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16. Abstract

Aggregate, the main constituent of concrete, constitutes 60 to 80% of the total volume of concrete. Proper selection of the type and particle size distribution of the aggregates affects the workability and the hardened properties of the concrete. There are two main reasons for increasing the amount of aggregates in concrete. The first is that cement is more expensive than aggregate, so using more aggregate reduces the cost of producing concrete. The second is that most of the durability problems, e.g. shrinkage and freezing and thawing, of hardened concrete are caused by cement. Generally, concrete shrinkage increases with increase in cement content; aggregates, on the other hand, reduce shrinkage and provide more volume stability. Furthermore, cement production is a key source of carbon dioxide (CO_2) emissions, and reducing its usage should be a goal for concrete production Various projects have explored methods of minimizing cement in concrete; amongst the most common of those is replacing cement with cementitious and pozzolanic materials such as fly ash.

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Chapter 1: Introduction

1.1 PROJECT BACKGROUND

Aggregate, the main constituent of concrete, constitutes 60 to 80% of the total volume of concrete. Proper selection of the type and particle size distribution of the aggregates affects the workability and the hardened properties of the concrete. There are two main reasons for increasing the amount of aggregates in concrete. The first is that cement is more expensive than aggregate, so using more aggregate reduces the cost of producing concrete. The second is that most of the durability problems, e.g. shrinkage and freezing and thawing, of hardened concrete are caused by cement. Generally, concrete shrinkage increases with increase in cement content; aggregates, on the other hand, reduce shrinkage and provide more volume stability. Furthermore, cement production is a key source of carbon dioxide (CO_2) emissions, and reducing its usage should be a goal for concrete production Various projects have explored methods of minimizing cement in concrete; amongst the most common of those is replacing cement with cementitious and pozzolanic materials such as fly ash.

1.2 PROBLEM STATEMENT

Aggregate shape, texture, and grading significantly affect concrete workability. To achieve the same workability, poorly shaped and poorly graded aggregates usually require more paste (cement and water). The additional paste is needed to compensate for the low packing density of those aggregates and for the higher inter-particle friction between them. Selecting the proper gradations for different blends of aggregates can minimize the paste volume and thus minimize the amount of cement. To maintain the desired workability at lower paste volumes, the flowability of the concrete should be increased.

1.3 REASEARCH OBJECTIVES

Cement content can be reduced for a given strength level in several ways. This research had the objective of decreasing paste volume by varying aggregate grading and replacing cement with mineral fillers (microfines). The effects of packing density and inter-particle friction were also tested by varying the types and gradations of the aggregates used.

1.4 SCOPE OF STUDY

The research study was divided in two phases. Phase I was concerned with modifying the grading of the mixtures using aggregates with different properties such as angularity, texture and grading. In Phase II, cement content was reduced by replacing cement with microfines. Before concrete testing began, a literature review was conducted to identify methods previously used in optimizing concrete mixtures (Chapter 2). Several types of aggregates were chosen and tests were performed on each of them (Chapters 3 and 4). Mortar tests were then performed to identify performance differences between the fine aggregates (Chapter 5), Finally, using the information obtained, concrete mixtures were designed and tested (Chapters 6, 7, and 8)

Chapter 2: Literature Review

2.1 INTRODUCTION

A literature review of some properties of natural and manufactured aggregates and their effect on the plastic and hardened properties of concrete are discussed in this chapter. Aggregate optimization methods and mixture proportioning methods are also presented.

2.2 AGGREGATE PROPERTIES

2.2.1 Shape

The shape of the aggregate particles influences paste demand, placement characteristics such as workability and pumpability, strength and cost. (O'Flynn 2000). Shape is related to sphericity, form, angularity, and roundness (Quiroga and Fowler 2004; Galloway 1994).

- The sphericity measures how nearly equal are the three principal axis of the aggregate (length L, width W, and height H). The sphericity increases as the three dimensions approach equal values. (Brzezicki and Kasperkiewicz 1999; Quiroga and Fowler 2004; Graves 2006)
- The form or the shape factor, describes the relative proportions of the three axes of a particle. It helps distinguish between particles that have the same sphericity (Quiroga and Fowler 2004; Graves 2006; Hudson 1999).
- The angularity describes the proportions of the average radius of curvature of corners and edges to the radius of maximum inscribed circle (Quiroga and Fowler 2004; Graves 2006).
- The roundness describes the sharpness of the edges and corners (Lamond and Pielert; Quiroga and Fowler 2004; Graves 2006).

Particle shape can be classified by the following descriptions:

- *Sphericity & form*: cubical, spherical, flat or elongated. (Quiroga and Fowler 2004; Brzezicki and Kasperkiewicz 1999).
- *Angularity & roundness:* Angular, subangular, subrounded, rounded, well-rounded. (Quiroga and Fowler 2004; Brzezicki and Kasperkiewicz 1999).

The descriptions of angularity and roundness are detailed here and illustrated in Figure 2.1:

- *Angular*: little evidence of wear on the particle surface
- *Subangular*: evidence of some wear, but faces untouched
- *Subrounded*: considerable wear, faces reduced in area
- *Rounded*: faces almost gone
- *Well rounded*: no original faces left

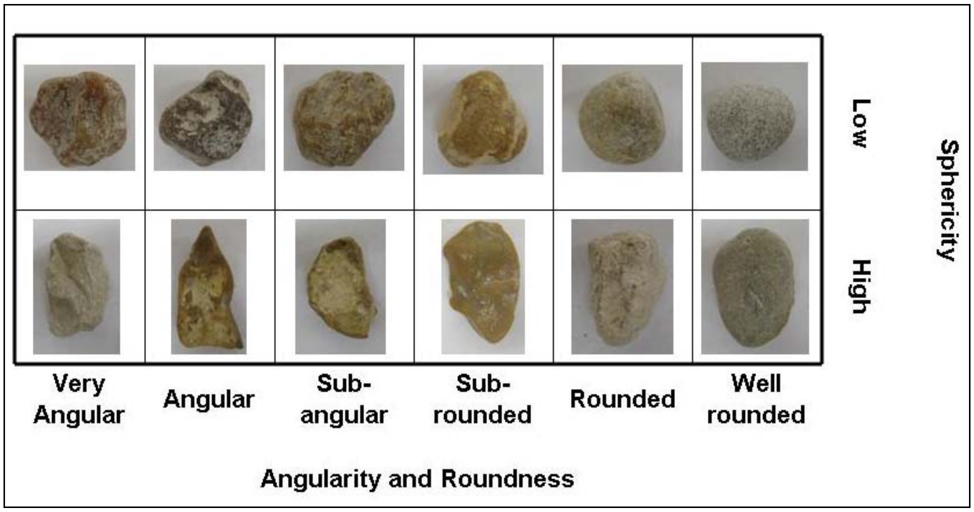

Figure 2.1: Particle Shape.

Round or nearly cubical shaped aggregates are desirable due to the ease in which they move in the mixing and handling process. However, aggregate can also contain flat or elongated shapes. Methods used to measure the shape of aggregates are the elongation factor and flatness factor (ASTM C 125). A flat particle has a width/thickness ratio greater than or equal to 3, while an elongated particle has a length/width ratio greater or equal to 3. Specifications usually define limiting elongation ratios of 3:1 or 5:1 to describe undesirable shapes of aggregates. The shape can modify the strength of the concrete, as in the case where a thin, flat particle is oriented in the hardened concrete where outside stresses are introduced (Graves 2006).

The shape of natural aggregates depends on the strength, abrasion resistance, and on the degree of wear to which they have been subjected in their depositional environment. Natural aggregates tend be more spherical and less angular. On the other hand, the shape of manufactured aggregate depends on the rock type and the crushing equipment. Manufactured aggregates are more angular when compared to natural aggregates.

The shape of an aggregate influences the workability of the mixture as well as the void content and packing density. For the same amount of paste, a mixture with round or cubical-shaped aggregate will have better workability than a mixture with flaky and elongated aggregates. Moreover, for the same mass of aggregates, round and cubical aggregates produce mixtures with higher packing, which results in a lower void content. The decreased percentage of voids lowers the amount of cement paste required for that particular mixture. Some specifications, such as the Spanish or British standards (Quiroga and Fowler 2004), limit the percent of use of flaky and elongated particles, but ASTM (American Society for Testing and Materials) has set no limits. Some state transportation departments (DOTs) have set limits on the percentage of flaky and elongated particles ranging from 8 to 20%.

2.2.2 Texture

Surface texture is the degree to which the surface may be defined as either: 1) being rough or smooth (referring to the height of asperities) or 2) coarse grained or fine grained (referring to the spacing between grains) (Graves 2006). The surface texture influences the workability, quantity of cement and bond between particles and the cement paste. Two independent geometric properties are the roughness or rugosity (degree of surface relief) and the roughness factor (the amount of surface area per unit of dimensional or projected area) (Graves 2006).

Natural aggregates have a smooth surface (Lamond and Pielert 2006). Natural gravel subject to transport mechanisms tends to be smoother than manufactured aggregates. For instance, gravel would have a surface smoother than crushed limestone. Nevertheless, there is no reliable method to determine the surface texture of manufactured aggregate (Ahn and Fowler 2001).

An improvement in the bond to the matrix is obtained as the surface roughness increases (Ahn and Fowler 2001). Rough-textured angular grains bond better with the cement paste to generate higher tensile strengths (O'Flynn 2000). The strength of the bond between cement and aggregate increases as absorption increases, but the durability decreases with an absorption increase (Quiroga and Fowler 2000). Although rougher textures lead to better bond between paste and aggregate, they also lead to harsher mixtures, as texture roughness increases, the internal friction increases between the aggregates, and therefore more paste is needed to achieve a given workability.

2.2.3 Grading

The gradation of an aggregate is defined as the frequency of a distribution of the particle sizes of a particular aggregate (Lamond and Pielert 2006). Grading limits are specified in ASTM C 33 section 6. (ASTM C 33) The size distribution or grading divides aggregates in three categories (Quiroga and Fowler 2004):

- *Coarse aggregate:* material retained by No. 4 sieve.

- *Fine aggregate:* material passing No. 4 sieve and retained in No. 200 sieve.
- *Microfines:* material passing No. 200 sieve.

Gradation plays an important role in the workability, segregation, and pumpability of the concrete. Grading changes are more prevalent than shape and surface texture in the case of coarse aggregates. For example, uniformly distributed aggregates require less paste which will also decrease bleeding, creep and shrinkage while producing better workability, more durable concrete and higher packing (Quiroga and Fowler 2004). A graded aggregate, as opposed to a single-size aggregate, will have a greater packing density. The smaller aggregates will fill in the voids created by the larger aggregates (Lamond and Pielert 2006). Optimization by blending more than two aggregates at a time is not recommended, especially if each fraction complies with ASTM C 33 grading separately (Quiroga and Fowler 2004).

Fine aggregate grading has a greater effect on workability of concrete than coarse aggregates. Manufactured sands require more fines than natural sands to achieve the same level of workability, probably due to the angularity of the manufactured sands particles (Graves 2006). A decrease in the workability and durability of concrete are possible consequences of using an aggregate with either an excess or a lack of a particular size fraction (Galloway 1994; Shilstone 1990).

Concrete mixtures with fine aggregate grading near the minimum for percent passing the No. 50 and No. 100 sieve may pose some problems with workability, pumping or excessive bleeding (ASTM C 33). A fine aggregate that is too coarse will lead to harshness, bleeding, and segregation, but fine aggregate that is too fine will result in an increased water demand and segregation (Lamond and Pielert 2006). There is also an increase in water demand as dust of fracture percentage is increased. This increase was attributed to an increase in the specific surface due to the particle size decrease (Ann and Fowler 2000; O'Flynn 2000). The greater the maximum size aggregate in a mixture the less paste is needed, and the more the fine particles the more the paste required.

Particles of irregular shape do not fit together perfectly and voids are created when these particles are assembled in a single container. The greater the void content, the more the paste required to fill these voids. The void content is affected by the particle size, grading, and packing efficiency. When a portion of two aggregates are combined and placed in a single container, the quantity of water needed to fill the voids for the same volume decreases. Thus, combining aggregates of different size fractions reduce the void ratio.

2.3 APPROACHES TO OPTIMIZING AGGREGATE GRADATION

2.3.1 Packing Density Methods

Packing density is defined as the volume of solids as a percentage of the total bulk volume. It provides an indirect mean of measuring aggregate geometric characteristics and a means of calculating the void content that needs to be filled with cement paste. Aggregate gradations with higher packing density allow for larger volumes of aggregates and lower volumes of paste (Figure 2.2).

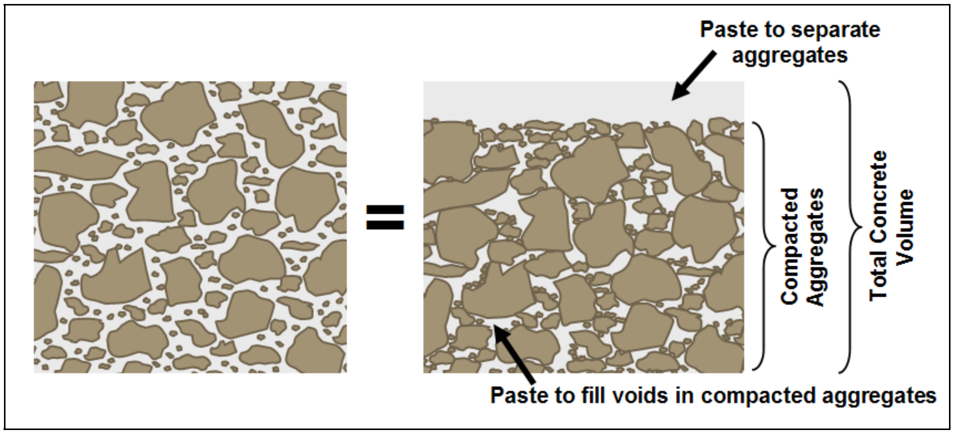

Figure 2.2: Paste Needed to Fill Voids between Aggregates (Koehler and Fowler 2007)

Research done by Fuller and Thompson (1907) on adjusting gradation to render the greatest strength and workability concluded that aggregates should be graded in sizes and combined with water to give the greatest density. They developed a gradation curve that represented the greatest density of aggregates, but concluded that this gradation might not produce the greatest density when combined with cement and water because of the way cement particles fit in the pores. Work done by Wig et al. (1916) showed that the curve suggested by Fuller and Thompson (1907) does not always give the maximum density when aggregates different than the ones they studied were used. Talbot and Richart (1923) developed the following equation:

$$P = \left(\frac{d}{D}\right)^n$$

Where P is the amount of material in the system finer than size d, D is the maximum particle size, and n is the exponent governing the distribution of sizes. They concluded that for a given maximum particle size D, the maximum density can be achieved when n=0.5, but the resulting mixtures were harsh and not usable.

Many modifications have since been made to this equation; Shilstone (1990) and Quiroga (2003) suggested that the optimum value of n is 0.45. Work done by Bolomey (1947) extended the concept of parabolic grading and added an empirical value to the equation that reflected the desired level of workability. Furthermore, many other mathematical models based on empirical measurements have been developed to compute packing density.

2.3.2 Surface Area

According to Edwards (1918), the amount of water required for a concrete mixture is a function of the surface area of the aggregate particles. Young (1919) found that quantity of water required was dependent upon the quantity and consistency of the cement and the total surface area of the aggregate, which in turn is dependent on the grading. Young (1919) also found that the less the surface area of the aggregates, the less the excess water needed for the cement.

2.3.3 0.45 Power Chart

The 0.45 Power Chart is similar to a semi-log graph (Figure 2.3). It was originally used to obtain uniform gradation for asphalt mixture designs. The x-axis contains the sieve size, and the y-axis contains the percent of aggregates passing a given sieve. According to this method, the best combined grading, i.e. the grading with the least amount of voids is defined by a straight line (ACI 302-04; IM 532).

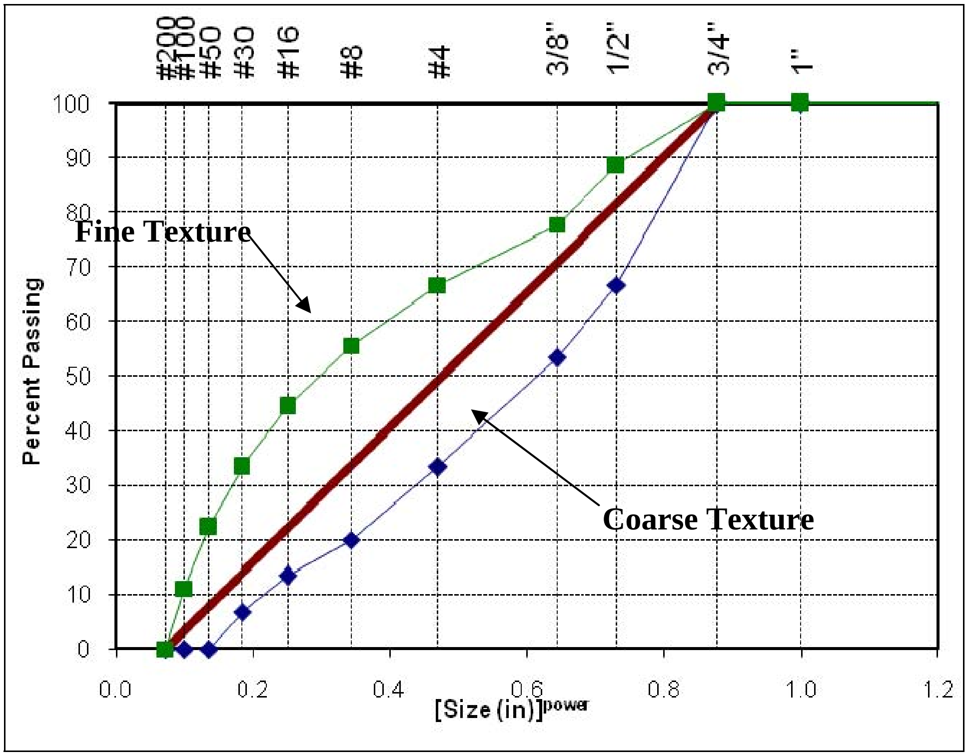

Figure 2.3: 0.45 Power Chart.

In this chart, deviations from the 0.45 power line help identify the location of grading problems. "Zigzags" across the line are undesirable. Gap-graded aggregate combinations will form an S-shape curve deviating from the optimum (ACI 302-04).

2.3.4 Coarseness Factor Chart

The Coarseness Factor Chart developed by Shilstone (1990) is an alternative method of analyzing the size and uniformity of the combined aggregate particle distribution (Figure 2.4). For the Coarseness Factor Chart a consideration of the grading of the whole aggregate is made, instead of considering the coarse and fine aggregate separately. Aggregate is divided in three fractions: large, Q, intermediate, I, and fine, W. Large aggregate is larger than 3/8-in., intermediate aggregate is considered to be between 3/8-in. and the No. 4 sieve and fine aggregate is defined as smaller than a No. 4 sieve and larger than a No. 200 sieve. All minus No. 200 sieve materials are classified as paste and the combination of paste and fine aggregate is considered mortar. The Coarseness Factor Chart gives the relationship between the modified workability factor, which is equal to W corrected for cement content when more or less than 6 sacks per cubic yard are used, and the coarseness factor, which is defined as Q/(Q+I) (Quiroga and Fowler 2004).

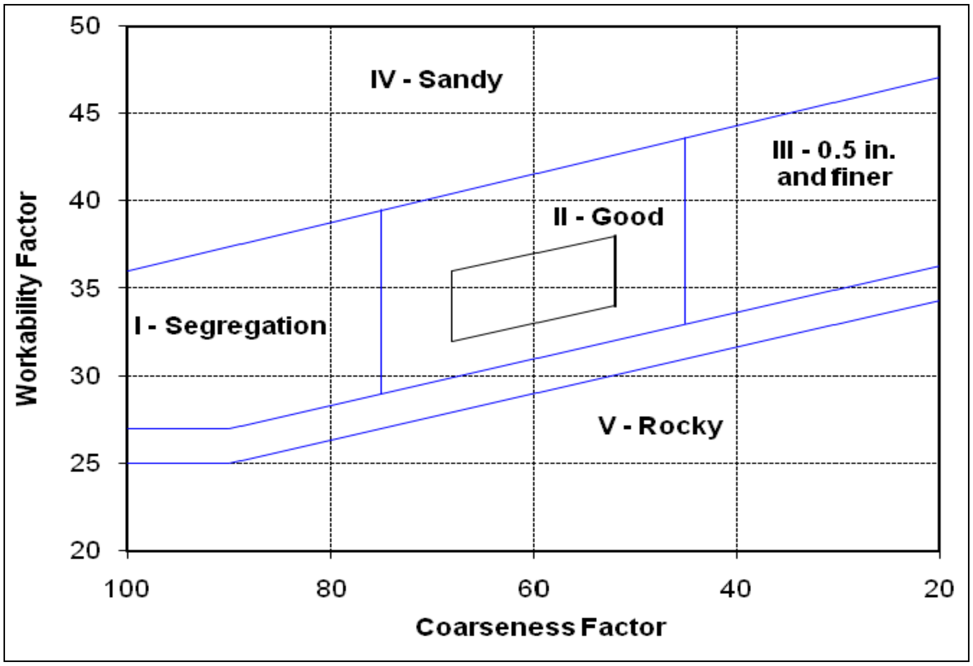

Figure 2.4: Coarseness Chart proposed by Shilstone.

This chart is based on the assumptions that as cementitious materials are increased, the fine aggregate content should be reduced to maintain the same workability factor and vice versa. An increase or decrease in the cementitious materials or fine aggregate content without compensation in the other of these two components will impact the workability of the mixture (ACI 302-04).

Five zones are defined in the chart:

- Zone I – This zone includes seriously gap-graded mixtures with high potential for segregation during placement or consolidation due to a deficiency in intermediate particles. They are not cohesive mixtures and are not recommended for paving or slabs due to segregation potential.

- Zone II – This is the optimum zone, including mixtures with nominal maximum aggregate size from 1-1/2 to 3/4 inch. These mixtures generally produce consistent, high quality concrete. Mixtures with slivered or flat intermediate aggregate require more fine sized aggregate due to their non-rounded shapes that create mobility problems.
- Zone III – This zone is an extension of Zone II for maximum aggregate size equal to or smaller than 1/2 inch.
- Zone IV – These mixtures have excessive fines leading to a high potential for segregation during consolidation and finishing. Mixtures in this zone will produce variable strength; have high permeability and exhibit shrinkage.
- Zone V – Mixtures falling in this zone are very coarse or non-plastic, creating a need to increase the fines content (ACI 302-04; IM 532).

2.3.4 Percent Retained

The current ASTM C 33 specification could lead to poor workability mixtures and gap-graded mixtures due to an excess or a deficiency of some sizes. The goal of the "Percent Retained" method, sometimes referred to as the "18-8" method, is to produce uniform blends by limiting the maximum and minimum amount of aggregate fractions to a ceiling value of 18% and a floor value of 8% (Quiroga and Fowler 2004).

A deficit in particles retained on the No. 8, 16 and 30 sieves and an excess of particles retained in the No. 50 and 100 sieves can be found in many areas of the U.S. This leads to problems such as cracking, curling, blistering and spalling of concrete. If there is a deficit in one sieve but an excess on the adjacent sieve, the two sieve sizes can balance one another. However, if there are three adjacent deficient sieve sizes, the grading distribution in these sieves needs to be adjusted. These deficits can be seen through adjacent peaks and dips in the “18-8” chart (ACI 302-04; IM 532).

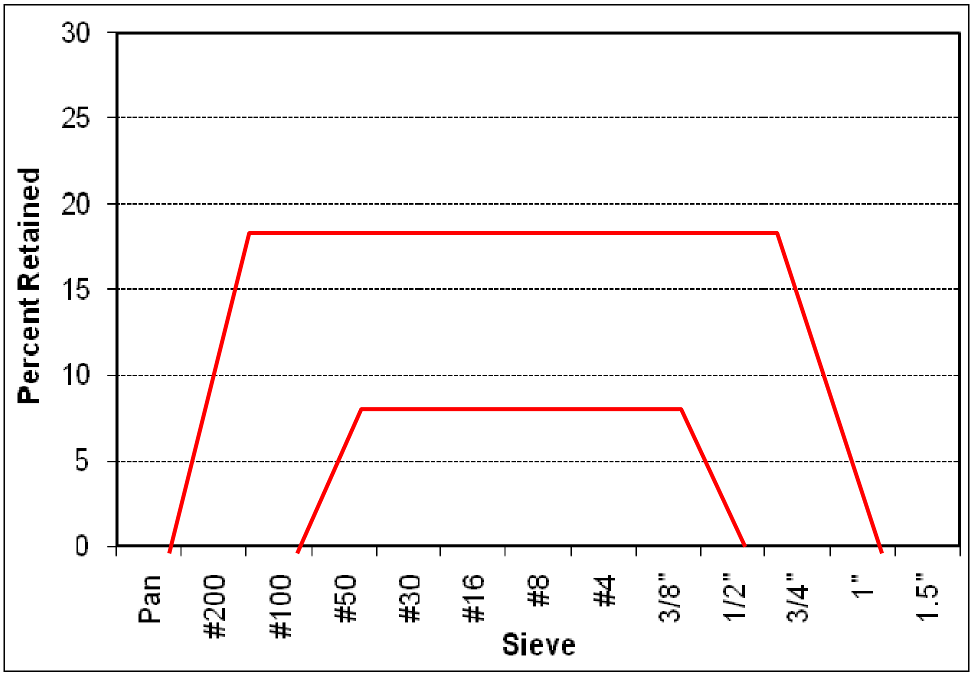

Figure 2.5 - Iowa DOT "18-8" Chart.

This specification published by the Iowa DOT, however, is not intended to be used for aggregate with high microfines content. The mixtures meeting the “18-8” limits could still have workability problems and low packing density due to an excess or deficit of either fine or coarse aggregate (Quiroga and Fowler 2004).

2.3.5 ACI Mixture Design Method

The ACI 211 (2002) method is based on an empirical formula that indirectly determines the amount of aggregates in a mixture. The values recommended by ACI assume that the aggregates are well graded and no guidance is given on how to blend two or more aggregates.

The ACI method relates the amount of cement needed in a mixture to strength and durability criteria in terms of minimum amount of cement and required water-to-cement ratio (*w/c*). The amount of water required increases with increasing aggregate angularity, increasing slump, decreasing maximum aggregate size, lack of air entrainment, or use of water-reducing admixtures. The volume of coarse aggregate is a function of the dry-rodded unit weight of the coarse aggregate, the fineness modulus of the fine aggregate, and the maximum aggregate size. The volume of fine aggregates depends on the amount of all other ingredients.

One of the major shortcomings of the ACI approach is that it over simplifies the proportioning process by using the fineness modulus of the sand as a factor. Research done by Young (1921), Besson (1935), and Kennedy (1940) suggest that the fineness modulus is inadequate to differentiate between sands. ACI also relates strength and durability of concrete to cement content (by specifying a minimum cement content), which is also misleading.

Furthermore, ACI 211 is based on ASTM C 33 which limits the amount of microfines to a maximum of 7%. Microfines are defined as a mineral powder or dust of fracture that passes the No. 200 sieve (smaller than 75-µm). The amount of microfines allowed by specifications has been limited for three reasons:

1. Microfines may reduce workability due to large surface areas that need to be wetted. Microfines may increase the water requirement, which increases the amount of cement, therefore increasing shrinkage.
2. Microfines tend to adhere to larger particles, preventing proper bonding between paste and aggregate. Improper bonding promotes cracking and weakens concrete.

3. Clay particles may be present. These particles change volume when either they absorb or lose water. As a result, they expand when wet in fresh concrete and shrink when they dry in hardened concrete. Shrinkage increases cracking sensitivity, allowing for deleterious substances to ingress and reduce concrete strength (Katz and Baum 2006).

Different limits than those required by ASTM C 33 can be found in specifications outside of the U.S. One example is the European Standard for Aggregates which allows up to 22% microfines content; however, should the content of microfines exceed 3%, the European specification requires testing for the presence of clay particles. On the other hand, the Israeli Standard for Concrete Aggregates limits the microfines content to 5% (Katz and Baum 2006).

2.3.6 Other Methods

Among the other methods/softwares for optimization of concrete mixtures, the following can be found:

- Europack.
- Compressible Packing Model (CPM).
- Theory of Particle Mixture (TPM).

Europack is a program that calculates the packing density of dry mixtures based on the modified Toufar model, which allows for two aggregates to be combined at a time. Europack is not a proportioning method, as it requires the use of other methods such as ACI 211, to determine the amount of cement and water (Quiroga and Fowler 2004).

CPM, developed by De Larrard (1999), in France, is based on packing concepts. It uses the packing density of aggregates, cement and other cementitious materials to predict fresh and hardened properties of concrete (Quiroga and Fowler 2004).

TPM, developed by Dewar (1999), is a mathematical model that seeks to find the percent of a given material needed to determine the minimum void content. Water demand can be derived from this void content (Quiroga and Fowler 2004).

2.4 EFFECT OF AGGREGATE OPTIMIZATION ON CONCRETE PROPERTIES

Concrete mixtures with well-graded or optimized gradations have a less likely chance to segregate and will minimize finishing labor (Shilstone 1990). Shilstone (1990) also believes that the wear resistance of concretes with optimized gradations is greater than concretes with gap graded aggregate. In addition, by optimizing gradation, the water to cementitious (*w/c*) ratio of a concrete mixture can be lowered, thus producing a stronger, less permeable, and more durable concrete.

Due to the restraining effect of aggregate particles, concrete generally shrinks less than cement paste. According to Torben el al. (1965), the degree of restraint provided by the aggregates in concrete is dependent on the quantity of aggregate, elastic properties of the aggregate, and the shrinkage of the cement paste and aggregate; the greater the volume of the aggregate in the concrete, the less the shrinkage. Furthermore, the lower the aggregate modulus of elasticity the lower the restraining effect on the cement paste during shrinkage.

2.5 PREVIOUS STUDIES OF HIGH MICROFINES CONCRETE

During the production of crushed sands, a significant proportion of the fine aggregate may be smaller than the No. 200 sieve. This portion can be as high as 15% or more of the total aggregate production by weight. To obtain the full benefits of fines in the concrete, they need to be properly dispersed (Felekoglu 2006; Katz and Baum 2006).

Most of the previous work found in the literature on microfines used as mineral fillers is in regards to self-consolidating concrete (SCC). It has been previously used to optimize particle packing and to modify the flow behavior of the cementitious paste in SCC mixtures. The presence of microfines in the paste helps reduce the viscosity in the paste. Limestone and dolomite were found to be among the most frequently used mineral fillers for SCC mixtures (Felekoglu 2006; Katz and Baum 2006; Bosiljkov 2003).

One of the biggest concerns when using microfines is the possibility of clay particles being present, which can weaken the paste-aggregate bond in the concrete. Clays also delay the cement hydration and affect the volume stability of concrete. On the other hand, microfines like silts can improve the concrete performance (Felekoglu 2006).

In the case of limestone microfines, better particle packing can considerably improve stability and workability of fresh concrete. However, in most cases, the addition of a small amount of microfines can lead to a reduction in workability of fresh concrete. At the same time, the addition of high dosages of water reducer admixture needed to maintain a constant slump due to the large amount of microfines can affect the properties of concrete. Alternatively, the amount of cement paste may need to be increased, which will require additional water (Katz and Baum 2006; Bosiljkov 2003).

The increase in water reducer admixture or water was found to be non-linear, with a particular high increase at higher levels of fines. Increasing the amount of water reducer was found to have an effect on the mixture air content (increasing the air content with increasing amount of water reducer), while altering the workability by adding water (controlling the paste) did not have such an effect. In mixtures where the desired workability was achieved through the use of water reducer admixtures, the slump decreased more rapidly compared to the mixtures where the slump was decreased through adding water (Katz and Baum 2006).

In the past it has been shown by Topcu and Ugurlu (2003) that the addition of mineral fillers (between 7% and 10%) can improve compressive and flexural strength in concrete. Katz and Baum found that this improvement can be as much as a 30% gain in strength. This is believed to be due to an increase in the density of the paste matrix and interfacial transition zone, once the concrete hardens. The main contribution to strength due to fines occurred during the first 28 days. After the 28-day period, the strength gain was negligible (Felekoglu 2006; Katz 2006; Bosiljkov 2003).

