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SUBSTITUTION OF FLY ASH, SLAG, AND ADMIXTURES IN FDOT CONCRETE MIX DESIGN

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16. Abstract

Florida Department of Transportation (FDOT) requires contractors for FDOT's projects to submit a proposed concrete mix design prior to the production of any concrete. The contractor must use mix designs approved by FDOT. Substitutions of ingredients other than coarse aggregate must be justified through trial mixtures, and authorized in writing by FDOT Engineers. The study reported herein investigated whether substitutions of fly ash, slag, air-entraining admixtures, and Types A, D, and G admixtures could be performed and allowed in FDOT approved concrete mix designs. Substitutions of the ingredients were performed on two typical FDOT hot weather mix designs in this study. The concrete properties considered were slump, air content, and compressive strength. Test data for substitution mix designs were compared with the data for the original mix design. Results show that the substitutions cause variability in concrete properties for both the fly ash and slag mix designs. Statistically reliable conclusions cannot be made because of small sample sizes for test data sets. This study is preliminary in nature; more extensive research based on statistically significant sample sizes is needed to validate the findings from this study.

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ABSTRACT

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CHAPTER 1

INTRODUCTION

Concrete is composed principally of aggregates, portland cement, and water, and may contain other cementitious materials such as fly ash or slag and/or chemical admixtures. Concrete mix design is the procedure of ascertaining the mix ingredient proportions involved in a particular batch of concrete to assure that various materials are combined and mixed together properly. A proper mix design satisfies the requirements of strength, durability, workability, safety, economics and other specified elements.

Section 346 of the FDOT Standard Specifications for Road and Bridge Construction (FDOT Specifications [14]) requires the contractors to submit a proposed concrete mix design prior to the production of any concrete. The contractor must use design mixes approved by FDOT for the purpose of quality control. Any change on the approved mix design must be authorized by the FDOT Engineer in writing. In fact, concrete producers are increasingly finding alternatives for concrete ingredients for improvements, innovations and shortage of raw materials. The contractors would like to substitute equivalent ingredients in FDOT mixes with the alternatives. According to FDOT 346 stipulations, such substitution must be justified through the re-testing of approved mix designs. The only allowed exception is the substitution of aggregates, which is specified in Section 346. It states that the aggregates can be substituted with the same type of materials with similar physical and chemical properties to the original aggregate but from different sources. But if unsatisfactory results are obtained with the different source aggregate, the contractor still needs to return to the originally approved aggregate source of supply. This stipulation of substitution means that concrete producers at present may have to re-test and re-batch many FDOT mix designs that were previously approved for a particular mix design, in case of product substitution such as fly ash, cement, slag and admixtures. Even if one product is to be substituted, the process is likely to be very costly in terms of manpower, time and material. In fact, manufacturers who supply concrete products and who may replace one product with another similar product may necessitate the product substitution. Such substitution may affect quite a few concrete producers and may require the re-testing of hundreds of mix designs.

This project was initiated to determine if substitutions of fly ash, slag and admixtures could be made without significant change to the concrete properties. The objective of the study is to demonstrate through experimental work whether the substitution of ingredients with similar products will result in negligible change in the properties of approved FDOT concrete mixes. Such a conclusion will provide the FDOT with background and justification to allow the substitution of the ingredients with similar and economic alternatives in approved mixes without the requirement of re-testing and re-batching.

A parametric study was conducted to meet the objective. Two typical FDOT approved mix designs were used as prototype for substitutions. The substitutions of fly ash, slag and several common admixtures including Type A, D, and G admixtures were investigated. The concrete properties considered are slump, air content, and 28-day compressive strength. A parametric approach was followed, whereby one ingredient was substituted with products from different sources, and other materials were kept constant as in the original mix designs. Conclusion was drawn based on the comparison of the test data for the original mix designs and substitution mix designs.

CHAPTER 2

BACKGROUND REVIEW

A literature review was undertaken to gather information regarding fly ash, slag and admixtures, and the substitution of these ingredients in portland cement concrete. Since the two mix designs investigated in this research were hot weather mix designs, some information related to hot weather concreting was also reviewed. The literature review covered information that was found in authorized guidelines, research reports, referred journals and magazines.

2.1 Fly Ash Concrete

It was suggested that fly ash be incorporated into cement concrete as a supplementary cementing material several decades ago. This incorporation was initiated as a means for eliminating problems associated with disposal of large amounts of by-products from coal burning power plants. Since the 1980s, increasing research has been performed on fly ash concrete [21]. It has been generally accepted that the proper quality and amount of fly ash in a properly proportioned mixture can provide concrete with superior qualities, usually at a lower cost.

Fly ash has been widely used as a replacement of portland cement in concrete, especially in aggressive environments. Table 2.1 shows the requirements for fly ash and slag with different types of cement used in structural concrete under different environmental conditions specified in FDOT Specifications [14]. For moderately and extremely aggressive environment, fly ash or slag

Table 2.1: FDOT Requirements for the Use of Fly ash and Slag with Types of Cement Used in Structural Concrete*

Bridge Superstructures			
Component	**Slightly Aggressive Environment**	**Moderately Aggressive Environment**	**Extremely Aggressive Environment**
Precast Superstructure and Prestressed Elements	Type I, Type II, Type III, Type IP, Type IS, or Type IP (MS)	Type I, Type II, and Type III all with Fly Ash or Slag; Type IP, Type IS, or Type IP (MS)	Type II with Fly Ash or Type II with Slag
C.I.P. Superstructure Slabs and Barriers	Type I, Type II, Type IP, Type IS, or Type IP (MS)	Type I with Fly Ash or Slag; Type II, Type IP, Type IS, or Type IP (MS)	Type II with Fly Ash or Type II with Slag
Bridge Substructure, Drainage Structures, and Other Structures			
Component	**Slightly Aggressive Environment**	**Moderately Aggressive Environment**	**Extremely Aggressive Environment**
All Structure Components	Type I, Type II, Type III, Type IP, Type IS, or Type IP (MS)	Type I with Fly Ash or Slag; Type II, Type IP (MS), or Type IS	Type II with Fly Ash or Type II with Slag

* FDOT Specifications [14] Section 346 Table 1

is required to be used with Type I, II and III cement for all precast superstructure and prestressed elements of bridges. For cast in place superstructure slabs and barriers of bridges, and bridge substructure, drainage structures and other structures, fly ash or slag is required to be used with Type I cement under moderately aggressive environment, and with Type II cement for extremely aggressive environment.

Fly ash is a pozzolanic material obtained as a by-product from combustion of coal. Defined as a mineral admixture in ASTM C-618 [6], fly ash is categorized into two classes: Class F and Class C, according to the chemical composition. The sum of SiO_2, Al_2O_3, and Fe_2O_3 is not less than 70% in Class F fly ash and not less than 50% in Class C Fly ash. Class F fly ash is normally produced from burning anthracite or bituminous coal and has only pozzolanic properties. Class C fly ash is normally produced from lignite or sub-bituminous coal and has pozzolanic properties as well as some cementitious properties [6]. Class N fly ash, which is a naturally occurring material forms when a large amount of ground water in a volcano conduit meets with silica rich magma. Water dissolves into the magma of the volcano, under high temperature and high pressure, mixing with the sulfur gases and the dissolved carbon dioxide. Natural pozzolan can quickly react with calcium hydroxide and can trap the alkali inside cement paste. Thus, it helps to form a denser paste with almost no alkali aggregate reaction at all.

However, fly ashes from the same class still exhibit significant variation in their chemical and physical properties [6]. Such variations make the properties of fresh and hardened concrete highly dependent on the type of fly ash used [3]. The type of cement used also directly influences the cement-fly ash reaction. Thus, it is suggested that the users of fly ash concrete always make trial mixtures for the ingredients to be used in any project to ensure that the desired characteristics of the concrete are attained. It is also recommended that such trials include the admixtures to be used as well as the cement, fly ash, and aggregate [15].

The percentage of fly ash in the cementitious materials can greatly affect the properties of concrete. FDOT Specifications [14] has different requirement on the quantity of cementitious materials replaced with fly ash for different types of concrete. For mass concrete, the limit is from 18 to 50%, drilled shaft concrete, 35 $\pm$ 2%, and other concrete from 18 to 22% by weight of the total cementitious content.

The incorporation of fly ash into concrete affects fresh concrete in such aspects as workability, bleeding, pumpability, durability and time of setting of concrete. The spherical shape of most fly ash particles permits greater workability for equal water-cement ratios, or in other words, the water-cement ratio can be reduced for equal workability. Class F fly ash generally increases the time of setting, which is usually considered advantageous for highway construction, as do most Class C fly ash. However, some Class C materials are reported to reduce the time of setting, and others have no effect [15].

Fly ash also affects the properties of hardened concrete. These include temperature rise, strength and rate of strength gain, resistance to damage from freezing and thawing, resistance to ingress of aggressive liquids and reinforcing bar corrosion, alkali-silica reaction, resistance to chlorides and sulfates and a number of other properties. Fly ash concrete develops less heat per unit time at early ages than does similar concrete without fly ash. This characteristic significantly reduces the temperature rise in large masses of concrete, and consequently reduces the risk of thermal cracking. Pozzolanic reactions that occur at a slower rate also provide for equal or greater ultimate strength for such concrete with fly ash than is attained by concrete without fly ash. Concrete using fly ash with proper pozzolanic properties (as defined in ASTM C 618 [6]) can ultimately develop greater strength than similar concrete without fly ash. However, this effect is still dependent on characteristics of the fly ash, the proportions of fly ash to cement, and the curing regimen. It has been reported that resistance of concrete to sulfate attack can be improved by the use of Class F fly ash. There is some evidence that Class C fly ash may reduce sulfate resistance when used in normal proportions. The resistance of fly ash concrete to damage from freezing and thawing, as with all other concrete, depends on the adequacy of the air-void system, the soundness of the aggregates, age, strength, and moisture condition. Even with adequate entrained air, fly ash concrete has a lower resistance to freezing and thawing than concrete without fly ash. However while the comparisons were made under conditions that ensure the fly ash concrete has developed adequate strength, no significant differences were observed [15].

