IMPROVING CONCRETE PERFORMANCE THROUGH THE USE OF BLAST FURNACE SLAG

FINAL REPORT
FHWA/OK 00 (01)

by

THOMAS D. BUSH, JR.
BRUCE W. RUSSELL
MUSHARRAF M. ZAMAN
Co-Principal Investigators
and
MICAH W. HALE
TIENG A. LING
Graduate Research Assistants

AUGUST 2000

sponsored by

OKLAHOMA DEPARTMENT OF TRANSPORTATION
RESEARCH AND DEVELOPMENT DIVISION
in cooperation with the
FEDERAL HIGHWAY ADMINISTRATION

conducted at

FEARS ENGINEERING LABORATORY
SCHOOL OF CIVIL ENGINEERING AND ENVIRONMENTAL SCIENCE
UNIVERSITY OF OKLAHOMA, NORMAN, OKLAHOMA

TECHNICAL REPORT DOCUMENTATION PAGE

1. REPORT NO.
FHWA/OK 00(01)

2. GOVERNMENT ACCESSION NO.

3. RECIPIENT'S CATALOG NO.

4. TITLE AND SUBTITLE
Improving Concrete Performance Through the Use of Blast Furnace Slag

5. REPORT DATE
August 2000

6. PERFORMING ORGANIZATION CODE

7. AUTHOR(S)
Thomas D. Bush, Jr., Bruce W. Russell, Musharraf M. Zaman, Micah W. Hale, and Tieng A. Ling

8. PERFORMING ORGANIZATION REPORT

9. PERFORMING ORGANIZATION NAME AND ADDRESS
Fears Engineering Laboratory
University of Oklahoma
303 E. Chesapeake
Norman, OK 73019

10. WORK UNIT NO.

11. CONTRACT OR GRANT NO.
Item 2136

12. SPONSORING AGENCY NAME AND ADDRESS
Oklahoma Department of Transportation
Research and Development Division
200 N.E. 21st Street, Room 2A2
Oklahoma City, OK 73105

13. TYPE OF REPORT AND PERIOD COVERED
Final Report
January 1997 - July 2000

14. SPONSORING AGENCY CODE

15. SUPPLEMENTARY NOTES
Conducted in cooperation with the U.S. Department of Transportation, Federal Highway Administration

16 . ABSTRACT

A laboratory testing program was undertaken to evaluate the performance of ODOT Class AA and Class A concretes, specifically containing Oklahoma cements and aggregates, and utilizing partial replacement of portland cement (PC) with Grade 120 ground granulated blast furnace slag (BFS) and/or Class C fly ash (FA). Studies were conducted to examine performance aspects related to constituent materials (types and amounts used) as well as to construction/field issues. Blast furnace slag was used to replace portland cement on a 1:1 basis by mass. Class C fly ash replaced portland cement at a 1.35:1 ratio, i.e., 1.35 lb. of fly ash replaced 1.0 lb. of portland cement. Replacements rates examined were: none (control), 25 percent BFS, 15 percent FA, and the combination of 25 percent BFS plus 15 percent FA. The primary variables examined were: 1) BFS and FA contents, 2) source of Type I cement, 3) mixing and curing temperature, and 4) concrete class (A and AA). Use of high range water reducers and treatment with silanes were also examined.

As compared to control portland cement concrete, the use of Grade 120 BFS at the replacement rate tested had the following beneficial effects: 1) increased compressive, flexural, and tensile strengths (typically by 7 days for compressive strength), 2) substantially lower permeability (greatly reduced RCIP values and chloride ion absorption in the upper half inch depth), 3) reduced creep, and similar or slightly higher elastic modulus, and 4) consistent nature of performance. Blast furnace slag replacement (Grade 120) was also found to cause slight reductions in workability, and reduced effectiveness in entraining air when workability was decreased, or with low or elevated casting temperature. Setting times, freeze thaw resistance, shrinkage, and chloride ion absorption when treated by silane, were found similar for concrete with blast furnace slag when compared to concrete made with ordinary portland cement.

17. KEY WORDS
pozzolans, blast furnace slag, fly ash, durability

18. DISTRIBUTION STATEMENT
No restrictions. This publication is available from the Research and Development Division, Oklahoma DOT.

19. SECURITY CLASSIF. (OF THIS REPORT)	20. SECURITY CLASSIF. (OF THIS PAGE)	21. NO. OF PAGES	2. PRICE
Unclassified	Unclassified	133	

SI (METRIC) CONVERSION FACTORS

Approximate Conversions to SI Units

Symbol	When you know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	25.40	millimeters	mm
ft	feet	0.3048	meters	m
yd	yards	0.9144	meters	m
mi	miles	1.609	kilometers	km
		AREA		
in^2	square inches	645.2	square	mm^2
ft^2	square feet	0.0929	square meters	m^2
yd^2	square yards	0.8361	square meters	m^2
ac	acres	0.4047	hectares	ha
mi^2	square miles	2.590	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.0283	cubic meters	m^3
yd^3	cubic yards	0.7645	cubic meters	m^3
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.4536	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams	Mg
		TEMPERATURE (exact)		
°F	degrees Fahrenheit	(°F -32)/1.8	degrees Celsius	°C
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.448	Newtons	N
lbf/in^2	poundforce per square inch	6.895	kilopascals	kPa