A decrease in permeability, absorption and porosity with increasing microfines content was also noted during the experiments performed by Topcu and Ugurlu (2003). Katz and Baum (2006) also found that the addition of microfines reduced the carbonation rate and depth in concrete (Katz and Baum 2006).

A 10% limit was recommended by Topcu and Ugurlu (2003) to avoid the increase in specific surface and the high water-holding capacity that causes high shrinkage. It was found by Bosiljkov (2003) that limestone can modify the moisture changes in concrete, controlling shrinkage and creep strains. Katz and Baum found that in mixtures with low fines content, final shrinkage increased by 25% (Katz and Baum 2006).

Chapter 3: Test Methods

3.1 INTRODUCTION

Standard test methods were used to evaluate the properties of aggregates and performances of mortar and concrete mixtures. These test methods along with any modifications are discussed in this Chapter.

3.2 AGGREGATE CHARACTERIZATION TESTS

3.2.1 Sieve Analysis

The test method described in ASTM C 136 “Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates” was used to determine the gradation of the fine and coarse aggregates. The sieve analysis of the coarse aggregates was done assuming 1-in. and smaller sieves. The amount of fine aggregates passing the No. 200 sieve was determined following ASTM C 117 “Standard Test Method for Materials Finer than 75-μm (No. 200) Sieve in Mineral Aggregates by Washing”. The maximum size aggregate was computed as defined in ASTM C 125 “Standard Terminology Relating to Concrete and Concrete Aggregates”.

3.2.2 Specific Gravity and Absorption

The specific gravity and absorption capacity of the coarse aggregates was determined using ASTM C 127 “Standard Test Method for Density, Relative Density (specific gravity), and Absorption of Coarse aggregates”. ASTM C 128 “Standard Test Method for Density, Relative Density (Specific Gravity), and Absorption of Fine Aggregate” was used to determine the specific gravity and absorption capacity of the fine aggregates.

3.2.3 Bulk Density and Voids in Aggregates

The bulk density of the aggregates was determined following ASTM C 29 “Standard Test Method for Bulk Density (Unit Weight) and Voids in Aggregates”. The test was performed on both fine and coarse aggregates separately and then on combinations of fine and coarse aggregates. The combinations included the different proportions of aggregates used throughout the project.

3.2.4 Methylene Blue

The methylene blue test was performed on the all microfines used in this project according to AASHTO TP 57-06. The objective of the methylene blue test is finding if there was any clay-like material present in the microfines. No modification was made to the standard test method.

3.2.5 Single Drop Test

The single drop test was used to test for the presence of clay in microfines (in addition to the methylene blue). The test was conducted based on the method used by Bigas and Gallias (2003). The test is performed by placing a bed of loosely packed microfines in an open dish. A 0.2-ml drop of water is added to the microfines. After 15 to 20 seconds, the resulting agglomeration of water and microfines is removed with a needle. The results of the test are expressed as the water-to-fines volume ratio (*w/f*) of the agglomeration. The packing density of the fines in the agglomeration is also computed. The test is repeated 15 times on each material.

3.2.6 Laser Diffraction

The laser diffraction test was conducted by the National Institute for Standard and Technology (NIST) using the wet method with isopropyl alcohol. It should be noted that these measurements assume the particles to be spherical. The specific surface area and span are determined from the laser diffraction data. The details of the span calculations are given by Koehler and Fowler (2007). The span is calculated using Equation 3.1:

$$span = \frac{d(0.9) - d(0.1)}{d(0.5)} \qquad (3.1)$$

where *d*(0.9) is the diameter with 90% passing, *d(*0.5) is the diameter with 50% passing, and *d*(0.1) is the diameter with 10% passing. The span and specific surface area represent the particle size distribution while the packing density reflects both the particle size distribution and shape characteristics.

3.3 FRESH MORTAR TESTS

Mortar tests were performed on all the fine aggregates used in the project. The goal of the mortar tests was to identify differences in performances of aggregates having different grading, shape, and texture while varying the water to powder ratio (*w/p*) and the paste content of the mixtures.

The performance of the mortar was based on it reaching target workability. For that purpose, a high-range water-reducing admixture (HRWRA) was added to the mortar mixtures. To incorporate the HRWRA, a modified version of the mixing procedure described in ASTM C 305 was used. These procedures are described here:

1. The fine aggregate and water were placed in a mixing bowl and mixed at a low speed for 30 seconds.
2. The mixer was then turned off and the material was allowed to rest undisturbed for 4 minutes.
3. On low speed, the cement was added to the mixture over a period of 30 seconds.
4. The mixer was then turned to medium speed for an additional 30 seconds and then turned off.

5. The mortar was allowed to rest for 1 minute and during this time the sides of the bowl were scraped and a dose of HRWRA was added.
6. The mortar was then mixed for an additional 1 minute at medium speed.
7. The mortar flow test was then performed (as described in ASTM C 1437).
8. In the case where the mortar did not meet the target workability, additional HRWRA was added, and the mixture was mixed for an additional 1 minute at medium speed; the mortar flow test was then performed again.

The mortar flow tests were done in accordance with ASTM C 1437 “Standard Test Method for Flow of Hydraulic Cement Mortar”. The goal was to reach a maximum flow for specified paste content at 25 drops of the table. The dose of HRWRA was increased until the target workability was reached.

3.4 CONCRETE TESTS

3.4.1 Slump

During the whole project, the slump test was used to measure the workability of the concrete mixtures. The test was done according to ASTM C 143 “Standard Test Method for Slump of Hydraulic-Cement Concrete”. All concrete mixtures were made to meet a slump value of 6-in.± 1-in. by the addition of a HRWRA. Whenever a mixture did not meet the requirements, additional HRWRA was added to it, the concrete mixture was then re-mixed and re-tested until it reached the target slump.

3.4.2 Compressive Strength

The compressive strength was determined using the procedure provided in ASTM C 39 “Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens”. Since the maximum size aggregate used for all mixtures was less than 3/4-in., standard plastic 4-in. x 8-in.

cylinder molds was used for this research. The cylinders were tapped and rodded to insure proper consolidation. Three cylinders were tested for each different mixture; all tests were performed after 28 days of curing and using the same testing machine.

3.4.3 Drying Shrinkage

Drying shrinkage tests were performed on the concrete mixtures by following ASTM C 157 “Standard Test Method for Length Change of Hardened Hydraulic-Cement Mortar and Concrete”. The concrete was placed in 3-in. x 3-in. steel prism molds with a 10-in.gauge length. Three specimens were cast for each mixture; the specimens were rodded and tamped to ensure proper consolidation. After 24 hours of curing, the specimens were striped and allowed to soak in limewater buckets for 30 minutes before initial measurements were taken. The specimen were then soaked in limewater for three additional days, after that they were removed from the buckets and placed in a temperature controlled room for the remaining duration of the test. Shrinkage measurements were taken at 3, 7, 14, 28, 56, and 112 days after removal from limewater.

3.4.4 Permeability

Permeability tests were performed in accordance with ASTM C 1202 “Standard Test Method for Electrical Indication of Concrete’s Ability to Resist Chloride Ion Penetration”. Due to laboratory equipment limitations, not all tests were done after exactly 91 days of casting and curing; most tests were postponed. This was assumed to be acceptable since all concrete mixtures in the project had no supplementary cementitious material, and therefore permeability at ages higher than 91 days should not have been significantly affected by additional curing or aging of the concrete. ASTM C 1202 estimates the permeability of concrete based on electrical conductance. The values are expressed in coulombs and can be interpreted as shown in Table 3.1:

Table 3.1: Permeability Based on Charge on Charge Passed (ASTM C 1202)

Charge Passed (Coulombs)	Permeability
>4000	High
4000-2000	Moderate
2000-1000	Low
1000-100	Very Low
<100	Negligible

3.4.5 Abrasion Resistance

One 4-in. by 4-in. by 14-in. beam was used for the abrasion resistance testing of the concrete mixtures made with the addition of microfines (Phase II). The testing method used was based on ASTM C 944 “Standard Test Method for Abrasion Resistance of Concrete or Mortar Surfaces by the Rotating-Cutter Method”.

Chapter 4: Materials

4.1 INTRODUCTION

To identify differences in the performance relating to material properties of mortar and concrete mixtures, materials used in this research are discussed in this Chapter. Two coarse aggregates were used, a limestone and a natural river gravel. Three fine aggregates were tested, one river sand and two manufactured limestone sands; one well shaped, and another poorly shaped. Three microfines that included a limestone obtained as pond fines, a limestone obtained by sieving from screenings, and granite obtained by sieving from screenings. A Type I/II cement was used along with one high-range water-reducing admixture (HRWRA).

4.2 CEMENT

The portland cement used in this project was a TXI Type I/II cement. This cement satisfies the ASTM C 150 “Standard Specification for Portland Cement” specifications for a hydraulic portland cement. Type I/II satisfy the composition of a Type I (normal cement) and a Type II (moderate sulfate resistant cement).

4.3 CHEMICAL ADMIXTURE

Since the study had the goal of achieving concrete mixtures with slumps of 6-in. ± 1-in., a HRWRA, Glenium 3030 NS was chosen. Glenium 3030 NS (manufactured by BASF), is a polycarboxylate-based HRWRA that meets ASTM C 494 “Standard Specification for Chemical Admixtures for Concrete” requirements for Type A (water-reducing) and Type F (high-range water-reducing admixture). Glenium 3030 NS can be added to concrete mixtures with the initial mixing water or delayed until the final water is added.

4.4 COARSE AGGREGATES

Two coarse aggregates were tested and used. The coarse aggregates (3/4-in. maximum size) included a cubical, well-rounded natural coarse aggregate (NAT-CA) and a cubical, angular crushed limestone coarse aggregate (LS-A-CA). The aggregate properties refer to the standardized ASTM tests performed on the materials (Table 4.1). These tests were described in Chapter 3 and include bulk density and voids in aggregates, specific gravity, and absorption.

Table 4.1: Summary of Coarse Aggregate Properties

ID	Source	Mineralogy	SG_{SSD}	Absorption (%)	Dry-rodded Pkg. Density (%)
NAT-CA	Austin, TX	River Gravel	2.56	1.30	62.4
LS-A-CA	Garden Ridge, TX	Limestone	2.55	1.43	58.6

The specific gravity and absorption of both materials are nearly the same. The main difference was in the dry-rodded packing density. The natural gravel has a higher packing density; therefore, mixtures containing natural gravel usually need less mortar to fill the voids as compared to angular, crushed aggregate.

Using ASTM C 136 as described in Chapter 3, the gradation of the two coarse aggregates was measured. Figure 4.1 shows the particle size distribution obtained in terms of percent passing. The particle size distribution of the coarse aggregates is somewhat similar; the limestone aggregate is slightly coarser.

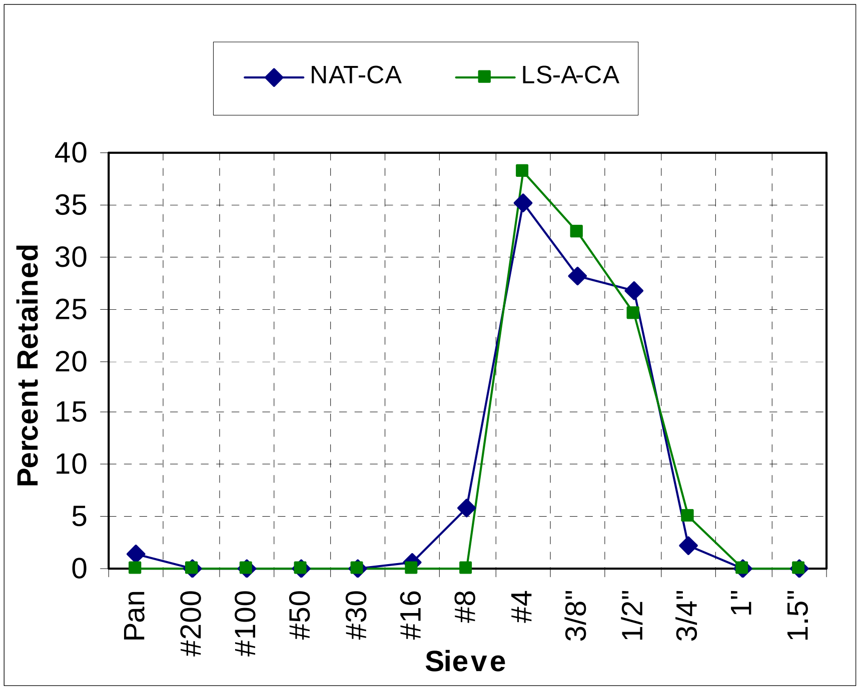

Figure 4.1: Percent Retained for Coarse Aggregate

4.5 FINE AGGREGATES

Three fine aggregates were tested and used in the project: a natural sand (NAT-FA), a well-shaped limestone manufactured sand (LS-A-FA), and a poorly shaped limestone manufactured sand (LS-B-FA). Table 4.2 shows the fine aggregate properties as obtained using the tests described in Chapter 3. The specific gravities of the three fine aggregates were about the same. The well-shaped manufactured limestone (LS-A-FA) has a higher absorption capacity, while the river sand (NAT-FA) has the highest packing density.

Table 4.2: Summary of Fine Aggregate Properties

ID	Source	Mineralogy	SG_{SSD}	Absorption (%)	Dry-rodded Pkg. Density (%)
NAT-FA	Austin, TX	River Sand	2.60	0.56	67.6
LS-A-FA	Garden Ridge, TX	Limestone	2.61	1.62	66.6
LS-B-FA	Perch Hill, TX	Limestone	2.67	0.58	64.2

Figure 4.2 contains the particle size distribution of the fine aggregates. The river sand (NAT-FA) is finer than the other two sands, while the poorly shaped manufactured sand (LS-B-FA) is the coarsest.

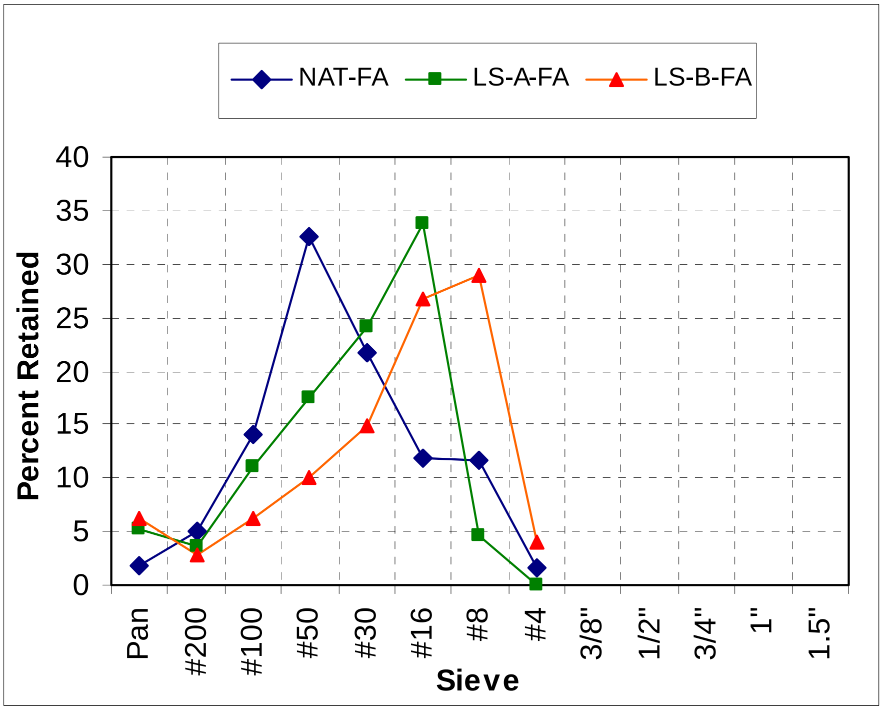

Figure 4.2: Percent Retained for Fine Aggregate

4.6 MICROFINES

The properties of the three microfines used in Phase II of the project are shown in Table 4.3. These properties include the methylene blue, single drop, and laser diffraction test described in Chapter 3.

Table 4.3: Microfines Properties.

Source Location	Mineralogy	ID	MBV	Single Drop Test		Laser Diffraction	
			mg/g	w/f	Packing Density	Span	SSA
Garden Ridge, Tx	Limestone	LS-A	1.63	0.401	0.714	6.673	1.394
Calica, Mx	Limestone	LS-C	2.25	0.415	0.707	4.688	1.806
Liberty, Sc	Granite	GR-A	0.63	0.559	0.642	2.192	0.467

Notes:

1. SSA = specific surface area = surface area/volume in 1/μm.

4.6 COMBINED AGGREGATE PROPERTIES

To estimate the minimum paste content needed for the concrete mixtures, the dry-rodded unit weight was obtained for the different blends of aggregates. The same method used to determine the dry-rodded unit weights for individual aggregates was used (described in Chapter 3). Four combinations of fine and coarse aggregates were blended to achieve four different gradings: three gradings with sand-to-aggregate (S/A) ratios of 0.30, 0.40, and 0.50 and a fourth gap grading where all coarse aggregate finer than the 3/8-in. sieve were removed and the remaining material used with an *S/A* of 0.40. The aggregate combinations included NAT-CA with NAT-FA, NAT-CA with LS-A-FA, NAT-CA with LS-B-FA, and LS-A-CA with NAT-FA.

Table 4.3 contains the values of the combined dry-rodded unit weight of different combinations of aggregate. For each *S/A* ratio the percent solids and percent voids were computed. Those values were later used to estimate the minimum percent paste for the concrete mixtures.

Table 4.3: Percentage Voids in Compacted Aggregate Blends

Coarse Aggregate ID	Fine Aggregate ID	S/A	Dry-rodded Unit Weight (lb/ft^3)	% Solids	% Voids
NAT-CA	NAT-FA	0.3	118.8	74.11	25.89
NAT-CA	NAT-FA	0.4	120.4	75.02	24.98
NAT-CA	NAT-FA	0.5	122.0	75.93	24.07
NAT-CA (GAP)	NAT-FA	0.4	120.4	75.02	24.98
NAT-CA	LS-A-FA	0.3	112.4	70.28	29.72
NAT-CA	LS-A-FA	0.4	116.8	73.00	27.00
NAT-CA	LS-A-FA	0.5	119.2	74.47	25.53
NAT-CA (GAP)	LS-A-FA	0.4	118.0	73.75	26.25
NAT-CA	LS-B-FA	0.3	110.4	68.39	31.61
NAT-CA	LS-B-FA	0.4	114.0	70.37	29.63
NAT-CA	LS-B-FA	0.5	116.4	71.61	28.39
NAT-CA (GAP)	LS-B-FA	0.4	115.2	71.12	28.88
LS-A-CA	NAT-FA	0.3	115.6	72.31	27.69
LS-A-CA	NAT-FA	0.4	119.6	74.69	25.31
LS-A-CA	NAT-FA	0.5	123.6	77.07	22.93
LS-A-CA (GAP)	NAT-FA	0.4	116.8	72.95	27.05

4.7 COMBINED AGGREGATE GRADATIONS

The following section shows the gradations and the 0.45 power curve corresponding to different combinations of coarse and fine aggregates. The workability factor is also plotted as a function of the coarseness factor; this plot helps identify expected performance relating to the combined gradations.

4.7.1 NAT-CA and NAT-FA

Figure 4.3 shows the combined gradation for the different combinations of the river gravel (NAT-CA) and the river sand (NAT-FA). The curve corresponding to the gap graded gradation is the coarsest, while the gradation corresponding to *S/A*=0.5 has the highest amount of finer aggregates.

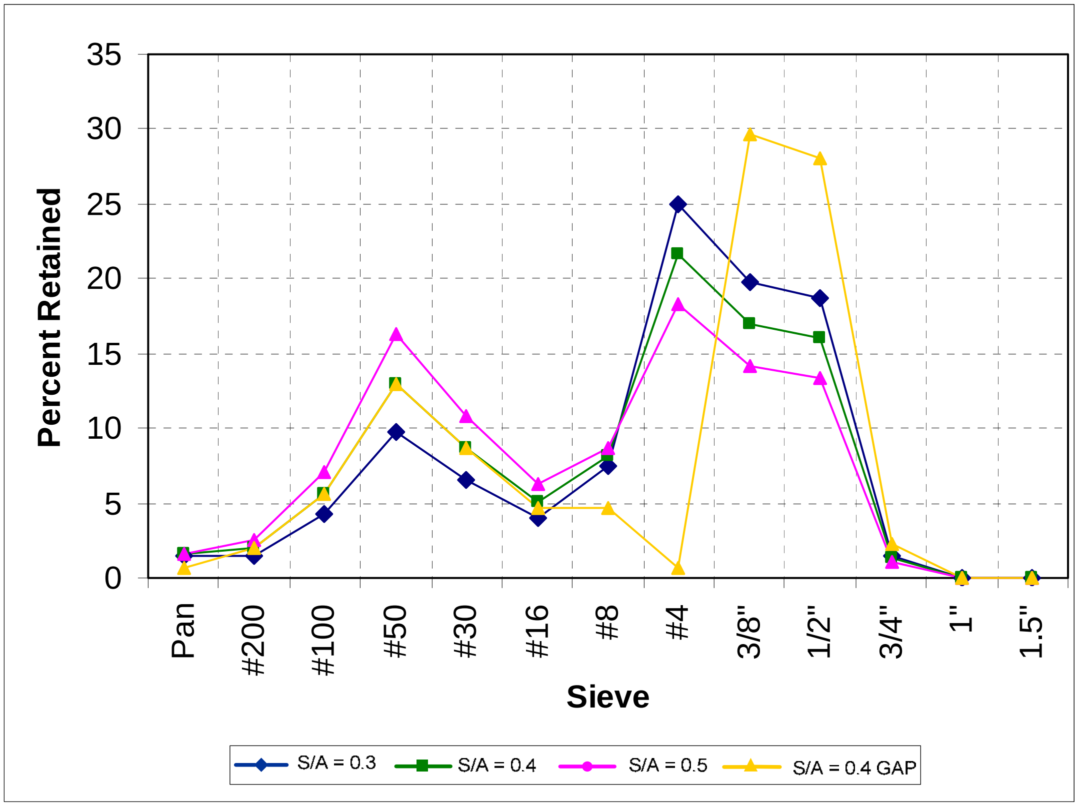

Figure 4.3: Percentage Retained for NAT-CA and NAT-FA Blends

The 0.45 power curve for combinations of NAT-CA and NAT-FA is shown in Figure 4.4. The best combined gradation for those two aggregates is *S/A*=0.4; since it is the closest to the 0.45 power line. *S/A*=0.3 is too coarse (the curve is below the 0.45 power line) while *S/A*=0.5 is too fine (the curve is above the 0.45 power line). The gap graded gradation is the coarsest among the four blends.

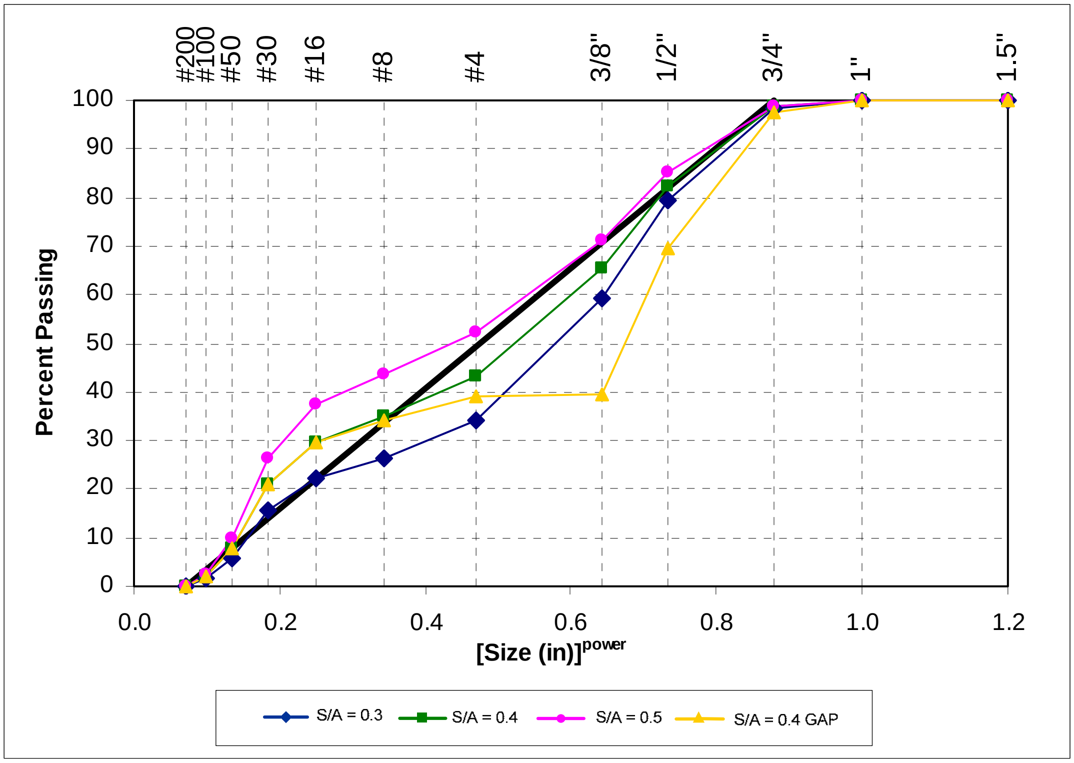

Figure 4.4: 0.45 Power Chart for NAT-CA and NAT-FA Blends

The workability factor is plotted as a function of the coarseness factor for the blends of NAT-CA and NAT-FA (Figure 4.5). The results obtained from Figure 4.5 confirm what was previously deduced from Figure 4.4. The gradation corresponding to *S/A*=0.4 is expected to yield a good result. *S/A*=0.5 is too sandy and concrete mixtures containing this gradation are likely to segregate and yield a low strength. *S/A*=0.3 is too coarse, while the gap graded gradation is very likely to segregate.

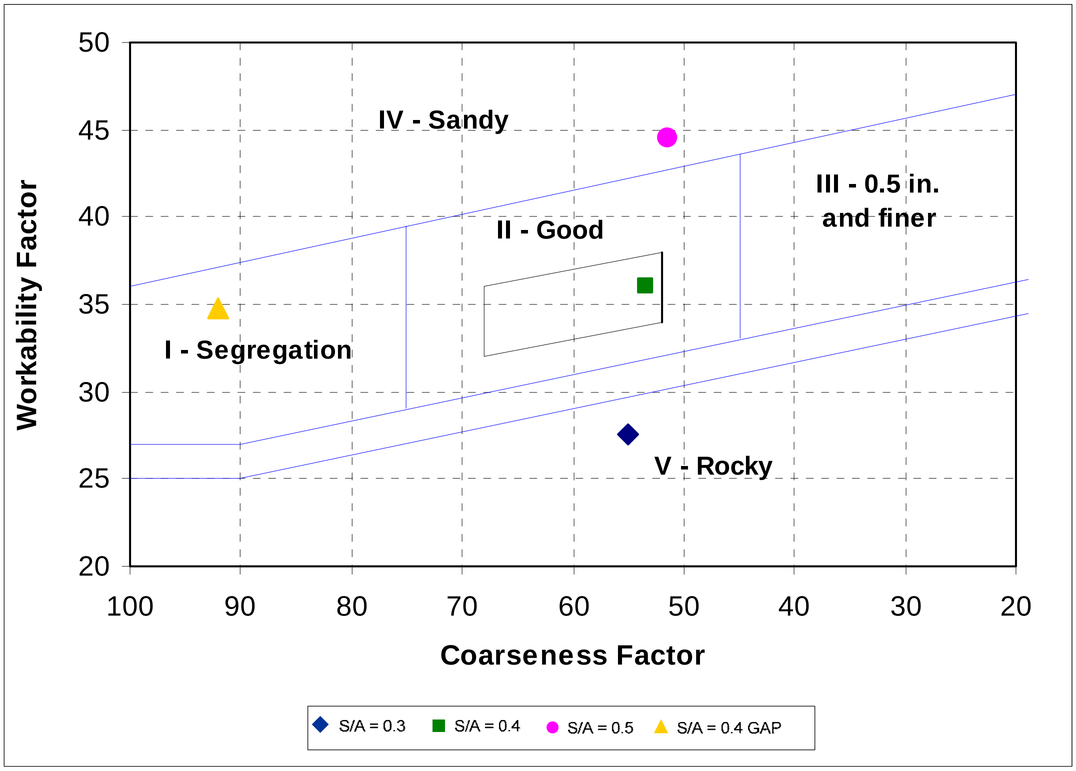

Figure 4.5: Coarseness Chart for NAT-CA and NAT-FA Blends

4.7.2 NAT-CA and LS-A-FA

The combined gradation for the different combinations of the river gravel (NAT-CA) and the well-shaped limestone sand (LS-A-FA) are shown in Figure 4.6. The combined gradations for this set are coarser than the previous one, because the limestone sand LS-A-FA is coarser than the river gravel NAT-FA. Among the gradations shown in Figure 4.6, the gap graded gradation is the coarsest and is missing more material retained on the #8 as compared to the other gradations.

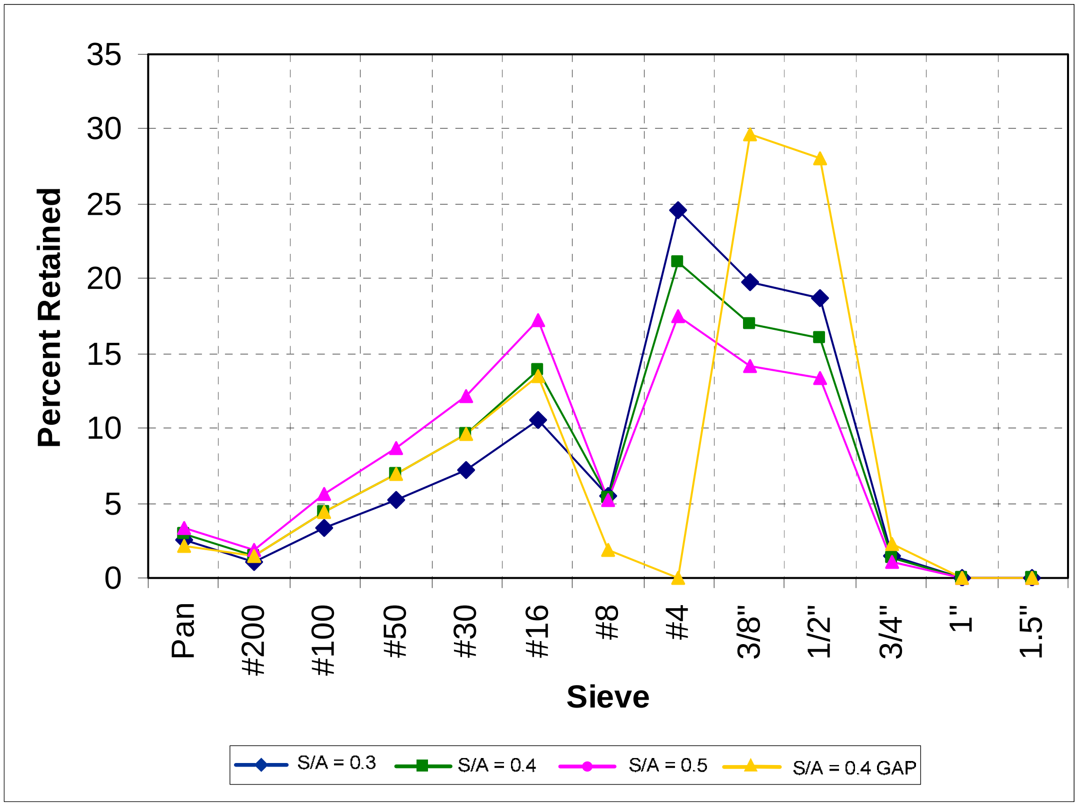

Figure 4.6: Percentage Retained for NAT-CA and LS-A-FA Blends

Figure 4.7 shows the 0.45 power curve for combinations of NAT-CA and LS-A-FA. *S/A*=0.4 is the closest to the 0.45 power line and is therefore expected to have the best performance. *S/A*=0.3 and the *S/A*=0.4 GAP are too coarse since their curves are below the 0.45 power line. *S/A*=0.5 is too fine (the curve is above the 0.45 power line). Even though LS-A-FA is a bit coarser than NAT-FA, the optimum gradation was still at *S/A*=0.4.