A major concern of transportation agencies using fly ash concrete is ensuring that the desired air content is obtained in the hardened concrete. Fly ash concrete requires more air-entraining agents than regular concrete to obtain a given amount of air in the hardened concrete. Two reasons contribute to this phenomenon. First, fly ash is normally finer than cement, and the amounts of fly ash used is usually more than those of the cement replaced, so that the total surface area within the concrete mixture of fly ash concrete is greater than that of the regular concrete. The increased total surface area requires more air-entraining agents to obtain a given amount of air in the concrete. Second, the carbon content in fly ash adsorbs a portion of the air-entraining agent, which decreases the actual portion of the air-entraining agent that can help to entrain stable air bubbles. The amount of the adsorption varies with the amount of carbon content and, possibly, also the form of such carbons [15]. The amount of carbon is related to one of the chemical properties of fly ash, called “loss on ignition”. Therefore, variations in the loss on ignition of fly ash require the amount of air-entraining agent to be varied to entrain a given amount of air. Moreover, research [15] has shown that there can be a significant loss of air with time and possibly erratic behavior for some combinations of ingredients, and that different cements and different air-entraining agents could react differently with the same proportions of other ingredients in the fly ash concrete. It is also noted that the presence of adsorptive carbon in fly ashes may also alter the effectiveness of other admixtures [15].

Poor performance of some fly ash concrete in Virginia resulted from inadequate entrained air in some parts of the projects, while satisfactory results were attained at other portions of the project with the same materials and with adequate entrained air. Other reports in Virginia also exist regarding erratic results of air entrainment in fly ash concrete [15]. However, according to a survey developed among the transportation agencies in North America, most states indicated that problems with erratic amounts of entrained air content for the same ingredients do not occur when the loss on ignition of the fly ash is about 3 percent or less. Nevertheless, it also has been reported that the loss of air with time occurred even when the loss of ignition of fly ash is as low as 2.9 percent [15].

According to ASTM C 618 [6], up to 12% loss on igniting can be allowed for Class F fly ash. FDOT Specifications [14] Section 929 requires that fly ash meet the requirement of ASTM C 618. For fly ashes with high loss on ignition, the Uniformity Requirements in the Supplementary Optional Physical Requirements as specified in ASTM C 618 [6] becomes mandatory when loss on ignition exceeds 5%. No other additional requirement is indicated in FDOT Specifications [14].

2.2 Slag Concrete

Granulated blast furnace slag has been used as a primary or secondary binder in concrete for over 100 years in Europe. The history of the use of slag as an ingredient in quality concrete in North America dates back for 50 years. Granulated blast furnace slag is the most widely investigated and most effective type of slag for cement and concrete manufacturing. It was originally used to be underground with portland cement clinker (blended cement) around 60 years ago. Since the late 1970s, it has been used as a mineral admixture added separately to cement in the mixer. The application of granulated blast furnace slag used as a mineral admixture added separately to cement in concreting is investigated herein. Like fly ash, slag also has been widely used as a replacement of portland cement in concrete under aggressive conditions. Table 2.1 also shows the wide usages of slag in Florida concrete.

Granulated blast furnace slag, also called slag, is the glassy granular material formed when molten blast-furnace slag is rapidly chilled by immersion in water [8]. ASTM classifies slag in three grades: 80, 100, and 120, according to the slag activity index. The index is mainly based on the ratio of the compressive strength of a mortar cube made with 50-50 mass combinations of slag and Portland cement to that of a mortar cube made with a reference cement [8]. For a given mix, the substitution of grade 120 slag for up to 50 percent of the cement will generally yield a compressive strength at 7 days and beyond equivalent to or greater than that of the same concrete without slag. Substitution of grade 100 slag will generally yield an equivalent or greater strength at 28 days. However, concrete made with grade 80 slag will have a lower strength at all ages than regular concrete without slag [20]. FDOT Specifications [14] 929 indicates that only Grade 100 and 120 is permitted in FDOT concrete.

Between 20% to 70% of cementitious material in concrete may be replaced by slag. Research shows that typically 50% is an optimum substitution percentage that produces the greatest 28-day strength, but the percentage also depends on the grade of slag used [20]. FDOT Specifications requires that the quantity of cementitious material replaced with slag be 60 $\pm$ 2% in drilled shaft concrete; not less than 25% or greater than 70% when used in slightly and moderately aggressive environments, and not less than 50% or greater than 70% when used in extremely aggressive environments in other kinds of concrete.

The effects of slag on properties of fresh concrete vary with the replacement level, but generally include improved workability, decreased water demand, and increased setting time. However, the retardation of set time is temperature sensitive and more pronounced at lower temperatures. At about 20 ^{o}C (68 ^{o}F) or in hot climates, finishing times may not be extended (or may be extended by only a few minutes). Slag concrete usually requires a slightly higher (10 – 15%) dosage of admixtures to entrap the equivalent amount of air than does the regular concrete. The reason is believed to be different morphology of the slag particles, as well as their higher fineness and total surface area as compared to that of cement [17]. However, since slag doesn't contain carbon like fly ash, it may not cause problems of instability and air loss in concrete [20].

In reference to hardened concrete, slag can help to enhance the durability of concrete by means of improving its resistance to chloride, sulphate, and alkali-silica reactions, provided that the concrete is properly proportioned and cured. Studies have shown that properly designed slag concrete can have far lower permeability and diffusion coefficients than regular concrete. The low permeability and other chemical characteristics of slag concrete help to improve the resistance to sulphate, chloride corrosion of reinforcement and carbonation-related corrosions of the slag concrete. The freezing and thawing resistance of concrete generally will not be adversely affected by incorporating slag. Slag also has been found to be effective in controlling deleterious expansions from alkali-silica reactivity when used in sufficient quantity [16]. The levels and rate of strength development of slag concrete depend on the properties of the slag, the properties of the portland cement, the relative and total amounts of slag and cement, and the concrete curing temperatures. Slag concrete strengths at 1, 3 and even 7 days may tend to be lower, particularly at low temperatures or at high slag percentages than does the strength of regular concrete without slag. However, studies have shown that compressive strength of slag concrete after 28 days exceeds that of the reference concrete if cured properly [16].

2.3 Chemical Admixtures

AASHTO M 194 [2] defines seven types of chemical admixtures based on their effects on the properties of concrete made with these admixtures. FDOT recognizes the following: Type A—water-reducing admixture, Type C—accelerating admixture, Type D—water-reducing and retarding admixture, Type E—Water-reducing and accelerating admixture, Type F—water reducing, high range admixture, and Type G—water-reducing, high range and retarding admixture. Three of them were involved in this study, Type A, Type D and Type G admixtures. Type A—water-reducing admixture can reduce the quantity of mixing water required to produce concrete of a given consistency. Type D—water-reducing and retarding admixture can reduce the quantity of mixing water required to produce concrete of a given consistency, as well as retards the setting of concrete. Type G—water-reducing, high range and retarding admixture can reduce the quantity of mixing water required to produce concrete of a given consistency by 12% or greater, and retard the setting of concrete [2]. Water reducing admixtures are used to produce concrete of higher strength, obtain specified strength at lower cement content, or increase the slump of a given mix without an increase in water content. Set-retarding admixtures are used primarily to offset the accelerating effect of high ambient temperature and to keep concrete workable during the entire placing period, thereby eliminating form-deflection cracks. High-range water-reducing admixtures, also known as superplasticizers, can be used to produce high-strength concrete with a very low water-cement ratio while maintaining a slump of 76 mm (3 in) or more [4]. It can also increase the initial slump considerably. However, the increase is only transient, and generally not maintained beyond 30-60 min. Several methods are used to control the slump loss. These methods include adding the superplasticizers at the point of discharge, adding a higher than normal dosage, re-dosing the superplasticizers at different intervals of time, etc. [20].

Some considerations in the use of chemical admixtures were pointed out in ACI 212.3R-91 [4]. The effect of an admixture should be evaluated whenever possible by use with the particular materials and intended conditions of use. When the admixture is used for the first time with the particular combination of materials, and/or more than one admixture is to be used, such an evaluation is particularly important. It was also indicated that many admixtures affect more than one property of concrete, sometimes adversely affecting desirable properties, and the effects of some admixtures are significantly modified by such factors as water content and cement content of the mix, by aggregate type and grading, and by type and length of mixing. Appropriate methods of preparation and batching are also important for the successful use of admixtures. In some instances, changing the time of adding the admixtures can alter the effectiveness of the admixture, and possibly, the water requirement.

FDOT Specifications [14] 346 states that chemical admixtures should be used in a dosage rate that is recommend by the manufacturer. However, the dosage rate may be adjusted up to 2.5

times when necessary based on 2000 FDOT specifications. Use of other admixtures may be approved with statistical evidence supporting successful laboratory and field trial mixes which demonstrate improved concrete quality or handling characteristics.

For High Range Water Reducer (HRWR), including Type G, some special requirements are specified in FDOT Specifications [14] 346. When a HRWR mix is proposed without the production of demonstration batches, the Contractor needs to provide a previously approved HRWR mix of the same class, which has demonstrated satisfactory performance under the same job placing conditions with a minimum of fifteen consecutive Department acceptance tests. It is stressed that the cement and water reducing admixtures, not only the proposed HRWR, used in the proposed mix must be the same materials from the same source used in the previously approved mix. Also, the other materials and mix proportions should be approved as similar by the Engineer.

2.4 Air–Entraining Admixtures

AASHTO M 154 [1] defines air-entraining admixture as a material that is used as an ingredient of concrete, added to the batch immediately before or during its mixing, for the purpose of entraining air. The use of the air-entraining admixtures should cause a substantial improvement in durability and none of the essential properties of the concrete should be seriously impaired.

Air entrainment is the process whereby many small air bubbles are incorporated into concrete and become part of the matrix that binds the aggregate together in the hardened concrete. Air entrainment is recommended for several reasons. The entrained air can significantly improve the concrete’s resistance to freezing and thawing attacks. Moreover, air-entrained concrete can also improve the workability of concrete. However, air entrainment usually reduces strength, particularly in concretes with moderate to high cement contents, in spite of the decreased water requirements [1].

The air content and the size distribution of air voids produced in concrete depend on many factors [1]. These factors include the nature and quantity of the air-entraining admixtures, the nature and quantity of the constituents of the concrete mix, the type and duration of mixing employed, the slump of concrete and the kind and degree of consolidation applied in placing the concrete. Numerous other factors also influence the amount of air entrained in concrete. These factors include: the aggregate grading and particle shape, organic impurities in the aggregate, water hardness, cement content and fineness, amount of finely divided materials such as pozzolans, pigments (or bentonite), concrete temperature, presence of other admixtures, water-cement ratio, type and condition of the mixer, amount of concrete being mixed, mixing speed and time, method used to transport concrete after mixing, and type and degree of consolidation. FDOT Specifications [14] 346 requires that all concrete except counterweight concrete should contain an air-entraining admixture. Dosage rates can be established by manufacturers recommendations, and adjusted to meet field conditions.

