USE OF AGGREGATE SCREENINGS AS A SUBSTITUTE FOR SILICA SAND IN PORTLAND CEMENT CONCRETE (PCC)

Florida Department of Transportation Contract No.: BDL13 977-01

FINAL REPORT

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16. Abstract

The State of Florida is the third largest consumer of crushed rock products in the United States and is the largest single contractor/user of crushed stone resources in the state. Crushed stone in Florida is produced from limestone, which is mined or extracted from naturally occurring deposits. This crushing for coarse aggregate results in a fine byproduct called screenings. The stockpiling and disposal of fines produced as a result of aggregate crushing and production operations are some of the major problems facing the aggregate industry. This project investigated the use of these screenings as a substitute for natural sand in PCC. Influence of screenings was tested in the mortar and in concrete specimens for fresh and hardened state properties, including flow, strength and durability. It is concluded that the screenings can be used safely in blended form for projects where durability is not the main concern.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
LENGTH				
in	Inches	25.4	millimeters	mm
ft	Feet	0.305	meters	m
yd	Yards	0.914	meters	m
mi	Miles	1.61	kilometers	km

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
AREA				
in^2	Square inches	645.2	square millimeters	mm^2
ft^2	Square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	Acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
VOLUME				
fl oz	fluid ounces	29.57	milliliters	mL
gal	Gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
NOTE: volumes greater than 1000 L shall be shown in m^3				

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
MASS				
oz	Ounces	28.35	grams	g
lb	Pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
TEMPERATURE (exact degrees)				
^oF	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^oC

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
ILLUMINATION				
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
FORCE and PRESSURE or STRESS				
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
LENGTH				
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
AREA				
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
VOLUME				
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
MASS				
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
TEMPERATURE (exact degrees)				
^oC	Celsius	1.8C+32	Fahrenheit	^oF

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
ILLUMINATION				
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
FORCE and PRESSURE or STRESS				
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.

(Revised March 2003)

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Thanks are also due to Thomas Dellibovi, Branden Reed, Thoma Panda, Melvin Nicolas and Lenny Phillips for their laboratory assistance during the research project. I would also like to acknowledge the contribution of Dr. Ibrahim Kaba to the statistical analysis of the test data.

EXECUTIVE SUMMARY

The State of Florida is the third largest consumer of crushed rock products in the United States and is the largest single contractor/user of crushed stone resources in the state. Crushed stone in Florida is produced from limestone, which is mined or extracted from naturally occurring deposits. This crushing for coarse aggregate results in a fine byproduct called screenings. The stockpiling and disposal of fines produced as a result of aggregate crushing and production operations are some of the major problems facing the aggregate industry. This project, including the conclusions of the study, applies to and is limited to use of screenings in Portland cement concrete only. Screenings have also been used in hot mix asphalt concrete, road bases and other applications not studied in this project.

Screenings are inherently more angular and have rough surface texture, thus raising concerns of workability, increase water demand and poor finishibility. To study the suitability of screenings in Portland cement concrete, screenings from four mines from across the state of Florida were obtained and tested during this project. These four screenings represented Suwannee limestone, Shelly sediments of Plio-Pleistocene series and Miami limestone.

The influence of screenings on mortar and concrete properties was investigated in great detail. Mortar and concrete mixes were tested in fresh and hardened state. Properties such as flow, slump, air content, unit weight, compressive strength, splitting tensile strength modulus of elasticity and electrical resistivity were measured.

Mortar Study

For the mortar phase of the study, flow, compressive strength and autoclave expansion were studied for wide range of variables. The results of the study clearly demonstrated that the flow of mortar is function of angularity, fineness modulus, sand to cement ratio, water to cement ratio, and presence of fly ash. The presence of Screenings caused a slight reduction in the 28 days compressive strength of mortar cubes.

The model for predicting flow of mortar (*f*) and compressive strength (psi) of mortar cubes (f'_{cm}) were developed with R^2 of 93% and 69% respectively as follows:

$$f = 1.064\,U_m - 1.045\,FA + 11.90\,FM - 42.43\,s\_c + 213.97\,w/c$$

$$f'_{cm} = 8462 + 95.09U_m - 651FM - 7944w/c - 540s\_c - 47FA$$

Where,

- U_m = uncompacted voids using method B of ASTM C 1252,
- FA = percent of fly ash,
- s_c = sand to cement ratio
- w/c = water to cement ratio.

Mortar bars were tested in autoclave as per ASTM C151, to study the influence of screening types on expansion ability. It was found that the source of screening significantly affected the autoclave expansion and is expected to have a similar influence on concrete prepared with the same screening and cement type and exposed to similar conditions. Autoclave expansion was significantly reduced when 50% or more of the fine aggregate was natural silica sand. The model for predicting autoclave expansion in mortar bars (ε_{ae}) was developed with 95% R^2 as:

$$\varepsilon_{ae} = -0.00013098s\_c + 0.00170531w/c - 0.00085470U_m + 0.00014759FM$$

Where,

- FM = Fineness modulus of fine aggregate.

Concrete Study

A factorial design was developed to study the influence of the angularity of fine aggregate, blending of screenings with natural silica sand, cement content, water cement ratio, sand to total aggregate ratio and fly ash on Portland cement concrete. The control mix was FDOT Class IV concrete with target slump of 6±1 inch and air content of 2.5%.

28 days compressive strength of concrete with screenings was found to be comparable to normal concrete for a given w/c and cement content. A model to predict compressive strength of concrete (psi) with various factors was developed as follows:

$$f_c^{'} = -5.896 * MS + 3437.29 * s\_a - 10391.5 * w/c + 21263.1 * U_m - 34.487 * FA$$

Where,

MS = percent screenings in the blend

s_a = sand to total aggregate ratio

w/c = water cement ratio,

U_m = uncompacted voids of fine aggregate

FA = percent fly ash in the mix.

It was found that blending with natural sand improved workability and lowered the demand for admixture. Mix can be optimized by studying and adjusting the sand to aggregate ratio. Lower s_a concrete generally required a lower quantity of admixture due to reduced overall angularity. Fly ash was found to positively influence the fresh concrete properties. The introduction of fly ash improved surface electrical resistivity, especially for mixes with greater than 20% replacement level of fly ash.

Concrete prepared with screenings did not show any adverse effect on elastic modulus or Poisson's ratio. The model developed to predict the modulus of elasticity (psi) closely matches the standard ACI 318 modulus equation as shown below:

$$E = 33.076(w)^{1.5}\sqrt{f_c^{'}}$$

Where, *w* is unit weight of concrete in pcf and f'_c is compressive strength in psi.

Economic Benefits

The substitution of natural sand with screenings will not only help alleviate shortage and diminishing of resources of natural sand, but reduce the also environmental burden resulting from their disposal as waste material. The use of screening can help mitigate the stockpile of this waste material.

Cost savings were analyzed for Miami, Ft. Myers and the Orlando area. It was shown that the Miami area is already realizing benefits from the permitted use of screenings in concrete, while there is potential to save money in the Ft. Myers area based on the price difference between screenings and natural sand. Currently, in Orlando and Tallahassee area screenings are sold at a premium and market conditions are not set to immediately benefit from the allowance of screenings in concrete.

Impact on Fine Aggregate Specification 902

Currently, fine aggregate specification section 902-5.2.3 only allows screenings from the Miami area (mine M of this study), and specifies a minimum specific gravity of 2.48 and a maximum percent finer than #200 sieve.

Based on the findings of this study it is recommended that the bulk specific gravity requirement of FDOT Specification 902-5.2.3 be reduced to at least 2.38 to accommodate use of screenings that were part of this project. Only Mine C had higher fine content and did not meet the current specification requirement.

This project has also clearly demonstrated that screenings can be successfully used as a substitute for natural sand in PCC. Based on this study, it is thus concluded that up to 50 percent replacement of natural silica sand with screenings of attributes studied in this project can be permitted for structural concrete, especially where durability is not a primary concern. For non structural elements, a 100 percent replacement can be permitted.

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NOMENCLATURE

ANOVA	Analysis of Variance
ASG	Apparent Specific Gravity
B	FDOT MINE ID 08005
BSG, dry	Dry Bulk Specific Gravity
BSG, SSD	SSD Bulk Specific Gravity
C_t	Truck Transportation cost per ton per mile
C	FDOT MINE ID 38268
d_{NS}	Haulage Distance in miles for natural sand
d_S	Haulage Distance in miles for screenings
D50	Aggregate Size corresponding to 50% passing
DI	Durability Index
ε_{ae}	Strain due to autoclave expansion
E_c	Elastic modulus of concrete
ER	Electric resistivity, KΩ-cm
F	FDOT MINE ID 12260
f	Mortar flow %
FA	Fly ash
f_c	28-days Compressive strength of concrete, psi
f_{cm}	28-days Compressive Strength of mortar cube
FDOT	Florida Department of Transportation
FM	Fineness modulus of sand
FSTM	Florida Sampling and Testing Methods
HRWR	High Range Water Reducer
I_a	Particle Index value
ICAR	International center for Aggregate Research
LA	LA Abrasion %
M	FDOT Mine ID 87090
MBV	Methylene Blue Value
MD	Micro Deval value

MFA	Manufactured Fine Aggregate
MS	Manufactured Sand
MS%	Percent Manufactured Sand in Blend
N	Natural silica sand
NAA	National Aggregate Association
NCSA	National Crushed Stone Association
NS	Natural Sand
NSGA	National Sand and Gravel Association
S	Cost Savings ($/ton)
s_a	Sand to total aggregate ratio
s_c	Sand to cement ratio
SE	Sand Equivalent %
U_s	Uncompacted Voids, ASTM C 1252 Test Method A
U_m	Uncompacted Voids, ASTM C 1252 Test Method B
U_R	Uncompacted Voids, Test Method C
VSI	Vertical Shaft Impactor
w	Unit weight of concrete, pcf
w/c	Water to cement ratio

CHAPTER 1: INTRODUCTION

1.1 BACKGROUND AND RESEARCH NEEDS

In a recent Strategic Aggregates Study [1], the Florida Department of Transportation (FDOT) initiated research to address the current and future availability of crushed stone for building roads. It was reported that the State of Florida is the third largest consumer of crushed rock products in the United States. The Florida road-building and construction industries were expected to consume 143 million short tons of crushed stone in 2007. Forty-two million tons of rock will go to construction of roads, bridges, runways, and other infrastructure, making the FDOT the largest single contractor/user of crushed stone resources in the state (Figure 1).

Crushed stone in Florida is produced from limestone, which is mined or extracted from naturally occurring deposits found in 22 counties [Figure 2]. Approximately 93 percent of the crushed stone material used by the road-building and construction industries in Florida is mined within the state; 43 percent of this total comes from an area known as "the Lake Belt" in Miami-Dade, Southeast Florida, because of the characteristics of the rock resource.

This crushing for coarse aggregate results in a fine byproduct called screenings, sometimes also referred as manufactured sand (MS) or manufactured fine aggregate (MFA). It is estimated that more than 100 million tons of aggregate fines were either stockpiled or disposed of in the United States every year. The stockpiling and disposal of fines produced as a result of aggregate crushing and production operations are some of the major problem facing the aggregate industry.

There are many problems on the horizon in the aggregates supply chain such as [1]:

- Existing mining permits have been challenged in the Lake Belt.
- The output from sources around the state continues, but the quality is declining for many engineering purposes.
- Florida limestone formations outside the Lake Belt are generally not as high in quality.
- Both large and small land developments are over-running the lands where limestone and sand deposits are found.
- Local land use decisions fueled by homeowner's and neighbor's complaints have made planning and permitting new mines extremely costly or impossible.
- Even expanding existing mines is impossible in some areas, because the reserve lands have been hemmed in by development.
- Infrastructure for increasing imports is not in place.
- Quarry waste fine aggregate, which is generally considered as a waste material, causes an environmental load due to disposal problem.

This shortage and the diminishing of resources of natural sand and a desire for better usage of the screenings has opened the possibility for the use of these screenings as fine aggregate in Portland cement concrete. The use of screenings as fine aggregate in concrete mixtures will not only reduce the demand for natural sand (NS), but also the environmental burden resulting from their disposal as waste material.

As compared to natural sands, screenings (manufactured sands) are generally characterized as having:

- Sharp, angular shaped particles
- High fines content (particles passing a No. 200 sieve)
- Larger numbers of flat and elongated particles

These properties thus result in higher water demand, and concretes that are generally hard to pump or finish. These deficiencies can be avoided with proper proportioning of concrete, which may also include making changes to the current specification requirements for sand used in concrete by allowing higher percent passing a No. 200 sieve, and implementation of new test methods to evaluate screenings characteristics.

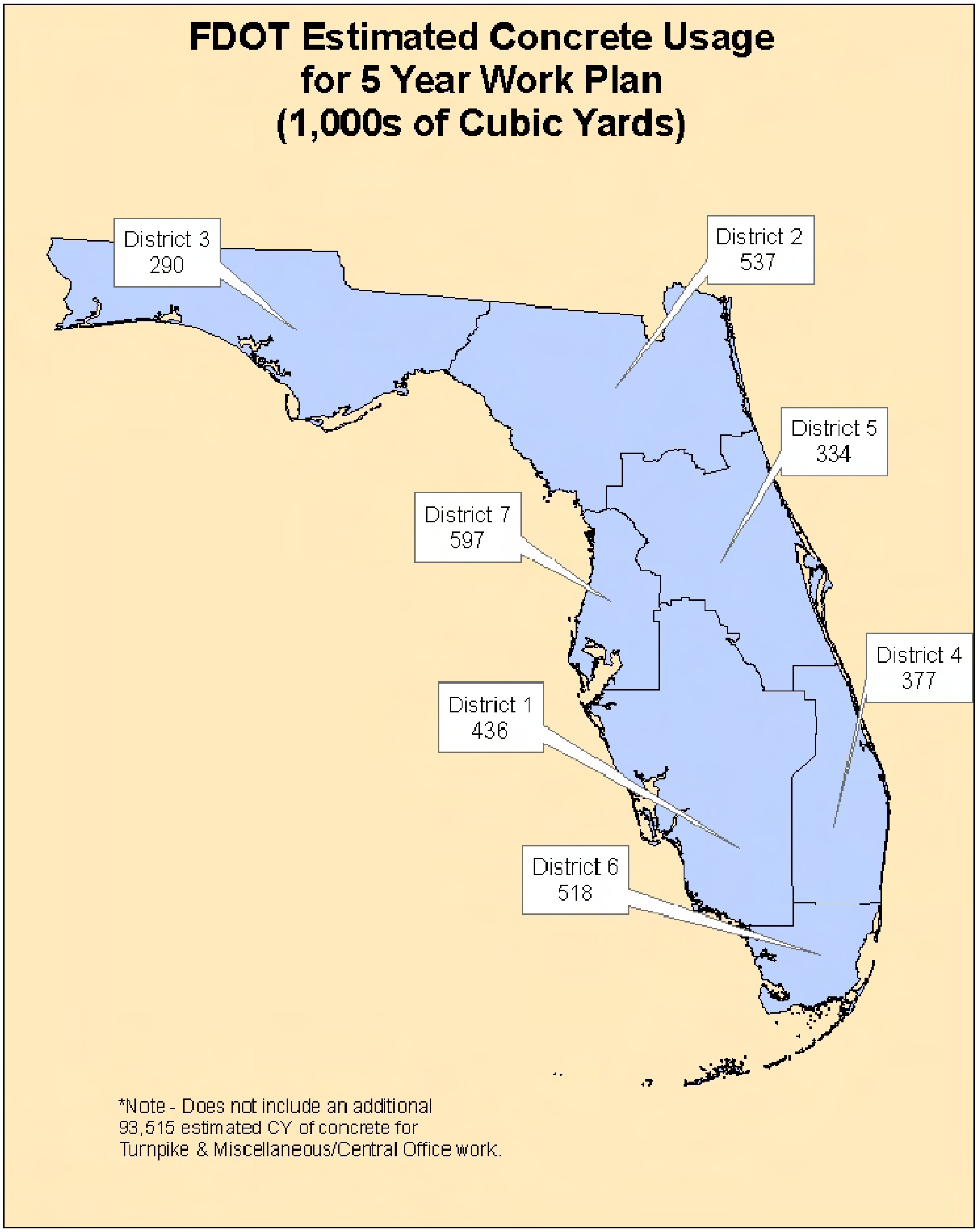


Figure 1. FDOT Estimates Concrete Usage for Five Year Work Plan [1]

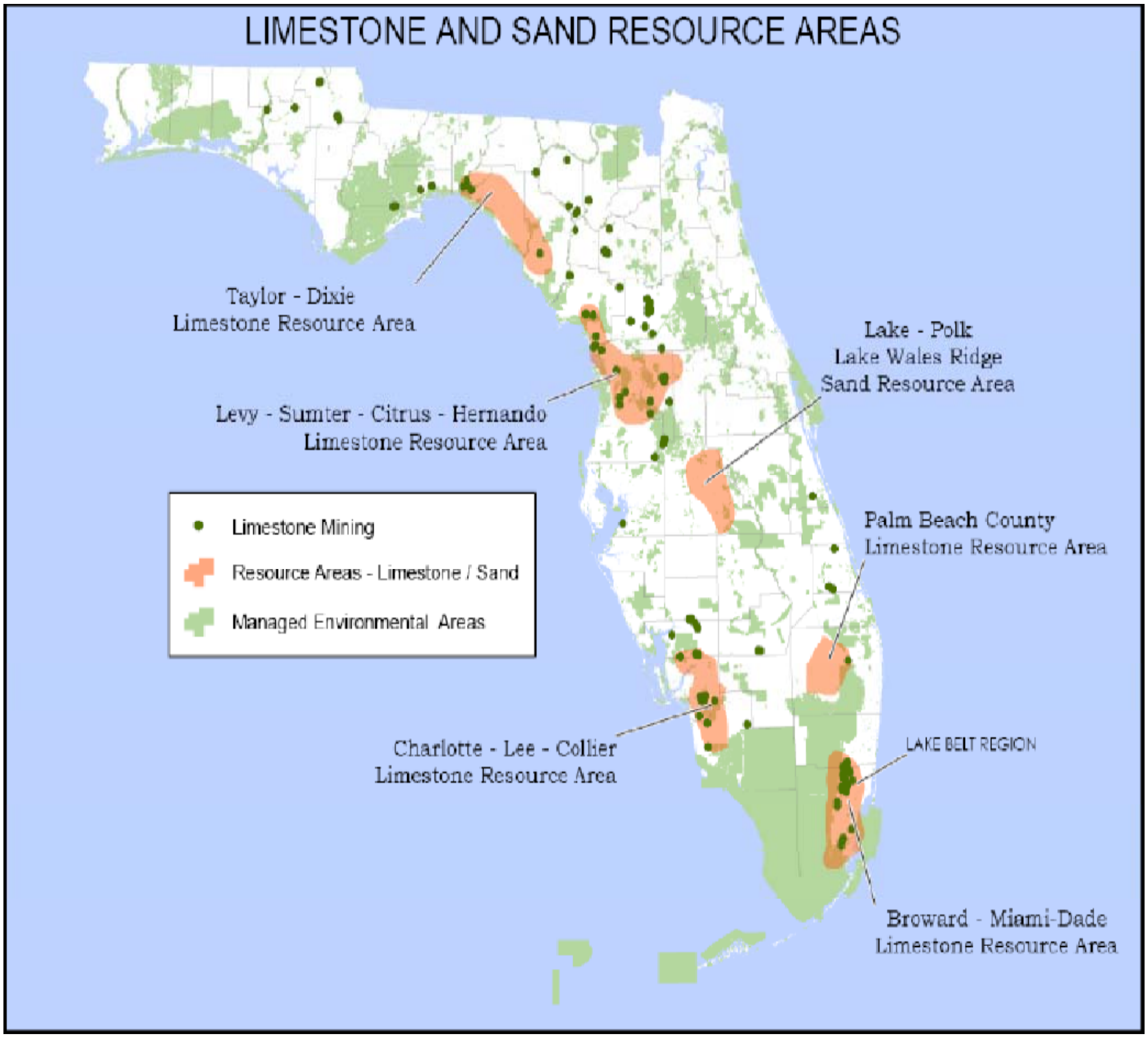


Figure 2. Limestone and Sand Resources in Florida [1]

1.2 RESEARCH OBJECTIVES

The main research objective of this study is to evaluate the potential use of screenings as a substitute for natural sand in Portland cement concrete.

1.3 RESEARCH APPROACH

The following approach was used in this research:

1) Perform a literature review on past and present studies on the use of screenings as a substitute for natural sand in concrete
2) Prepare mortar mixtures containing screenings from different sources in Florida in varying proportions and blends.
3) Prepare mortar mixtures with varying blend with natural sand and fly ash substitution
4) Evaluate the properties of mortar in fresh and hardened state in the laboratory
5) Prepare Concrete mixtures containing screening and blend of natural sand with varying proportions
6) Evaluate the fresh and hardened concrete properties of the concrete mixtures
7) Carry out a field demonstration of concrete mixture with screenings as a substitute for natural sand.
8) Perform economic analysis of use of screening as a substitute for natural sand in concrete.

CHAPTER 2: LITERATURE REVIEW

2.1 INTRODUCTION

The International Center for Aggregate Research (ICAR) [2] conducted "An Investigation of the Status of By-Product Fines in the United States" recently and found that the industry markets nearly 80% of minus 3/8" fines produced. Marketing sources include asphalt uses, aggregate-related uses, environmental applications, manufactured sand production, concrete pipe manufacturing, and other uses such as industrial fillers and in the paint industry. Only 23% of minus #200 fines produced each year reach the market, since most construction specifications in use today limit the proportions of fine materials.

At current production rates, the aggregate industry in US stockpiles nearly 180 million tons of by-product fines each year. It is estimated that there are currently 300-325 million tons of minus 3/8" fines and 400 million tons of minus #200 fines in stockpiles in the United States. Officials believe that the amount of stockpiles will increase in the near future if the industry makes no serious efforts to market these fines.

Researchers found that information about the quantities, characteristics, and properties of fines, and specifications and regulations limiting the proportions of fines in pavement mixtures, were major factors inhibiting the marketing and use of fines on a large scale.

In another study, ICAR [3] reported on the "Guidelines for Using Higher Contents of Aggregate Microfines in Portland Cement Concrete". Concrete fine aggregate gradation limits in ASTM C 33 permit a maximum of 7% microfines in some applications, if the fines consist of dust-of-fracture essentially free of clay or shale. Since the production process for screenings (manufactured fine aggregate, MF) normally generates 10 to 20% of these microfines, excess fines must be separated from the desired sizes by screening or washing. Many countries permit much higher microfines contents based on their experiences. India permits up to 20%, Spain, 15%, and Australia, 25%.

This ICAR[3] study found that

- Aggregate processing, e.g. crusher tip speed, significantly affected the aggregate particle shape and amount of microfines produced
- High-fines manufactured sand concrete generally had higher flexural strength, improved abrasion resistance, higher unit weight, and lower permeability due to filling of the pores with microfines.
- Compressive strength varied but was acceptable and shrinkage, although slightly higher, was within generally acceptable ranges.
- Good-quality concrete could be made from nearly all of the aggregates (with microfines contents ranging from 7 to 18%) used in the test program without the use of admixtures.

Kandhal and Khatri [4] evaluated the particle shape and texture of screenings (manufactured sand) versus natural sand and quantified the particle shape and texture of various natural and manufactured (crushed) sands of different mineralogical compositions from Pennsylvania using ASTM D3398 (Index of Particle Shape and Texture), and National Aggregate Association's (NAA) proposed method using uncompacted void content (both methods A and B).

2.2 PARTICLE SHAPE AND TEXTURE

The particle shape and surface texture of both coarse and fine aggregates have a significant influence on the properties of the plastic concrete. Rough textured, angular, or elongated particles require more water to produce workable concrete than smooth, rounded, compact aggregates, and as a result, these aggregates require more cementing materials to maintain the same water-cement ratio. Angular or poorly graded aggregates might result in the production of concrete that is more difficult to pump and also might be more difficult to finish. The hardened concrete strength will generally increase with increasing coarse aggregate angularity, and flat or elongated coarse aggregate particles should be avoided. Rounded fine aggregate particles are more desirable because of their positive effect on plastic concrete workability.

Figure 3 shows two charts for visual assessment of particle shape. [[5]]

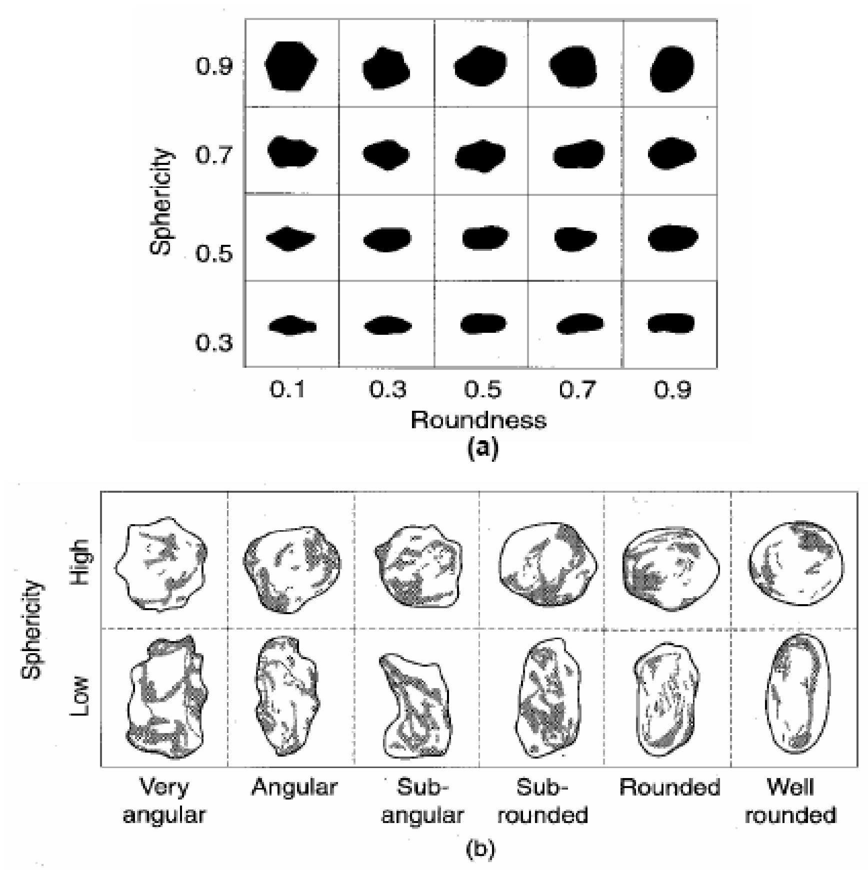


Figure 3. Visual Assessment of particle shape[5] (a) Derived from measurements of sphericity and roundness (b) Based upon Morphological Observations

There is a noticeable difference between the particle shape and the surface characteristics of the natural sand (NS) and manufactured sand (MS) (screenings), as seen in Figures 4 through 7 [[6]]. The NS particles are more rounded and smooth, which is why the void content was measured lower than the MS. The MS has a more angular shape and microroughness is revealed on the surface of the particles at higher camera resolutions (Figure 6). Another interesting observation was the particles retained on the #50 sieve have greater amounts of dust adhering to their surface. This observation reinforces the findings from the gradation of MS, which had greater amounts of fines than the NS. The increased angularity, fines, and void content will also increase the water demand for a mix to obtain the same slump, but the mechanical properties of the concrete do not seem to be affected.

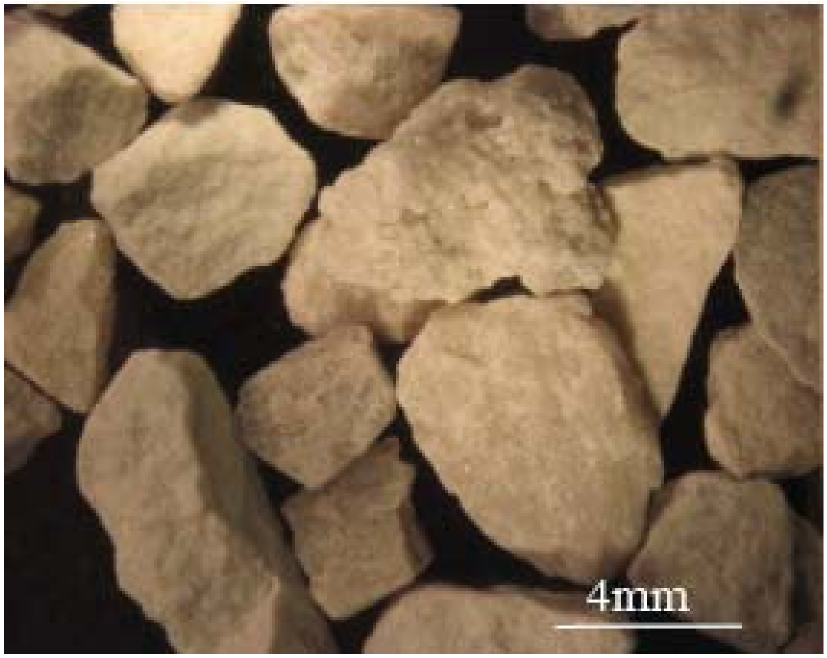


Figure 4. MS retained in sieve #8.

Figure 5. NS retained in sieve #8.

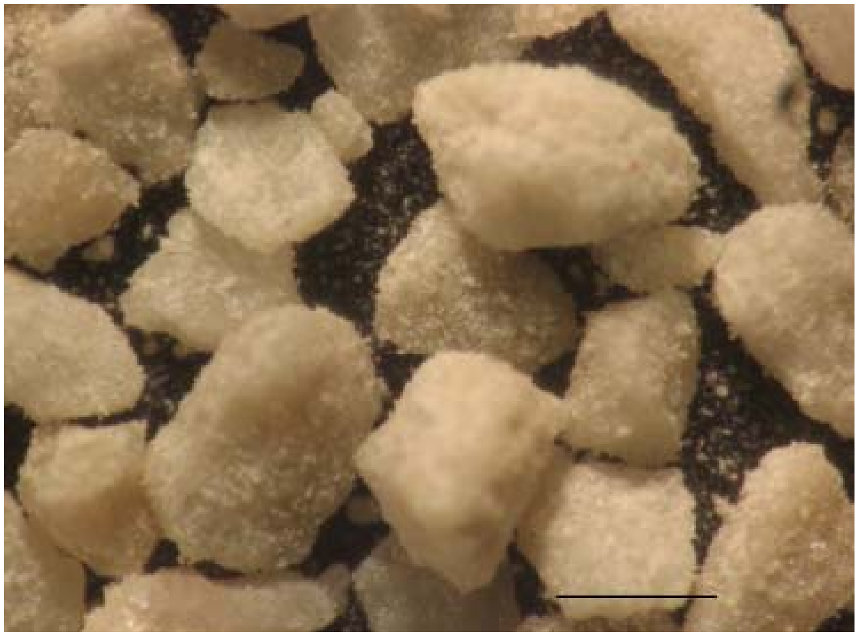


Figure 6. MS retained in sieve #50

Figure 7. NS retained in sieve #50.

Cubical or spherical particles have less specific surface area than flat and elongated particles. Consequently, cubical or spherical particles require less paste and less water for workability [7]. For a given workability, flaky and elongated particles increase the demand for water thus affecting strength of hardened concrete. Generally, spherical or cubical particles tend to have better pumpability, and finishability and produce lower shrinkage than flaky and elongated aggregates.

Nichols [8] reported that as the angularity of the particles increased, the voids content increased and water-cement ratios were greater than comparable mixtures with less angular fine aggregate. As shown in Figure 8, the water demand increases for concrete with a given slump as the National Crushed Stone Association (NCSA) particle shape index increases. The water demand increases significantly when the shape index is greater than 53 for both cement contents. The increase in water demand above the 53-shape index is attributed to flaky particles in the aggregate, which require more water to obtain the same slump.