Approximate Conversions from SI Units

Symbol	When you know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.0394	inches	in
m	meters	3.281	feet	ft
m	meters	1.094	yards	yd
km	kilometers	0.6214	miles	mi
		AREA		
mm^2	square	0.00155	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.196	square yards	yd^2
ha	hectares	2.471	acres	ac
km^2	square kilometers	0.3861	square miles	mi^2
		VOLUME		
mL	milliliters	0.0338	fluid ounces	fl oz
L	liters	0.2642	gallons	gal
m^3	cubic meters	35.315	cubic feet	ft^3
m^3	cubic meters	1.308	cubic yards	yd^3
		MASS		
g	grams	0.0353	ounces	oz
kg	kilograms	2.205	pounds	lb
Mg	megagrams	1.1023	short tons (2000 lb)	T
		TEMPERATURE (exact)		
°C	degrees Celsius	9/5 + 32	degrees Fahrenheit	°F
		FORCE and PRESSURE or STRESS		
N	Newtons	0.2248	poundforce	lbf
kPa	kilopascals	0.1450	poundforce per square inch	lbf/in^2

IMPROVING CONCRETE PERFORMANCE THROUGH THE USE OF BLAST FURNACE SLAG

FINAL REPORT
FHWA/OK 00 (01)

by

THOMAS D. BUSH, JR.
BRUCE W. RUSSELL
MUSHARRAF M. ZAMAN
Co-Principal Investigators
and
MICAH W. HALE
TIENG A. LING
Graduate Research Assistants

AUGUST 2000

sponsored by

OKLAHOMA DEPARTMENT OF TRANSPORTATION
RESEARCH AND DEVELOPMENT DIVISION
in cooperation with the
FEDERAL HIGHWAY ADMINISTRATION

conducted at

FEARS ENGINEERING LABORATORY
SCHOOL OF CIVIL ENGINEERING AND ENVIRONMENTAL SCIENCE
UNIVERSITY OF OKLAHOMA, NORMAN, OKLAHOMA

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

IMPROVING CONCRETE PERFORMANCE THROUGH THE USE OF BLAST FURNACE SLAG

CHAPTERi1

INTRODUCTION

1.1 BACKGROUND

ODOT specifications permit partial replacement of portland cement with Class C fly ash (FA), ground granulated blast furnace slag (BFS), and their combination. While Class C FA has been used for a number of years, prior to this research no data currently existed as to how mixtures with Oklahoma cements and aggregates would perform with BFS. A database was needed to provide guidance for use of FA and BFS in Oklahoma concretes.

Research studies, and experiences gained both in the US and abroad, strongly suggest that concretes made in Oklahoma will benefit from introduction of FA and BFS. Many studies have been conducted on BFS concretes, yet the test database is still very limited as compared to that of traditional portland cement concrete. But more importantly, the existing research database on BFS does not include mixes made with the specific materials available in Oklahoma. Documented behavioral information was needed so that guidelines could be developed and tailored for use of BFS in Oklahoma. This research program builds on the existing knowledge of performance of Oklahoma portland cement concrete by characterizing the behavior of FA and BFS concretes *specifically containing Oklahoma cements and aggregates*.

Fly ash and ground granulated blast furnace slag are capable of producing substantial improvements in strength, permeability, and durability (when properly proportioned) as compared to ordinary portland cement concrete. The concrete is improved through the effects of *pozzolanic reactions* that continue to improve concrete properties well after initial hardening has occurred. Both FA and BFS are often referred to as pozzolans. In the context of concrete technology, pozzolans are defined as silicious, or silicious and aluminous, materials that react with portland cement products to form cementitious materials (Mehta 1986). Pozzolans, in and of themselves, are essentially inert. However, when finely ground and in the presence of water and portland cement reaction products, pozzolans become cementitious. Class C FA and BFS are pozzolanic *and* cementitious. In fact, BFS should more properly be called a hydraulic cement. However, without the presence of portland cement, the cementitious properties of FA and BFS are insufficient for structural purposes due to their slow reaction rates and mild strength development.

The fundamental reason for improved strength and durability achieved using FA and BFS lies in their ability to refine the concrete paste's crystalline structure. *In simple terms, pozzolans such as FA and BFS react in such a way that much of a relatively weak, porous hydration by-product normally present in portland cement concrete is consumed and replaced by a dense, more desirable product. This reaction process **continues to occur after the concrete hardens**.* The reaction products of FA and BFS produce a denser crystalline structure, with smaller pores and more compact crystalline formations, leading to increased strength and greatly reduced permeability (and thus improved durability).

Enhanced concrete performance will benefit Oklahoma in a number of ways. Improved durability should lead to concrete structures and structural elements with lower life cycle costs as maintenance requirements are reduced and service life increased. Implementation of the research findings will also expand the technical capabilities of contractors and suppliers, making them better equipped to produce these (and other) high performance concretes to the benefit of Oklahoma citizensi Also, since BFS and FA are recycled materials, the current supply of portland cement can be extended, resulting in overall energy savings and reduced environmental emissions while at the same time producing superior concrete performance.

1.2 OBJECTIVES

The purpose of this research is to characterize the fresh and hardened properties of portland cement concrete containing BFS and Class C FA, and to determine the extent of enhancement, potential problems, or special considerations that must be taken, as a result of using these materials as partial replacement for portland cement. The **primary variables** examined are:

1) BFS and FA contents (subject to ODOT specification limits),
2) Source of Type I cement,
3) Mixing and curing temperature, and
4) Cementitious materials content and water to cementitious materials ratio (i.e., mixture Classes AA and A).

The test results improve our understanding of physical properties of portland cement concretes containing these materials, with specific attention given to concretes produced with Oklahoma cements and aggregates. Guidelines can now be developed for producing mixtures that take advantage of FA and BFS's beneficial effects on concrete permeability, durability and strength, thereby enhancing the performance of Oklahoma's transportation structures.

Behavior of fresh and hardened concrete is documented through laboratory tests on concrete mixtures containing these Oklahoma materials, and the research incorporates test variables relevant to producing concrete in Oklahoma. In so doing, the results expand the overall BFS database, and improve understanding of the behavior of BFS concretes in general.