2.5 Hot Weather Concreting

FDOT Specifications [14] 346 defines hot weather concreting as the production, placing and curing of concrete when concrete temperature at placing exceeds 30^o C (85^o F) but is less than 40^o C (100^o F). The most favorable temperature for freshly mixed concrete is around 10^o to 15.5^{o}C (50^{o}F- 60^{o}F) [18]. However, it is impractical to limit the temperature of placed concrete in this range because circumstances vary widely. Therefore the effects of temperature on concrete's properties must be considered and taken into account while a concrete mix is designed. This is particularly important for mix designs used under hot weather conditions, because hot weather concreting may cause various difficulties. These difficulties include: increased water demand, accelerated slump loss, increased rate of setting, difficulties in controlling entrained air, and critical need for prompt early curing.

For mix designs developed for use under hot weather conditions, a special mixing procedure is specified in FDOT Specifications [14] 346. The trial mix should be prepared at a minimum temperature of 35 ^{o}C (94 ^{o}F), and held in the mixer for 90 minutes after completion of initial mixing. The extended mixing period follows the initial mixing. During the extended mixing period, the mixing drum should be turned intermittently for 30 seconds every 5 minutes, and covered with wet burlap or an impermeable cover material during the rest periods. The mix temperature at the end of the extended mixing period should not be less than 35 ^{o}C (94 ^{o}F).

CHAPTER 3

MIX DESIGNS AND TEST MATRICES

3.1 Mix Designs

Two FDOT approved mix designs containing ingredients to be substituted were selected herein (Appendix A). The original materials used in the mix designs were substituted by same material ingredients form a different source. Concrete was mixed according to the original mix designs and mix designs with substituted ingredients, and tests were performed on the concrete. Comparison of the test results was made to analyze the influences that the substitutions can cause on concrete's properties.

Because fly ash and slag are normally not used together in one mix design, at least two mix designs were needed. The selected mix designs were to contain admixtures that are commonly used in FDOT concrete. Based on this criteria and the convenience of obtaining materials, two common mix designs were chosen from FDOT's approved mix design database. The mix designs are presented in Appendix A. Both are Class IV, hot weather concrete mix designs. The fly ash mix design, designated Mix 1 herein, contains Class F fly ash, air-entraining admixture, and Types A and G admixtures. The fly ash was supplied by Florida Fly Ash, and all admixtures were produced by W. R. Grace. The slag mix design, designated Mix 2 herein, contains blast furnace slag, air-entraining admixture, and Type D admixture. The slag was produced by Tarmac (previously Pennsuco C& S), and all admixtures were produced by W. R.

Grace. The mix ingredients selected are identical to the original FDOT approved ones, except the source of the sand in Mix 2. In the FDOT approved Mix 2, the sand source is Silver Sand Co. For this study, the sand was actually obtained from Florida Rock Industries. However, since both sands are silica based and have similar fineness modulus and specific gravity, no significant influence should be expected on concrete properties.

3.2 Test Matrices

For each investigated ingredient, four different products with similar properties as the original material were chosen from FDOT's approved producers list based on the recommendation from FDOT's State Materials Office about the most popular materials used. The term "similar properties" refers to the same category in ASTM to which the products belong. For example, if the fly ash was classified as ASTM Class F [6], as the one used in the original fly ash mix design, it was considered having similar properties as the original fly ash. Similarly, if the admixtures or slag was classified as the same type as those used in the original mix design, they were considered having similar properties as the original materials. The materials from different sources were used to substitute for the original ones. In order to simplify narrative, these materials will be called "substitutes" as a comparison to the original materials.

The original materials and substitutes are listed for fly ash and slag mix designs in Table 3.1 and Table 3.2, respectively. The mix designs were named by combining two or three letters and one number, for example S-O-1, and F-AE-1. The first letter, "F" or "S", represents fly ash mix design or slag mix design. The second letter tells whether the mix design is the original mix design, or a substitution mix design and what kind of substitution. "O" stands for original mix design; "FA" fly ash substitution mix design; "AE" air-entraining agent substitution

Table 3.1. Test Matrix for Fly Ash Mix Design

Fly Ash					
	Original	**Substitute**			
	F-O-1,2,3	**F-FA-1**	**F-FA-2**	**F-FA-3**	**F-FA-4**
Product	Florida Mining & Materials	FA-1	FA-2	FA-3	FA-4
Dose (kg/m^3)	80.63	80.63	80.63	80.63	80.63
(lbs/cu yd)	(136)	(136)	(136)	(136)	(136)
Air-Entraining Agent					
	Original	**Substitute**			
	F-O-1,2,3	**F-AE-1**	**F-AE-2**	**F-AE-3**	**F-AE-4**
Product	DAREX	AE-1	AE-2	AE-3	AE-4
Dose (ml/m^3)	657	271	657	329	475
(fl oz/cu yd)	(17.0)	(7.0)	(17.0)	(8.5)	(12.3)
Type A Admixture					
	Original	**Substitute**			
	F-O-1,2,3	**F-A-1**	**F-A-2**	**F-A-3**	**F-A-4**
Product	WRDA 64	A-1	A-2	A-3	A-4
Dose (ml/m^3)	475	1163	955	475	715
(fl oz/cu yd)	(12.3)	(30.1)	(24.7)	(12.3)	(18.5)
Type G Admixture					
	Original	**Substitute**			
	F-O-1,2,3	**F-G-1**	**F-G-2**	**F-G-3**	**F-G-4**
Product	DARCEM 100	G-1	G-2	G-3	G-4
Dose (ml/m^3)	2860	3494	3324	3494	5238
(fl oz/cu yd)	(74.0)	(90.4)	(86.0)	(90.4)	(135.5)

Table 3.2. Test Matrix for Slag Mix Design

	Original	Substitute			
Slag					
	S-O-1,2,3	**S-SL-1**	**S-SL-2**	**S-SL-3**	**S-SL-4**
Product	PENN-CEM	S-1	S-2	S-3	S-4
Dose (kg/m^3) (**lbs/cu yd**)	250.80 (423)	250.80 (423)	250.80 (423)	250.80 (423)	250.80 (423)
Air-Entraining Agent					
	Original	**Substitute**			
	S-O-1,2,3	**S-AE-1**	**S-AE-2**	**S-AE-3**	**S-AE-4**
Product	DAREX	AE-1	AE-2	AE-3	AE-4
Dose (ml/m^3) (**fl oz/cu yd**)	193 (5.0)	97 (2.5)	425 (11.0)	213 (5.5)	193 (5.0)
Type D Admixture					
	Original	**Substitute**			
	S-O-1,2,3	**S-D-1**	**S-D-2**	**S-D-3**	**S-D-4**
Product	WRDA 64	D-1	D-2	D-3	D-4
Dose (ml/m^3) (**fl oz/cu yd**)	1635 (42.3)	1871 (48.4)	680 (17.6)	1364 (35.3)	1090 (28.2)

mix design; “A” Type A substitution mix design; “G” Type G substitution mix design; “SL” slag substitution mix design; and “D” Type D substitution mix design. The last number represents the substitution number for the substitution mix design. For instance, S-O-2 is the second mix of the Original Slag mix design; F-G-1 is the first Type G substitution for the Fly ash mix design.

In the process of substitution, the admixture producers were consulted to obtain appropriate dosage of admixtures that are suitable for the investigated mix design. However, for fly ash and slag, the dosage was kept identical to those of the original materials. The reason is that producers provided considerably different recommended dosage rates for their admixture products, while they usually do not provide such dosage rates for fly ash and slag. The dosage of fly ash and slag is usually determined by the mix design based on FDOT Specifications and the desired effect on concrete’s properties, and trial mixes. Tables 3.1 and 3.2 show the dosage of materials used in this study.

3.3 Material Properties

The properties of materials were collected from the manufacturers. Chemical and physical analysis from mill certifications for the cements for fly ash and slag mix designs are shown in Table 3.3. Since the certification is based on monthly productions, the actual constitution of the cements used in this study may be different. Tables 3.4 and 3.5 list the chemical and physical analysis for the fly ash, and slag from different sources. In these tables, the requirements for the material specified by AASHTO and ASTM were also included as references.

Table 3.3: Physical and Chemical Analysis of Cement (from Mill Certification)

Parameter	Fly Ash Mix Design (Southdown Inc, Brooksville, FL)	Slag Mix Design (Tarmac, Medley, FL)	AASHTO M-85 Specifications Type II
Chemical Analysis			
Silicon Dioxide (SiO_2), %	20.7	21.76	20.0, Min
Aluminum Oxide (Al_2O_3), %	5.8	5.23	6.0, Max
Ferric Oxide (Fe_2O_3), %	4.6	3.64	6.0, Max
Calcium Oxide (CaO), %	63.5	64.17	-
Magnesium Oxide (MgO), %	0.5	1.14	6.0, Max
Sulfur Trioxide (SO_3), %	2.6	2.71	3.0, Max
Tricalcium Silicate (C_3S), %	48	48	58 Max
Tricalcium Aluminate (C_3A), %	8	7.4	8, Max
Alkalis (Na2O equivalent), %	0.54	0.33	-
Insoluble Residue, %	0.29	0.14	0.75, Max
Loss on Ignition, %	1	1.11	3.0, Max
Physical Analysis			
Finess: Blaine, m^2/kg	377	375.8	280, Min 400, Max
Autoclave Expansion, %	0.01	0.01	0.80, Max
Time of Setting (Gilmore): Initial, minute	123	144	60, Min
Time of Setting (Gilmore): Final, minute	243	256	600, Max
Air Content, %	7	7.2	12, Max
Compressive Strength at 1 day, psi	1830	1894	-
Compressive Strength at 3 day, psi	3420	3156	1450, Min
Compressive Strength at 7 day, psi	4770	4808	2470, Min

Table 3.4: Physical and Chemical Analysis of Fly Ash (from Mill Certification)

Parameter	Original (Florida M & M)	Substitute				ASTM C-618 Specifications Class F
		FA-1	FA-2	FA-3	FA-4	
Chemical Analysis						
Sum of SiO_2, Al_2O_3, & Fe_2O_3, %	84.6	90.5	91.35	73.4	92.0	70.0, Min
Sulfur Trioxide (SO_3), %	0.4	0.1	0.44	1.0	0.0	5.0, Max
Moisture Content, %	-	0.1	0.24	0.2	0.2	3.0,Max
Loss on Ignition, %	3.3	3.1	4.39	2.5	1.9	6.0, Max
Available Alkaiies, as Na_2O, %	-	0.4	0.60	0.81	0.5	1.5, Max
Calicium Oxide, CaO, %	-	1.3	2.34	10.20	1.5	-
Physical Analysis						
Finess, amount retained on No. 325 sieve, %	29	24.1	19.7	14.7	22.6	34, Max
Strength Activity Index, at 7 days, %	78	75.1	83	80	74	75, Min
Strength Activity Index, at 28 days, %	81	91.7	88	94	89.9	75, Min
Water Requirement, %	-	96.7	98	100	98.3	105, Max
Soundness, Autoclave expansion	-0.10	-0.02	-0.03	-0.01	-0.04	0.8, Max
Specific Gravity	2.13	2.11	2.27	2.38	2.06	-

