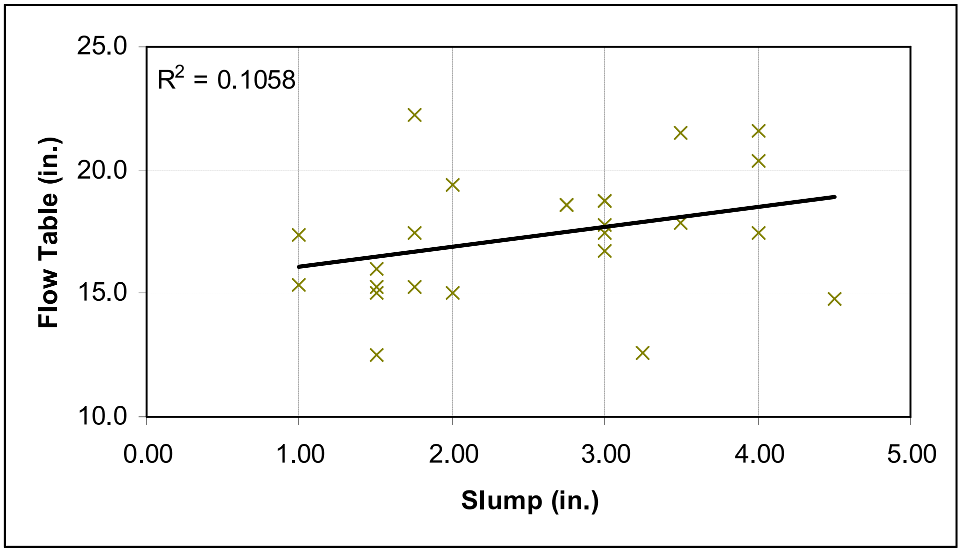

Figure 5.1: Slump versus Flow Table Results of "Sand Blends Study" Mixtures

Section 5.2.1.3: HRWRA Demand

The high-range water-reducing admixture demand to achieve a specified slump, in this case 2 in., can also be used to indicate the workability of a mixture. The HRWRA demands of each grading are presented in Fig. 5.2. The HRWRA demand values are listed in Appendix C. The admixture demand recorded could have been affected by the method of addition to the mixture. In order to identify the correct dosage, HRWRA was added incrementally to each mixture. Unfortunately, this process may have decreased the effectiveness of the HRWRA. Mixtures with high dosages may have stayed in the mixer for a longer period of time. If larger dosages of admixture had been included in the mixture earlier, the total amount of admixture required to reach the target slump value may have been reduced. However, the trend would remain that HRWRA demand increases with an increasing percentage of manufactured sand.

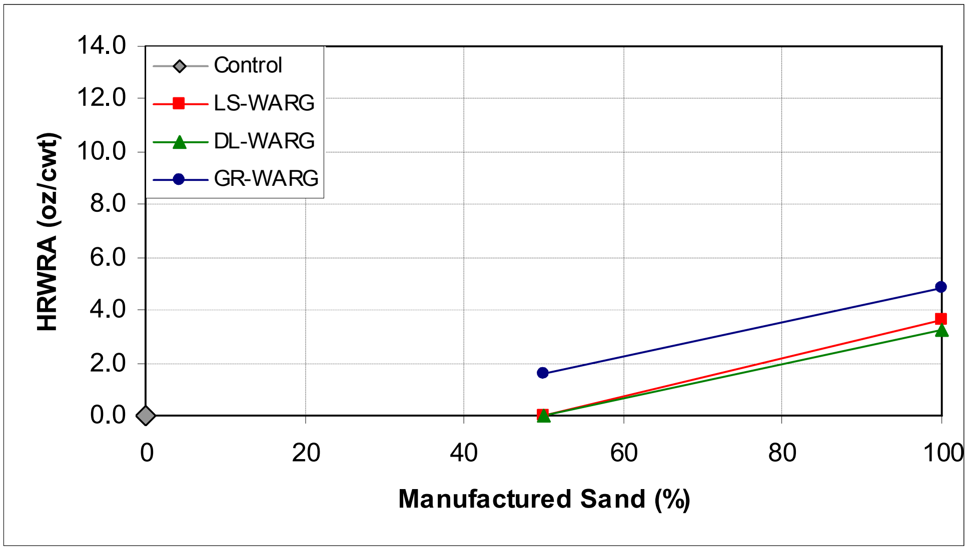

Figure 5.2(a): HRWRA Demand of WARG Mixtures

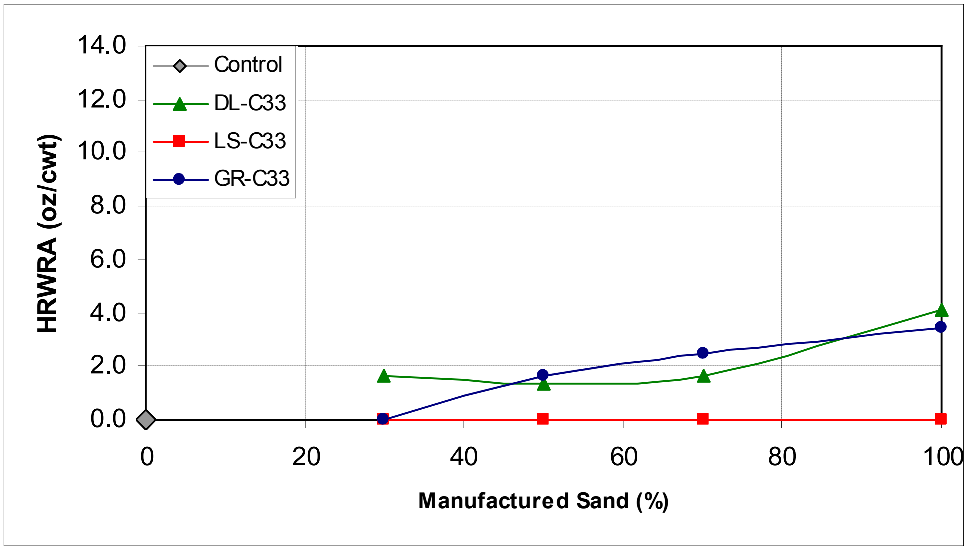

Figure 5.2(b): HRWRA Demand of C33 Mixtures

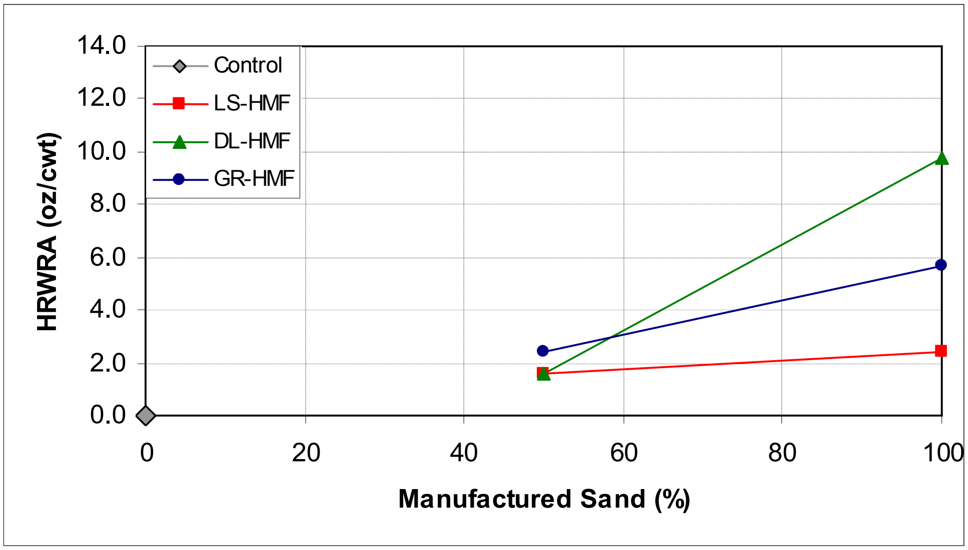

Figure 5.2(c): HRWRA Demand of HMF Mixtures

The control mixture did not require any addition of admixture to reach a 3.25-in. slump. Of the mixtures containing 50% MFA with WARG grading; only the concrete with GR required any addition of HRWRA to meet the required slump value. GR was the worst-shaped aggregate, and it was expected to require additional admixture to achieve the desired workability. All of the mixtures containing 100% MFA with WARG grading required some addition of HRWRA to reach an acceptable slump value.

None of the mixtures containing any percentage of LS with C33 grading required HRWRA to reach a 2-in. slump. This aggregate was well-shaped and behaved similarly to river sand. All of the concretes containing some proportion of DL with C33 grading required addition of admixture. Surprisingly, GR-C33-30 did not need any admixture to reach a 2-in. slump. GR was more poorly-shaped than DL and was expected to have required more admixtures to reach a similar workability.

The greatest difference in HRWRA dosage was observed for the mixtures containing 100% MFA with HMF grading. DL-HMF-100 surprisingly required about 4 oz/cwt more HRWRA than GR-HMF-100. All of the mixtures with HMF grading required some addition of HRWRA to meet the acceptable slump range. These mixtures contained very high percentages of microfines, which can decrease workability if they are poorly-shaped.

The mixtures with MFA with HMF grading required more admixture than the mixtures with MFA with C33 grading or WARG grading. The increase in HRWRA demand is due to the high percentage of microfines included in the sands. It is less obvious if the C33 grading or WARG grading is better for workability. Neither grading contained microfines, but the C33 grading was specifically selected so as to fit within the grading envelope provided by ASTM C 33. Only LS with WARG grading fit within the ASTM C 33 limits, but LS-WARG-100 required HRWRA while LS-C33-100 did not. DL and GR with WARG were slightly outside the envelope. DL-WARG-100 required less HRWRA than DL-C33-100, and GR-WARG-100 required more HRWRA than GR-C33-100. There is no decisive relationship between workability and WARG or C33 grading.

LS-HMF-100, even with the high percentage of microfines, required less HRWRA than all of the mixtures containing 100% MFA with WARG grading. This result is surprising since the WARG grading contained no microfines, and the HMF grading had 18% microfines by weight. This would indicate that the limestone microfines were well-shaped with a desirable particle-size distribution. However, the slump for LS-HMF-100 was 1.5 in. while the slump of LS-WARG-100 was 4.00 in. If less HRWRA had been included in LS-WARG-100, the slump would have likely been reduced to a similar value.

Regardless of sand type or grading, the HRWRA demand increased with increasing proportions of manufactured sand. There are a few exceptions to this trend as evidenced in Fig. 5.2, but it appears that higher percentages of manufactured sand do require higher dosages of high-range water-reducing admixture to obtain the same slump. The mixtures containing LS consistently required less HRWRA for workability than the mixtures containing GR or DL sand. LS was better-shaped than the DL and GR and behaved more like a natural sand.

The workability was influenced by the type of and thus the shape of the fine aggregate. As mentioned in Section 2.1.3, ASTM C 1252 can be used to indirectly measure the shape of aggregate, but the test may not be suitable for manufactured sands. The effect of uncompacted void content on workability (as indicated by HRWRA) demand is presented in Fig. 5.3. The control mixture is also shown, and the rest of the mixtures contain 100% manufactured aggregate.

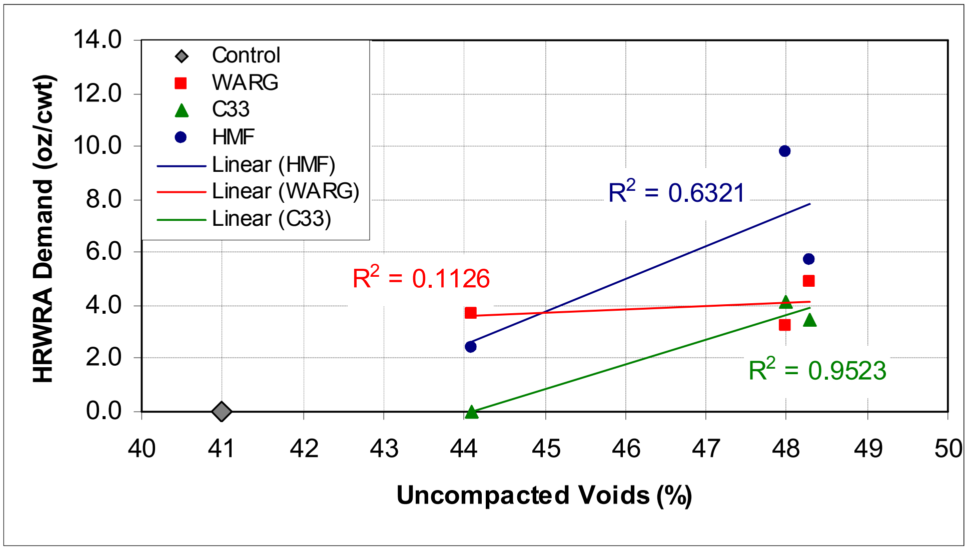

Figure 5.3: The Effect of Uncompacted Void Content on HRWRA Demand

The correlation between uncompacted void content and workability is very high for the C33 grading. Based on these data points, workability is better when the uncompacted void volume is lower. This is a logical deduction; a higher uncompacted void volume generally means that the aggregate is angular and poorly-shaped. However, the correlations between uncompacted void content and HRWRA for WARG and HMF grading were much lower. These results emphasize that the test is not suitable for manufactured sands. WARG and HMF represent gradings that are often encountered in the aggregate industry while C33 represents the grading that is currently accepted by ASTM standards. C33 is an ideal grading that was developed for natural sands, and another test may need to be developed to determine uncompacted void content of manufactured sands. There are only three data points for each series, so the results must be viewed with some caution.

There was very low correlation between HRWRA demand and flow table. This result was not surprising because HRWRA dosage incorporated into each mixture was based on slump measurement. However, slump is a poor test for workability for stiff mixtures with high microfines. Had the HRWRA dosage been based on a target flow table result instead of a slump test result, the correlation between HRWRA demand and flow table would likely be very high.

The shape and particle size distribution of the microfines can also affect the HRWRA demand of concrete. The methylene blue value (MBV), packing density, and span was measured for all of the microfines. The values were previously listed in Table 3.5. The mixtures with the largest amounts of microfines were the HMF mixtures with 100% manufactured sand. The MBV, packing density, and span were plotted against HRWRA demand for these mixtures in Fig. 5.4.

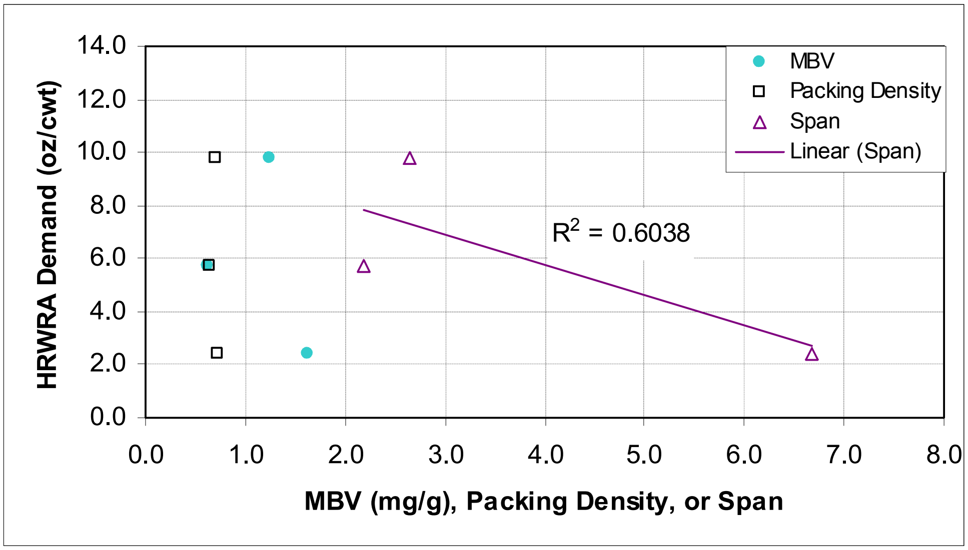

Figure 5.4: The Effects of Microfine Properties on HRWRA Demand

There was not strong correlation between MBV and HRWRA demand or packing density and HRWRA demand, as evidenced in Fig. 5.4. Only the linear regression line for the span versus HRWRA demand is shown on the graph. The MBV values were quite low, indicating that the microfines did not contain clays. The HRWRA demand would have increased if the microfines had contained clays. There is a relatively strong correlation between span and HRWRA demand. Span is related to the size distribution of the microfines. The relationship tentatively observed from the data is that higher spans lead to decreased HRWRA. A larger span may indicate microfines with particle size distribution that will improve workability. Again, here are only three data points, so the results must be viewed with some caution.

Section 5.2.2: Air Content

Air content was another fresh concrete property measured for the mixtures in the Sand Blend Study. Air contents were measured by the pressure meter method and the gravimetric method, but gravimetric air contents were negative for many mixtures and are not presented. Air contents as measured by the pressure meter method were also unavailable for GR-WARG-50, GR-WARG-100, GR-C33-30, GR-C33-70, and GR-HMF-50, GR-HMF-100, LS-WARG-50, and LS-WARG-100. Available air contents are presented in Fig. 5.5. The air contents are also listed in Appendix C. The average air content for all mixtures in the "Sand Blends Study" was 1.8% with a coefficient of variation of 13%. The control mixture had an air content of 1.8%, close to the assumed value of 2%. The maximum air content was 2.4% and the minimum air content was 1.5%. No strong relationships were observed between sand types, grading, or blend ratio and air content.