1.3 SCOPE

A central focus of the research was performance of BFS and FA in concretes made with Oklahoma materials. It was important to identify primary behavioral characteristics that can be expected over a representative range of materials and conditions. However, a selective subset of the wide array of available materials was used in the research. Because the research centered around performance of cementitious materials, potential interactions with various cements were examined. Three locally available Type I cements, a single source of Grade 120 blast furnace slag, and a single source of Class C fly ash were used in the experimental program. It should be recognized that properties of materials, particularly fly ash, can be variable. However, to limit the experimental program to a manageable size, the same (single) sources of FA and BFS were used. Similarly, the same coarse and fine aggregate materials and admixtures were used throughout the research program.

Likewise, many combinations of pozzolan replacement fractions are possible. For this research, only the maximum and minimum (zero) replacement fractions for BFS and FA were studied. The experimental program was not intended to be comprehensive from the standpoint of optimizing performance using all possible FA, BFS, cements and aggregates available in Oklahoma.

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

Blast furnace slag (BFS) cements have been in use since 1774. In 1889 slag cements were used to build the Paris underground metro system (ACI233, 1995). As of 1974, slag cement accounted for 20 percent of the cement production in Europe compared to only 0.1 percent in the United States (Hogan, 1981). However, the growing concern over environmental issues and the need for more durable concrete have created new interest in the use of BFS as a partial replacement for cement.

When blended properly with Portland Cement (PC), BFS can improve the fresh and hardened properties of concrete. The appropriate addition of BFS can increase compressive and flexural strength, reduce permeability, increase sulfate resistance, and improve workability.

BFS improves the properties of hardened concrete by reacting with products formed during the hydration of cement. Equations 2.1 and 2.2 show the hydration of PC.

$$2C_3S + 6H_2O \rightarrow C_3S_2H_3 + 3CH \tag{2.1}$$

$$2C_2S + 4H_2O \rightarrow C_3S_2H_3 + CH \tag{2.2}$$

The calcium silicate hydrate ($C_3S_2H_3$), which has a dense crystalline structure, is the major contributor to the strength of concrete. The calcium hydroxide (CH) that is formed is less dense than the $C_3S_2H_3$, and therefore it is not a major contributor to strength. However, BFS contains amorphous silica (S) which reacts (Equation 2.3) with CH to form additional $C_3S_2H_3$ which improves the density of the cement paste matrix thereby improving strength and reducing permeability of the concrete.

$$CH + S + H_2O \rightarrow C_3S_2H_3 \tag{2.3}$$

This reaction continues to occur, even in the hardened state, and the resulting microstructure is made more dense in two ways. First, the new reaction products fill in some of the pores formerly present in the microstructure. This is termed *pore size refinement* of the microstructure. Second, many of the CH crystals formerly present are consumed and replaced with C-S-H, which has a more dense microstructure. This replacement of larger crystals with more dense reaction products is called *grain size refinement* of the microstructure. Both pore size refinement and grain size refinement contribute to a much more dense overall paste structure, resulting in higher strength and greatly reduced permeability.

There are different classifications (or grades) of BFS. BFS is classified by its ability to improve the compressive strength of mortar cubes (ASTM C 989). There are three classifications for BFS. The first classification is Grade 80 BFS, which means the 28 day compressive strength of the BFS cubes (50 percent BFS and 50 percent PC) is at least 75 percent as high as the compressive strength of the reference cubes (100 percent PC). The second classification is Grade 100 BFS, which means the 28 day compressive strength of the BFS cubes is at least 95 percent of the strength of the reference cubes. The third classification is Grade 120 BFS, where the 28 day compressive strength of the BFS cubes is at least 115 percent greater than that of the reference cubes.

2.2 FRESH CONCRETE PROPERTIES

2.2.1 Slump

The addition of BFS can have beneficial or detrimental effects on the fresh properties of concrete. BFS particles are smoother and denser than PC particles. Therefore, they require less water than PC particles, which in turn improves workability and increases slump (ACI 233, 1995). Tomisawa et. al. (1992) found that concrete with BFS contents ranging from 50-90 percent and a w/cm of approximately 0.50 requires less water to produce an equivalent slump of a PC concrete. They found that concrete containing 85 percent BFS required 8 to 9 percent less water to produce the same slump of a concrete containing only PC. Sivasundaram and Malhotra (1992) also investigated the fresh properties of concrete containing 50 to 75 percent BFS. However, they examined concretes with a low water to cementitious material ratio (w/cm). Sivasundaram and Malhotra (1992) found that the BFS concrete became sticky and required a greater dosage of High Range Water Reducer (HRWR) as the w/cm was lowered under 0.30. For example, a mixture with a w/cm of 0.27 and a BFS content of 65 percent required 16.70 lb/yd^3 of HRWR versus 9.90 lb/yd^3 for the 100 percent PC mixture. It should be recognized that just as for portland cement, the fineness of the BFS will affect slump (the greater the fineness, the higher the water demand). Therefore, more finely ground BFS may cause slump reductions, particularly if the BFS is much finer than the portland cement.

2.2.2 Time to Set

The time to set of concrete is also affected by the BFS content. Sivasundaram and Malhotra (1992) found that the initial set times of concretes containing a high volume of BFS were close to that of the control concrete (100 percent PC). Final set times of BFS concretes were affected to a greater magnitude than was PC concrete. In some instances, the final set times were extended an additional

4 hours. However, all the mixtures they tested contained high range water reducers (HRWR), which generally retard set times. The volume of BFS used by Sivasundaram and Malhotra was also quite large.