Table 3.5: Physical and Chemical Analysis of Slag (from Mill Certification)

Parameter	Original (Penncem)	Substitute				ASTM C-989 Specifications
		SL-1	SL-2	SL-3	SL-4	
Chemical Analysis						
Sulfide Sulfur (S), %	0.88	1.34	0.95	1.20	0.62	2.5, Max
Sulfate ion (SO_3), %	2.40	2.27	1.63	-	0.22	4.0, Max
Physical Analysis						
Finess, amount retained on No. 325 sieve, %	1.00	4.20	0.51	14.70	0.50	20, Max
Air Content, %	4.40	4.50	5.30	-	5.10	12, Max
Slag Activity Index, at 7 days, %	116.00	109.00	102.00	99.00	102.00	70 (Grade 100); 90(Grade 120); Min
Slag Activity Index, at 28 days, %	127.00	125.00	133.00	128.00	135.80	70 (Grade 80); 90(Grade 100); 110(Grade 120);Min
Specific Gravity	2.95	2.94	2.91	2.93	2.90	-

CHAPTER 4

TESTING PROCEDURE

4.1 Parametric Study

The effect of the substitution of different materials on the two original mix designs was investigated through a parametric study. As the control experiment, three batches of the original mix designs were made and tested first. Then, substitutions of fly ash, air-entraining agent, Type A and Type G admixture were performed on the fly ash concrete mix design, and substitutions of slag, air-entraining agent and Type D admixture on the Slag concrete mix design. While one ingredient was substituted, other ingredients remained same as required in the original mix designs. In this study, the effect of the substitute ingredient was studied.

4.2 Testing Background

All tests performed in this research were in accordance with the methods specified by the ASTM except the concrete mixing procedure. The concrete was mixed in accordance with both ASTM C192 [9] and FDOT Specifications [14] 346.

Absorption tests (ASTM C127 [11] and C128 [12]) were performed to determine the absorption rate of coarse and fine aggregate. Total moisture content test (ASTM C566 [13]) of coarse and fine aggregate was performed every time prior to the concrete mixing. Subtracting absorption from total moisture content gives the surface moisture content of coarse or fine aggregate, which should be counted as part of the mixing water. As mentioned above, concrete was mixed in accordance with both ASTM C192 [9]: “Making and Curing Concrete Test Specimens in the Laboratory”, and FDOT Specifications [14] 346, requirements for the quality control purpose “for design mixes developed under hot weather concreting conditions”. Tests performed on fresh concrete include slump (ASTM C143 [10]) and air content (ASTM C173 [5]) tests. Three 150 by 300 mm (6 by 12 in) cylindrical specimens were made and cured for each batch of concrete in accordance with (ASTM C192 [9]) for 28-day compressive strength test (ASTM C39 [7]).

All tests were performed at the Solid Mechanics/Structural Laboratory in the FAMU-FSU College of Engineering and by the same research group throughout the length of the project. This process is likely to decrease multiple operator differences in results. Mr. Jack Johnson, ACI certified laboratory technician, was in charge of the overall supervision of the testing process.

4.3 Absorption Test Methods

The absorption test of coarse aggregate was performed in accordance with ASTM C-127 (11) specifications. The absorption test of fine aggregate was performed in accordance with ASTM C-128 (12) specifications. The total moisture content of coarse and fine aggregates are needed to adjust the batch weights of these ingredients. This test was performed according to ASTM C-566 (13) specifications.

4.4 Making Concrete Under Hot Weather Conditions in the Laboratory (ASTM C192 [9], FDOT Specifications [14] 346

While ASTM C192 [9] “Making and Curing Concrete Test Specimens in the Laboratory,” only specifies the procedure of making concrete under regular condition, FDOT

Specifications [14] 346 "For design mixes developed under hot weather concreting conditions," specifies the requirement of mixing time and temperature for hot weather mix designs. Therefore, both standards were followed to prepare concrete for this study.

All concrete materials were kept with the temperature in the range of 20 to 30 ºC (68 to 86 ºF) before mixing the concrete. Cement was stored in a dry place, and kept uniform throughout the tests. Aggregates were maintained in a saturated condition until being used in testing. The quantity of moisture present on the surface of aggregates was counted as a part of the required amount of mixing water. The water that might have been in the admixtures was not included in the mix water for batching. The weights of aggregates (W_a') and water (W_w') were determined as follows:

Weight of aggregate, $W_a' = W_{ssd}$ (1 + Surface moisture content, %) (4.1)

Weight of water, $W_w' = W_w - W_{ssd} \times$ Surface moisture content, % (4.2)

Where:

$W_{ssd} =$ saturated surface-dry weight of aggregates required in the mix design

$W_w =$ weight of mixing water from mix design

Aggregates, cement, fly ash or slag, and water were measured as weights using a scale, and admixtures were measured as volumes. Admixtures were dispersed into a part of the mixing water. Each admixture was added separately to the concrete mixture.

A Gilson HM-224 170 l (6 cu. ft) portable concrete mixer was used to mix concrete. All materials were added to the mixer with the mixer running. Coarse aggregate, fine aggregate, and part of the mixing water were added first. Then air entrainer solution was added, followed by the water reducer and/or retarder (Type A or D). Cement, fly ash or slag, and the rest of the mixing water were added to the mixer to the end. If a high-range admixture (Type G) was used, it was introduced to the mixer after other materials were added and mixed for 3 minutes.

The mixing sequence used herein is slightly different than that suggested in ASTM C-192 [9]. The modified sequence was followed under advise from admixture and concrete producers. Adding high-range additives after the ingredients were well mixed increased the effectiveness of the admixtures. ASTM C-192 mixing sequence is not well suited for hot-weather mix designs, or for mixes with high-range admixtures. It should be noted that FDOT specifications for hot-weather concrete mixing method also do not conform to ASTM C-192. The mixing sequence used in this study was found to work well, especially for the slump test.

The mixture was held at a minimum temperature of 34 ºC (94 ºF) in the mixer for 90 minutes after completion of initial mixing. The mix temperature at the end of the 90-minute extended mixing period was maintained at not less than 35 ºC (95 ºF). During the extended mixing period, the mixer was turned intermittently for 30 seconds every five minutes. The concrete was remixed for 1 minute at the end of the 90-minute period. During the mixing process, a kerosene garage heater was used to maintain the temperature of the mixture, and the temperature was checked manually every ten minutes. Figure 4.1 shows the mixing process.

The slump test was performed in accordance with ASTM C-143 [10] specifications. Figure 4.2 shows the slump test in progress. The air content test by the volumetric method, shown in Fig. 4.3, was performed in accordance with ASTM C-173 [5] specifications.

4.5 Making and Curing Concrete Test Specimens in the Laboratory (ASTM C192 [9], as modified)

Three cylinder specimens 150 by 300 mm (6 by 12 in) were made for 28-day compressive strength test. The molds were placed on a rigid surface, and filled with concrete in

Figure 4.1: Concrete Mixing

Figure 4.2: Slump Test

Figure 4.3: Air Content Test

Figure 4.4: Making Concrete Specimen

three equal layers. Each layer was rodded 25 times, and the outside of the mold was tapped lightly 10 to 15 times. The bottom layer was rodded throughout its depth, and the upper layers were penetrated to about 12 mm (0.5 in) depth. For concrete with slump less than 25 mm (1 in), concrete was vibrated using a vibrator instead of manual rodding for consolidation. After consolidation, excess concrete on the top surface was struck off. The specimen was then covered by a lid, and stored inside on a rigid flat surface. Specimens were removed from the molds 24 ± 8 h after casting. They were moist cured in a water tank at a temperature of 23±2 ºC (73 ± 3 ºF). The curing temperature was maintained through the use of water heaters in the curing tanks. The temperature in the curing tanks was regularly monitored with a thermometer. Figures 4.4 and 4.5 show the making and curing of concrete specimens, respectively.

4.6 Compressive Strength Test (ASTM C39 [7])

Compressive strength test was carried out at 28 days ± 20 h after the cylinders were made. They were tested as soon as possible after removal from the curing tank, according to ASTM C39. Capping was performed according to ASTM C167 procedures. The specimen was placed in a Forney testing machine with its axis directly under the center of the compressive plate. A steady rate of loading was used until the specimen failed. The average of the strengths from the three cylinders was recorded as the compressive strength of the batch. Figure 4.6 shows the compressive strength test set-up.

Figure 4.5: Concrete Curing

Figure 4.6: Compressive Strength Test

CHAPTER 5

TEST RESULTS

5.1 Introduction

The test results obtained from the fly ash and slag original and substitution mix designs are listed in Tables 5.1 and 5.2, respectively. Three series of test results for each original mix design and one for each substitution mix design were included in the tables. Sample mean and standard deviation for the test results were calculated using the following equations and are listed in Tables 5.3 and 5.4.

Sample Mean: $$\mu = \frac{\sum x}{n} \tag{5.1}$$

Sample Standard Deviation: $$s = \sqrt{\frac{n\sum x^2 - (\sum x)^2}{n(n-1)}} \tag{5.2}$$

Graphical comparison of test results for the original mix design and substitution mix designs is illustrated in Appendix B, Figures B.1 – B.20. In these figures, the original mix design is represented by the mean of the test results for that mix design.