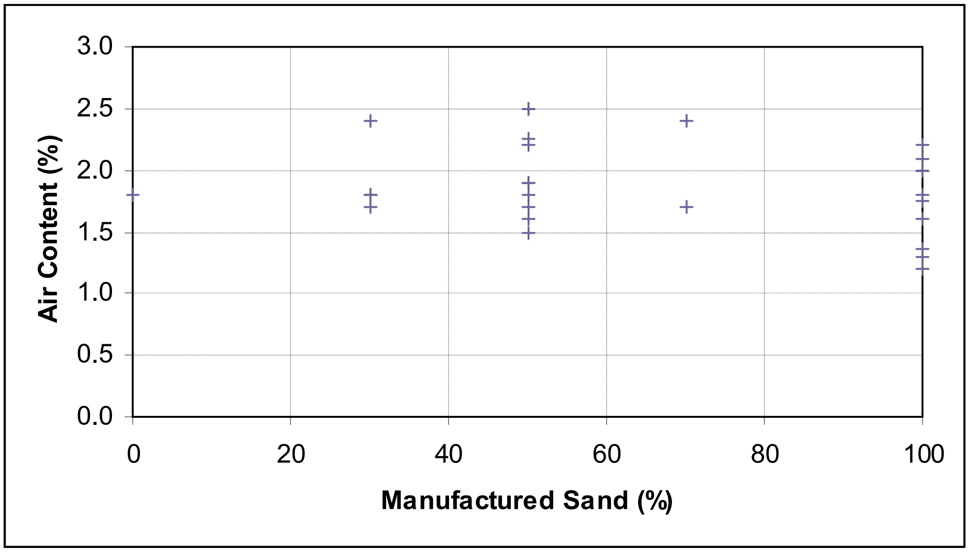

Figure 5.5: Air Contents of "Sand Blends Study" Mixtures

SECTION 5.3: HARDENED CONCRETE PROPERTIES

Section 5.3.1: Compressive Strength

The 28-day compressive strength results of the mixtures completed in the Sand Type, Grading, and Blend Ratio Study are presented in Fig. 5.6. The compressive strengths are also listed in Appendix C. All mixtures achieved a compressive strength greater than the target strength of 4400 psi. The control mixture had an average compressive strength of 7023 psi and is shown in all of the figures for comparison.

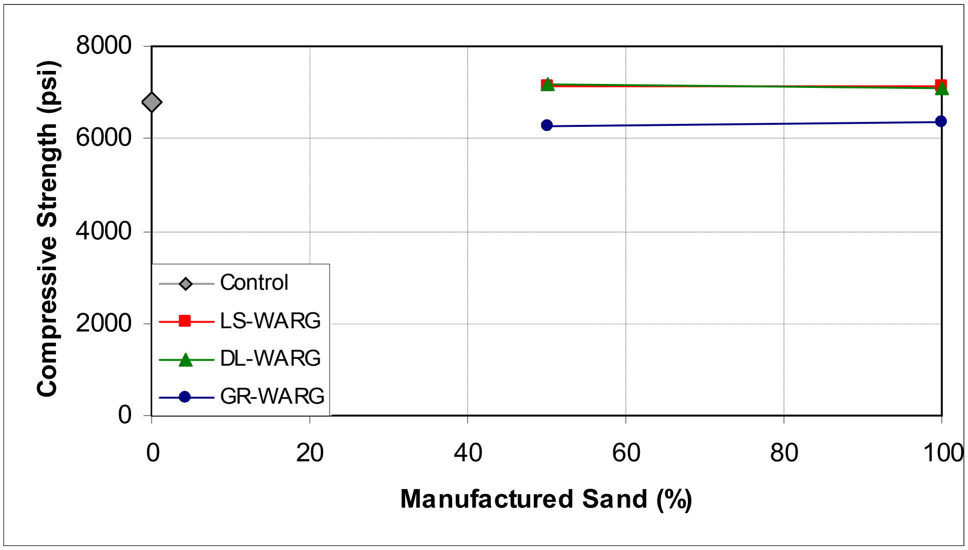

Figure 5.6(a): Compressive Strengths of WARG Mixtures

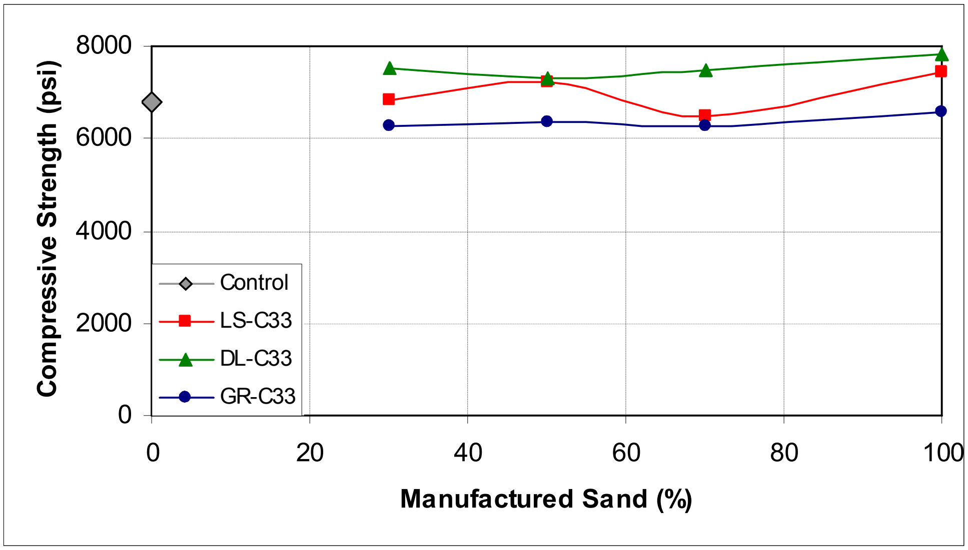

Figure 5.6(b): Compressive Strengths of C33 Mixtures

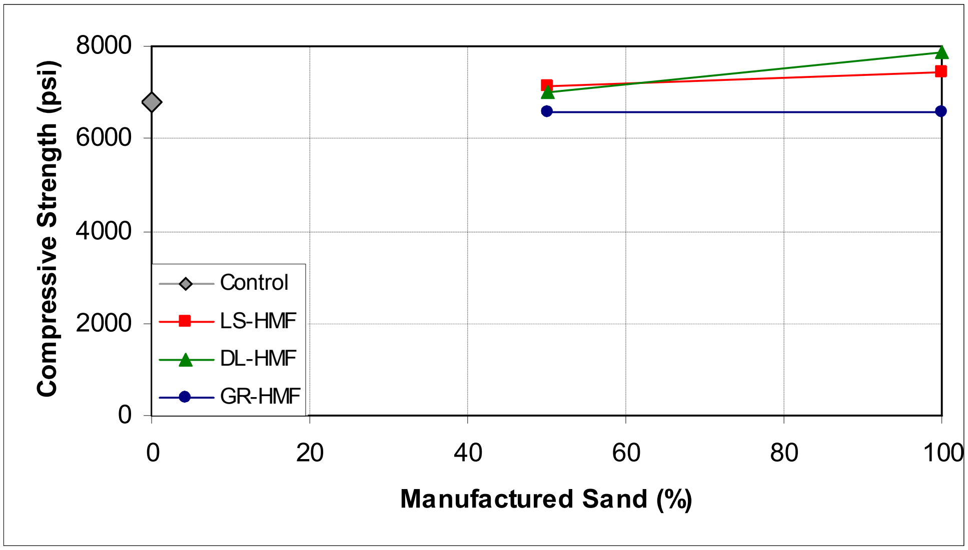

Figure 5.6(c): Compressive Strengths of HMF Mixtures

The compressive strengths of the mixtures containing MFA with WARG grading did not change greatly as percentage of MFA was increased. The mixtures containing LS and DL with WARG grading showed less than a 1% change in compressive strength as the percentage of MFA was increased. There was no significant change in compressive strength as the percentage of washed manufactured aggregate was increased. The allowable coefficient of variation for compressive strength testing is 2.4% according to ASTM C 39. The change in compressive strength values is less than the allowed single-operator error, so the differences may be due simply to experimental error.

The mixtures containing manufactured sand with C33 grading produced increasing compressive strengths as the percentage of manufactured sand increased from 50% to 100% of the fine aggregate. The compressive strengths of the mixture with LS with C33 grading increased by about 8% from 30% to 100% replacement of NS with manufactured sand. The compressive strengths of the mixture with DL with C33 grading increased by about 4% from 30% to 100% replacement of NS with manufactured sand.

The compressive strengths of the mixture with GR with C33 grading increased by about 5% from 30% to 100% replacement of NS with manufactured sand. The mixtures with C33 grading show a definite trend of increasing compressive strength with increasing percentages of MFA.

The mixtures with LS and DL with HMF grading both show increased compressive strengths of 4% and 11%, respectively, as the percentage of MFA is increased from 50% to 100% of the fine aggregate. The mixture with GR with HMF grading showed less than 1% change in compressive strength as the percentage of MFA is increased from 50% to 100% of the fine aggregate. For the mixtures containing manufactured sand with HMF grading, the increased amount of microfines improved packing density and increased compressive strength.

Regardless of grading, the concretes with GR consistently had lower strength values and showed little or no increase in compressive strength as more GR was incorporated into the mixture. This could be due to the poor shape of the aggregate. Because the sand was angular, the sand particles may not have been coated well by the paste and could have resulted in decreased strength values. The concretes with LS showed intermediate compressive strengths. The concretes with DL generally had the highest strengths of the manufactured sand concretes. It was expected that the compressive strength would be dependent on the mineralogy of the manufactured sand. The strength and stiffness of the concrete may be affected by the type of aggregate that is included in the mixture [Alexander, 1996]. Modulus of elasticity, creep, and shrinkage results may vary by up to 100% due to mineralogical differences [Alexander, 1996].

It appeared that the concrete with GR showed the lowest compressive strengths, and it was likely due to the poor shape of the aggregate. The shape of the fine aggregate can be determined indirectly by calculating the uncompacted void content. The uncompacted void content is plotted against the compressive strength for the mixtures containing 100% manufactured sand in Fig. 5.7. However, the uncompacted void content was very poorly correlated with compressive strength. This property was strongly related to HRWRA demand for the C33 grading. According to this data set, uncompacted void content is not suitable for predicting compressive strength.

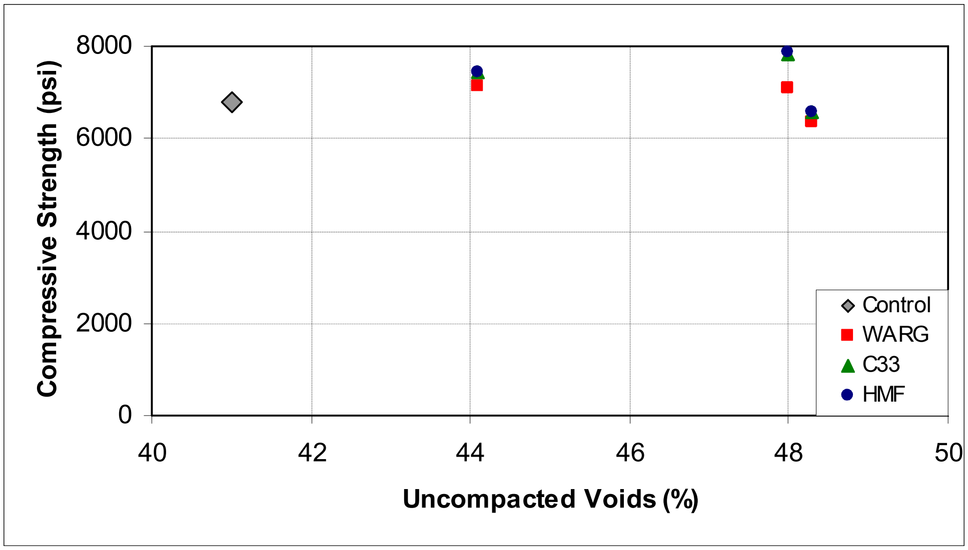

Figure 5.7: Effects of Uncompacted Void Content on Compressive Strength

The shape of the microfines could influence compressive strength. The methylene blue value (MBV), packing density, and span of the microfines are plotted against the compressive strength values for the mixtures containing 100% MFA with HMF grading in Fig. 5.8. The linear regression lines are not shown on the chart, but the correlations between MBV and compressive strength as well as packing density and compressive strength were relatively strong (0.78 and 0.57, respectively). The correlation between span and compressive strength was very low. This could indicate that the particle size distribution does not impact compressive strength in the same way that it affects HRWRA demand.

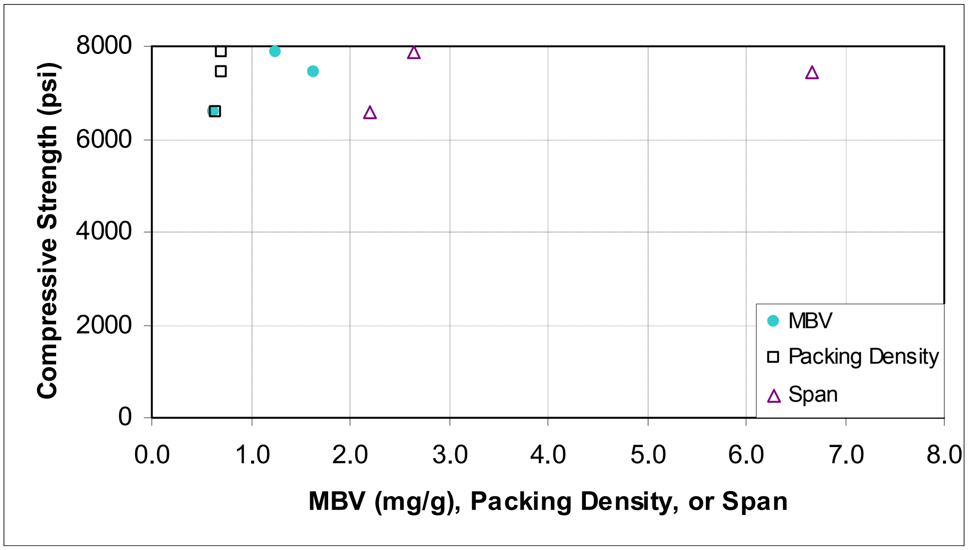

Figure 5.8: Effects of Microfine Properties on Compressive Strength

Section 5.3.2: Flexural Strength

In addition to the compressive strength, the flexural strength of every mixture was also measured. The values of the modulus of rupture at 28 days for all mixtures in the "Sand Blends Study" are presented in Fig. 5.9. The flexural strengths are also listed in Appendix C. The average flexural strength of the control mixture was 870 psi and is presented on all charts for comparison.

The flexural strength generally increased with increasing percentages of MFA with WARG grading. The mixtures containing LS and DL with WARG grading increased by 5% and 24%, respectively, as the percentage of MFA increased from 50% to 100% of the fine aggregate. The mixtures containing GR with WARG grading showed a decrease in flexural strength of about 7% as the percentage of manufactured sand increased from 50% to 100%. The coefficient of variation for a single-operator for flexural strength tests is 5.7% according to ASTM C 78.