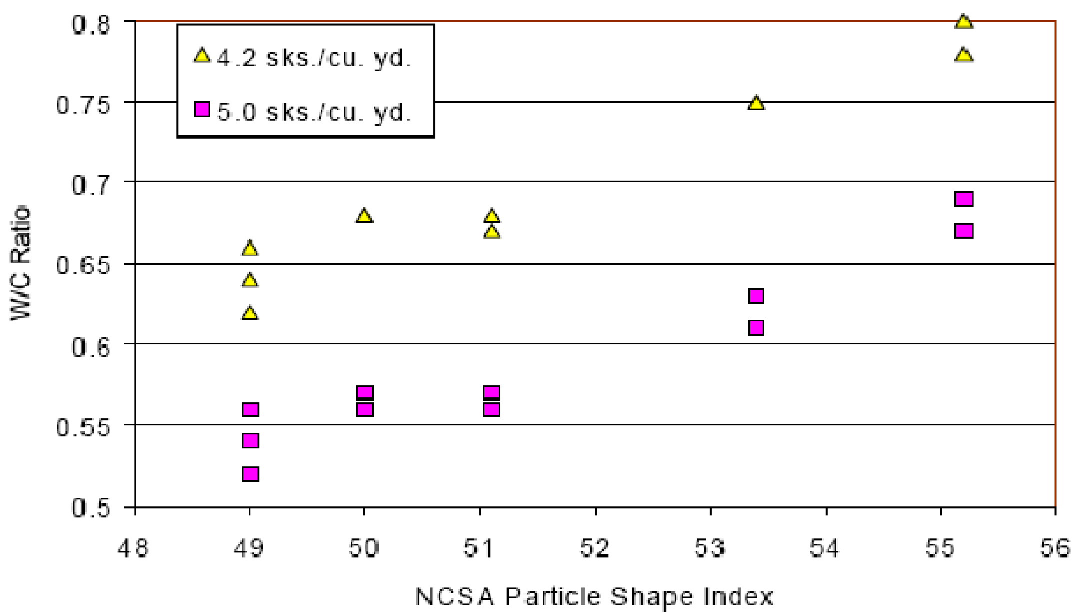


Figure 8. Influence of Particle Shape Index on Water Demand[8]

In an attempt to explain variations in mixing water requirements, Wills [9] investigated the effect of particle shape of both fine and coarse aggregates on water demand on concrete. He found that the shape of the fine aggregate has a more significant impact on water demand than the shape of the coarse aggregate. Further, within the permitted standard limits, the particle size distribution of the fine aggregate was found to have a greater influence in the properties of concrete than that of the coarse aggregate [10].

Jarvenpaa [11], investigated 6 different mixes and 21 fine aggregate types, and found that the characteristics of fine aggregate were responsible for differences in compressive strength between 1200 and 2700 psi for mixes identical except for the type of fine aggregate. The most important characteristics were the flakiness and the Los Angeles (modified) value of the semicoarse fraction. He also found that the effect of fine aggregate shape and porosity on flow was greater than the effect of cement amount.

Various methods have been reported in the literature for evaluating particle shape and texture of fine aggregates. These test methods can be divided generally into two categories – direct and indirect. Direct methods can be defined as those wherein particle shape and texture are measured, described qualitatively, and possibly quantified through direct measurement of individual particles. In indirect methods, measurement of the bulk properties of the fine aggregate are made separately, or as mixed in the end product. A brief summary of the test methods found in the literature follows[4].

2.2.1 Direct Tests

a) *Corps of Engineers Method CRD-C120-55*. "Method of Test for Flat and Elongated Particles in Fine Aggregate." In this method, particle shape is evaluated by observation with a microscope. The sample is separated into five sizes and the number of particles having a length-to-width ratio of more than three in each group are counted and reported as a percentage. It should be noted that this method evaluates only the particle shape and not the surface texture of the particles.

b) *Laughlin Method*. In this method, which was basically developed for fine aggregate used in Portland cement concrete, measurements are made using enlarged photographs of particles retained on various sieves. The radii of curvature of the particles and the radius of an inscribing circle are measured. Using these measurements, a parameter referred to as the roundness of the particles is then computed. Again, this method only tests the angularity (or roundness) of the particles, and not the surface texture.

2.2.2 Indirect Tests

a) *ASTM D3398. Standard Test Method for Index of Aggregate Particle Shape and Texture.* In this method, the sample is first separated into individual sieve fractions. The gradation of the sample thus is determined. Each size material is then separately compacted in a cylindrical mold using a tamping rod at 10 and 50 drops from a height of 2 inches. The mold is filled completely by adding extra material so that it just levels off with the top of the mold. Weight of the material in the mold at each compactive effort is determined, and the percent voids computed. A particle index for each size fraction is then computed and, using the gradation of the sample, a weighted average particle index for the entire sample is also calculated.

b) *National Aggregate Association's (NAA)(AASHTO TP33) Method of Test for Particle Shape and Texture of Fine Aggregate using Uncompacted Void Content*. In this method, a 100 cm^3 cylinder is filled with fine aggregate of prescribed gradation by allowing the sample to flow through the orifice of a funnel into the calibrated cylinder. Excess material is struck off and the cylinder with aggregate is weighed. Uncompacted void content of the sample is then computed using this weight and the bulk dry specific gravity of the aggregate. Two variations of the method are proposed. Method A uses a graded sample of specified gradation, while in method B the void content is calculated using the void content results of three individual size fractions: #8 to #16, #16 to #30, and #30 to #50.

c) *New Zealand Method*. This method is also a flow test, similar to the NAA's proposed method. Here the orifice is ½ in. diameter and any material larger than 5/16 in. sieve is removed. The void content and time required by 1000-g of the material to flow through the orifice is measured and reported as basic measures of particle shape and texture.

d) *National Crushed Stone Association (NCSA) Method.* This is also a flow test in which the material is broken down into three sizes. Void content of each size fraction is determined separately by allowing to flow through an orifice of 1 in. diameter. Arithmetic mean of the void contents of the three sizes is computed as the basic measure of particle shape and texture.

e) Virginia Method . This is substaintially similar to the NCSA method.

f) National Sand and Gravel Association (NSGA) Method. This method is basically the same test developed by Rex and Peck and later used by Bloem, Gaynor and Wills, but with different details. This is also a flow test with the size of an orifice of 0.4 in diameter. The sample is broken down into four size fractions and then recombined in specified proportions. Void content of the sample thus prepared is determined and reported as the basic measure of particle shape and texture.

g) Ishai and Tons Method . This test attempts to relate results from flow test to more basic measures of geometric irregularity of particles, i.e., macroscopic and microscopic voids in particles. The size of the orifice depends on the size of the particles being tested. The sample may be broken down into as many as six size fractions. One-sized glass beads are needed for each fraction. Flow test performance is reported on one-sized aggregate and corresponding one-sized glass beads.

h) Specific Rugosity by Packing Volume. This method is also a flow test and was used for direct measurement of the packing specific gravity of one-sized aggregate particles. Aggregate sample is broken into four sizes: each is placed in a cone shaped bin and then poured into a calibrated constant volume container. Packing specific gravity is computed using the weight of this calibrated volume of aggregate. The macrosurface and microsurface voids are computed using the apparent, bulk and packing specific gravities. The addition of the macrosurface and microsurface voids thus obtained is done to arrive at the specific rugosity.

i) Direct Shear Test. This test method is used to measure the internal friction angle of a fine aggregate under different normal stress conditions. A prepared sample of the aggregate under consideration is consolidated in a shear mold. The sample is then placed in a direct shear device and sheared by a horizontal force while applying a known normal stress.

In natural sands, deleterious particles such as clay minerals and organic matter which generally form the bulk of minus 75 μm portion are cause for increase water demand and adversely affect the plastic and hardened concrete properties. ASTM C 33 limits the amounts of particles passing the N 200 mesh (75 μm) to 3 and 5 percent in natural sands, and to 5 to 7 percent in crushed sands.

Screenings resulting from the process of crushing rock produces high microfines contents up to 20 percent. Hudson [12] has demonstrated that manufactured sands could have minus 75 μm percentages up to 15 or 20 percent without necessarily producing a negative effect on concrete quality. Small amounts of crushed fines passing 75 μm can improve strength, workability, and density for lean concrete mixtures [13]. Inclusion of minus 75 μm in a suitably graded form leads to high packing density, and to denser concrete and consequently to less permeability [12]. Mixtures with high amounts of microfines can also reduce bleeding and segregation.

Hudson however, reported that shrinkage properties have to be monitored when using concrete with high minus 75 μm content, particularly in climates of low humidity and dry winds. High microfines also impair finishability and decrease the entrained-air content, problems that could be overcome by using admixtures.

Ahmed [25] monitored the drying shrinkage of seven mixtures and, as shown in Figure 9, the concrete shrinkage increased with increasing dust of fracture content. Shrinkage effects were more pronounced for lean concrete containing more than 10 percent dust-of-fracture. Factors attributed to influencing the test results are accelerated hydration, carboaluminate formation, and large superplasticizer dosages in the specimens incorporating 15 and 20 percent limestone dust of fracture.

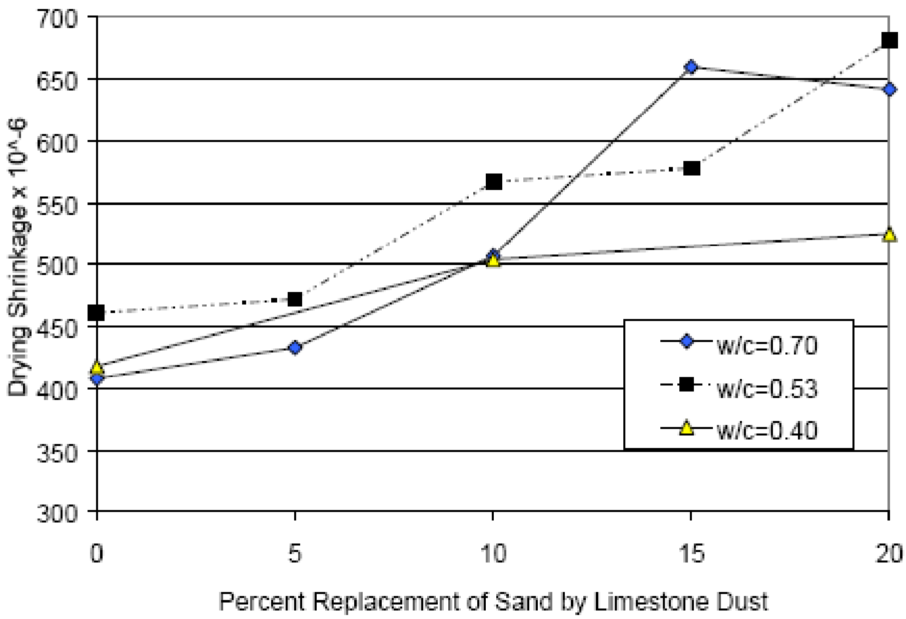


Figure 9. Influence of Dust of Fracture Content and W/C

Celik and Marar [14] batched concrete specimens with constant w/c, fine aggregate, coarse aggregate, and cement contents. The only variation was the percentage of the fine aggregate replaced with dust of fracture. Air content measurements were taken for the various mixtures, with the results shown below in Figure 12 below.

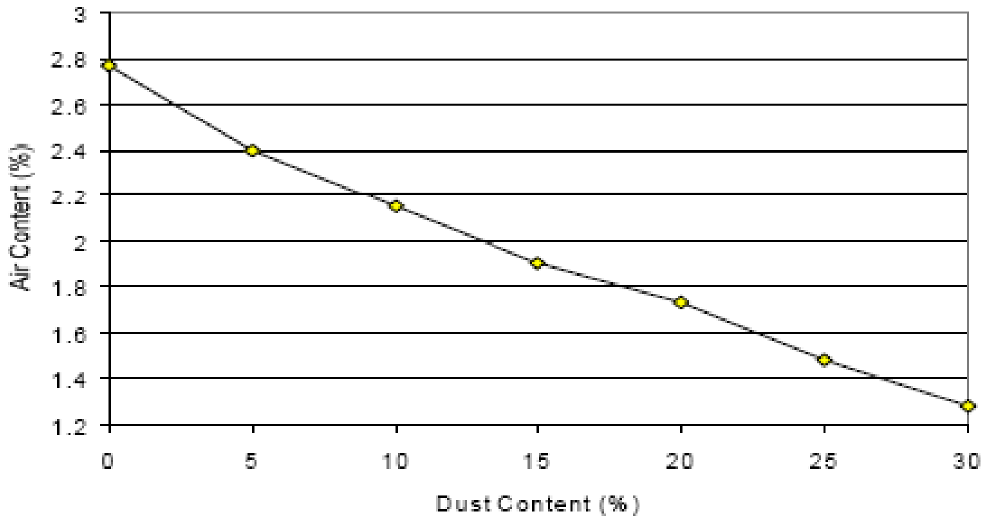


Figure 10. Effect of Increasing Dust of Fracture Content on Air Content in Concrete.

ASTM C 33 limits the fines content in manufactured sands to 5 to 7 percent. Table 1 shows specifications from different countries with greater limits.

Table 1. Microfines Limits in Different Countries[5]

Country	Microfines Allowed (Percentage of Sand)
United States	5% to 7% passing 75µm sieve
Spain	6% passing 63µm sieve (for natural sand) 15% passing 63µm sieve (for crushed sand)
England	15% passing 63µm sieve
India	15% to 20%
Australia	25%
France	12% to 18% passing 63µm sieve

2.3 INFLUENCE OF CRUSHER TYPE

The manufacture of sand and shaped aggregates is essentially a size reduction operation and can be achieved by the following mechanisms[15]:

- Impact or shatter
- Cleavage
- Attrition
- Abrasion.

Table 2 below summarizes the commonly used crushers and their typical uses.

Table 2. Types of Crushers

Type	**Hardness**	**Abrasion limit**	**Moisture content**	**Reduction ratio**	**Main use**
Jaw crushers	Soft to very hard	No limit	Dry to slightly wet, not sticky	3/1 to 5/1	Quarried materials, sand & gravel
Gyratory crushers	Soft to very hard	Abrasive	Dry to slightly wet, not sticky	4/1 to 7/1	Quarried materials
Cone crushers	Medium hard to very hard	Abrasive	Dry or wet, not sticky	3/1 to 5/1	Sand & gravel
Horizontal shaft impactors	Soft to medium hard	Slightly abrasive	Dry or wet, not sticky	10/1 to 25/1	Quarried materials, sand & gravel
Vertical shaft impactors (shoe and anvil)	Medium hard to very hard	Slightly abrasive	Dry or wet, not sticky	6/1 to 8/1	Sand & gravel
Horizontal shaft impactors (autogenous)	Soft to medium hard	No limit	Dry or wet, not sticky	2/1 to 5/1	Quarried materials, sand & gravel

Jaw crushers use compression crushing to produces fracture through cleavage and generally produces inferior material for concrete usage. Gyratory and cone crushers achieve size reduction with a combination of cleavage fracture and attrition. The Vertical Shaft Impactor (example Figure 11. Barmac B-Series VSI) is unique in its construction, principle of operation and utilizes all the four modes of size reduction operation, i.e. impact, cleavage, attrition and abrasion.

Figure 11. Barmac B-Series VSI.

Impact crushers of various types have been employed in screenings production, but in particular vertical shaft impactors [[16]] are most common. This type of crusher propels particles with a rotor moving at high speeds, against an anvil or a curtain of falling particles. Such loading conditions leads to a higher probability of fracture of either weak or flaky particles, with fracture occurring by cleavage, with a marked contribution from surface attrition. The result is that particles with greater integrity and more isometric shapes are produced by this crushing process as compared to other machines, such as cone, jaw and roll crushers. In the case of cone crushers, particle fracture depends on loading conditions [[17]]. Under starve–fed conditions, particles are crushed from direct contact with the crusher plates (low coordination number), resulting in their breakage by cleavage alone in a way that is irrespective of particle shape and strength, leaving particles of highly irregular shapes and moderate integrity in the product. Under choke–fed conditions, particles are crushed predominantly by interparticle forces (high coordination number), through a combination of cleavage and attrition, so that shape and integrity of particles in the product are intermediate in comparison to those produced in impact crushers and cone crushers operating under starve–fed conditions.

Besides particle shape, crushing processes also influence grading of the screenings, and the proportion of microfines (minus 75 μm material), particularly when compared to natural fine aggregates. This proportion of non-deleterious microfines, however, may be controlled not only by setting the appropriate crushing conditions, but also by using appropriate size classification processes. As a result, the application of crushing and classification processes to a given rock type potentially enables reaching grading curves and particle shapes that vary significantly, meeting almost any desired specification.

J.P. Gonçalves [18] compared the natural and manufactured fine aggregates produced by cone crushing or impact crushing in cement mortars. Particle shape analyses indicated that material produced by impact crushing presented intermediate sphericity and aspect ratio, between those found in natural fine aggregate and cone-crushed material, and that the aspect ratio of the cone-crushed material increased for finer particle sizes.

The type of process and feed material will directly influence the grading, shape [19], surface texture, and even integrity [20] of the aggregate manufactured by crushing, and thus its performance in mortars and concrete.

A number of studies have dealt with the influence of both grading and particle shape of the fine aggregate in mortars and concrete. At a given water/cement ratio, it has been found that concrete made with screenings (with up to 7% microfines) achieved compressive strength equal to or higher than concrete made with natural sand [21], reducing the void content of the aggregate, thereby lubricating the aggregate system without increasing the water requirement of the mixture [22]. In a comprehensive investigation of screenings of various rock types produced in vertical impact crushers, it was observed that, for a fixed flow, the greater the content in microfines, the greater the water/cement ratios required, and that with increased fineness modulus, flow and compressive strength increased. However, no studies were found that compared in great enough detail the performance in mortars of screenings produced in different crushing and size classification routes.

Lukkarila, [23] studied the effect of two crusher types, viz, a typical jaw crusher and a vertical shaft impactor (VSI) crusher, known for creating an optimal particle shape. Material that passed the No. 50 (300 mm) sieve and was retained on the No. 100 (150 mm) sieve and used in an image analyzer to measure mean length, width, area, elongation, CE diameter, circularity, and convexity for each sample. The instrument measured a better shape (circularity) and a smoother particle (convexity) for the manufactured sand created with the VSI crusher.

Md. Safiuddin [24] studied the "Utilization of Quarry Waste Fine Aggregate in Concrete Mixtures" and the effects of quarry waste fine aggregate on several fresh and hardened properties of the concretes were investigated. He found that quarry waste fine aggregate enhanced the slump and slump flow of the fresh concretes. In hardened concretes, the compressive strength was decreased in the presence of quarry waste fine aggregate. In addition, the dynamic modulus of elasticity and initial surface absorption were marginally increased but the ultrasonic pulse velocity was unaffected.

Ahmed and El-Kourd [25] tested concrete with constant slump and concrete with a constant w/c. The concrete made to have a constant slump of 4.0 ±0.5-in. required more water as the content of dust was increased. As shown in Figure 12, the w/c required to maintain a constant slump was greater for the natural sand than for MFA with the same dust content. Concrete batched with a constant w/c had decreasing slump as the dust content increased.

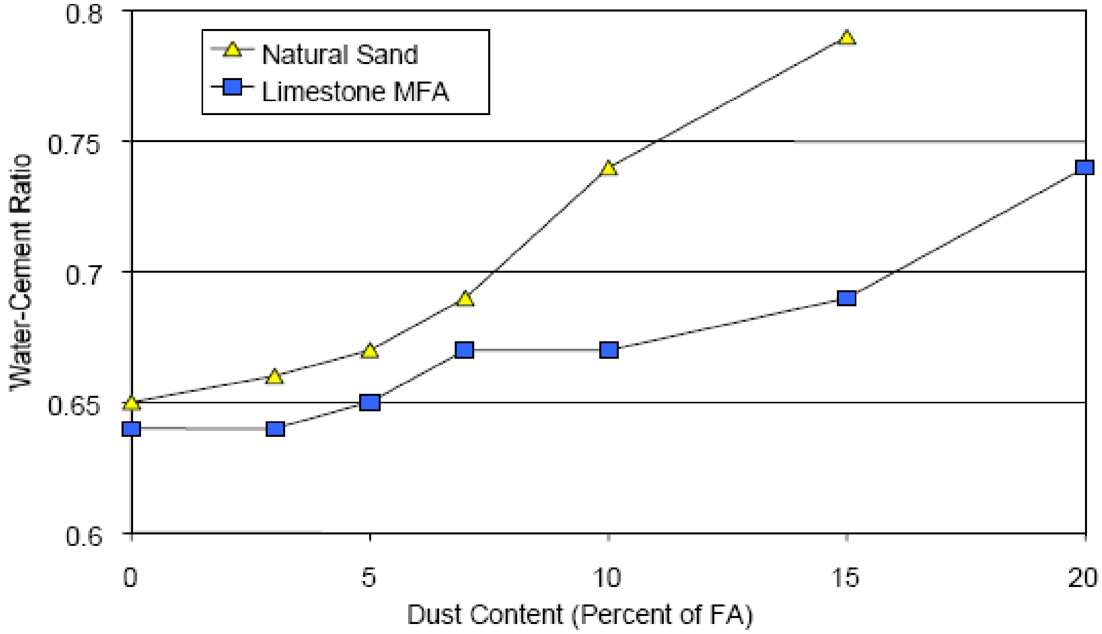


Figure 12. Influence of Aggregate Type and Dust Content on w/c.

CHAPTER 3: LABORARTORY TEST PROGRAM

3.1 INTRODUCTION

This chapter describes the laboratory test procedures and program used to evaluate screenings as a substitute for natural sand in Portland cement concrete. This chapter not only provides information on the material and test procedures employed to accomplish the tasks, but also provides the design of experimentation for mortar and concrete phases of the study.

3.2 TESTING METHODS

Table 3 lists the properties and test methods used to investigate fine and coarse aggregate properties. Wherever applicable and appropriate, Florida Sampling and Testing Methods (FSTM) were used. Table 4 list the fresh and hardened mortar and concrete properties measured and method used.

Table 3. Aggregate Property and Test Procedures

Property	Test Method	Reference
General Specifications	Concrete Aggregates	ASTM C33[26]
Gradation	Sieve Analysis of Fine and Coarse Aggregate	AASHTO T 27[27]
Absorption	Specific Gravity and Absorption of Coarse Aggregate	FM 1-T 85[28]
	Specific Gravity and Absorption of Fine Aggregate	FM 1-T 84[29]
Particle Shape and Surface Texture	Uncompacted Voids Content of Fine Aggregate	ASTM C1252[30]
	Index of Aggregate Particle Shape and Texture	ASTM D3398[31]
Durability	Aggregate Durability Index	ASTM D3744[32]
	Micro Deval	AASHTO T 120 [33]
Toughness	LA Abrasion Test	FM 1-T 96 [34]
Deleterious Components	Clay Lumps and Friable Particles in Aggregates	ASTM C142[35]
	Plastic Fines in Graded Aggregates and Soils by Use of the Sand Equivalent Test	ASTM D2419[36]

Table 4. Mortar and Concrete Properties and Test Procedures

Property	Test Method	Reference
General Specifications	Chemical Admixtures for Concrete	ASTM C494[[37]]
Flow	Flow of Hydraulic Cement Mortars	ASTM C1437[[38]]
Slump	Slump of Hydraulic Cement Concrete	ASTM C143[[39]]
Strength	Compressive Strength of Mortar Cube Specimens	ASTM C109[[40]]
	Compressive Strength of Cylindrical Concrete Specimens	ASTM C39[[41]]
	Splitting Tensile Strength of Cylindrical Concrete Specimens	ASTM C496 [[42]]
Air Content	Air Content of Freshly Mixed Concrete by the Pressure Method	ASTM C231[[43]]
	Unit Weight, Yield, and Air Content of Concrete	ASTM C138[[44]]
	Concrete Resistivity as an Electrical Indicator of its Permeability	FM 5-578 [[45]]
Durability	Length Change of Hardened Hydraulic-Cement Mortar and Concrete	ASTM C157[[46]]
Volume Stability	Autoclave Expansion	ASTM C151[[47]]

ASTM C 1252. Uncompacted Void Content of Fine Aggregate (as Influenced by Particle Shape, Surface Texture, and Grading)

These test methods cover the determination of the loose uncompacted void content of a sample of fine aggregate. When measured on any aggregate of a known grading, void content provides an indication of that aggregate's angularity, sphericity, and surface texture compared with other fine aggregates tested in the same grading. When void content is measured on an as-received fine-aggregate grading, it can be an indicator of the effect of the fine aggregate on the workability of a mixture in which it may be used.

Three procedures are included for the measurement of void content. Two use graded fine aggregate (standard grading or as-received grading), and the other uses several individual size fractions for void content determinations:

1. *Standard Graded Sample (Test Method A)*—This test method uses a standard fine aggregate grading that is obtained by combining individual sieve fractions from a typical fine aggregate sieve analysis.

2. *Individual Size Fractions (Test Method B)*—This test method uses each of three fine aggregate size fractions: *(a)* 2.36 mm (No. 8) to 1.18 mm (No. 16); *(b)* 1.18 mm (No. 16) to 600 m (No. 30); and *(c)* 600 m (No. 30) to 300 m (No. 50). For this test method, each size is tested separately.

3. *As-Received Grading (Test Method C)*—This test method uses that portion of the fine aggregate finer than a 4.75-mm (No. 4) sieve.

ASTM D 3398 (2006). Index of Aggregate Particle Shape and Texture

This test method provides an index value to the relative particle shape and texture characteristics of aggregates. This value is a quantitative measure of the aggregate shape and texture characteristics that may affect the performance of road and paving mixtures. This test method has been successfully used to indicate the effects of these characteristics on the compaction and strength characteristics of soil-aggregate and asphalt concrete mixtures

In this test, a clean, washed, oven dried, one-sized sample is used. Five cylindrical molds of various diameters are used, along with steel tamping rods of different weights. Each cylinder is filled in three layers, with each layer receiving ten tamps. Each tamp consists of a drop with the tamping rod from two inches above the surface. The procedure is repeated using the same material, but applying 50 tamps instead of ten. The particle index value is calculated using the following equation:

$$I_a = 1.25V_{10} - 0.25V_{50} - 32.0$$

Where,

I_a = particle index value

V_{10} =percent voids in the aggregate compacted with 10 blows per layer

V_{50} = percent voids in the aggregate compacted with 50 blows per layer

According to Kandhal, Lynn and Parker [48], this method is not practical for testing fine aggregates because it requires separating different sieve fractions, thus it is time consuming and expensive.

ASTM C295 - 03 Standard Guide for Petrographic Examination of Aggregates for Concrete[49]

The ASTM C 295 test method provides guidelines for petrographic evaluation of aggregates. This guide outlines the extent to which petrographic techniques should be used, the selection of properties that should be looked for, and the manner in which such techniques may be employed in the examination of samples of aggregates for concrete. Petrographic examination provides excellent information very rapidly.

Besides shape and texture, petrography could be used to:

- Determine physical and chemical characteristics of aggregate.
- Describe and classify constituents of a sample.
- Establish if aggregates are compound or covered by chemically unstable mineral such as soluble sulfates or smectites.
- Determine weathering and porous characteristics of aggregate, as they can affect freezing and thawing resistance of aggregate.
- Verify whether aggregates have alkali-silica or alkali-carbonate reactive constituents and determine the presence of contaminants.

Some petrographic techniques are microscopy analysis, X-ray diffraction, differential thermal analysis, infrared spectroscopy, scanning electron microscopy, and energy-dispersive x-ray analysis.

ASTM D7428 - 08e1 Standard Test Method for Resistance of Fine Aggregate to Degradation by Abrasion in the Micro-Deval Apparatus[33]

The Micro-Deval abrasion test is a test of fine aggregate to determine abrasion loss in the presence of water and an abrasive charge. Many aggregates are more susceptible to abrasion when wet than dry, and the use of water in this test incorporates this reduction in resistance to degradation. The test results are helpful in evaluating the toughness, abrasion resistance of fine aggregate subject to abrasion when adequate information is not available from service records. This test is suitable for measuring the amount of weak, soft material, such as shale or shaley carbonate in fine aggregate. Materials that give a low loss in this test are unlikely to exhibit significant degradation during handling, mixing, or placing. There is a relationship between drying shrinkage of cement mortar and Micro-Deval abrasion loss of fine aggregate, with higher loss materials resulting in higher drying shrinkage. The Micro-Deval abrasion test on fine aggregate is useful for detecting changes in properties of aggregate produced from an aggregate source as part of a quality control or quality assurance process.

The Micro-Deval abrasion test on fine aggregate, in contrast to the version on coarse aggregate, has a significant correlation with the Magnesium Sulfate soundness loss of fine aggregate. The Micro-Deval test on fine aggregate has better precision than the sulfate soundness test, is quicker, and may be used in place of that test. Advice on specific values for selection of aggregate will be found in the appendix of the test standard.

ASTM WK158[50] Methylene Blue Test [5]

This test is used to identify harmful clays, such as smectite, kaolinite and illite, organic matter, and iron hydroxides present in fine aggregate. The method is based on the ability of these clays to exchange cations, and therefore adsorb the methylene blue dye. There are many variations of the test for which results are different and difficult to correlate. The methylene blue value (MBV) may depend on some aggregate characteristics such as mineralogy, particle size, and porosity. In addition, it has been found that MBV of minus 75 µm material is higher if the sample has been obtained from wet sieving. Research at ICAR indicates that there is no strong correlation between MBV and the performance of concrete made with sand with high fines [[51]]. However, it was found that materials with very high MBV could potentially generate problems, such as high water demand and would require further investigation.

ASTM C1437 - 07 Standard Test Method for Flow of Hydraulic Cement Mortar

This test method covers the determination of flow of hydraulic cement mortars and is used as a quantitative index of workability. A truncated cone shaped mold is used. Mortar is tamped into the mold, and dropped 25 times in 15 seconds to spread the mortar. The horizontal spread of the mortar is measured along the 4 lines marked on the table using special caliper. When added these four readings give the percent increase in the diameter, which is reported as the mortar flow.

FM 5-578 Surface Resistivity

This non destructive test measures the electrical resistivity across the face of a saturated concrete specimen to provide an indication of its permeability. The test result is a function of the electrical resistance of the specimen. The electrical resistivity of saturated concrete depends primarily upon the capillary pore size, pore system complexity, and interconnectivity of pore system.

A Surface Resistivity meter with a Wenner linear four-probe array should have a range of 0 to 100 KΩ-cm, with a resolution of 0.1 KΩ-cm and an Accuracy of ± 2% of reading. The Wenner probe array spacing should be set at 1.5 inches (38.1 mm). All test specimens were 4.0 × 8.0 inches (100 × 200 mm) cylinders prepared in accordance with ASTM C192 or ASTM C31. Surface resistivity was determined in accordance with FM

5-578 test procedure at 28 days of age. Table 5 is used to characterize the permeability of the concrete.

Table 5. Surface Resistivity Test and Permeability relationships

Chloride Ion Permeability	Surface Resistivity kΩ−cm
High	< 12
Moderate	12 – 21
Low	21 – 37
Very Low	37 – 254
Negligible	> 254

ASTM C151 **Standard Test Method for Autoclave Expansion of Hydraulic Cement**

ASTM C151 provides an index of potential delayed expansion caused by the hydration of CaO or Mgo, or both, when present in the hydraulic cement. A specimen, 1 × 1 × 10 inches, is prepared and stored in under stable climatic conditions. After 24 ± 0.5 h of casting, they are unmolded and initial length measured by a micrometer comparator. The samples are then placed in the autoclave and exposed to the action of steam under pressure of 300 psi for 3 hours. The rate at which the pressure and temperature is increased at the beginning of the test and released at the end of test are specified. The samples are immersed into a heated water bath and afterwards gradually cooled to room temperature, following specific instructions in ASTM C151. The lengths of the specimens are measured using the micrometer comparator and percent expansion is calculated.

ASTM C157 Standard Test Method for Length Change of Hardened Hydraulic-Cement Mortar and Concrete

ASTM C157 provides a method for potential volumetric expansion or contraction of mortar or concrete due to various causes other than applied stress or temperature change. The method is particularly useful for comparative evaluation of potential expansion or shrinkage in different hydraulic mortar or concrete mixtures. This test method provides useful information for experimental purposes or for products that require testing under nonstandard mixing, placing, handling, or curing conditions, such as high product workability or different demolding times. The test utilizes 1x1x10" mortar prisms or 3 × 3 × 10" concrete prisms. The specimens are kept in the mold for 23.5 ± 0.5 h, or longer if necessary to prevent damage, then demoded and moist cured for 28 days. The comparator readings are taken after 4, 7, 14, and 28 days, and after 8, 16, 32 and 64 weeks, unless otherwise specified.

ASTM C596 - 07 Standard Test Method for Drying Shrinkage of Mortar Containing Hydraulic Cement

This test method establishes a selected set of conditions of temperature, relative humidity, and rate of evaporation of the environment to which a mortar specimen of stated composition shall be subjected for a specified period of time, during which its change in length is determined and designated "drying shrinkage".

The drying shrinkage of mortar as determined by this test method has a linear relation to the drying shrinkage of concrete made with the same cement and exposed to the same drying conditions. Hence, this test method may be used when it is desired to develop data on the effect of hydraulic cement on the drying shrinkage of concrete made with that cement.

Strength Tests

Three cubes were tested at the ages of 28-days in accordance to ASTM C 109, *Standard Test Method for Compressive Strength of Hydraulic Cement Mortars*. Concrete samples were tested for their compressive strength at 28 days in accordance to ASTM C39, *Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens,* and for their splitting tensile strength in accordance to ASTM C496, *Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens*.

3.3 MATERIALS USED

3.3.1 Water

Regular potable tap water supplied by the city of Daytona Beach water system was used without further testing. Precautions were taken to not contaminate the mixing water.

3.3.2 Cement

For all mixes, Type I cement meeting the requirements of the applicable AASHTO and FDOT specifications section 921 were used, and were obtained from the FDOT approved supplier.

3.3.3 Coarse Aggregate

No. 57 Limestone aggregates meeting the requirements of section 901 from FDOT approved aggregate supplier were obtained and used for the mix production. The test procedures and properties observed for this coarse aggregate are as summarized in Table 6.