5.2 Discussion of Test Results

5.2.1 Fly Ash Mix Design

Figures B.1, B.2 and B.3 show the slump, air content and 28-day compressive strength data for the original fly ash mix (Mix 1) and the fly ash substitution mixes. The slumps obtained from F-FA-3 and F-FA-4 (165 and 114 mm) are much larger than those from the other two substitution mixes (57 and 165 mm) and the original mix design (70 mm). F-FA-3 also had the

Table 5.1: Test Data for Fly Ash Mix Design *

Mix Designs		Temperature (C)	Temperature (F)	Slump (mm)	Slump (in)	Air Content (%)	Compressive Strength (MPa)	Compressive Strength (Psi)
Original	F-O-1	35	(95.0)	83	(3.3)	3.8	38.4	(5570)
	F-O-2	35	(95.0)	63	(2.5)	3.2	43.2	(6268)
	F-O-3	36	(96.8)	63	(2.5)	1.8	42.4	(6146)
Fly Ash Substitution	F-FA-1	36	(96.8)	32	(1.3)	2.0	42.7	(6201)
	F-FA-2	38	(100.4)	57	(2.3)	2.0	43.9	(6369)
	F-FA-3	34	(93.2)	165	(6.5)	4.8	43.4	(6293)
	F-FA-4	35	(95.0)	114	(4.5)	2.5	37.1	(5389)
Air-Entraining Agent Substitution	F-AE-1	36	(96.8)	178	(7.0)	1.3	51.9	(7533)
	F-AE-2	35	(95.0)	140	(5.5)	1.8	42.9	(6231)
	F-AE-3	40	(104.0)	127	(5.0)	2.8	38.4	(5567)
	F-AE-4	40	(104.0)	173	(6.8)	3.2	37.7	(5472)
Type A Admixture Substitution	F-A-1	35	(95.0)	102	(4.0)	3.2	39.7	(5768)
	F-A-2	37	(98.6)	190	(7.5)	7.5	28.6	(4144)
	F-A-3	37	(98.6)	127	(5.0)	5.0	35.4	(5139)
	F-A-4	35	(95.0)	140	(5.5)	3.0	38.1	(5534)
Type G Admixture Substitution	F-G-1	37	(98.6)	140	(5.5)	4.5	29.5	(4275)
	F-G-2	36	(96.8)	44	(1.8)	2.0	38.9	(5649)
	F-G-3	35	(95.0)	13	(0.5)	1.3	48.1	(6985)
	F-G-4	35	(95.0)	6	(0.3)	1.5	40.3	(5849)

* F: Fly ash mix
O: Original FDOT mix 1
FA: Fly ash substitution mix
AE: Air entraining agent substitution mix
A: Type A admixture substitution mix
G: Type G admixture substitution mix

Table 5.2: Test Data for Slag Mix Design *

Mix Designs		Temperature (C)	(F)	Slump (mm)	(in)	Air Content (%)	Compressive Strength (MPa)	(Psi)
Original	S-O-1	35	(95.0)	38	(1.5)	1.8	57.2	(8298)
	S-O-2	37	(98.6)	46	(1.8)	2.0	55.5	(8060)
	S-O-3	34	(93.2)	127	(5.0)	3.8	49.6	(7196)
Slag Substitution	S-SL-1	35	(95.0)	13	(0.5)	2.5	54.2	(7863)
	S-SL-2	35	(95.0)	19	(0.8)	2.3	51.3	(7445)
	S-SL-3	35	(95.0)	13	(0.5)	1.5	59.6	(8654)
	S-SL-4	34	(93.2)	13	(0.5)	0.8	53.5	(7759)
Air-Entraining Agent Substitution	S-AE-1	36	(96.8)	152	(6.0)	1.6	48.6	(7052)
	S-AE-2	36	(96.8)	63	(2.5)	2.8	48.5	(7037)
	S-AE-3	36	(96.8)	76	(3.0)	2.8	46.4	(6727)
	S-AE-4	34	(93.2)	44	(1.8)	2.1	58.9	(8554)
Type D Admixture Substitution	S-D-1	34	(93.2)	13	(0.5)	1.8	43.4	(6299)
	S-D-2	34	(93.2)	127	(5.0)	4.0	52.0	(7540)
	S-D-3	34	(93.2)	46	(1.8)	2.5	55.8	(8098)
	S-D-4	34	(93.2)	83	(3.3)	2.8	52.9	(7681)

* S: Slag mix design
O: Original FDOT mix 2
SL: Slag substitution mix
AE: Air entraining agent substitution mix
D: Type D admixture substitution mix

Table 5.3: Statistical Results for Original Fly Ash Mix Design Data

	Slump		Air Content	Compressive Strength	
	(mm)	(in)	(%)	(MPa)	(Psi)
Mean	70	(2.8)	2.9	41.3	(5995)
Standard Deviation	11	(0.4)	1.0	2.6	(373)

Table 5.4: Statistical Results for Original Slag Mix Design Data

	Slump		Air Content	Compressive Strength	
	(mm)	(in)	(%)	(MPa)	(Psi)
Mean	70	(2.8)	2.5	54.1	(7851)
Standard Deviation	49	(1.9)	1.1	4.0	(580)

highest air content, 4.8%; however, F-FA-4's air content is just about average, 2.5%. For 28-day compressive strength, the results of the substitution mix designs range from 37.1 MPa to 43.9 MPa. As mentioned in the literature review, the study by Meininger and others [6] has shown that higher loss on ignition of fly ash could result in significant loss of air and possibly to give erratic results for some combinations of ingredients. According to the information provided by the manufacturers (Table 3.4), the loss on ignition for the fly ash in F-FA-3 and F-FA-4 is 2.5% and 1.9%, respectively, lower than that of the original mix design (3.3%) and the other two substitution mixes (3.1 and 4.39%).

Figures B.4, B.5 and B.6 show the slump, air content and 28-day compressive strength data for the original fly ash mix design and air-entraining agent substitution mixes. The original mix design (Mix 1) showed the lowest slump (70 mm). The slump results from the four substitution mix design ranges from 127 to 178 mm, with the largest slump from F-AE-1. The air content result from the four substitution mixes range from 1.3% (F-AE-1) to 3.2% (F-AE-4), the highest result being from F-AE-4, a slightly higher than that of the original mix design (Mix 1). F-AE-1 yielded the greatest compressive strength of 51.9 MPa, while the four substitution mixes yielded compressive strengths ranging from 37.7 (F-AE-4) to 51.9 MPa (F-AE-1).

Figures B.7, B.8 and B.9 show the slump, air content and 28-day compressive strength data for the original fly ash mix design (Mix 1) and Type A substitution mixes. F-A-2 yielded the largest slump (190 mm), and largest air content (7.5%), but with the smallest strength, 28.6 MPa. The slump of the substitution mixes ranged from 102 mm (F-A-1) to 190 mm (F-A-2), the air content from 3% (F-A-4) to 7.5% (F-A-2), and the compressive strength from 28.6 MPa (F-A-2) to 39.8 MPa (F-A-1).

Figures B.10, B.11 and B.12 show the slump, air content and 28-day compressive strength data for the original fly ash mix design 1 and Type A substitution mixes. The slump values for F-G-3 and F-G-4 were small, 13 mm and 6 mm, respectively. These two samples also had low air contents, 1.3 and 1.5%, respectively, but showed the largest compressive strengths, 48.1 and 40.3 MPa. On the other hand, F-G-1 yielded the largest slump, 140 mm, the highest air content 4.5%, but the lowest strength, 29.5 MPa, among the substitution mix designs.

5.2.2 Slag Mix Design

Figures B.13, B.14 and B.15 show the slump, air content and 28-day compressive strength data for the original slag mix design (Mix 2) and slag substitution mixes. The slump from the substitution mixes, ranging from 13 mm (S-SL-1, S-SL-3, and S-SL-4) to 19 mm (S-SL-2), is much less than that of the original slag mix design, 70 mm. However, the differences in air content and compressive strengths between the results of original and substitution slag mix designs are smaller. The air content of the substitution mix designs ranged from 0.8% (S-SL-4) to 2.5% (S-SL-1), and the compressive strengths from 51.3 MPa (S-SL-2) to 59.6 MPa (S-SL-3). The air content and compressive strength for the original mix design (Mix 2) were 2.5% and 54.1 MPa, respectively.

Figures B.16, B.17 and B.18 present the slump, air content and 28-day compressive strength data for the original slag mix design 2 and air-entraining agent substitution mixes. The slump from the substitution mixes ranged from 44 mm (S-D-4) to 152 mm (S-D-1), the air content from 1.6% (S-D-1) to 2.8% (S-D-2), and the compressive strength from 46.4 MPa (S-D-3) to 58.9 MPa (S-D-4).

The slump, air content and 28-day compressive strength data for the original slag mix design 2 and Type D admixture substitution mixes are shown in Figures A.19, A.20, and A.21, respectively. The slump of the substitution mix designs ranged from 13 mm (S-D-1) to 127 mm (S-D-2), the air content from 1.8% (S-D-1) to 4% (S-D-2), and the compressive strength from 3.4 MPa (S-D-1) to 55.8 MPa (S-D-3).

5.2.3 Method of Comparison

The test data from each substitution mix design were compared with the average of the test results from original mix design. It may be observed that there is significant difference between the test results from the substitution mixes, and the average of the original mix design tests. This observation is valid for the slump, air content and compressive strength tests, both for the fly ash and slag mix designs.

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

The following conclusions can be made based on the findings of this study:

1. The slump of fly ash and slag concrete varies significantly with the substitution of fly ash, air entraining agent, and Type A, D and G admixtures compared with that of the original fly ash and slag concrete mixtures.
2. The air content of fly ash and slag concrete also varies significantly due to the substitution of fly ash, air-entraining agent, Type A, D and G admixtures.
3. The compressive strength of fly ash and slag concrete is also affected significantly by the substitution of fly ash, air-entraining agent, Type A, D and G admixtures.
4. In this study, only three or four samples of data points were available for each substitution test. This sample size is not large enough based on which reliable statistical conclusions may be made.

It is therefore recommended that the results from this study be considered as an initial or preliminary effort. The results obtained show that substitutions of fly ash, slag, Type A, Type D, and Type G admixtures cause variability in concrete properties such as compressive strength, air content and slump. The statistical viability of the variation due to ingredient substitution cannot be established with such small sample sizes. It is recommended that more extensive studies involving statistically significant sample sizes be performed to validate the findings from this study.