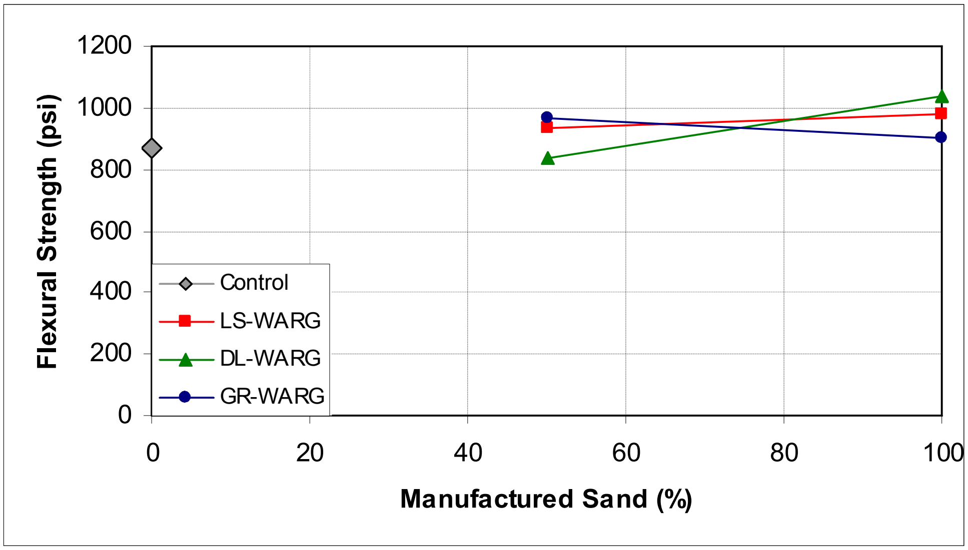

Figure 5.9(a): Flexural Strengths of WARG Mixtures

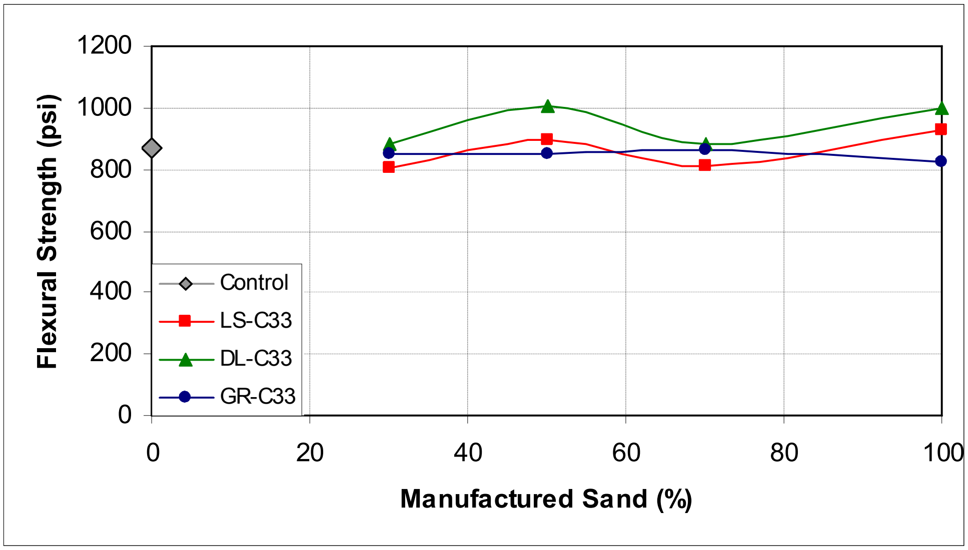

Figure 5.9(b): Flexural Strengths of C33 Mixtures

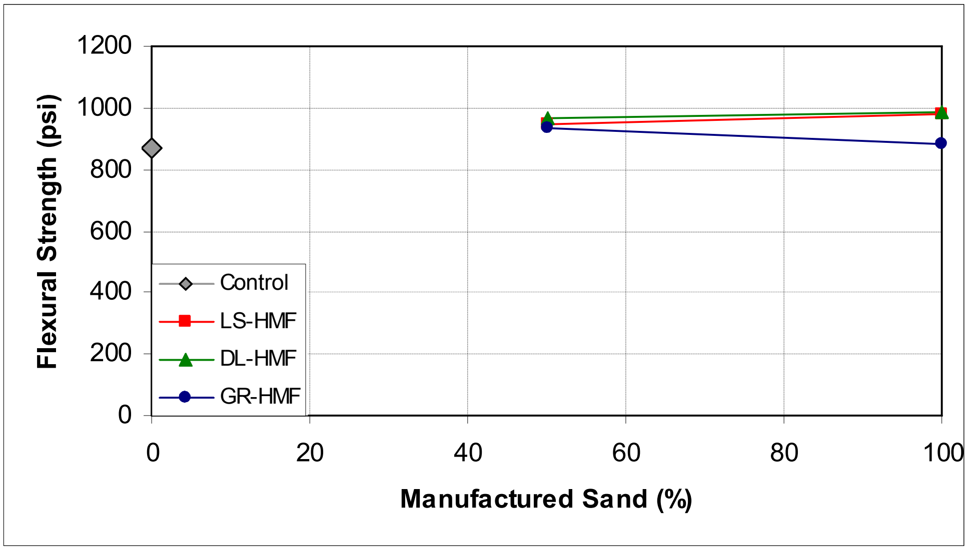

Figure 5.9(c): Flexural Strengths of HMF Mixtures

The flexural strength also increased with increasing percentages of LS and DL with C33 grading. However, the mixture containing GR with C33 grading showed a decrease in flexural strength of about 3% as the percentage of MFA increased from 30% to 100%. The flexural strength results for the mixtures with C33 grading do not show a simple straight-line increase or decrease with increasing percentages of manufactured sand. Both LS and DL concretes showed the same pattern of higher strengths for mixtures containing 50% and 100% manufactured sand with C33 grading and lower strengths for mixtures containing 30% and 70% manufactured sand with C33 grading. The GR concretes showed the opposite trend, with mixtures containing 30% and 70% manufactured sand with C33 grading exhibiting higher flexural strengths and mixtures containing 50% and 100% manufactured sand with C33 grading exhibiting lower flexural strengths.

For the mixtures containing LS and DL with HMF grading, the flexural strength increased as the percentage of MFA increased. The mixtures with GR with HMF grading again showed a decrease in flexural strength of about 5%.

The mixtures containing GR had lower flexural strengths overall, just as with the compressive strength values. With a few exceptions, the DL concretes generally had the highest flexural strengths. However, as with the compressive strength, the flexural strength does not seem to be related to the uncompacted void content of the fine aggregate, as seen in Fig. 510. The correlation between uncompacted void content and flexural strength of the mixtures containing 100% MFA was very low for all gradings.

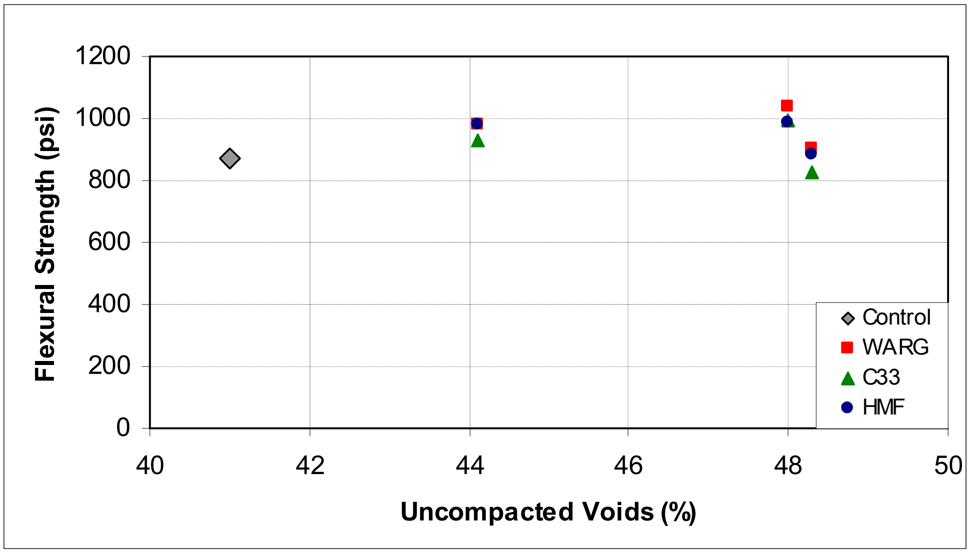

Figure 5.10: Effects of Uncompacted Void Content on Flexural Strength

The increased flexural strengths as the percentage of MFA with HMF increased can be explained by the increase in microfines. Microfines can help to improve hardened concrete properties if suitably shaped and graded. Both the compressive and flexural strengths increased with increases in microfines. The properties of the microfines versus the flexural strength of concrete mixtures with 100% MFA with HMF grading are presented in Fig. 5.11. There was high correlation between MBV and flexural strength and packing density and flexural strength (0.82 and 0.95, respectively). The strong correlation indicates that a greater packing density of the microfines will produce concrete with greater flexural strengths. There was low correlation between span and flexural strength. As mentioned previously, hardened concrete properties may not be as dependent upon particle size distribution as fresh concrete properties.

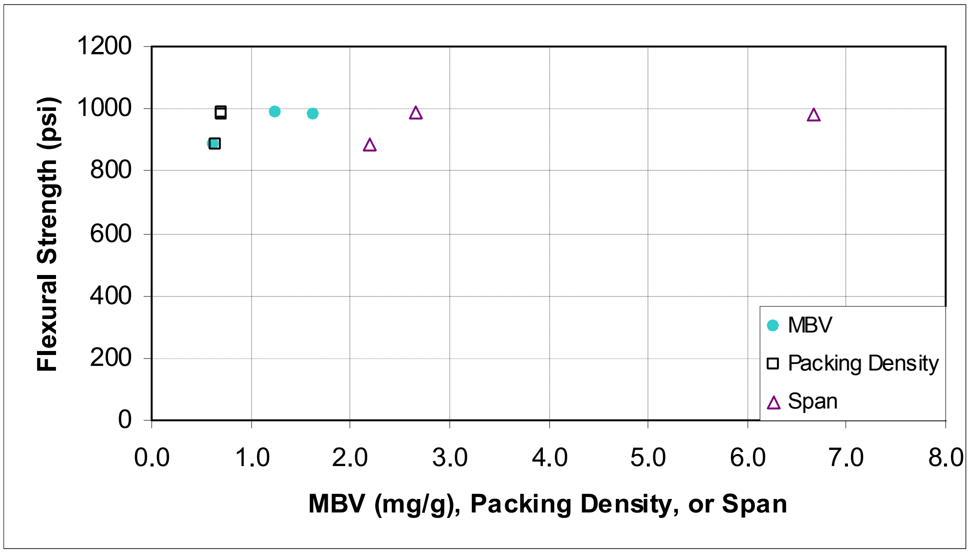

Figure 5.11: Effects of Microfine Properties on Flexural Strength

Section 5.3.3: Modulus of Elasticity

The measured values of modulus of elasticity at 28 days for the mixtures tested in the "Sand Blends Study" are presented in Fig. 5.12. The modulus of elasticity values are listed in Appendix C. The modulus of elasticity of the control mixture was 4.8×10^6 psi, greater than any of the modulus of elasticity values measured for the mixtures tested in the "Sand Blends Study."

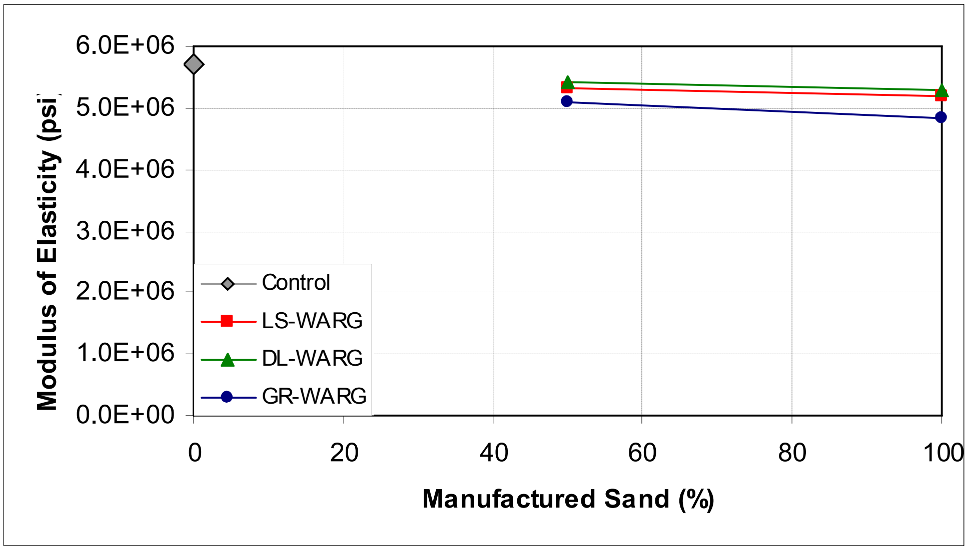

Figure 5.12(a): Modulus of Elasticity of WARG Mixtures

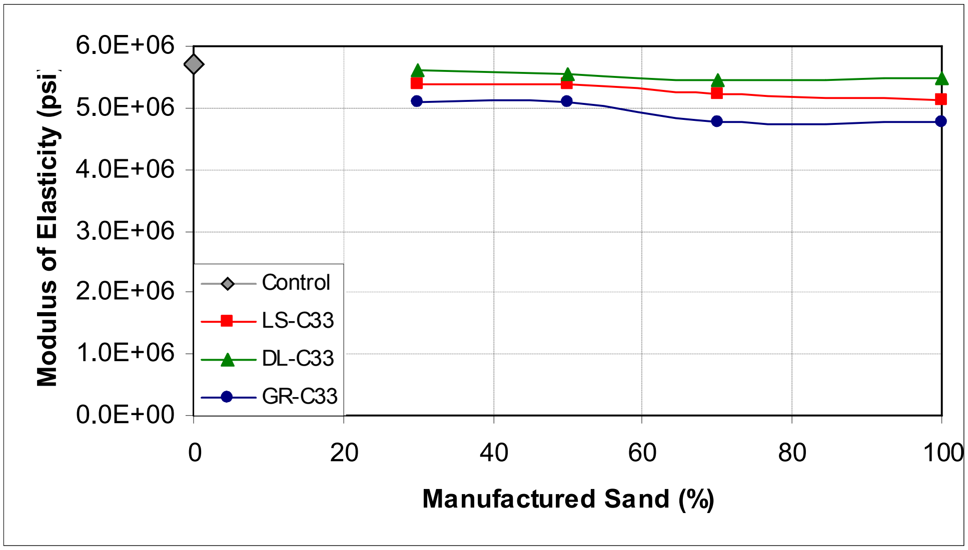

Figure 5.12(b): Modulus of Elasticity of C33 Mixtures

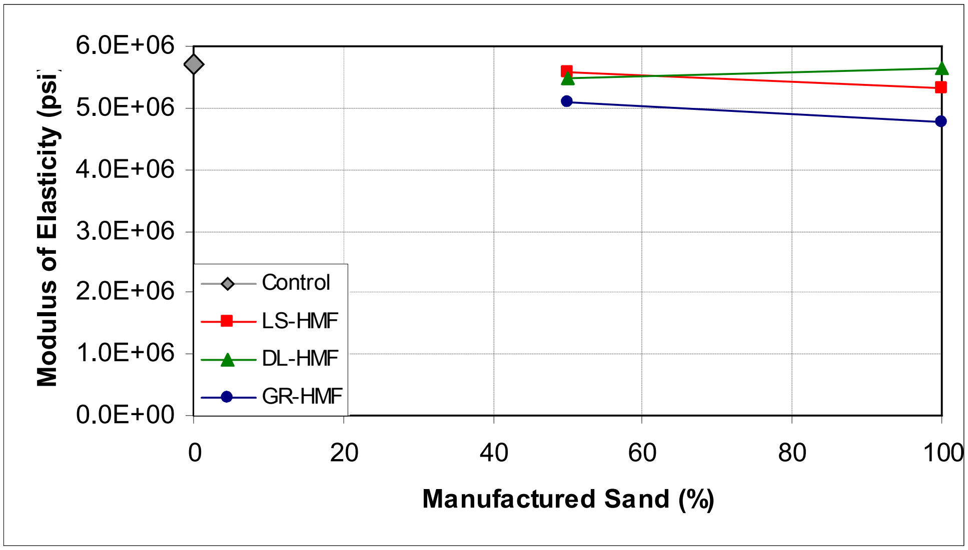

Figure 5.12(c): Modulus of Elasticity of HMF Mixtures

The modulus of elasticity values decreased with increasing percentages of MFA with WARG grading. The mixtures with GR with WARG grading experienced the greatest decrease in modulus of elasticity as the percentage of MFA was increased from 50% to 100% of the fine aggregate. According to ASTM C 469, the single-operator-machine precision is 4.25%, but this precision is valid over the range of 2.5 to 4 x 10^6 psi. The modulus of elasticity values were all greater than 4 x 10^6 psi, outside the range given in ASTM C 469. There is no comparison available between single-operator precision and differences in modulus of elasticity values.

The modulus of elasticity values also decreased with increasing percentages of MFA for all concrete containing sands with C33 grading. Again, the mixture with GR with C33 grading experienced the greatest decrease in modulus of elasticity from 30% to 100% MFA. GR-C33-50 had a modulus of elasticity value about 6% greater than GR-C33-100.

Those mixtures containing GR and LS with HMF grading also showed decreasing values of modulus of elasticity as the percentage of manufactured sand increased. The modulus of elasticity values decreased by about 6% for the mixtures containing GR with HMF grading, and the modulus of elasticity values decreased by about 5% for the mixtures containing LS with HMF grading. Only the mixture containing DL with HMF grading showed an increase in the modulus of elasticity with increasing proportions of manufactured sand.

The mixtures containing GR had low modulus of elasticity values compared to the other sand types. The lower modulus values would be expected since GR concretes also had the lowest strengths. DL concretes tended to have greater modulus of elasticity values than LS or GR concretes. This result was expected since the mixtures containing DL showed the greatest compressive strengths. A lower modulus of elasticity is not necessarily a detrimental attribute of a mixture. A lower modulus will decrease the amount of thermal stress a concrete pavement will experience.

Though it is clear that the modulus of elasticity decreased with increasing proportions of MFA and that the mixtures with GR produced lower values of modulus of elasticity, the effect of grading on modulus of elasticity is not as obvious. The maximum modulus of elasticity value is 5.6×10^6 psi, and the minimum modulus of elasticity value is 4.8×10^6 psi of the mixtures in the “Sand Blends Study,” but there does not appear to be a clear trend between modulus of elasticity and sand grading.

The compressive strengths versus the modulus of elasticity values of the mixtures in the “Sand Blends Study” are displayed in Fig. 5.13. The concrete composed of GR consistently produced lower strengths and lower modulus of elasticity values. Mixtures with DL tended to have the highest strengths and higher modulus of elasticity values.

Higher strengths were associated with higher modulus of elasticity values for all sand types and gradings.