Table 6. Measured Coarse Aggregate Properties

Property	Test Procedure	Value
Dry-Rodded Unit Wt (lb/ft^3)	FM 1-T 019	90.82
Bulk Specific gravity, SSD	FM 1-T 085	2.40
Absorption capacity (%)	FM 1-T 085	3.12

The particle size distribution was determined using the FDOT FM1-T 027 procedure on dry samples and the results are summarized below. Table 7 shows the particle size distribution, along with FDOT specification for No. 57 coarse aggregates. The results of the tests verified that the aggregate met the gradation requirements of FDOT specifications.

Table 7. Coarse aggregate gradation (Percent passing)

Sieve Size (in)	FDOT Spec. Sec. 901	Average Percent Passing
1.5	100	100
1	95-100	98
3/4	-	79
1/2	25-60	36.9
3/8	-	20.2
#4	0-10	4.9

3.3.4 Natural Fine Aggregate

Natural silica sand meeting the FDOT specification section 902 was used to prepare control mixes and where blending with screenings was studied. Properties of the natural sand (N) used are as shown in Table 8 and Table 9. Natural sand used was very fine with fineness modulus of 2.02, and was the only readily available sand.

Table 8. Measured Fine Aggregate Properties

Property	Test Procedure	Value
Bulk Specific Gravity, dry	FM 1-T 084	2.63
Absorption Capacity (%)	FM 1-T 084	0.35
Fineness Modulus	FM 1-T 027	2.02
Uncompacted Void Content, (Method B)	ASTM C 1252	43.83

Table 9. Average Fine Aggregate Gradation (Percent Passing)

Sieve Size	FDOT Sect.	Average Percent Passing
#4	95-100	100
#8	85-100	99.6
#16	65-97	95.21
#30	25-70	65.9
#50	5-35	29.9
#100	0-7	7.8
#200	0-4	0.1

3.3.5 Screenings

3.3.5.1 Sources of Screenings Used

For the project four sources of screenings were identified representing the various geological and rock formations found in the state of Florida. Figure 13 below shows the location and source of the screenings used for this project. Table 10 below shows the identification used for the four screenings used in this report.

Table 10. FDOT Mine ID and Project ID used

Mine ID	Project ID
08005	B
38268	C
12260	F
87090	M

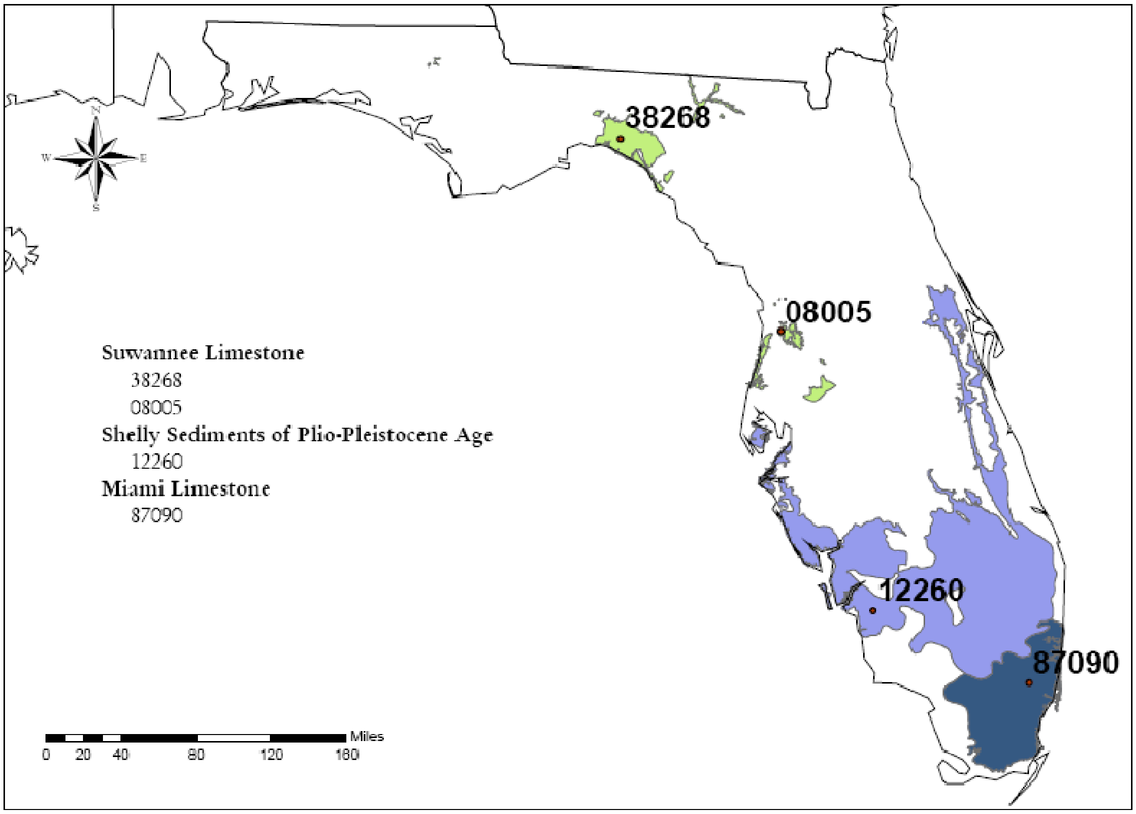


Figure 13. Location of Sources of Screenings Used.

A brief description of the geologic structure of the above four screenings is found in the Florida geologic stratigraphy data is listed below.

Suwannee Limestone - Peninsular Lower Oligocene carbonates crop out on the northwestern, northeastern and southwestern flanks of the Ocala Platform. The Suwannee Limestone consists of a white to cream, poorly to well indurated, fossiliferous, vuggy to moldic limestone (grainstone and packstone). The dolomitized parts of the Suwannee Limestone are gray, tan, light brown to moderate brown, moderately to well indurated, finely to coarsely crystalline, dolostone with limited occurrences of fossiliferous (molds and casts) beds. Silicified limestone is common in Suwannee Limestone. Fossils present in the Suwannee Limestone include mollusks, foraminifers, corals, and echinoids.

Pliocene - Pleistocene Series - Lithologically these sediments are complex, varying from unconsolidated, variably calcareous and fossiliferous quartz sands to well indurated, sandy, fossiliferous limestones (both marine and freshwater). Clayey sands and sandy clays are present. These sediments form part of the surficial aquifer system

Miami Limestone - The Miami Limestone forms the Atlantic Coastal Ridge and extends beneath the Everglades, where it is commonly covered by thin organic and freshwater sediments. The Miami Limestone consists of two facies, an oolitic facies and a bryozoan facies. The oolitic facies consists of white to orangish gray, poorly to moderately indurated, sandy, oolitic limestone (grainstone) with scattered concentrations of fossils. The bryozoan facies consists of white to orangish gray, poorly to well indurated, sandy, fossiliferous limestone (grainstone and packstone). Beds of quartz sand are also present as unindurated sediments and indurated limey sandstones.

3.3.5.2 Representative Pictures of Screenings Used

The following figures show the optical microscope pictures of various screenings of different sieve sizes. These photos clearly display the inherent angular and dusty nature of the screenings.

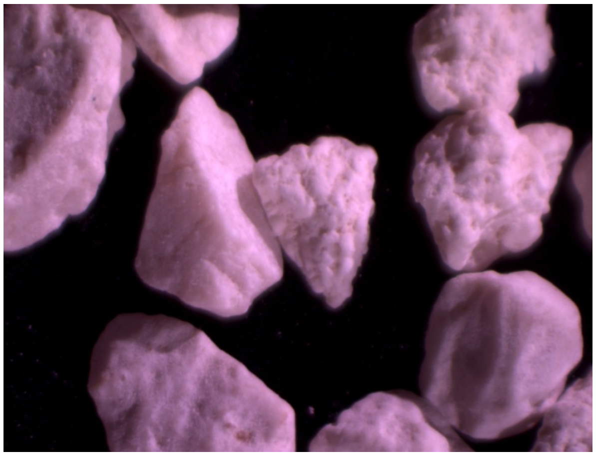


Figure 14. Mine B, #8 sieve

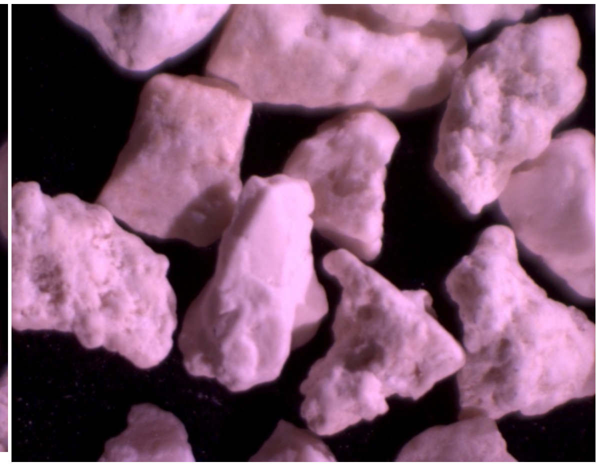


Figure 15. Mine B, #16 Sieve

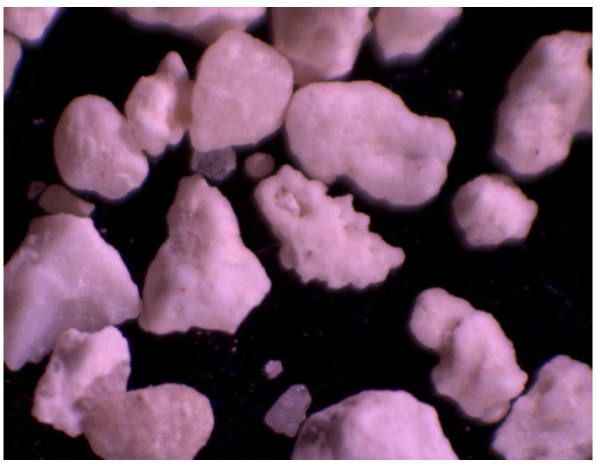


Figure 16. Mine B, #30 Sieve

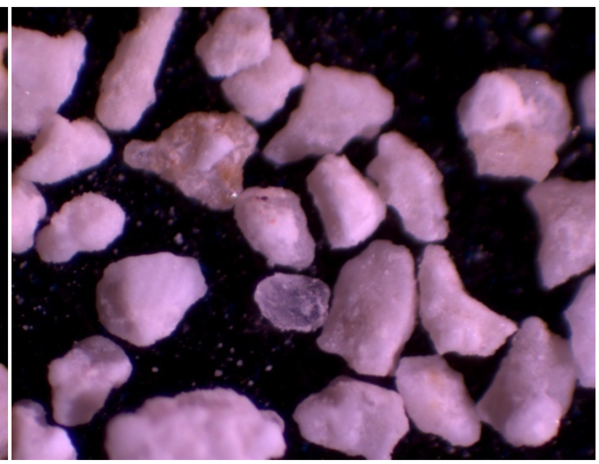


Figure 17. Mine B #50 Sieve

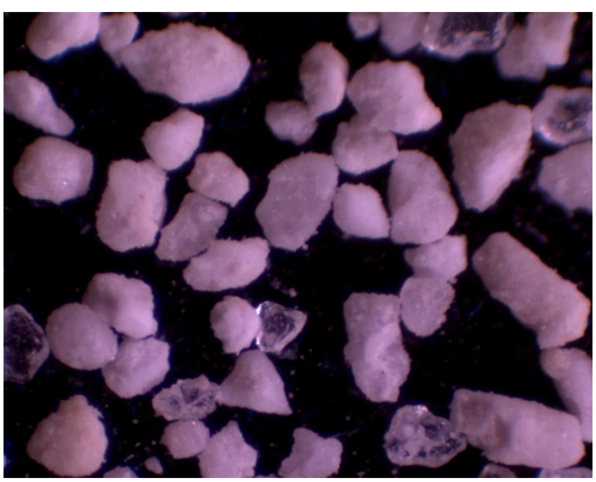


Figure 18. Mine B, #100 Sieve

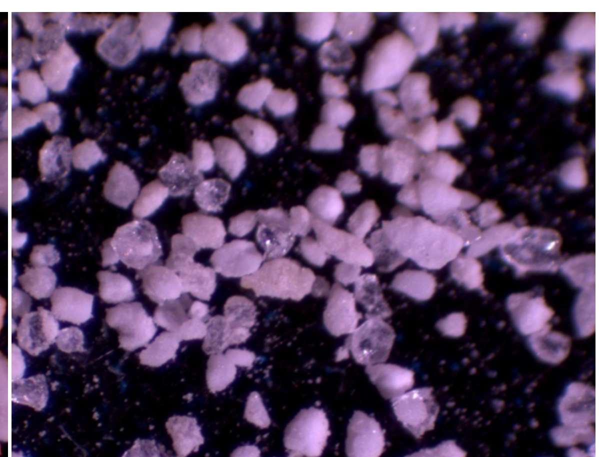


Figure 19. Mine B, #200 Sieve

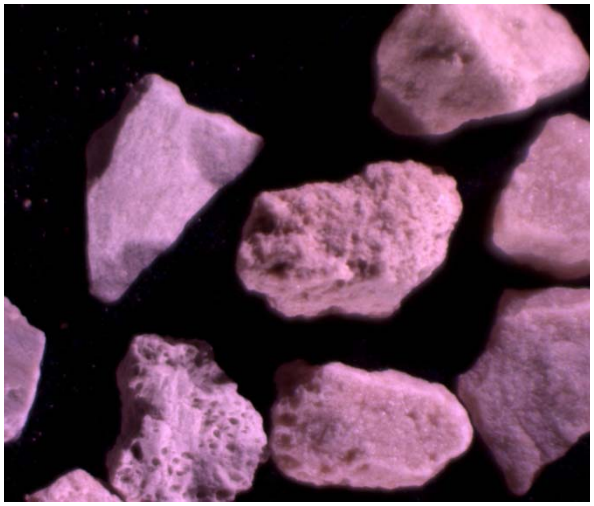


Figure 20. Mine C, #8 sieve

Figure 21. Mine C, #16 sieve

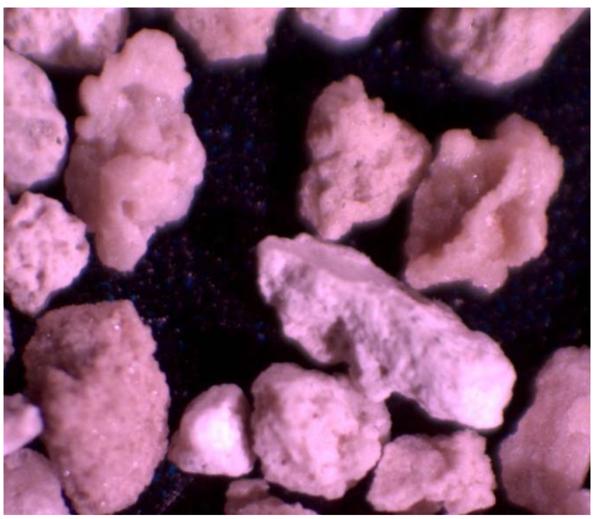


Figure 22. Mine C, #30 sieve

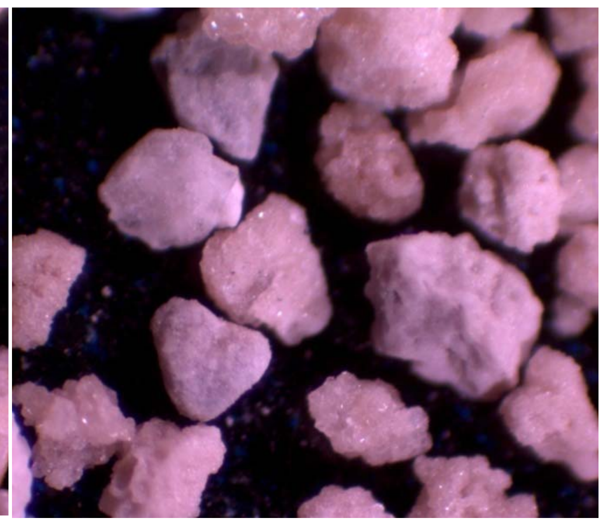


Figure 23. Mine C, #50 sieve

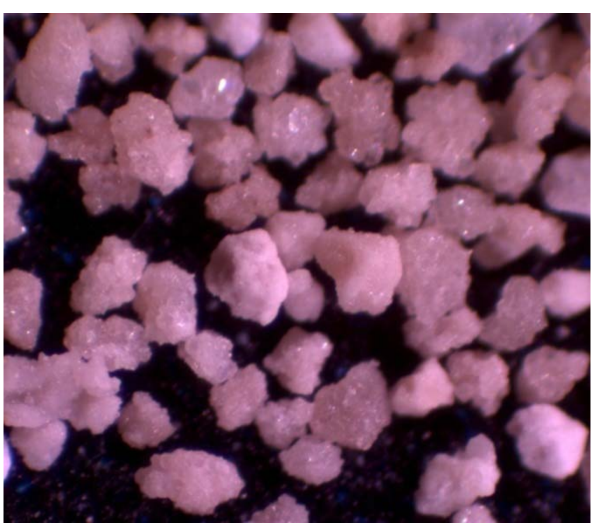


Figure 24. Mine C, #100 sieve

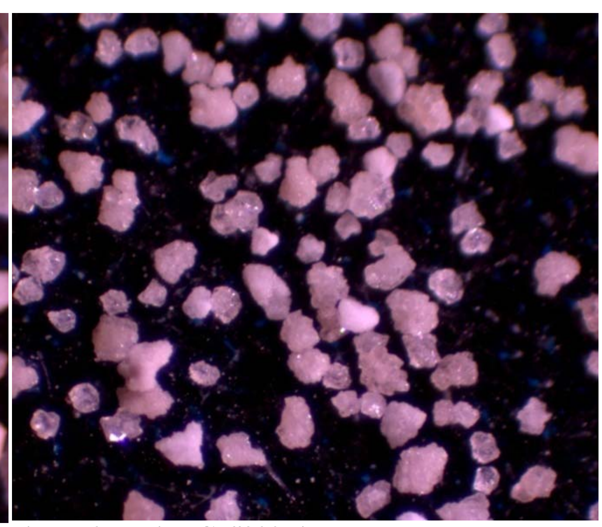


Figure 25. Mine C, #200 sieve

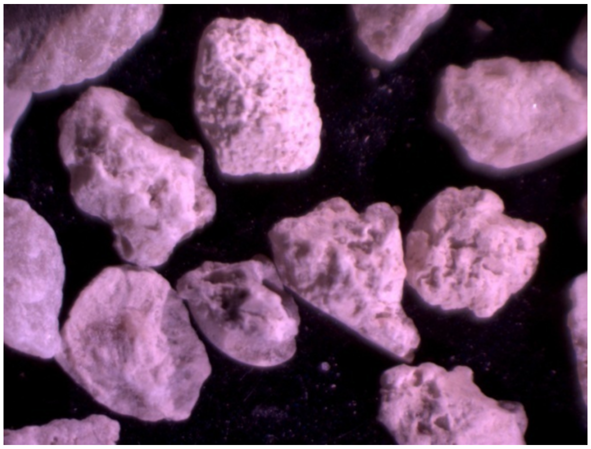


Figure 26. Mine F, #8 Sieve.

Figure 27. Mine F, #16 Sieve.

Figure 28. Mine F, #30 Sieve.

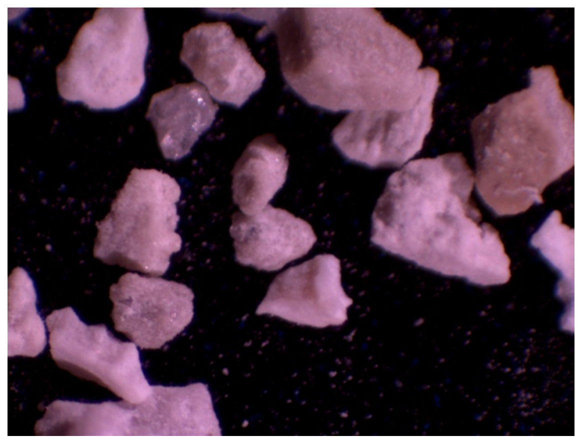


Figure 29. Mine F, #50 Sieve.

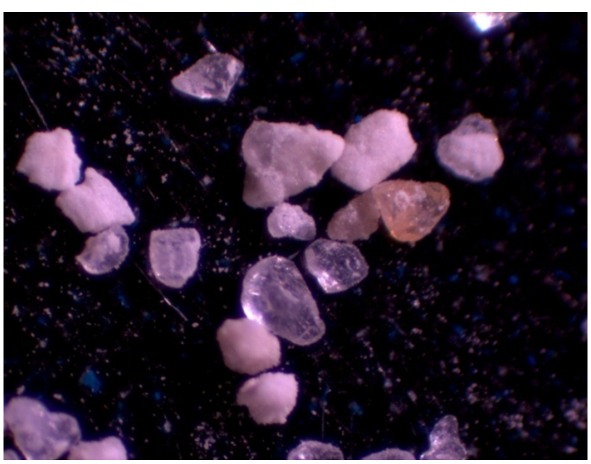


Figure 30. Mine F, #100 Sieve.

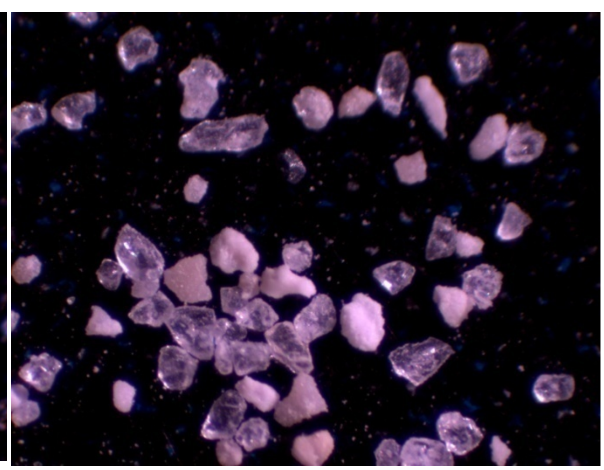


Figure 31. Mine F, #200 Sieve.

Figure 32. Mine M, #8 Sieve.

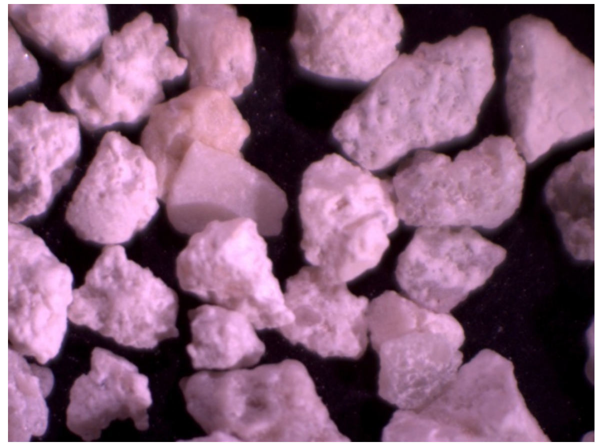


Figure 33. Mine M, #16 Sieve.

Figure 34. Mine M, #30 Sieve.

Figure 35. Mine M, #50 Sieve.

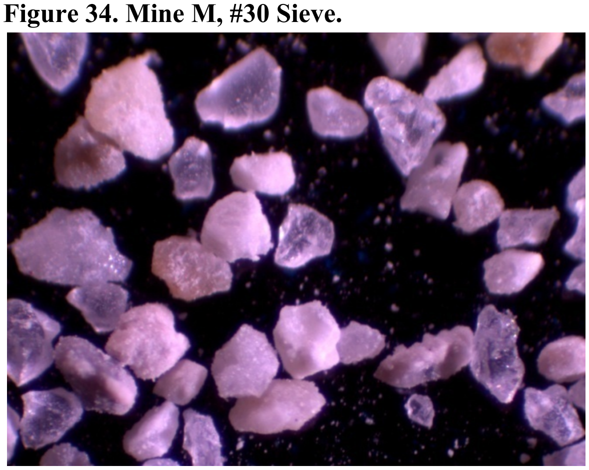


Figure 36. Mine M, #100 Sieve.

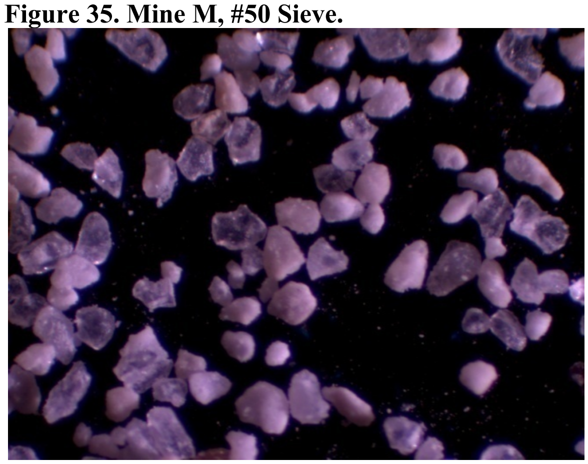


Figure 37. Mine M, #200 Sieve.

3.3.5.3 Physical Properties of Screenings used

To characterize the four screenings used in this project , they were subjected to a number of physical tests. Figure 38 and Figure 39 show the participle size distribution of the four screenings and the natural sand on a semi log and FHWA 0.45 power chart respectively. Screenings from Mine B were generally much coarser, and had significant amount of material larger than No.4 sieve and were removed prior to testing and usage.

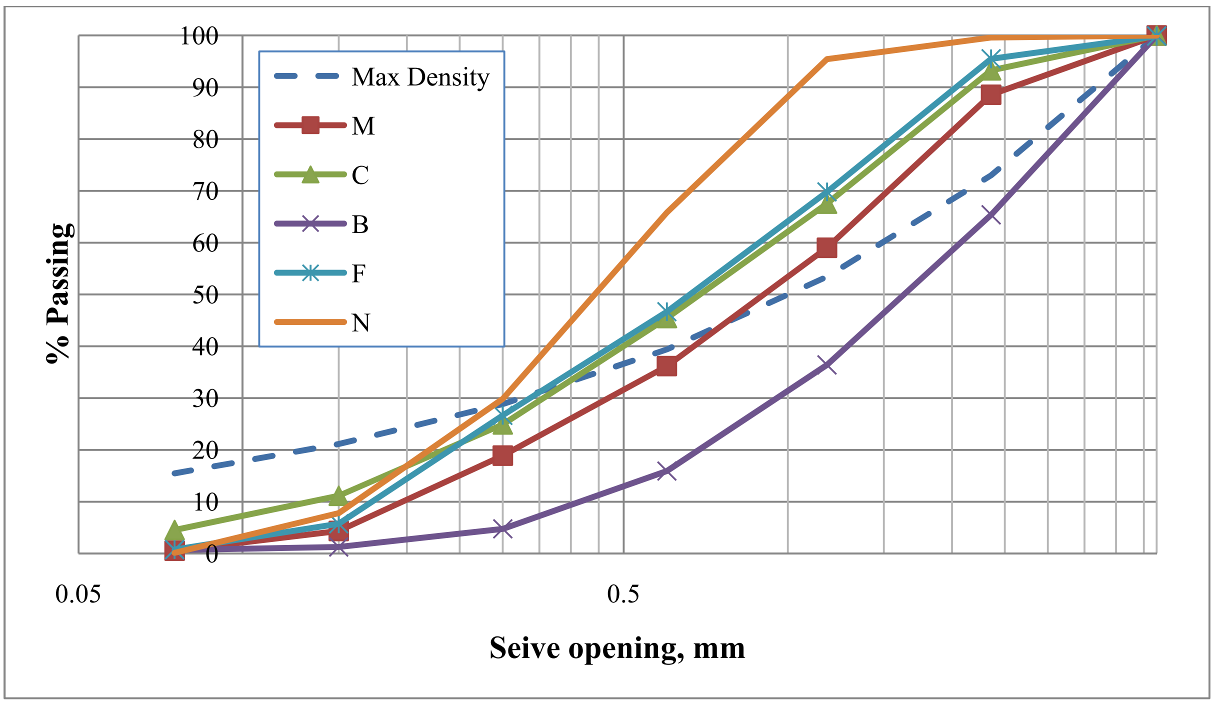


Figure 38. Particle size distribution of the fine aggregates.

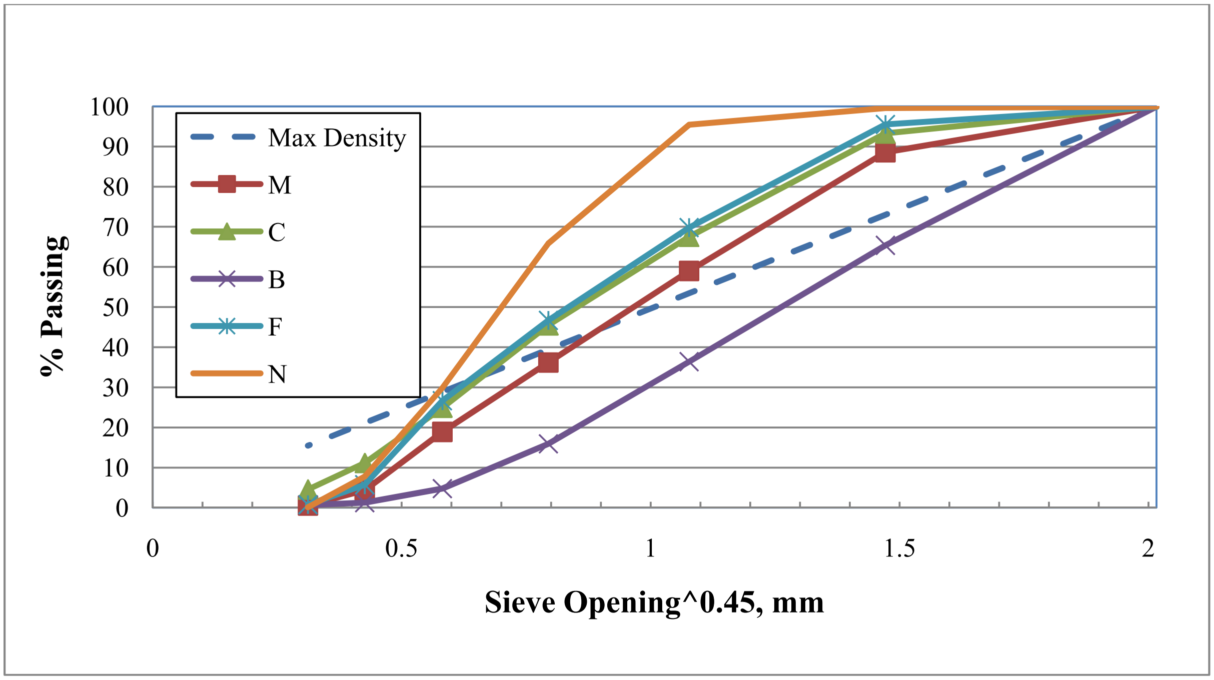


Figure 39. Particle size distribution of fine aggregates on a FHWA 0.45 power chart.

Table 11 below list the fineness modulus and percent passing #200 sieve of the fine aggregates observed. Table 12 summarizes the absorption, specific gravities, and dry-rodded unit weight of the fine and coarse aggregates.

Table 11. FM and Percent Minus #200 of screenings used

Mine	FM	Total Minus #200 Washed
B	3.76	2.79%
M	2.93	2.09%
F	2.56	3.24%
C	2.58	7.89%

Table 12. Physical properties of fine and coarse aggregates used

Property	Mine				Natural Sand N	Gravel
	B	M	F	C		
Absorption(%)	6.00	3.10	4.50	2.20	0.35	3.12
ASG	2.56	2.60	2.61	2.67	2.65	2.51
BSG, dry	2.26	2.41	2.34	2.44	2.63	2.33
BSG, SSD	2.38	2.48	2.44	2.53	2.64	2.40
Dry Rodded Unit Wt (pcf)	89.35	99.93	96.09	99.02	106.7	90.82

The screenings were further subjected to a battery of tests to evaluate and characterize them. LA Abrasion, Micro Deval, Sand Equivalent and Aggregate Durability Index tests were conducted by FDOT personnel at the State materials Office facilities in Gainesville, Florida. Table 13 summarizes the result of these tests.

Table 13. Other Material Properties of Screenings used

Test	Test Standard	Mine			
		B	M	F	C
Los Angeles Abrasion	FM 1-T 096 (Modified LA)	19	10	14	17
Micro Deval	ASTM D7428	29	14	20	24
Sand Equivalent	AASHTO T 176	96	98	89	99
Aggregate Durability Index	AASHTO T 210	79	81	80	94

The higher angularity of the screenings, as compared to natural sand, is the most important distinguishing characteristic, and was studied carefully. As mentioned before, the angularity is quantified as uncompacted void content according to ASTM C1252.

The uncompacted void content (angularity) was measured using all three methods, A, B, and C; results are summarized in Table 14 and Table 15.