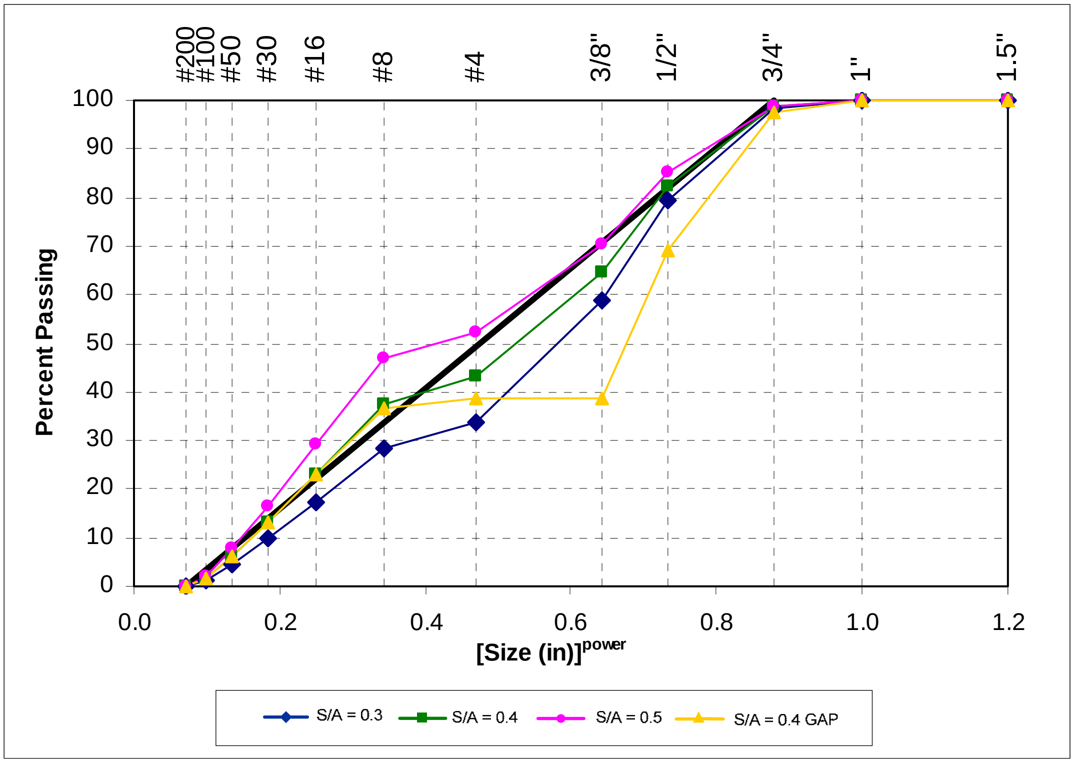

Figure 4.7: 0.45 Power Chart for NAT-CA and LS-A-FA Blends

The coarseness chart for the blends of NAT-CA and LS-A-FA is shown in Figure 4.8. Based on the results of the coarseness chart, the gradation corresponding to *S/A*=0.4 is expected to yield a good result; *S/A*=0.5 is too sandy and is likely to segregate and yield low strength. *S/A*=0.3 lacks fine aggregate and is coarsest of the three gradations. The coarseness chart identifies the gap graded gradation as being “sandy”, but Figure 4.7 shows that it is the coarsest.

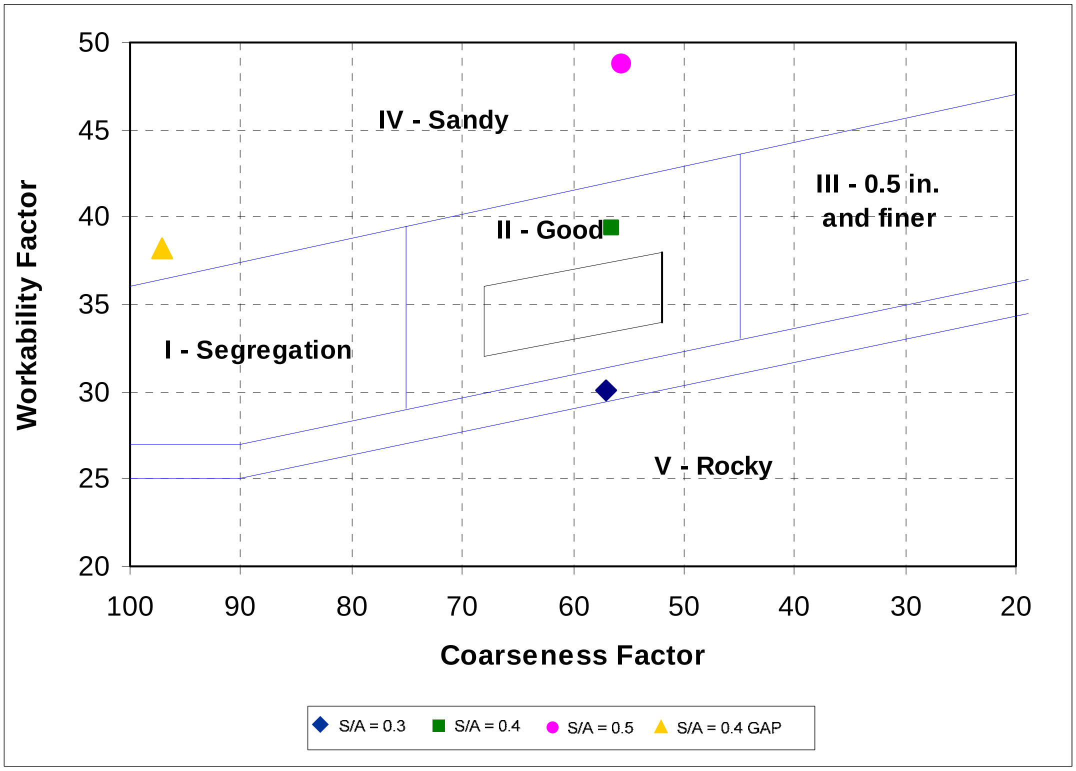

Figure 4.8: Coarseness Chart for NAT-CA and LS-A-FA Blends

4.7.3 NAT-CA and LS-B-FA

Figure 4.9 shows the combined gradation for the different combinations of the river gravel (NAT-CA) and poorly shaped limestone sand (LS-B-FA). LS-B-FA is the coarsest of the three sands and that is why the combined gradations containing LS-B-FA are generally coarser than other combinations. Compared to other curves, the curve corresponding to the gap graded gradation has little aggregate retained on the #4 sieve.

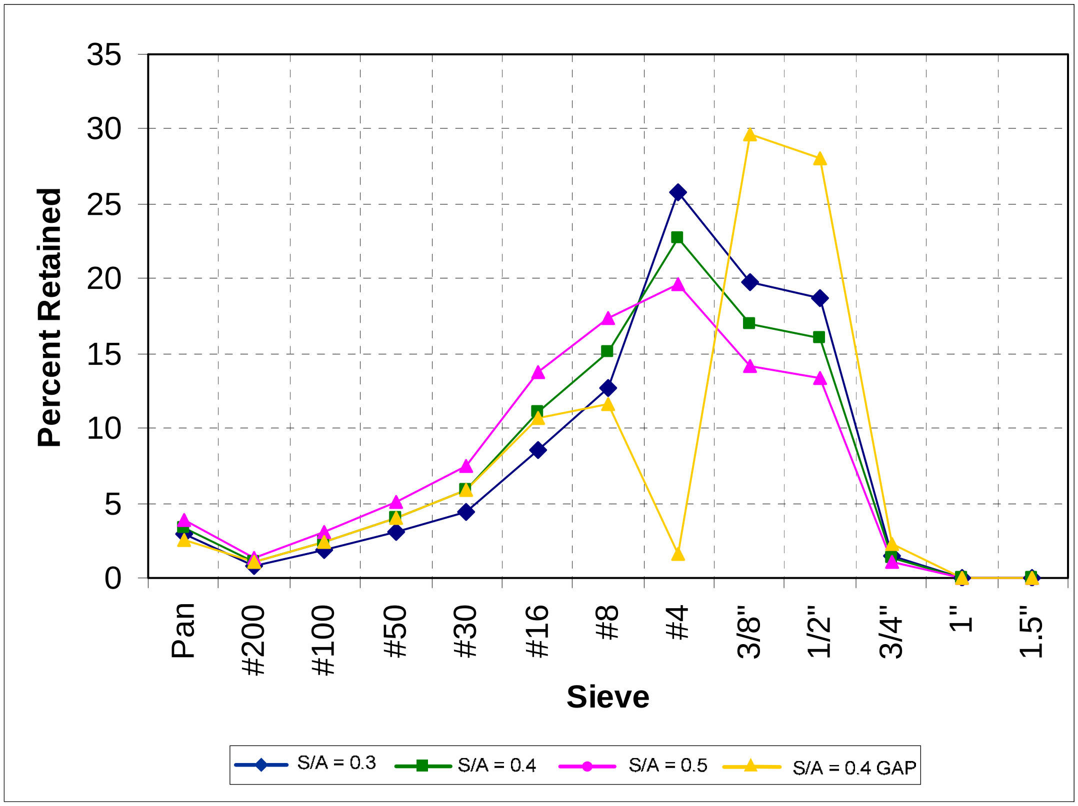

Figure 4.9: Percentage Retained for NAT-CA and LS-B-FA Blends

The curve corresponding to *S/A*=0.5 was the closest to the 0.45 power line (Figure 4.10). All other gradations including *S/A*=0.4, *S/A*=0.5, and the gap graded gradation were too coarse. This was because LS-B-FA is coarse sand, and therefore the optimum gradation based on the 0.45 power curve should have more sand and less coarse aggregate. As in all other coarse and fine aggregate combinations, the gap graded gradation was also the coarsest in this series.

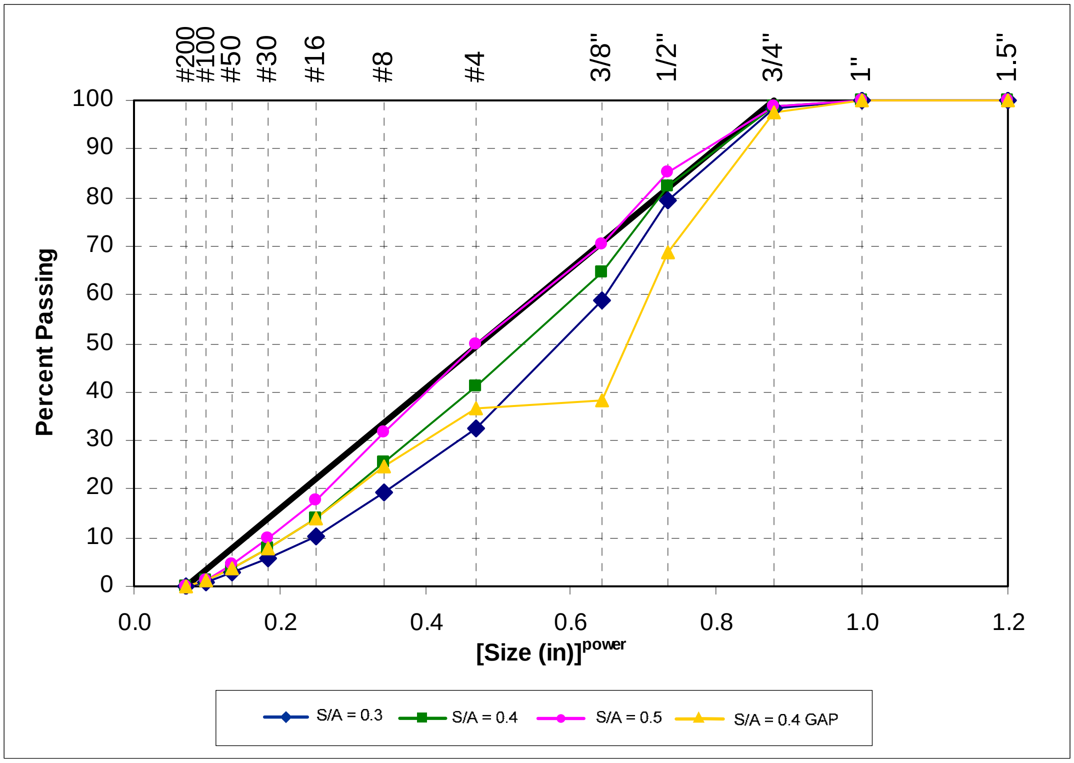

Figure 4.10: 0.45 Power Chart for NAT-CA and LS-B-FA Blends

The coarseness chart for the NAT-CA and LS-B-FA is shown in Figure 4.11. The coarseness chart predicted that only the gradation of *S/A* will was "good". The rest of the gradations were too coarse; concrete mixtures made with those gradations will probably bleed.

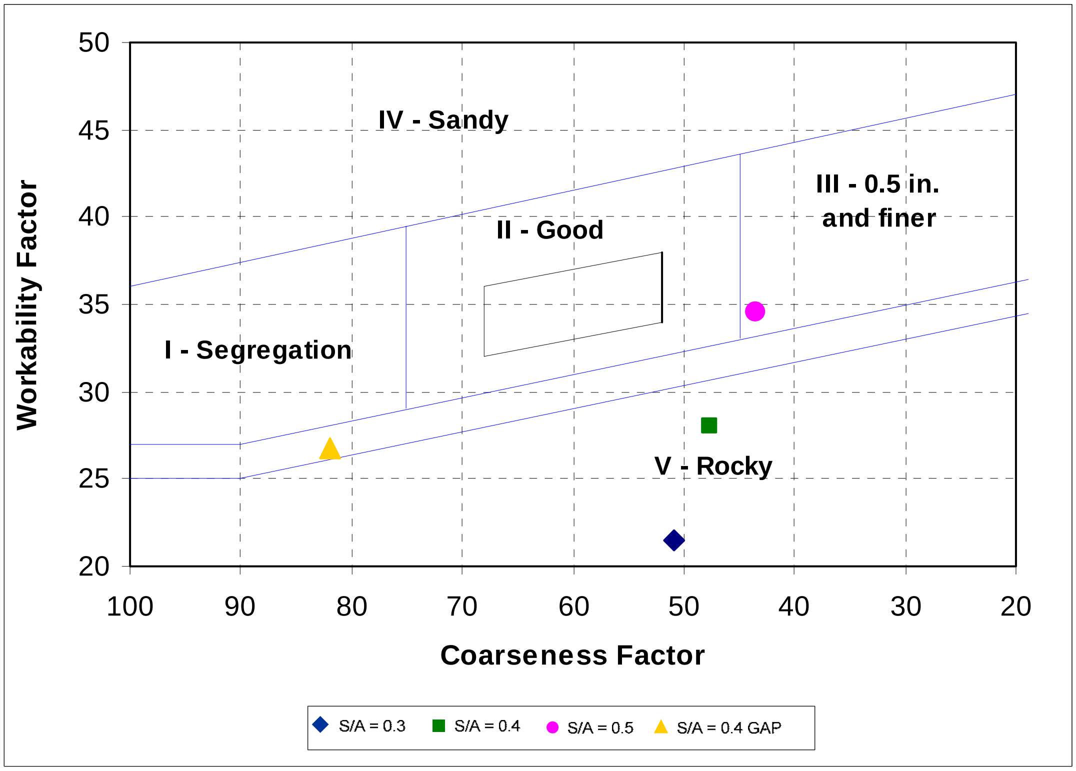

Figure 4.11: Coarseness Chart for NAT-CA and LS-B-FA Blends

4.7.4 LS-A-CA and NAT-FA

The main difference between NAT-CA and LS-A-CA is shape and texture; the gradations of the two materials were nearly the identical (LS-A-CA was slightly coarser). The combined gradation of LS-A-CA and NAT-FA (Figure 4.12) was very similar to that of NAT-CA and NAT-FA. Here also, the gap graded gradation (Figure 4.12) was the coarsest, while the gradation of *S/A*=0.5 had the highest amount of finer aggregates.

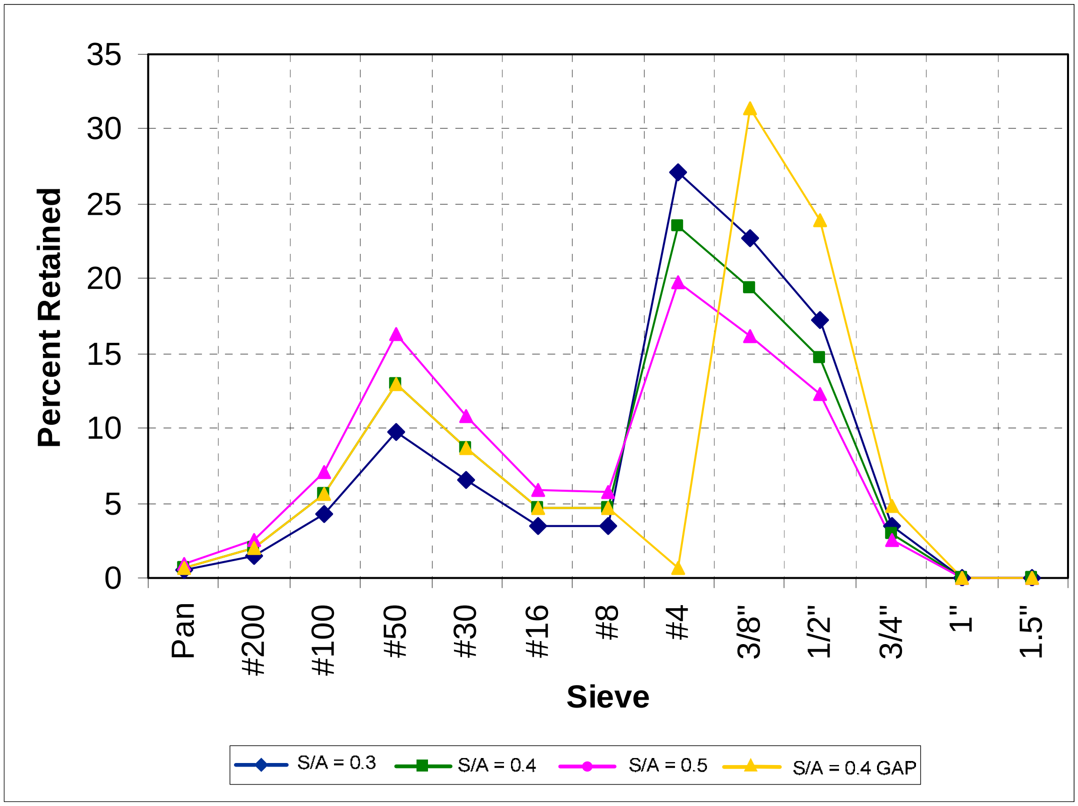

Figure 4.12: Percentage Retained for LS-A-CA and NAT-FA Blends

The 0.45 power curve for combinations of LS-A-CA and NAT-FA is shown in Figure 4.13. The optimum combined gradation for those two aggregates was at *S/A*=0.4 since it is the closest to the 0.45 power line. *S/A*=0.3 was too coarse (the curve was below the 0.45 power line) while *S/A*=0.5 was too fine (the curve is above the 0.45 power line). The gap graded gradation was the coarsest among the four blends.

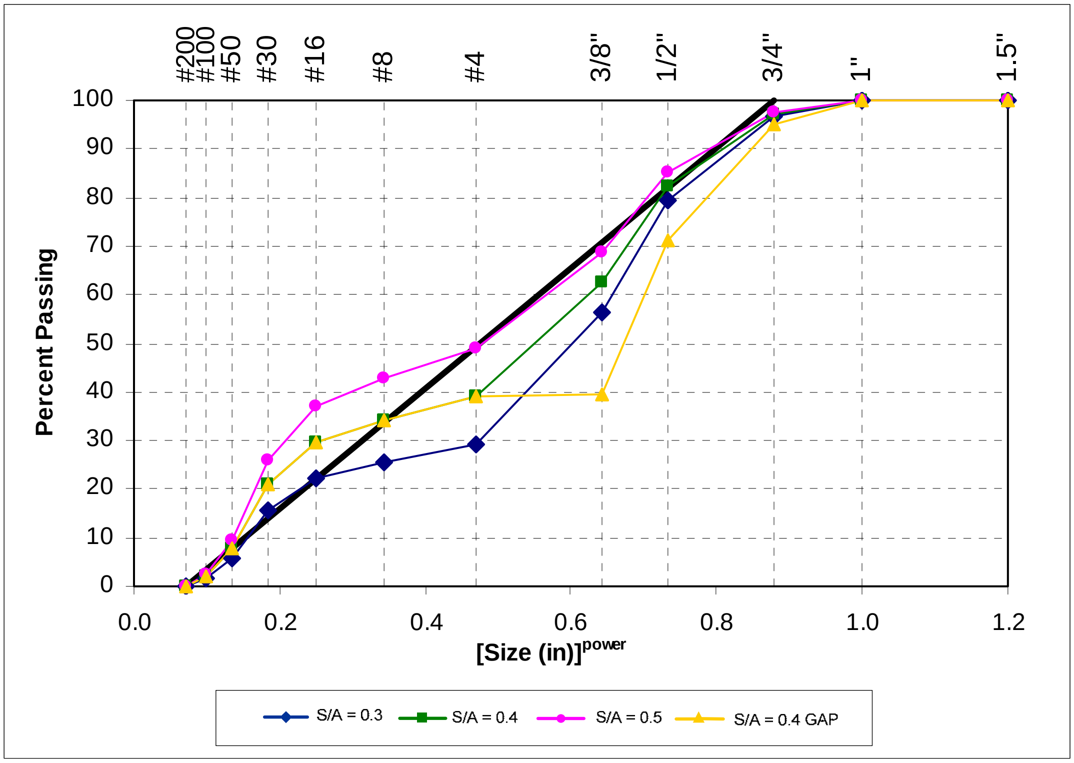

Figure 4.13: 0.45 Power Chart for LS-A-CA and NAT-FA Blends

The workability factor is plotted as a function of the coarseness factor for the blends of LS-A-CA and NAT-FA (Figure 4.14). The gradation corresponding to *S/A*=0.4 was expected to yield a good result. *S/A*=0.5 was sandy and was likely to segregate and yield a low strength. *S/A*=0.3 was too coarse, while the gap graded gradation was very likely to segregate. The results in Figure 4.14 are very similar to what was obtained in Figure 4.5 but the difference in shape and texture between NAT-CA and LS-A-CA is expected to distinguish the performance of those blends.

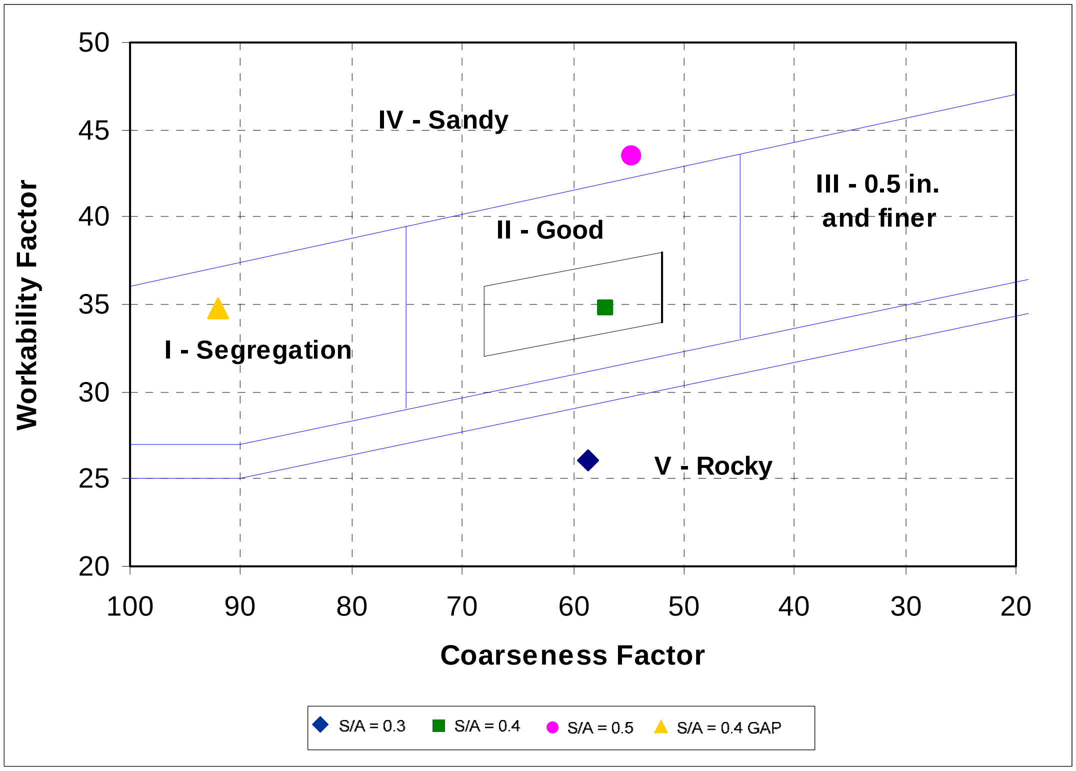

Figure 4.14: Coarseness Chart for LS-A-CA and NAT-FA Blends

Chapter 5: Mortar Tests: Method, Results and Interpretation

5.1 INTRODUCTION

Initial testing of the effect of different fine aggregates was performed using mortar mixtures. These smaller mixtures provided a good means of rapidly identifying performance differences of the fine aggregates.

The mortar testing had the objective of determining the minimum paste volume needed for a given workability level. Any amount of paste below the minimum required level cannot achieve the required workability. This amount of paste varies based on the shape, texture, and gradation of the aggregate used. The paste is assumed to consist of water, cement, and the fraction of sands passing the No. 200 (microfines). To test this hypothesis, the paste volume for different aggregates was varied, and the minimum paste volume needed to achieve a certain level of workability with HRWRA (ASTM C 1437) was determined.

The second goal was to investigate if that the minimum paste volume is independent of the paste composition. In other words, the goal was to determine if the workability of a mixture is not a function of the individual amount of cement, water, or microfines present, or if it is dependent on the total volume of all three components. To test this hypothesis, the tests were conducted with different water to powder ratios (*w/p*) – i.e. different paste compositions.

5.2 MORTAR PROPORTIONING METHOD

The mortar tests were conducted in series, where for each series the sand type and *w/p* were constant and the paste volume was varied. The volume of paste was reduced until the minimum paste volume was reached. The *w/p* was calculated on a volume basis, where the paste volume was assumed to comprise of water, cement, and the fraction of the sand passing the No. 200 sieve (microfines). The range of *w/p* was selected to represent the range likely to be used in concrete. The purpose of changing the *w/p* was to change the viscosity of the mortar associated with the target mini-slump flow. The HRWRA dosage in each mixture was adjusted to achieve the target workability (mini-slump flow to reach edge of drop table at 25 drops of the table). All aggregates were batched in an oven-dry condition and were mixed and tested as previously described in Chapter 3. Tests for all three aggregates included values of *w/p* equal to 1, 1.4, 1.8, and 2.2. Overall, 12 series were considered and a total 42 mortar mixtures were tested.

5.3 TESTING RESULTS AND INTERPRETATIONS

The results of the mortar mixtures for all three aggregates are presented and discussed in this section. For each aggregate the HRWRA demand was plotted as a function of paste and water volume. Note that the values for the paste were adjusted to include the volume of HRWRA added to each mixture. The volume of water is expressed in ml of water needed for 1 liter of mortar (ml/l).

5.3.1 NAT-FA Mixtures

Figure 5.1 shows the amount of HRWRA that was added to each mortar mixture to reach the target workability at different paste volumes. The results correspond to mixtures done with NAT-FA (natural sand). To get the same workability, mixtures with lower *w/p* ratios needed more HRWRA, and that was the case for any paste volume. At lower paste volumes, the difference between the dosages of HRWRA needed for mixtures with different *w/p* ratio were larger.

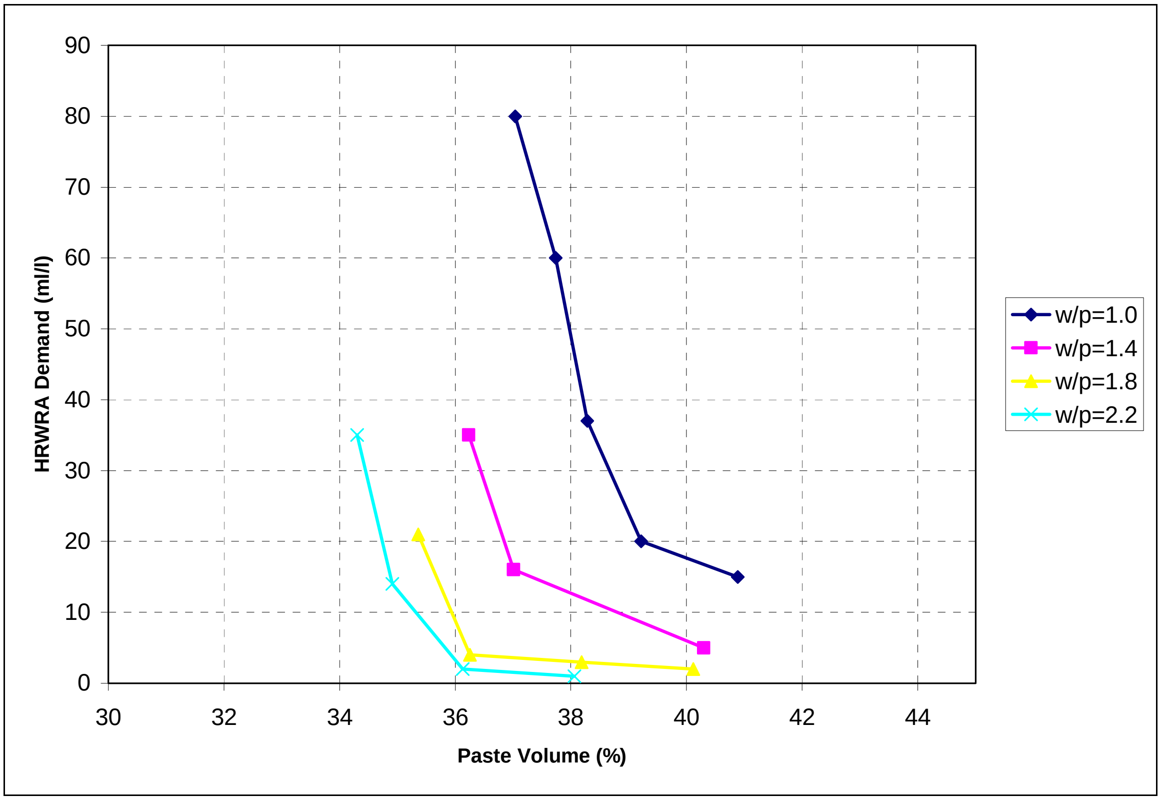

Figure 5.1: HRWRA as a Function of Paste for NAT- FA

The amount of HRWRA needed for different volumes of water is shown in Figure 5.2. Those results also correspond to mixtures done with NAT-FA. The dosage of HRWRA was smaller for mixtures containing more water. This effect was more pronounced for mixtures made with low *w/p* ratios.