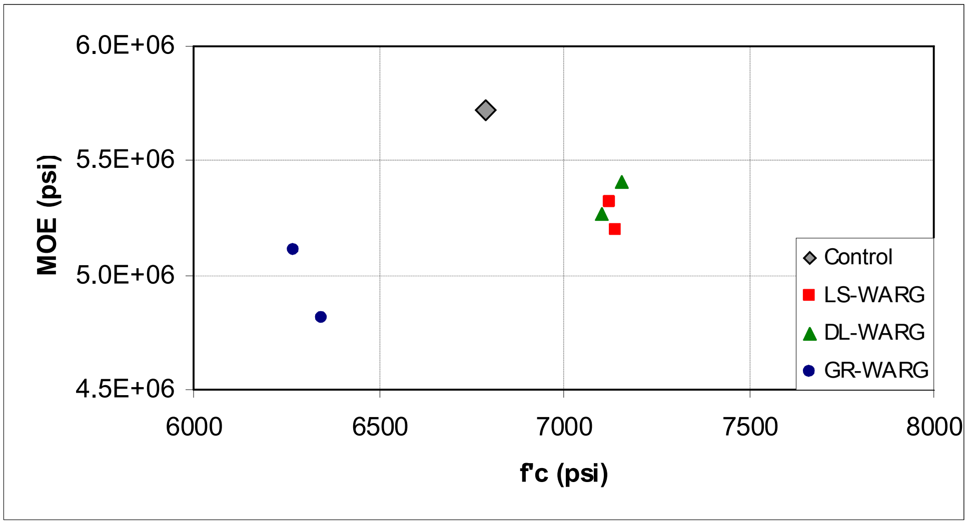

Figure 5.13(a) Compressive Strength versus Modulus of Elasticity for WARG Mixtures

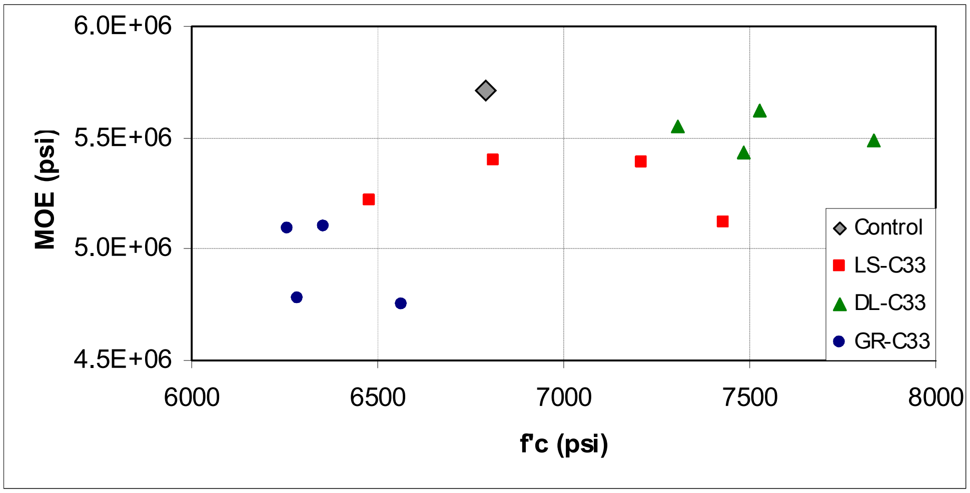

Figure 5.13(b): Compressive Strength versus Modulus of Elasticity for C33 Mixtures

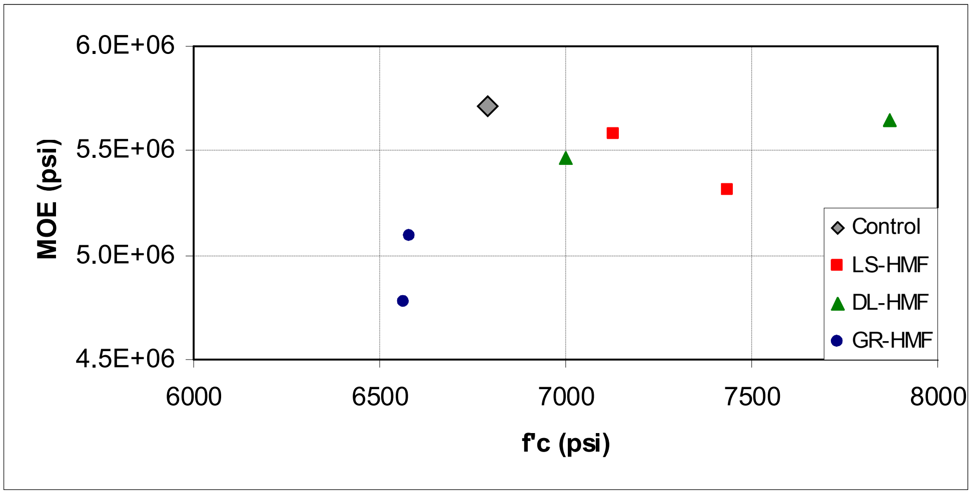

Figure 5.13(c): Compressive Strength versus Modulus of Elasticity for HMF Mixtures

The shape of the fine aggregate greatly influenced the modulus of elasticity values. The aggregates that produced greater compressive strengths also produce higher modulus of elasticity values. The uncompacted void content was plotted against modulus of elasticity for mixtures containing 100% MFA in Fig. 5.14. However, there was also little correlation between the uncompacted void content of the fine aggregate and the modulus of elasticity values for mixtures containing 100% MFA. The uncompacted void content likely can not be used to identify which sands will produce higher modulus of elasticity values.

An increase in microfines resulted in a decrease in modulus of elasticity for the mixtures with HMF grading. The properties of the microfines are plotted against modulus of elasticity for mixtures containing 100% MFA with HMF grading in Fig. 5.15. The correlations between any of the properties and modulus of elasticity were low to very low. This indicates that the properties of the microfines do not influence the modulus of elasticity.

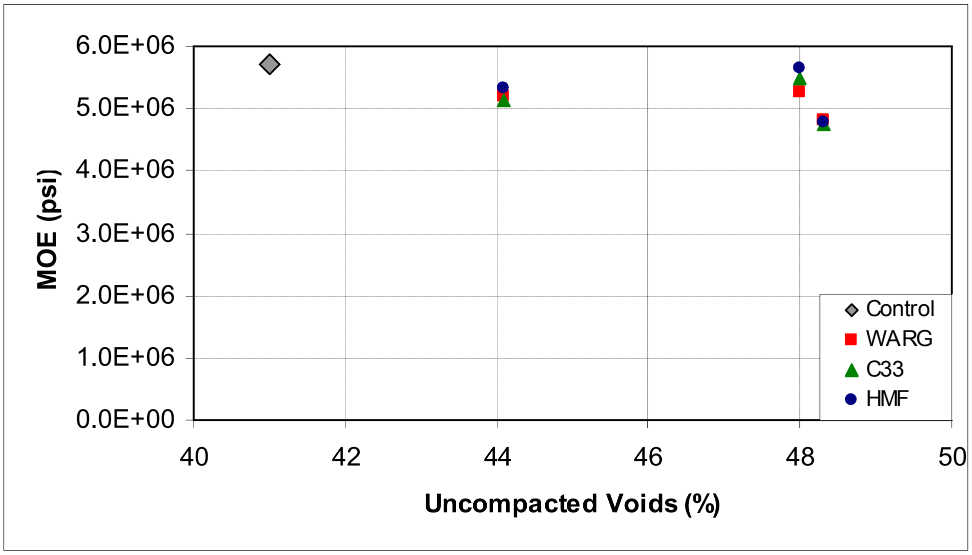

Figure 5.14: Effects of Uncompacted Void on Modulus of Elasticity

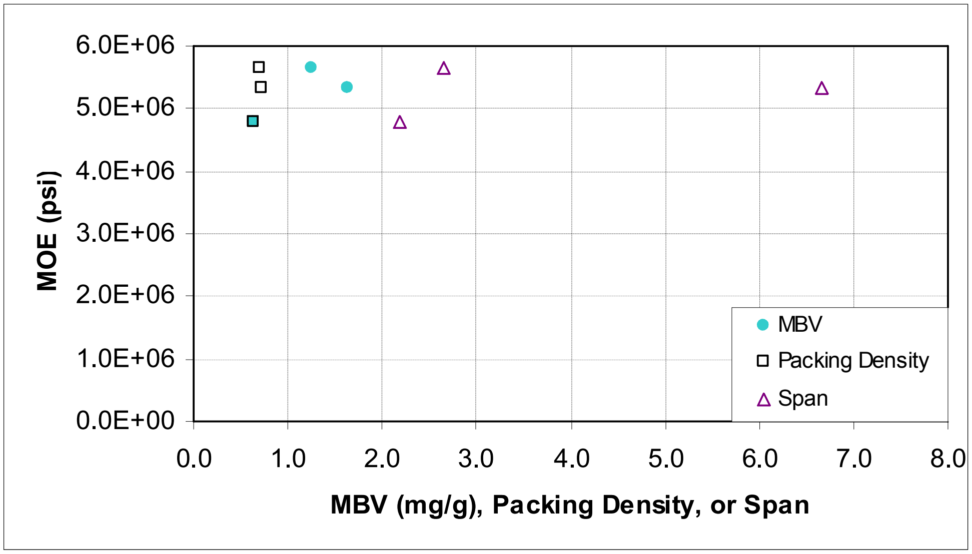

Figure 5.15: Effects of Microfine Properties on Modulus of Elasticity

Section 5.3.4: Length Change

Shrinkage measurements were taken for the mixtures containing 50% and 100% manufactured sand with C33 grading and the control mixture. The percent length changes of the mixtures in the "Sand Blends Study" are shown in Fig. 5.16. The percent length change values are listed in Appendix C. All of the mixtures containing sand with C33 grading ultimately decreased in length over a period of 56 days. The control mixture actually showed the greatest length change. None of the mixtures exceeded 0.08% shrinkage at 56 days.

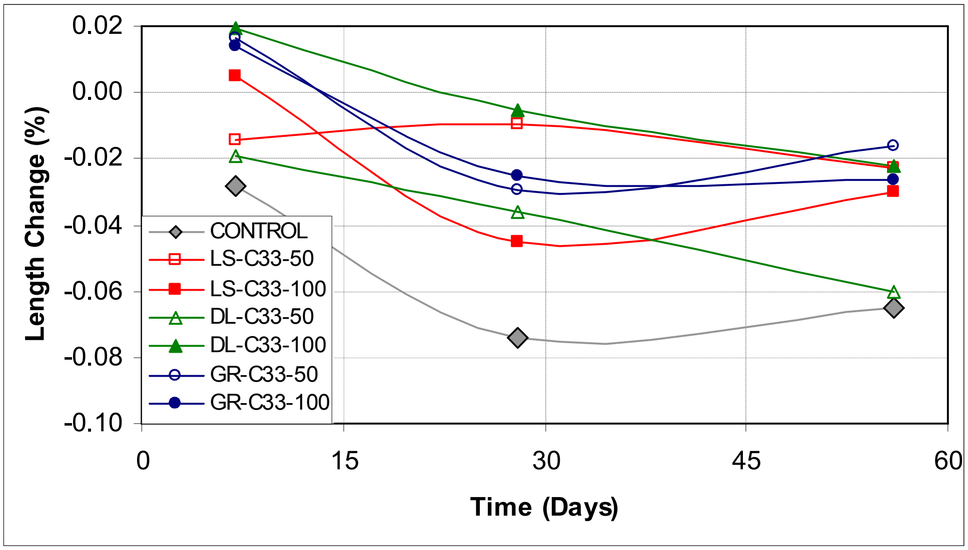

Figure 5.16: Length Change of "Sand Blends Study" Mixtures

The mixtures containing GR with C33 grading showed consistent length changes, even though the mixtures contained 50% and 100% GR. It appears as though several mixtures expanded between 28 and 56 days, but these are likely errors in the comparator measurements. It also appears as though LS-C33-50 expanded between 7 and 28 days, but, again, these are likely errors in the measurements. Except for the mixtures with DL with C33 grading, the mixtures with 100% MFA showed greater length change at 56 days than the mixtures with 50% MFA. An increase in microfines when the proportion of MFA is increased from 50% to 100% would explain an increase in shrinkage. However, because the mixtures tested contained manufactured sand with C33 grading, they did not contain any microfines. The trend appears to be that shrinkage increased slightly with an increase in MFA, even if the MFA does not contain microfines.

Section 5.3.5: Abrasion

Paving concrete is particularly vulnerable to surface deterioration due to abrasion. Previously-tested flexural beams were tested for abrasion resistance in accordance with ASTM C 944 "Standard Test Method for Abrasion Resistance of Concrete or Mortar Surfaces by the Rotating-Cutter Method." A finished surface and a formed surface were tested for all of the beams except for LS-HMF-50 and LS-HMF-100. Only the formed surfaces were tested for these mixtures. The results of the abrasion tests are presented in Table 5.3.

Table 5.3: "Sand Blends Study" Abrasion Results

Specimen Name	**Size**	**Mass Loss of Finished Surface (g)**	**Mass Loss of Formed Surface (g)**
Control	8 in.x6 in.x3 in.	1.7	0.3
LS-HMF-50	8 in.x6 in.x3 in.	-	1.7
LS-HMF-100	8 in.x6 in.x3 in.	-	0.7
DL-HMF-50	8 in.x6 in.x3 in.	0.1	0.1
DL-HMF-100	8 in.x6 in.x3 in.	0.2	0.3
GR-HMF-50	6 in. x 6 in. x 6 in.	1.2	0.8
GR-HMF-100	6 in. x 6 in. x 6 in.	0.9	0.9

The greatest mass loss of a finished surface was recorded for the control mixture. This was unexpected because this mixture contained 100% NS and a very low percentage of microfines. There were also no supplementary cementing materials included in this mixture. The mixtures containing DL provided the best abrasion resistance as measured by mass loss of the finished surface. However, the finished surfaces may not provide the best basis for comparison. Not all specimens were finished by the same individual, and the inconsistency in finish quality could introduce error into the test results.

The formed surfaces of the specimens may provide better relative comparisons of abrasion resistance. The greatest mass loss of a formed surface was 1.7 g and was attributed to LS-HMF-50. The mixtures containing GR had consistent mass loss of the formed surfaces due to abrasion. Concretes with DL resulted in very little mass loss of the formed surfaces due to abrasion.

SECTION 5.4: SUMMARY OF "SAND BLENDS STUDY" RESULTS

The purpose of the "Sand Blends Study" was to determine how sand type, grading, and blend ratio affect fresh and hardened concrete properties. The results of the "Sand Blends Study" are summarized in Table 5.4.

Table 5.4: "Sand Blends Study" Results Summary

	Effect of Sand Type	**Effect of Grading**	**Effect of % MFA**
Workability	↓ with poorly-shaped aggregate (GR and DL) and ↑ with better-shaped aggregate (LS)	↓ with ↑ microfines	↓ with ↑ amounts of MFA
Air Content	No observed relationship	No observed relationship	No observed relationship
Compressive Strength	↓ for mixtures with GR and ↑ for mixtures with DL	No observed relationship	↑ with ↑ amounts of MFA
Flexural Strength	↓ for mixtures with GR and ↑ for mixtures with DL	No observed relationship	↑ with ↑ amounts of MFA (except for GR)
Modulus of Elasticity	↓ for mixtures with GR and ↑ for mixtures with DL	No observed relationship	↓ with ↑ amounts of MFA
Length Change	No observed relationship	N/A (only C33 grading was tested)	↑ with ↑ amounts of MFA (except for DL)
Abrasion Resistance	↑ for mixtures with	N/A (only HMF	↓ with ↑ amounts of

	DL	grading was tested)	MFA (except for LS)

It was seen that mixtures containing sand with poorly and intermediately shaped (GR and DL, respectively) aggregate required more HRWRA than mixtures containing well-shaped aggregate (LS). The HRWRA demand also increased with increasing proportions of manufactured sand for all three sand gradings. As expected, the HRWRA demand was higher for the mixtures containing sand with high microfines than the mixtures containing either washed sand or sand graded to meet ASTM C 33 limits. Air content was another fresh property that was measured for every mixture, but there did not appear to be any relationships between sand types, grading, or blend ratio and air content. Moreover, the air contents were all about 2.0%, which was the assumed air content of the design mixture.

The hardened concrete properties also varied with sand type, grading, and blend ratio. The compressive strength was higher for mixtures containing DL and lower for mixtures containing GR. Compressive strength also increased slightly as increasing amounts of manufactured sand were incorporated into the mixture. Mixtures containing LS and DL showed increasing flexural strengths with increasing proportions of manufactured sand for all gradings. Mixtures containing GR, regardless of grading, tended to have lower flexural strengths with greater percentages of manufactured sand. The modulus of elasticity decreased with increasing amounts of manufactured sand, regardless of type or grading. Mixtures with GR produced the lowest modulus of elasticity values while mixtures with DL sand produced the highest modulus of elasticity values. The mixtures in the “Sand Blends Study” experienced a length change at 56 days ranging from -0.02 to -0.06. The mixture with the greatest length change (-0.08%) was the control mixture, but the greatest length change of a mixture containing manufactured sand was -0.06% for DL-C33-50. In addition to high strength and stiffness values, the mixtures with DL also demonstrated the best resistance to abrasion.

Chapter 6: "Optimization Study" Results

SECTION 6.1: INTRODUCTION

The purpose of this study was to redesign selected mixtures from the "Sand Blends Study" for optimization. The mixtures containing 50% manufactured sand with high microfines (HMF) grading were redesigned with the microfines considered to be powder instead of aggregate. The paste content was kept at 30%, decreasing the water and cement contents and increasing the amount of fine aggregate included in the mixture. In addition, cement was replaced by fly ash in several mixtures. The *w/cm* was also lowered for one mixture, and the microfines were replaced entirely by cement in another mixture to demonstrate how a large amount of powder negatively impacts workability. The mixture proportions of the mixtures tested in the "Optimization Study" were presented in Table 4.3.

SECTION 6.2: FRESH CONCRETE TEST RESULTS

Section 6.2.1: Workability

Section 6.2.1.1: Slump

The values obtained for slump are presented in Table 6.1. The maximum slump was found to be 5.5 in. for LS-C33-30-25%FA. The minimum slump was found to be 1.3 in. for GR-HMF-50-P. The average slump was 2.3 in, lower than that of the "Sand Blends Study." LS-C33-30-25%FA and LS-C33-30-25%FA-0.40W/CM required no additions of HRWRA to reach slumps above 2 in. LS-C33-30-25%FA-0.40W/CM had a lower slump than LS-C33-30-25%FA because it had a lower *w/cm*. Both of these mixtures incorporated fly ash as a supplementary cementing material, and the spherical shape of the fly ash helped to improve workability. LS is also well-shaped which contributes to the improved workability of the mixtures.

Table 6.1: "Optimization Study" Slump Results

Mixture	Slump (in.)
LS-HMF-50-P	1.5
LS-C33-30-25%FA	5.5
LS-C33-30-25%FA-0.40W/CM	2.0
LS-HMF-100-CEMENT	2.3
DL-HMF-50-P	1.8
DL-HMF-50-P-25%FA	1.5
GR-HMF-50-P	1.3

Section 6.2.1.2: Flow Table

The flow table test was a dynamic indicator of workability used in addition to the slump test. The flow table test results are presented in Table 6.2. The maximum flow table result was recorded for LS-C33-30-25%FA, and the lowest flow table result was recorded for LS-HMF-50-P. LS-C33-30-25%FA had a high flow table value because the mixture had greater inherent workability without the addition of high-range water-reducing admixture.