Table 14. Uncompacted Void Content Using Method A and C (ASTM C1252)

Mine	Uncompacted Void Content (%)		
	Method A Unwashed	**Method A Washed**	**Method C Unwashed**
B	43.7	43.1	43.5
M	44.2	47.5	43.8
F	44.9	47.3	45.3
C*	48.7	49.2	48.2

*Minus #4 sieve material

Table 15. Uncompacted Void Content Using Method B (ASTM C1252)

Method B	Mine			
	B	**M**	**F**	**C**
No. 16	46.95	50.18	51.39	50.86
No. 30	48.84	50.06	51.75	52.88
No. 50	48.54	48.14	49.11	52.67
Average Uncompacted Voids	48.11	49.50	50.75	52.10

Method A was repeated with washed sample where minus No. 200 material was removed and it showed a significant increase in the angularity of Screenings M and F.

3.3.6 Admixtures

For this project, the only admixture used was ADVA 140M, a high-range water-reducing admixture (HRWR) produced by W. R. Grace & Co. ADVA 140M is an ASTM C494 Type A and F, and an ASTM C1017 Type I admixture. ADVA 140M is a high-range water-reducing admixture based on polycarboxylate technology. One gallon weighs approximately 8.8 lbs, and does not contain intentionally added chloride. It is a low viscosity liquid that has been formulated by the manufacturer for use as received.

Addition rates of ADVA 140M can vary with type of materials and application. The addition rate can range between 2 and 20 oz per 100lb of cement.

Typical addition rates suggested by manufacturer are [52]:

- High-range water reducer—9 to 16 oz/cwt (590 to 1040 mL/100 kg)
- Mid-range water reducer—5 to 9 oz/cwt (325 to 590 mL/100 kg)

No admixtures were used for the mortar study and HRWR was only used during the concrete investigation phase.

3.4 FABRICATION, CURING AND TESTING OF MORTAR AND CONCRETE SPECIMENS

Upon completion of the flow test on fresh mortar mixes, 2 inch cubes and 1x1x10 inch prism specimens were molded for compressive strength and autoclave expansion test respectively. Fresh concrete mixtures were tested for slump, air content, unit weight and 4x8 inch cylinders and 3x3x10 inch prisms were molded for hardened concrete properties and shrinkage study respectively. All standardized procedures as noted in previous sections were followed.

3.5 DESIGN OF EXPERIMENT FOR CEMENT MORTAR

To determine the impact of screenings on mortar properties, a detailed experimental program was set up with a focus on the following three aspects.

- Effect of Pure Screenings on Mortar properties
- Effect of Blending with natural sand on mortar properties
- Effect of Fly Ash with 100% screenings on mortar properties

Mortar with Pure Screenings

For this set of testing, w/c ratio and sand/cement (s_c) ratio were varied for all four screenings sources. The water cement ratio was varied from 0.38 to 0.60 in the increment of 0.04, while s_c was studied at 1.75, 2.25 and 2.75 levels. The main purpose of this set of mixes was to determine the range of flow for each level of s_c. The flow was the independent variable and recorded for each combination of w/c and s_c.

Mortar with blended aggregates

To study the effect of blending screenings with natural sand, mortar mixes were prepared at 0%, 25%, 50%, 75%, and 100% natural sand levels for all three s_c ratios, namely, 2.75, 2.25, and 1.75. For this part of investigation the w/c ratio was varied to achieve a flow of 100 ±5% where possible. No admixtures were used.

Mortar with Fly Ash

To study the effect of Fly Ash on mortar properties, additional mortar mixes were prepared with 20%, 30%, and 40% substitution levels for 2.75 s_c ratio only. Here again the w/c ratio levels were fixed and flow measured for each mix.

Table 16 lists the variables and their levels chosen to design a full factorial experimental program for the mortar phase of the study.

Table 16. Variables and their Levels Investigated for Mortar Properties

Variable Studied	Abbreviation used in plots	# of Levels	Levels
w/c	w_c	Varies	0.36 and 0.60
Fly ash (%)	FA	4	0, 20, 30 and 40
Sand to cement ratio	s_c	3	1.75, 2,25 & 2.75
Percent Screening (%)	MS	4	25, 50, 75 and 100

3.6 DESIGN OF EXPERIMENT FOR PORTLAND CEMENT CONCRETE

For the second part of experimental investigation, various influences of screenings on concrete properties were sought. These experiments were designed to reveal following effects of screenings on concrete properties:

1. Effect of blending screenings with natural sand
2. Effect of fly ash on concrete properties
3. Effect of w/c and cement content on concrete properties
4. Effect of sand to total aggregate (s_a) ratio on concrete properties.

Table 17 lists the variables and their levels chosen to design a full factorial experimental program for the concrete phase of the study.

Table 17. Variables and their Levels Investigated for Concrete Properties

Variable Studied	Abbreviation used in plots	# of Levels	Levels
w/c	w_c	2	0.37 and 0.41
Fly ash (%)	FA	3	0, 20 and 40
Cement Content (lbs/yd^3)	C	2	658 and 752
Sand to total aggregate ratio	s_a	Varies	0.28 to 0.5
Percent Screening (%)	MS	4	25, 50, 75 and 100

The control mix was chosen to represent Class IV concrete as per FDOT Spec 301. The max w/c ratio for Class IV concrete is 0.41 and minimum cement content is 658 lb/yd^3. Table 18 through Table 23 show the experimental design and concrete mix ID for screenings M, C, F and B respectively. The composition of each mix can be found in Appendix. In addition to matching w/c (0.41) and cement content (658 lb/yd^3) to Class IV concrete, mixes were also prepared at a lower w/c of 0.37 and a higher cement content of 752lb/yd^3 to study the influence of screenings on mixes.

Table 18. Mix Design Factorial and ID for Screening M

M		w/c=0.41				w/c=0.37			
		C=658		C=752		C=658		C=752	
		0% FA	20% FA	0% FA	20% FA	0% FA	20% FA	0% FA	20% FA
Blending	0	1	23	8	10	30	31	32	43
	25	26	27	28	29	39	42	36	47
	50	6	7	12	13	38	41	35	46
	75	14	15	24	25	37	40	34	45
	100	2	3	9	11	48	49	33	44

Table 19. Mix Design Factorial and ID for Screening C

C		w/c=0.41				w/c=0.37			
		C=658		C=752		C=658		C=752	
		0% FA	20% FA	0% FA	20% FA	0% FA	20% FA	0% FA	20% FA
Blending	0	1	23	8	10	30	31	32	43
	25	209	218	212	221	215	224	228	232
	50	208	217	211	220	214	223	227	231
	75	207	216	210	219	213	222	226	230
	100	201	202	203	204	205	206	225	229

Table 20. Mix Factorial and ID for Screening F

F		w/c=0.41				w/c=0.37			
		C=658		C=752		C=658		C=752	
		0% FA	20% FA	0% FA	20% FA	0% FA	20% FA	0% FA	20% FA
Blending	0	1	23	8	10	30	31	32	33
	25	304	330	310	333	316	336	353	359
	50	303	329	309	332	315	335	352	358
	75	302	328	308	331	314	334	351	357
	100	301	325	307	326	313	327	350	356

Table 21. Mix Factorial and ID for Screening B

B		w/c=0.41				w/c=0.37			
		C=658		C=752		C=658		C=752	
		0% FA	20% FA	0% FA	20% FA	0% FA	20% FA	0% FA	20% FA
Blending	0	1	23	8	10	30	31	32	33
	25	404	424	409	428	414	432	419	436
	50	403	423	408	427	413	431	418	435
	75	402	422	407	426	412	430	417	434
	100	401	421	406	425	411	429	416	433

To further study the effect of fly ash on concrete, additional mixes as shown in Table 22, were prepared and tested. This resulted in concrete mixes with three levels of fly ash substitution. All fly ash were substituted on weight basis.

Table 22. Design Factorial and Mix ID for Fly Ash Study

MINE	w/c	Cement Content (lb/yd^3)	Fly Ash		
			0%	20%	40%
M	0.41	658	2	3	59
		752	9	11	60
	0.37	658	48	49	61
		752	33	44	62
C	0.41	658	201	202	257
		752	203	204	250
	0.37	658	205	206	251
		752	225	229	252
F	0.41	658	301	325	360
		752	307	326	361
	0.37	658	313	327	362
		752	350	356	363
B	0.41	658	401	421	441
		752	406	425	442
	0.37	658	411	429	443
		752	416	433	444

The effect of angularity on fresh concrete is undeniable and the extent of its influence is dependent on relative proportion of fine aggregate to coarse aggregate. In order to understand this influence, mixes were prepared at varying amount of sand to total aggregate ratios (s_a). Table 23 shows the experimental design factorial and the actual s_a ratio investigated for each screening. Mix proportions were determined using ACI absolute volume method for each combination of w/c and cement content. The s_a ratio resulting from this design was labeled as control s_a and is listed in Table 23. With this information, three s_a levels were chosen of each combination of w/c and cement content, with a maximum s_a of 0.5. In general the range of s_a tested was from 0.3 to 0.5. The compositions of these mixes can be found in the Appendix.

Table 23. Mix Design Factorial and Mix ID for s_a Study

	w/c & Cement		**s_a**		
	0.41/658	**Control s_a**	**0.31**	**0.40**	**0.50**
MINE	M	0.40	54	2	4
	C	0.34	201	234	233
	F	0.31	301	306	305
	B	0.41	437	401	405
	0.41/752	**Control s_a**	**0.28**	**0.40**	**0.50**
MINE	M	0.36	55	58	16
	C	0.30	254	236	235
	F	0.28	307	312	311
	B	0.37	438	445	410
	0.37/658	**Control s_a**	**0.33**	**0.40**	**0.50**
MINE	M	0.40	56	48	50
	C	0.36	255	238	237
	F	0.33	313	318	317
	B	0.40	439	411	415
	0.37/752	**Control s_a**	**0.30**	**0.40**	**0.50**
MINE	M	0.41	57	33	42
	C	0.32	256	240	239
	F	0.30	319	324	323
	B	0.40	440	416	420

CHAPTER 4: RESULTS OF CEMENT MORTAR STUDY

4.1 INTRODUCTION

This chapter presents the results and findings of experimental work pertaining to the mortar study. There are three important attributes of mortar that were studied, namely, flow, compressive strength, and autoclave expansion. For the purpose of the investigation, a commercial statistical software (STATGRAPHICS) was used to conduct analysis of variance (ANOVA) and regression analysis to develop prediction models.

4.2 MORTAR FLOW

Flow characteristics were studied in two stages. In the first stage, mortar mixes were prepared to study the flow alone. A wide range of w/c ratio from 0.36 to 0.60 in the increment of 0.04 for each fine aggregate was studied. This was done to establish the workable range of w/c ratio for each fine aggregate. In the second stage, with a narrower w/c range determined, fresh mixes for flow and samples for compressive strength and autoclave expansion were prepared. The following sections describe the results of this study on flow characteristics.

4.2.1 ANOVA for Mortar Flow

This procedure performs a multifactor analysis of variance for mortar flow and constructs various tests and graphs to determine which factors have a statistically significant effect on flow. It also tests for significant interactions amongst the factors, given sufficient data. The F-tests in the ANOVA table allow identification of the significant factors. For each significant factor, the Multiple Range Tests also indicates what means are significantly different from what others. The Means Plot and Interaction Plot help interpret the significant effects.

The screenings attributes used for the analysis were

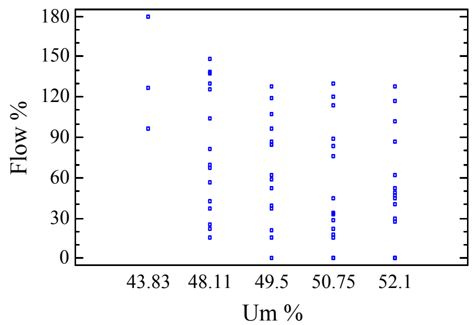
- Measure of Angularity (U_m)
- Fineness Modulus, (FM)
- LA Abrasion, (LA)
- Micro Deval, (MD)
- D_{50}, (D50)
- Durability Index, (DI)
- Sand equivalent (SE)

Using forward selection analysis, it was determined that the measure of angularity (U_m) and fineness modulus (FM) were enough to statistically represent the screenings used. In the following sections, the findings of one-way and multifactor ANOVA of flow are presented.

4.2.1.1 One-Way ANOVA of Mortar Flow

This procedure performs a one-way analysis of variance for flow. It constructs various tests and graphs to compare the mean values of flow for the 5 levels of angularity, 3 levels of s_c, 6 levels of w/c ratio and 4 levels of fly ash. In one–way analysis of variance, we assume that only the factor being studied affect the variability. This helps with the basic understanding of the influence of that one factor on the property studied, but does not reveal the interactions with other variables.

Figure 40 through Figure 47 show the scatter plot and means and 95 percent LSD intervals of flow versus U_m, s_c, w/c and FA respectively. It is clearly seen from Figure 41 that the flow decreases as the angularity of the fine aggregate increases. At 95 percent LSD, all screenings form a homogeneous group and there are no statistically significant differences among them. Figure 43 suggests that s_c ratio of 2.75 is statistically different from the other two s_c levels at 95 percent LSD. Figure 47 suggest that at 95 percent LSD, increasing the amount of fly ash increases the mortar flow.



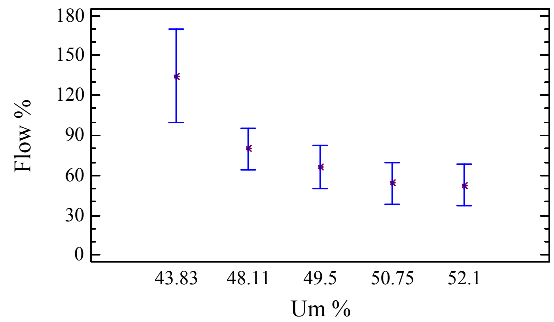
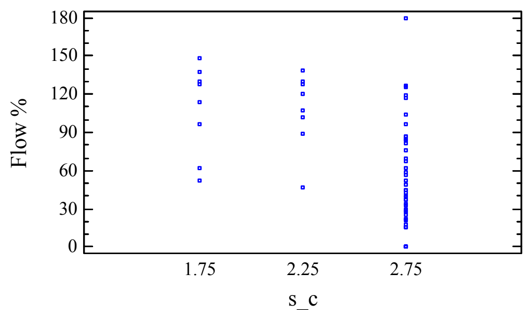


Figure 40. Scatter plot of Flow by Angularity Levels.

Figure 41. Means and 95 Percent LSD Intervals for Flow by Angularity Levels.



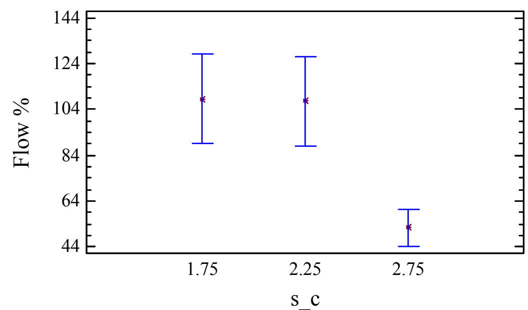
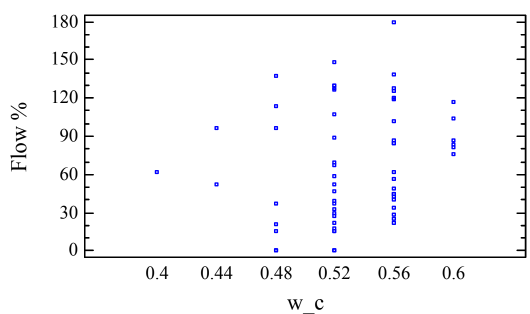


Figure 42. Scatter plot of Flow by s_c Levels.

Figure 43. Means and 95 Percent LSD Intervals for Flow by s_c Levels.



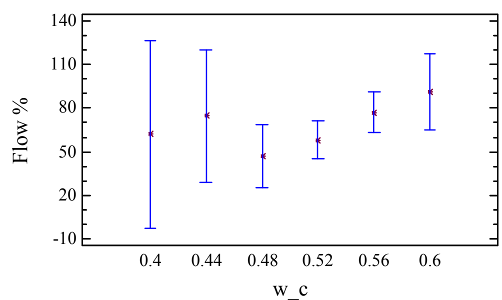
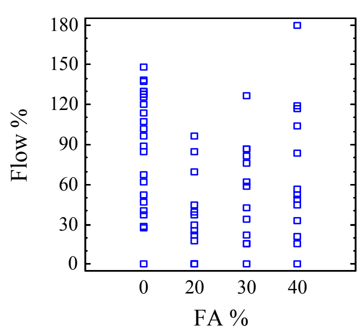


Figure 44. Scatter plot of Flow by w/c Levels.

Figure 45. Means and 95 Percent LSD Intervals for Flow by w/c Levels.



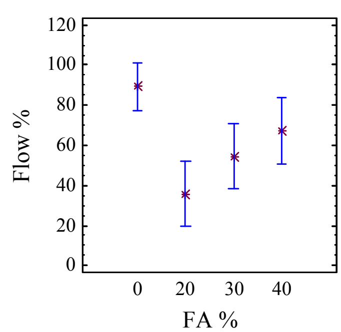


Figure 46. Scatter plot of Flow by Flyash Levels.

Figure 47. Means and 95 Percent LSD Intervals for Flow by Flyash Levels.

4.2.1.2 Multifactor ANOVA of Mortar Flow

This procedure performs a multifactor analysis of variance for flow. It constructs various tests and graphs to determine which factors have a statistically significant effect on flow. It also tests for significant interactions amongst the factors, given sufficient data. The F-tests in the ANOVA table will assist in identification of the significant factors. For each significant factor, the Multiple Range Tests indicate what means are significantly different from what others. The Means Plot and Interaction Plot assist in interpretation of the significant effects. Figure 48 shows the scatter plot of flow versus angularity (U_m) of fine aggregates. Figure 49 shows the means and 95 percent LSD for flow versus angularity. ANOVA in Table 24 suggests angularity, fly ash, s_c and w/c ratio are all statistically significant factors. Figure 49 clearly shows that there is a significant difference between natural sand and screenings used.

Table 25 applies a multiple comparison procedure to determine which means are significantly different from which others. Three homogenous groups are identified using columns of X's. Within each column, the levels containing X's form a group of means within which there are no statistically significant differences. The method used to discriminate among the means is Duncan's multiple comparison procedure. With this method, there is a 5.0 percent risk of calling one or more pairs significantly different when their actual difference equals 0. At 95 percent LSD, those screenings with angularity below 49.5 percent and angularity above 50.75 percent were grouped as homogeneous.

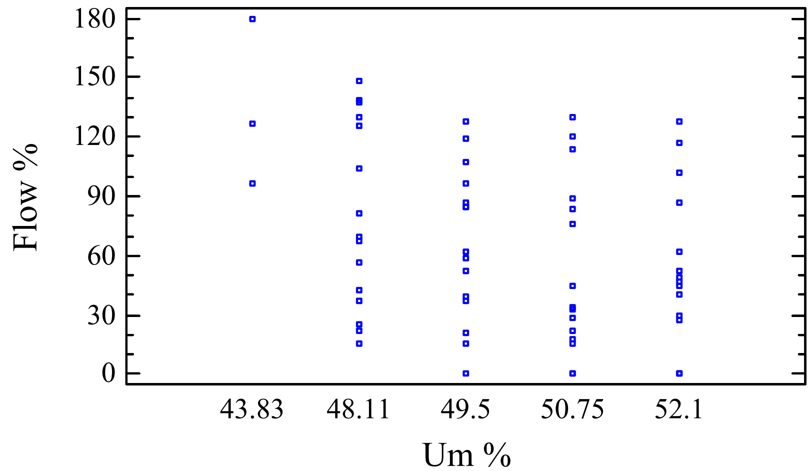


Figure 48. Scatter Plot of Flow vs. Angularity B.

Table 24. ANOVA for Flow

Source	Sum of Squares	Df	Mean Square	F-Ratio	P-Value
MAIN EFFECTS					
A:Um %	40320.2	4	10080.0	26.16	0.0000
B:FA %	1138.26	3	379.421	0.98	0.4079
C:s_c	33480.2	2	16740.1	43.44	0.0000
D:w_c	37459.7	5	7491.95	19.44	0.0000
RESIDUAL	18496.2	48	385.338		
TOTAL (CORRECTED)	128786.0	62			

All F-ratios are based on the residual mean square error.

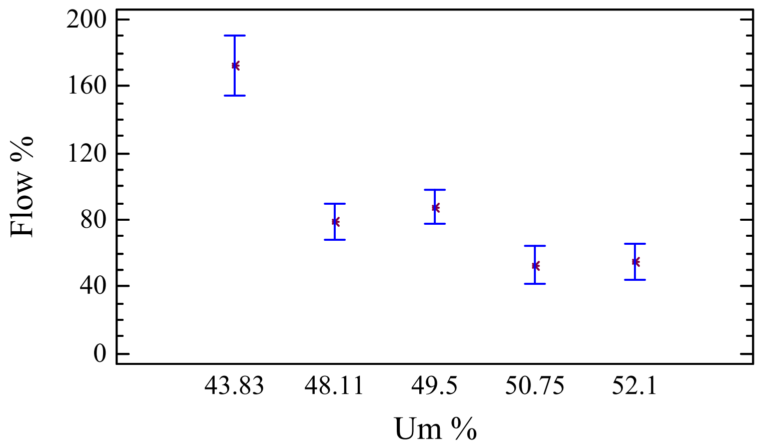


Figure 49. Means and 95% LSD interval for Flow vs. Angularity.

Table 25. Multiple Range Tests for Flow by U_m

Method: 95.0 percent Duncan

Um %	Count	LS Mean	LS Sigma	Homogeneous Groups
50.75	15	53.0031	7.88459	X
52.1	15	54.8924	7.58775	X
48.11	15	79.0698	7.88459	X
49.5	15	87.8442	7.08375	X
43.83	3	172.571	12.7944	X

4.2.2 Multiple Regression Analysis of Flow

A multiple regression model for the flow of mortar was developed based on both set of flow data. In the previous section it was demonstrated that the angularity of fine aggregate, fly ash content, s_c ratio and w/c ratio were significant parameters.

The following model for predicting flow of mortar was determined:

$$f = 1.064\,U_m - 1.045\,FA + 11.90\,FM - 42.43\,s\_c + 213.97\,w/c$$

where,

f	= Mortar Flow (%)
U_m	= Uncompacted voids, Method B (%)
FA	= Fly Ash content (%)
FM	= Fineness modulus
s_c	= Sand to cement ratio
w/c	= Water to cement ratio

R^2 of the flow model was found to be 93% and Figure 50 below shows the plot of observed versus predicted flow according to the above model.

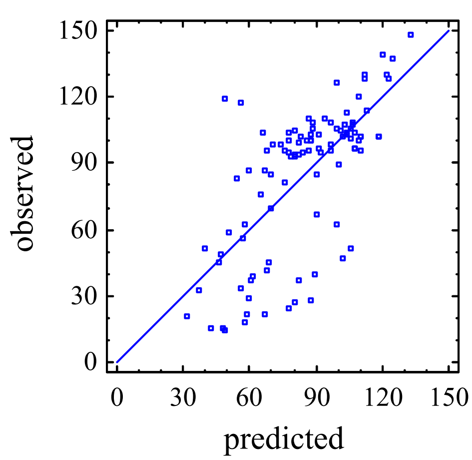


Figure 50. Plot of Observed vs. Predicted Flow in %.

4.3 COMPRESSIVE STRENGTH OF MORTAR

The compressive strength of mortar cubes were measured after 28-days of moist curing. The data were analyzed and a regression model was developed to predict 28-days compressive strength of mortar cubes.

4.3.1 ANOVA for Compressive Strength

As seen in Table 26, angularity (U_m), s_c and fly ash were found to be significant factors affecting compressive strength of mortar cubes. Figure 51 shows the scatter plot of 28-days compressive strength of mortar cubes for the four screenings and natural sand. Figure 52 through Figure 54 shows the means and 95 percent LSD intervals for the angularity, fly ash, and s_c ratio respectively. Within screenings, Mine B (U_m=48.11%) was found to be statistically different than other mines when compressive strength is concerned. As expected, fly ash was found to be a significant factor affecting 28-days compressive strength. Fly ash substitution of 20% and 30% were found to be statistically homogeneous. It is observed that the sand to aggregate ratio is significant at all levels, and that compressive strength is reduced with increased sand to cement ratio.

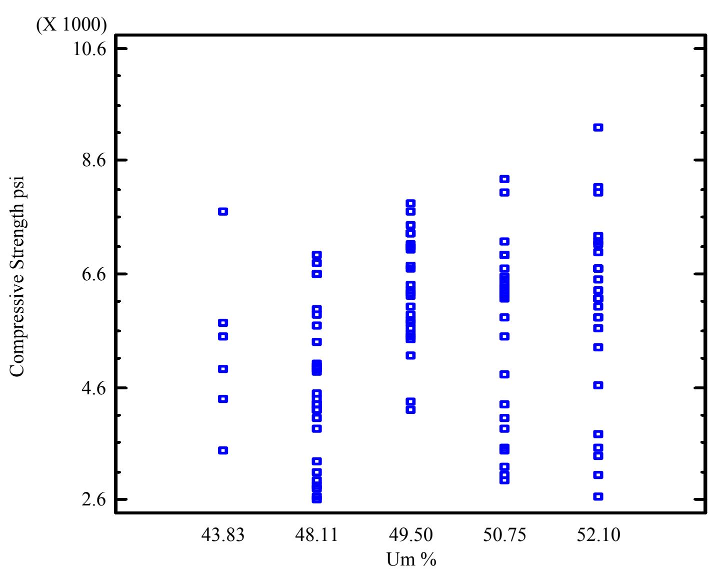


Figure 51. Scatter Plot of Compressive Strength of Mortar Cubes vs. Angularity.

Table 26. ANOVA for Compressive Strength of Mortar Cubes

Source	Sum of Squares	Df	Mean Square	F-Ratio	P-Value
MAIN EFFECTS					
A:Um	3.9106E7	4	9.77649E6	14.24	0.0000
B:s_c	1.58572E7	2	7.92858E6	11.55	0.0000
C:FA	4.55078E7	3	1.51693E7	22.09	0.0000
RESIDUAL	6.72871E7	98	686603.0		
TOTAL (CORRECTED)	2.50377E8	107			

All F-ratios are based on the residual mean square error.

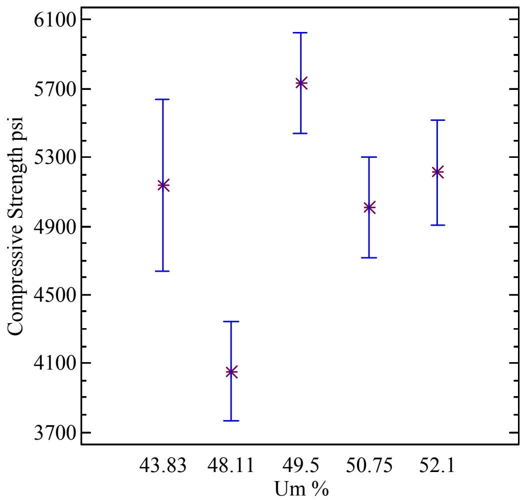


Figure 52. Means and 95% LSD interval for Compressive Strength by U_m Levels.

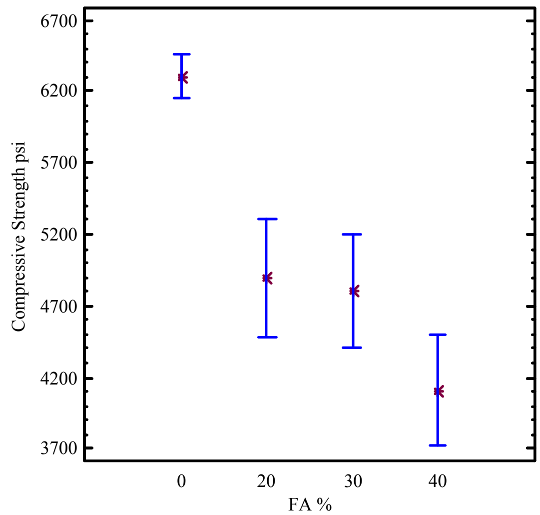


Figure 53. Means and 95% LSD interval for Compressive Strength by Fly Ash Levels.

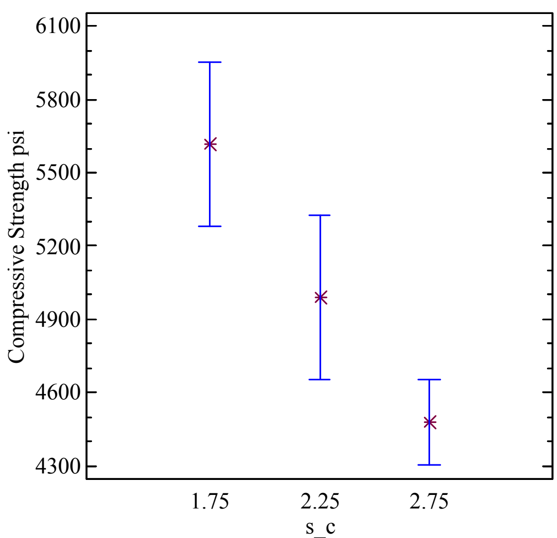


Figure 54. Means and 95% LSD Interval for Compressive Strength by s_c levels.

4.3.2 Multiple Range Tests for Compressive Strength by Mine

A multiple comparison procedure is applied to determine what means are significantly different from what others. Homogenous groups are identified using columns of X's. Within each column, the levels containing X's form a group of means within which there are no statistically significant differences. There are many methods currently being used to discriminate among the means such as the Duncan, LSD, Tukey and Bonferroni procedures. With these methods, there is a 5.0% risk of calling each pair of means significantly different when the actual difference equals 0.

A multiple range test for compressive strength by mine using the Duncan Method at 95% confidence interval shows that Mine B is significantly different than all others mines. It was also found that while Mine F and mine C are similar and that mine M is similar to mine C only.

Table 27. Multiple Range test for Compressive Strength by Mine

Method: 95.0 percent Duncan

Mine*	Count	LS Mean	LS Sigma	Homogeneous Groups
B	27	4054.44	203.474	X
F	25	5008.65	206.951	X
N	6	5139.72	356.375	XX
C	24	5210.87	216.582	XX
M	26	5729.78	207.852	X

Method: 95.0 percent Duncan

Mine*	Count	LS Mean	LS Sigma	Homogeneous Groups
N	6	5139.72	356.375	XX
B	27	4054.44	203.474	X
M	26	5729.78	207.852	X
F	25	5008.65	206.951	X
C	24	5210.87	216.582	XX

* Mines arranged in ascending order of angularity

4.3.3 Multiple Regression Model for Compressive Strength

Using backward selection analysis, significant variables, namely, angularity, fineness modulus, w/c, s_c, and fly ash were identified. Using these factors a multiple regression model for 28 days compressive strength of mortar cube with R^2 of 69% was developed as follows:

$$f'_{cm} = 8462 + 95.09U_m - 651FM - 7944w/c - 540s\_c - 47FA$$

where,

f'_{cm}	= Compressive strength of Mortar Cube
U_m	= Uncompacted Void Method B (%)
FM	= Fineness Modulus of Sand
w/c	= Water cementitious ratio
s_c	= Sand to cement ratio
FA	= Fly ash content (%)

Low R^2 in predicting flow is consistent with other studies found in literature and indicative of sensitivity of flow to small changes in water content of the mixture. Figure 55 shows the plot of observed versus predicted values of 28 days compressive strength of mortar cubes.

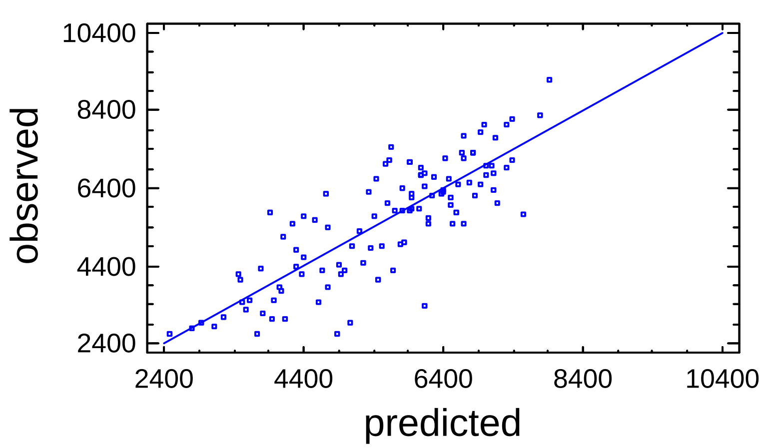


Figure 55. Plot of Observed vs. Predicted Compressive Strength of Mortar Cubes (psi).

4.4 AUTOCLAVE EXPANSION OF CEMENT MORTAR

The 1×1×10 inch mortar bars specimens were subjected to autoclave curing in accordance to ASTM C151 to study the expansion potential. Upon demolding at the end of 24±0.5 h, an initial reading was taken using a digital micrometer comparator. After subjecting the specimens to autoclave curing, they were brought to room temperature and length measured again. Using this information, the strain due to autoclave expansion was calculated as

$$\varepsilon_{ae} = \frac{(L_f - L_0)}{L_0} 100\%$$

Where,

ε_{ae} = Strain due to autoclave expansion

L_0 = Initial length of test prism

L_f = Length of test prism after autoclave curing

4.4.1 ANOVA Analysis for Autoclave Expansion

Figure 56 shows the scatter plot of expansion for different levels of fly ash. ANOVA for autoclave expansion was performed at various levels of sand angularity and fly ash as seen in Table 30. Again, both variables were found significant.