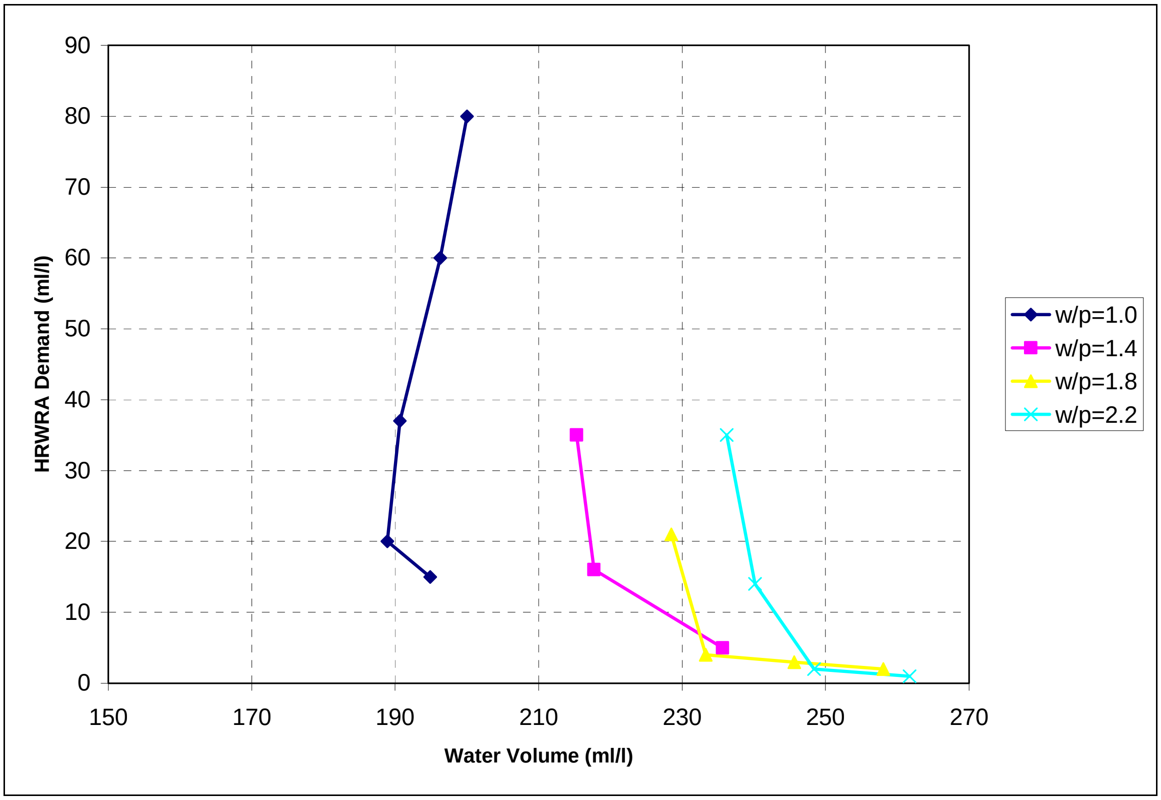

Figure 5.2: HRWRA as a Function of Water for NAT- FA

5.3.2 LS-A-FA Mixtures

The results of the HRWRA demand as a function of paste volume for the well-shaped manufactured sand LS-A-FA is presented in Figure 5.3. Similar to the results of NAT-FA, the HRWRA demand increased as the *w/p* ratio decreased. This sand, however, seemed to be more sensitive to paste volume reductions at lower *w/p* ratios. Although the LS-A-FA was coarser than NAT-FA, the minimum amount of paste needed for NAT-FA was lower than that of LS-A-FA. This is probably because NAT-FA had a smoother texture and a lower absorption capacity (as shown in Chapter 4).

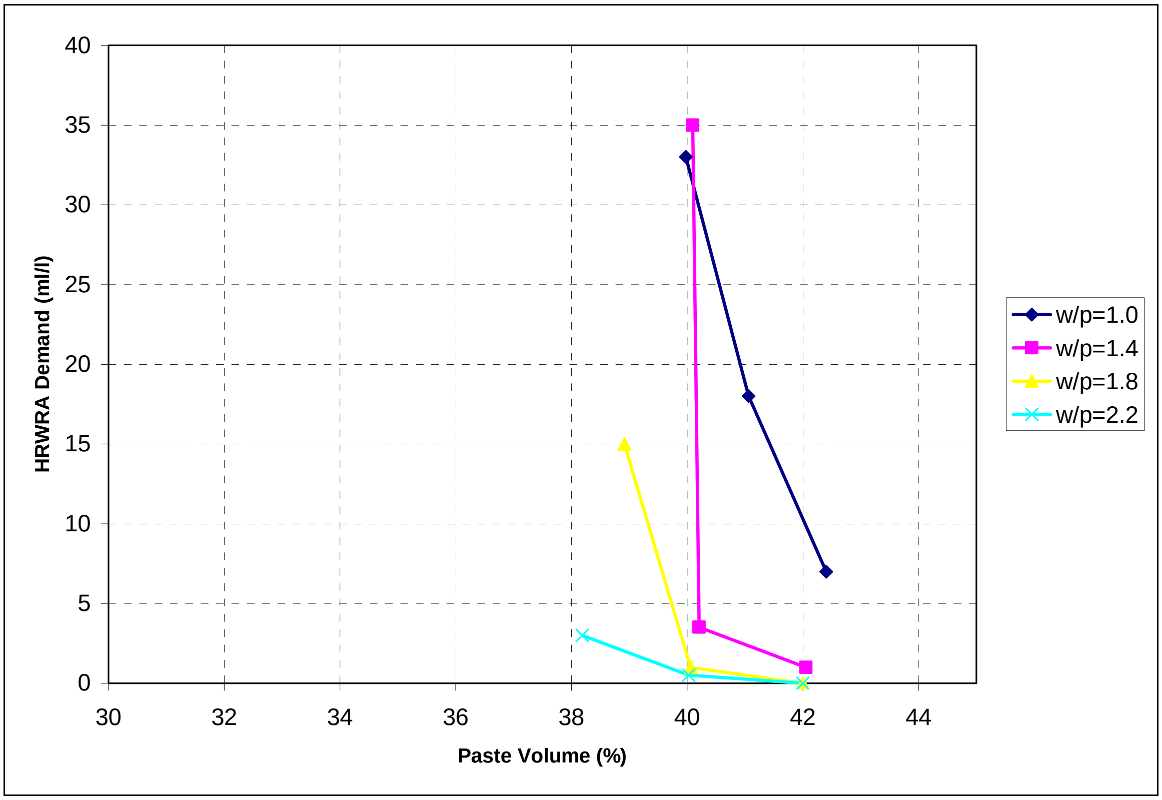

Figure 5.3: HRWRA as a Function of Paste for LS-A- FA

Figure 5.4 shows the HRWRA demand as a function of water content for the LS-A-FA aggregate. The aggregate seemed to be very sensitive to water reductions, especially at low *w/p* ratios. For a *w/p* ratio equal to 1, a 5% percent reduction in the volume of water was enough to increase the HRWRA demand by around 125%. Such results were not observed in NAT-FA mixtures because the natural sand had a lower absorption capacity.

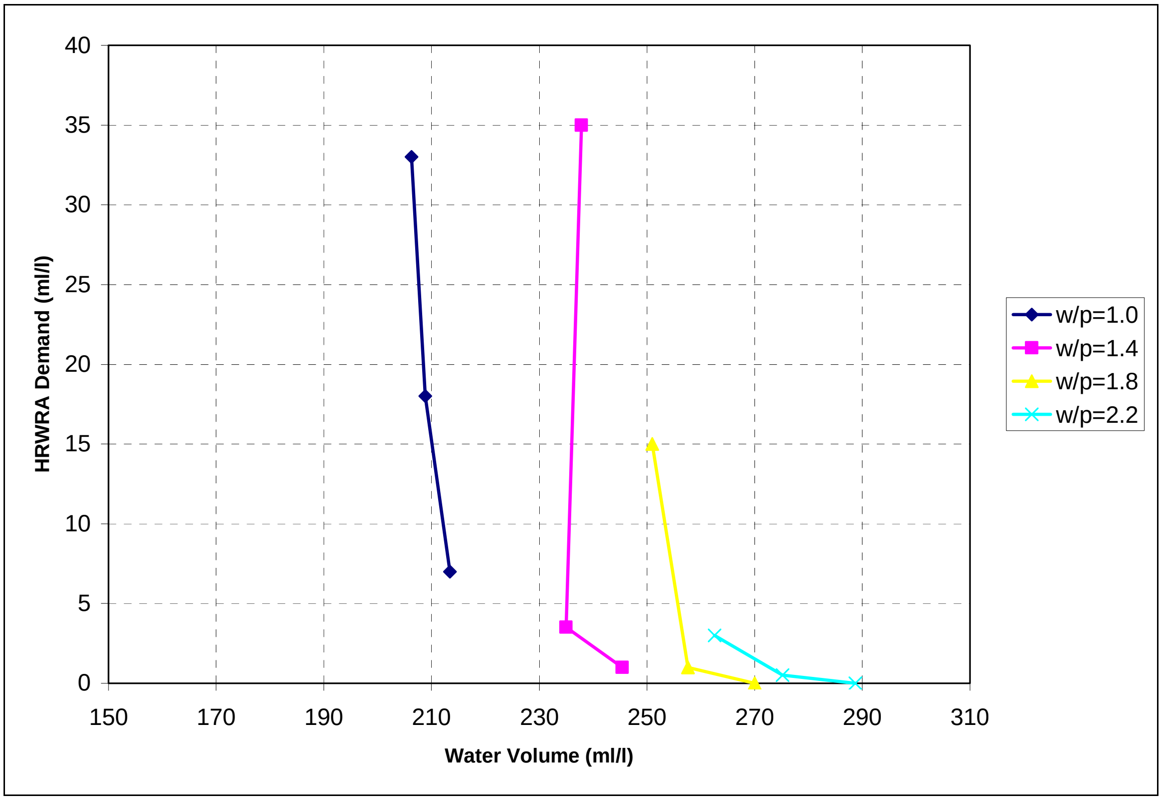

Figure 5.4: HRWRA as a Function of Water for LS-B- FA

5.3.3 LS-B-FA Mixtures

The HRWRA demand as a function of paste volume for the poorly-shaped manufacture limestone aggregate is shown in Figure 5.5. As for the previous aggregates, the HRWRA demand increased as the *w/p* ratio decreased and the paste volume increased. The minimum paste volume reached for the LS-B-FA aggregate was around 34%. This value is similar to the value reached for the NAT-FA sand. It should be observed that, although LS-B-FA had a rougher texture than NAT-FA, LS-B-FA was coarser than both NAT-FA and LS-A-FA.

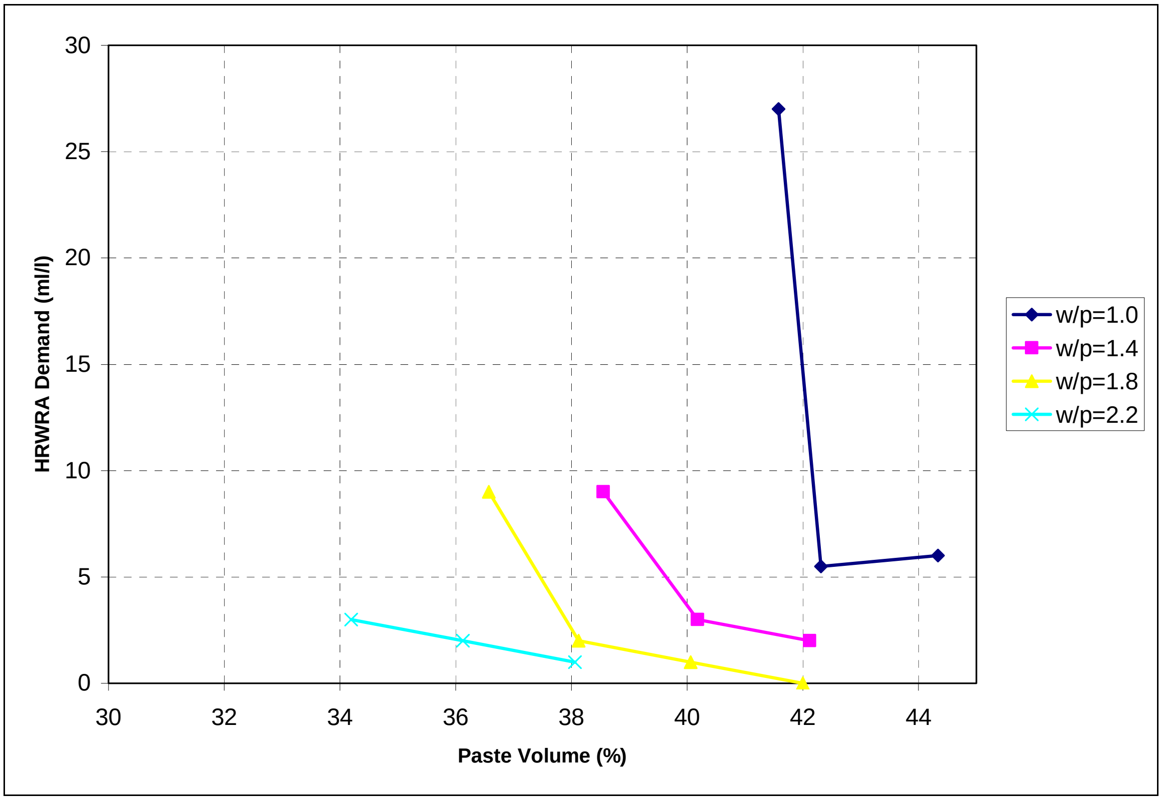

Figure 5.5: HRWRA as a Function of Paste for LS-B- FA

Figure 5.6 shows the HRWRA demand as a function of water volume. At higher *w/p* ratios (1.4, 1.8, and 2.2), the HRWRA was not affected by water volume (it was affected by the paste volume as shown in Figure 5.5). The minimum amount of water needed at the lowest *w/p* ratio was around 214ml/l; beyond that any addition of HRWRA only led to more bleeding of the mortar.

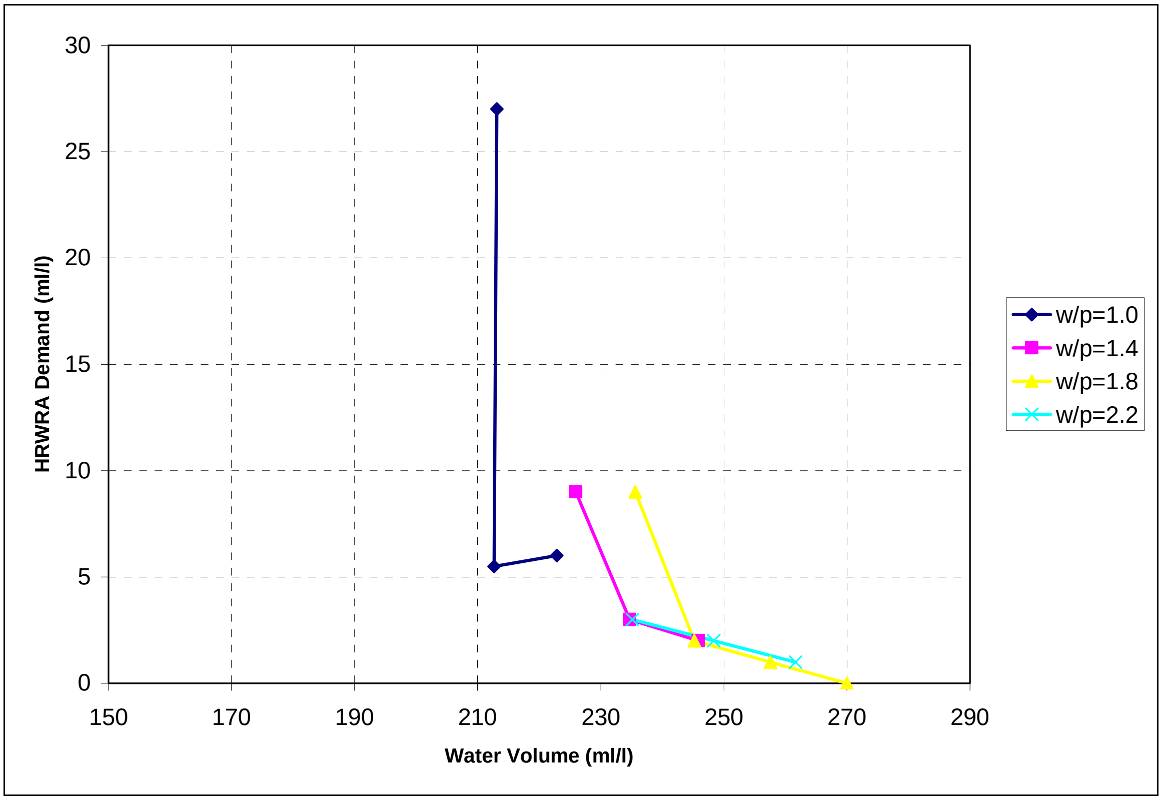

Figure 5.6: HRWRA as a Function of Water for LS-B- FA

5.4 SUMMARY OF THE RESULTS

The best results were obtained with NAT-FA aggregate because less paste was needed to reach the target workability. Figure 5.7 shows the minimum paste needed for each fine aggregate at different *w/p* ratios. At high *w/p* ratios, the minimum paste volume needed for LS-B-FA was similar to that of NAT-FA. However, LS-B-FA was very sensitive to *w/p* ratio reductions. The minimum paste volume needed for LS-B-FA changes at a higher rate than the other two aggregates when *w/p* ratio was varied. The minimum paste volume reached with LS-A-FA was higher than that of NAT-FA, but the rate of change as *w/p* varied was similar.

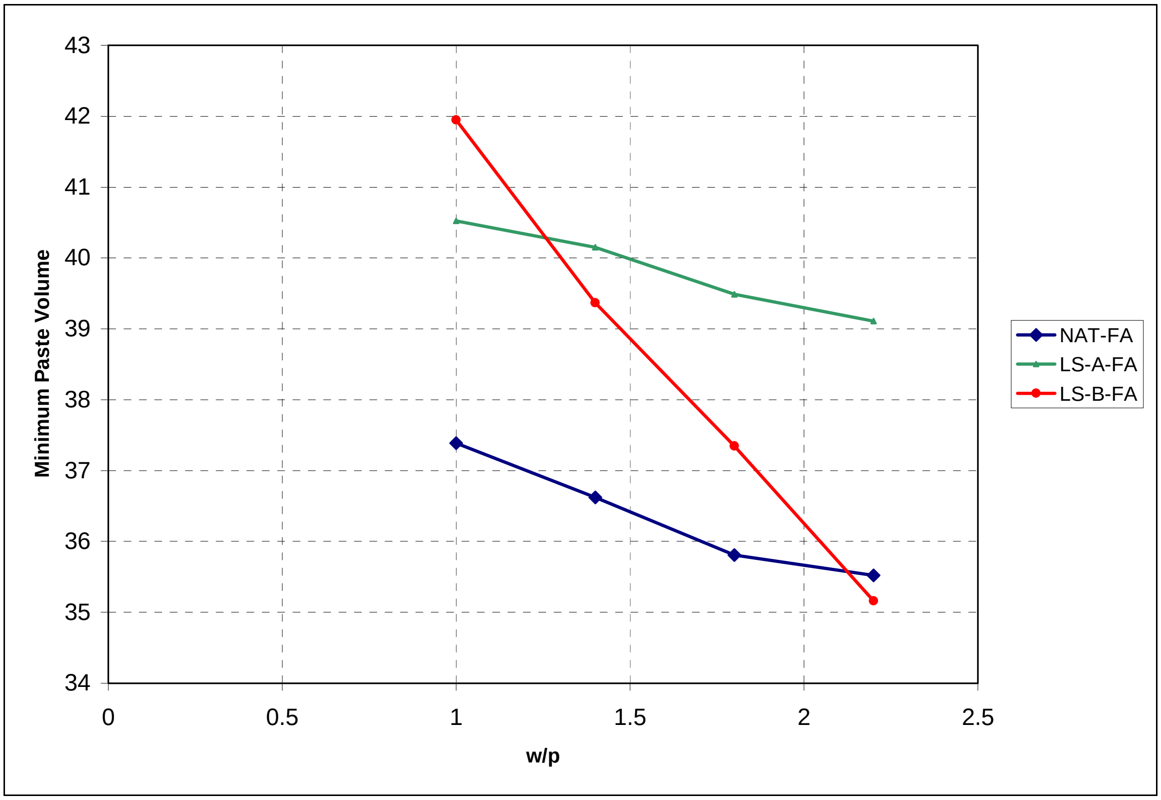

Figure 5.7: Minimum Paste Requirements for Different Fine Aggregates

The minimum amount of water need for the three aggregates at different *w/p* ratios is shown in Figure 5.8. LS-A-FA had the highest water demand, probably because of its higher absorption capacity. NAT-FA, on the other hand, had the lowest water demand.

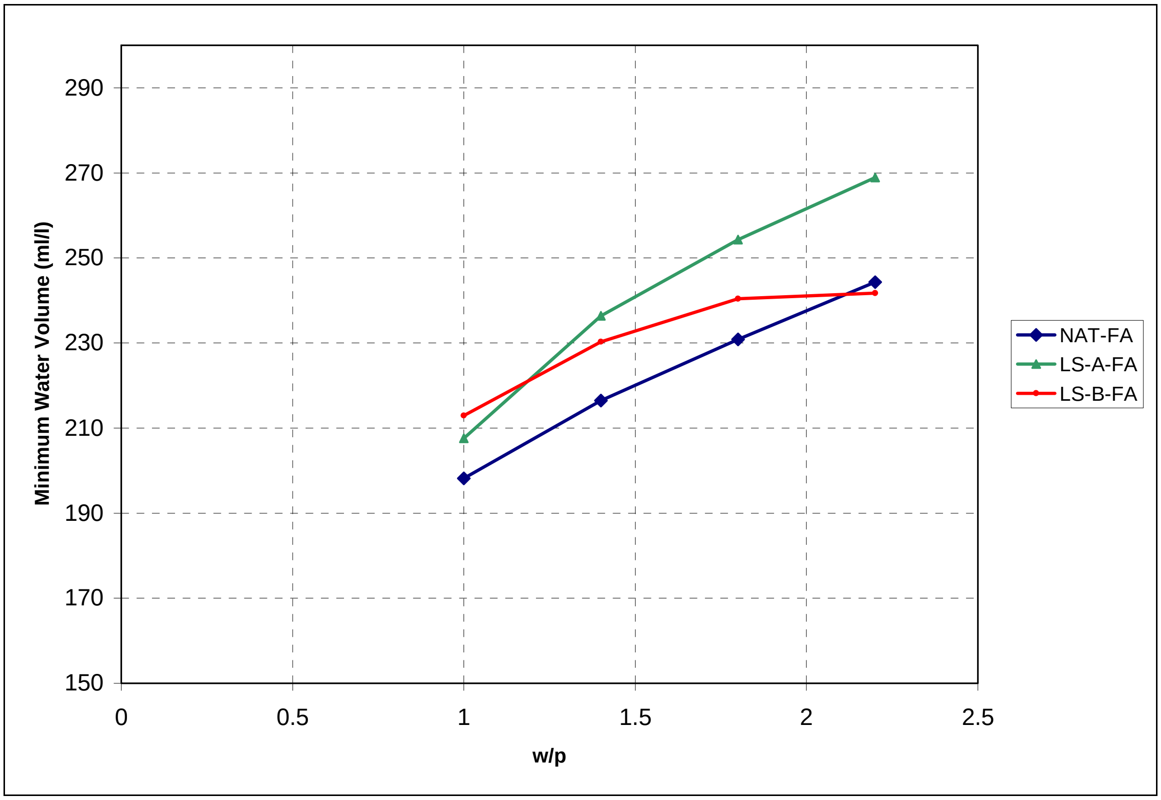

Figure 5.8: Minimum Water Requirements for Different Fine Aggregates

5.5 CONCLUSIONS

The mortar tests identified performance differences in fine aggregates with different shape, texture, and grading. The minimum paste and water volumes, as well as the HRWRA dosages needed to achieve a specified workability for the different aggregates, were determined. These results show that, unlike SCC, the minimum paste volume is dependent on paste composition. Therefore, the second hypothesis stated in the introduction does not apply to low workability concrete mixtures. Furthermore, it was found that there is less sensitivity between aggregates at higher *w/p*.

Chapter 6: PHASE I: Testing Methods, Results and Discussion Optimization through Aggregate Blending

6.1 INTRODUCTION

Testing was performed on all the different blends presented in Chapter 4. The aim of the concrete testing was to reach the minimum paste volume for each different blend of aggregate with different combinations of fine and coarse aggregate. The testing also aimed to show the effects of shape, texture, and gradation of fine and coarse aggregate on the fresh and hardened properties of concrete. Sixty-four mixtures were prepared and tested. For every mixture, the dosage of HRWRA needed to reach a slump of 6-in. ± 1-in. was recorded. Compressive strength, drying shrinkage, and permeability were also tested following ASTM standards (as explained in Chapter 3). Furthermore, cost estimations for one of the *S/A* ratios were computed and are discussed in this chapter.

6.2 MIXTURE PROPORTIONING METHOD

For all the concrete mixtures used in this project, the water-to-cement ratio (*w/c*) was taken to be equal to 0.5. The reason a constant value was used was to be able to compare the concrete mixtures based on paste volume, aggregate gradation, shape and texture criteria. Calculations were made on a volumetric basis and then converted to equivalent weights. As mentioned in Chapter 4, all concrete mixtures were straight cement mixtures; no other cementitious materials were used.

Proportioning of the mixtures was done as follows:

1. Knowing the percentage void for the different aggregate combinations, a range of paste volumes was considered to be tested.

2. For each of those paste volumes the amount of coarse and fine aggregate was calculated; the volume of aggregate was taken to be equal to the total volume of the concrete mixture minus the volume of the paste (water + cement).
3. The values of the fine and coarse aggregate were then computed based on the *S/A* ratio of the mix.
4. The mixture size (volume) was approximated based on the numbers of specimen to be cast. All batch sizes for this phase were 1.33ft^3.
5. The volumes obtained for the aggregates, cement, and water were then converted into weights.
6. The amount of HRWRA to be added was determined during the mixing of the concrete. The dosage of HRWRA was increased until a slump of 6-in. ± 1-in. was reached.

6.3 MIXING AND TESTING PROCEDURE

The following procedures were used for all mixing of concrete described in this thesis:

1. The coarse aggregate, fine aggregate, and cement were weighed and placed in containers (buckets) 24 hours prior to mixing.
2. To measure the moisture content of the aggregates, samples were removed and allowed to dry in the oven overnight.
3. The moisture content of the aggregate was calculated and the necessary adjustments were made to the batched aggregate quantities.
4. The inside of the mixing drum was moistened, and then excess water was removed.
5. The aggregates were placed in the drum.

6. Approximately half the water was added to the aggregate; the aggregates were allowed to mix for about 1 minute.
7. The mixer was stopped and the cement was added to the drum; after that the mixer was turned on again.
8. While the mixer was running, the remaining water was gradually added to the drum; the concrete was mixed for 3 minutes.
9. At the end of the 3 minutes, the mixer was stopped and the slump of the mixture was measured (as described in Chapter 3).
10. Each time the measured slump was less than 6-in. ± 1-in., an amount of HRWRA was added to the mixture. The concrete was then allowed to mix for at least 1 additional minute.
11. After the concrete reached the required slump, it was placed in shrinkage molds and plastic cylinders.
12. The drum and the other tools used were cleaned.
13. If the performance of the mixed concrete was observed to be satisfactory (bleeding was minimal), another mixture with a lower paste volume was mixed; else a mixture with a higher paste volume was mixed.

6.4 RESULTS AND INTERPRETATIONS

This section contains the results of the tests performed on the concrete mixtures. For each combination of coarse and fine aggregate, the results of the HRWRA demand, compressive strength, shrinkage, and permeability are presented separately. The results are compared based on differences in paste volumes, *S/A* ratio (combined gradation), and shape and texture.

6.4.1 NAT-CA and NAT-FA

Figure 6.1 shows the amount of HRWRA added to concrete mixtures containing combinations of the river gravel (NAT-CA) and river sand (NAT-FA). At any paste volume the amount of HRWRA needed to achieve the desired workability was equal or higher for *S/A*=0.5 compared to *S/A*=0.4, and higher for *S/A*=0.4 compared to *S/A*=0.3. The gap-graded mixture had the least HRWRA requirements among all the four mixtures. *S/A*=0.3 mixtures at all paste values resulted in shear slumps. Minor bleeding was observed for this mixture at 25% paste, while at 23% paste the mixture was bleeding even more. At paste volumes below 25%, *S/A*=0.5 and *S/A*=0.4 were excessively bleeding.

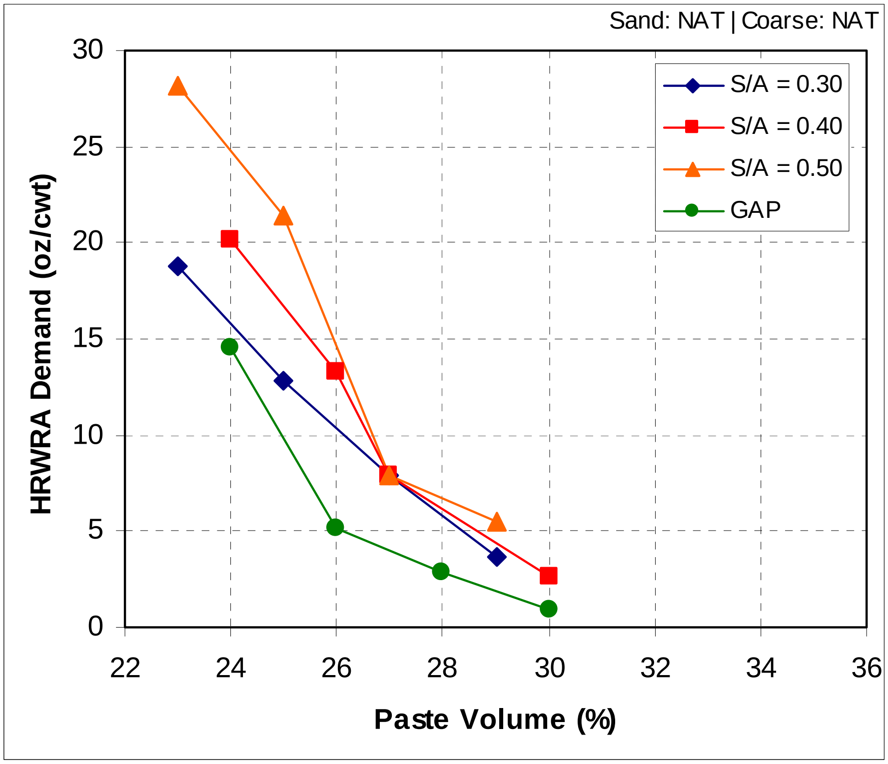

Figure 6.1: HRWRA demand for NAT-CA and NAT-FA

Generally, paste content did not have a noticeable effect on the concrete compressive strength (Figure 6.2). Even at lower paste volumes, *S/A*=0.3, *S/A*=0.4, and the gap-graded mixture were not affected by decreases in paste volumes. *S/A*=0.5 however, had a lower strength compared to all other mixtures (as predicted by the coarseness chart in Chapter 4). As opposed to the other mixtures, the reduction in paste seems to have had a greater effect on *S/A*=0.5; as the paste volume of *S/A*=0.5 was reduced, the strength was also reduced.

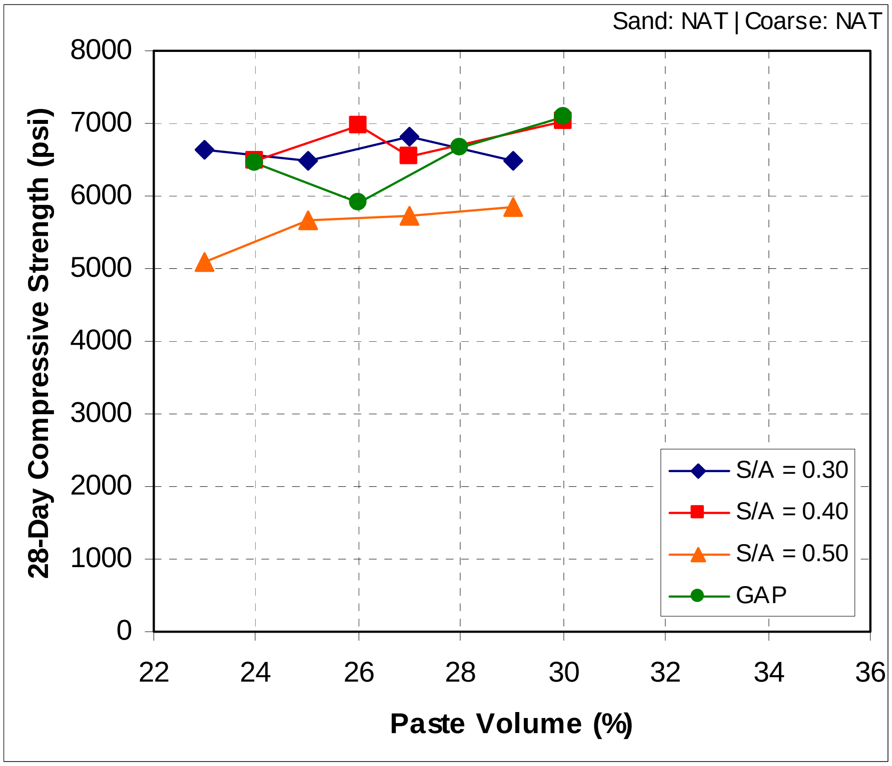

Figure 6.2: Compressive Strength for NAT-CA and NAT-FA

The shrinkage values for the NAT-CA and NAT-FA mixture are shown in Figure 6.3. As expected, reducing the paste volume reduced the shrinkage in all the specimens tested because the cement paste is what causes the concrete to shrink; the aggregates act as restraints, so the more the aggregate and the less the paste, the less the shrinkage. *S/A*=0.3 had the lowest shrinkage values, while the gap graded mixtures had the highest. *S/A*=0.4 had slightly lower shrinkage values as compared to *S/A*=0.5. Except for the gap graded aggregates, the increase in coarse aggregate content decreased the shrinkage in the concrete.