Sakai et. al. (1992) also found that while initial set times were similar between BFS and PC concrete, final set times increased with increasing BFS content. At elevated temperatures, Hogan and Meusel (1981) found that the set times, both initial and final, of BFS concretes were comparable to those of PC concrete. These findings are similar to those reported by ACI Committee 233.

2.2.3 Air Content

There is a limited amount of data concerning the effects of BFS on the air content of concrete. Sivasundaram and Malhotra (1992) studied concrete proportioned with BFS (grade not reported) to have an air content of 5 ± 1 percent. They found that as the BFS content of the concrete increased, the amount of air entraining agent (AEA) needed to achieve the required air content, also increased. For similar mixtures, the increase from 60 percent BFS to 75 percent BFS almost doubled the required dosage of AEA. In some instances, the dosage of AEA required was 1743 ml/m^3 for the BFS concrete compared to only 300 ml/m^3 for the 100 percent PC concrete. In general, air entrainment ability is also related to workability. More workable mixtures tend to entrain air more easily than drier, low slump mixtures.

2.3 HARDENED CONCRETE PROPERTIES

2.3.1 Compressive Strength

Hogan and Meusel (1981) examined the compressive strength of BFS concrete. The BFS content in the concrete mixtures examined was 0, 40, 50, and 65 percent of the total cementitious material. The w/cm was 0.38 and 0.55 for non-air-entrained mixtures and 0.40 and 0.55 for air-entrained mixtures. Prior to 1981, there was no classification for BFS. However, the fineness of the BFS used in their study ranged from 4500 to 6000 cm^2/g.

The results from the compressive strength tests showed that the BFS concretes gained strength more slowly than the 100 percent PC mixture (control mixture). However, between 7 and 10 days the strength of the BFS concretes overtook the control mixture. Shown in Fig. 2.1 are the results of the 28 day compressive strength data for all mixtures tested. As the slag content increased (from 40 to 65 percent), the 28 day compressive strength decreased. The concrete containing 40 percent BFS with w/cm of 0.38 and no air entrainment had the greatest 28 day strength which was 8220 psi compared to 7240 psi for the like control mixture. For non-air-entrained mixtures, the increase from 40 percent BFS to 50 percent BFS had a minimal effect on the compressive strength (28 day). The increase from 50 percent to 65 percent decreased the 28 day compressive strength of like mixtures by as much as 24 percent.

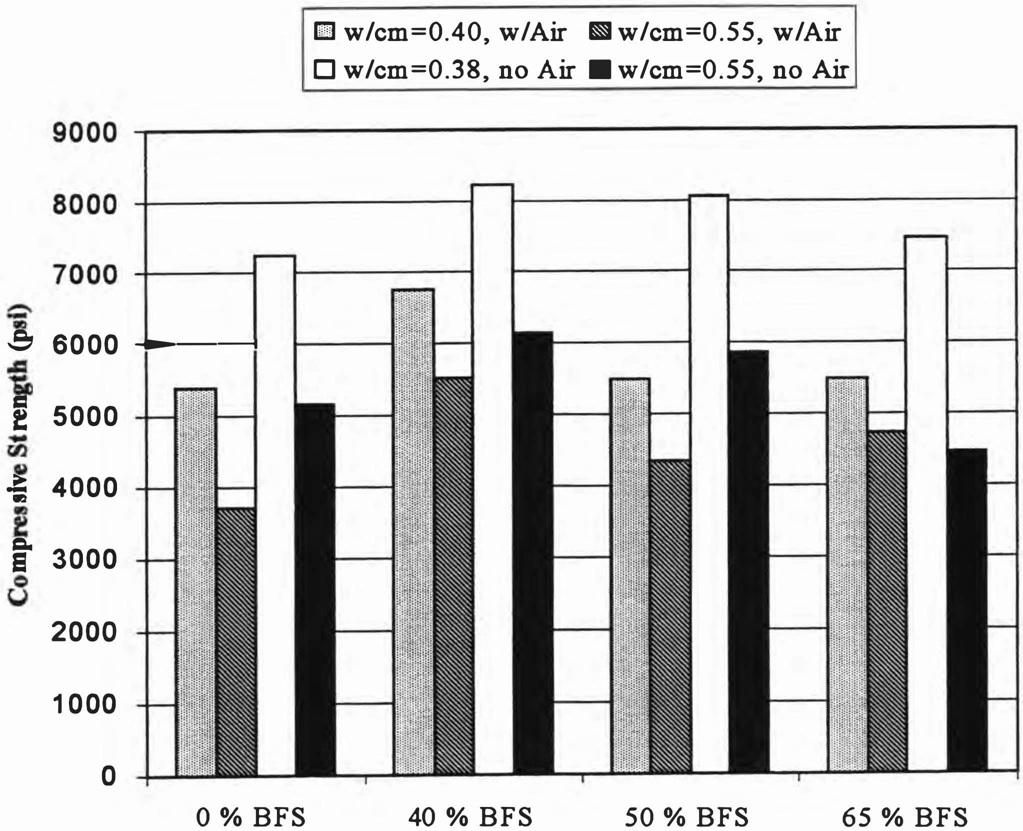


Fig. 2.1 Hogan and Meusel (1981) Compressive Strength Results

Sivasundaram and Malhotra (1992) investigated the compressive strength of concretes that contained large quantities of BFS (no mention of grade). The concretes had BFS contents that ranged from 50 to 75 percent of the total cementitious material, and a w/cm that ranged from 0.27 to 0.45. Each concrete mixture contained an air entraining agent (AEA) and a high range water reducer (HRWR). All concrete specimens were cured at 68 ± 2 F and 100 percent relative humidity (RH).