From the means and 95% LSD chart (Figure 57) and multiple range test (Table 29), it can be seen that fly ash tends to reduce the expansion slightly as compared to natural sand, but not statistically significant for within the fly ash subset.

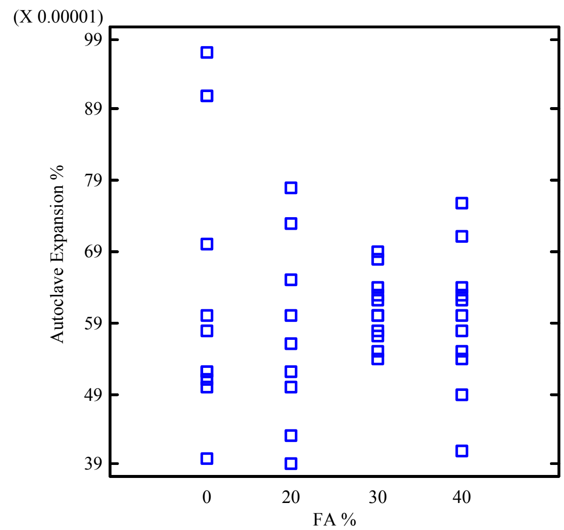


Figure 56. Autoclave Expansion of Mortar by FA Levels.

Table 28. ANOVA of Autoclave Expansion of Mortar Bar

Source	Sum of Squares	Df	Mean Square	F-Ratio	P-Value
MAIN EFFECTS					
A:FA	3.69049E-8	3	1.23016E-8	3.88	0.0204
B:Um	3.28745E-7	3	1.09582E-7	34.56	0.0000
INTERACTIONS					
AB	2.358E-7	9	2.62E-8	8.26	0.0000
RESIDUAL	8.24333E-8	26	3.17051E-9		
TOTAL (CORRECTED)	6.71012E-7	41			

All F-ratios are based on the residual mean square error.

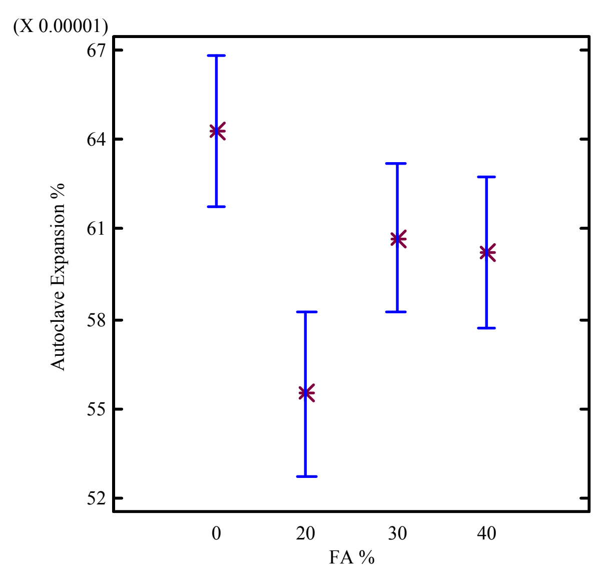


Figure 57. Means and 95% LSD interval for Autoclave Expansion vs. Fly Ash of Mortar.

Table 29. Multiple Range Tests for Autoclave Expansion by FA

Method: 95.0 percent Duncan

FA	Count	LS Mean	LS Sigma	Homogeneous Groups
20	9	0.000555	0.0000190601	X
40	11	0.000602083	0.0000172405	XX
30	11	0.000607083	0.0000172405	XX
0	11	0.0006425	0.0000172405	X

4.4.2 Autoclave Expansion of Mortar vs. Mine

When the autoclave expansion is compared between mines, the significance of source is clearly revealed (Figure 58 and Figure 59). The box and whisker plot (Figure 60) of expansion versus mine type indicates that the source of material is important and must be carefully studied where concrete expansion would be a concern. To determine the homogenous groups the LSD, Tukey and Bonferroni methods at 95% confidence interval were applied as seen in Table 32: all of them concluded that Mine M and F, F and C are similar while Mine B is statistically different than all other sources of fine aggregates.

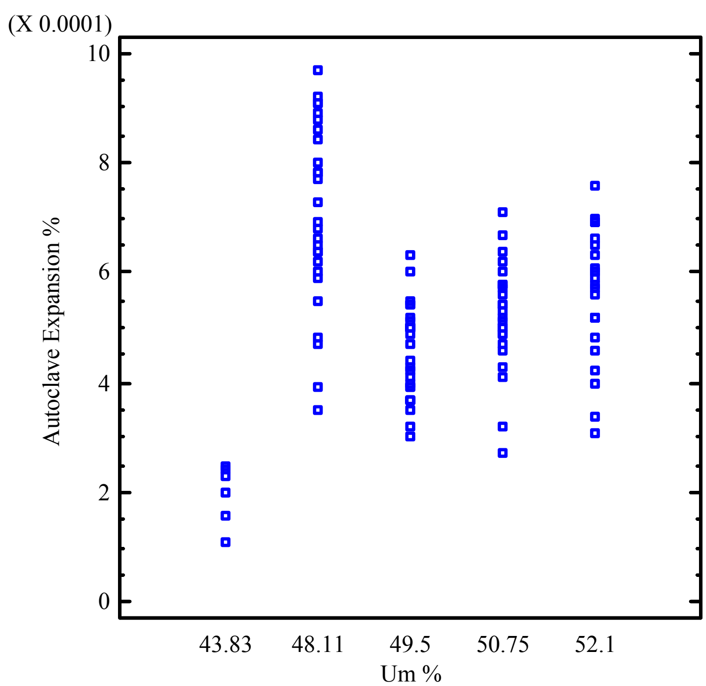


Figure 58. Scatter plot of Autoclave Expansion vs. Angularity (Mine).

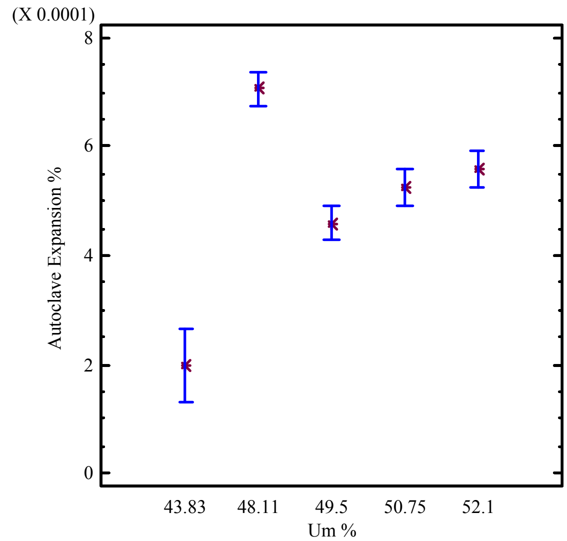


Figure 59. Means and 95% LSD interval for Autoclave Expansion vs. Angularity (Mine) of Mortar.

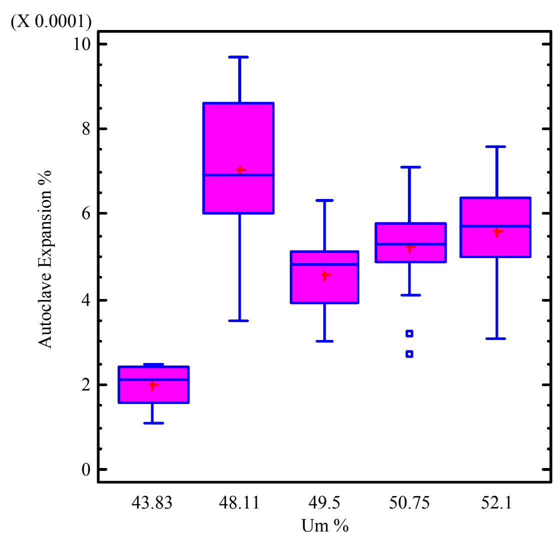


Figure 60. Box and Whisker Plot of Autoclave Expansion vs. Angularity (Mine) for Mortar.

Table 30. Multiple Range Tests for Autoclave Expansion by Um

Method: 95.0 percent LSD

Mine*	Count	Mean	Homogeneous Groups			
N	6	0.000198333	X			
B	27	0.000705556				X
M	26	0.000459231		X		
F	25	0.0005236		X	X	
C	24	0.0005575			X	

Method: 95.0 percent Tukey HSD

Mine	Count	Mean	Homogeneous Groups			
N	6	0.000198333	X			
B	27	0.000705556				X
M	26	0.000459231		X		
F	25	0.0005236		X	X	
C	24	0.0005575			X	

Method: 95.0 percent Bonferroni

Mine	Count	Mean	Homogeneous Groups			
N	6	0.000198333	X			
B	27	0.000705556				X
M	26	0.000459231		X		
F	25	0.0005236		X	X	
C	24	0.0005575			X	

* Mines arranged with ascending angularity

4.4.3 Effect of Blending on Autoclave Expansion of Cement Mortar

Figure 61 shows the effect of blending of natural sand in the mix on expansion. MS represents the percent of manufactured sand in the mix. From means and box and whisker plots (Figure 62 and 63) certain distinctions can be made. First it is clear that blending of natural sand with screenings reduces strains caused by autoclave curing. From the multiple range tests at 95 percent confidence (Table 31), it can be concluded that more than 50 percent natural sand is required in the mix to significantly reduce the expansion strains. A more detailed surface response analysis would reveal the exact percentage of blending where this change occurs. It is a potentially important finding as it suggests that a tiered approach to screenings usage could be adopted.

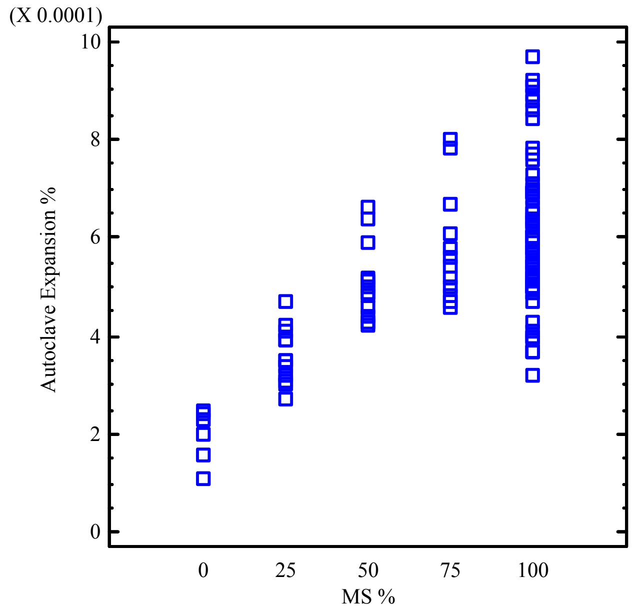


Figure 61. Scatter plot of Autoclave Expansion vs. Blending for Mortar.

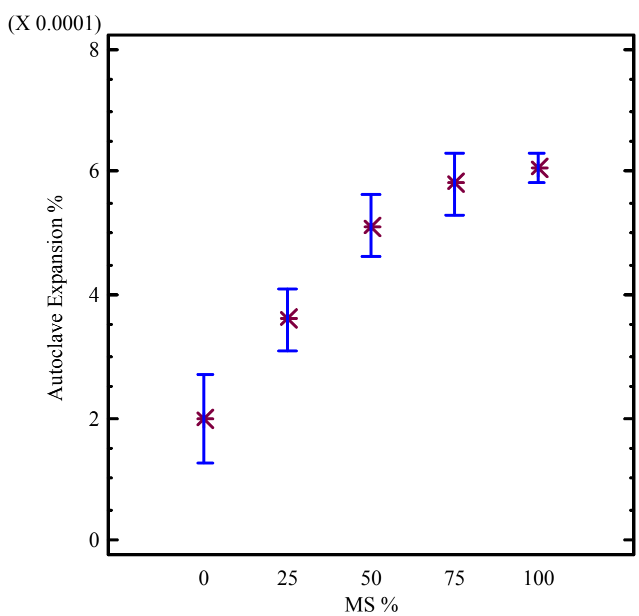


Figure 62. Autoclave Expansion vs. Blending for Mortar.

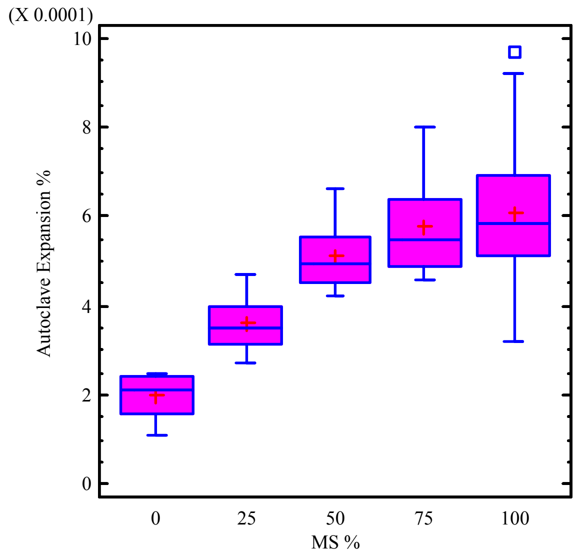


Figure 63. Box and Whisker Plot of Autoclave Expansion vs. Blend for Mortar

Table 31. Multiple Range Tests for Autoclave Expansion by MS%

Method: 95.0 percent Duncan

MS	Count	Mean	Homogeneous Groups
0	3	0.000156667	X
25	12	0.00036	X
50	12	0.000511667	X
75	12	0.000580833	X
100	35	0.000618286	X

4.4.4 Multiple Regression Model for Autoclave Expansion of Cement Mortar

A multiple regression analysis (Table 32) of autoclave expansion at various levels of s_c. w/c, U_m and FM was carried out to develop a model for predicting autoclave expansion strains in mortar bars as follows:

Table 32. Multiple Regression Analysis for Autoclave Expansion in Mortar Bar

Dependent variable: Autoclave Expansion %

Parameter	Estimate	Standard Error	T Statistic	P-Value
FM	0.000147589	0.0000206053	7.16265	0.0000
s_c	-0.00013098	0.0000384787	-3.40396	0.0009
Um %	-0.00000854727	0.0000021641	-3.94958	0.0001
w_c	0.00170531	0.000283714	6.01067	0.0000

Analysis of Variance

Source	Sum of Squares	Df	Mean Square	F-Ratio	P-Value
Model	0.0000334465	4	0.00000836163	583.40	0.0000
Residual	0.0000014906	104	1.43327E-8		
Total	0.0000349371	108			

R-squared = 95.7335 percent

$$\varepsilon_{ae} = -0.00013098\, s\_c + 0.00170531\, w/c - 0.00085477\, U_m + 0.00014759\, FM$$

where,

- ε_{ae} = Strain due to autoclave expansion
- s_c = Sand to cement ratio
- w/c = Water to cement ratio
- U_m = Uncompacted Void contents by Method B
- FM = Fineness Modulus of fine aggregate

A R^2 of 95.73% was achieved with the above model. Figure 64 shows the observed versus predicted strains due to autoclave expansion.

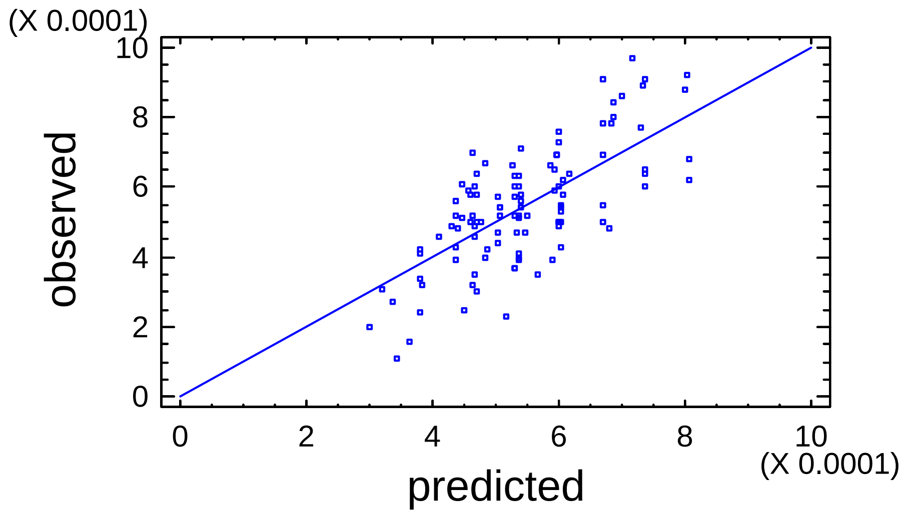


Figure 64. Plot of Observed vs. Predicted Autoclave Expansion for Mortar(%).

CHAPTER 5: RESULT OF CONCRETE STUDY

5.1 INTRODUCTION

This chapter presents the results and analysis of influence of screenings on concrete properties. The following section is further divided to study concrete properties and:

- Influence of angularity of fine aggregate
- Influence of blending of fine aggregate
- Influence of cement
- Influence of water cement ratio
- Influence of sand to total aggregate ratio
- Influence of fly ash
- Study of factors affecting durability
- Regression model for compressive strength
- Regression model for modulus of elasticity

5.2 INFLUENCE OF ANGULARITY OF FINE AGGREGATE

Concrete mixes were prepared at four levels (0, 25, 50, 75 and 100 %) of screenings, at two levels of cement (658 and 752 lb/yd^3) and two levels of w/c ratio (0.37 and 0.41) for each screenings. A control mix (0% screening) was established to represent Class IV FDOT concrete with a target slump of 6±1 inch and air content of 2.5%. Actual test results of the concrete mixes can be found in the Appendix. Figure 65 below shows the scatter plot of compressive strength for each screening source. From the chart of means (Figure 66) and 95% LSD intervals and multiple range tests in Table 34 it is clear that Mine M and C are statistically significantly different than mine B (which has the lowest angularity). There is also a significant difference between mines F and M.

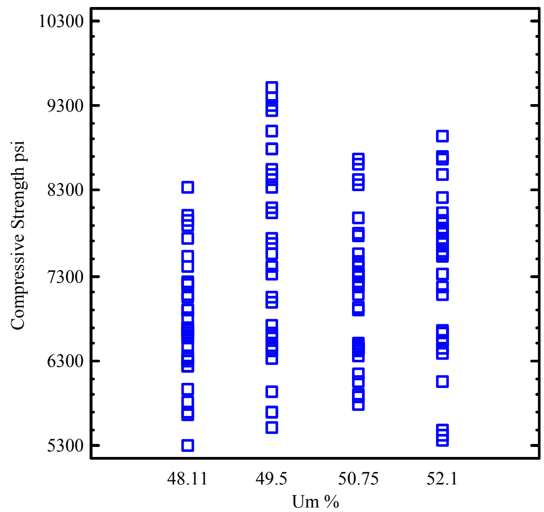


Figure 65. Scatter Plot of Compressive Strength vs. Screenings Source.

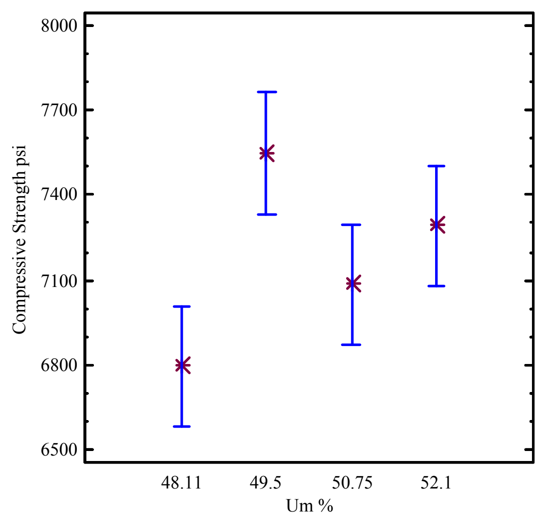


Figure 66. Means and 95% LSD Interval for Compressive Strength vs. Screenings Source.

Table 33. Analysis of Variance for Compressive strength

Source	Sum of Squares	Df	Mean Square	F-Ratio	P-Value
MAIN EFFECTS					
A:Um %	9.73386E6	3	3.24462E6	4.38	0.0062
B:MS %	1.62603E6	3	542011.0	0.73	0.5354
C:Cement Content p	119866.0	1	119866.0	0.16	0.6883
D:w_c	2.12153E7	1	2.12153E7	28.65	0.0000
INTERACTIONS					
AB	5.80592E6	9	645102.0	0.87	0.5536
AC	1.52622E6	3	508741.0	0.69	0.5621
AD	4.30035E6	3	1.43345E6	1.94	0.1288
BC	562280.0	3	187427.0	0.25	0.8589
BD	1.63703E6	3	545678.0	0.74	0.5325
CD	13264.1	1	13264.1	0.02	0.8938
RESIDUAL	7.18226E7	97	740439.0		
TOTAL (CORRECTED)	1.18363E8	127			

All F-ratios are based on the residual mean square error.

Table 34. Multiple Range Tests for Compressive Strength psi by Um %

Method: 95.0 percent Duncan

Um %	Count	LS Mean	LS Sigma	Homogeneous Groups
48.11 (B)	32	6796.34	152.114	X
50.75 (F)	32	7085.13	152.114	XX
52.1 (C)	32	7291.69	152.114	XX
49.5 (M)	32	7548.13	152.114	X

5.3 INFLUENCE OF BLENDING ON CONCRETE PROPERTIES

Figure 67 and Figure 68 shows the influence of blending of natural sand with screenings in concrete mixes. MS in the plots below indicates percent manufactures sand in the mix. The means and 95% LSD plot suggest that increasing amount of natural sand has positive influence on the compressive strength of concrete samples. Multiple range tests in Table 35 suggest that blending of natural sand and manufactured sand will significantly affect the compressive strength of concrete. Mixes with 25 to 50 percent natural sands were statistically homogenous and mixes with 100 percent manufactured sand are significantly different than blended mixes.

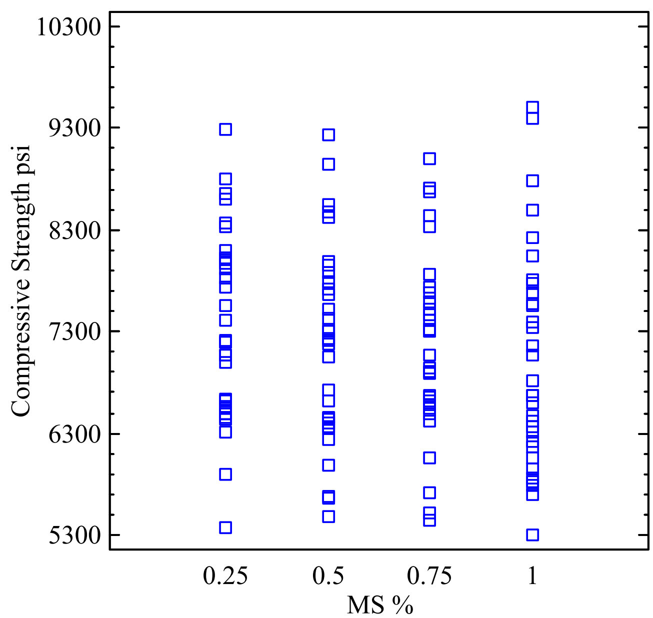


Figure 67. Scatter Plot of Compressive Strength vs. Blend Levels.

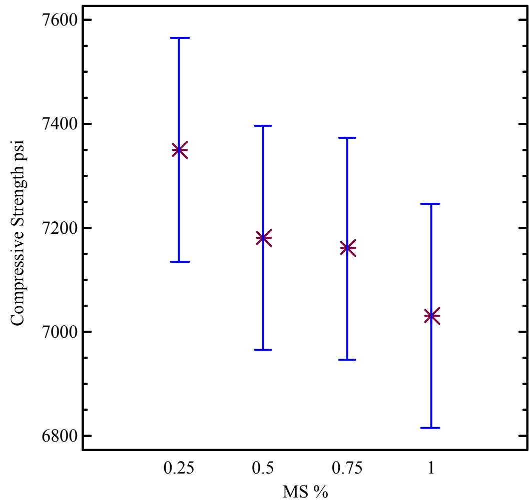


Figure 68. Means and 95% LSD Intervals for Compressive Strength vs Blend Levels.

Table 35. Multiple Range Tests for Compressive Strength psi by MS%.

Method: 95.0 percent LSD

MS%	Count	LS Mean	LS Sigma	Homogeneous Groups
1	32	7031.81	152.114	X
0.75	32	7160.56	152.114	X
0.5	32	7180.16	152.114	X
0.25	32	7348.75	152.114	X

5.4 INFLUENCE OF CEMENT CONTENT ON CONCRETE PROPERTIES

Figure 69 and Figure 70 shows the influence of cement content on compressive strength. The mixes are slightly stronger for higher cement content, but at the 95% confidence interval they are statistically indifferent (Table 36).

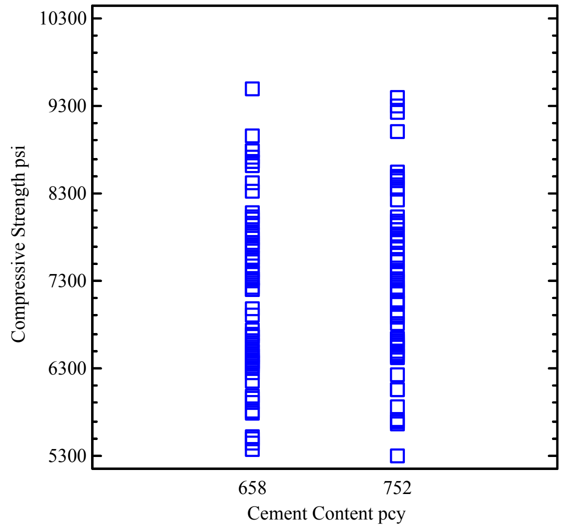


Figure 69. Scatter plot of Compressive Strength vs. Cement Content.

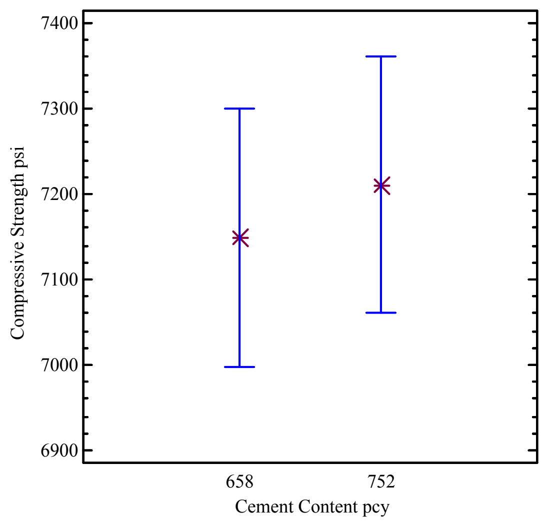


Figure 70. Means and 95% LSD intervals for Compressive Strength vs. Cement Content.

Table 36. Multiple Range Tests for Compressive Strength by cement content.

Method: 95.0 percent LSD

CEMENT	Count	LS Mean	LS Sigma	Homogeneous Groups
658	64	7149.72	107.561	X
752	64	7210.92	107.561	X

5.5 INFLUENCE OF WATER CEMENT RATIO ON CONCRETE PROPERTIES

Figure 71 and Figure 72 shows the influence of w/c on 28 days compressive strength; as expected the strength drops with increased w/c. With the multiple range test, it is clearly established that w/c inversely affects the compressive strength (Table 37).

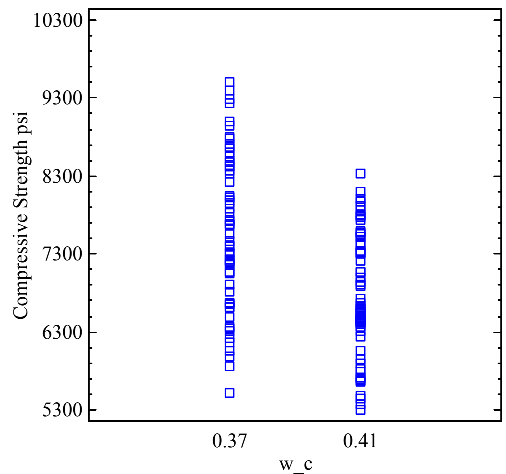


Figure 71. Scatter plot of Compressive Strength vs. w/c ratio.

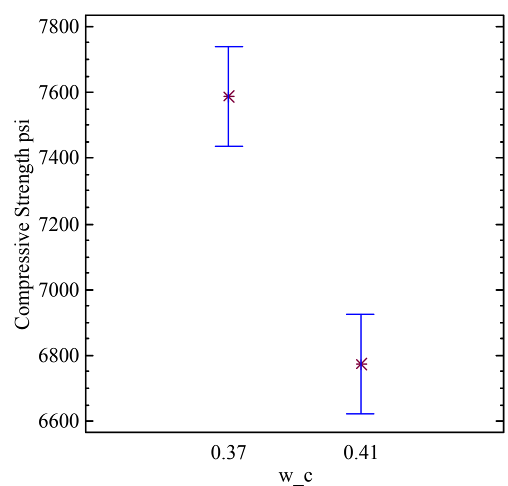


Figure 72. Means and 95% LSD intervals for Compressive Strength vs. w/c ratio.

Table 37. Multiple Range test for Compressive Strength by w/c.

Method: 95.0 percent LSD

W_C	Count	LS Mean	LS Sigma	Homogeneous Groups
0.41	64	6773.2	107.561	X
0.37	64	7587.44	107.561	X

5.6 INFLUENCE OF SAND/AGGREGATE RATIO (s_a) ON CONCRETE PROPERTIES

Sand to aggregate ratio is an important criterion as it is expected to directly affect the fresh concrete properties. Figure 73 through Figure 78 show the influence of s_a on compressive strength. The influence of s_a on compressive strength is not clear, and is probably confounded by other factors. It was also observed that with increasing s_a ratio, demand for admixture also generally increased to compensate the increased angularity of aggregate in the mix.

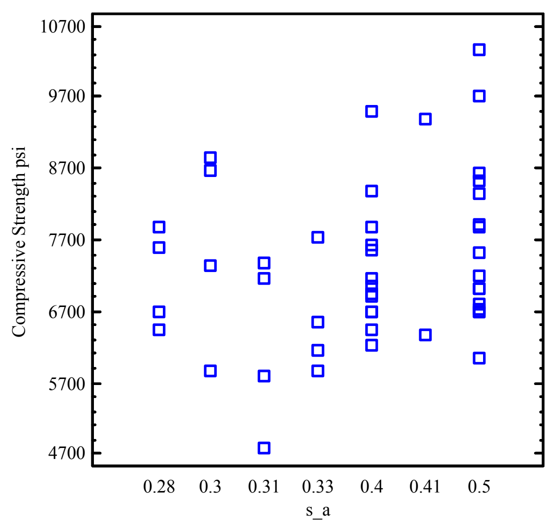


Figure 73. Scatter plot of Compressive strength vs. s_a ratio.

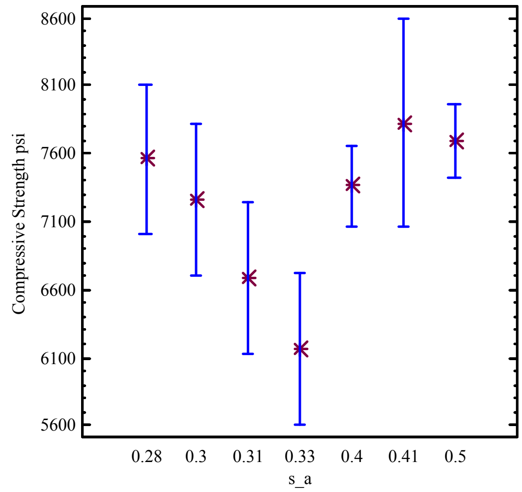


Figure 74. Means and 95% LSD intervals for Compressive strength vs. s_a ratio.