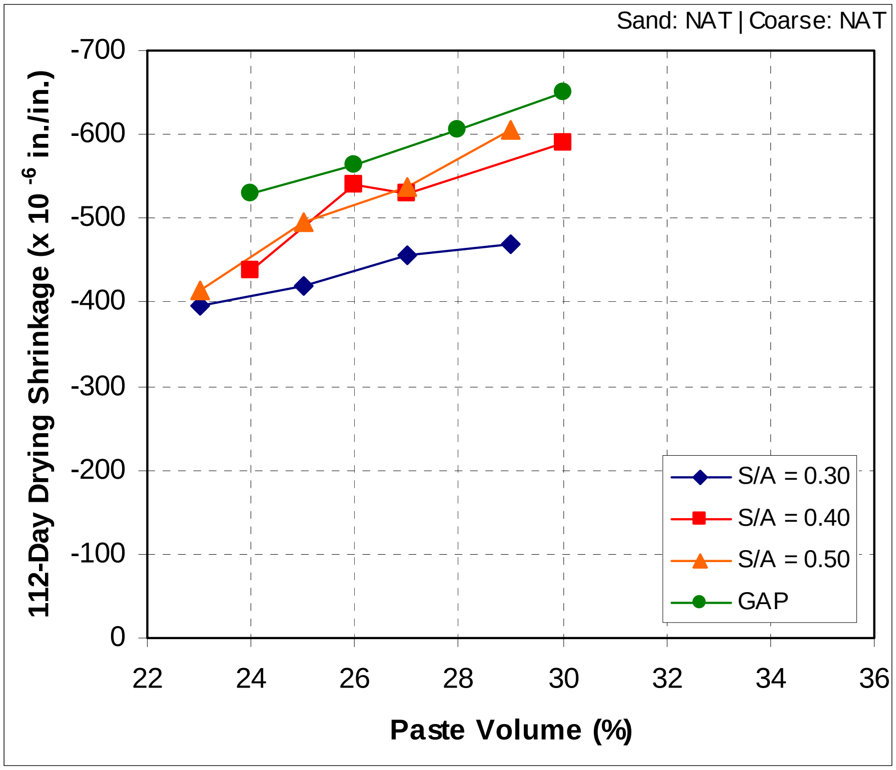

Figure 6.3: Shrinkage for NAT-CA and NAT-FA

According to ASTM C 1202, a coulomb value between 2000 and 4000 indicates that the chloride permeability of the concrete is moderate. Figure 6.4 show that the paste reductions decreased the permeability of the mixtures. Such results are expected, since when the paste volume was reduced while maintaining the same *w/c* ratio, the total volume of water was reduced, thus the permeability of the concrete decreased. It is not clear, however, how differences in gradations affected the permeability. The best performance was achieved for *S/A*=0.3; at 30% paste the permeability was moderate, while at 23% the permeability was low (the coulomb value is between 1000 and 2000).

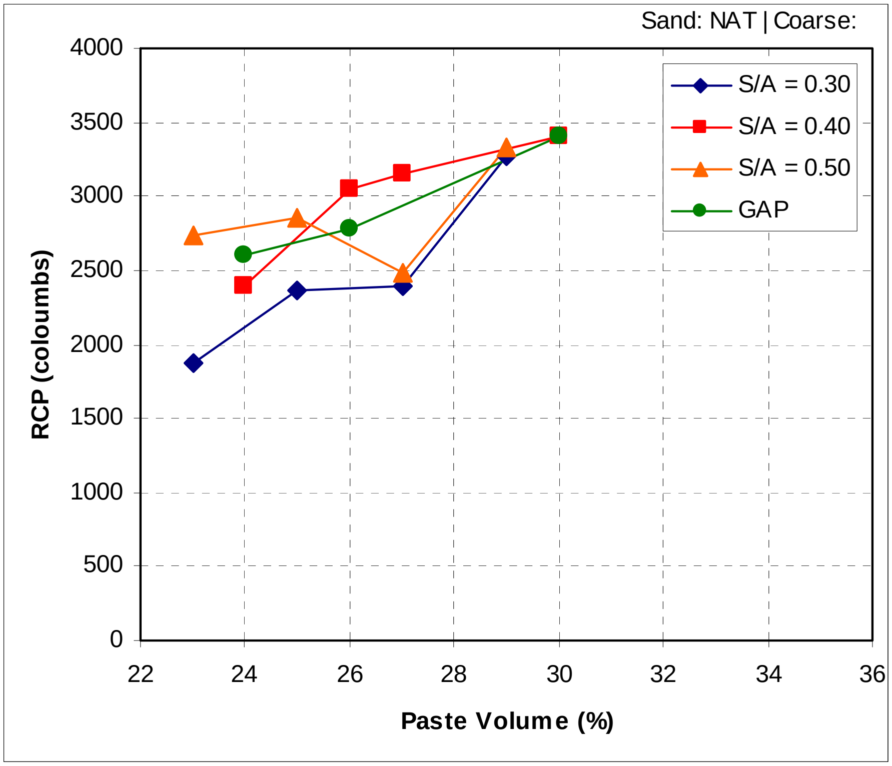

Figure 6.4: RCP for NAT-CA and NAT-FA

6.4.2 NAT-CA and LS-A-FA

The HRWRA demand for each concrete mixture containing combinations of the river gravel (NAT-CA) and the well-graded limestone sand (LS-A-FA) is shown in Figure 6.5. More HRWRA was needed to achieve the desired workability at higher sand volumes; *S/A*=0.5 had the highest HRWRA requirement, while the gap-graded mixture had the lowest. In general the mixtures were slightly harsh at low paste volumes. Severe bleeding was observed for *S/A*=0.5 at 25% paste. Although the gap-graded mixtures looked “rocky”, no bleeding was observed at any paste volume, and they had the best performance compared to the other mixtures

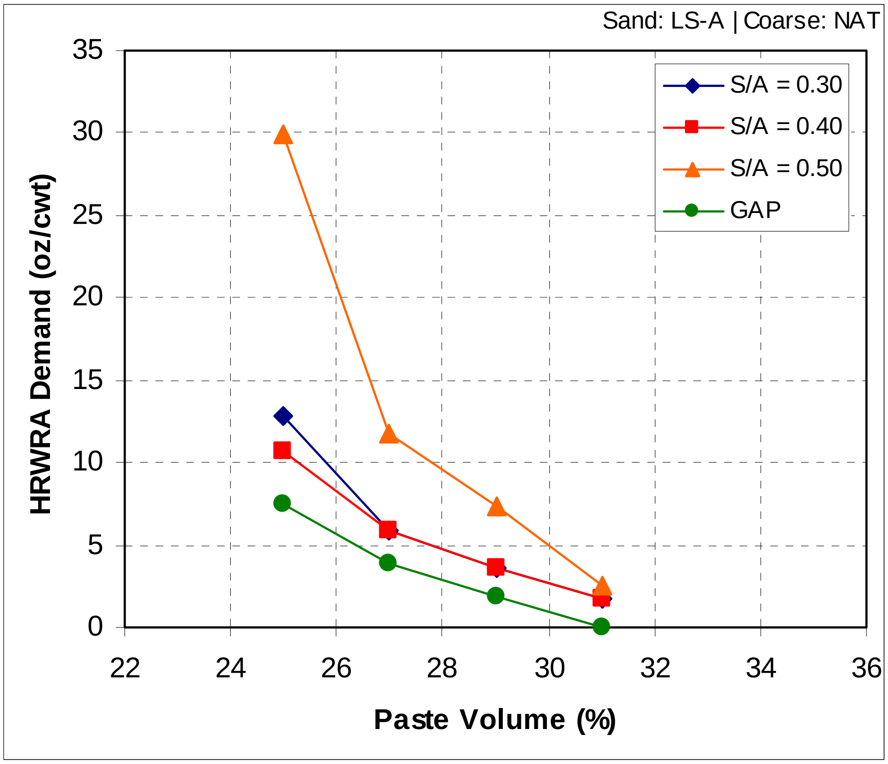

Figure 6.5: HRWRA demand for NAT-CA and LS-A-FA

Neither the change in the *S/A* ratio nor the reduction in paste had any effect on most of the compressive strength of the mixtures containing NAT-CA and LS-A-FA (Figure 6.6). The only exception was *S/A*=0.5 at the lowest attained paste volume of 25%. A similar result was observed in the NAT-CA and NAT-FA mixtures; at high sand contents and low paste volumes, the compressive strength of the concrete was affected. *S/A*=0.3, *S/A*=0.4, and the gap-graded mixture yielded nearly the same compressive strength at all paste volumes. Therefore, when an appropriate combined gradation of fine and coarse aggregate is used, reducing the paste volume does not affect the compressive strength of the concrete.

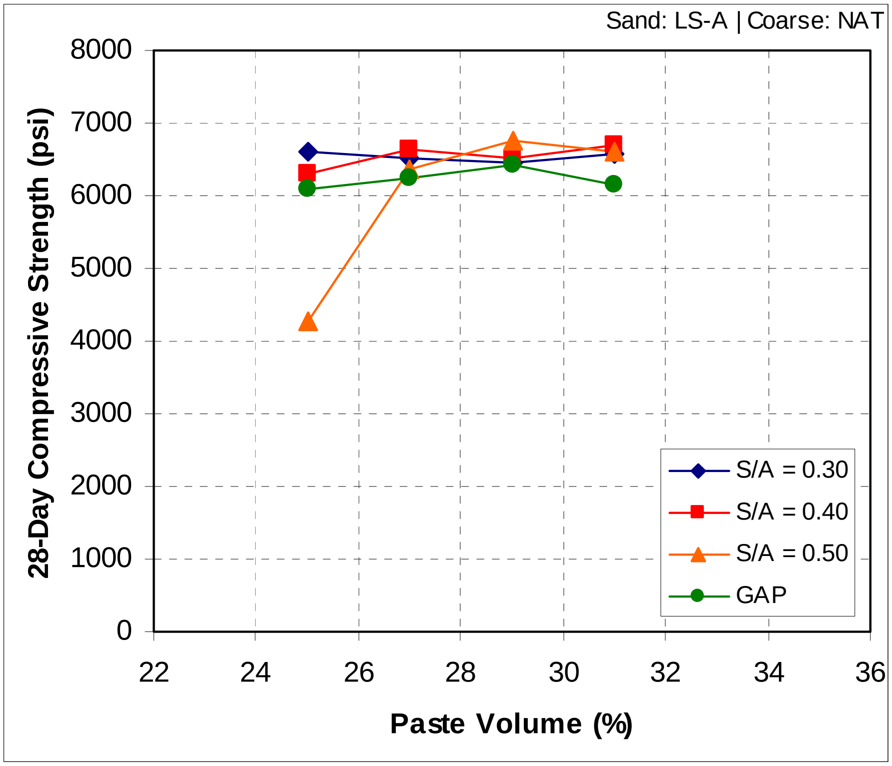

Figure 6.6: Compressive Strength for NAT-CA and LS-A-FA

Figure 6.7 shows the shrinkage values for the NAT-CA and LS-B-FA mixtures. In general, reducing the paste volume reduced the shrinkage in all the specimens tested. *S/A*=0.4 had the lowest shrinkage values, while the gap graded mixtures had the highest. Unlike the NAT-CA and NAT-FA series, increasing the coarse aggregate did not improve the shrinkage performance of the concrete mixtures.

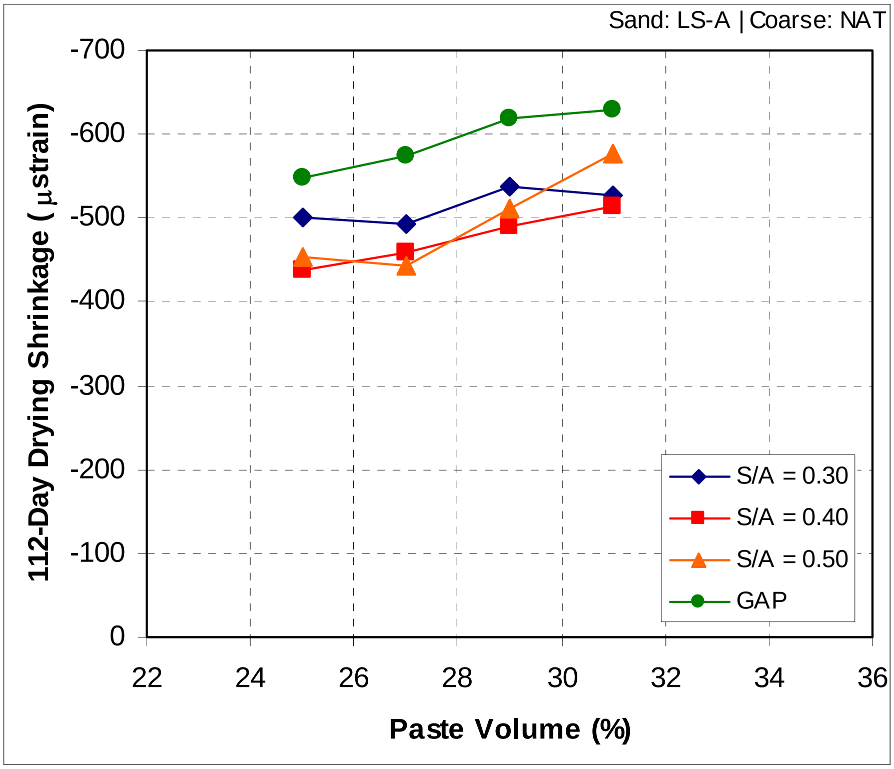

Figure 6.7: Shrinkage for NAT-CA and LS-A-FA

Rapid Chloride Penetration (RCP) values for NAT-CA and LS-A-FA show that reductions in paste volume reduced the permeability of the concrete (Figure 6.8). The obtained values are in the range of 2000 to 3500 coulombs, which is considered as moderately permeable. The gap-graded mixture at 25% paste was the only mixture to have a coulomb value below 2000, and is considered to have a low permeability. Similar to the NAT-CA and NAT-FA combination, there is no clear pattern to how the changes in gradation of the aggregates affected the permeability.

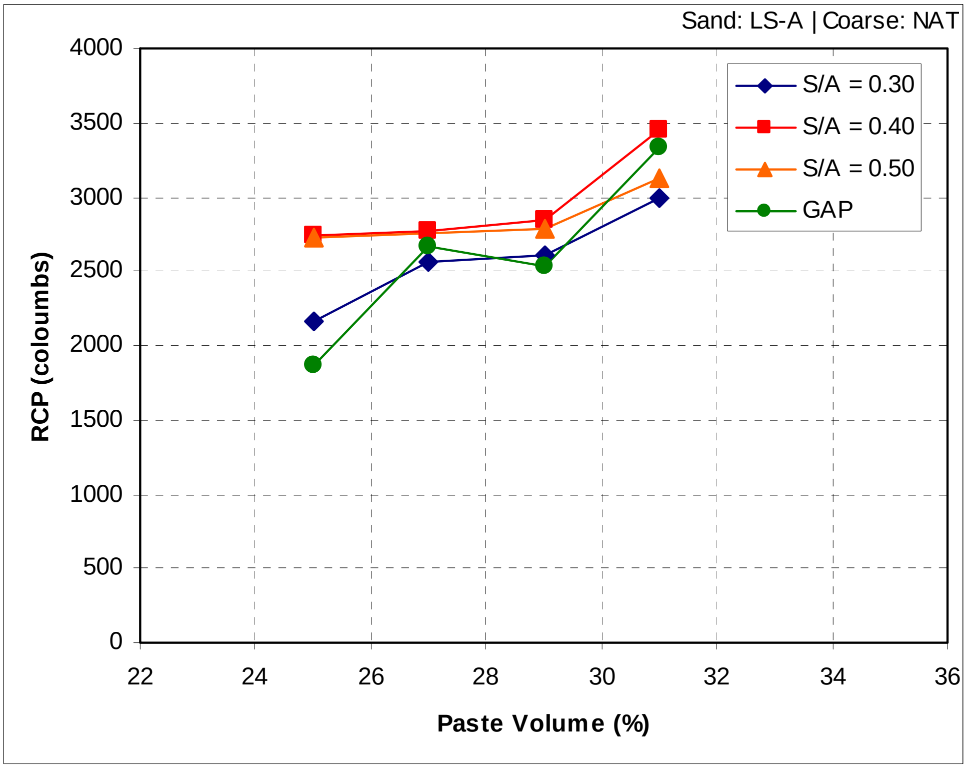

Figure 6.8: RCP for NAT-CA and LS-A-FA

6.4.3 NAT-CA and LS-B-FA

The HRWRA demand for each concrete mixture containing combinations of the river gravel (NAT-CA) and the poorly-graded limestone sand (LS-B-FA) is shown in Figure 6.9. Slightly more HRWRA was needed to achieve the desired workability at higher sand volumes; *S/A*=0.5 had the highest HRWRA requirement, while *S/A*=0.3 had the lowest HRWRA demand. The mixtures in this series were harsh, and it was not possible to reduce paste content below 28%. Bleeding was observed for *S/A*=0.4 at a paste volume of 29%. Such a behavior was expected, because LS-B-FA is poorly shaped and is lacking fine materials (it is the coarsest of the three sands).

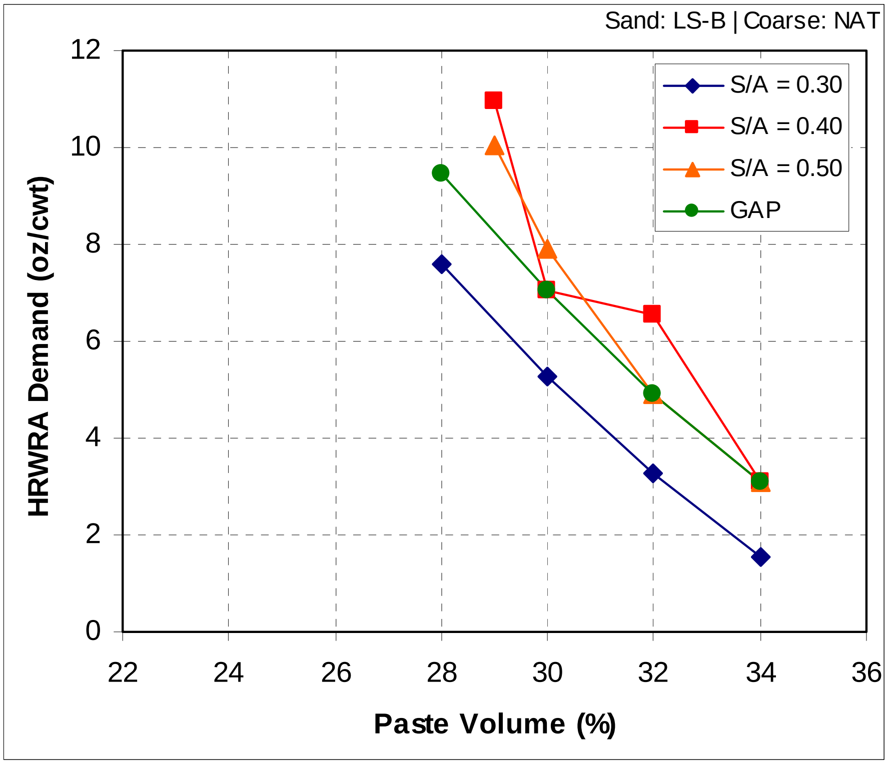

Figure 6.9: HRWRA demand for NAT-CA and LS-B-FA

Mixtures of NAT-CA and LS-B-FA were not affected by differences in combined gradations. Figure 6.10 shows that all the obtained values for the compressive strength of this series are about the same. It should be noted that paste volume reductions for NAT-CA and LS-B-FA mixtures were not as large as for other mixtures, and therefore the same effect previously observed for sandy gradation could not be confirmed for this series.

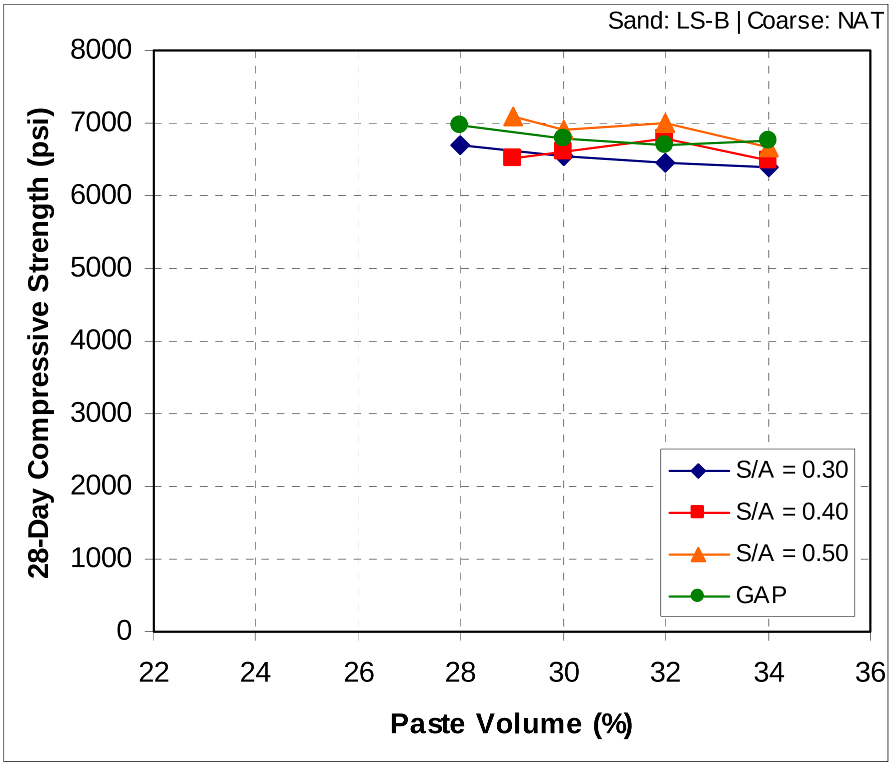

Figure 6.10: Compressive Strength for NAT-CA and LS-B-FA

Figure 6.11 shows the shrinkage values obtained for mixtures of NAT-CA and LS-B-FA. Shrinkage was reduced for mixtures with paste volumes less than 30% for *S/A*=0.5 and *S/A*=0.4. There seems to be no correlations between the different *S/A* values and shrinkage, and unlike the NAT-CA and NAT-FA mixtures, increasing the coarse aggregate content did not improve shrinkage.

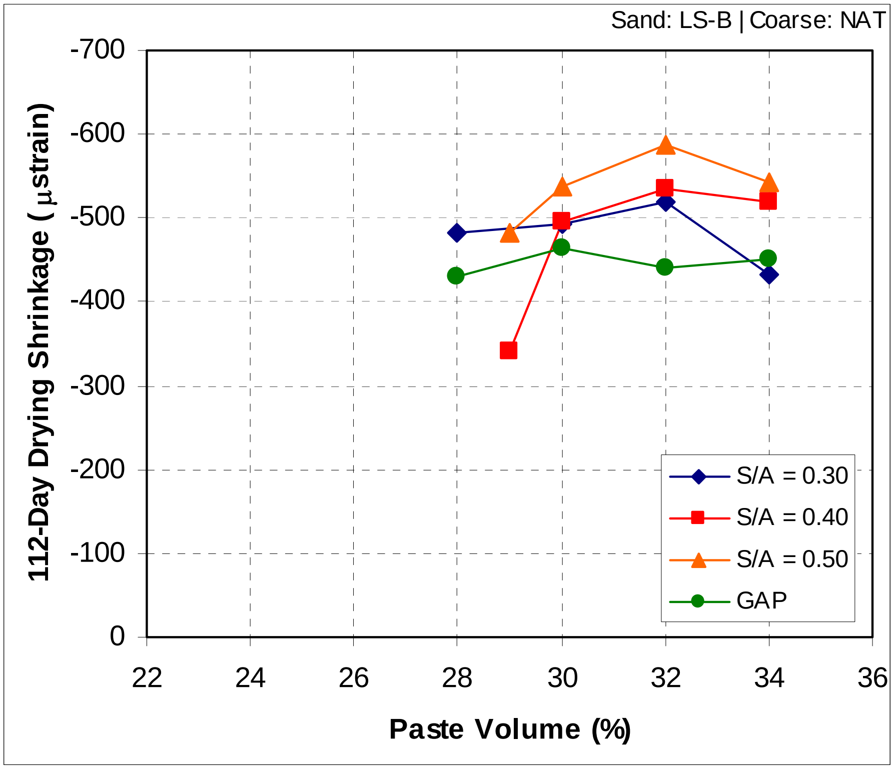

Figure 6.11: Shrinkage for NAT-CA and LS-B-FA

Except for the gap-graded mixture, the RCP value dropped as the paste content was reduced (Figure 6.12). It is unclear why the coulomb value of the gap-graded mixture at 32% paste volume is lower than that at 30% paste. A similar result was also obtained for *S/A*=0.3 at 34% and 32% paste (probably an outlier).

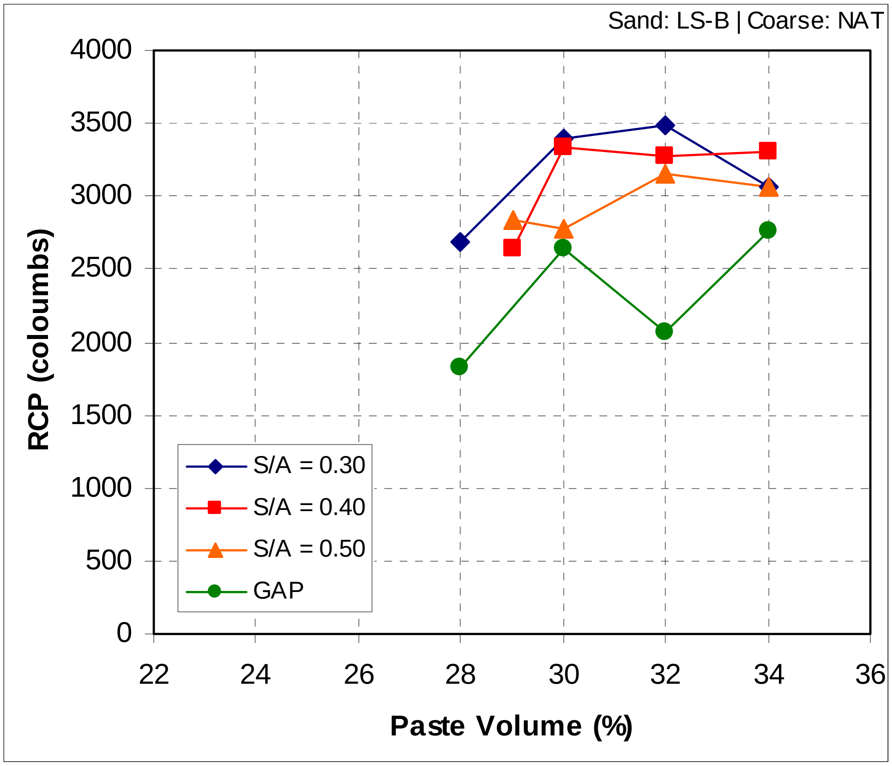

Figure 6.12: RCP for NAT-CA and LS-B-FA

6.4.4 LS-A-CA and NAT-FA

The HRWRA demand for mixtures containing LS-A-CA and NAT-CA are shown in Figure 6.13. Water requirements for the different blends was similar; *S/A*=0.3, *S/A*=0.4, and the gap-graded gradation all had about the same amount of HRWRA. *S/A*=0.5 had the highest HRWRA demand for all paste volumes. The only difference between those three gradations was that a lower paste volume was attained for *S/A*=0.3. *S/A*=0.3 lacked fine aggregates, and bleeding was observed at 27% and 28% paste volumes, even though the amount of HRWRA added was considerably low.

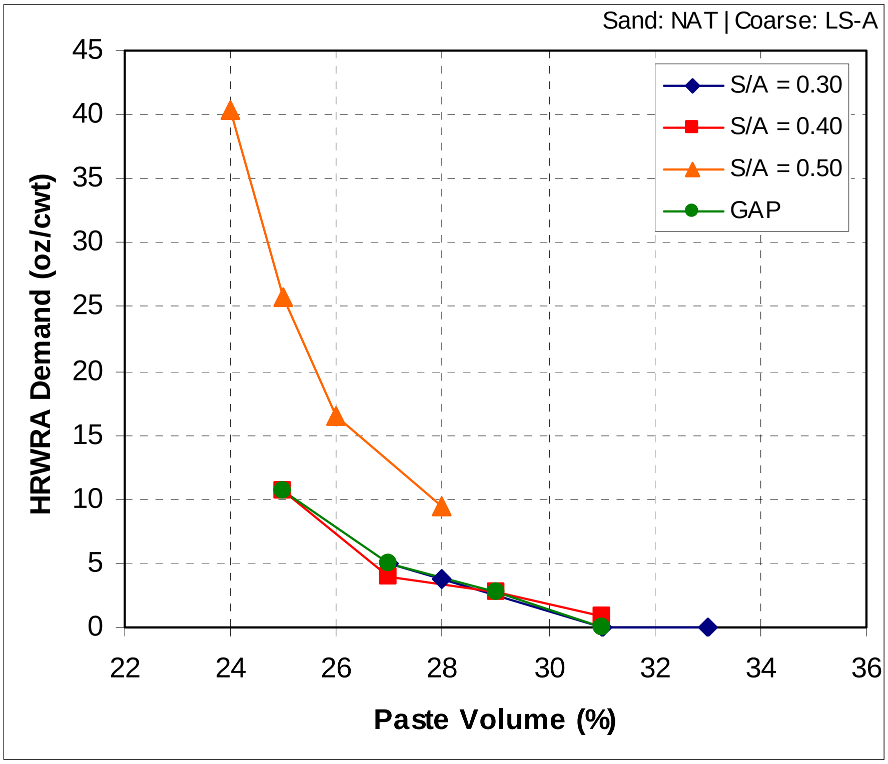

Figure 6.13: HRWRA demand for LS-A-CA and NAT-FA

The compressive strengths of the mixtures of LS-A-CA and NAT-FA are shown in Figure 14. There was a slight decrease in compressive strength for *S/A*=0.3 at lower paste volumes. *S/A*=0.5 had the largest drop in strength when paste volume was decreased; cutting the paste volume by 2% reduced the compressive strength by around half its value. The results for these blends of aggregates resemble the previous results in that paste volume reductions had minor effects on compressive strength when *S/A* was less than 0.5.