Sivasundaram and Malhotra (1992) concluded that incorporating large quantities of BFS in concrete does not have any detrimental effects on the strength (7 days and beyond) of concrete. As expected, the early strength of the BFS concrete was somewhat less than the control mixture. However, at 28 days of age the strength of the BFS concretes was greater than that of the control concrete. The concrete containing 70 percent BFS had a strength of 9170 psi at 28 days compared to 8890 psi for the control concrete.

Baalbaki et. al. (1992) compared the compressive strength of concretes containing different amounts of silica fume (SF), BFS, and fly ash (FA) (Class F) at a w/cm of 0.30 or lower. The grade of BFS used was not reported. Five different concrete mixtures were used (Table 2.1). At 7 days of age, the strength of the 100 percent PC was at least 50 percent greater than the other mixtures except for the 90 percent PC and 10 percent SF mixture which had a strength that was slightly greater. At 28 days, all the mixtures except for the 20 percent FA and 80 percent PC mixture had strengths greater than the control. The 10 percent SF and 60 percent BFS had a 28 day strength that was 15 percent greater than the control.

Table 2.1 Batching Matrix for Baalbaki et. al. (1992)

	Mixture					Compressive Strength (psi)	
	PC	SF	BFS	FA	w/cm	7 day	28 day
Mix 1	100%				0.30	11,340	14,400
Mix 2	90%	10%			0.30	10,670	15,920
Mix 3	50%	10%	40%		0.30	8920	15,230
Mix 4	80%			20%	0.30	10,350	13,050
Mix 5	30%	10%	60%		0.25	10,370	16,570

Campbell and Detwiler (1993) also examined the compressive strength of concretes containing different proportions of BFS and SF, but the concrete specimens were subjected to 18 hours of steam curing. The BFS content ranged from 30 to 50 percent, and the SF content ranged from 5 to 10 percent. At 1 day of age all the mixtures except for the 30 percent BFS mixture had strengths that were greater than the control. The mixture containing 50 percent BFS had the greatest compressive strength when compared to those mixtures containing only PC and BFS. The strength of a 50 percent BFS mixture was 4190 psi compared to 3960 psi for the control mixture. Of all the mixtures, the 10 percent SF mixture had a 1 day strength that was 33 percent greater than the control. Their results showed that elevated curing can improve the early strength of mixtures containing pozzolans.

Hamling and Kriner (1992) investigated the compressive strength of mortar cubes containing 50 percent BFS. As expected, they found that the BFS mortar cubes developed strength more slowly than 100 percent PC mortar cubes. However, at 28 days the BFS cubes were 16 percent stronger than the 100 percent PC cubes. They also found that, like PC concrete, the strength of BFS concrete increased as the fineness of the BFS increased. For example, as the BFS fineness increased from 4080 cm^2/g (representative of Grade 80) to 6230 cm^2/g (representative of Grade 120) the 28 day compressive strength increased from 6320 psi to 7750 psi.

Douglas and Pouskouleli (1991) examined the compressive strength of mortar cubes containing 50 percent BFS. However, they also compared the 50 percent BFS mortars to cubes containing 50 percent FA (Class C and F) and 50 percent PC, and to cubes containing 33 percent FA, 33 percent BFS, and 33 percent PC. At all ages the mortar cubes containing 50 percent FA (class C) were stronger than the mortar cubes containing 50 percent FA (class F). At 28 days of age, the class C FA mortar cubes were 32 percent stronger than the class F mortar cubes. Of all the mixtures, the 50 percent BFS and 50 percent PC mixture obtained the greatest 28 day strength of 5210 psi, as compared to 4840 psi for the 50 percent PC and 50 percent class C FA mortar.

2.3.2 Permeability

Rose (1987) examined the effects of BFS on the permeability of concrete. Three concrete mixtures with three different w/cm and varying amounts of BFS were studied. The w/cm's were 0.35, 0.42, and 0.56. The BFS content was either 0, 40, 50, or 65 percent. Each mixture was designed to have a 3 ± 1 inch slump and an air content of 6 ± 1 percent. After batching, the concrete prisms were moist cured or cured at an elevated temperature. The elevated curing consisted of 19 hours of curing at 165 F, then 6 days of curing in laboratory air.

The permeability of the concrete specimens was tested by the rapid chloride ion penetrability (RCIP) test (ASTM C 1202) and also by continuously soaking a specimen in a 5 molar solution of sodium chloride. In all the tests and at the different curing conditions, the results showed that the permeability decreased as the BFS content increased. At an age of 90 days, the concrete containing 65 percent BFS had a total charge passed of less than 200 coulombs, whereas the control concrete had a total charge passed of 6000 coulombs. The continuous soaking test showed that increases in the w/cm had a lesser effect on the permeability of BFS concrete than on 100 percent PC concrete. Increasing the w/cm from 0.40 to 0.50 doubled the chloride concentration of the 100 percent PC mixture, but the chloride concentration of BFS concrete remained virtually the same as the w/cm increased.

Campbell and Detwiler (1993) investigated the effects of steam curing on specimens containing varying amounts of BFS, SF, or a combination of both. Ordinarily, curing at elevated temperatures increases the permeability of concrete. This is because the crystal formation of concrete cured at elevated temperatures is not as consistent as concrete cured at lower temperatures. This causes larger capillary pores, which increases permeability (Mindess and Young, 1981). However, Campbell and Detwiler found that permeability of the concretes containing BFS and/or SF was less than that of concrete containing only PC. The concrete containing 50 percent BFS had a total charge passed of 4500 coulombs versus 11,130 coulombs for the 100 percent PC concrete. The concrete containing 30 percent BFS and 10 percent SF had the lowest charge passed which was 150 coulombs.