APPENDIX A

MIX DESIGNS

Appendix A.1

Fly Ash Mix Design

Mix 1

CLASS CONCRETE: IV (37.9 MPa) 5500PSI

SOURCE OF MATERIALS

COARSE AGG.:	RINKER MATERIALS	GRADE:	57 S.G.(SSD): 2.450
FINE AGG.:	FLORIDA ROCK IND	F.M.:	2.20 S.G.(SSD): 2.630
Pit No. (COARSE):	87-090	TYPE:	CRUSHED LIMESTONE
Pit No. (FINE):	36-256	TYPE:	SILICA SAND
CEMENT:	BROCO (BROOKSVILLE)	SPEC:	AASHTO M-85 TYPE II
AIR ENTR. ADMIX.:	DARAEX W.R.GRACE	SPEC:	AASHTO M-154
1ST ADMIX.:	WRDA 64 W.R.GRACE	SPEC:	AASHTO M-194 TYPE A
2ND ADMIX.:	DARCEM 100 W.R.GRACE	SPEC:	ASTM C-494 TYPE G
3RD ADMIX.:	NONE	SPEC:	NONE
FLY ASH:	FLORIDA MINING & MATERIALS	SPEC:	ASTM C-618 CLASS F

HOT WEATHER CONCRETE DESIGN MIX
AGGREGATE CORRECTION FACTOR 0.7

CEMENT (Kg) LBS:	(279.9)	617.0	SLUMP RANGE IN:	4.5 to 7.5
COARSE AGG. (Kg) LBS:	(757.5)	1670.0	SLUMP RANGE mm:	114 to 190
FINE AGG. (Kg) LBS:	(493.5)	1088.0	AIR CONTENT:	2.4% to 5.6%
AIR ENT. ADMIX. (ml) OZ:	(502.7)	17.0	UNIT WEIGHT (WET) PCF:	139.8
1ST ADMIX. (ml) OZ:	(363.7)	12.3	W/C RATIO (PLANT) LBS/LB:	0.35
2ND ADMIX. (ml) OZ:	(2188.2)	74.0	W/C RATIO (FIELD) LBS/LB:	0.35
3RD ADMIX. (ml) OZ:	0.0	0.0	THEO YIELD CU FT:	26.99
WATER GAL:		31.4		
WATER (Kg) LBS:	(118.7)	261.6		
FLY ASH (Kg) LBS:	(61.7)	136.0		

PRODUCER TEST DATA:

CHLORIDE CONT. LB/C:		0.123
SLUMP (mm) IN:	(158.7)	6.25
AIR CONTENT %:		3.80%
TEMPERATURE (C) F:	(36.7)	98
28 DAY COMP. STRENGTH (MPa) PSI:	(49.3)	7160

Appendix A.2

Slag Mix Design

Mix 2

CLASS CONCRETE IV (37.9 MPa) 5500PSI

<u>SOURCE OF MATERIALS</u>

COARSE AGG.:	RINKER MATERIALS	GRADE:	57 S.G.(SSD): 2.430
FINE AGG.:	FLORIDA ROCK IND	F.M.:	2.18 S.G.(SSD): 2.630
Pit No. (COARSE):	87-090	TYPE:	CRUSHED LIMESTONE
Pit No. (FINE):	36-256	TYPE:	SILICA SAND
CEMENT:	Tarmac (Medley)	SPEC:	AASHTO M-85 TYPE II
AIR ENTR. ADMIX.:	DARAEX W.R.GRACE	SPEC:	AASHTO M-154
1ST ADMIX.:	WRDA 64 W.R.GRACE	SPEC:	AASHTO M-194 TYPE D
2ND ADMIX.:	NONE	SPEC:	NONE
3RD ADMIX.:	NONE	SPEC:	NONE
SLAG:	PENN-CEM PENNSUCO C& S	SPEC:	ASTM C-989

HOT WEATHER CONCRETE DESIGN MIX
SLAG: BLAST FURNACE SLAG

CEMENT (Kg) LBS:	(127.9)	282.0	SLUMP RANGE IN:	1.5 - 4.5
COARSE AGG. (Kg) LBS:	(748.4)	1650.0	SLUMP RANGE mm:	114 to 190
FINE AGG. (Kg) LBS:	(523.0)	1153.0	AIR CONTENT:	2.4% to 5.6%
AIR ENT. ADMIX. (ml) OZ:	(147.9)	5.0	UNIT WEIGHT (WET) PCF:	139.6
1ST ADMIX. (ml) OZ:	(1250.8)	42.3	W/C RATIO (PLANT) LBS/LB:	0.37
2ND ADMIX. (ml) OZ:	0.0	0.0	W/C RATIO (FIELD) LBS/LB:	0.37
3RD ADMIX. (ml) OZ:	0.0	0.0	THEO YIELD CU FT:	27.00
WATER GAL:		31.5		
WATER (Kg) LBS:	(119.1)	262.5		
SLAG (Kg) LBS:	(61.7)	423.0		

<u>PRODUCER TEST DATA:</u>

CHLORIDE CONT. LB/C:		0.071
SLUMP (mm) IN:	(82.5)	3.25
AIR CONTENT %:		4.30%
TEMPERATURE (C) F:	(35.6)	96
28 DAY COMP. STRENGTH (MPa) PSI:	(50.1)	7270

APPENDIX B

SUBSTITUTION TEST RESULTS

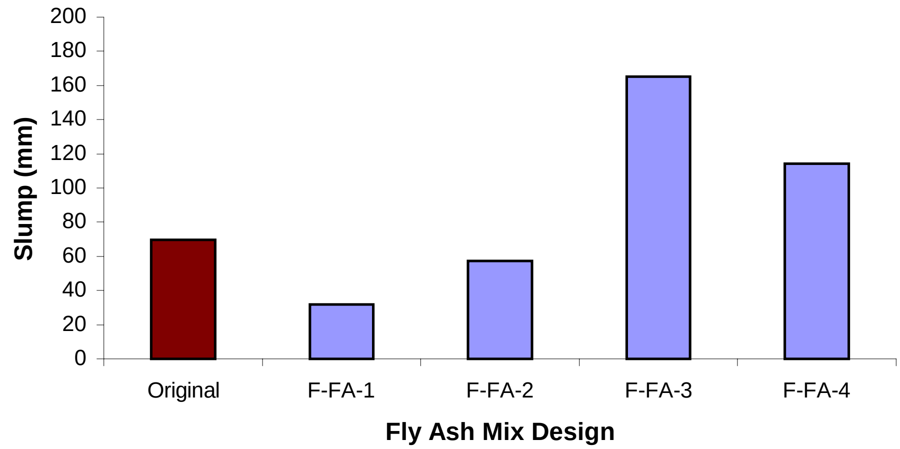

Figure B.1: Slump Comparison for Fly Ash Mix Design with Fly Ash Substitution

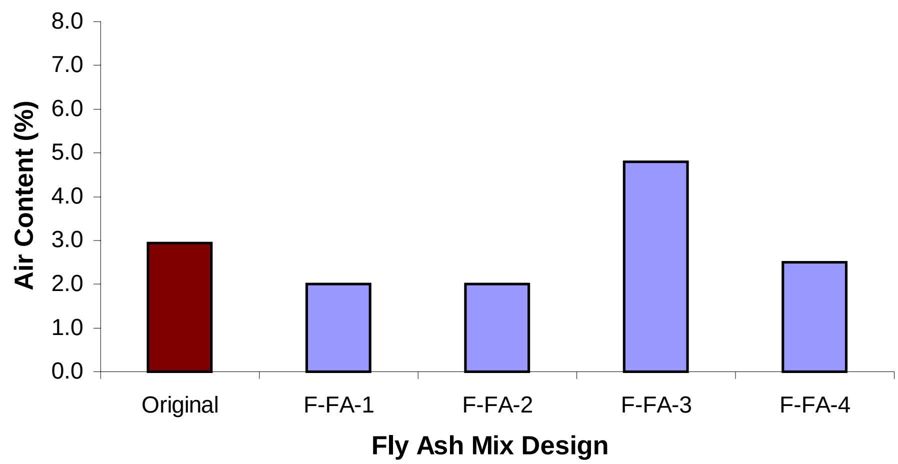

Figure B.2: Air Content Comparison for Fly Ash Mix Design with Fly Ash Substitution

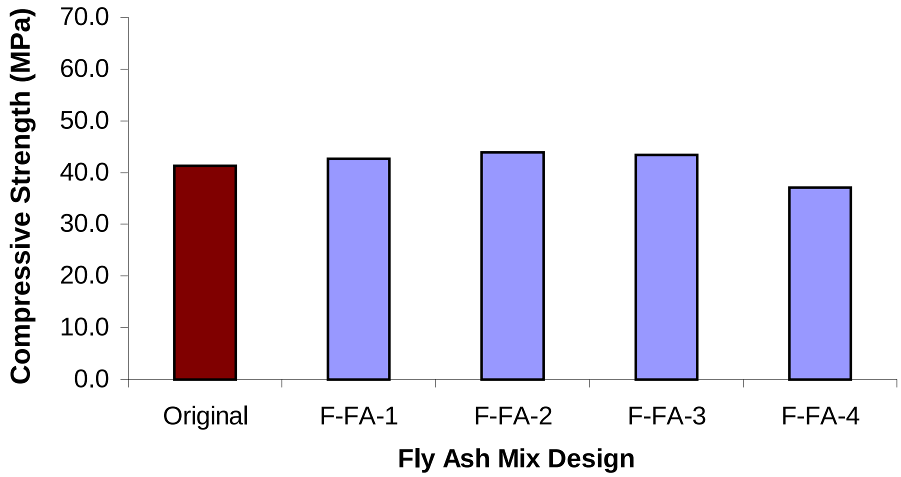

Figure B.3: Compressive Strength Comparison for Fly Ash Mix Design with Fly Ash Substitution

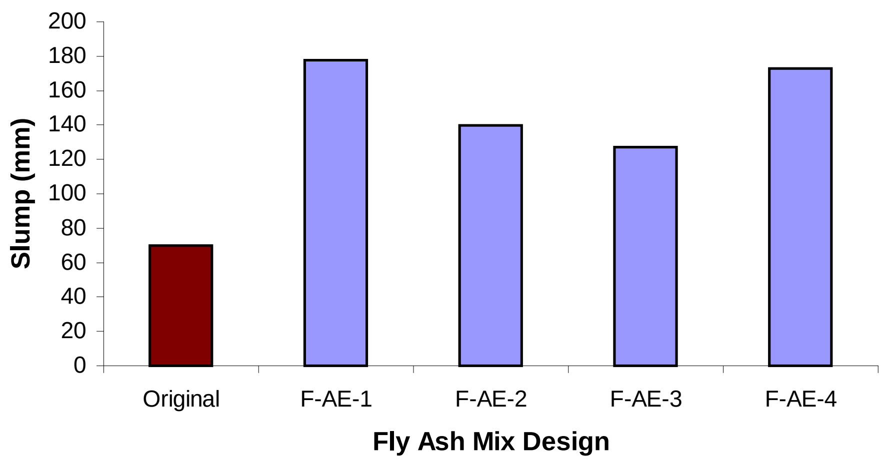

Figure B.4: Slump Comparison for Fly Ash Mix Design with Air-Entraining Agent Substitution

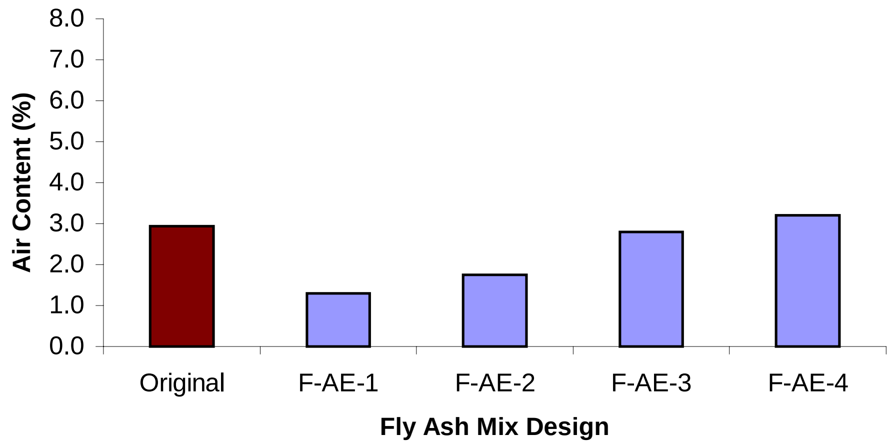

Figure B.5: Air Content Comparison for Fly Ash Mix Design with Air-Entraining Agent Substitution