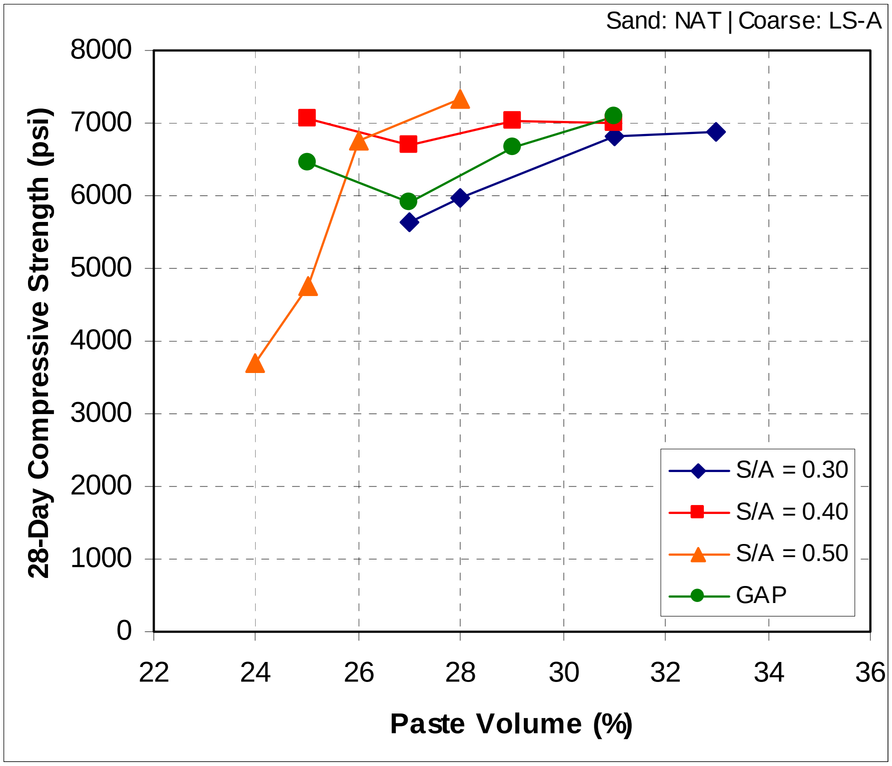

Figure 6.14: Compressive Strength for LS-A-CA and NAT-FA

The reduction in paste volume for the different gradations had a positive effect on the shrinkage (Figure 6.15). The gap-graded gradation had the worst performance, while *S/A*=0.3 performed better compared to the others at higher paste volumes. *S/A*=0.5 shrunk less than *S/A*=0.4 at a paste volume of 25%, while *S/A*=0.4 performed better at higher paste volumes. It is therefore unclear what effect gradation had on shrinkage in this series also.

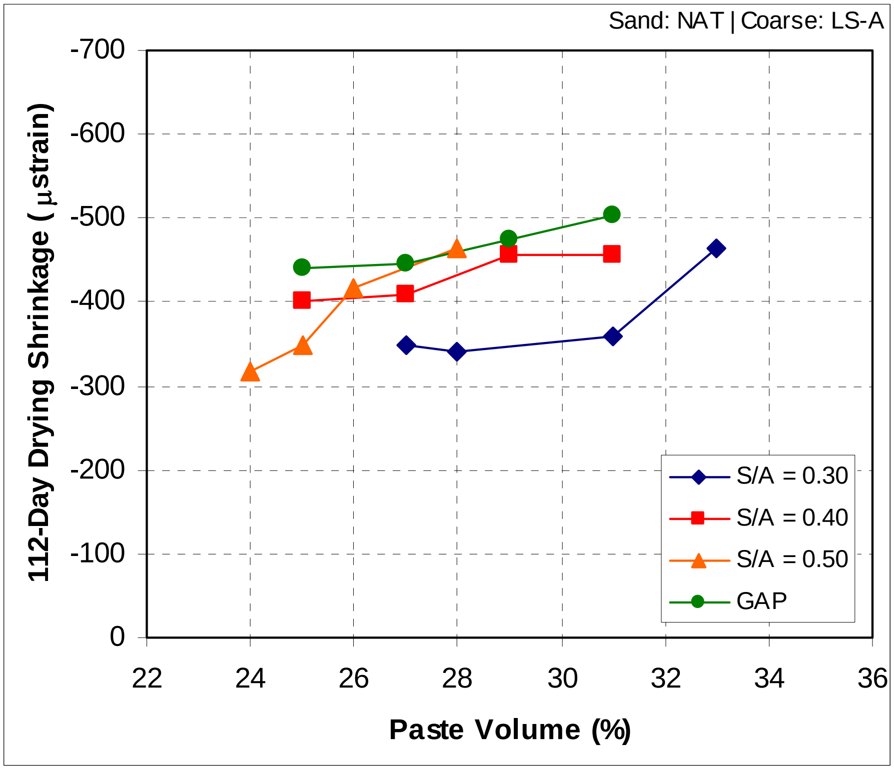

Figure 6.15: Shrinkage for LS-A-CA and NAT-FA

For *S/A*=0.4, paste volume reductions reduced the coulomb value (Figure 6.16). The only exception occurred for the gap-graded mixture at 29 and 31% paste volumes and for *S/A*=0.3 at 31and 33% percent paste.

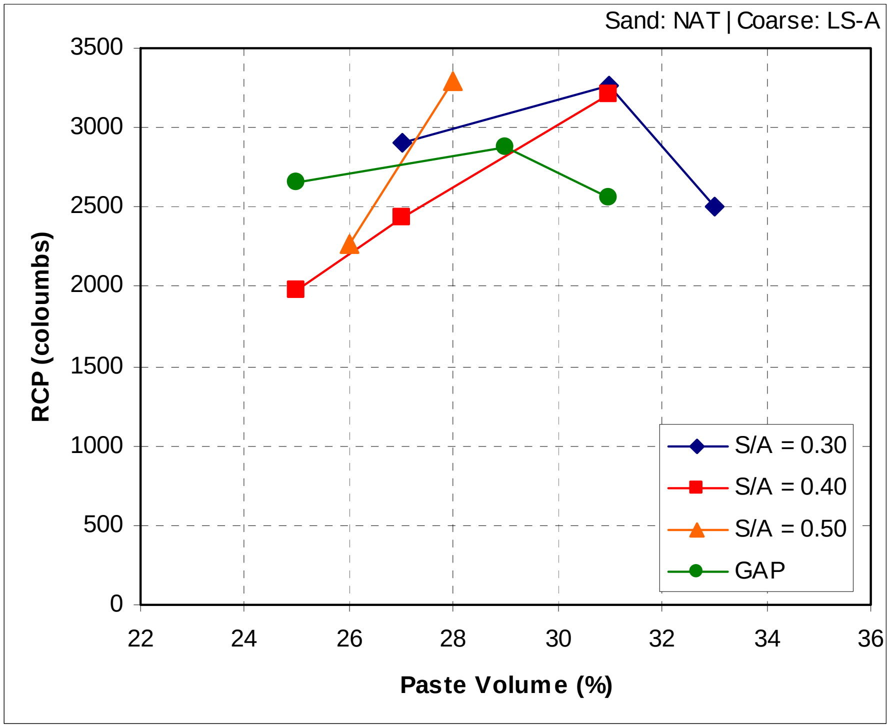

Figure 6.16: RCP for LS-A-CA and NAT-FA

6.4.5 Gradations with *S/A*=0.4

In this section values corresponding to *S/A*=0.4 for different aggregate types will be compared to each other. The goal was to evaluate how differences in the shape and texture of aggregates have an effect of concrete performance.

Among all the mixtures in which river gravel (NAT-CA) was used, the mixtures containing the well-shaped limestone sand (LS-A-FA) had lowest HRWRA demand, while the mixtures containing the poorly-shaped limestone sand (LS-B-FA) had the highest demand (Figure 6.17). The river sand (NAT-FA) had a higher HRWRA demand compared to LS-A-FA not because of shape and texture differences, but because it is finer than LS-A-FA. Overall, the lowest paste volume attained for *S/A*=0.4 was between 24% and 29%. A lower paste was reached for the mixtures containing NAT-CA and NAT-FA as compared to the mixtures containing LS-FA and NAT-FA. The HRWRA demand for LS-FA and NAT-FA was lower.

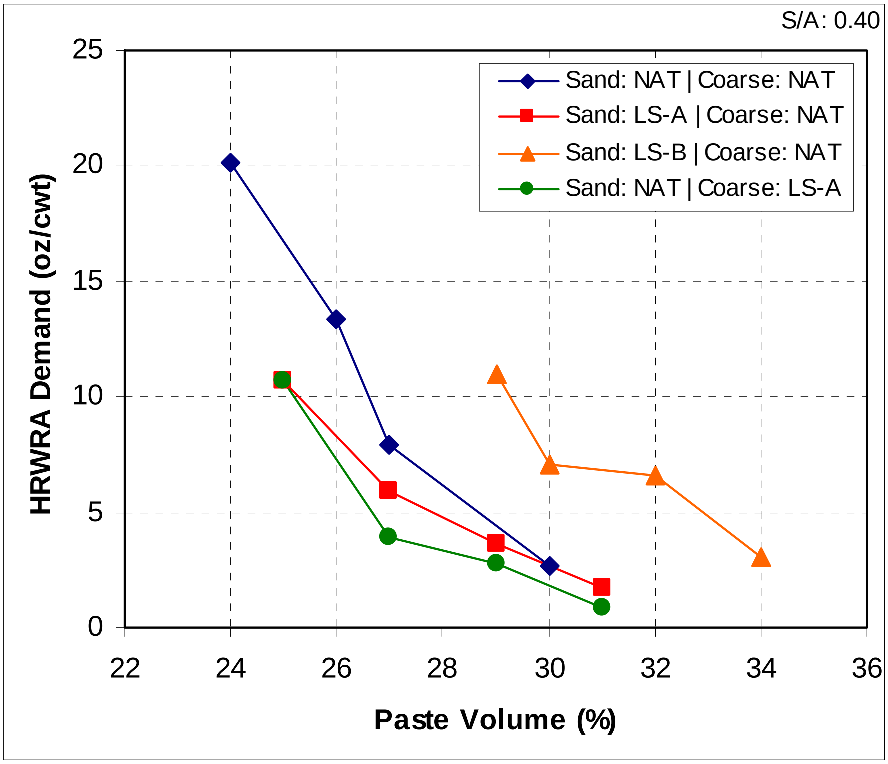

Figure 6.17: HRWRA demand for *S/A*=0.4

Using different aggregates while maintaining the same *S/A* did not have a noticeable effect on the compressive strength of the concrete (Figure 6.18). Based on these results, it is obvious that for the tested ranges of compressive strength (none high strength concrete), when a proper gradation is used lowering the paste volume or changing the aggregate source has no negative impact on strength.

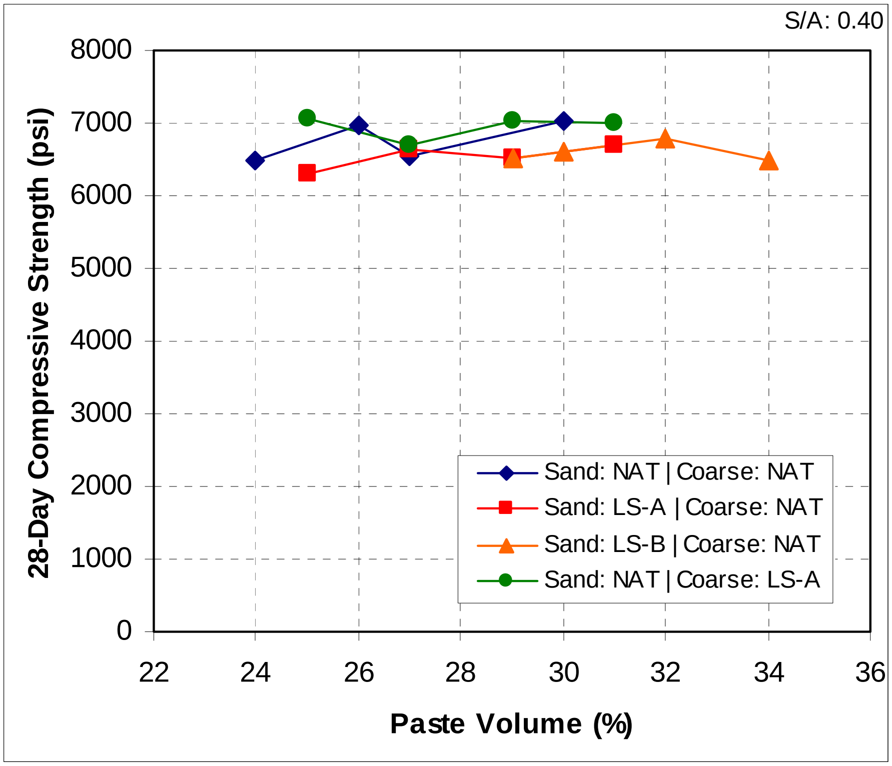

Figure 6.18: Compressive Strength for *S/A*=0.4

Figure 6.19 shows the shrinkage as a function of paste volume for the different combinations of aggregates used at *S/A*=0.4. All the different aggregate combinations had improved shrinkage performance at lower paste volumes, the mixtures containing LS-A-CA shrunk less than the ones containing NAT-CA. In addition, the mixtures containing the limestone fine aggregate LS-A-FA and LS-B-FA shrunk less than the mixtures containing the siliceous aggregates NAT-CA and NAT-FA.

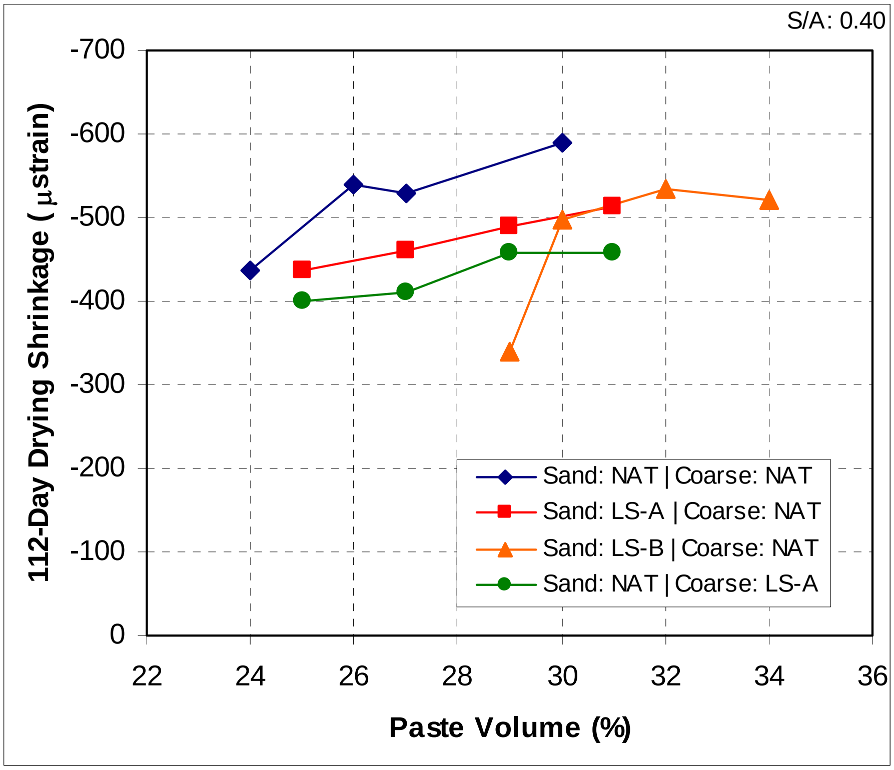

Figure 6.19: Shrinkage for *S/A*=0.4

Regardless of the type of aggregate, reductions in paste reduced the permeability of the concrete mixtures (Figure 6.20). The combination of LS-A-CA and NAT-FA performed the best, while NAT-CA and NAT-FA had the highest permeability. Nevertheless, it is not possible to draw conclusions on how differences in permeability of mixtures made with limestone aggregate compared to mixtures made with siliceous aggregates.

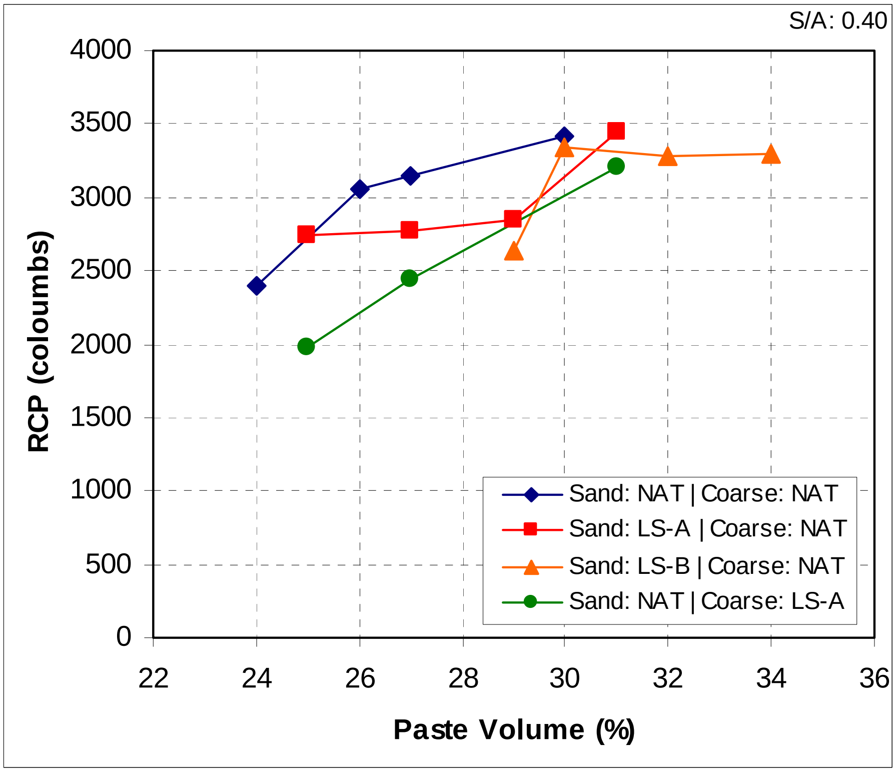

Figure 6.20: RCP for *S/A*=0.4

6.5 EFFECT OF SHAPE AND GRADING ON PASTE VOLUME

The minimum paste volume needed to reach the target slump with a HRWRA dosage of 6 oz/cwt (6 oz per 100 lbs of cement) for the combinations of aggregates used is presented in Figure 6.21. The paste requirements for the combination of the NAT-CA and LS-B-FA were the highest; more paste was needed for those mixtures to compensate for the poor shape of the limestone sand. For the combinations of NAT-CA with NAT-FA and LS-A-FA, the gap-graded mixtures required the least amount of paste; this is because the gap-graded gradations are the coarsest amongst the other gradations. Except for the mixtures where LS-A-FA was used, *S/A*=0.5 mixtures had the highest paste volume requirements. *S/A*=0.5 mixtures were too sandy and lacked coarse aggregates.

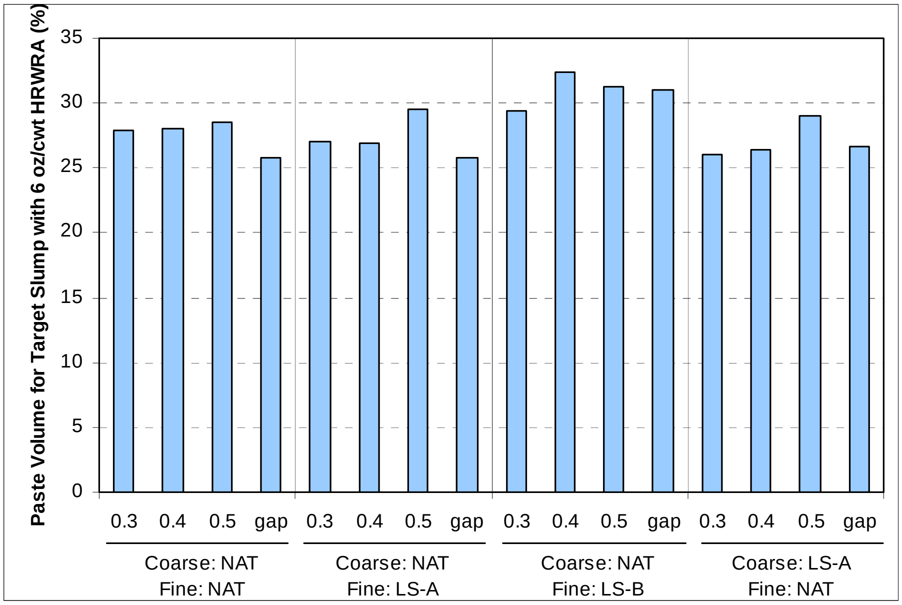

Figure 6.21: Paste Volume for Slump with 6 oz/cwt HRWRA

Figure 6.22 shows the minimum paste volume needed to avoid a shear slump (a shear slump indicates a loss in cohesion). Mixtures containing the NAT-FA fine aggregate had the least paste volume requirements, while the mixtures containing LS-B-FA had the highest paste requirements. Except for the combinations of NAT-CA and LS-B-FA, the increase in fine aggregate decreased the paste volume.

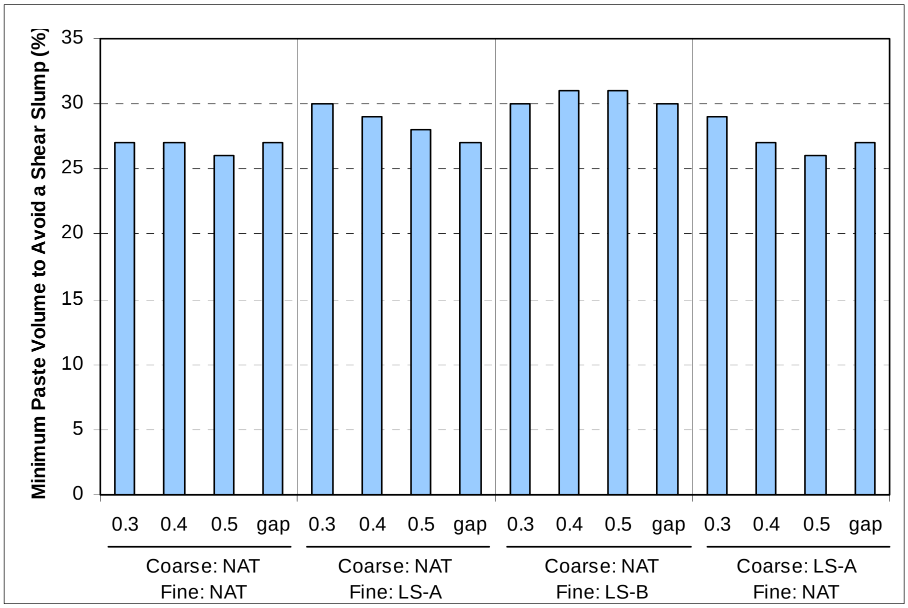

Figure 6.22: Minimum Paste Volume to Avoid Shear Slump

6.6 COST SAVINGS

In Phase I the goal was to reduce the paste content of the mixture by changing the aggregate gradation while maintaining a 6 ± 1 in. slump. Assuming the unit cost of Type I/II is 110 dollars/ton and the cost of the HRWRA is 11.50 dollars/gallon, an estimate of the cost of the concrete mixtures made in phase I was computed (the cost of aggregates was not included). Figure 23a shows the total cost of mixtures made with combinations of NAT-FA and NAT-CA. The lowest cost was achieved when a gap-graded mixture was used at a paste content of 26%. Mixtures with *S/A*=0.5 had a higher cost as the paste content decreased; all other mixtures had a lower or equal cost as the paste content decreased. By optimizing a mixture made with NAT-FA and NAT-CA, a cost saving of 1 to 2 dollars per cubic yard of concrete can be achieved.

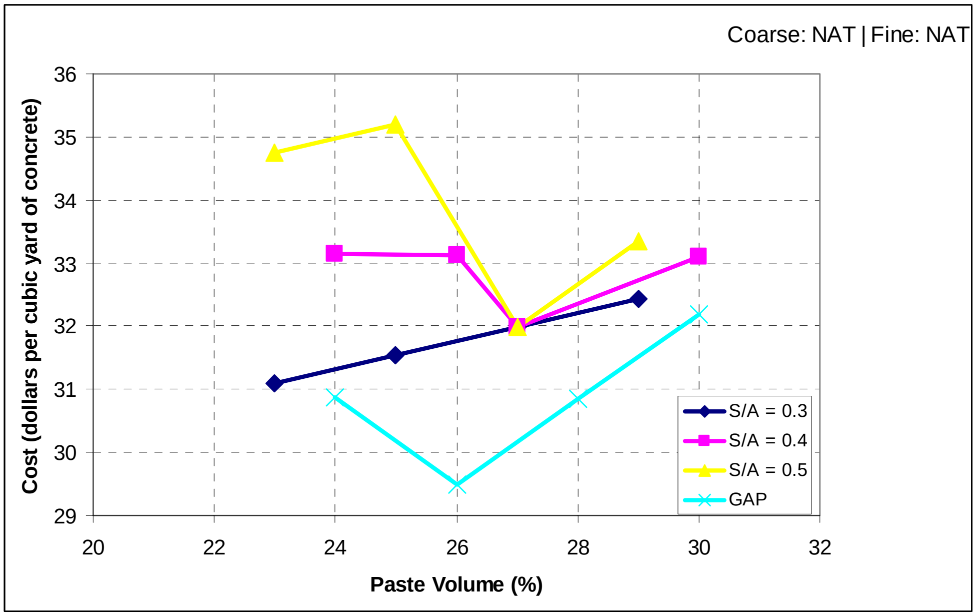

Figure 6.23a: Cost Comparison Charts for NAT-CA & NAT-FA

The cost of mixtures made with NAT-CA and LS-A-FA is shown in Figure 23b. For all mixtures except mixtures with *S/A*=0.5, the cost decreased as paste content decreased. The lowest cost at any paste content was achieved with gap-graded mixtures. Cost savings of about 2 to 4 dollars per cubic yard of concrete were achieved by decreasing the paste content when using an appropriate gradation.

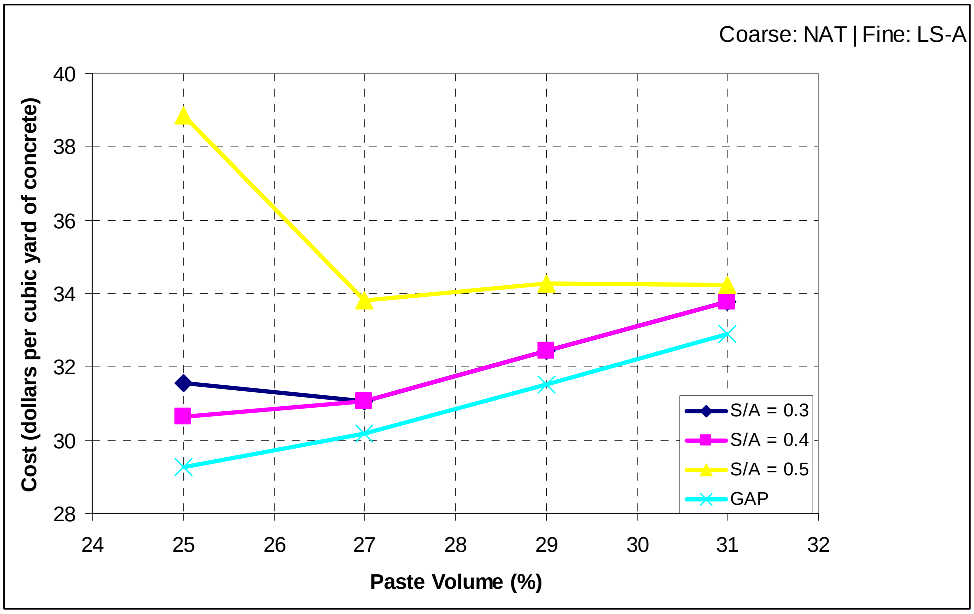

Figure 6.23b: Cost Comparison Charts for NAT-CA & LS-A-FA

Figure 23c shows the cost of mixtures made with NAT-CA and LS-B-FA. In general, the cost of mixtures decreased as paste content decreased. The lowest cost of any paste content was achieved for *S/A*=0.3. Unlike other coarse and fine aggregate combinations, the cost of mixtures with NAT-CA and LS-B-FA at *S/A*=0.5 decreased as paste content decreased. Similar to NAT-CA and LS-A-FA, savings of 2 to 4 dollars per cubic yard of concrete were achieved made by reducing the paste content.

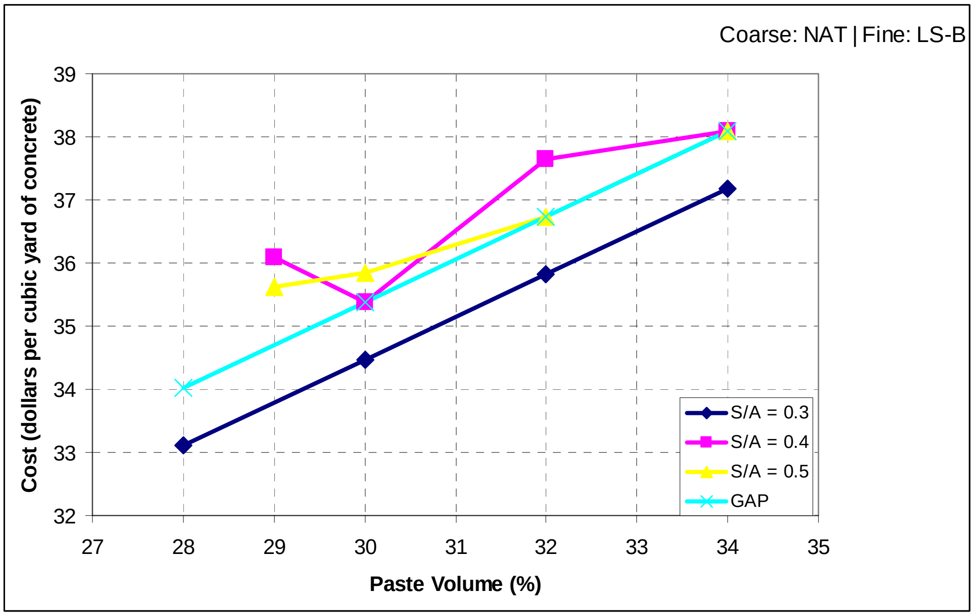

Figure 6.23c: Cost Comparison Charts for NAT-CA & LS-B-FA

Figure 23d shows the cost of mixtures made with LS-A-CA and NAT-FA. Except for *S/A*=0.5, the cost of mixtures decreased as paste content decreased. For *S/A*=0.3, *S/A*=0.4, and GAP, savings of 1 to 3 dollars per cubic yard of concrete were found when reducing the paste content.

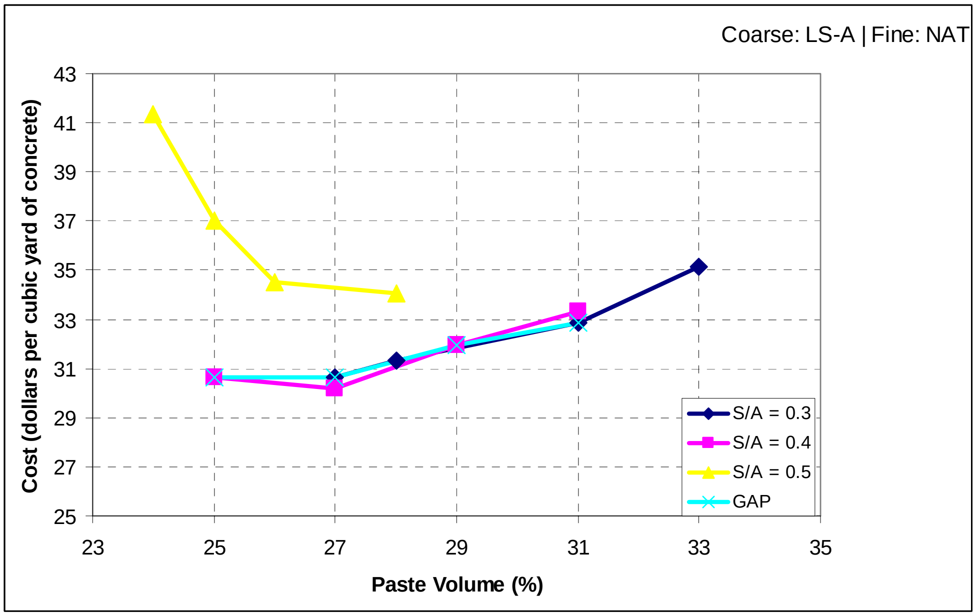

Figure 6.23d: Cost Comparison Charts for LS-A-CA & NAT-FA

Figures 23a, 23b, 23c, and 24d showed that by optimizing aggregate gradation and reducing paste content, the cost of concrete could be reduced. However, the optimum gradation needed to achieve the highest cost reduction depends on the type of fine and coarse aggregate used. The results also showed that the highest cost reductions were not necessarily associated with the lowest paste volumes. The cost of mixtures made with a manufactured sand (LS-A-NAT & LS-B-NAT) was higher than for those made with a natural sand (NAT-FA), but the savings achieved when optimizing a mixture made with a manufactured sand was higher (2 to 4 compared to 1 to 2 dollars per cubic yard).