Sivasundaram and Malhotra (1992) investigated the permeability of concrete that contained large quantities of BFS. The concretes had BFS contents that ranged from 50 to 75 percent of the total cementitious material, and the w/cm ranged from 0.27 to 0.45. Each concrete mixture contained air entraining agents (AEA) and HRWR. All concrete specimens were cured at 68 ± 2 F and 100 percent RH. The permeability of the specimens was determined by measuring the concrete's resistance to chloride ion penetration. The test results showed that as the BFS content increased, the permeability of the concrete decreased. The concrete containing 70 percent BFS had a total charge passed of 213 coulombs versus 1305 coulombs for the 100 percent PC concrete. The test results also showed that for mixtures with w/cm less than 0.38, the replacement rate had little affect on the RCIP values. For instance, the mixture with 75 percent BFS and a w/cm of 0.29 had a RCIP value of 174 coulombs compared to a mixture with 50 percent BFS, a w/cm of 0.38, and a RCIP value of 383 coulombs. Their test results also showed that as the w/cm decreased, the RCIP also decreased. For example, as the w/cm of three similar mixtures decreased from 0.45 to 0.36 to 0.30, the RCIP also decreased from 829 coulombs to 325 coulombs to 276 coulombs, respectively.

2.3.3 Durability

When added in the appropriate amounts, BFS can improve the durability of concrete. There are several measures that can be used to determine the durability of concrete, but freeze-thaw, sulfate resistance, and corrosion resistance are the most commonly used.

2.3.3.1 Sulfate Resistance. Frearson and Higgins (1992) researched the sulfate resistance of mortar prisms containing 0 to 70 percent BFS. After casting the prisms, measurement points were placed on the sides of the specimens to allow measurement of any expansion. The prisms were water cured for 14 days, and then placed in a 0.31 molar solution of Na_2SO_4 for 4 years. They found that the sulfate resistance of the prisms increased as the BFS content increased. After 4 years of immersion in the solution, the expansion of the prism containing 70 percent BFS was less than 0.01 percent, whereas the 100 percent PC prism disintegrated in 4 months.

Hogan and Meusel (1981) also found that BFS increased the sulfate resistance of mortar specimens. Using the Wolochow Method (lean mortar bar method), they determined that 65 percent BFS mortar bars had an expansion of 0.07 percent at an age of 70 weeks, compared to 0.12 percent for the 100 percent PC mortar bars.

Mangat and Khatib (1995) investigated the sulfate resistance of concrete containing varying amounts of BFS, SF, and FA. Twelve concrete mixtures were developed. Three mixtures contained FA at cement replacement levels of 11, 22, and 32 percent. Three mixtures contained SF at cement replacement levels of 5, 9, and 15 percent. Two mixtures contained BFS at replacement levels of 40 and 80 percent. The control mixture contained 100 percent PC, and one mixture had 22 percent and 9 percent of the cement replaced by FA and SF, respectively .

After casting, the concrete specimens were either wet or air cured, covered or uncovered, and cured at different ambient conditions for 28 days. For the following 28 days, the specimens were cured in water. After the 28 days of water curing, the specimens were placed in a 7 percent Na_2SO_4 and 3 percent $MgSO_4$ solution until time of test. They found that the addition of SF, BFS, and FA improves the sulfate resistance of concrete. At 500 days, the SF, BFS, and FA specimens all had expansion values of less than 0.1 percent, whereas the control concrete had disintegrated in 200 days.

2.3.3.2 Corrosion Resistance. Al-Moudi et. al. (1993) investigated the corrosion resistance of concrete prisms with different proportions of pozzolans. The mixtures studied included a control mixture of 100 percent PC, a mixture containing 20 percent FA, a mixture containing 20 percent of a Class N natural pozzolan, and a mixture containing 60 percent BFS. The w/cm of the mixtures was 0.45. Concrete prisms were cast with a ½ in. diameter steel bar placed in the center. The prisms were water cured for 28 days and then placed in a 5 percent NaCl solution for 7 years. The corrosion activity was monitored by using a voltmeter and a standard calomel electrode. After 7 years of immersion, the corrosion rates in the pozzolan and BFS specimens were 1/2 to 1/12 that of the control mixture.

2.3.3.3 Freeze-Thaw. Hogan and Meusel (1981) examined the durability of BFS concretes by using the freeze-thaw test (ASTM C 666). Concrete prisms were cast that contained either 100 percent PC or 50 percent PC and 50 percent BFS. The prisms were subjected to 301 cycles in a freeze-thaw chamber. The test results showed that the 100 percent PC concrete had a durability factor of 98 versus 91 for the BFS concrete. Hogan and Meusel concluded that the differences in weight loss and expansion were negligible and that both concretes were of sound quality. Sakai et. al. (1992) also determined that concrete containing BFS had satisfactory resistance to the detrimental effects of freeze-thaw cycles.

2.3.4 Volume Changes

2.3.4.1 Drying Shrinkage. Results from drying shrinkage studies found in the literature are mixed. Sivasundaram and Malhotra (1992) examined the drying shrinkage of concretes with BFS contents varying from 50 to 70 percent of the total cementitious material. The specimens were cured at 100 percent RH until tested. They found that the drying shrinkage was approximately the same for concrete containing BFS as for ordinary PC concrete. Sakai et. al. (1992) and Tomisawa et. al. (1992) also concluded that the drying shrinkage for BFS concrete was similar to that of PC concrete.

However, Hogan and Meusel (1981) found that the addition of BFS increased the drying shrinkage of concrete mixtures containing 40 to 65 percent BFS. In air entrained concrete, the addition of BFS increased the drying shrinkage from 0.04 percent to 0.06 percent at 12 weeks age. Chern and Chan (1984) also concluded that the drying shrinkage increased with increasing amounts of BFS. At 90 days age, the addition of BFS resulted in an increase in shrinkage of 200×10^{-6} in./in.