LS-HMF-50-P had the lowest flow table result, but it also required a very low dosage of HRWRA. DL-HMF-50-P had the greatest flow table result of the mixtures with HMF grading and the microfines considered as powder, but this mixture required almost 4 times as much HRWRA as LS-HMF-50-P. LS was better-shaped than DL, so it would be expected to require less HRWRA. HRWRA demand was based on slump, which, as previously mentioned, is a flawed test for measuring workability of mixtures with high microfines. Had a target flow table value been set instead of a target slump value, the HRWRA dosages would have greater correlation with the flow table results and would have likely produced better HRWRA results.

Table 6.2: “Optimization Study” Flow Table Results

Mixture	**Flow Table (in.)**
LS-HMF-50-P	12.3
LS-C33-30-25%FA	17.2
LS-C33-30-25%FA-0.40W/CM	14.8
LS-HMF-100- CEMENT	13.8
DL-HMF-50-P	17.0
DL-HMF-50-P-25%FA	15.5
GR-HMF-50-P	14.6

The mixtures in the “Optimization Study” produced lower flow table test results than those mixtures in the “Sand Blends Study.” This indicates that the mixtures were stiffer and did not consolidate as easily upon vibration. The mixtures with HMF grading and the microfines considered to be powder had greater amounts of microfines and fine aggregate than the comparable mixtures in the “Sand Blends Study.”

The flow table test results were not well correlated with the slump test results; the R^2 value is only 0.28, as seen in Fig. 6.1. This is better correlation than the mixtures in the “Sand Blends Study.”

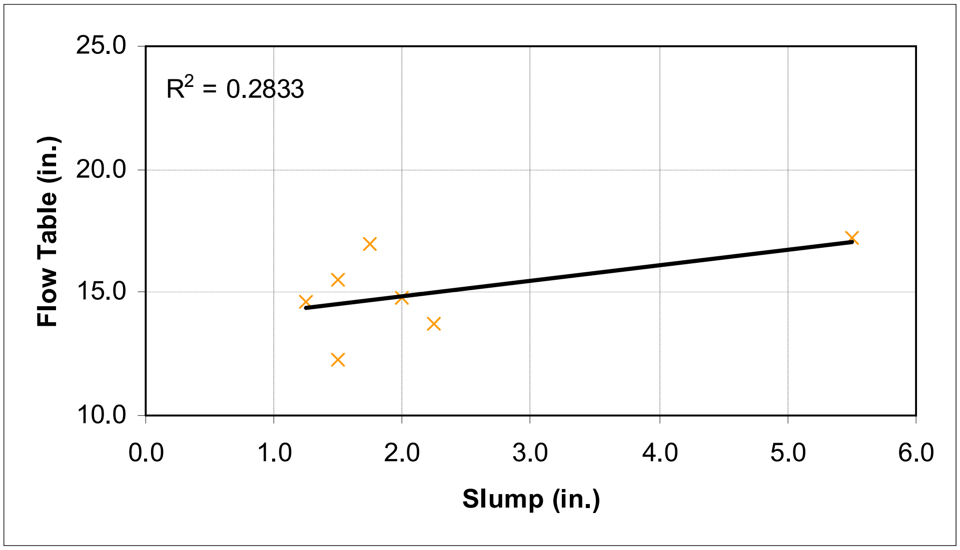

Figure 6.1: Slump versus Flow Table Results of “Optimization Study” Mixtures

Section 6.2.1.3: HRWRA Demand

The high-range water-reducing admixture demands of the mixtures tested in the "Optimization Study" are presented in Fig. 6.2. The values of the HRWRA demand are presented in Appendix D. As mentioned previously, LS-C33-30-25%FA and LS-C33-30-25%FA-0.40W/CM required no addition of HRWRA to meet the desired slump. The mixture requiring the greatest amount of HRWRA to reach the required slump was GR-HMF-50-P. This was expected since GR is a poorly-shaped aggregate.

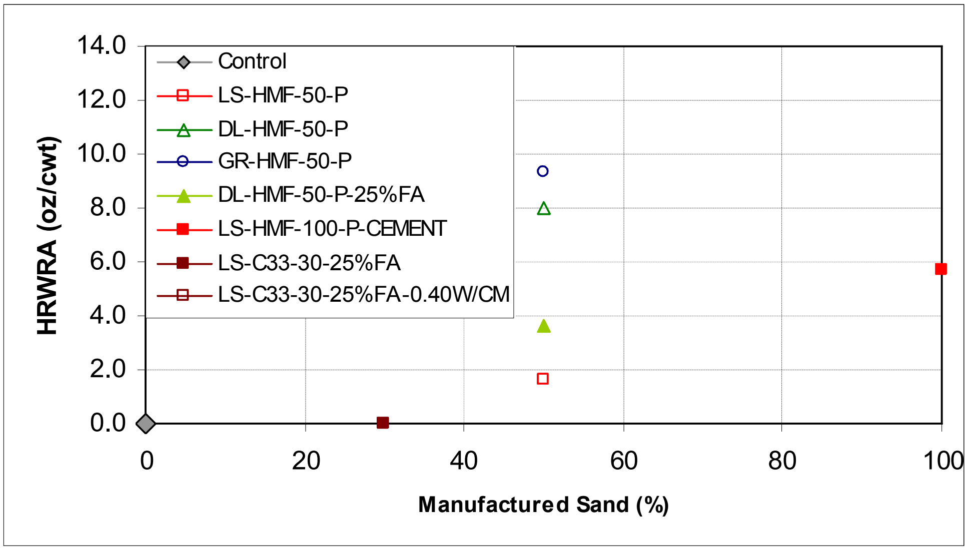

Figure 6.2: HRWRA Demand of "Optimization Study" Mixtures

Water-reducing admixture was used to control the slump of DL-HMF-50-P-25%FA. The addition of fly ash to the mixture improved workability so that a WRA could be used instead of a HRWRA. The mixture required only 3.6 oz/cwt of WRA, and the same mixture minus the fly ash (DL-HMF-50-P) required 8.0 oz/cwt of HRWRA to reach a 2-in. slump. The spherical shape of the fly ash greatly contributed to the workability of the mixture, and the incorporation of fly ash in mixtures may have offset any negative impacts on workability from poorly-shaped microfines.

LS-HMF-100-CEMENT required 5.7 oz/cwt of HRWRA to reach a suitable slump. The same mixture from the “Sand Blends Study” (LS-HMF-100) required 2.5 oz/cwt of HRWRA to reach an acceptable slump value. The cement particles were likely poorly-shaped in comparison to the limestone microfines, reducing the workability and increasing the HRWRA demand. Cement particles are also attracted to each other and tend to form agglomerates, reducing workability. The workability would also decrease as the hydration of the cement particles progressed.

All of the mixtures with HMF grading and the microfines considered to be powder required more HRWRA than the comparable mixtures from the “Sand Blends Study.” Both DL-HMF-50-P and GR-HMF-50-P required almost four times as much admixture as DL-HMF-50 and GR-HMF-50 from the “Sand Blends Study.” The huge increase in HRWRA demand indicates that the DL and GR microfines are both poorly-shaped. Also, the mixtures from the “Sand Blends Study” had 32.5% paste volume while the mixtures from the “Optimization Study” had only 30% paste volume. To use DL-HMF-50-P and GR-HMF-50-P effectively in the field, the paste volume would need to be increased.

Section 6.2.2: Air Content

Air content was another fresh concrete property measured for the mixtures in the “Optimization Study.” Air contents were measured by the pressure meter method and the gravimetric method, but gravimetric air contents were negative for many mixtures and are not presented. The air contents as determined by ASTM C 231 Standard Test Method for Air Content of Freshly Mixed Concrete by the Pressure Method are presented in Fig. 6.3. The air contents are also listed in Appendix D. The maximum air content was 2.5%, and it was recorded for DL-HMF-50-P and DL-HMF-50-P-25%FA. The minimum measured air content was 1.8% for LS-C33-30-25%FA. The average air content was found to be 2.2%, slightly above the value assumed for mixture design. As with the "Sand Blends Study," no strong relationship was observed between sand types, grading, or blend ratio and air content. No significant differences were observed between the air contents of the mixtures in the "Sand Blends Study" and those of the "Optimization Study."

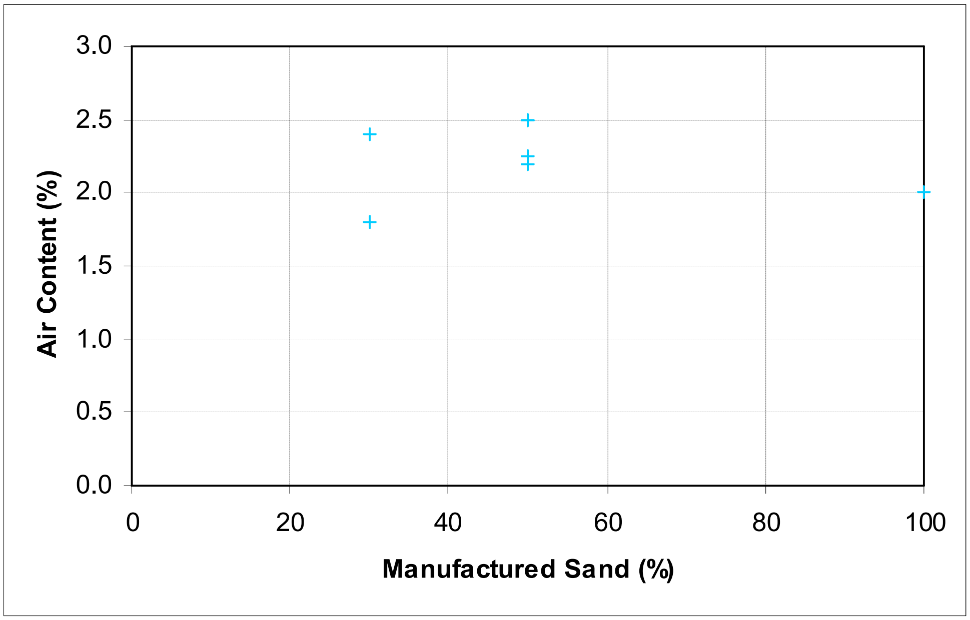

Figure 6.3: Air Content of "Optimization Study" Mixtures

Section 6.2.3: Time of Set

The time of set was also measured for mixtures in the "Optimization Study," and the results are presented in Fig. 6.4. The time of set was not measured for LS-C33-30-25%FA-0.40W/CM or LS-HMF-100-CEMENT.

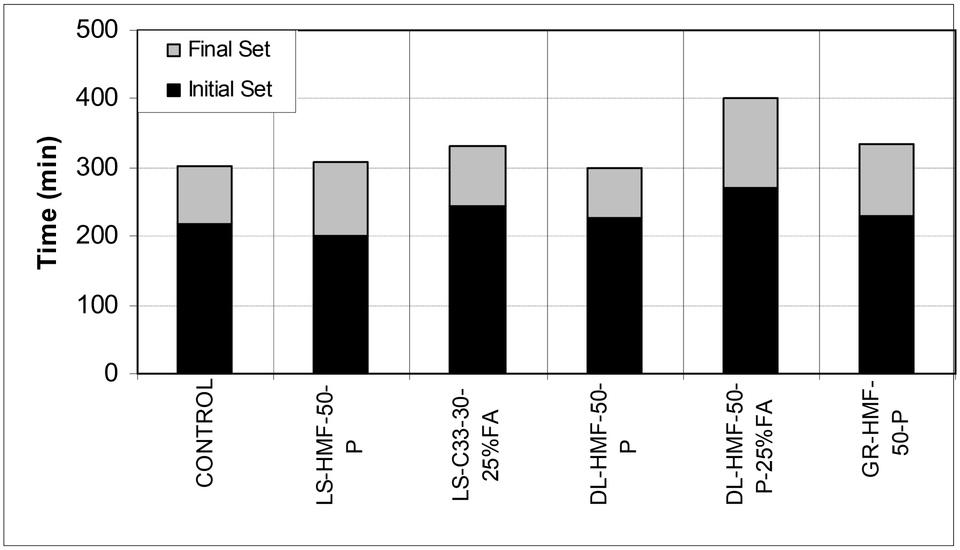

Figure 6.4: Time of Set of "Optimization Study" Mixtures

DL-HMF-50-P-25%FA required additional time to reach the appropriate strength. This mixture contained fly ash, and the workability was achieved by using water-reducing admixture instead of high-range water-reducing admixture. Higher dosages of water-reducing admixture can have retarding effects on the setting time of the concrete. The addition of fly ash to the mixture should also delay setting time. LS-C33-30-25%FA and DL-HMF-50-P-25%FA both contain fly ash and showed longer initial and final set times than the control mixture.

SECTION 6.3: HARDENED CONCRETE TEST RESULTS

Section 6.3.1: Compressive Strength

The 28-day compressive strengths of the mixtures completed in the "Optimization Study" are presented in Fig. 6.5. The compressive strength values are listed in Appendix D. All mixtures achieved a compressive strength greater than the goal of 4400 psi. The control mixture had a compressive strength of 7023 psi and is shown on all of the graphs for comparison. The greatest compressive strength was achieved by LS-HMF-100-CEMENT, and the lowest compressive strength was exhibited by LS-C33-30-25%FA.

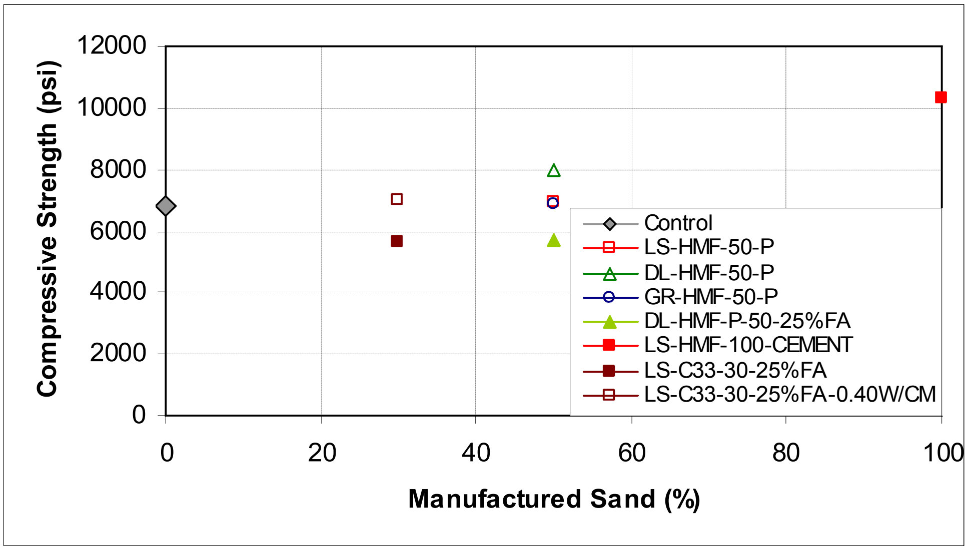

Figure 6.5: Compressive Strength of "Optimization Study" Mixtures

LS-C33-30-25%FA had a lower compressive strength than the same mixture with the decreased *w/cm* (LS-C33-30-25%FA-0.40W/CM). This was obviously an expected result because a lower *w/cm* will produce higher strength concrete. LS-HMF-100-CEMENT had the highest compressive strength. This mixture contained the highest cement content and the lowest *w/cm*.

Both mixtures that incorporated fly ash and 0.45 *w/cm*, DL-HMF-50-P-25%FA and LS-C33-30-25%FA, had lower compressive strength values than the control mixture. LS-C33-30, tested in the "Sand Blends Study," had a compressive strength almost 1200 psi greater than that of LS-C33-30-25%FA. DL-HMF-50-P had a compressive strength about 2300 psi greater than DL-HMF-50-P-25%FA. The fly ash likely retarded the strength gain of the concrete. Also, DL-HMF-50-P-25%FA incorporated large dosages of water-reducing admixture, which could have negatively affected the strength gain of the concrete at 28 days.

DL-HMF-50-P and GR-HMF-50-P from the "Optimization Study" both showed slightly higher compressive strengths than DL-HMF-50 and GR-HMF-50 mixtures from the "Sand Blends Study." LS-HMF-50-P exhibited a slightly lower compressive strength than LS-HMF-50 from the "Sand Blends Study." The mixtures with the microfines considered to be powder did have decreased cement contents, which would normally result in lower compressive strengths. However, more microfines were included in these mixtures, which led to increased packing density and compressive strength.

Section 6.3.2: Flexural Strength

The flexural strengths of the mixtures tested in the "Optimization Study" are shown in Fig. 6.6. The flexural strength values are available in Appendix D. The greatest flexural strength was achieved by LS-HMF-100-CEMENT, and the lowest flexural strength was exhibited by DL-HMF-50-P-25%FA. LS-HMF-100-CEMENT was expected to have the greatest flexural strength since it had a large percentage of cement and a low *w/c*. DL-HMF-50-P-25%FA contained fly ash and water-reducing admixture, which could have delayed flexural strength gain.