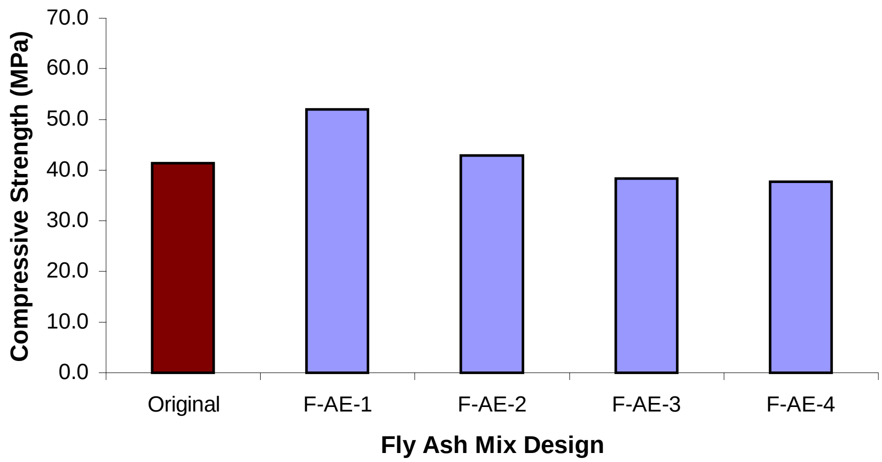

Figure B.6: Compressive Strength Comparison for Fly Ash Mix Design with Air-Entraining Agent Substitution

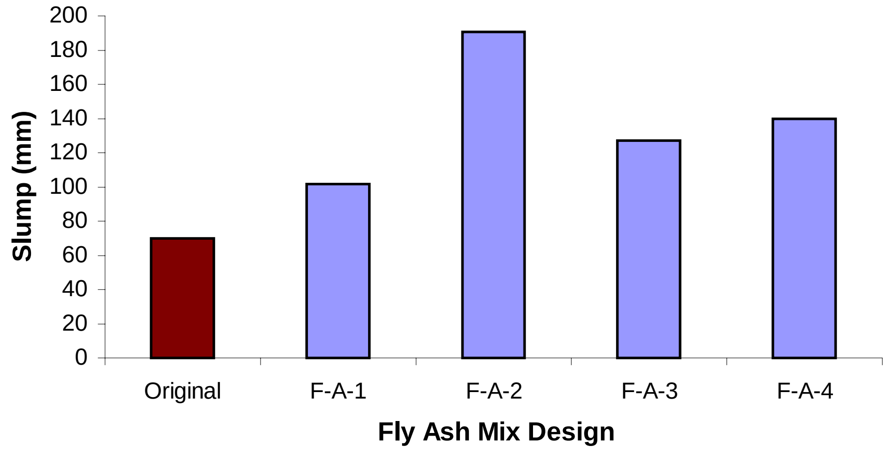

Figure B.7: Slump Comparison for Fly Ash Mix Design with Type A Admixture Substitution

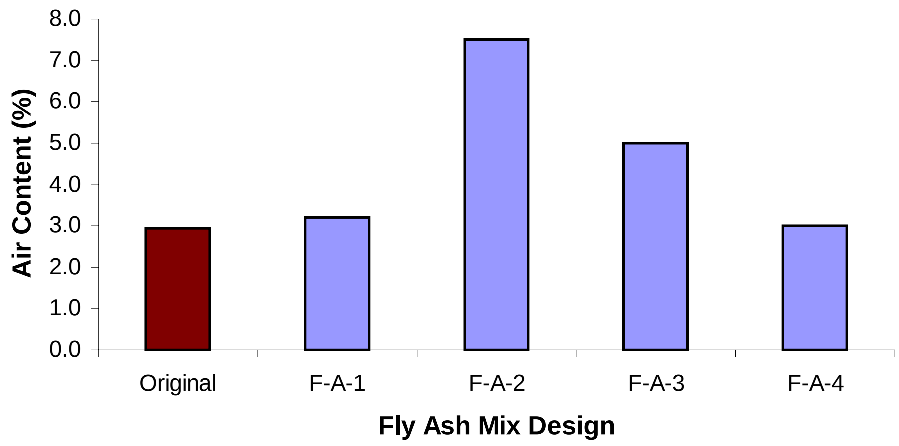

Figure B.8: Air Content Comparison for Fly Ash Mix Design with Type A Admixture Substitution

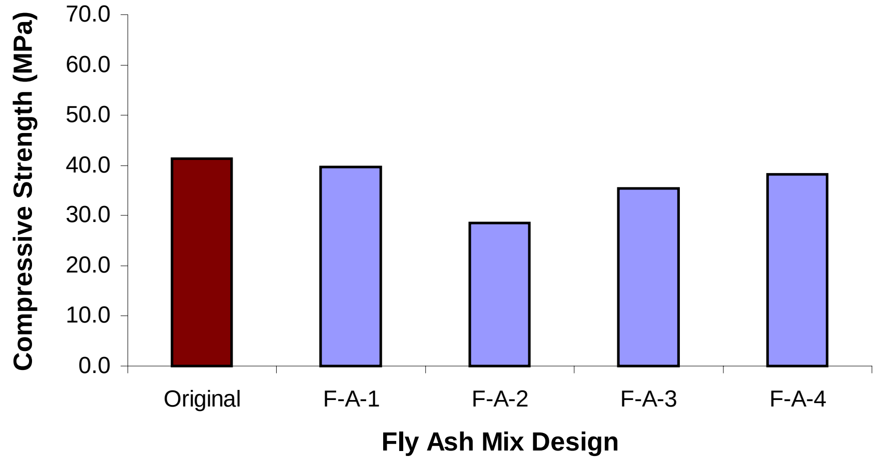

Figure B.9: Compressive Strength Comparison for Fly Ash Mix Design with Type A Admixture Substitution

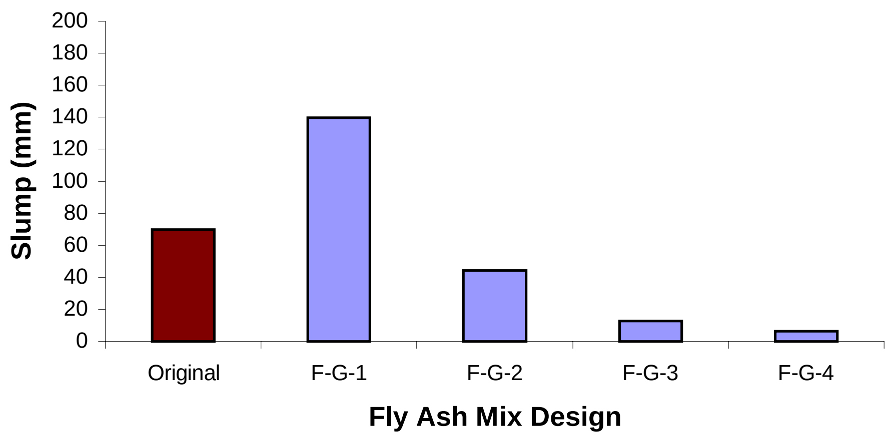

Figure B.10: Slump Comparison for Fly Ash Mix Design with Type G Admixture Substitution

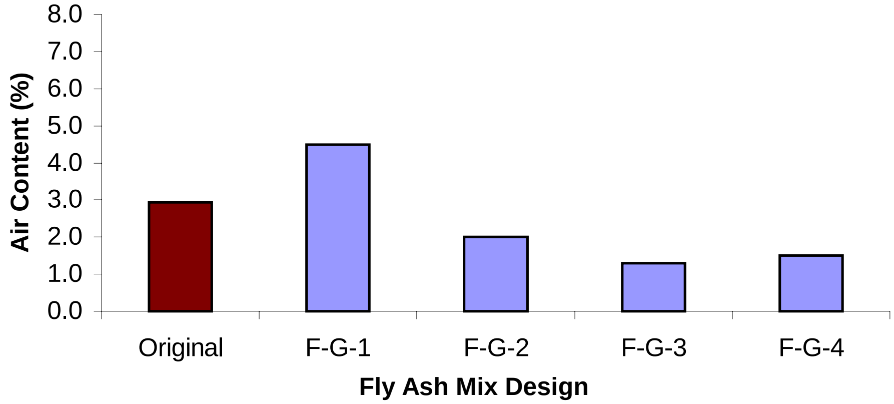

Figure B.11: Air Content Comparison for Fly Ash Mix Design with Type G Admixture Substitution

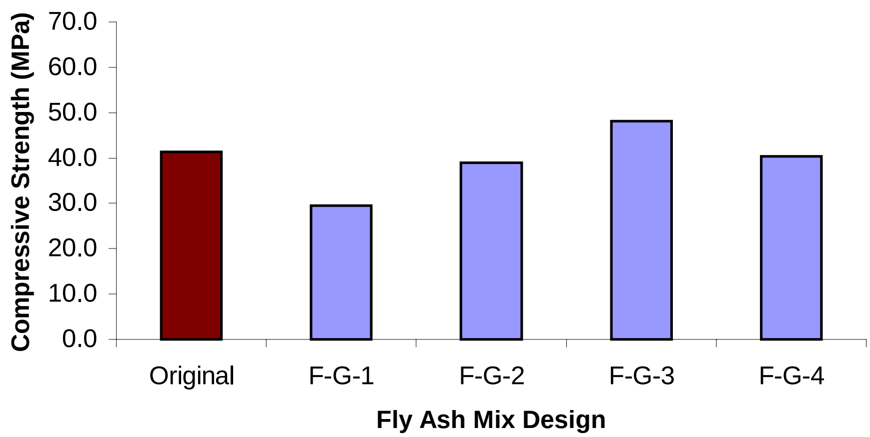

Figure B.12: Compressive Strength Comparison for Fly Ash Mix Design with Type G Admixture Substitution