Togawa et. al. (1992) found that the addition of BFS decreased the drying shrinkage. Concrete specimens were cast containing 0 percent BFS and 45 percent BFS. The specimens were water cured for 28 days and then cured at 68 F (20 C) and 60 percent RH until tested. At 36 weeks of age, the addition of BFS resulted in a decrease of drying shrinkage of 100×10^{-6} in./in.

2.3.4.2 Creep. There is a limited amount of information on the effects of BFS on the creep of concrete. Chern and Chan (1989) investigated concrete specimens cast with BFS contents varying from 0 to 68 percent. The specimens were either moist or dry cured. The results showed that under moist curing conditions, increases in BFS content decreased basic creep up to 12 percent. (Basic creep is defined as the amount of creep determined while the specimen is loaded but not drying). Under dry curing conditions, increases in BFS content increased basic creep up to 19 percent.

2.4 ALKALI ACTIVATED BLAST FURNACE SLAG

As previously mentioned, BFS concrete develops strength at a slower rate than PC concrete. Therefore, concrete made with 100 percent BFS slag would not be practical in most instances because of the slow strength development. However, the addition of alkaline reagents, such as NaOH, $Ca(OH)_2$, and sodium or potassium silicates, can increase the strength development of concrete made with a large proportion of BFS (Douglas, 1990).

Douglas and Branstetr (1990) investigated the compressive strength of mortar cubes made with BFS. The mortar cubes were made with either 100 percent BFS, 95 percent BFS and 5 percent PC, or 90 percent BFS, 8 percent SF, and 2 percent $Ca(OH)_2$. All mortar mixtures were activated with sodium silicate. The compressive strength of all the BFS cubes was greater than that of the control mixture (100 percent PC) at 28 days of age. The blended mixture with SF and PC was 50 percent stronger than the control mixture at 7 days and 90 percent stronger at 28 days. However, the 100 percent BFS cubes were too soft to be tested at 1 and 7 days.

Douglas et. al. (1991) studied alkali activated BFS concrete. They also found that BFS concretes activated with sodium silicate could be produced that were workable and could achieve 28 day compressive strengths equal to or greater than that of concrete made with only portland cement.

Gifford and Gillott (1996) examined the alkali-silica reactions (ASR) and alkali-carbonate reaction (ACR) in activated BFS cement (ABFSC) concrete. Concrete prisms were cast using ABFSC and ordinary PC. An aggregate was used that was known to promote ASR or ACR. When compared with PC concrete, they found that ABFSC concrete was more vulnerable to expansion due to ACR and less vulnerable to expansion due to ASR.

2.5 SUMMARY

The literature review indicates that there are gaps in the available information on BFS. This study will examine the effects of a smaller percentage (25 percent) of cement replacement by BFS, whereas the majority of the literature concentrated on larger quantities of BFS. The study will also examine using BFS in combination with Class C FA, which was not considered in most of the studies found in the literature. Also there is a limited amount of literature concerning volume changes, and the conclusions vary from researcher to researcher. In addition to other aspects, this study will address the creep and shrinkage of concretes containing BFS and/or FA.

CHAPTER 3

RESEARCH PROGRAM AND EXPERIMENTAL METHODS

3.1 OVERVIEW

The research program is divided into seven studies. Within each study, performance aspects of using BFS and/or FA were examined. The studies are listed below:

1. *Materials* - Establish properties of all materials to be used in the research.
2. *Cement* - Determine if BFS and/or FA react differently with various Type I cements. Four different Class AA concrete mixtures batched with three different Type I cements were examined. All materials were held constant in each mixture except for the amount and type of cementitious material.
3. *Pozzolan Replacement Fractions* - Determine, through more comprehensive testing, the effects of replacing portions of the portland cement with BFS and/or FA. Class AA concrete (with a single cement source) was used, and all materials were held constant except the amounts of cement/pozzolans. There is some overlap between this study and the Cement Study; however, additional hardened concrete tests were performed.
4. *Mixing/Curing Temperature* - Determine the effects of lowered or elevated mixing/curing temperature on concrete containing BFS and/or FA. For this study the source of cement was held constant. Four Class AA concrete mixtures with varying amount of cementitious material were batched and cured at three different temperatures representative of hot, standard, and cold weather applications.
5. *Class A Concrete* - Determine the performance of Class A concrete utilizing partial cement replacement with BFS and/or FA. All materials were held constant except the amounts and types of pozzolans.
6. *Use of High Range Water Reducer (HRWR)* - Establish the performance of Class AA concrete containing HRWR. Two goals were examined: a) increase workability without changing basic mixture proportions, and b) produce the same workability (as Class AA concrete with no HRWR) but using a lower w/cm.
7. *Use of Silane* - Examine chloride susceptibility of Class AA concrete containing BFS and treated with silane.

In this chapter, each of the studies is described followed by detailed descriptions of the batching, curing, and testing methods used in the research. The chapter is prefaced by a brief summary of the Oklahoma Department of Transportation's (ODOT) requirements for Class AA and Class A concrete.

3.2 SPECIFICATIONS FOR CLASS AA AND CLASS A CONCRETE

ODOT has several different classes of concrete. For all but one portion of this research program, concrete mixtures were designed to meet the requirements of Class AA concrete. Class AA concrete is structural concrete used in members such as bridge decks or concrete piles. The specifications require that the concrete mixture has at least 610 lb/yd^3 (362 kg/m^3) of cementitious material, a w/cm of no more than 0.44, and a #67 size coarse aggregate. ODOT also requires a slump of 1 to 4 in. (25 to 100 mm), a minimum 28 day compressive strength of 4000 psi (28 MPa), and total air content of 7 ± 1.5 percent.