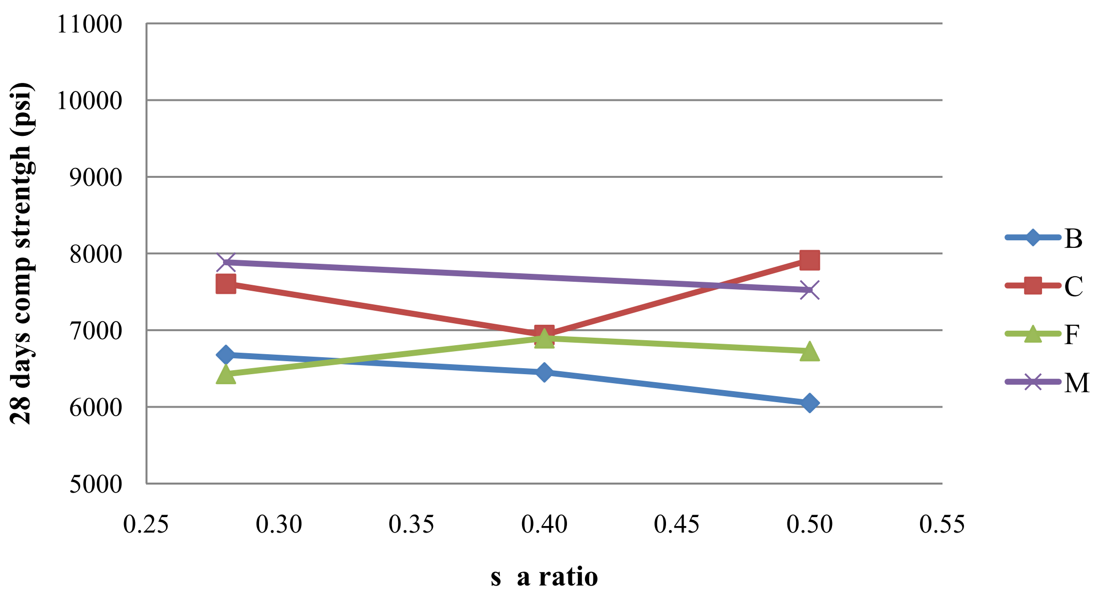


Figure 75. Influence of s_a ratio on compressive strength for w/c =.41, c=752lb/yd^3.

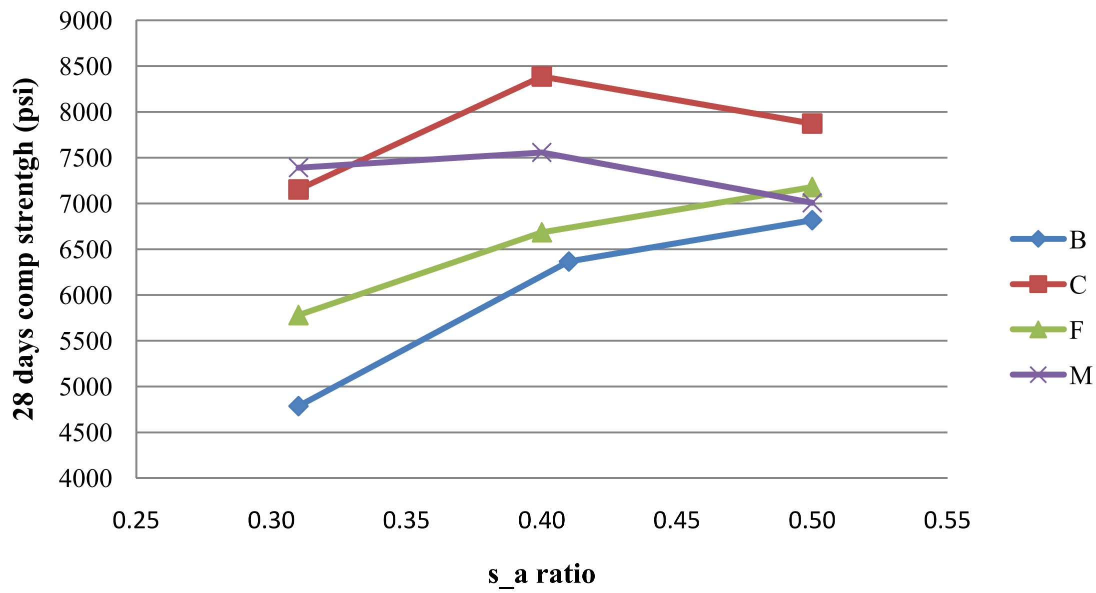


Figure 76. Influence of s_a ratio on compressive strength for w/c =.41, c=658lb/yd3.

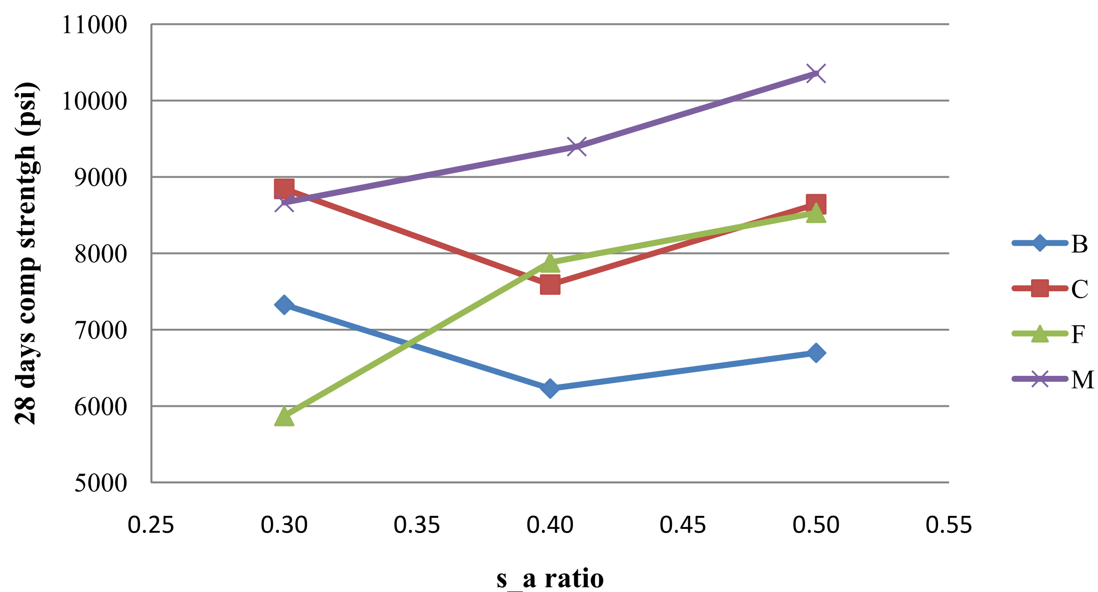


Figure 77. Influence of s_a ratio on compressive strength for w/c =.37, c=752lb/yd3.

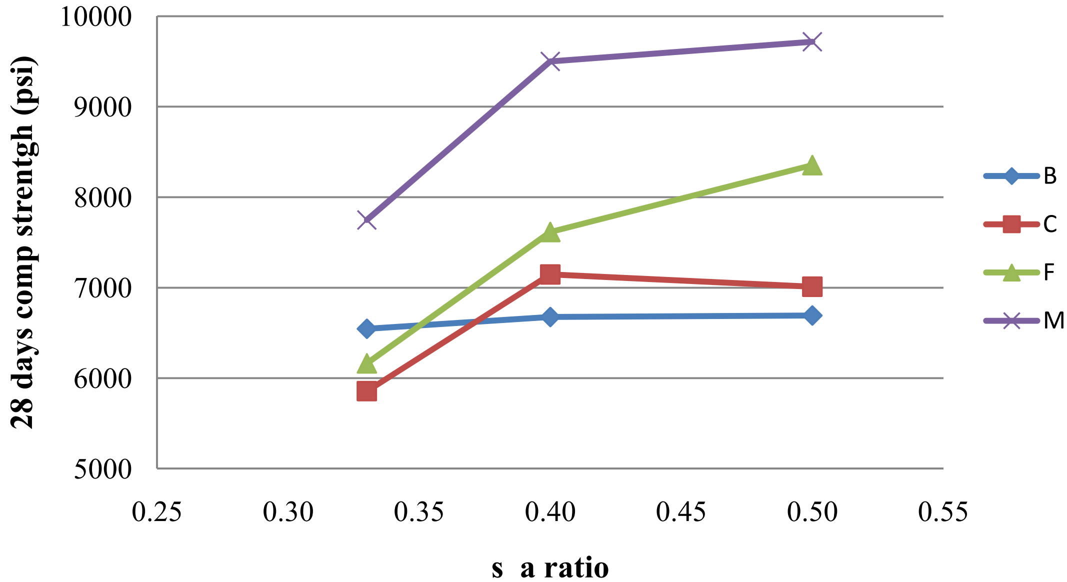


Figure 78. Influence of s_a ratio on compressive strength for w/c =.41, c=658lb/yd3.

5.7 INFLUENCE OF FLY ASH ON CONCRETE PROPERTIES

5.7.1 Effect of Fly Ash on Electric Resistivity

Electrical resistivities of concrete samples were tested in accordance to the FM 5-578 method on 4 × 8 inch cylindrical concrete samples at 28 days of age. The surface resistivity measured is related to chloride ion permeability and values under 12kΩ-cm indicate high potential for chloride ion permeability. From Figure 79 through Figure 81, it can be seen that fly ash presence of more than 20 % is beneficial in significantly improving the resistivity, but still falls under high ion permeability probability zone. Fly ash of up to 20% is not statistically significant in improving surface resistance (Table 38).

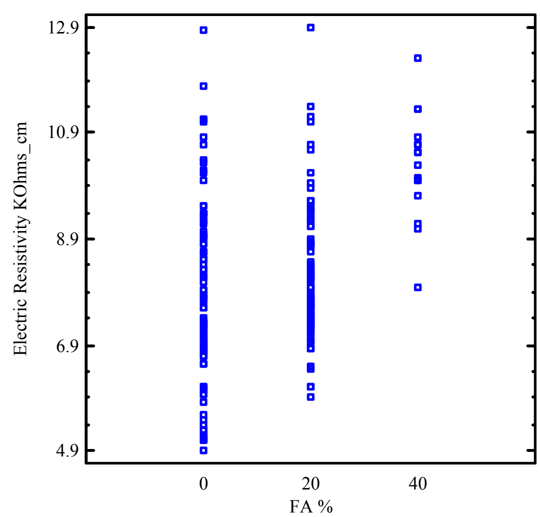


Figure 79. Scatter plot of Electric resistivity vs. Fly ash.

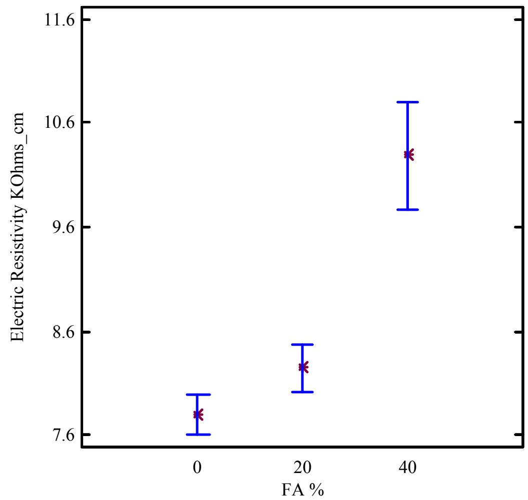


Figure 80. Means and 95% LSD intervals for Electric resistivity vs. Fly ash.

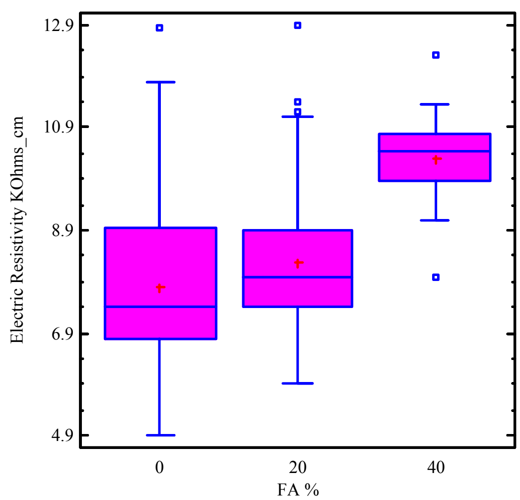


Figure 81. Box and Whisker Plot of Electric resistivity vs. Fly ash.

Table 38. Multiple Range Tests for Electric Resistivity KOhms_cm by FA %

Method: 95.0 percent LSD

FA %	Count	Mean	Homogeneous Groups
0	107	7.80262	X
20	81	8.25383	X
40	16	10.2869	X

5.7.2 Effect of Fly Ash on Compressive Strength

When the influence of fly ash is studied on concrete with 100 % screenings as fine aggregate, it is clear that increasing the amount of fly ash tends to reduce the compressive strength. All levels of fly ash were found to be significantly different for 28 days compressive strength (Figure 82 to Figure 84 and Table 39).

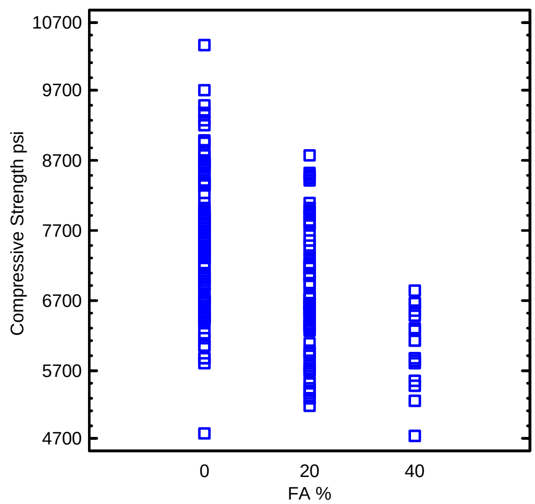


Figure 82. Scatter plot of Compressive strength vs. Fly ash.

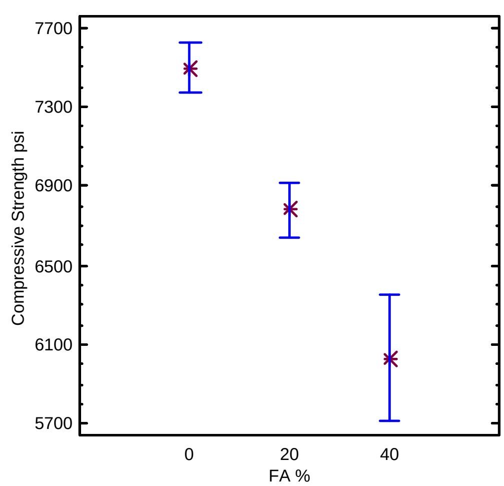


Figure 83. Means and 95% LSD intervals of Compressive strength vs. Fly ash.

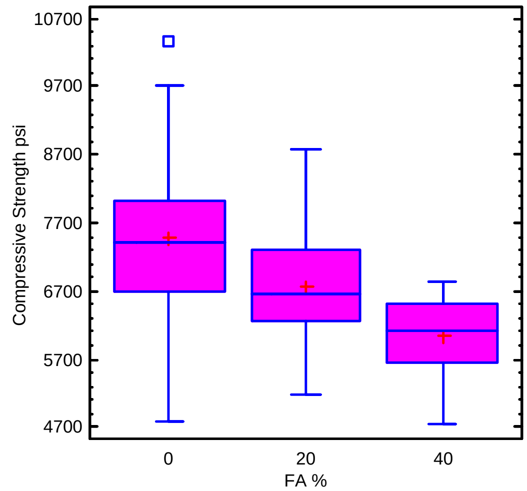


Figure 84. Box and Whisker plot of Compressive strength vs. Fly ash.

Table 39. Multiple Range Tests for Compressive Strength by FA %

Method: 95.0 percent LSD

FA %	Count	Mean	Homogeneous Groups
40	16	6031.81	X
20	81	6780.25	X
0	107	7497.58	X

5.7.3 Effect of Fly Ash on Tensile Strength

Figure 85 through Figure 87 suggest that with high levels of fly ash, the 28 splitting tensile strength of concrete is slightly reduced, but statistically not significant (Table 40).

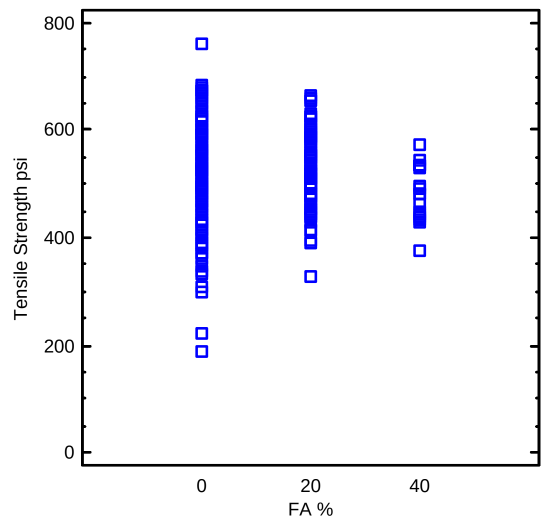


Figure 85. Scatter plot of Tensile strength vs. Fly ash.

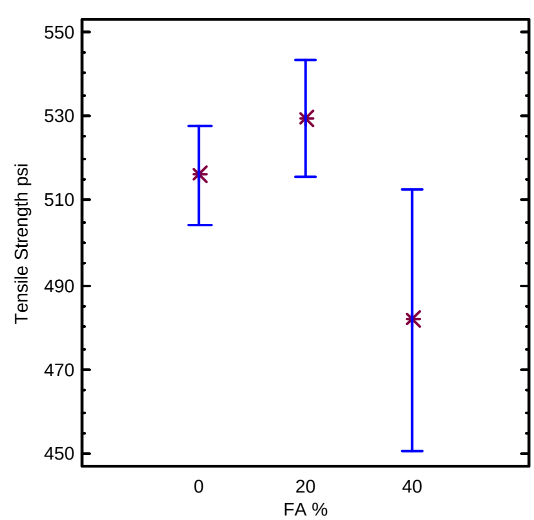


Figure 86. Means and 95% LSD intervals Tensile strength vs. Fly ash.

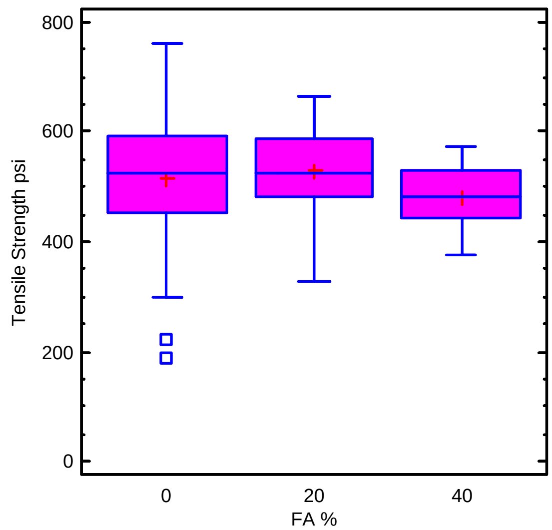


Figure 87. Box and Whisker plot Tensile strength vs. Fly ash.

Table 40. Multiple Range Tests for Tensile Strength psi by FA %

Method: 95.0 percent LSD

FA %	Count	Mean	Homogeneous Groups
40	16	481.726	X
0	107	515.901	X
20	81	529.283	X

5.8 FACTORS EFFECTING ON DURABILITY

Durability is a important design criteria for concrete and there is general prejudice against screenings and manufactured aggregate, assuming that they possess poor durability. Durability of concrete specimens was measured using the surface reisistivty of clyinderical specimen and a length change of a 3×3×10 inch concrete prism over a certain duration of time. Below the influence of angularity, blending and w/c ratio is provieded.

5.8.1 Effect of Angularity of Fine Aggregate on Concrete Durabilty

When the surface resistivity is studied against angularity of fine aggregate (Figure 88 and Figure 89), and even though all of them fall under high permeability category, there are significant differences present. Only Mines B and F were similar at 95 % confidence, while the others were significantly different from each other (Table 41 and Table 42). Interestingly, the aggregate with highest angularity showed most the surface electric resistivity.

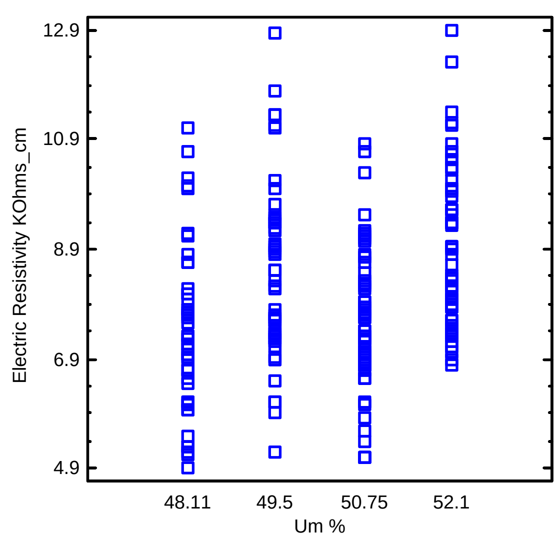


Figure 88. Scatter plot of Electric Resistivity vs. Angularity of Fine aggregate.

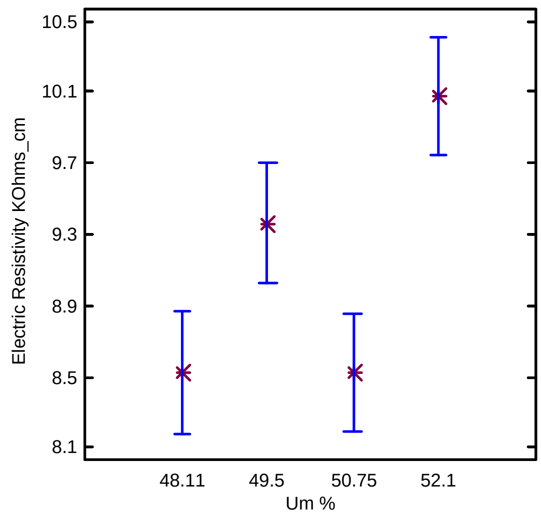


Figure 89. Means and 95% LSD Intervals Resistivity vs. Angularity of Fine Aggregate.

Table 41. Analysis of Variance for Electric Resistivity

Source	Sum of Squares	Df	Mean Square	F-Ratio	P-Value
MAIN EFFECTS					
A:Um %	68.5148	3	22.8383	16.04	0.0000
B:MS %	31.2564	3	10.4188	7.32	0.0001
C:FA %	89.7686	2	44.8843	31.53	0.0000
D:Air Content %	55.3148	35	1.58042	1.11	0.3248
E:w_c	35.4041	1	35.4041	24.87	0.0000
RESIDUAL	223.509	157	1.42363		
TOTAL (CORRECTED)	512.077	201			

All F-ratios are based on the residual mean square error.

Table 42. Multiple Range Tests for Electric Resistivity

Method: 95.0 percent Duncan

Um %	Count	LS Mean	LS Sigma	Homogeneous Groups
50.75	53	8.51764	0.23758	X
48.11	45	8.51971	0.24778	X
49.5	47	9.36257	0.241672	X
52.1	57	10.0764	0.234989	X

5.8.2 Effect of Sand Blending on Concrete Durability

Figure 90 and Figure 91 below show the scatter plot and means and 95% LSD interval for electrical resistivity against different blending levels. It suggests that with more natural fine aggregate the resistivity tends to increase and that mixes with 25 to 50% natural sand blend behave similarly.

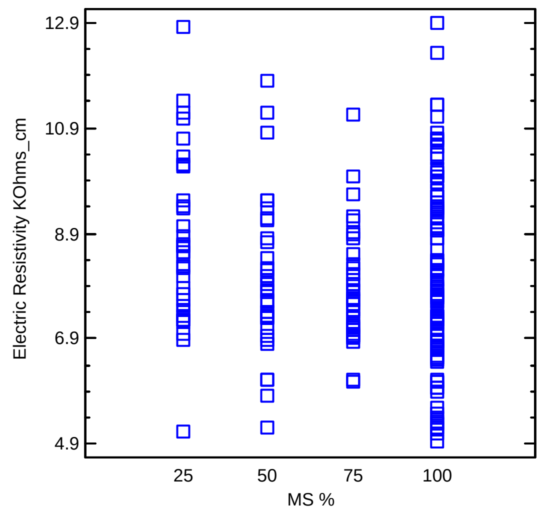


Figure 90. Scatter plot of Electric Resistivity by MS% Levels.

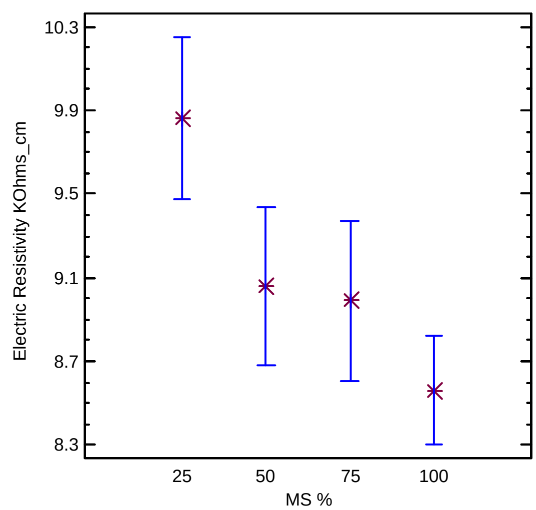


Figure 91. Means and 95% LSD intervals Resistivity vs. Blending.

5.8.3 Effect Water Cement Ratio on Concrete Durability

Figure 92 and Figure 93 show the influence of w/c on surface resistivity of concrete for mixes with 100% screenings as fine aggregate. As expected with higher w/c and the resulting higher porosity, the permeability of concrete increases thus reducing the resistivity.

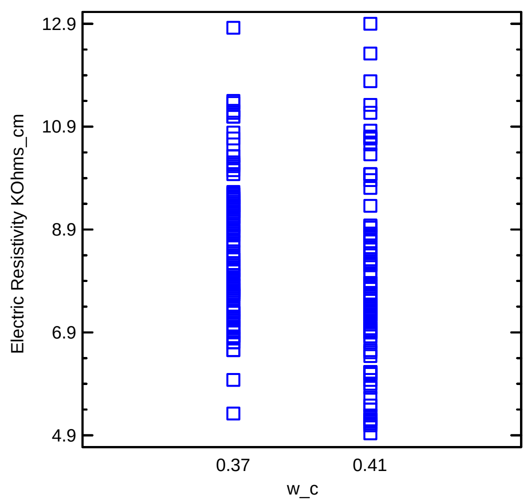


Figure 92. Scatter plot of Electric Resistivity by w/c Levels.

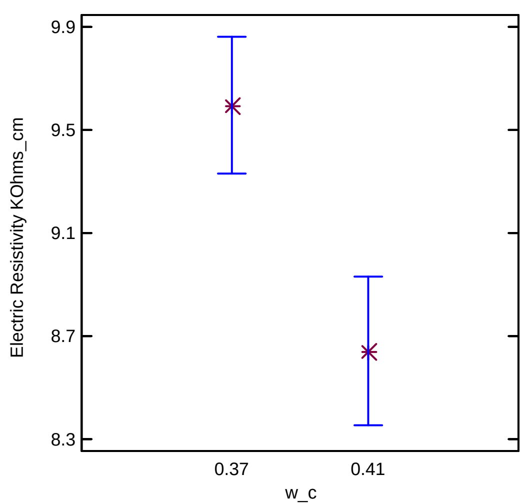


Figure 93. Means and 95% LSD intervals Resistivity vs. w/c ratio.

5.9 MULTIPLE REGRESSION MODEL FOR COMPRESSIVE STRENGTH OF CONCRETE

Using percent blending (MS), s_a, w/c, angularity (U_m) and fly ash, a linear regression analysis was performed (Table 43) and a model was developed to predict the compressive strength of concrete using screenings as a full or partial substitute for natural sand in PCC. R^2 for the model was determined to be 98.65 percent and Figure 94 shows the plot of observed versus predicted compressive strength of concrete mixes.

Table 43. Multiple Regression Analysis for 28 days Compressive Strength of Concrete

Dependent variable: Comp

Parameter	Estimate	Standard Error	T Statistic	P-Value
MS	-589.456	213.988	-2.75462	0.0064
s_a	3437.29	901.791	3.81162	0.0002
w_c	-10391.5	2559.15	-4.06053	0.0001
Um	21263.1	2015.61	10.5492	0.0000
FA	-3448.86	465.128	-7.41486	0.0000

Analysis of Variance

Source	Sum of Squares	Df	Mean Square	F-Ratio	P-Value
Model	1.03435E10	5	2.0687E9	2926.44	0.0000
Residual	1.40673E8	199	706900.0		
Total	1.04842E10	204			

$$f_c^{'} = -5.896 * MS + 3437.29 * s\_a - 10391.5 * w/c + 21263.1 * U_m - 34.487 * FA$$

Where,

$f_c^{'}$ = Compressive strength of concrete in psi

MS = Percent screenings as fine aggregate (%)

s_a = Sand to total aggregate ratio

U_m = Angularity of Fine aggregate by Method B of ASTM C1292 (%)

FA = Fly ash content in fraction (%)

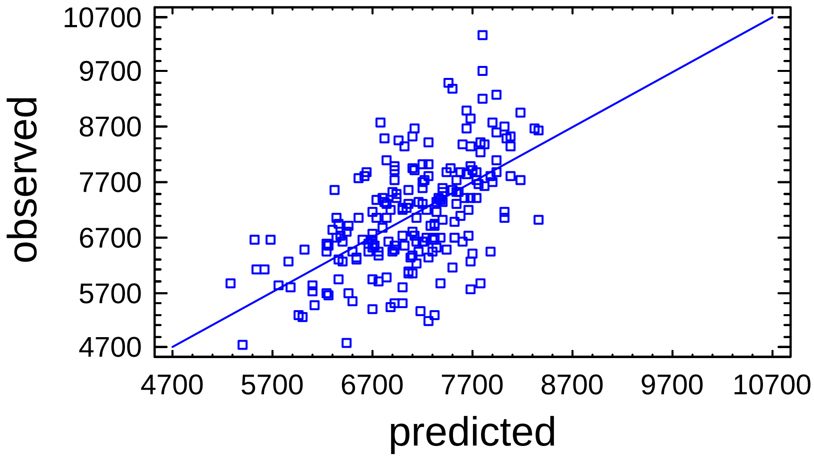


Figure 94. Plot of observed vs. Predicted Compressive Strength (psi).

5.10 NONLINEAR REGRESSION MODEL FOR MODULUS OF ELASTICITY

Using unit weight and 28-days compressive strength data from all the concrete mixes a non linear regression model to predict elastic modulus of concrete was determine similar in form to the ACI 318 equation to predict concrete modulus. The model for concrete modulus matches closely with the ACI equation.

$$E = 33.076(w)^{1.5}\sqrt{f_c^{'}}$$

Where,

E = Modulus of Elasticity

w = Unit weight of concrete in pcf

f'_c = Compressive strength in psi

Figure 95 shows the response surface of elastic modulus vs. compressive strength and unit weight of concrete. Figure 96 shows the plot predicted versus observed E values of concrete samples tested.

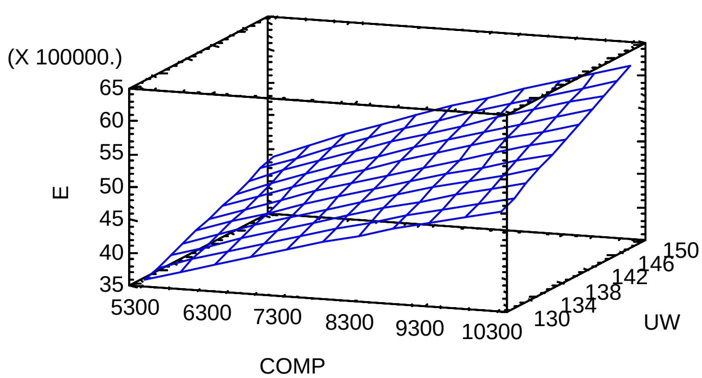


Figure 95. Estimated Response Surface of E vs. Compressive strength and Unit weight.

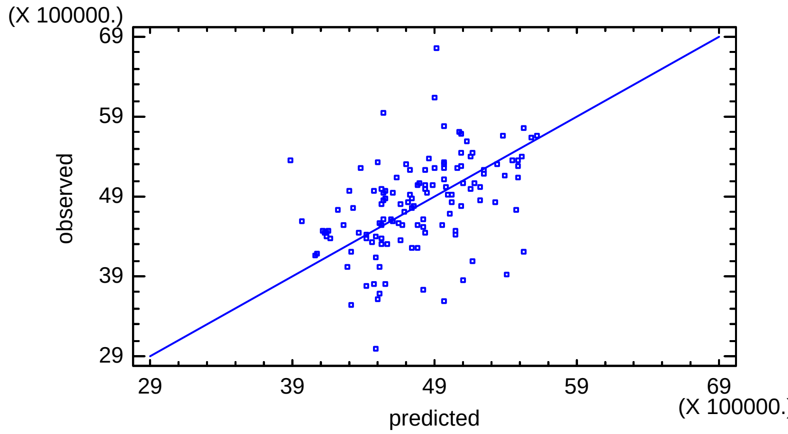


Figure 96. Plot of observed vs. predicted E value of concrete.

CHAPTER 6: ECONOMIC AND ENVIRONMENTAL PAYOFF

6.1 INTRODUCTION

In the recent past, the cost of natural sand has increased in many parts of the country due to the depletion of local existing sources, residential developments over running the lands where sand deposits exists, and delay in development and permitting of new sources or expansion of existing mines due to environmental concerns and resistance to such developments by neighboring homeowners. This has generally resulted in importing sand from distant sources thereby increasing the transportation cost.

Acceptance of manufactured fine aggregates would provide an alternate source for fine-aggregate. With sources closer to the consumer, it has the potential to save millions of dollars a year as well as reducing the impact to the environment. As an example, Lukkarila [[53]] recently reported there are no longer any natural sand and gravel aggregate suppliers producing natural sand in California's San Diego County. Sand must be shipped in and it is estimated that the use of manufactured sand would save the San Diego metropolitan area at least $60 million a year, based on 2005 fuel prices. These annual savings will only increase with the increases in the fuel prices, and as the existing natural sand sources are exhausted.