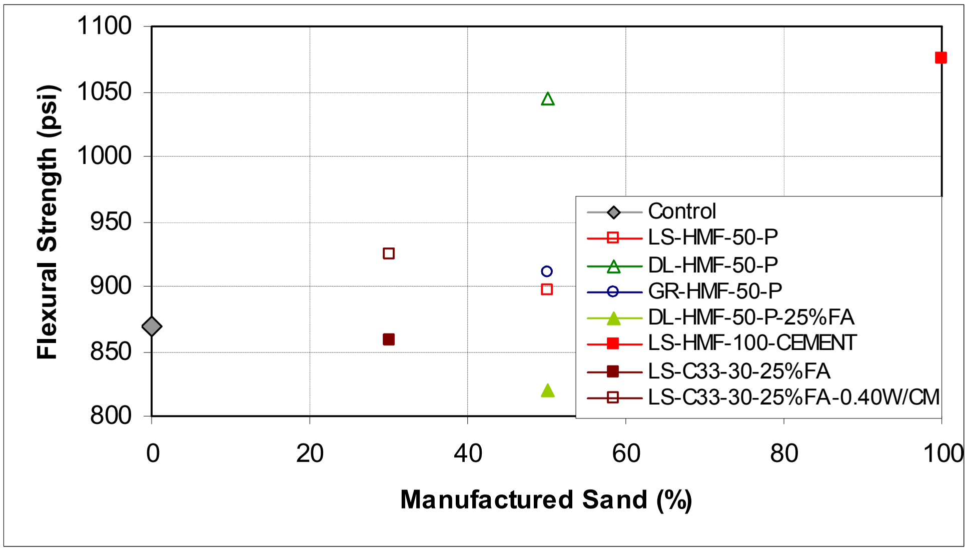

Figure 6.6: Flexural Strength of "Optimization Study" Mixtures

DL-HMF-50-P-25%FA exhibited a lower flexural strength than its comparable mixture, DL-HMF-50-P. The only difference in the mixtures was the substitution of Class F fly ash for cement. The fly ash may have slightly delayed strength gain, and had the mixtures been tested at a later date, the large discrepancy in flexural strength would likely not have been observed. However, LS-C33-30-25%FA exhibited greater flexural strength than LS-C33-30.

LS-HMF-50 and GR-HMF-50, tested in the "Sand Blends Study," both exhibited greater strength values than LS-HMF-50-P and GR-HMF-50-P, tested in the "Optimization Study." DL-HMF-50-P did show an increase in flexural strength from its previous mixture, DL-HMF-50. The mixtures in the "Optimization Study" had lower cement contents but higher microfine contents; the decreased flexural strength resulting from the lower cement content may have been balanced by the increased packing density provided by the increased microfines content.

Section 6.3.3: Modulus of Elasticity

The modulus of elasticity values for the mixtures tested in the "Optimization Study" are presented in Fig. 6.7. Modulus of elasticity values are listed in Appendix D. All mixtures containing DL had higher modulus of elasticity values, reflecting the same results that were found in the "Sand Blends Study." LS-HMF-100-CEMENT had the greatest modulus of elasticity value, which was not surprising since this mixture also had the greatest compressive and flexural strengths. LS-C33-30-25%FA also had the lowest modulus of elasticity value, reflecting its lower compressive and flexural strengths. The lower strength and modulus of elasticity decreases the likelihood of cracking due to thermal stresses.

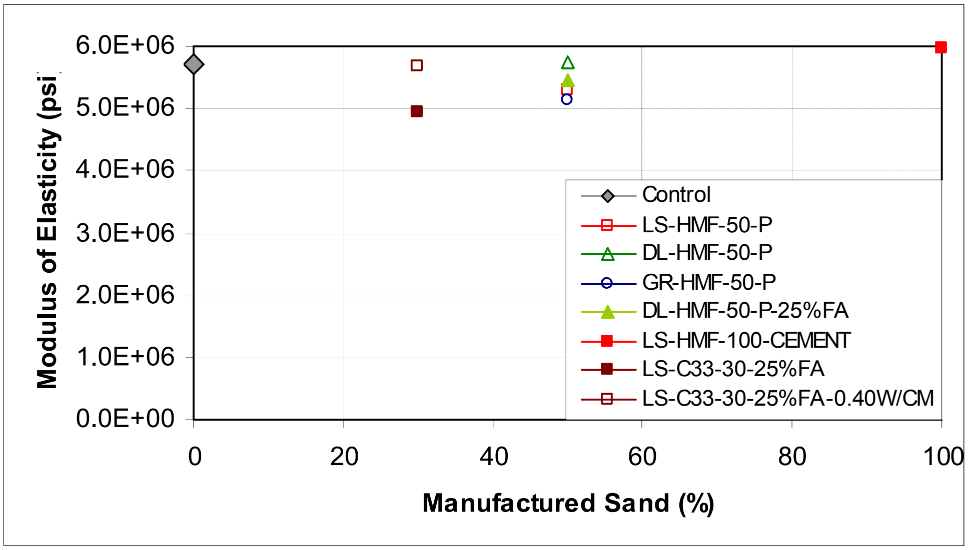

Figure 6.7: Modulus of Elasticity of "Optimization Study" Mixtures

GR-HMF-50-P had the lowest modulus of elasticity value of the three mixtures with microfines counted as powder instead of aggregate, and DL-HMF-50-P had the greatest modulus of elasticity value of the three mixtures containing microfines counted as powder instead of aggregate. These two mixtures also showed the lowest and highest compressive strengths of the three mixtures containing microfines counted as powder instead of aggregate. The same trend was observed in the "Sand Blends Study."

Only LS-HMF-50-P had a lower modulus of elasticity than its comparable mixture, LS-HMF-50, tested in the "Sand Blends Study." GR-HMF-50-P and DL-HMF-50-P both had greater modulus of elasticity values than GR-HMF-50 and DL-HMF-50. This matches the same trend observed in the compressive strength values.

The compressive strength versus modulus of elasticity values are shown in Fig. 6.8. DL-HMF-50-P produced the highest strengths and the highest modulus of elasticity aside from LS-HMF-100-CEMENT. GR-HMF-50-P and LS-HMF-50-P both had lower compressive strengths and lower modulus of elasticity values. LS-C33-30-

25%FA had the lowest compressive strength and modulus of elasticity of the mixtures tested in the "Optimization Study." DL-HMF-50-P-25%FA had a similar compressive strength as LS-C33-30-25%FA but a much higher modulus of elasticity. DL-HMF-50-P-25%FA contains more manufactured sand and microfines than LS-C33-30-25%FA.

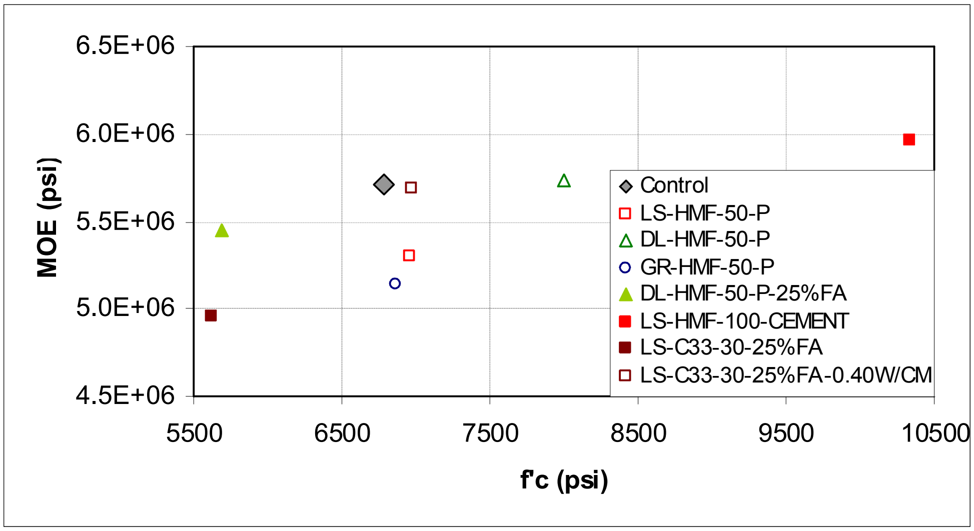

Figure 6.8: Compressive Strength versus Modulus of Elasticity of "Optimization Study" Mixtures

Section 6.3.4: Length Change

The length change of the concrete specimens tested in the "Optimization Study" was measured over 56 days. The results are presented in Fig. 6.9. The length change values are listed in Appendix D.

The 7-day measurements of the DL-HMF-50-P-25%FA mixture were removed from the data set due to errors in measurement. Since increased cement contents can lead to greater shrinkage of concrete specimens, it was expected that LS-HMF-100-CEMENT would experience the greatest shrinkage. Ultimately, this mixture had less length change than the control mixture. GR-HMF-50-P showed the least amount of length change over 56 days, and the total length change was very close to that measured for GR-C33-50 in the "Sand Blends Study." The total length changes measured for DL-HMF-50-P and LS-HMF-50-P were very close to those measured for DL-C33-50 and LS-C33-50, tested in the "Sand Blends Study." The mixtures tested in the "Optimization Study" contained microfines while the mixtures tested in the "Sand Blends Study" contained none. It does not appear that the grading made a noticeable difference in shrinkage values.

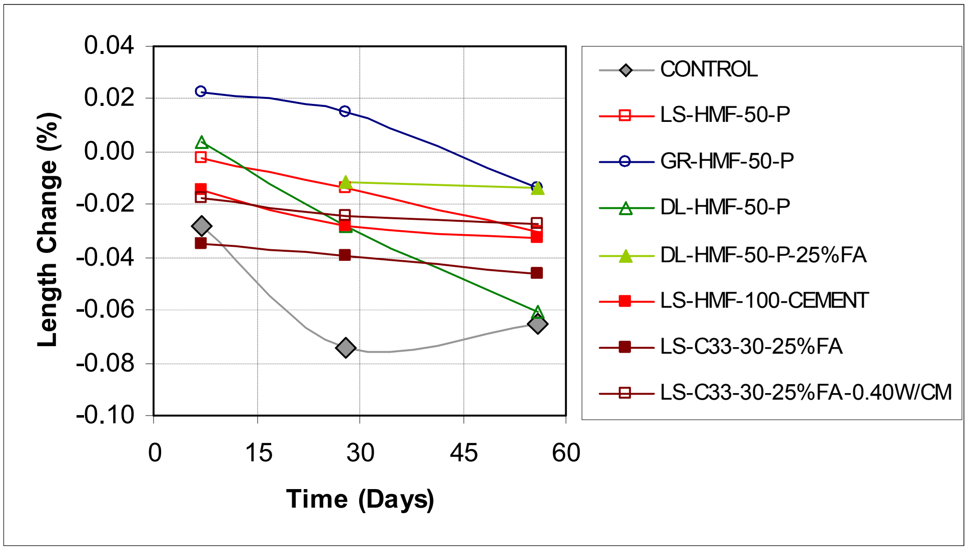

Figure 6.9: Length change of "Optimization Study" Mixtures

Section 6.3.5: Abrasion

Previously-tested flexural beams were tested for abrasion resistance in accordance with ASTM C 944 Standard Test Method for Abrasion Resistance of Concrete or Mortar Surfaces by the Rotating-Cutter Method. Formed and finished surfaces of the specimens were tested. The control mixture demonstrated the greatest mass loss of a finished surface, as seen in Table 6.3. As with the mixtures in the "Sand Blends Study," the specimens were finished by different individuals. The mass losses from the abrasion test on the finished surface of the concrete may not be suitable for comparison between mixtures.

Table 6.3: “Optimization Study” Abrasion Results

Specimen Name	Size	Mass Loss of Finished Surface (g)	Mass Loss of Formed Surface (g)
Control	8 in.x6 in.x3 in.	1.7	0.3
LS-HMF-50-P	8 in.x6 in.x3 in.	1.2	1.2
LS-C33-30-25%FA	8 in.x6 in.x3 in.	0.8	0.2
LS-C33-30-25%FA-0.40W/CM	8 in.x6 in.x3 in.	0.9	0.5
LS-HMF-100-CEMENT	8 in.x6 in.x3 in.	0.3	0.0
DL-HMF-50-P	8 in.x6 in.x3 in.	1.3	0.4
DL-HMF-50-P-25%FA	8 in.x6 in.x3 in.	0.8	0.6
GR-HMF-50-P	8 in.x6 in.x3 in.	1.5	0.4

The mixtures containing DL tended to have lower mass losses of the formed surfaces due to abrasion. The mixture that experienced the least amount of abrasion was LS-HMF-100-CEMENT. This mixture contained no microfines and a large amount of cement. LS-HMF-50-P experienced the greatest amount of mass loss of a formed surface of the mixtures tested in the “Optimization Study.” LS-HMF-50, tested in the “Sand Blends Study,” also showed high mass loss due to abrasion. The mass losses due to abrasion of the formed surfaces of the mixtures tested in the “Optimization Study” were generally less than those recorded for the mixtures tested in the “Sand Blends Study.” These mixtures had a greater amount of microfines, and the results indicate that microfines do not lower abrasion resistance. Only DL-HMF-50-P had a greater mass loss due to abrasion than its comparable mixture, DL-HMF-50.

Section 6.3.6: Density, Absorption, and Voids

The density, absorption, and voids of hardened concrete were measured for all of the mixtures tested in the “Optimization Study.” The density, absorption, and voids contents of the mixtures are presented in Appendix D. The absorption values of hardened concrete specimens of mixtures tested in the “Optimization Study” are shown in Fig. 6.10. The absorption values of mixtures tested in the “Optimization Study” were very similar. The absorption values after the concrete was boiled were all higher than the absorption values after the concrete was only immersed in water. This was to be expected; boiling the concrete completely saturated the voids, increasing the calculated absorption. The mixtures with LS, DL, and GR with the microfines considered as powder tended to have lower absorption values than the other mixtures tested in the "Optimization Study." These mixtures have increased amounts of microfines which fill capillary voids and lower absorption. LS-C33-30-25%FA-0.40W/CM also had lower absorption values because it had a lower *w/cm* and a dense microstructure.

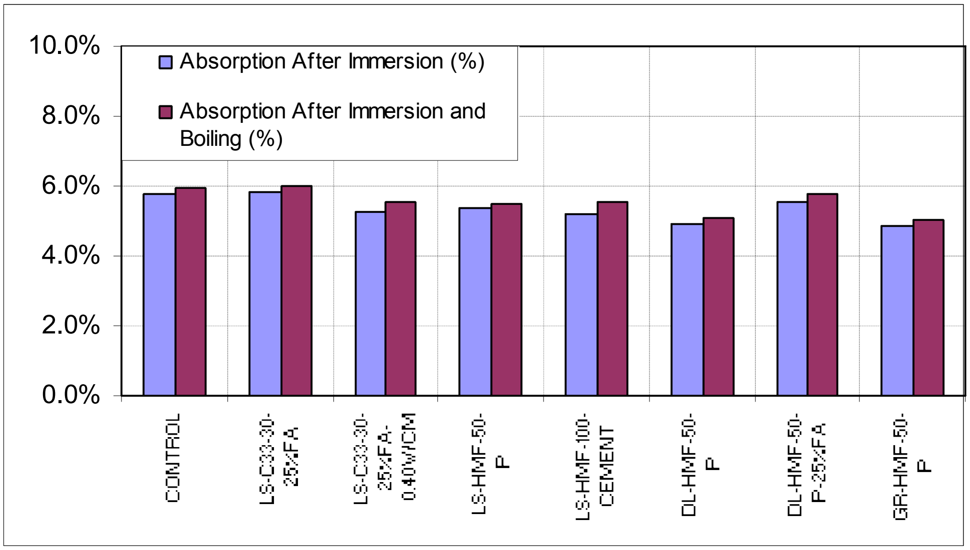

Figure 6.10: Absorption of "Optimization Study" Mixtures

The dry density values, density after immersion values, density after immersion and boiling values, and the apparent density values are shown in Fig. 6.11. The values were very consistent between the mixtures. Unlike the absorption values, the bulk densities did not change significantly between immersion and immersion after boiling.

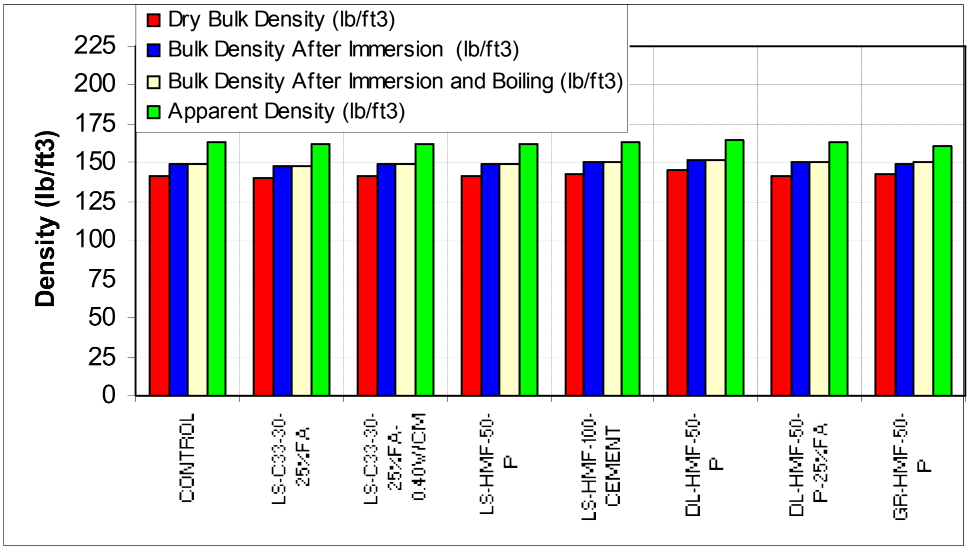

Figure 6.11: Density of “Optimization Study” Mixtures

The volumes of voids were also calculated for the mixtures in the “Optimization Study” and are shown in Fig. 6.12. The mixtures with microfines considered as powder had lower volumes of voids than the other mixtures tested in the “Optimization Study.” This was also observed for the absorption values. It would be expected that mixtures with lower absorption values would also have decreased void volumes. The void volume is decreased because the mixtures contain microfines. LS-C33-30-25%FA-0.40W/CM also had a lower percentage of voids, again due to the lower *w/cm*.