Chapter 7: Phase II: Experimental Program Optimization Through the Use of Microfines

7.1 INTRODUCTION

In Phase II, the goal was to evaluate the behavior of concrete and to determine the maximum reduction in cement that could be obtained when microfines were used as mineral fillers. Three different microfines were used in this phase.

As described in Chapter 4, two limestone and one granite microfines were used in this research. The microfines were characterized by the methylene blue test, the single drop test and laser diffraction.

7.2 SERIES A

In Series A, all aggregate proportioning was calculated on a volumetric basis. The microfines in this series were considered as part of the paste volume. The objective of this series was to hold the water-to-cement ratio constant while substituting a percentage of the paste volume for an equivalent volume of aggregate microfines. This was achieved through specific gravity corrections based on the weight of cement substituted.

A set of four mixtures was prepared first to be able to compare the results of Phase I and Phase II. These mixtures were composed of the crushed limestone (LS-A) coarse aggregate and the well shaped manufactured (LS-A) fine aggregate. The sands used in these four mixtures were not modified, i.e. the microfines were not washed out.

The entire Series A was composed of eleven mixtures. First, there was one base mixture with unmodified fine sands, i.e. the sands contained the original microfines from the factory. Second, there were three mixtures for each microfine; each mixture had a different level of microfine substitution (10, 20 and 30% cement reduction). Finally, one mixture was batched with all the microfines washed out (including the original microfines from production of the crushed sand). Table 7.1 shows the mixture proportions for the eleven mixtures in Series A. First, a calculation was run considering the microfines to be a fraction of the cement content. Also, an additional calculation was run considering the microfines to be a fraction of the fine aggregate. The cement reductions (by volume) of 10, 20 and 30% were found to be equivalent to fine aggregate fractions (by volume) of 9.1, 16.7 and 23.1%. Also, it should be noted that the substitution of cement for microfines led to a reduction of water content in the final mixture.

Table 7.1: Optimization Mixtures Considering Microfines as part of Paste Volume

	Cement	**Water**	**MF**	**Coarse**	**Fine**	**w/p***	**% MF volume (per fine)**	**MF Material**
	lb/yd^3	**lb/yd^3**	**lb/yd^3**	**lb/yd^3**	**lb/yd^3**			
Baseline	**536**	**268**		**1833**	**1231**	0.500		None
10% cement reduction	482	241	118	**1833**	**1231**	0.402	9.1%	GR-A
20% cement reduction	429	214	236	**1833**	**1231**	0.323	16.7%	
30% cement reduction	375	188	354	**1833**	**1231**	0.257	23.1%	
10% cement reduction	482	241	114	**1833**	**1231**	0.404	9.1%	LS-A
20% cement reduction	429	214	229	**1833**	**1231**	0.326	16.7%	
30% cement reduction	375	188	343	**1833**	**1231**	0.261	23.1%	
10% cement reduction	482	241	102	**1833**	**1231**	0.413	9.1%	LS-C
20% cement reduction	429	214	204	**1833**	**1231**	0.339	16.7%	
30% cement reduction	375	188	306	**1833**	**1231**	0.275	23.1%	
LS-A (Washed no mf)	375	188		**1833**	**1585**	0.500		None

Note: w/p = water to powder ratio.
MF = Microfines or dust of fracture.

7.3 SERIES B

The mixtures in Series A that had a 30% cement reduction were compared with the mixtures in Series B. Series B was different from Series A in that instead of considering the volume of microfines as part of the paste it considered the microfines as part of the fine aggregate. All of the aggregate proportioning for this series was also done on a volumetric basis.

Figure 7.1 shows the difference between Series A and Series B. It should be noted that the same baseline mixture was used for both series. In Series B, the microfines were considered as part of the fine aggregates, which reduced the amount of sand by replacing it with mineral filler without changing the water-to-cement ratio or the original amount of cement used in the mixture. For this reason, the paste volume (by definition, anything finer than a No. 200 sieve) increased from 28 to 34%.

Series A, on the other hand, considered the microfines as part of the paste volume. The effect of such consideration was that, although the water-to-cement ratio was kept constant, the amount of cement was decreased by an equal amount of mineral filler incorporated in the mixture. In all these mixtures the paste volume was held constant at 28%. The percentage of the volume of fine aggregates that needed to be substituted was 23.1%; this fine aggregate volume substitution (Series B) translated into a 30% cement volume substitution (Series A) after making specific gravity corrections. This is shown in Figure 7.1.

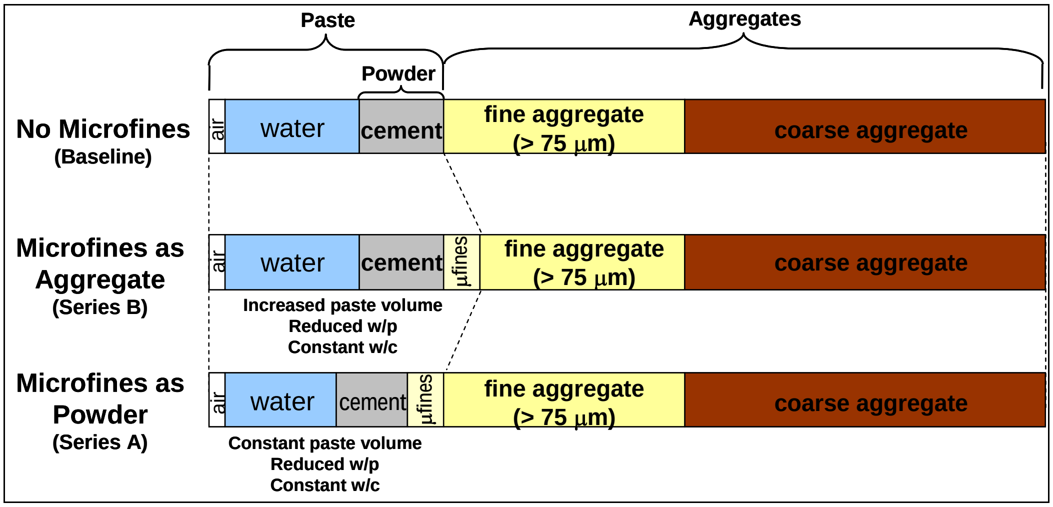

Figure 7.1: Comparison between Series A and Series B, Phase II.

Three mixtures were batched for Series B. These mixtures corresponded to the mixtures with the maximum amount of cement reduction that were found to be practical in Series A. In all three cases, these mixtures corresponded to the 30% cement reduction mixtures in Series A.

The mixture proportions used for Series B can be found in Table 7.2. The paste volumes for the mixtures in Series B were found to be higher than those in Series A for all cases.

Table 7.2: Microfines Considered as Part of the Aggregate.

	Cement lb/yd^3	**Water lb/yd^3**	**MF lb/yd^3**	**Coarse lb/yd^3**	**Fine lb/yd^3**	**w/p**	**Paste Volume**	**MF Material**
Baseline (same as Series A)	**536**	**268**		**1833**	**1231**	0.500	0.28	None
23.1% microfines	**536**	**268**	293	**1833**	947	0.323	0.34	GR-A
23.1% microfines	**536**	**268**	284	**1833**	947	0.327	0.34	LS-A
23.1% microfines	**536**	**268**	254	**1833**	947	0.339	0.34	LS-C

Note: MF = Microfines or dust of fracture.

7.4 MIXING PROCEDURE, SPECIMENS & FRESH PROPERTIES

To prepare the aggregates for the addition of the microfines, the manufactured sands (LS-A) had to be washed to get rid of the fines inherently present in these sands (about 5.3% by weight). This was achieved by using a large No. 200 sieve screen and applying large amounts of water with a fairly amount of pressure. The process is shown in Figure 7.2.

Figure 7.2: Washing Microfines out of Manufactured Sands.

In preparing the mixtures and specimens the procedure ASTM C 192 was followed. The batches were prepared for a 4-cu.ft. mixer. All of the batches for Phase I and Phase II were 1.33 ft^3 in volume. Four cylinders and four beams were cast from each batch. The cylinders were 4-in. in diameter by 8-in. in height; three for compressive strength and one for rapid chloride penetration testing. Three 3-in. by 3-in. by 11.25-in. beams were used for drying shrinkage and one 4-in. by 4-in. by 14-in. beam was used for abrasion resistance testing. All other preparations and mixing procedures were done as described in Chapter 6.

Chapter 8: Phase II Test Results Optimization Through the Use of Microfines

8.1 INTRODUCTION

This section presents the test results for the concrete specimens in Phase II of the overall research project. Two comparisons will be made for each test. The first chart will contain a comparison between the baseline mixture and the different microfines used in the project with the different percentages of cement reduction (Series A). The baseline will be shown as the mixture with no cement reduction (0%) for all different microfines. The second chart will contain a comparison between mixture proportioning methods considering the microfines as part of the aggregate (Series B, in red) and considering the microfines as part of the cement (Series A, 30% cement reduction mixtures, in blue). In the second graph, the baseline mixture results will be indicated by a black line across the chart. It should be noted that there is no record of the mixture where all the microfines were washed out (mixture "LS-A (Washed no mf)" in Table 7.1). This is due to the fact that the mixture was too sandy even after 12 ounces of HRWRA (high range water reducer admixture). This mixture crumbled every time the slump cone test was run because it did not have enough paste to bond the aggregate particles together.

8.2 SLUMP

The only fresh concrete property measured was slump (ASTM C 143). The target slump for this project was 6±1-in., a typical specified value for structural concrete. Slumps for the mixtures in Phase II, Series A are shown in Figure 8.1. The mixtures containing microfines with an intermediate (LS-C) or poor (GR-A) shape were the most difficult slumps to control. However, at higher microfines content it was easier to control the mixtures to yield a desired slump as is shown by the mixtures containing 30% cement reduction. This is most likely caused by the large amount of microfines present in the mixture which created a large amount of interparticle friction within the paste. This interparticle friction was mainly due to the angularity and roughness of the intermediate and poorly shaped microfines.

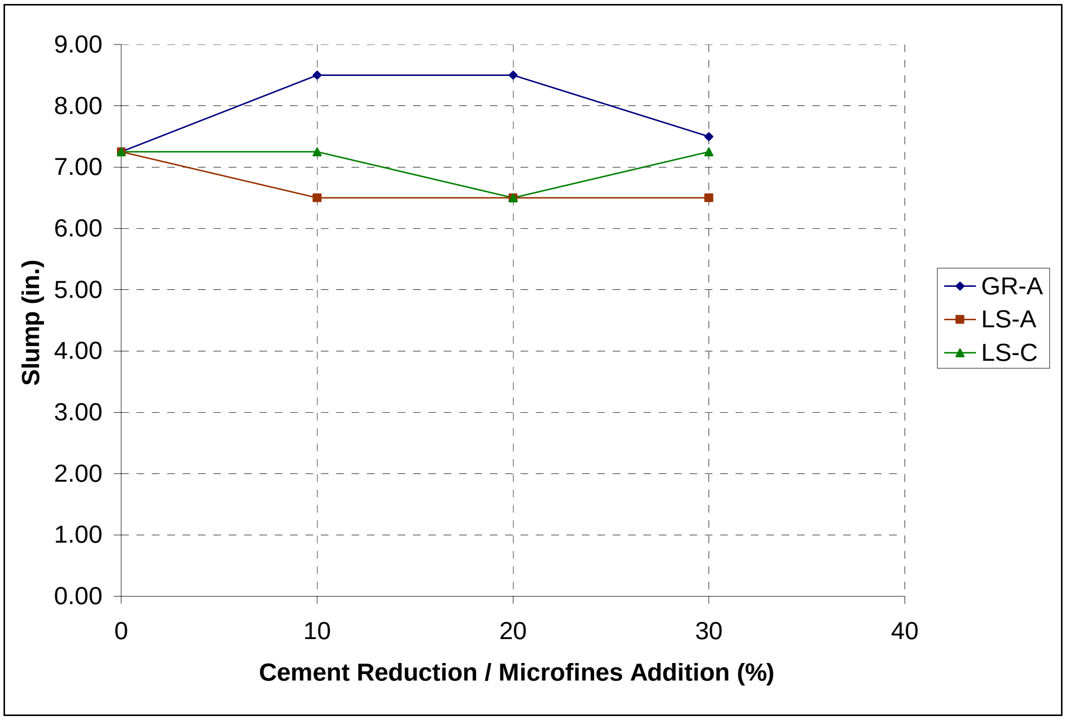

Figure 8.1: Slump, Series A.

Figure 8.2 shows a comparison of slumps between mixtures prepared considering the microfines as part of the aggregates (in red) and mixtures prepared considering the microfines as part of the paste (in blue).

No particular trend was found between the mixtures. The mixtures proportioned considering the fines as part of the paste were, in general, closer to the target slump than those prepared considering the microfines as part of the aggregate.

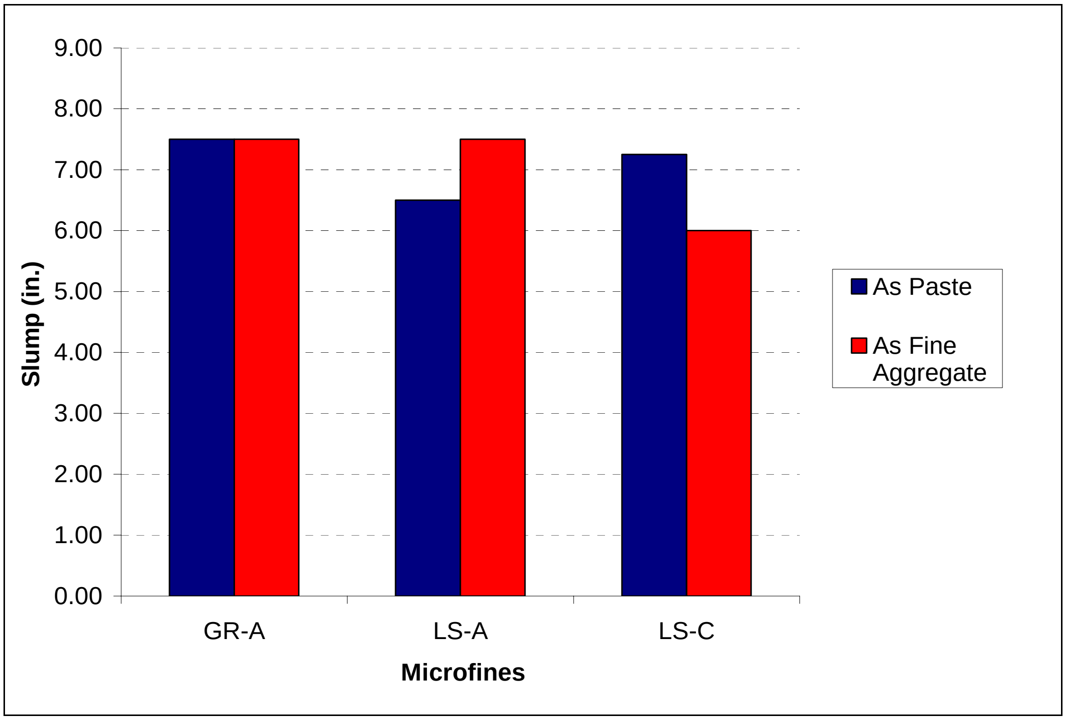

Figure 8.2 - Comparison of Slump, Series A (30% cement reduction) vs. Series B.

8.3 HRWRA DEMAND

The amount of water reducer required is shown in Figures 8.3 and 8.4. In Figure 8.3, the different amounts of HRWRA required by the different levels of cement substitution for each aggregate type are shown. It is clear that the granite mixtures had the highest demand of water reducing admixture. This may be due to the fact that the granite microfines (GR-A) had the poorest shape.

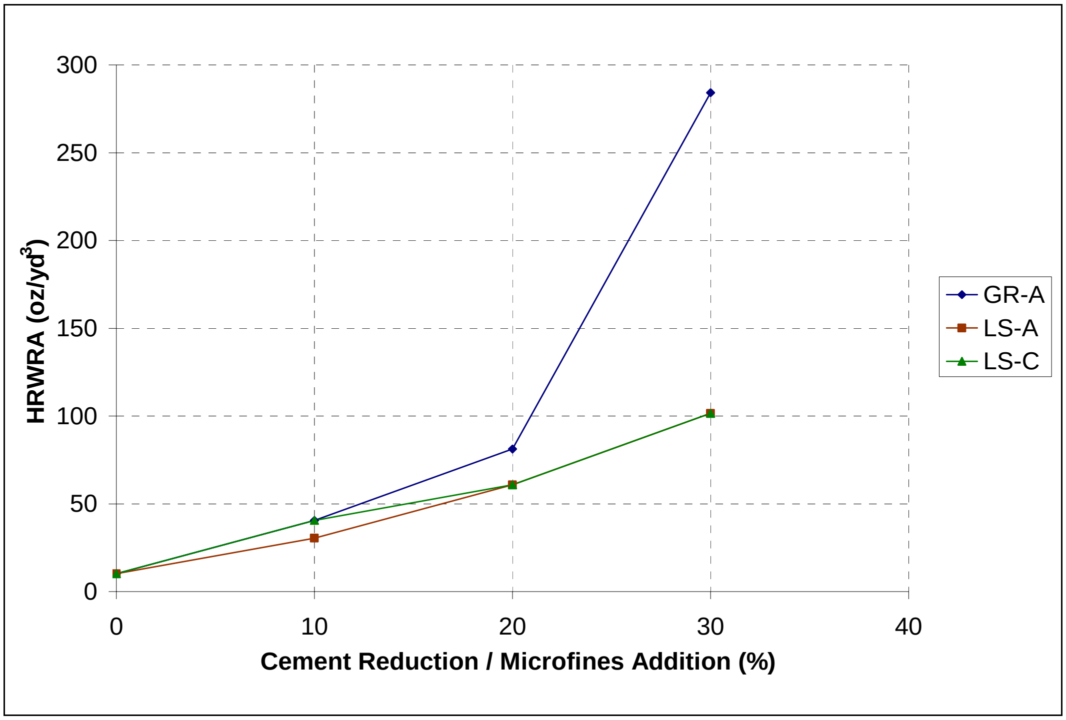

Figure 8.3 - HRWRA Demand, Series A.

The granite microfines had the lowest packing density. This suggests that they were the most angular of the three microfines used. Moreover, all microfines had low methylene blue values which indicated a low probability of harmful clay presence in the microfines.

The water reducer demand in mixtures prepared considering the microfines as part of the aggregate are compared to the mixtures prepared considering the microfines as part of the paste in Figure 8.4. From this figure, the large requirement of water reducer from the mixture containing granite microfines (GR-A) is obvious. It nearly triples the amount of water reducer required by the mixtures prepared with the other two mineral fillers in order to obtain the same workability level.

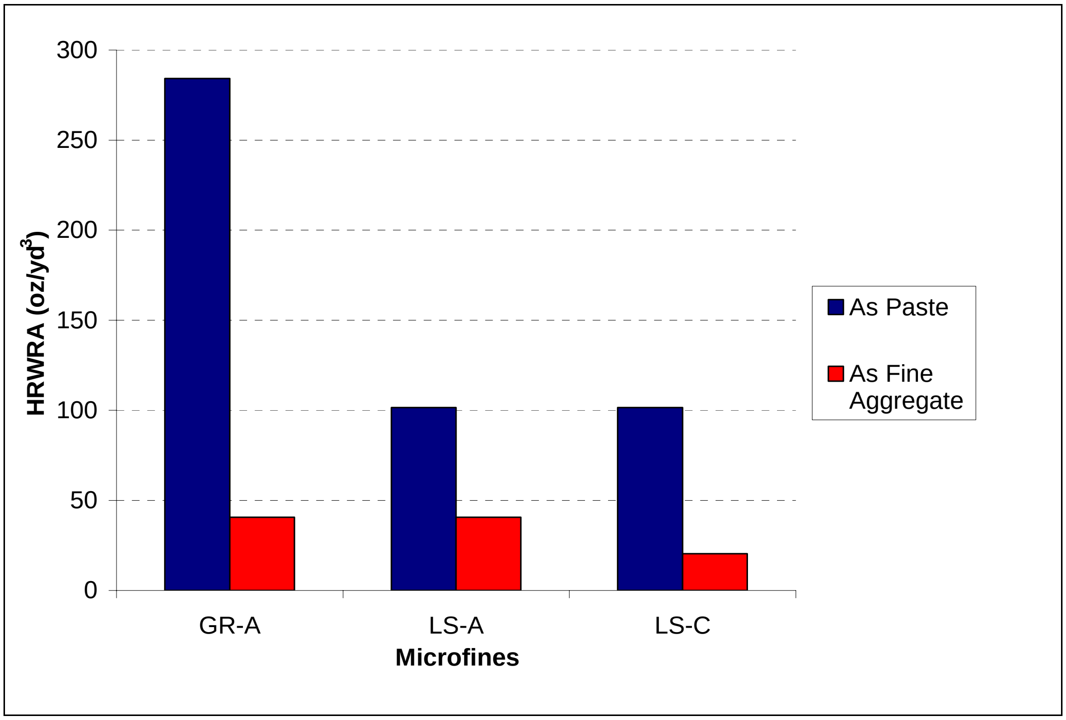

Figure 8.4 – Comparison of HRWRA Demand - Series A (30% cement reduction) vs. Series B.

All the mixtures considering the microfines as part of the aggregate had a lower water reducer demand than their counterparts considering the aggregate as part of the paste when compared to the 30% cement reduction mixtures. This difference in water reducer requirement may be attributed to the fact that the mixtures prepared considering the microfines as part of the aggregate had a much higher water and cement content than the mixtures prepared considering the microfines as part of the paste. The cement content in the mixtures considering the microfines as part of the aggregate is 30% higher than the mixtures prepared considering the microfines as part of the paste.

8.4 COMPRESSIVE STRENGTH

The compressive strengths were determined in accordance with ASTM C 39. For each mixture, three 4-in. diameters by 8-in cylinders were used. Only 28-day strengths were measured.

The strength test results for the mixtures in Series A of Phase II are shown in Figure 8.5. It is obvious that in nearly all cases the addition of microfines, and a corresponding reduction in cement, resulted in higher strength. The mixtures with the least benefits were in most cases those produced with granite microfines (GR-A). The only mixture that had lower strength than the baseline mixture was the 30% cement reduction mixture using granite microfines. It is possible that this mixture did not have enough paste to cover the large surface area introduced by the addition of the granite microfines which were poorly shaped and possibly required a higher amount of water and cement than the other mixtures.

The mixtures produced with limestone microfines (LS-A and LS-C) showed an increase in strength with increasing microfines content. The increase in strength averaged about 10% with the maximum increase being 20% for the intermediate shape limestone microfine with 20% cement substitution. The results had a maximum standard deviation of 284 psi.

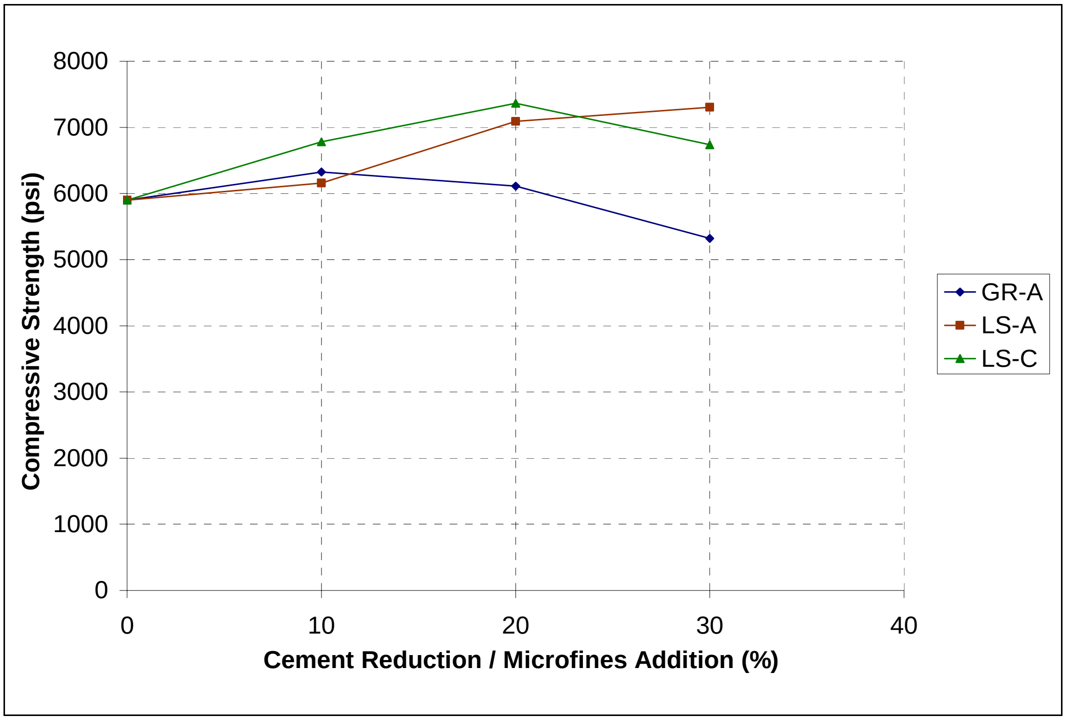

Figure 8.5 - Compressive Strength Results, Series A.

In Figure 8.6 a comparison between the strength of the mixtures obtained through considering the microfines as part of the aggregate and considering the microfines as part of the paste is shown. All the mixtures prepared by the considering the microfines as part of the aggregate yield strength values above the baseline mixture. The higher strength of the GR-A (containing granite microfines) mixture batched considering the microfines as part of the aggregate is attributed to the higher cement and water content present in this mixture. In Table 4.2, it was shown that the paste volume was 6% higher in the mixtures produced considering the microfines as part of the aggregate.

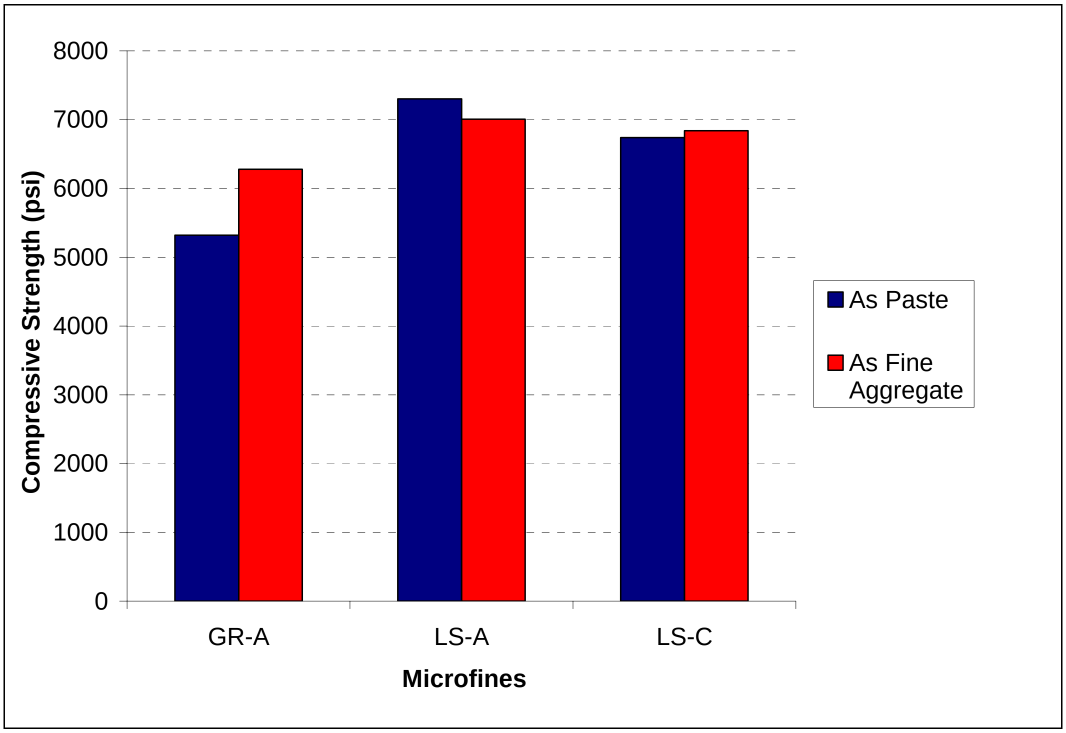

Figure 8.6 - Comparison of Compressive Strength, - Series A (30% cement reduction) vs. Series B.

8.5 SHRINKAGE

Shrinkage was measured in accordance with ASTM C 157. The specimen beams were 3-in. by 3-in. by 11.25-in. with Humboldt pins on each end face. The values in Figures 8.7 and 8.8 are shown assuming zero shrinkage at the transfer date (shown in figures as: Measurement at 112 days – Measurement at Transfer).

In Figure 8.7, the results for Series A are shown. It is evident that the mixtures containing the granite microfines (GR-A) exhibited the largest amount of shrinkage of all the mixtures with cement reduction, but little difference was found between mixtures prepared with different microfines and cement substitution of 10 and 20%. The shrinkage corresponding to a 30% cement reduction may be an outlier. However, the drying shrinkage exhibited by all of the mixtures from Series A was still smaller than the shrinkage obtained from the baseline mixture.

The highest value of shrinkage from the mixtures of Series A, the 10% cement reduction mixture containing granite microfines, was about 15% smaller than the baseline mixture shrinkage.

The measurements taken for the mixtures containing the two limestone microfines (LS-A and LS-C) were nearly the same. The specimens prepared with up to 20% cement reduction were nearly the same as those obtained from the mixtures containing granite microfines (GR-A). These low values are possibly due to the low amount of paste and the high amount of aggregates in the mixtures. The cement paste is what usually drives shrinkage by releasing moisture from the concrete voids to the surrounding environment through the hydration process. It is also possible that aggregate interlock may have an effect in reducing drying shrinkage by providing internal restraint to the cement paste.

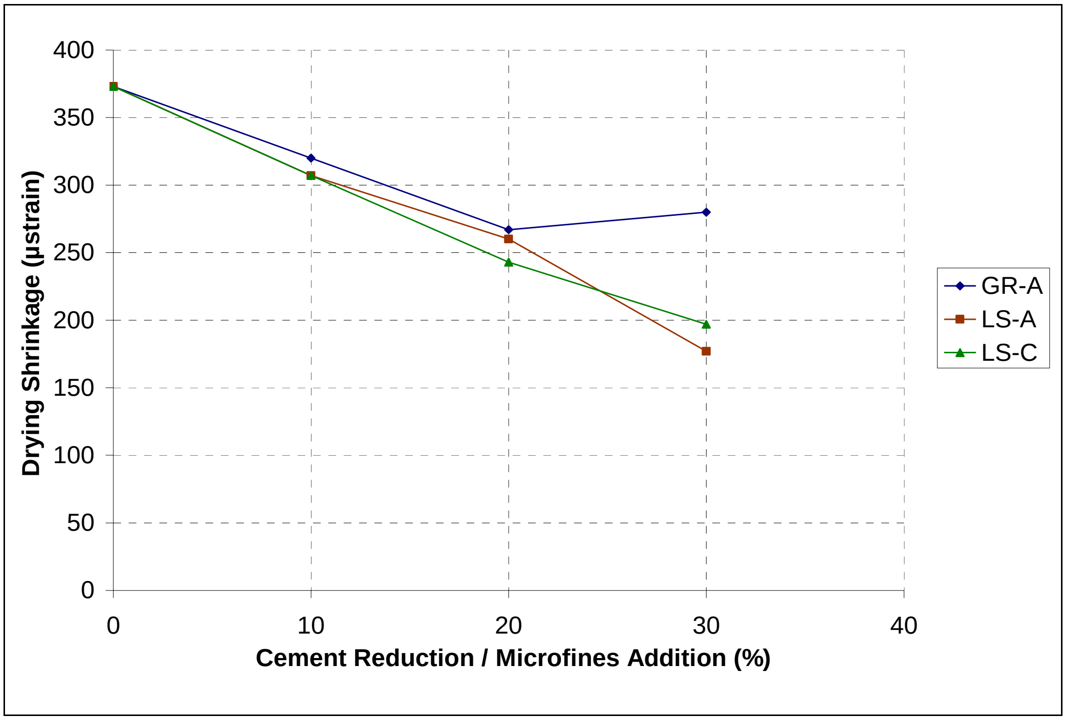

Figure 8.7 - Drying Shrinkage at 112 days, Series A.