A ready supply of crushed stone, sand and gravel is necessary to support future economic development and growth. The biggest concern facing the aggregates industry in coming years is obtaining zoning favorable to the extraction of aggregates. Near urban areas where construction materials are critically needed, it is most important to allow appropriate zoning and the necessary permits to assure a continued supply of aggregates.

6.2 FLORIDA FORECAST

Recently, the FDOT initiated research to strategically assess opportunities and risks in the highway construction materials marketplace. The "2009 Strategic Resource Evaluation Study: Highway Construction Materials" report provides data on the existing state of the materials marketplace and outlook as of the end of Fiscal Year 2009[[54]].

The Balmoral Group [54] reported that in 2009, the FDOT appears to consume half to one-third of total highway construction materials in the state, while two years ago, FDOT was estimated at only one fourth of total state consumption. Table 44 below shows the projected materials requirement for the five year work plan based on data as provided the Balmoral Group in the report. These estimates are subject to considerable increase, pending passing of various new highway funding bills by congress.

Table 44. FDOT 5 Year Estimates of Materials Requirements.

	Unit	2010	2011	2012	2013	2014
Structural Concrete	Yd^3	303,810	444,101	371,808	369,484	374,940
Ancillary Concrete**	Yd^3	3,162,470	1,505,133	1,612,938	1,542,418	1,436,778
Total Concrete	Yd^3	3,466,279	1,949,234	1,984,747	1,911,902	1,811,718
Base Material and Other Aggregate Base	Tons	2,125,000	987,400	615,200	512,600	1,189,000
Aggregate for Asphalt	Tons	6,649,600	3,416,500	3,742,900	4,517,300	4,832,600
Aggregate for Concrete	Tons	4,749,700	2,670,900	2,719,600	2,619,800	2,482,500
Total Aggregate	Tons	13,524,300	7,074,800	7,077,700	7,649,700	8,504,100

** Concrete Pipe, Sidewalk, Drainage Structures, etc.

Florida has four significant resource areas of quality limestone reserves: Lake Belt, Charlotte-Lee County, Sumter-Hernando-Citrus County, and the Taylor-Dixie-Big Bend area. The Lake Belt area has historically produced up to 45% of statewide output, with the remainder split almost evenly between other mines located in South Florida, and those that are north of Tampa. Reported Lake Belt production of year 2009 (22 million Tons) is near 40% of peak year production of year 2005 (51 million Tons).

It was also reported by the Balmoral Group that there is concern that rail infrastructure would be inadequate to transport rock from other ports or mines if Lake Belt were to become unavailable for an extended period of time. Aggregate imports to Florida arrive mainly from Canada, Georgia, Mexico, and the Bahamas. Three years ago, imports were estimated at no more than 15% of Florida's crushed stone consumption.

Figure 97 below shows the forecast materials requirements over the five year work plan of FDOT [54].

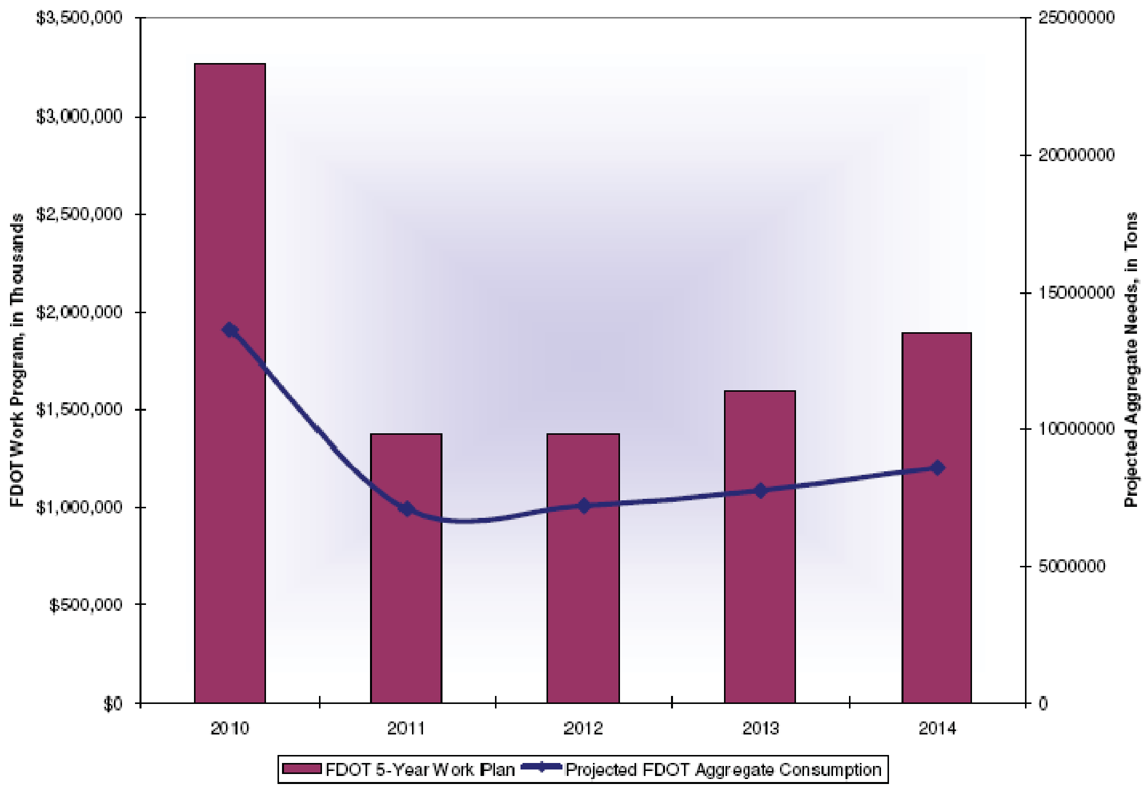


Figure 97. Aggregate Needs Forecast for FDOT % Year Work Plan.

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Figure 98 shows the distribution of FDOT's materials requirements by district and Figure 99 shows the past and future aggregate consumption estimated under various economic recovery and oil price scenarios [54].

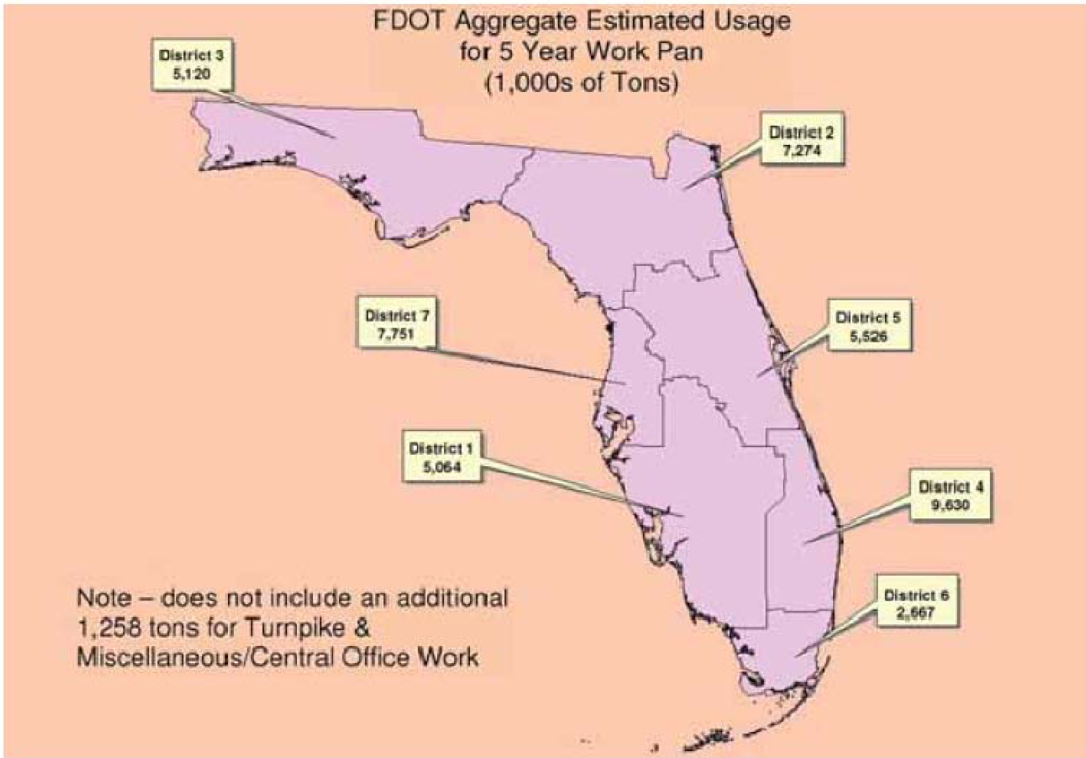

Figure 98. FDOT Aggregate Usage for 4 Year Work Plan.

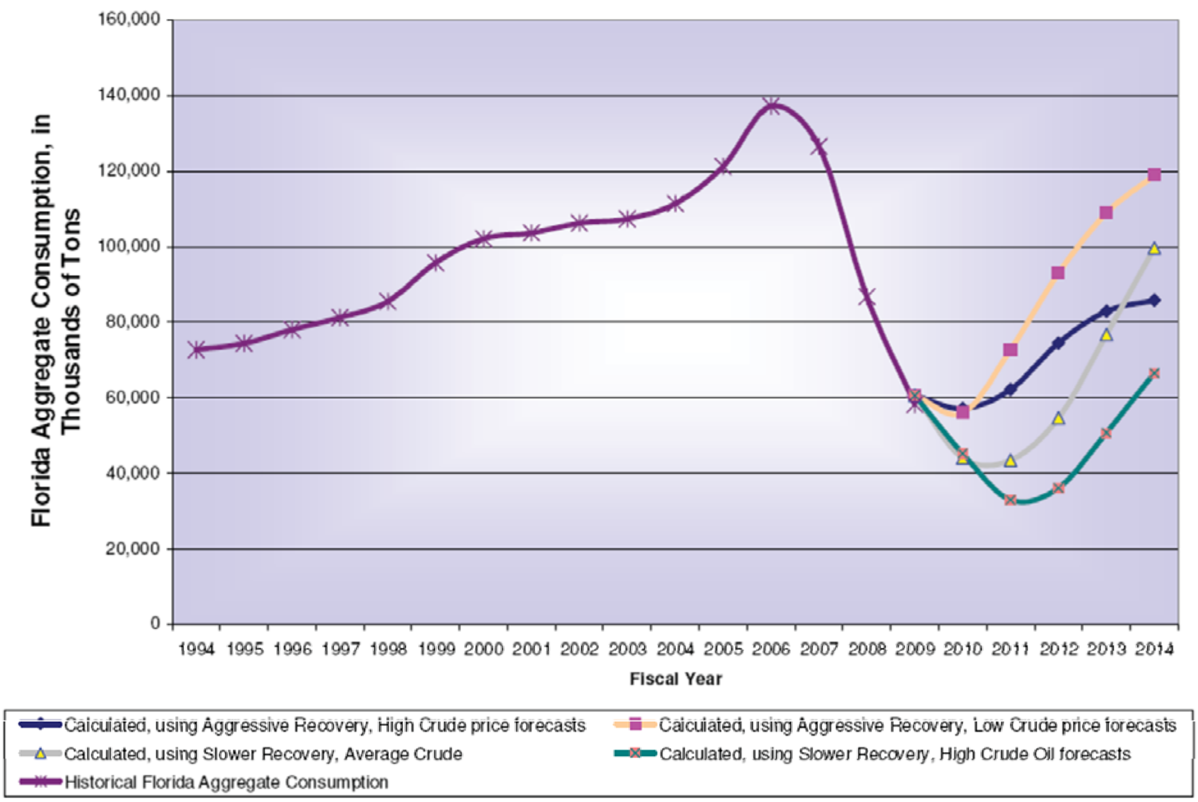

Figure 99. Predicted Florida Aggregate Consumption.

6.3 ESTIMATE OF ECONOMIC IMPACT

Because aggregate is a heavy and low cost per ton product, the haul distance has a large influence on the price of aggregate. Truck haul costs approximately 25 to 35 cents per ton-mile. Transportation cost is one of the main factor in establishing the market area of an aggregate operation. As rule of thumb, one-way haulage distance of 20-25 miles or a one-hour round trip of about 40-50 miles, approximately doubles the final delivered price of aggregate to the consumer [55]. Permitting substitution of screening as fine aggregate can help lower delivered costs by encouraging optimal use of local material.

6.3.1 Cost Savings

In estimating the savings that can be achieved by permitting the substitution of natural silica sand with screenings in concrete, one has to forecast the need of fine aggregate and take into account the production and transportation cost. Generally, screenings are by-product of the crushed stone production process, and as such are treated as waste material. In some areas across Florida, screenings are sold at a considerable price discount compared to natural silica sand. Currently, FDOT standard specifications permit the use of screenings in PCC from mines in District 4 and 6.

Based on typical a s_a ratio of 0.4 for PCC and the estimated demand for the aggregate in concrete over the FDOT five year work plan (Table 44), one can estimate the demand for fine aggregate (natural sand and or screenings) in year 2010-2014 to be approximately 6,097,000 tons. This is a conservative estimate and is subject to increase with recovery in the economy and passing of highway funding bills by congress.

The cost of screenings relatively to natural sand varies considerably across Florida. Not all regions are expected to realize the savings on cost basis alone. The following is the cost analysis for three regions in Florida.

Miami Area

Currently, FDOT Standard Specifications permit use of screenings in PCC from mines in District 4 and 6. Permitting the use of screenings avoided importing natural sand from distant sources for most concrete applications. It is estimated that the Miami area would have to import natural silica sand from at least 120 miles away if screenings were not permitted in PCC. At $0.35 per ton truck haul cost this translates to a $42 per ton saving, while at $0.11 per ton rail haul cost this suggests a savings of at least $13.20 per ton is being achieved in Miami area.

Ft. Myers Area

It was found that for South West Florida (Ft. Myers area) the silica sand sells free on board (FOB) for $5 per ton more than limestone screenings FOB. The actual savings realized can be calculated based on FOB price difference, amount of substitution and transportation cost of the two fine aggregates as:

$$S = [PD_{FOB} + (d_{NS} - d_S)C_t]MS$$

Where,

S = Savings ($/ton)

PD_{FOB} = FOB Price difference between Silica sand and Screenings ($/ton)

d_{NS} = Haul Distance for Silica Sand (miles)

d_S = Haul Distance for Screenings (miles)

C_t = Transportation cost per ton per mile

MS = Percent Screenings in the blend

For a truck transportation cost of $0.35 per ton, Table 45 below displays the cost savings per ton for the likely values of d_{NS} (30 to 50 miles), d_s(5 to10 miles), and a fixed PD_{FOB} of $5 for various percentage of screenings in the concrete.

Table 45. Cost Savings per ton vs percent MS in Ft. Myers Area.

		d_s=5miles			d_s=10miles		
		d_{NS}			d_{NS}		
		30	**40**	**50**	**30**	**40**	**50**
MS	**0**	0	0	0	0	0	0
	25	3.44	4.31	5.19	3.00	3.88	4.75
	50	6.88	8.63	10.38	6.00	7.75	9.50
	75	10.31	12.94	15.56	9.00	11.63	14.25
	100	13.75	17.25	20.75	12.00	15.5	19.00

It is obvious that maximum benefit is realized when 100 percent of natural sand is replaced with screenings and when the haul distance of screenings is shorter than the natural sand. Inversely, in the Fort Myers area, for a price difference of \$5 per ton and \$0.35 per ton per mile transportation cost, screenings up to 14 miles (=\$5/0.35) further away from natural sand source can still be used without net increase in the total cost of fine aggregate.

Table 46 below shows the total estimated quantity of aggregate for concrete in Charlotte, Collier and Lee county for the 2010 -21014 FDOT work plan (Balmoral Study). Based on these numbers, the actual savings that can be achieved with the usage of screenings in Ft. Myers area are shown in Table 47. Cost savings were calculated based on sand to aggregate ratio of 0.4 and price difference of \$5 between the two fine aggregates.

Table 46. Estimated Quantity of Aggregate for Concrete in 3 Counties of District 1.

	2010	**2011**	**2012**	**2013**	**2014**
CHARLOTTE	9,538	5,337	328	10,615	29,691
COLLIER	85,266	30,250	56,692	51,513	16,779
LEE	112,463	35,249	25,670	47,454	1,799
TOTAL (tons)	**207,268**	**70,837**	**82,689**	**109,583**	**48,269**

Table 47. Achievable Cost Savings In Ft. Myers Area for Current FDOT Work Plan.

		d_s = 5miles			d_s = 10miles		
		d_{NS}			d_{NS}		
		30	40	50	30	40	50
MS	25	713,657	894,146	1,076,709	622,375	804,939	985,427
	50	1,427,314	1,790,366	2,153,418	1,244,750	1,607,803	1,970,855
	75	2,138,896	2,684,512	3,228,053	1,867,126	2,412,741	2,956,282
	100	2,852,553	3,578,657	4,304,762	2,489,501	3,215,605	3,941,710

Savings illustrated in Table 47 are based on estimates for the structural and nonstructural concrete combined and does not distinguish for various levels of aggressive environmental conditions. At present, the recommendation of this project is to permit up to 50 percent replacement of natural sand with the screenings for structural concrete and 100 percent for nonstructural concrete and thus the actual savings will fluctuate.

Orlando/Tallahassee Area

In some parts of Florida, the cost of screenings is higher than that of natural sand. As an example the granite screenings and limerock screenings in the Orlando area sells for $25 to $27 per ton compared to $8 to $10 for natural sand per ton for concrete. The Tallahassee area has similar price structure. Thus, Orlando and Tallahassee markets are currently not favorable, and are not likely to achieve savings or cost reduction by permitting substitution natural silica sand with screenings.

Importing from Outside Florida

In another scenario, if local mines in central Florida run out of coarse silica sand and/or were required to import it from Georgia, it would likely increase the delivered price of natural sand by about $10 per ton. This is based on CSX data to travel half the State from the Georgia line. Thus, if substitution is allowed when reserves start to run low at some time in future and a conservative usage of just 1,000,000 tons of screenings per year, it would mean a saving of at least $10 million in delivery cost alone to central Florida.

6.4 ENVIRONMENTAL AND SCOCIO-ECONOMIC ISSUES

The environmental benefit of reduced stockpiles and conservation of natural resources by reduced mining for natural sand cannot be understated. Although they are generally inert and non-hazardous, the mining operations have been a source of friction between aggregates producers, local communities, and other stakeholders. This conflict can be generally reduced and minimized with proper site design and involvement of the community at the planning stage.

Once reclaimed, crushed stone quarries can be used as water reservoirs or recreational lakes and can provide a useful locale for wildlife habitats or agricultural fields, or as lakes for a variety of uses, including groundwater recharge. Wetlands are often created as a result of mining [56].

The nature and extent of the environmental and social impacts generally varies from site to site, according to their characteristics and specific local context. The impacts experienced by the local community are significantly influenced by the nature and proximity of housing, amenity areas, and local businesses. Different stakeholders will have quite different opinions regarding the impacts that they consider most important. Many of the potential impacts can be prevented or mitigated by the use of good practice. The acceptability of impacts that remain after good practice measures have been put in place should be considered in the context of the economic and other benefits that accrue from aggregates production.

Additional benefits of using local material include shorter truck haulage distance, thus reducing greater traffic, accidents, traffic congestion, fuel consumption, road maintenance, and vehicle replacement costs. Sustaining local mines and their operations also maintains and create jobs in the community and its revenue.

CHAPTER 7: CONCLUSIONS AND RECOMMENDATIONS

The State of Florida is the third largest consumer of crushed rock products in the United States, and is the largest single contractor/user of crushed stone resources in the state. Crushed stone in Florida is produced from limestone, which is mined or extracted from naturally occurring deposits. This crushing for coarse aggregate results in a fine byproducts called screenings. The stockpiling and disposal of fines produced as a result of aggregate crushing and production operations are some of the major problems facing the aggregate industry. The conclusions of the study apply to and are limited to the use of screenings in Portland cement concrete only. Screenings have also been used in hot mix asphalt concrete, road bases, and other applications not studied in this project.

Screenings are inherently more angular, and have a rougher surface texture, thus raising concerns of workability, increase water demand and poor finishibility. Screenings from four mines from across the state of Florida were obtained and tested during this project. The influence of screenings on mortar and concrete properties was investigated in great detail. The results of the project suggest following conclusions can be made about use of screenings as a substitute for natural sand in PCC:

- Flow of mortar was demonstrated to be function of angularity, fineness modulus, sand to cement ratio, water to cement ratio, and presence of fly ash.

- Screenings caused a slight reduction in compressive strength of mortar cubes.

- The model for predicting flow of mortar (*f*) and compressive strength (psi) of mortar cubes (f'_{cm}) were developed with R^2 of 93% and 69% respectively as follows:

$$f = 1.064\,U_m - 1.045\,FA + 11.90\,FM - 42.43\,s\_c + 213.97\,w/c$$

$$f'_{cm} = 8462 + 95.09U_m - 651FM - 7944w/c - 540s\_c - 47FA$$

- Mortar bars were tested in autoclave as per ASTM C151, to study the influence of screening types on expansion ability. It was found that the source of screening significantly affected the autoclave expansion and is expected to have a similar influence on concrete prepared with the same screening and cement type and exposed to similar conditions.

- Autoclave expansion was significantly reduced when more than 50% fine aggregate in the mix was natural sand.

- The model for predicting autoclave expansion in mortar bars (ε_{ae}) was developed with 95% R^2 as:

$$\varepsilon_{ae} = -0.000130988 s\_c + 0.00170531 w/c - 0.00085477 U_m + 0.00014759 FM$$

- Compressive strength comparable to normal concrete for a given w/c and cement content was easily achieved with the use of screenings. A model to predict compressive strength of concrete (psi) with various factors was developed as follows:

$$f_c^{'} = -5.896 * MS + 3437.29 * s\_a - 10391.5 * w/c + 21263.1 * U_m - 34.487 * FA$$

- It was found that blending with natural sand improved workability and lowered the demand for admixture.

- Blended mix produced higher compressive strength at 28 days.

- Mix can be optimized by studying and adjusting the sand to aggregate ratio. Lower s_a concrete generally required lower quantity of admixture due to lower overall angularity.

- Use of fly ash is strongly recommended.

- The introduction of fly ash improved surface electrical resistivity, especially for mixes with greater than 20% replacement level of fly ash.

- Higher percentage of screenings in a blended mix generally resulted in lower surface resistivity.

- Concrete prepared with screenings did not show any adverse effect on elastic modulus or Poisson's ratio. The model developed below to predict the modulus of elasticity (psi) closely matches the standard ACI 318 modulus equation.

$$E = 33.076(w)^{1.5}\sqrt{f_c^{'}}$$

- Substitution of natural sand with screenings will not only help alleviate shortage and diminishing of resources of natural sand, but also relieve the environmental burden resulting from their disposal as waste material.

- There are economic benefits of using screenings both at the state and local levels, not only from direct and indirect employment basis, but also in helping mitigate the stockpile of waste material.

- Cost savings were analyzed for Miami, Ft. Myers and Orlando area. It was shown that the Miami area is already realizing benefits from the permitted use of screenings in concrete, while there is potential to save money in Ft. Myers area based on the price difference between screenings and natural sand. Currently, in the Orlando and Tallahassee area, screenings are sold at a premium and market conditions are not set to immediately benefit from the allowance of screenings in concrete.

Impact on Fine Aggregate Specification 902

Currently, fine aggregate specification section 902-5.2.3 only allows mine M of this study, and specifies a minimum specific gravity of 2.48 and a maximum percent finer than #200 sieve.

Based on the study of means and analysis of results of the four screenings in this study at 95 percent confidence interval, it is recommended that bulk specific gravity requirement can be reduced to 2.38 to accommodate use of screenings studied in this project. Only Mine C had higher fine content and did not meet the current specification requirement.

This project has also clearly demonstrated that screenings can be successfully used as a substitute for natural sand in PCC. Based on this study, it is thus concluded that up to 50 percent replacement of natural silica sand with screenings of attributes studied in this project can be permitted for structural concrete, especially were durability is not a primary concern. For non structural elements, a 100 percent replacement can be permitted.

Although, the concrete produced with screenings possessed properties comparable to that of control mix, more detailed study is needed for its usage in extremely aggressive environment. Long term properties such as shrinkage and creep, and the interaction of screenings with different maximum coarse aggregate size should also be studied in future.

APPENDIX

Table 48. Mortar Study Data.

Mix #	Mine	Fly Ash %	s_a	MS %	w/c	Compressive Strength, psi	Flow, %	AutoClave Expansion, %
1	M	0	2.75	75	0.528	7024	95	0.00052
2	M	0	2.75	50	0.5	6413	104	0.00044
3	M	0	2.75	25	0.482	5863	98	0.0003
4	M	0	2.25	75	0.464	6256	103	0.00054
5	M	0	2.25	50	0.437	5798	100	0.0005
6	M	0	2.25	25	0.423	5477	94	0.00039
7	M	0	1.75	75	0.425	7826	113	0.00047
8	M	0	1.75	50	0.415	6717	102	0.00042
9	M	0	1.75	25	0.403	6766	106	0.00035
10	C	0	2.75	75	0.511	5641	93	0.00061
11	C	0	2.75	50	0.505	6192	100	0.00052
12	C	0	2.75	25	0.472	6174	98	0.00042
13	C	0	2.25	75	0.481	7168	110	0.00058
14	C	0	2.25	50	0.452	6501	103	0.00046
15	C	0	2.25	25	0.433	6972	102	0.00034
16	C	0	1.75	75	0.428	8158	103	0.00056
17	C	0	1.75	50	0.43	7133	104	0.00048
18	C	0	1.75	25	0.36	9188	108	0.00031
19	B	0	2.75	75	0.528	4411	95	0.00078
20	B	0	2.75	50	0.472	4875	94	0.00066
21	B	0	2.75	25	0.461	6622	95	0.00035
22	B	0	2.25	75	0.493	4048	101	0.0008
23	B	0	2.25	50	0.451	4974	108	0.00064
24	B	0	2.25	25	0.409	6793	100	0.00047
25	B	0	1.75	75	0.45	6933	102	0.00048
26	B	0	1.75	50	0.398	6624	108	0.00059
27	B	0	1.75	25	0.396	5953	107	0.00039
28	F	0	2.75	75	0.528	6178	93	0.00067
29	F	0	2.75	50	0.505	6425	96	0.00051
30	F	0	2.75	25	0.469	6320	96	0.00032
31	F	0	2.25	75	0.479	6493	97	0.00046
32	F	0	2.25	50	0.458	6549	110	0.00049
33	F	0	2.25	25	0.428	6956	105	0.00041
34	F	0	1.75	75	0.447	6372	106	0.0005
35	F	0	1.75	50	0.424	6952	105	0.00043
36	F	0	1.75	25	0.364	8260	106	0.00027
37	M	0	2.75	100	0.521	7109	99	0.0004

Mix #	Mine	Fly Ash %	s_a	MS %	w/c	Compressive Strength, psi	Flow, %	AutoClave Expansion, %
38	C	0	1.75	100	0.455	6013	100	0.0004
39	B	0	2.75	100	0.549	5402	98	0.00097
40	B	0	2.25	100	0.499	5665	104	0.00086
41	B	0	1.75	100	0.453	5879	102	0.00084
42	F	0	2.75	100	0.558	5843	100	0.0006
43	F	0	2.25	100	0.501	7177	96	0.00057
44	F	0	1.75	100	0.465	8033	96	0.00054
45	M	0	2.25	100	0.52	7077	107	0.0005
46	M	0	1.75	100	0.44	7305	97	0.00037
47	C	0	2.75	100	0.546	5814	96	0.00052
48	C	0	2.25	100	0.56	6720	102	0.00069
51	M	20	2.75	100	0.48	3335	0	0.00031
52	M	20	2.75	100	0.52	6236	39	0.00039
53	M	20	2.75	100	0.56	5662	85	0.00043
54	M	30	2.75	100	0.48	5564	16	0.0006
55	M	30	2.75	100	0.52	5469	59	0.00063
56	M	30	2.75	100	0.56	5759	87	0.00055
57	M	40	2.75	100	0.48	5137	21	0.00049
58	M	40	2.75	100	0.52	4348	52	0.00041
59	M	40	2.75	100	0.56	4208	119	0.00054
60	C	20	2.75	100	0.48	2208	0	0.00022
61	C	20	2.75	100	0.52	5317	29	0.00052
62	C	20	2.75	100	0.56	2668	45	0.0006
63	C	30	2.75	100	0.52	3440	0	0.00055
64	C	30	2.75	100	0.56	4621	62	0.00057
65	C	30	2.75	100	0.6	3774	87	0.0006
66	C	40	2.75	100	0.52	3210	0	0.00058
67	C	40	2.75	100	0.56	3053	49	0.00063
68	C	40	2.75	100	0.6	3524	117	0.00076
69	B	20	2.75	100	0.48	4194	37	0.00073
70	B	20	2.75	100	0.52	3855	70	0.00078
71	B	20	2.75	100	0.56	2671	25	0.00065
72	B	30	2.75	100	0.52	3267	22	0.00069
73	B	30	2.75	100	0.56	3101	42	0.00064
74	B	30	2.75	100	0.6	2963	81	0.00068
75	B	40	2.75	100	0.52	2869	15	0.00055
76	B	40	2.75	100	0.56	2788	56	0.0006
77	B	40	2.75	100	0.6	2634	104	0.00062
78	F	20	2.75	100	0.48	1998	0	0.00046

Mix #	Mine	Fly Ash %	s_a	MS %	w/c	Compressive Strength, psi	Flow, %	AutoClave Expansion, %
79	F	20	2.75	100	0.52	2942	18	0.0005
80	F	20	2.75	100	0.56	3878	22	0.00056
81	F	30	2.75	100	0.52	3463	16	0.00058
82	F	30	2.75	100	0.56	4807	34	0.00054
83	F	30	2.75	100	0.6	3509	76	0.00062
84	F	40	2.75	100	0.52	3029	33	0.00064
85	F	40	2.75	100	0.56	3208	45	0.00071
86	F	40	2.75	100	0.6	4045	83	0.00058
87	N	20	2.75	0	0.48	4932	96	0.00024
88	N	30	2.75	0	0.52	4408	127	0.00025
89	N	40	2.75	0	0.56	3460	180	0.00023
90	N	0	2.75	0	0.459	5490	99	0.00011
91	N	0	2.25	0	0.431	7728	102	0.00016
92	N	0	1.75	0	0.357	5727	107	0.0002
101	M	0	2.75	100	0.52	7470	37	0.00051
102	M	0	2.25	100	0.52	7077	107	0.0005
103	M	0	1.75	100	0.4	7688	62	0.00032
104	M	0	2.75	100	0.56	6302	85	0.0005
105	M	0	2.25	100	0.56	6015	128	0.0005
106	M	0	1.75	100	0.44	7305	97	0.00037
107	C	0	2.75	100	0.52	3388	27	0.0007
108	C	0	2.25	100	0.52	6329	47	0.00066
109	C	0	1.75	100	0.44	8026	52	0.00059
110	C	0	2.75	100	0.56	5814	40	0.00052
111	C	0	2.25	100	0.56	6720	102	0.00069
112	C	0	1.75	100	0.52	7289	128	0.00065
113	B	0	2.75	100	0.52	4274	67	0.00091
114	B	0	2.25	100	0.52	4489	130	0.00089
115	B	0	1.75	100	0.48	4994	137	0.00077
116	B	0	2.75	100	0.56	4284	126	0.00091
117	B	0	2.25	100	0.56	4212	139	0.00092
118	B	0	1.75	100	0.52	4908	148	0.00088
119	F	0	2.75	100	0.52	3052	0	0.00058
120	F	0	2.25	100	0.52	6690	89	0.00052
121	F	0	1.75	100	0.48	6196	114	0.00047
122	F	0	2.75	100	0.56	4294	28	0.00058
123	F	0	2.25	100	0.56	6263	120	0.00053
124	F	0	1.75	100	0.52	5503	130	0.00049

Table 49. Concrete Mix Proportions.