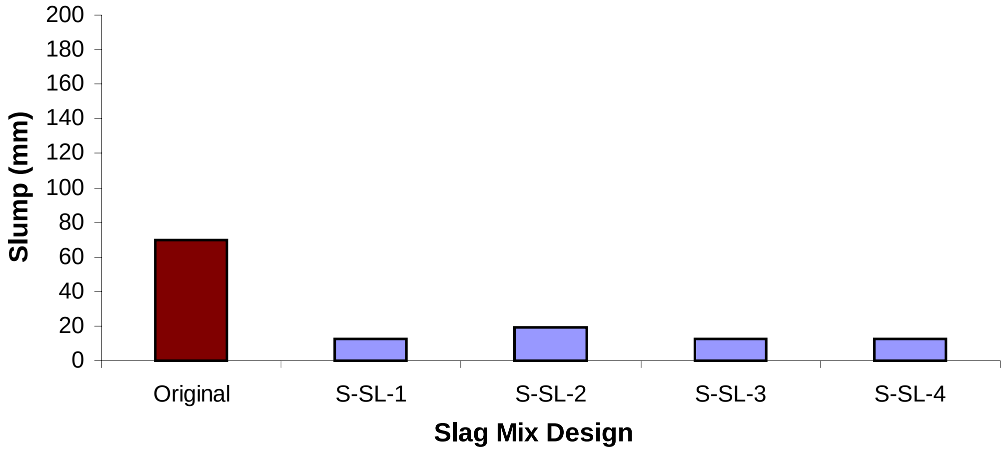

Figure B.13: Slump Comparison for Slag Mix Design with Slag Substitution

Figure B.14: Air Content Comparison for Slag Mix Design with Slag Substitution

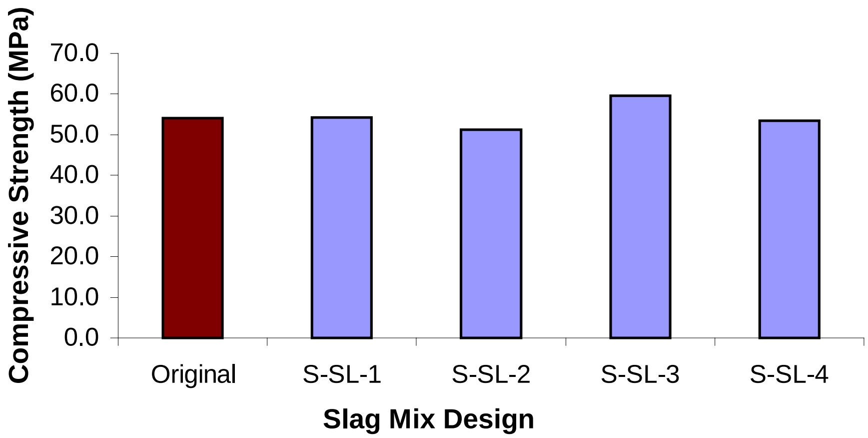

Figure B.15: Compressive Strength Comparison for Slag Mix Design with Slag Substitution

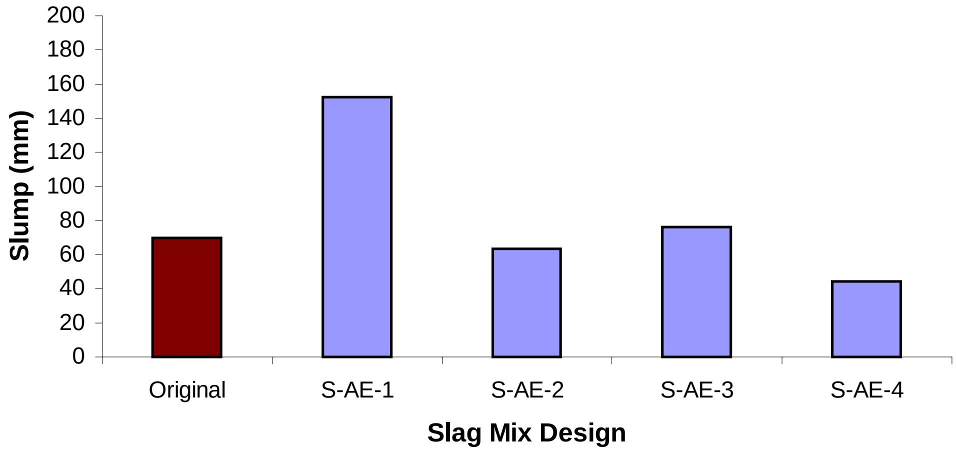

Figure B.16: Slump Comparison for Slag Mix Design with Air-Entraining Agent Substitution

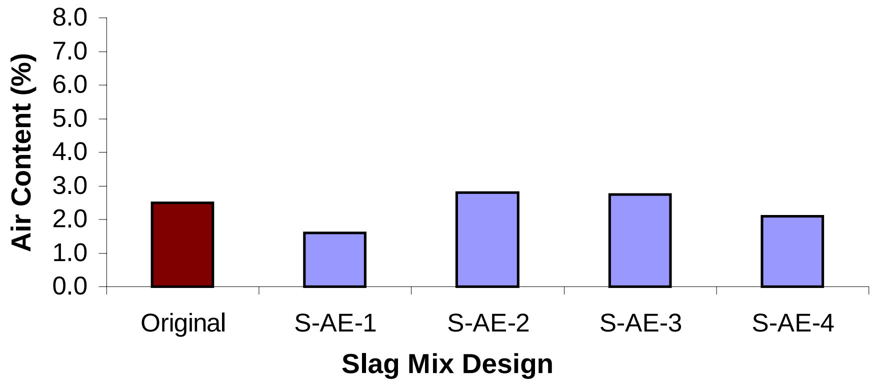

Figure B.17: Air Content Comparison for Slag Mix Design with Air-Entraining Agent Substitution

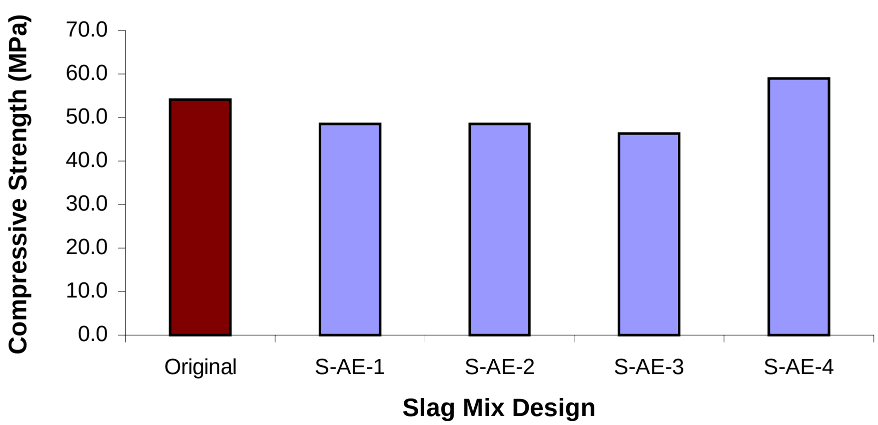

Figure B.18: Compressive Strength Comparison for Slag Mix Design with Air-Entraining Agent Substitution

Figure B.19: Slump Comparison for Slag Mix Design with Type D Admixture Substitution

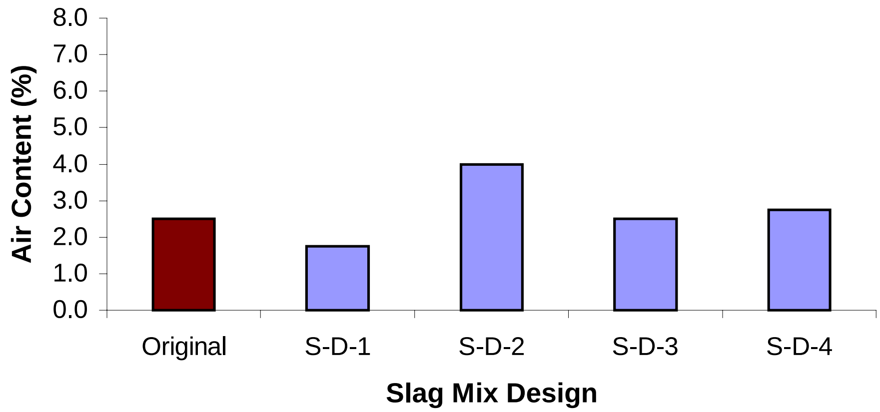

Figure B.20: Air Content Comparison for Slag Mix Design with Type D Admixture Substitution

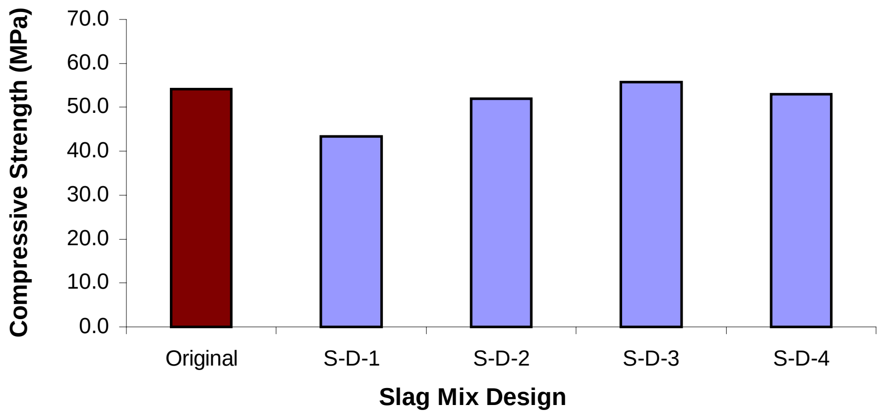

Figure B.21: Compressive Strength Comparison for Slag Mix Design with Type D Admixture Substitution

APPENDIX C

LIST OF SUPPORTING INDUSTRIES

This research has received donation of materials and valuable advices from the following industries.

Addmiment, Inc.

Arr-Maz Products, Inc.

Boral Material Tech., Inc.

Blue Circle Cement

CSR America Rinker

Florida Mining & Materials

Florida Rock Industries, Inc.

Fox Industries, Inc.

Fritz Chemical Co.

ISG Resources, Inc.

Lafarge Corp.

Lone Star Industries, Inc.

Separation Technologies, Inc.

Southdown, Inc.

Tamarc America, Inc.

VFL Techonology

W. R. Grace

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10. ASTM, Slump of Hydraulic-Cement Concrete *ASTM* C 143M-97 American Society for Testing and Materials, 1998.

11. ASTM, Specific Gravity and Absorption of Coarse Aggregate. *ASTM* C 127. American Society for Testing and Materials, 1998.

12. ASTM, Specific Gravity and Absorption of Fine Aggregate. *ASTM* C 128. American Society for Testing and Materials, 1998.

13. ASTM, Total Moisture Content of Aggregate by Drying. *ASTM* C 566. American Society for Testing and Materials, 1998.

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