From Figure 8.8, it is obvious that the mixtures containing the granite microfines (GR-A) have the highest amount of drying shrinkage after 112 days. This seems to be independent of the proportioning method used in the mixture. In the case of the limestones (LS-A and LS-C), the drying shrinkage was nearly half that of the baseline mixture when the proposed optimizing proportioning method was used.

It is clear from Figure 8.8 that all the mixtures prepared considering microfines as part of the paste yielded considerably smaller shrinkage values than the baseline mixture and the mixtures prepared considering the microfines as part of the aggregate. This was most likely due to the higher amount of cement present in the mixtures where the microfines were considered as part of the aggregate. As previously mentioned, the mixtures on which the microfines were considered as part of the fine aggregate have 30% more cement and water than the mixtures that consider the microfines as part of the paste volume.

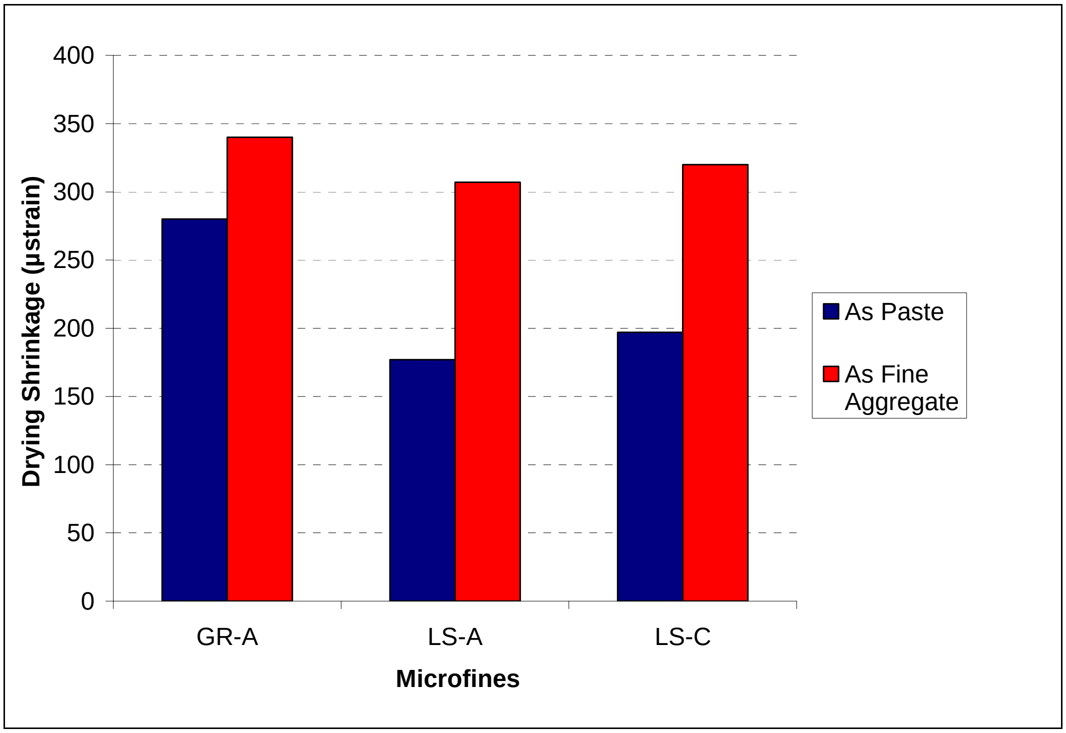

Figure 8.8 - Comparison of Drying Shrinkage at 112 days - Series A (30% cement reduction) and Series B.

8.6 ABRASION RESISTANCE

The abrasion resistance tests were conducted in accordance with ASTM C 944. For this test one 4-in. by 4-in. by 14-in. concrete beam specimen was used. The molds for making the specimens were made of galvanized steel. Oil was used on the faces of the mold to prevent the concrete bonding to the mold.

The specimens were stored in the mixing room for the first 24 hours to avoid sudden changes in temperature in the fresh concrete. After 24 hours the specimens were demolded and moved to the moist room where they were stored for 96 days. At this time, each beam was cut into three blocks. Each block was at least 4 in. wide on each side to ensure that there was enough surface area to run the abrasion resistance test.

The test was run using Soiltest equipment on the finished surface. The finished surface has been proven to have the highest water-to-cement ratio and therefore shown to be the weakest portion of the concrete.

It is clear by inspection of Figures 8.9 and 8.10 that the addition of microfines at 10, 20 and 30% levels was beneficial with regard to abrasion resistance. From Figure 8.10 it is also clear that, in most cases, the larger the addition of microfines, the higher the abrasion resistance shown by the different mixtures.

The mixtures containing well-shaped limestone microfines (LS-A) showed the most abrasion of all the mixtures with microfines. This may be due to the fact that these microfines were the least angular and/or the most prone to polishing. Since these microfines are not as angular or as rough in texture, there is less interparticle friction between fines and hydrated cement particles as well as a smaller surface contact area.

The comparison between the abrasion resistance test results of mixtures prepared considering the microfines as part of the aggregate versus considering the microfines as part of the paste is shown in Figure 8.10. In general, the abrasion resistance was slightly higher for the mixtures prepared considering the microfines as part of the aggregates (GR-A and LS-A) due to the higher paste volume (higher cement content) because the microfines were considered as part of the fine aggregate rather than as part of the paste.

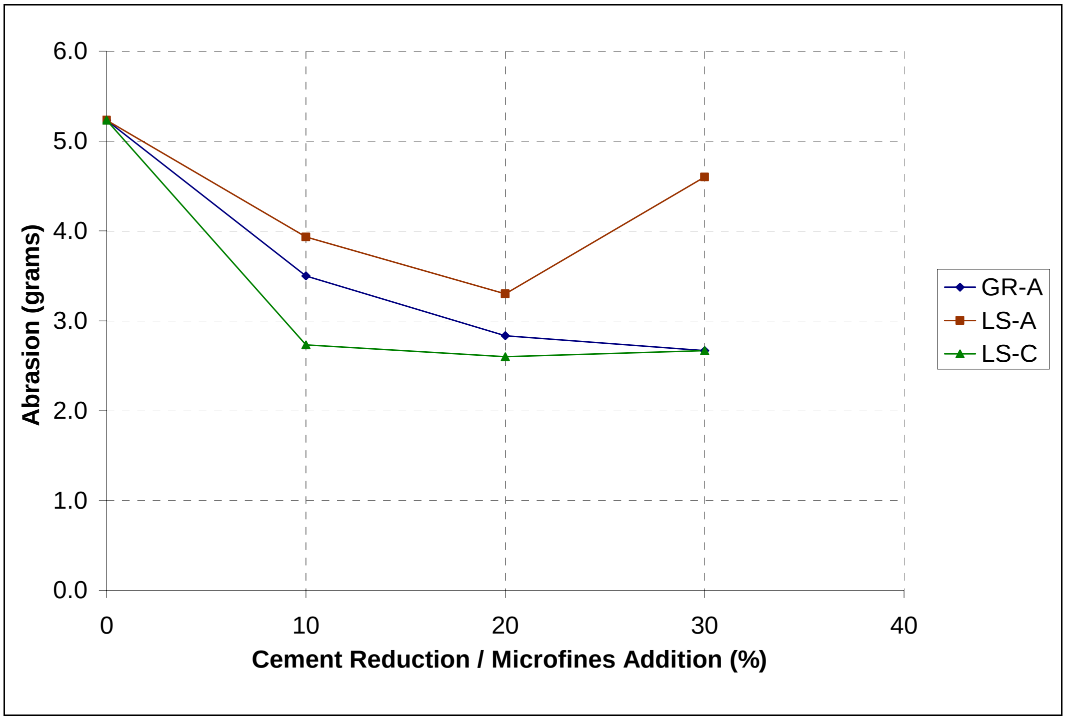

Figure 8.9 - Abrasion Resistance Test Results, Series A.

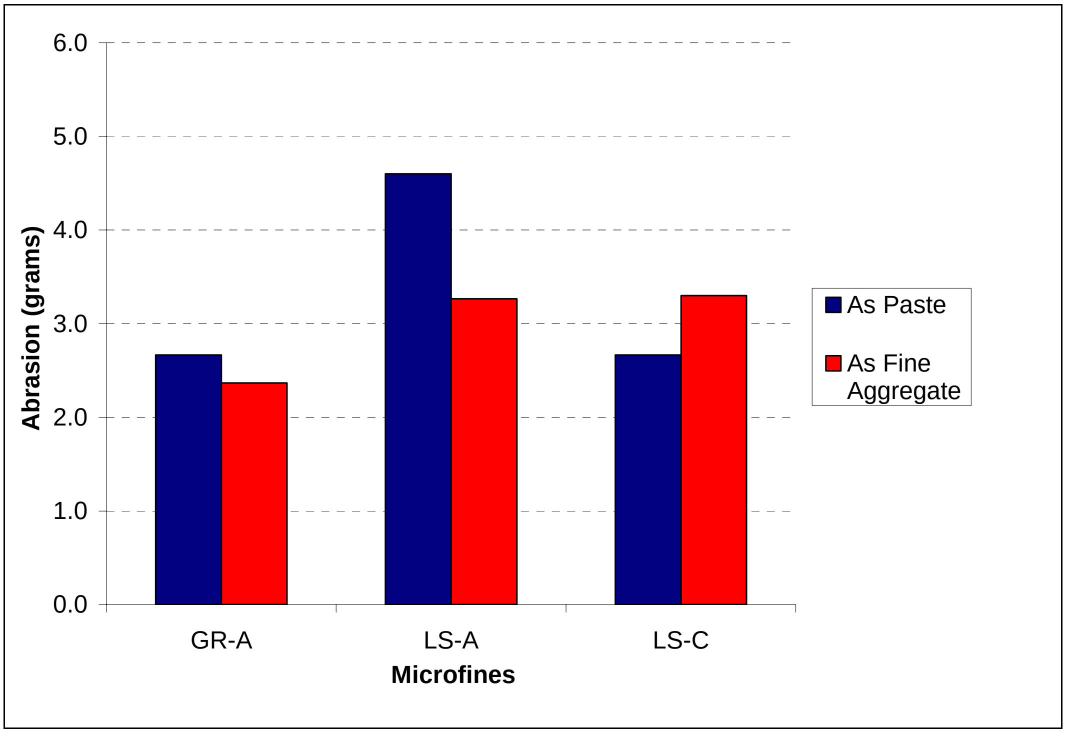

Figure 8.10 - Comparison of Abrasion Resistance Results - Series A (30% cement reduction) vs. Series B.

8.7 RCP Test

The rapid chloride penetration test (RCP) was conducted in accordance with ASTM C 1202. Results for the RCPT tests are shown in Figure 8.11. There is little correlation between the coulombs passed and the type of microfines. However, it is clear that as the amount of microfines increased, the permeability of the concrete was reduced. This is evident when the results from mixtures prepared with a 30% cement reduction are compared to those prepared with 10% cement reduction. The scatter is much smaller for the larger amount of microfines in the mixtures.

Given the ASTM C 1202 categories for low permeability readings (readings between 1000 and 2000 coulombs), the mixtures prepared with the well-shaped microfines (LS-A) showed a low permeability and limited variability from one cement reduction to another. These microfines allowed for good packing of the cement paste at all levels. However, it is hard to explain why microfines with a higher angularity such as the granite (GR-A) and the poorly shaped limestone (LS-C) produced a lower permeability than the well shaped limestone (LS-A) at larger cement substitution levels.

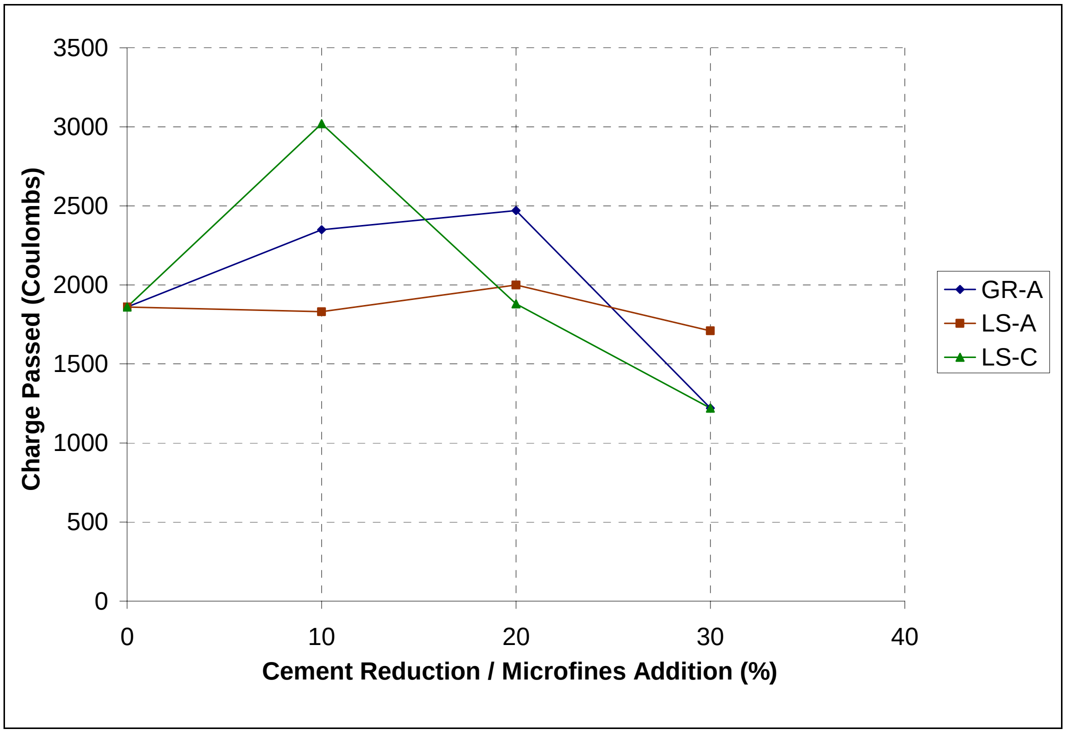

Figure 5.11 – Rapid Chloride Penetration Tests, Series A.

In Figure 5.12 all the mixtures prepared considering the microfines to be part of the paste were found to have a lower permeability than the baseline mixture; at the same time, it was found that the permeabilities of the mixtures prepared considering the microfines as part of the fine aggregate are all higher than the permeability obtained from the baseline mixture. This is attributed to the higher water and cement content of the mixture and the lower amount of fine aggregate found in these mixtures. The higher cement content combined with the lower amount of fine aggregates made it possible for larger voids to be formed inside the concrete, therefore producing a higher permeability.

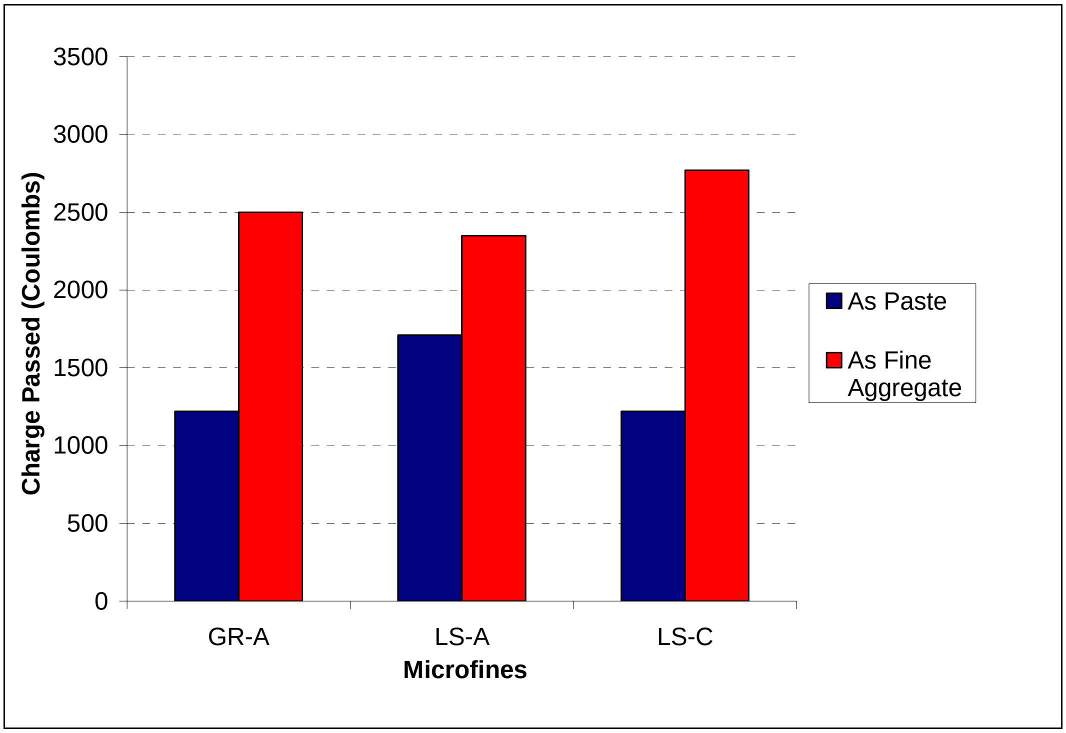

Figure 8.12 - Comparison of Rapid Chloride Penetration Tests – Series A (30% cement reduction) vs. Series B.

8.8 COST SAVINGS

Calculations were performed to estimate cost savings if microfines were used to replace a portion of the cement content in concrete mixtures. The cost of water and aggregate were ignored since their costs, per gallon of water and per ton of aggregates, are relatively low when compared to that of cement and high range water reducer admixture (per pound and per ounce, respectively) and the cost would be similar for the different aggregates. The cost of microfines was ignored as well, since microfines are considered a waste product of aggregate production.

The price of cement and admixture were obtained from a Texas ready-mix concrete producer:

- Price of cement: $110 per ton as of July 2008.
- Price of polycarboxylate ether-based admixture: $11.50 per gallon as of July 2008.

In most mixtures, the average savings with respect to the baseline mixture were about $3.80 per cubic yard. Two sets of values were computed:

- Table 8.1 contains the savings with respect to the baseline mixture for mixtures considering the aggregate as part of the paste volume.
- Table 8.2 contains a comparison of savings obtained when the mixtures containing microfines considered as part of the aggregate were compared to the baseline mixture.

Table 8.1 shows that the maximum cost benefit is not necessarily found for the mixture containing the maximum amount of cement substitution. In most cases, the mixture containing a 20% cement reduction was more cost effective than the other mixtures in the set. This was due to the large amount of water reducer admixture necessary to obtain the desired workability as the portion of substituted cement increased.

The amount shown in red in Table 8.1 represents a mixture that cost more than the baseline mixture. This cost was due to the high amount of water reducer needed to obtain the desired 6-in. slump for the GR-A mixture (30% cement reduction only). A substitution greater than 20% is not recommended when using microfines with properties similar to this granite for cost and durability reasons. However, it should be noted that, although the cost and strength of the GR-A mixture with a 30% cement reduction were not benefited, the drying shrinkage, abrasion and chloride penetration improved significantly compared to the baseline mixture.

Based on information from Table 8.1, it is very important to perform a full characterization of the microfines before using them as mineral filler. Two characteristics are of special interest: methylene blue value and packing density of the microfines. A low methylene blue value will indicate that no deleterious clays are present in the powder; hence, a high water demand in the mixture will be avoided. On the other hand, high packing density will help reduce the drying shrinkage and voids in the mixture.

Table 8.2 shows the savings relative to the baseline mixture of mixtures prepared considering the microfines as part of the aggregate and considering the microfines as part of the paste. This table shows that mixtures prepared considering the microfines as part of the paste usually produced larger savings compared to mixtures in which the microfines were considered as part of the aggregate. Mixtures that considered the microfines as part of the aggregate required the same amount of cement as the baseline mixture. For this reason, the paste volume of the mixtures that considered the microfines as part of the aggregates was 34% as shown in Table 8.2.

Mixtures considering the microfines as part of the paste had a 28% paste volume (shown in Table 8.1). The amount of cement used in these mixtures was reduced by 30%, resulting in a savings of about $10.00 in cement per cubic yard. However, an increase in the amount of water reducer admixture to obtain the desired workability increased the price by approximately $5.00 per cubic yard.

Table 8.1 – Cost Savings Series A.

Microfines	Mixture	Cement lb/yd^3	Admixture oz/yd^3	Microfines lb/yd^3	Cost of Cement	Cost of Admixture	Combined Cost	Savings
None	Baseline	536	45.68	---	$29.48	$4.10	$33.58	$ ---
GR-A	10% reduction	482	40.60	118	$26.51	$3.65	$30.16	$3.43
	20% reduction	429	81.20	236	$23.60	$7.30	$30.89	$2.69
	30% reduction	375	284.21	354	$20.63	$25.53	$46.16	$(12.58)
LS-A	10% reduction	482	30.45	114	$26.51	$2.74	$29.25	$4.34
	20% reduction	429	60.90	229	$23.60	$5.47	$29.07	$4.52
	30% reduction	375	101.50	343	$20.63	$9.12	$29.74	$3.84
LS-C	10% reduction	482	40.60	102	$26.51	$3.65	$30.16	$3.43
	20% reduction	429	60.90	204	$23.60	$5.47	$29.07	$4.52
	30% reduction	375	101.50	306	$20.63	$9.12	$29.74	$3.84

Note: Savings computed in reference to Baseline Mixture.

Table 8.2 – Cost Comparison Series A vs. Series B.

Microfines	Mixture	Cement lb/yd^3	Admixture oz/yd^3	Microfines lb/yd^3	Cost of Cement	Cost of Admixture	Combined Cost	Savings
None	Baseline	536	45.68	---	$29.48	$4.10	$33.58	$ ---
GR-A	As Fine Aggregate	536	40.60	293	$29.48	$3.65	$33.13	$0.46
	As Paste	375	284.21	354	$20.63	$25.53	$46.16	$(12.58)
LS-A	As Fine Aggregate	536	40.60	284	$29.48	$3.65	$33.13	$0.46
	As Paste	375	101.50	343	$20.63	$9.12	$29.74	$3.84
LS-C	As Fine Aggregate	536	20.30	254	$29.48	$1.82	$31.30	$2.28
	As Paste	375	101.50	306	$20.63	$9.12	$29.74	$3.84

Note: Values computed here are for 30% cement reduction. Savings computed in reference to Baseline Mixture.

Chapter 9: Summary, Conclusions, and Guidelines

9.1 SUMMARY OF PHASE I

The aim of Phase I was to minimize cement content in concrete mixtures by changing the aggregate grading. For this purpose, mortar and concrete mixtures were made with aggregates having different shapes, textures, and grading. The testing began by characterizing the three fine aggregates and the two coarse aggregates used in this project. To indentify workability performance differences, mortar testing was performed on the three fine aggregates. These results showed that workability was dependent on paste volume, paste composition, and the type of aggregate used.

Concrete testing was performed, and concrete properties including slump, compressive strength, shrinkage, and permeability were measured. The effect of aggregate shape on workability was evaluated by comparing one aggregate combination to another. It was found that:

1. The aggregate combination with LS-B-FA and NAT-CA consistently had the highest HRWRA demand, despite having the coarsest grading, which would be expected to result in lower HRWRA demand. It also exhibited the highest minimum paste volume to avoid a shear slump and the highest voids content. Of the two manufactured sands, LS-A-FA had better shape than LS-B-FA, although LS-A-FA was not as well shaped as NAT-FA. LS-A-FA had consistently lower HRWRA demand than LS-B-FA despite having a finer grading. Further, it had lower minimum paste volume to avoid shear slump and compacted aggregates void content. Compared to NAT-CA, LS-A-CA resulted in concrete mixtures with lower HRWRA demand at a given paste volume, similar minimum paste volume

to avoid shear slump, and similar compacted aggregate voids content, despite having worse shape. This trend was likely due at least partially to LS-A-CA being slightly coarser than NAT-CA.

2. Compressive strength was similar for all concrete mixtures, regardless of paste volume, aggregate shape, or aggregate grading. Reductions in compressive strength were only observed when *S/A*=0.5 at low paste values. The low strengths are believed to be due to mixtures having too much sand and too little binder (cement).
3. Drying shrinkage increased with increase in paste volume. Drying shrinkage was affected by aggregate source, which may have been related to the stiffness of the aggregates. No consistent trends between grading and drying shrinkage were observed.
4. Reducing the paste volume reduced the permeability of the concrete regardless of the aggregate and grading.
5. Using less paste reduced the cost of the concrete, but the lowest paste volume did not always correspond to the less costly mixture. Cost savings ranged from around $1 to $8 per cubic yard of concrete.

9.2 SUMMARY OF PHASE II

The addition of microfines to the baseline mixture of Phase II improved most of the durability properties of concrete and at the same time produced significant cost savings. The following advantages are found from the addition of microfines:

1. Compressive strength was found to increase in most cases with the addition of microfines.

2. Drying shrinkage was found to decrease with the addition of microfines to the mixture design. The reduction in drying shrinkage was higher for mixtures where the microfines were considered to be part of the paste, rather than part of the fine aggregate.
3. Abrasion resistance was found to increase with the addition of microfines, in any percentage (tested with a maximum of 30%) to the concrete.
4. Improvement in permeability resistance was found after enough microfines (30% substitution considered as part of the paste) were added to the concrete. This was not the case when the microfines were considered as part of the fine aggregate.

The main disadvantage was increased water reducing admixture demanded by the addition of microfines, whether they were considered as part of the paste or as part of the fine aggregate during the proportioning stage.

The average cost savings that was obtained by optimizing mixtures ranged from 1 to 4 dollars per cubic yard of concrete. Although the cost of mixtures made with manufactured sands (LS-A-FA & LS-B-FA) were higher than for the cost of mixtures made with the natural sand (NAT-FA), the cost savings that were achieved with manufactured sands were higher. Except for combinations of NAT-CA and LS-B-FA, cost reductions with *S/A*=0.5 were not achieved by paste volume reduction.

9.3 CONCLUSIONS

The results obtained in this research confirm that aggregate type and gradation can play an important role in optimizing the cement content of concrete mixtures. Improving the aggregate shape and grading allowed a reduction in paste volume while maintaining workability and hardened properties. Both shape and grading affected workability. Aggregates with angular shape resulted in increased paste volume and HRWRA demand. Aggregates with coarser grading generally required lower HRWRA demand but required higher paste volume to ensure adequate cohesiveness. Higher packing densities were associated with lower minimum paste volume to ensure adequate cohesiveness; however, it was not clear the extent to which the lower minimum paste volume was due to a finer grading or a higher packing density.

In Phase I, the compressive strength was only affected by paste reductions in sandy concrete mixtures, and no other major changes in compressive strength were observed for the different aggregate combinations. Both shrinkage and permeability improved when paste content was reduced; however, compared to mixtures containing siliceous aggregates, mixtures containing limestone shrunk less because of differences in stiffness.

The use of aggregate microfines allowed the reduction of cement content while maintaining or improving the performance of the baseline mixture. Since microfines are typically similar in size as cement, they should be considered as part of the paste not as part of the aggregates when evaluating the workability of a mixture. If the microfines are considered as part of the aggregate, the mixture would have too many fine particles (cement and microfines) which would decrease the workability or increases the HRWRA demand.

Microfine additions improved the hardened properties of the concrete. The compressive strength of the mixtures containing microfines was higher than for the baseline mixture. The performance of the concrete in shrinkage and permeability improved also. As for abrasion resistance, the mixtures containing more microfines were more resistant than the baseline mixture.

9.4 GUIDELINES FOR ASTM C 33

Based on the finding of Phase II, the following modifications are recommended to ASTM C 33 (ASTM C 33-03 was used as a basis for these recommendations):

1. The limits in the table in Section 6.1 of ASTM C 33 should be modified as suggested in an unpublished recommendation to ASTM C 33 by an aggregate industry committee. The grading suggested is presented in Figure 9.1 and contains the proposed limits (Table 9.1) as well as the current limits.

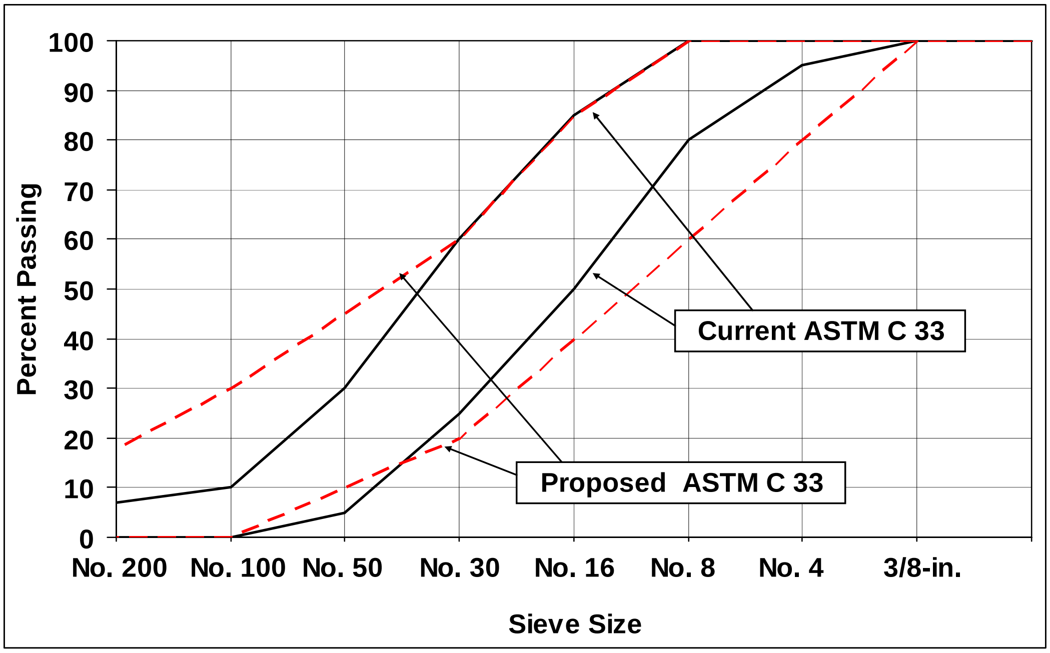

Figure 9.1 - Current ASTM C 33 Grading Compared to Proposed Grading by Industry.

2. The row containing limits for Percentage Passing of 75-µm (No. 200 sieve) material should be modified in Section 6.1 of ASTM C 33. The

recommended limit is 20% passing. This new row should come with a "Note 3" that will be described in the next item.

Table 9.1 – Suggested Limits by Aggregate Industry Committee.

Sieve (Specification E 11)	Percent Passing
9.5-mm (3/8-in.)	100
4.75-mm (No. 4)	80 to 100
2.36-mm (No. 8)	60 to 100
1.18-mm (No. 16)	40 to 85
600-µm (No. 30)	20 to 60
300-µm (No. 50)	10 to 45
150-µm (No. 100)	0 to 30
75-µm (No. 200)	0 to 18

3. A "Note 3" should be included in the table inside Section 6.1 of ASTM C 33 that reads as follows: "Note 3-Concrete made with fine aggregate containing an amount of minus 75-µm (No. 200 sieve) material larger than 7% is to be tested for Methylene Blue Value and Packing Density."
4. In Chapter 7 of ASTM C 33 an extra item is to be included that should read as follows:

   > "7.4 Methylene Blue Value based on AASHTO Designation: TP 57 should be limited to 6 mg/g unless additional testing is performed to determine the effect on properties important for the specific application."
   > This is the suggested limit in AASHTO Designation: TP 57 for microfines based on limiting harmful clays.

5. In Chapter 6 of ASTM C 33, it is recommended that a clause be added allowing for the use of a higher amount of minus 75-µm (No. 200 sieve) in concrete (up to 20% Percent Passing). This should only be allowed after trial batches have been prepared and tested.

A reference guide should be made available to the industry that presents an alternative method for proportioning mixtures containing high amounts of microfines. An effort should be made to change the industry view of material finer than 75-µm (No. 200 sieve). Microfines should be viewed as part of the paste volume, rather than as part of the fine aggregate. Concrete proportioning should be calculated on a volume basis, not on a weight basis.

The effect of changing the current industry view of microfines is best described in Figure 7.1. Figure 7.1 show that by considering the microfines as part of the fine aggregate (Series B), the amount of cement and water used remains the same. On the other hand, by considering the microfines as part of the paste (Series A), although the water-to-cement ratio is the same, the cement content will be reduced significantly, creating a more cost effective mixture.

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