Mix	Mine	Coarse Aggregate, pcy	Silica Sand, pcy	Screenings, pcy	Cement, pcy	Fly Ash, pcy	Water, pcy
2	M	1780.3	0.0	1181.3	658	0.0	269.8
3	M	1780.3	0.0	1181.3	527	131.6	269.8
4	M	1499.0	0.0	1499.0	658	0.0	269.8
5	M	1499.0	0.0	1499.0	527	131.6	274.0
6	M	1848.3	430.3	432.0	658	0.0	269.8
7	M	1848.3	430.3	432.0	527	131.6	269.8
9	M	1780.0	0.0	1018.6	752	0.0	308.3
11	M	1780.0	0.0	1018.6	602	150.5	308.3
12	M	1834.7	480.6	490.7	752	0.0	304.2
13	M	1834.7	480.6	488.9	602	150.5	308.3
14	M	1847.8	215.2	645.5	658	0.0	269.8
15	M	1847.8	215.2	645.5	527	131.6	269.8
16	M	1401.7	0.0	1415.7	752	0.0	308.3
17	M	1401.7	0.0	1415.7	602	150.5	308.3
24	M	1834.2	242.3	727.2	752	0.0	304.2
25	M	1834.2	242.3	741.6	602	150.5	308.3
26	M	1779.8	941.4	310.9	658	0.0	265.7
27	M	1779.8	914.0	304.7	527	131.6	265.7
28	M	1779.8	752.6	250.9	752	0.0	308.3
29	M	1779.8	774.0	260.6	602	150.5	308.3
33	M	1621.8	0.0	1135.8	752	0.0	278.2
34	M	1621.8	284.4	851.4	752	0.0	278.2
35	M	1618.2	567.0	567.0	752	0.0	278.2
36	M	1618.2	851.4	284.4	752	0.0	278.2
37	M	1780.2	295.2	887.4	658	0.0	243.5
38	M	1690.2	561.6	561.6	658	0.0	243.5
39	M	1779.8	887.4	295.2	658	0.0	243.5
40	M	1779.8	295.7	887.6	658	131.6	246.2
41	M	1779.8	591.8	591.8	658	131.6	246.2
42	M	1779.8	887.6	295.7	658	131.6	246.2
44	M	1618.6	0.0	1135.1	752	150.5	281.3
45	M	1618.6	283.7	851.4	752	150.5	281.3
46	M	1618.6	567.5	567.5	752	150.5	281.3
47	M	1618.6	851.4	283.7	752	150.5	281.3
48	M	1779.8	0.0	1183.5	658	0.0	243.5
49	M	1779.8	0.0	1183.5	658	131.6	246.2
50	M	1490.4	0.0	1490.4	658	0.0	243.5
51	M	1490.4	0.0	1490.4	658	131.6	246.2
52	M	1440.9	0.0	1440.9	752	0.0	278.2
53	M	1440.9	0.0	1440.9	752	150.5	281.3
54	M	1981.0	0.0	906.7	658	0.0	269.8

Mix	Mine	Coarse Aggregate, pcy	Silica Sand, pcy	Screenings, pcy	Cement, pcy	Fly Ash, pcy	Water, pcy
55	M	1999.1	0.0	777.3	752	0.0	308.3
56	M	1981.5	0.0	976.1	658	0.0	243.5
57	M	2004.8	0.0	851.0	752	0.0	278.2
59	M	1780.0	0.0	1181.0	394.8	263.2	269.8
60	M	1780.0	0.0	1003.5	451.2	300.8	308.3
61	M	1780.0	0.0	1479.3	394.8	263.2	243.5
62	M	1780.0	0.0	1418.9	451.2	300.8	278.2
201	C	1951.0	0.0	1005.1	658	0.0	269.8
202	C	1951.0	0.0	1005.1	526.4	131.6	269.8
203	C	1951.0	0.0	826.9	752	0.0	308.3
204	C	1951.0	0.0	826.9	601.6	150.4	308.3
205	C	1951.0	0.0	1072.3	658	0.0	243.5
206	C	1951.0	0.0	1072.3	526.4	131.6	243.5
207	C	1951.0	251.3	778.9	658	0.0	269.8
208	C	1951.0	502.6	502.6	658	0.0	269.8
209	C	1951.0	778.9	251.3	658	0.0	269.8
210	C	1951.0	206.8	620.3	752	0.0	308.3
211	C	1951.0	413.5	413.5	752	0.0	308.3
212	C	1951.0	620.3	206.8	752	0.0	308.3
213	C	1951.0	268.0	804.2	658	0.0	243.5
214	C	1951.0	536.2	536.2	658	0.0	243.5
215	C	1951.0	804.4	268.0	658	0.0	243.5
216	C	1951.0	251.3	778.9	526.4	131.6	269.8
217	C	1951.0	502.6	502.6	526.4	131.6	269.8
218	C	1951.0	777.6	251.3	526.4	131.6	269.8
219	C	1951.0	210.1	642.2	601.6	150.4	308.3
220	C	1951.0	419.6	428.2	601.6	150.4	308.3
221	C	1951.0	629.3	214.0	601.6	150.4	308.3
222	C	1950.1	272.0	832.9	526.4	131.6	243.5
223	C	1950.1	540.5	552.1	526.4	131.6	243.5
224	C	1950.1	810.7	276.1	526.4	131.6	243.5
225	C	1950.1	0.0	937.1	752	0.0	278.2
226	C	1950.1	226.3	686.5	752	0.0	278.2
227	C	1950.1	457.0	452.7	752	0.0	278.2
228	C	1950.1	682.4	235.6	752	0.0	278.2
229	C	1951.8	0.0	905.3	601.6	150.4	278.2
230	C	1951.8	226.3	678.9	601.6	150.4	278.2
231	C	1951.8	452.5	452.5	601.6	150.4	278.2
232	C	1951.8	678.9	226.3	601.6	150.4	278.2
233	C	1471.3	0.0	1531.3	657.9	0.0	243.4
234	C	1770.7	0.0	1234.8	657.9	0.0	243.4
235	C	1381.3	0.0	1381.3	751.86	0.0	308.3

Mix	Mine	Coarse Aggregate, pcy	Silica Sand, pcy	Screenings, pcy	Cement, pcy	Fly Ash, pcy	Water, pcy
236	C	1662.3	0.0	1108.3	751.86	0.0	308.3
237	C	1505.3	0.0	1505.3	657.9	0.0	243.4
238	C	1811.5	0.0	1099.8	657.9	0.0	243.4
239	C	1421.1	0.0	1421.1	751.86	0.0	278.2
240	C	1709.6	0.0	1139.8	751.86	0.0	278.2
241	C	1471.2	0.0	1471.2	526.4	131.6	269.8
242	C	1770.7	0.0	1180.4	526.4	131.6	269.8
243	C	1381.3	0.0	1381.3	601.6	150.4	308.3
244	C	1662.4	0.0	1108.4	601.6	150.4	308.3
245	C	1505.3	0.0	1505.3	526.4	131.6	243.5
246	C	1811.7	0.0	1207.7	526.4	131.6	243.5
247	C	1421.0	0.0	1421.0	601.6	150.4	278.2
248	C	1709.6	0.0	1139.8	601.6	150.4	278.2
249	C	1471.2	0.0	1471.2	526.4	131.6	269.8
250	C	1951.0	0.0	827.0	451.2	300.8	308.3
251	C	1951.0	0.0	1072.3	394.8	263.2	243.5
252	C	1951.7	0.0	905.2	451.2	300.8	278.2
253	C	1358.6	0.0	610.6	658	0.0	269.8
254	C	1999.4	0.0	763.8	752	0.0	308.3
255	C	2057.1	0.0	1013.3	658	0.0	243.5
256	C	2004.2	0.0	850.8	752	0.0	278.2
257	C	1951.0	0.0	1005.1	394.8	263.2	269.8
301	F	1958.6	0.0	897.2	658	0.0	269.8
302	F	1958.6	224.4	672.8	658	0.0	269.8
303	F	1958.6	448.7	448.7	658	0.0	269.8
304	F	1958.6	672.8	224.4	658	0.0	269.8
305	F	1409.4	0.0	1409.4	658	0.0	269.8
306	F	1703.2	0.0	1135.6	658	0.0	269.8
307	F	1958.6	0.0	759.0	752	0.0	308.3
308	F	1958.6	189.8	569.2	752	0.0	308.3
309	F	1958.6	379.6	379.6	752	0.0	308.3
310	F	1958.6	569.2	189.8	752	0.0	308.3
311	F	1334.3	0.0	1334.3	752	0.0	308.3
312	F	1614.6	0.0	1076.2	752	0.0	308.3
313	F	1958.6	0.0	958.8	658	0.0	243.5
314	F	1958.6	239.8	719.0	658	0.0	243.5
315	F	1958.6	479.5	479.5	658	0.0	243.5
316	F	1958.6	719.0	239.8	658	0.0	243.5
317	F	1441.3	0.0	1441.3	658	0.0	243.5
318	F	1741.8	0.0	1161.3	658	0.0	243.5
319	F	1958.6	0.0	829.4	752	0.0	278.2
320	F	1958.6	207.4	622.1	752	0.0	278.2

Mix	Mine	Coarse Aggregate, pcy	Silica Sand, pcy	Screenings, pcy	Cement, pcy	Fly Ash, pcy	Water, pcy
321	F	1958.6	414.7	414.7	752	0.0	278.2
322	F	1958.6	622.1	207.4	752	0.0	278.2
323	F	1357.8	0.0	1357.8	752	0.0	278.2
324	F	1647.5	0.0	1098.4	752	0.0	278.2
325	F	1958.6	0.0	897.2	526.4	131.6	269.8
326	F	1958.6	0.0	759.0	601.6	150.4	308.3
327	F	1958.6	0.0	958.8	526.4	131.6	243.5
328	F	1958.6	224.4	672.8	526.4	131.6	269.8
329	F	1958.6	448.7	448.7	526.4	131.6	269.8
330	F	1958.6	672.8	224.3	526.4	131.6	269.8
331	F	1958.6	189.8	569.2	601.6	150.4	308.3
332	F	1958.6	379.6	379.5	601.6	150.4	308.3
333	F	1958.6	569.2	189.7	601.6	150.4	308.3
334	F	1958.6	239.8	719.1	526.4	131.6	243.5
335	F	1958.6	479.4	479.4	526.4	131.6	243.5
336	F	1958.6	719.1	239.7	526.4	131.6	243.5
337	F	1958.6	0.0	829.4	526.4	131.6	243.5
338	F	1958.6	207.4	622.1	526.4	131.6	243.5
339	F	1958.6	414.7	414.7	526.4	131.6	243.5
340	F	1958.6	622.1	207.4	526.4	131.6	243.5
350	F	1958.6	0.0	829.4	752	0.0	278.2
351	F	1958.6	207.4	622.1	752	0.0	278.2
352	F	1958.6	414.7	414.7	752	0.0	278.2
353	F	1958.6	622.1	207.4	752	0.0	278.2
354	F	1357.8	0.0	1357.8	752	0.0	278.2
355	F	1647.5	0.0	1098.4	752	0.0	278.2
356	F	1958.6	0.0	829.4	601.6	150.4	278.2
357	F	1958.6	207.4	622.1	601.6	150.4	278.2
358	F	1958.6	414.7	414.7	601.6	150.4	278.2
359	F	1958.6	622.1	207.4	601.6	150.4	278.2
360	F	1958.6	0.0	897.2	394.8	263.2	269.8
361	F	1958.6	0.0	759.0	451.2	300.8	308.3
362	F	1958.6	0.0	958.8	394.8	263.2	243.5
363	F	1958.6	0.0	829.4	451.2	300.8	278.2
401	B	1664.6	0.0	1151.6	658	0.0	269.8
402	B	1664.6	287.6	861.8	658	0.0	269.8
403	B	1664.6	574.6	574.6	658	0.0	269.8
404	B	1664.6	861.8	287.3	658	0.0	269.8
405	B	1384.0	0.0	1384.0	658	0.0	269.8
406	B	1664.3	0.0	995.2	752	0.0	308.3
407	B	1664.3	248.8	746.4	752	0.0	308.3
408	B	1664.3	497.6	497.6	752	0.0	308.3

Mix	Mine	Coarse Aggregate, pcy	Silica Sand, pcy	Screenings, pcy	Cement, pcy	Fly Ash, pcy	Water, pcy
409	B	1664.3	746.4	248.8	752	0.0	308.3
410	B	1302.8	0.0	1302.8	752	0.0	308.3
411	B	1664.6	0.0	1208.5	658	0.0	243.5
412	B	1664.6	302.1	906.4	658	0.0	243.5
413	B	1664.6	604.3	604.3	658	0.0	243.5
414	B	1664.6	906.4	302.1	658	0.0	243.5
415	B	1415.3	0.0	1415.3	658	0.0	243.5
416	B	1664.6	0.0	1062.2	752	0.0	278.2
417	B	1664.6	265.5	796.6	752	0.0	278.2
418	B	1664.6	531.1	531.1	752	0.0	278.2
419	B	1664.6	796.6	265.5	752	0.0	278.2
420	B	1338.7	0.0	1338.7	752	0.0	278.2
421	B	1664.6	0.0	1149.1	526.4	131.6	269.8
422	B	1664.6	287.3	861.8	526.4	131.6	269.8
423	B	1664.6	574.6	574.6	526.4	131.6	269.8
424	B	1664.6	861.8	287.3	526.4	131.6	269.8
425	B	1664.3	0.0	995.2	601.6	150.4	308.3
426	B	1664.3	248.8	746.4	601.6	150.4	308.3
427	B	1664.3	497.6	497.6	601.6	150.4	308.3
428	B	1664.3	746.4	248.8	601.6	150.4	308.3
429	B	1664.6	0.0	1208.5	526.4	131.6	243.5
430	B	1664.6	302.1	906.4	526.4	131.6	243.5
431	B	1664.6	604.3	604.3	526.4	131.6	243.5
432	B	1664.6	906.4	302.1	526.4	131.6	243.5
433	B	1664.6	0.0	1062.2	601.6	150.4	278.2
434	B	1664.6	265.5	796.6	601.6	150.4	278.2
435	B	1664.6	531.1	531.1	601.6	150.4	278.2
436	B	1664.6	796.6	265.5	601.6	150.4	278.2
437	B	1936.4	0.0	886.4	658	0.0	269.8
438	B	1920.5	0.0	746.8	752	0.0	308.3
439	B	1931.0	0.0	951.1	658	0.0	243.5
440	B	1919.4	0.0	814.9	752	0.0	278.2
441	B	1664.6	0.0	1149.1	394.8	263.2	269.8
442	B	1664.3	0.0	995.2	451.2	300.8	308.3
443	B	1664.6	0.0	1208.5	394.8	263.2	243.5
444	B	1664.6	0.0	1062.2	451.2	300.8	278.2
445	B	1785.2	0.0	1190.2	752	0.0	308.3

Table 50. Summery of Concrete Test Results.

MIX	Admixture fl oz/100 lbs cementitious material	Air Content, %	Slum, in	Unit Weight, pcf	28-Days Compressive strength, psi	28-Days Splitting Tensile strength, psi	Elastic Modulus. psi	Poisson ratio	Electrical Resistivity KΩ̃cm
2	4.42	2.5	6.5	142.6	7557	605.54	5257583	0.23	8.19
3	4.42	2	6.5	141.5	5954	579.55	4974900	0.28	7.22
4	2.17	3.4	2.5	142.1	7007	370.48	6270056	0.34	7.29
5	4.27	2.5	7.8	140.9	5413	440.18	5383483	0.34	7.66
6	4.34	2.7	7.25	143.4	7305	434.12	5374727	0.25	11.8
7	0.00	2.5	8.5	143.3	6730	589.17	4804545	0.25	8.25
9	2.02	2.2	7.5	141.2	6467	625.23	4331542	0.23	6.89
11	2.02	2.2	3.75	140.4	5695	445.45	4476675	0.28	6.51
12	0.00	2.1	8.3	141.7	6456	468.13	4405333	0.23	5.2
13	0.00	1.7	8.5	140.8	5686	327.93	4385500	0.28	6.13
14	2.17	2.4	3	143.4	7737	371.34	4919654	0.21	7.81
15	2.17	2.3	2.7	143.0	6429	598.31	5940677	0.31	7.45
16	2.02	3.4	7.25	141.0	7525	482.71	4694308	0.21	6.1
17	2.02	2.6	3.5	141.4	6772	553.97	4627583	0.23	5.9
24	4.10	2.3		144.0	8337	588.63	4863000	0.2	8.52
25	1.21	2.1	3	143.8	7065	592	5063625	0.23	8.92
26	14.09	2.9	7.25	146.7	6993	509.69	6017667	0.34	11.18
27	4.70		4	143.0	8091	477.21	5480708	0.23	10.57
28	2.02	3.1	6	142.3	7407	388.71	4993625	0.23	8.54
29	0.81	2.4	6	143.4	6568	554.23	4938182	0.25	7.25
33	4.86	3.3	7	143.7	9398	528.79	5759923	0.21	10.14
34	3.24	2.8	4.5	145.2	9006	554.96	5278500	0.2	8.31
35	3.24	3.4	4	144.0	9227	457.52	5343750	0.2	9.54
36	3.24	2.9	8.5	144.1	9292	634.04	5394750	0.2	9.37
37	2.40	2.9	7	140.4	7414	496.43	4766192	0.21	6.95
38	2.31	2.8	7.5	143.2	7672	671.7	5102708	0.23	7.62
39	9.25	1.6	8.25	147.0	8793	625.43	4199176	0.18	12.83
40	0.91	2.2	4.75	141.4	5512	448.44	4443600	0.28	7.13
41	1.83	2.2	3.5	142.2	6344	592.88	4975950	0.28	7.35
42	1.65	2.2	3.5	143.8	6621	585.85	5131700	0.28	7.64
44	2.96	2.7	3	141.9	8486	654.99	4992750	0.2	7.7
45	3.60	3.9	5.25	142.7	8439	626.75	5062077	0.21	9.24
46	3.60	3	6.5	143.4	8541	580.48	5174346	0.21	9.38
47	2.40	3	7	143.4	8030	588.84	5453583	0.23	8.86
48	6.47	3.6	7.25	144.8	9500	617.41	5664500	0.2	8.99
49	6.40	2.1	7	144.6	8788	609.91	5151000	0.2	9.49
50	7.86	3.2	7.25	144.3	9717	673.82	5133625	0.21	8.82
51	14.18	2.2	7.5	144.6	6727	602.42	5033255	0.25	9.42
52	24.28	3.5	8	145.3	10356	758.6	5696833	0.2	11.1
53	10.73	2.9	7.75	143.9	7900	656.05	5524591	0.25	9.28

MIX	Admixture fl oz/100 lbs cementitious material	Air Content, %	Slum, in	Unit Weight, pcf	28-Days Compressive strength, psi	28-Days Splitting Tensile strength, psi	Elastic Modulus. psi	Poisson ratio	Electrical Resistivity KΩ̃cm
54	6.94	1.2	4.75	143.6	7391	592.22	5005292	0.23	7.42
55	7.28	1.2	5.75	143.6	7885	605.27	4945231	0.21	7.62
56	7.77	2.1	6.5	143.1	7748	581.01	4809808	0.21	7.34
57	8.74	2.1	4.25	142.8	8665	516.85	4899767	0.2	8.95
59	10.68	0.7	6	140.9	6674	430.54	4309083	0.23	11.33
60	3.64	2.1	3	140.0	6102	498.09	4036375	0.23	9.71
61	14.57	0.7	6.5	142.4	6553	443.93	5292350	0.28	11.35
62	7.53	1.3	7.75	140.6	6831	464.28	4586458	0.23	9.98
201	4.16	2.5	5.75	142.7	7334	554.17	4453000	0.2	8.32
202	6.94	2.5	6.5	143.6	6668	524.2	4558750	0.23	12.9
203	6.07	2.5	4	143.6	7801	529.57	4820038	0.21	10.38
204	4.25	2.4	3	142.8	7066	567.95	4866167	0.23	8.39
205	24.97	0.8	4	146.3	7812	188.59	5243583	0.23	9.33
206	0.00	1.3	6.5	145.6	7689	390.57	5077625	0.23	9.6
207	6.94	3.6	3.25	142.0	7870	299.29	5323208	0.23	9.99
208	2.91	2.3	7	143.0	6401	224.32	4292167	0.23	6.81
209	1.39	2.3	5.75	146.3	6440	501.2	5304600	0.28	7.35
210	4.86	2.6	5.5	143.7	7593	498.35	5253500	0.23	8.23
211	2.43	2.4	4.25	143.0	7523	538.66	6150550	0.28	6.89
212	3.64	2.9	5.5	144.0	7926	586.98	4788250	0.2	7.85
213	17.34	3.2	7.75	146.6	8713	430.34	5143250	0.2	11.16
214	26.36	2.1	7.5	147.0	8948	649.55	5627192	0.21	10.8
215	5.55	3.3	3.5	144.3	8659	657.71	5303750	0.2	10.34
216	3.88	2.2	3.75	142.2	5439	511.54	4445350	0.28	7.41
217	1.39	2.2	4.25	141.8	5491	496.16	4401950	0.28	7.59
218	0.00	2.1	5.75	142.2	5369	500.87	4463900	0.28	7.53
219	3.64	2.2	3	142.0	6548	483.17	4807091	0.25	8.01
220	3.04	2.3	3.75	141.0	6621	555.29	3605233	0.21	8.42
221	1.21	2.2	3.5	141.5	6540	393.35	5331500	0.28	7.45
222	11.38	2.1	6.75	145.4	7328	416.09	5786900	0.28	9.63
223	9.71	2.2	3	145.3	7951	666.26	5440750	0.23	11.2
224	8.32	2.2	3	144.2	7828	625.56	5708818	0.25	11.41
225	8.50	2.5	4.25	144.5	8231	677.66	5010115	0.21	9.36
226	5.22	2.3	6	143.3	7684	673.95	5297542	0.23	8.88
227	6.68	2.2	5.5	146.1	8475	489.2	5670269	0.21	9.51
228	4.25	3.1	5.5	145.1	7737	620.79	5275083	0.23	9.4
229	30.35	0.9	8.5	145.8	6062	553.3	4855200	0.28	8.01
230	22.46	1.2	8	145.4	6626	510.75	4835091	0.25	8.12
231	12.14	1.3	6	142.4	7176	625.89	4790917	0.23	8.01
232	26.71	0.65	9	147.6	7555	660.96	5392962	0.21	10.16
233	8.51	2.2	7.5	144.7	7873	530.3	4627500	0.2	7.34
234	7.40	2.2	3	146.0	8386	681.44	4984808	0.21	9.38

MIX	Admixture fl oz/100 lbs cementitious material	Air Content, %	Slum, in	Unit Weight, pcf	28-Days Compressive strength, psi	28-Days Splitting Tensile strength, psi	Elastic Modulus. psi	Poisson ratio	Electrical Resistivity KΩ̃cm
235	15.38	1.3	9.5	146.6	8112	669.84	5088192	0.21	8.96
236	6.48	2.2	9.75	143.8	6636	538.59	4773364	0.25	7.24
237	33.77	1.1	9	146.6	7011	451.62	5194955	0.25	8.4
238	18.50	1.3	7.25	148.3	7146	600.5	5272909	0.25	7.12
239	16.19	1.4	9	146.0	8643	602.42	4971500	0.2	7.84
240	6.48	2.4	5.25	144.7	7037	523.01	4713625	0.23	7.01
241	65.21	1.9	0	147.2	6333	501.07	4358667	0.23	9.96
242	18.04	1.2	7.25	145.0	7900	613.43	4651250	0.2	10.68
243	13.96	1.6	9	144.9	8430	630.46	4575433	0.23	8.8
244	15.18	1.2	9	145.2	7995	517.84	4771846	0.21	8.2
245	48.56	2.1	7.5	144.0	5758	474.55	4417000	0.25	9.61
246	59.66	0.9	6.5	145.8	5285	512.8	4264273	0.25	8.36
247	21.85	1.3	8.5	143.8	6272	521.09	4171708	0.23	7.61
248	25.50	1	9.5	145.7	6947	517.97	4597654	0.21	7.89
249	31.91	1.7	7	143.0	5189	461.65	3780000	0.25	9.85
250	12.14	1.3	8.75	141.6	5784	479.99	4391227	0.25	10.55
251	38.85	0.9	7.75	144.5	5546	534.55	4667600	0.28	10.67
252	13.35	1.2	8.5	141.8	6278	532.29	4442773	0.25	10.54
253	8.32	3.2	7.5	133.8	6639	664.93	4668682	0.25	8.96
254	4.86	1.9	3	142.4	7605	519.3	4134433	0.21	7.34
255	10.41	1.3	4	142.8	5857	545.48	4693500	0.23	9.36
256	10.32	0.7	3	145.8	8844	626.22	4933367	0.23	8.59
257	9.71	1.5	5.25	142.1	6486	574.91	4241708	0.23	12.32
301	3.47	3.3	4.125	142.0	5781	430.66	4534091	0.28	6.55
302	7.21	2.1	5.25	145.4	7331	526.33	3583806	0.18	6.95
303	5.55	2.2	7	144.1	6446	416.09	4603375	0.25	7.11
304	4.44	3.2	9	142.5	6484	525	5005955	0.28	6.89
305	9.57	3.8	10.5	140.4	7179	390.57	4163367	0.2	6.69
306	5.83	3.3	4	141.3	6685	401.31	3891767	0.2	5.4
307	5.83	2.2	5.75	143.4	6429	497.76	3794233	0.2	5.61
308	3.64	2.2	3.5	141.0	6054	409	3551567	0.2	6.08
309	3.64	3.1	6	140.9	7318	308.84	4267433	0.2	5.82
310	2.06	2.2	7.5	142.0	6496	570.08	3674767	0.2	5.13
311	4.49	3.6	8.5	140.4	6728	591.16	3828067	0.2	5.1
312	5.46	2.2	9	141.4	6894	592.68	3997700	0.2	6.12
313	8.74	3.4	4.5	140.4	6164	337.47	4760000	0.28	7.05
314	15.26	1.1	7	146.8	8670	444.59	4744906	0.21	6.83
315	20.81	0.6	8.75	146.9	8419	403.23	3930684	0.21	8.19
316	9.71	2.1	4.5	146.5	8605	347.81	5364000	0.21	9.04
317	19.42	1.5	8.75	145.1	8354	525.8	4871300	0.2	7.27
318	13.18	1.9	6.75	145.1	7748	509.89	4545333	0.2	7.75
319	6.07	1.4	3.75	142.7	7377	384.4	4435433	0.2	7.3

MIX	Admixture fl oz/100 lbs cementitious material	Air Content, %	Slum, in	Unit Weight, pcf	28-Days Compressive strength, psi	28-Days Splitting Tensile strength, psi	Elastic Modulus. psi	Poisson ratio	Electrical Resistivity KΩ̃cm
320	7.89	1.8	8	144.8	7504	469.78	5089538	0.23	7.68
321	5.46	2.2	5.5	143.3	7409	424.91	4908885	0.23	7.92
322	5.46	2.1	3.25	144.8	7620	416.09	5367654	0.23	7.2
323	7.89	3.2	7.5	142.5	7819	468.46	4337813	0.21	9.23
324	7.04	2.2	5.75	143.7	7429	462.89	4582200	0.2	6.56
325	18.04	1.2	7.5	144.7	7571	553.11	4694750	0.21	7.85
326	12.14	1.3	7.5	144.1	7770	557.55	4476267	0.2	7.67
327	10.41	2.3	6.25	142.7	7397	509.22	4943077	0.23	8.32
328	19.42	1.5	8.5	146.8	6904	546.01	5040292	0.25	8.81
329	12.49	1.2	7	144.2	7798	526.86	5256192	0.23	8.74
330	5.27	2.2	7.5	142.4	5905	502.74	4197136	0.25	8.29
331	8.50	1.2	7	141.9	6942	508.1	4363423	0.21	7.28
332	4.25	2.1	3	142.7	6454	549.73	4385792	0.23	7.41
333	4.86	2	8	142.8	6448	494.44	4623500	0.25	6.98
334	15.26	0.6	8	144.7	7469	536.2	5015208	0.23	9.13
335	6.24	2.1	6.75	142.9	6365	570.8	4577364	0.25	7.41
336	6.94	1.9	4.5	143.6	7196	602.89	5242682	0.25	9.51
337	6.24	1.9	3	140.2	5947	483.04	4438000	0.25	6.83
338	9.57	2.1	3	143.6	7065	412.97	4686792	0.23	7.63
339	6.94	2.3	7	137.2	6745	516.85	4668125	0.23	7.81
340	6.80	2.1	8	137.9	6624	495.17	3834750	0.2	8.46
350	12.14		2.75	134.9	5870	331.57	4586400	0.28	9.23
351	7.28	2.3	3	141.8	7312	445.06	5046417	0.23	7.93
352	6.68	2.4	8	138.7	7986	602.49	5041346	0.21	9.2
353	6.68	2.3	7	141.3	8374	653.66	5686917	0.23	8.68
354	10.32	2.8	3.75	144.0	8532	623.17	4150588	0.28	6.78
355	9.11	2	4	144.6	7882	537.26	4863385	0.21	6.77
356	8.50	1.3	6	140.7	7166	532.49	4545154	0.21	6.84
357	6.68	2.1	3	142.8	7295	532.95	4518769	0.21	7.05
358	6.07	2	5.75	142.4	7239	550.72	4541385	0.21	7.3
359	4.25	2.27	4.75	142.4	7066	621.58	4918958	0.23	8.25
360	8.19	1.9	5.25	139.4	6115	545.68	4265333	0.23	10.7
361	8.86	2	4.5	140.2	6670	531.56	4241462	0.21	10.82
362	11.52	2	4	141.2	5483	483.64	2837625	0.2	10.31
363	6.07	2.1	5	138.5	5247	447.18	3009500	0.2	9.09
401	20.81	1.3	8	141.0	6366	360.34	4434208	0.25	5.98
402	17.62	2.2	3.25	143.9	7518	492.05	4371500	0.2	7.09
403	8.32	3.3	3	142.5	7215	431.87	5329042	0.25	6.97
404	6.94	3.4	3.5	145.0	8016	483.17	5355538	0.23	8.65
405	20.81	2.2	6.5	143.2	6818	379.56	5998650	0.31	6.08
406	6.68	3.1	3	140.8	6595	450.69	4126500	0.21	5.48
407	6.43	2.2	5.75	140.4	6889	476.78	4314692	0.21	6.14

MIX	Admixture fl oz/100 lbs cementitious material	Air Content, %	Slum, in	Unit Weight, pcf	28-Days Compressive strength, psi	28-Days Splitting Tensile strength, psi	Elastic Modulus. psi	Poisson ratio	Electrical Resistivity KΩ̃cm
408	8.38	2.1	3	141.9	7425	496.03	4623500	0.21	7.32
409	9.23	2.3	3	144.5	7963	552.97	5589208	0.23	10.69
410	7.28	3.2	6.5	137.6	6050	508.03	3846231	0.21	5.2
411	21.51	2.2	4.5	142.7	6676	484.76	4053000	0.21	6.71
412	16.65	4.7	8.5	141.0	6679	552.44	4974958	0.25	7.17
413	15.96	2.3	3	144.5	7726	533.62	4951250	0.21	8.79
414	13.18	2.1	3.25	146.0	8336	645.38	5223250	0.21	10.21
415	22.89	2.1	5.5	143.4	6693	483.37	4870833	0.25	6.88
416	12.14	3.1	5.5	139.3	6229	563.58	4009385	0.21	6.71
417	10.68	3.2	3	140.0	6908	565.37	4868500	0.23	6.99
418	12.14	3.2	3.25	143.0	7889	635.83	4934731	0.21	7.79
419	5.58	3.1	3.75	141.4	7076	592.81	4702833	0.23	8.08
420	13.35	3.4	4.75	140.2	6696	565.7	4530750	0.23	6.55
421	15.26	2.2	5	141.0	5822	437.77	4180909	0.25	7.17
422	13.87	1.5	3	141.0	6574	464.35	4152346	0.21	7.78
423	7.63	2.5	3.25	142.0	6245	452.35	3801808	0.21	7.31
424	6.24	2.2	7.25	141.6	6305	441.34	4732636	0.25	7.74
425	6.07	2.4	3.75	137.4	5305	520.43	3933682	0.25	6.45
426	4.73	2.1	7	138.4	5712	451.09	4256000	0.25	6.93
427	3.04	2.3	6.5	138.6	5660	479.26	4079409	0.25	6.13
428	3.64	2	6.5	140.2	6637	511.88	4534542	0.23	7.26
429	18.73	2	6.5	140.3	6321	462.23	3738250	0.2	8.18
430	12.21	2.6	3.5	142.2	6494	479.46	4443833	0.23	7.57
431	8.32	2	3	143.2	5981	430.67	4007850	0.28	9.14
432	8.60	2.4	4.75	149.1	7193	470.38	5261136	0.25	11.09
433	14.57	2	4	140.5	6818	575.38	4591125	0.23	7.71
434	9.71	1.1	3	141.6	6647	588.24	4535125	0.23	7.65
435	7.28	1.4	3	142.5	7052	608.72	4433962	0.21	8.09
436	6.07	1.4	3	143.4	7211	557.55	4818625	0.23	8.64
437	8.05	3.5	5.5	132.4	4787	533	3739273	0.25	5.17
438	5.83	2.1	7.5	137.8	6679	579.75	3782000	0.2	4.94
439	12.49	2	3.5	142.7	6546	560.66	4105500	0.2	5.32
440	12.14	2.1	7.5	141.0	7326	490.07	4287750	0.2	5.96
441	7.63	2.2	5	137.3	4755	375.12	2983750	0.23	9.98
442	9.71	2.2	4.25	140.1	5881	439.82	3787583	0.23	8
443	20.81	2.3	6.25	140.6	6275	434.25	3849750	0.2	9.17
444	20.64	1.9	3	140.7	5829	491.79	4503722	0.31	10.07
445	8.50	2.1	7.75	136.6	6450	502.99	3948269	0.21	5.29

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