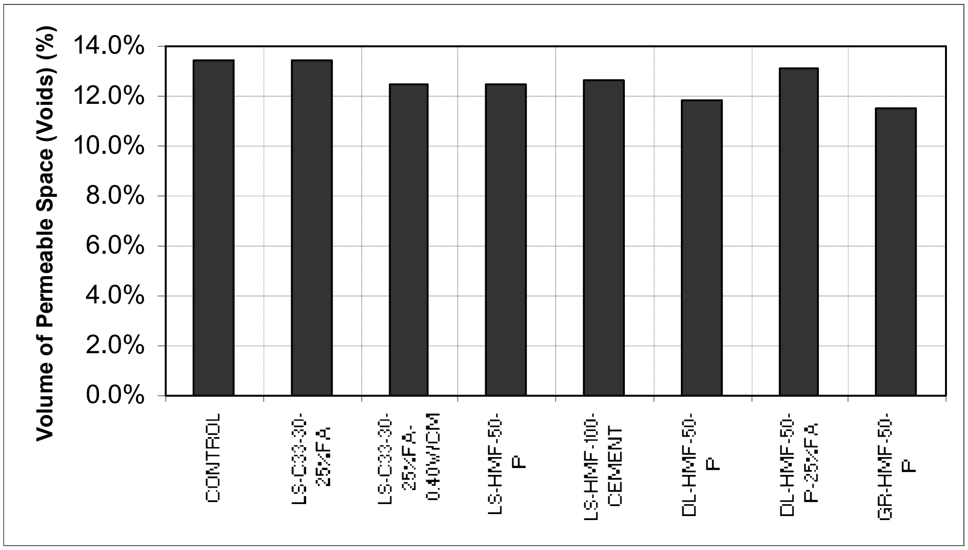

Figure 6.12: Voids Content of “Optimization Study” Mixtures

Section 6.3.7: Coefficient of Thermal Expansion

The coefficient of thermal expansion is important for paving concretes because the expansion or contraction can induce compression or tensile forces that can cause distress; the higher the coefficient, the greater the stresses for a given temperature change for concretes with the same modulus of elasticity. The coefficient of thermal expansion results are presented in Fig. 6.13. The coefficients of thermal expansion for the mixtures are presented in Appendix D. The greatest coefficient of thermal expansion was measured for DL-HMF-50-P-25%FA, and the lowest coefficient of thermal expansion was measured for LS-HMF-50-P. The CTE was very nearly the same as for the control mixture and LS-HMF-50-P. LS particles are well-shaped and most like NS out of the manufactured sands. A higher value of CTE would lead to increased stress from thermal expansion as well as increased movement.

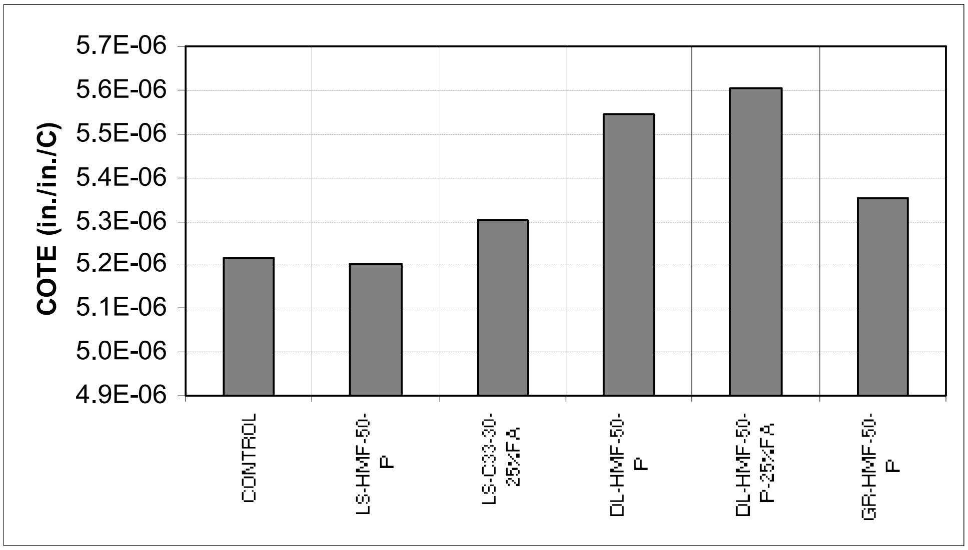

Figure 6.13: Coefficient of Thermal Expansion of "Optimization Study" Mixtures

SECTION 6.4: COST COMPARISON OF CONCRETE MIXTURES

Several of the mixtures from the "Sand Blends Study" were redesigned with the microfines considered to be powder instead of aggregate. In order to keep the paste content the same, the amounts of cement and water included in the mixtures were decreased. However, the mixtures with lower cement contents required more high-range water-reducing admixture to reach a similar slump. The costs of the concrete mixtures are presented in Table 6.4. The optimization mixtures had lower costs than the mixtures tested in the "Sand Blends Study." The decrease in cost was more noticeable for the mixtures containing limestone aggregate. The increased amount of limestone microfines did not harm the workability of the mixtures, so less HRWRA was required to achieve the necessary slump value.

The least expensive concrete mixture incorporated 25% by volume of cementing materials of Class F fly ash. Including fly ash in the mixture resulted in a savings of almost \$9.00/yd^3. Mixtures containing manufactured sand with high percentages of microfines can make suitable and economical concrete mixtures, especially if fly ash is included in the mixture.

Table 6.4: Cost of Concrete Mixtures

Type of Mixture	Mixture	Cement (lb/yd^3)	Fly Ash (lb/yd^3)	HRWRA (oz/cwt)	Cost of Cement (\$/yd^3)	Cost of Fly Ash (\$/yd^3)	Cost of HRWRA (\$/yd^3)	Total Cost of Concrete (\$/yd^3)	Optimization Savings (\$/yd^3)
Reg.	LS-HMF-50	614.7	0.0	1.6	33.81	0.00	0.90	34.71	-
Opt.	LS-HMF-50-P	547.2	0.0	2.0	30.10	0.00	0.98	31.08	3.62
Reg.	DL-HMF-50	614.7	0.0	1.6	33.81	0.00	0.90	34.71	-
Opt.	DL-HMF-50-P	547.2	0.0	8.0	30.10	0.00	3.93	34.03	0.68
Opt.	DL-HMF-50-P-25%FA	410.4	101.6	3.6	22.57	2.24	1.33	26.13	8.57
Reg.	GR-HMF-50	614.7	0.0	2.4	33.81	0.00	1.35	35.15	-
Opt.	GR-HMF-50-P	547.2	0.0	9.3	30.10	0.00	4.57	34.67	0.49

SECTION 6.5: SUMMARY OF "OPTIMIZATION STUDY" RESULTS

The purpose of the "Optimization Study" was to investigate how mixtures vary when they are designed more for the individual aggregate rather than a universal mixtures design. The workability results were similar to those observed in the "Sand Blends Study." The mixture with GR required the greatest dosage of HRWRA to reach the desired workability. The mixtures with LS with C33 grading did not require any HRWRA to reach acceptable slumps.

DL-HMF-50-P-25%FA required a low dosage of WRA to achieve an acceptable slump while DL-HMF-50-P required a high dosage of HRWRA to meet the appropriate slump value. This indicates that the fly ash particles are better-shaped than the cement particles and contribute to the workability of the mixture. LS-HMF-100-CEMENT also required more HRWRA than its equivalent mixture, LS-HMF-100. The microfine particles are more ideally-shaped and contribute to the workability of the mixture.

All of the mixtures with the microfines considered to be powder instead of aggregate required more HRWRA than the same mixtures with the microfines considered to be aggregate tested in the "Sand Blends Study." These mixtures had lower paste contents and increased fine aggregate contents, producing sticky mixtures with low workability.

As with the "Sand Blends Study," there did not appear to be any trends between air content and mixture design. All mixtures had air contents close to the assumed value of 2%.

The time of set was measured for only the mixtures tested in the "Optimization Study." The time of set of mixtures containing fly ash increased. DL-HMF-50-P-

25%FA had an especially high setting time because it also contained water-reducing admixture.

The highest compressive strength was recorded for LS-HMF-100-CEMENT, the mixture with a high amount of cement and low *w/c*. The fly ash tends to produce lower early compressive strength values as compared to portland cement. The strength difference may not have been observed had the specimens been tested at a later date. The compressive strengths of the mixtures tested in the "Optimization Study" tended to be greater than comparable mixtures tested in the "Sand Blends Study." This is likely due to the increased packing density provided by the higher microfine content.

The highest flexural strength was recorded for LS-HMF-100-CEMENT, the mixture with a high amount of cement and low *w/c*. The mixtures with fly ash again produced lower flexural strengths. The flexural strengths of the mixtures tested in the "Optimization Study" were generally lower than those of the mixtures tested in the "Sand Blends Study."

The highest modulus of elasticity was recorded for LS-HMF-100-CEMENT, the mixture with a high amount of cement and low *w/c*. The mixtures containing fly ash had lower modulus of elasticity values. These mixtures also had lower compressive strengths.

As with the "Sand Blends Study," the control mixture showed the greatest amount of length change in 56 days. The mixture with GR with the microfines considered to be powder showed the least amount of length change over 56 days. The length changes were close to those measured for the mixtures in the "Sand Blends Study." However, the length changes were only measured for mixtures containing 50% and 100% MFA with C33 grading in the "Sand Blends Study." This indicates that the grading does not affect shrinkage that much.

As in the “Sand Blends Study,” the mixtures with DL had better abrasion resistance than the other mixtures in the “Optimization Study.” The mixtures in the “Optimization Study” tended to have increased abrasion resistance than their comparable mixtures tested in the “Sand Blends Study.”

Mixtures containing microfines had lower absorption and void contents than mixtures without microfines. The microfines filled in the capillary voids and densified the pore structure. This decreases the porosity of the concrete.

The mixtures tested in the “Optimization Study” were less expensive than comparable mixtures tested in the “Sand Blends Study.” The “Optimization Study” mixtures contained less cement, which helped to decrease the cost of the concrete. The mixtures required more high-range water-reducing admixture for workability, but the increased cost of HRWRA did not offset the lower price due to the decreased cement content. The cost decreased further when fly ash was included in the mixture.

Chapter 7: Conclusions and Recommendations

SECTION 7.1: SUMMARY OF EXPERIMENTAL PROGRAM

Three manufactured sands and natural sand were added to concrete mixtures in various proportions. The manufactured sands were either washed over a No. 200 sieve, sieved and remixed to meet a grading that falls within the limits established by ASTM C 33, or sieved and remixed to meet a grading composed of 18% microfines by weight.

The "Sand Blends Study" was completed first, and its function was to determine how sand type, grading, or blend ratio (proportion of manufactured sand to the proportion of natural sand) might affect fresh and hardened concrete properties. The mixtures in this study were based on a universal mixture design that consisted of a 0.45 w/c, 30% paste content, and only cement, and the aggregate was made up of 45% coarse aggregate, 15% intermediate aggregate, and 40% blended sand. The microfines were not part of the powder or paste; instead, they were considered to be part of the aggregate.

The second part of the research program concerned the optimization of select mixtures. Mixtures with HMF grading were redesigned in the "Optimization Study" by lowering the paste content, decreasing the cement and water contents, and increasing the amount of fine aggregate and microfines. In other mixtures tested in the "Optimization Study," fly ash was substituted for cement, *w/cm* was lowered, and cement was substituted for microfines.

SECTION 7.2: SUMMARY OF TEST RESULTS

Section 7.2.1: Fresh Concrete Properties

Increasing the amount of manufactured sand was found to reduce concrete workability. The decrease in workability could be offset by the addition of high-range water-reducing admixture. Mixtures with high percentages of microfines require more HRWRA because the water/powder ratio of the mix was decreased. Measuring the workability of concrete containing high percentages of manufactured sand and/or microfines is challenging; it is difficult to properly compare the workability of low-slump concrete mixtures. Therefore, in addition to slump, the amount of HRWRA was varied as an alternate indicator of workability.

The shape of the aggregate did affect workability. Granite and dolomitic limestone concretes tended to require more HRWRA than limestone concretes, especially for the mixtures with high percentages of microfines. The uncompacted void content of the fine aggregate was shown to be related to the workability of mixtures with aggregate with C33 grading. The uncompacted void content is an indirect measure of shape. It showed that aggregates with lower uncompacted void contents will likely have greater workability. Angular aggregates have higher void contents.

It was desired to have a consistent baseline mixture (constant paste volume and *w/*c) when comparing mixtures. In optimizing mixtures, it would be possible to adjust the paste volume, add supplementary cementing materials, or make other modifications instead of only adjusting HRWRA dose. Mixtures with high percentages of microfines might need higher paste contents to achieve greater workability. Also, water-reducing admixture may not be sufficient to achieve a slump of 2 in, and including it in the mixture may have a retarding effect on the concrete.

There does not seem to be a strong relationship between air content and percentage of manufactured sand. If the mixtures had been air-entrained, the manufactured sands would have been expected to have a large effect on entrained air content. The concrete mixtures in the test series were not air-entrained to simplify the comparison of workability. All mixtures produced about 2% air content.

Time of set will be affected by the choice of water-reducing admixture, dosage of WRA, and if fly ash is included in the mixture. More water-reducing admixture will increase setting times. Fly ash can also have a negative effect on setting time.

Section 7.2.2: Hardened Concrete Properties

The compressive strength increases with increasing percentages of manufactured sand. The effects of hardened properties can be direct (effects of just changing aggregate) or indirect (the effects of changing mixture proportions due to changes in aggregates). For example, using the tested granite sand would have a direct effect on the hardened concrete properties; it would produce lower concrete strengths. Including the tested dolomitic limestone sand would produce higher concrete strengths. Mixtures with dolomitic limestone have greater amounts of fine aggregate because proportioning is calculated by volume, and dolomitic limestone has the greatest specific gravity. This can also affect the compressive strength.

The mixtures with the microfines considered as powder in the “Optimization Study” generally had greater compressive strengths than comparable mixtures in the “Sand Blends Study.” The increased compressive strength can be attributed to the greater packing density provided by the microfines included in the sand. There were strong correlations between flexural strength and MBV and between flexural strength and packing density. A greater packing density would fill in the voids in the concrete to increase strength and decrease permeability.

The flexural strength increased with increasing percentages of dolomitic limestone and limestone sand. However, it decreases with increasing percentages of granite sand. Mixtures with granite sand also produced the lowest flexural strengths. The mixtures with the microfines considered as powder in the "Optimization Study" showed lower flexural strengths in the "Sand Blends Study." This contradicts the compressive strength results.

The modulus of elasticity decreases with increasing percentages of manufactured sand. The tested granite sand produces concrete with the lowest values of compressive strength, flexural strength, and modulus of elasticity. The mixtures with the microfines considered as powder in the "Optimization Study" had greater modulus of elasticity values than those in the "Sand Blends Study."

The mixtures in the "Optimization Study" cost less than comparable mixtures in the "Sand Blends Study." The decreased cost was due to the decreased cement content in the "Optimization Mixtures." The mixture incorporating fly ash proved to be the cheapest concrete mixture.

SECTION 7.3: FHWA STRATEGIC GOALS

The research program helps to meet the FHWA strategic goal of environmental stewardship. Manufactured sand can replace natural sand in concrete mixtures. Using less natural sand leads to a decrease in river dredging and the disruption of river environments. As mentioned previously, the areas used for aggregate mining can be reclaimed and developed for new purposes, such as residential, commercial, or recreational usage. The aggregate mining locations may also be located closer to construction sites, lowering the amount of carbon dioxide emitted from the transportation of the aggregate.

SECTION 7.4: RECOMMENDATIONS AND GUIDELINES FOR THE USE OF MFA IN PAVEMENT CONCRETE

1. Expect that a higher blend ratio of manufactured sand to natural sand will decrease workability. Even the best-shaped manufactured sands are usually more poorly-shaped than siliceous river sand.
2. Incorporate fly ash into the mixture if possible. The negative impacts on workability caused by angular particles and high microfines can be counteracted by the addition of fly ash.
3. Poorly-shaped manufactured sands will require higher paste contents to reach the same workability as well-shaped manufactured sands.
4. It is viable to use mixtures with higher percentages of microfines in paving concrete. The workability is decreased, but it can be restored by increasing the paste content and including water-reducing admixture or high-range water-reducing admixture in the mixture.
5. Washed manufactured sands, even if they do not meet ASTM C33 limits, can make suitable paving concrete mixtures.
6. The cost of the concrete can be decreased by increasing the amount of microfines and lowering the cement content. The price of the concrete mixtures can be lowered further by including fly ash in the mixtures.
7. Acceptable concrete mixtures can be made with up to 18% microfines. These mixtures require higher amounts of high-range water-reducing admixture.
8. The uncompacted void content as determined by ASTM C 1252 has a high correlation with workability as measured by high-range water-reducing admixture demand. The uncompacted void content does not

correlate well with compressive strength, flexural strength, or modulus of elasticity.

9. The tests conducted on the microfines (methylene blue, single-drop test, and laser diffraction) did not correlate well with high-range water-reducing admixture demand, compressive strength, flexural strength, or modulus of elasticity.

Appendix A

Table A.1: “Sand Blends Study” Mixture Abbreviations

Abbreviation	Blend Description
CONTROL	100% NS with As-Received Grading
LS-WARG-50	50% NS and 50% LS Washed over No. 200 Sieve
LS-WARG-100	100% LS Washed over No. 200 Sieve
LS-C33-30	70% NS and 30% LS with ASTM C 33 Grading
LS-C33-50	50% NS and 50% LS with ASTM C 33 Grading
LS-C33-70	70% NS and 30% LS with ASTM C 33 Grading
LS-C33-100	100% LS with ASTM C 33 Grading
LS-HMF-50	50% NS and 50% LS with High Microfines Grading
LS-HMF-100	100% LS with High Microfines Grading
DL-WARG-50	50% NS and 50% DL Washed over No. 200 Sieve
DL-WARG-100	100% DL Washed over No. 200 Sieve
DL-C33-30	70% NS and 30% NDL with ASTM C 33 Grading
DL-C33-50	50% NS and 50% NDL with ASTM C 33 Grading
DL-C33-70	70% NS and 30% NDL with ASTM C 33 Grading
DL-C33-100	100% NDL with ASTM C 33 Grading
DL-HMF-50	50% NS and 50% NDL with High Microfines Grading
DL-HMF-100	100% NDL with High Microfines Grading
GR-WARG-50	50% NS and 50% GR Washed over No. 200 Sieve
GR-WARG-100	100% GR Washed over No. 200 Sieve
GR-C33-30	70% NS and 30% GR with ASTM C 33 Grading
GR-C33-50	50% NS and 50% GR with ASTM C 33 Grading
GR-C33-70	70% NS and 30% GR with ASTM C 33 Grading
GR-C33-100	100% GR with ASTM C 33 Grading
GR-HMF-50	50% NS and 50% GR with High Microfines Grading
GR-HMF-100	100% GR with High Microfines Grading

Table A.2: “Optimization Study” Mixture Abbreviations

Abbreviation	**Blend Description**
LS-HMF-50-P	50% NS and 50% LS with High Microfines Grading and the Microfines Considered as Powder
LS-HMF-100-P	100% LS with High Microfines Grading and the Microfines Considered as Powder
LS-HMF-100-P-CEMENT	100% LS with Microfines Replaced with Cement
LS-C33-30-25%FA	70% NS and 30% LS with ASTM C 33 Grading and 25% Fly Ash
LS-C33-30-25%FA-0.40W/CM	70% NS and 30% LS with ASTM C 33 Grading, 25% Fly Ash, and 0.40 w/cm
DL-HMF-50-P	50% NS and 50% DL with High Microfines Grading and the Microfines Considered as Powder
DL-HMF-100-P	100% DL with High Microfines Grading and the Microfines Considered as Powder
DL-HMF-50-P-25%FA	50% NS and 50% DL with High Microfines Grading with 25% Fly Ash
DL-HMF-100-P-25%FA	100% DL with High Microfines Grading with 25% Fly Ash
GR-HMF-50-P	50% NS and 50% GR with High Microfines Grading and the Microfines Considered as Powder
GR-HMF-100-P	100% GR with High Microfines Grading and the Microfines Considered as Powder

Appendix B

Table B.1: Combined Gradings of Washed Sand Blends

US Sieve	**Size**	**LS-WARG-50**		**LS-WARG-100**		**DL-WARG-50**		**DL-WARG-100**		**GR-WARG-50**		**GR-WARG-100**	
-	(in.)	% Ret.	% Pass.	% Ret.	% Pass.	% Ret.	% Pass.	% Ret.	% Pass.	% Ret.	% Pass.	% Ret.	% Pass.
1.5"	1.500	0.0	100.0	0.0	100.0	0.0	100.0	0.0	100.0	0.0	100.0	0.0	100.0
1"	1.000	8.9	91.1	8.9	91.1	8.9	91.1	8.9	91.1	8.9	91.1	8.9	91.1
3/4"	0.750	11.3	79.8	11.3	79.8	11.3	79.8	11.3	79.8	11.3	79.8	11.3	79.8
1/2"	0.500	12.5	67.3	12.5	67.3	12.5	67.3	12.5	67.3	12.5	67.3	12.5	67.3
3/8"	0.375	12.3	55.0	12.3	55.0	12.3	55.0	12.3	55.0	12.3	55.0	12.3	55.0
#4	0.187	14.2	40.8	13.9	41.1	15.0	40.0	15.5	39.5	14.2	40.8	13.9	41.1
#8	0.093	3.4	37.4	2.1	39.0	8.7	31.3	12.5	26.9	5.1	35.7	5.3	35.8
#16	0.046	9.5	27.9	14.3	24.8	7.9	23.4	11.0	15.9	5.8	29.9	6.9	28.9
#30	0.024	9.5	18.4	10.2	14.5	7.7	15.7	6.8	9.1	7.6	22.3	6.5	22.3
#50	0.012	10.2	8.2	7.4	7.2	8.7	7.0	4.3	4.8	10.6	11.7	8.2	14.2
#100	0.006	5.2	3.1	4.7	2.5	4.0	3.1	2.3	2.5	6.9	4.8	8.1	6.0
#200	0.003	1.9	1.1	1.7	0.8	1.9	1.1	1.7	0.8	3.7	1.1	5.2	0.8
Pan	-	1.1	0.0	0.8	0.0	1.1	0.0	0.8	0.0	1.1	0.0	0.8	0.0
Coarseness Factor	-	71.8		73.8		65.5		61.6		70.0		70.0	
Workability Factor	-	37.4		39.0		31.3		26.9		35.7		35.8	

Table B.2: Combined Gradings of C33 Sand Blends

US Sieve	**Size**	**C33-30**		**C33-50**		**C33-70**		**C33-100**	
-	(in.)	% Ret.	% Pass.	% Ret.	% Pass.	% Ret.	% Pass.	% Ret.	% Pass.
1.5"	1.500	0.0	100.0	0.0	100.0	0.0	100.0	0.0	100.0
1"	1.000	8.9	91.1	8.9	91.1	8.9	91.1	8.9	91.1
3/4"	0.750	11.3	79.8	11.3	79.8	11.3	79.8	11.3	79.8
1/2"	0.500	12.5	67.3	12.5	67.3	12.5	67.3	12.5	67.3
3/8"	0.375	12.3	55.0	12.3	55.0	12.3	55.0	12.3	55.0
#4	0.187	14.5	40.5	14.4	40.6	14.4	40.6	14.4	40.6
#8	0.093	5.7	34.9	6.2	34.3	6.8	33.8	7.7	33.0
#16	0.046	6.6	28.3	7.9	26.4	9.2	24.6	11.1	21.9
#30	0.024	8.4	19.8	8.3	18.2	8.1	16.5	7.9	14.0
#50	0.012	10.8	9.0	9.4	8.7	8.0	8.5	5.8	8.2
#100	0.006	5.2	3.8	4.8	3.9	4.5	4.0	4.0	4.2
#200	0.003	2.5	1.3	2.8	1.1	3.0	1.0	3.4	0.8
Pan	-	1.3	0.0	1.1	0.0	1.0	0.0	0.8	0.0
Coarseness Factor	-	69.1		68.5		67.9		67.1	
Workability Factor	-	34.9		34.3		33.8		33.0	

Table B.3: Combined Gradings of HMF Sand Blends

US Sieve	**Size**	**LS-HMF-50**		**LS-HMF-100**	
-	(in.)	% Ret.	% Pass.	% Ret.	% Pass.
1.5"	1.500	0.0	100.0	0.0	100.0
1"	1.000	8.9	91.1	8.9	91.1
3/4"	0.750	11.3	79.8	11.3	79.8
1/2"	0.500	12.5	67.3	12.5	67.3
3/8"	0.375	12.3	55.0	12.3	55.0
#4	0.187	14.4	40.6	14.3	40.7
#8	0.093	6.0	34.6	7.3	33.5
#16	0.046	6.7	27.8	8.8	24.7
#30	0.024	7.5	20.4	6.2	18.5
#50	0.012	8.8	11.6	4.6	13.9
#100	0.006	4.4	7.2	3.2	10.7
#200	0.003	2.4	4.7	2.7	8.0
Pan	-	4.7	0.0	8.0	0.0
Coarseness Factor	-	68.8		67.6	
Workability Factor	-	34.6		33.5	

Table B.4: Bulk Density and Voids Content of Sand Blends

Mixture	Bulk Density (lb/ft^3)	Voids Content (%)
BASELINE	128	19.6
LS-HMF-50	125	21.6
LS-HMF-100	120	24.6
LS-C33-30	123	23.1
LS-C33-50	122	23.3
LS-C33-70	123	22.9
LS-C33-100	121	24.3
LS-WARG-50	126	21.0
LS-WARG-100	125	21.9
DL-HMF-50	126	21.6
DL-HMF-100	126	22.1
DL-C33-30	127	20.9
DL-C33-50	128	20.2
DL-C33-70	124	23.5
DL-C33-100	122	25.1
DL-WARG-50	126	21.6
DL-WARG-100	118	27.5
GR-HMF-50	122	24.0
GR-HMF-100	128	21.3
GR-C33-30	126	21.2
GR-C33-50	129	19.8
GR-C33-70	124	23.2
GR-C33-100	122	24.9
GR-WARG-50	123	23.7
GR-WARG-100	124	23.3

Appendix C

Table C.1: HRWRA Demand of “Sand Blends Study” Mixtures

Mix Description	HRWRA Demand (oz/cwt)
CONTROL	0.0
LS-WARG-50	0.0
LS-WARG-100	3.7
LS-C33-30	0.0
LS-C33-50	0.0
LS-C33-70	0.0
LS-C33-100	0.0
LS-HMF-50	1.6
LS-HMF-100	2.4
DL-WARG-50	0.0
DL-WARG-100	3.3
DL-C33-30	1.6
DL-C33-50	1.4
DL-C33-70	1.6
DL-C33-100	4.1
DL-HMF-50	1.6
DL-HMF-100	9.8
GR-WARG-50	1.6
GR-WARG-100	4.9
GR-C33-30	0.0
GR-C33-50	1.6
GR-C33-70	2.4
GR-C33-100	3.4
GR-HMF-50	2.4
GR-HMF-100	5.7

Table C.2: “Sand Blends Study” Air Content

Mixture	Air Content (%)
Control	1.8
LS-WARG-50	-
LS-WARG-100	-
LS-C33-30	1.8
LS-C33-50	1.6
LS-C33-70	2.4
LS-C33-100	2.2
LS-HMF-50	1.8
LS-HMF-100	2.0
DL-WARG-50	1.5
DL-WARG-100	1.8
DL-C33-30	1.7
DL-C33-50	1.9
DL-C33-70	1.7
DL-C33-100	1.8
DL-HMF-50	1.7
DL-HMF-100	1.6
GR-WARG-50	-
GR-WARG-100	-
GR-C33-30	-
GR-C33-50	1.9
GR-C33-70	-
GR-C33-100	2.1
GR-HMF-50	-
GR-HMF-100	-

Table C.3: “Sand Blends Study” Compressive Strengths

Mix Description	**f'c (psi)**
CONTROL	6788
LS-WARG-50	7125
LS-WARG-100	7143
LS-C33-30	6814
LS-C33-50	7211
LS-C33-70	6476
LS-C33-100	7431
LS-HMF-50	7126
LS-HMF-100	7437
DL-WARG-50	7159
DL-WARG-100	7103
DL-C33-30	7526
DL-C33-50	7304
DL-C33-70	7481
DL-C33-100	7832
DL-HMF-50	7002
DL-HMF-100	7874
GR-WARG-50	6270
GR-WARG-100	6344
GR-C33-30	6259
GR-C33-50	6353
GR-C33-70	6285
GR-C33-100	6566
GR-HMF-50	6582
GR-HMF-100	6565

Table C.4: “Sand Blends Study” Flexural Strengths

Mix Description	Measured MOR (psi)
CONTROL	870
LS-WARG-50	934
LS-WARG-100	978
LS-C33-30	807
LS-C33-50	892
LS-C33-70	813
LS-C33-100	927
LS-HMF-50	950
LS-HMF-100	980
DL-WARG-50	838
DL-WARG-100	1037
DL-C33-30	881
DL-C33-50	1007
DL-C33-70	885
DL-C33-100	996
DL-HMF-50	966
DL-HMF-100	986
GR-WARG-50	968
GR-WARG-100	903
GR-C33-30	849
GR-C33-50	847
GR-C33-70	865
GR-C33-100	824
GR-HMF-50	932
GR-HMF-100	884

Table C.5: “Sand Blends Study” Modulus of Elasticity

Mix Description	MODULUS OF ELASTICITY (psi)
CONTROL	5.7E+06
LS-WARG-50	5.3E+06
LS-WARG-100	5.2E+06
LS-C33-30	5.4E+06
LS-C33-50	5.4E+06
LS-C33-70	5.2E+06
LS-C33-100	5.1E+06
LS-HMF-50	5.6E+06
LS-HMF-100	5.3E+06
DL-WARG-50	5.4E+06
DL-WARG-100	5.3E+06
DL-C33-30	5.6E+06
DL-C33-50	5.5E+06
DL-C33-70	5.4E+06
DL-C33-100	5.5E+06
DL-HMF-50	5.5E+06
DL-HMF-100	5.6E+06
GR-WARG-50	5.1E+06
GR-WARG-100	4.8E+06
GR-C33-30	5.1E+06
GR-C33-50	5.1E+06
GR-C33-70	4.8E+06
GR-C33-100	4.8E+06
GR-HMF-50	5.1E+06
GR-HMF-100	4.8E+06

Table C.6: "Sand Blends Study" Length Change

	Length Change (%)		
Mix Description	**7 Days**	**28 Days**	**56 Days**
CONTROL	-0.03	-0.07	-0.07
LS-C33-50	-0.01	-0.01	-0.02
LS-C33-100	0.01	-0.05	-0.03
DL-C33-50	-0.02	-0.04	-0.06
DL-C33-100	0.02	-0.01	-0.02
GR-C33-50	0.02	-0.03	-0.02
GR-C33-100	0.01	-0.03	-0.03

Appendix D

Table D.1: "Optimization Study" HRWRA Demand

Mixture	HRWRA Dosage (oz)
LS-HMF-50-P	2.0
LS-C33-30-25%FA	0
LS-C33-30-25%FA-0.40W/CM	0
LS-HMF-100-CEMENT	5.7
DL-HMF-50-P	8.0
DL-HMF-50-P-25%FA	3.6
GR-HMF-50-P	9.3

Table D.2: "Optimization Study" Air Content

Mixture	Air Content (%)
LS-HMF-50-P	2.2
LS-C33-30-25%FA	1.8
LS-C33-30-25%FA-0.40W/CM	2.4
LS-HMF-100-CEMENT	2.0
DL-HMF-50-P	2.5
DL-HMF-50-P-25%FA	2.5
GR-HMF-50-P	2.3

Table D.3: "Optimization Study" Time of Set

Mixture	Initial Set (min.)	Final Set (min.)
CONTROL	218	303
LS-HMF-50-P	202	308
LS-C33-30-25%FA	243	331
DL-HMF-50-P	226	300
DL-HMF-50-P-25%FA	271	401
GR-HMF-50-P	229	333

Table D.4: "Optimization Study" Compressive Strengths

Mixture	f'c (psi)
LS-HMF-50-P	6962
LS-C33-30-25%FA	5616
LS-C33-30-25%FA-0.40W/CM	6979
LS-HMF-100-CEMENT	10338
DL-HMF-50-P	8003
DL-HMF-50-P-25%FA	5686
GR-HMF-50-P	6868

Table D.5: "Optimization Study" Flexural Strengths

Mixture	Modulus of Rupture (psi)
LS-HMF-50-P	896
LS-C33-30-25%FA	859
LS-C33-30-25%FA-0.40W/CM	924
LS-HMF-100-CEMENT	1075
DL-HMF-50-P	1044
DL-HMF-50-P-25%FA	821
GR-HMF-50-P	910

Table D.6: "Optimization Study" Modulus of Elasticity

Mixture	Modulus of Elasticity (psi)
LS-HMF-50-P	5.3E+06
LS-C33-30-25%FA	5.0E+06
LS-C33-30-25%FA-0.40W/CM	5.7E+06
LS-HMF-100-CEMENT	6.0E+06
DL-HMF-50-P	5.7E+06
DL-HMF-50-P-25%FA	5.5E+06
GR-HMF-50-P	5.1E+06

Table D.7: "Optimization Study" Length Change

Mix Description	Length Change (%) 7 Days	28 Days	56 Days
LS-HMF-50-P	0.00	-0.01	-0.03
LS-C33-30-25%FA	-0.04	-0.04	-0.05
LS-C33-30-25%FA-0.40W/CM	-0.02	-0.02	-0.03
LS-HMF-100-CEMENT	-0.01	-0.03	-0.03
DL-HMF-50-P	0.00	-0.03	-0.06
DL-HMF-50-P-25%FA	-0.02	-0.01	-0.01
GR-HMF-50-P	0.02	0.02	-0.01

Table D.8: "Optimization Study" Absorption

Mix Description	Absorption After Immersion (%)	Absorption After Immersion and Boiling (%)
CONTROL	5.80	5.94
LS-C33-30-25%FA	5.83	5.99
LS-C33-30-25%FA-0.40W/CM	5.28	5.52
LS-HMF-50-P	5.37	5.49
LS-HMF-100-CEMENT	5.20	5.52
DL-HMF-50-P	4.91	5.11
DL-HMF-50-P-25%FA	5.57	5.76
GR-HMF-50-P	4.86	5.03

Table D.9: "Optimization Study" Voids

Mix Description	Volume of Permeable Space (Voids) (%)
CONTROL	13.41
LS-C33-30-25%FA	13.44
LS-C33-30-25%FA-0.40W/CM	12.50
LS-HMF-50-P	12.49
LS-HMF-100-CEMENT	12.65
DL-HMF-50-P	11.85
DL-HMF-50-P-25%FA	13.11
GR-HMF-50-P	11.50

Table D.10: "Optimization Study" Density

Mix Description	Dry Bulk Density (lb/ft^3)	Bulk Density After Immersion (lb/ft^3)	Bulk Density After Immersion and Boiling (lb/ft^3)	Apparent Density (lb/ft^3)
CONTROL	140.85	149.02	149.22	162.66
LS-C33-30-25%FA	140.10	148.27	148.49	161.86
LS-C33-30-25%FA-0.40W/CM	141.21	148.67	149.01	161.38
LS-HMF-50-P	141.89	149.51	149.69	162.15
LS-HMF-100-CEMENT	142.91	150.33	150.80	163.60
DL-HMF-50-P	144.74	151.85	152.14	164.20
DL-HMF-50-P-25%FA	141.99	149.90	150.17	163.41
GR-HMF-50-P	142.79	149.72	149.96	161.34

Table D.11: "Optimization Study" Coefficient of Thermal Expansion

Mix Description	CTE (in./in./°C)
CONTROL	5.2E-06
LS-HMF-50-P	5.2E-06
LS-C33-30-25%FA	5.3E-06
DL-HMF-50-P	5.5E-06
DL-HMF-50-P-25%FA	5.6E-06
GR-HMF-50-P	5.4E-06

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