Limits are also placed on the amounts of pozzolanic materials that can substituted for cement. Up to 15 percent of the cement can be replaced by Class C fly ash. However, the FA must be replaced at a ratio of 1.35 lb. of FA for every 1.00 lb. of cement. Up to 25 percent of the cement can be replaced by BFS at a 1.00 lb. to 1.00 lb. replacement ratio.

Specifications for Class A concrete require a minimum cementitious material content of 565 lb/yd^3 (335 kg/m^3), a maximum w/cm of 0.48, and #57 size coarse aggregate. Slump is specified to be from 1 to 3 in. (50 ± 25 mm), the minimum 28 day compressive strength is 3000 psi (21 MPa), and the total air content is to be 6 ± 1.5 percent. Pozzolan replacement is permitted subject to the same limitations described above.

3.3 MATERIALS

A river sand fine aggregate from Dover, OK, was used in all mixtures of the research. All Class AA concrete contained a #67 crushed limestone coarse aggregate from Davis, OK. Class A concrete utilized a #57 crushed limestone coarse aggregate from the same source. For the cements, three locally manufactured Type I cements were used. The three cement sources were Ash Grove from Midlothian, TX, Blue Circle from Tulsa, OK, and Holnam from Ada, OK. As for the pozzolans, a Class C FA from Oolagah, OK, and a ***Grade 120*** BFS were used. The BFS was provided by NewCem, which is manufactured in Sparrows Point, MD.

Specific gravity, absorption, and gradation were determined for the fine and coarse aggregates. The dry rodded unit weight was also measured for the coarse aggregate. Fineness, as measured by a Blaine Apparatus, was measured for the Type I cements. The slag activity index was also measured for the BFS. A summary of all material tests performed and their ASTM designations is shown in Table 3.1. Chemical compositions and fineness of the cements and blast furnace slag are shown in Table 3.2. Results of the slag activity test are shown in Table 3.3. Note that the slag activity index of 1.31 exceeded the minimum requirement of 1.15 necessary for classification as Grade 120. Properties of the aggregates are listed in Table 3.4.

3.4 CEMENT STUDY

The cement study was performed to determine if BFS reacts differently with various Type I cements, and also examined interaction between BFS and Class C fly ash. Three locally available Type I cements were used for the study. For each cement, four basic mixtures were batched: 1) control PC mixture (designated P), 2) 15 percent Class C fly ash replacement (designated FA), 3) 25 percent slag replacement (designated BFS), and 4) combination of 15 percent fly ash and 25 percent slag (designated FB). All mixtures had equal amounts of fine aggregate, coarse aggregate, and water. For each mixture, twin batches were made; therefore, a total of 24 mixtures were batched (three cements x four mixture designs x two batches/mixture). Mixture proportions (saturated surface dry conditions) and designations are shown in Table 3.5.

All mixtures were subjected to several tests in order to determine the fresh and hardened properties of concrete. Fresh concrete properties tested included slump, unit weight, total air content, and time to set. The hardened concrete properties tested included compressive strength (3, 7, 28, 56, and 90 day), modulus of elasticity (28 and 90 day), modulus of rupture (28 day), splitting tensile strength (28 and 90 day), length change, and rapid chloride ion penetrability (28 and 90 day). The fresh and hardened concrete tests and their ASTM designations are shown in Table 3.6. For this portion of the research, all batches were subjected to standard moist curing at 73.4 F (23 C).

Table 3.1 Material Tests

	MATERIAL TESTS	
Cements, FA, and BFS	Blaine Air Fineness	ASTM C 204
	Slag Activity Index	ASTM C 989
Coarse Aggregate	Specific Gravity and Absorption	ASTM C 127
	Sieve Analysis	ASTM C 136
	Dry Rodded Unit Weight	ASTM C 29
Fine Aggregate	Specific Gravity and Absorption	ASTM C 128
	Sieve Analysis	ASTM C 136

Table 3.2 Cement and BFS Properties†

	Ash Grove	Blue Circle	Holnam	BFS
	Chemical Composition(%)			
SiO_2	20.72	20.57	20.9	32-39
Al_2O_3	6.02	4.95	5.4	9-12
Fe_2O_3	2.69	2.58	2.6	0.7-1.0
CaO	-	62.43	64.8	38-42
MgO	1.04	2.01	1.8	8-13
SO_3	2.87	3.04	2.7	-
	Compound Composition (%)			
C_3S	54.4	52.3	57	-
C_2S	18.4	-	17	-
C_3A	11.40	9	10	-
C_4AF	-	-	8	-
	Blaine Air Fineness			
Blaine Fineness (cm^2/g)	3350*	3460*	3500*	4900-5800

† Composition and fineness of Class C fly ash unavailable.
*Measured for this research. All other values in the table reported by manufacturer.

Table 3.3 Slag Activity Index

	Compressive Strength (psi) Control Mix (1)	Compressive Strength (psi) 50% BFS (2)	Slag Activity Index (2)/(1)
7 Day	3260	3160	0.97
28 Day	5650	7390	1.31

Table 3.4 Aggregate Properties

	Fine Aggregate (River Sand, Dover, OK)	Coarse Aggregate (Crushed Limestone, Davis, OK)
Absorption (SSD)	0.68%	0.86%
Specific Gravity	2.63	2.68
Dry Rodded Unit Weight (lb/ft^3)	-	101.2

Table 3.5 Mixture Proportions for the Cement Study

	Mixture Designation			
Material	P	FA	BFS	FB
Cement (lb/yd^3)	658	559	494	395
FA (lb/yd^3)	-	134	-	134
BFS (lb/yd^3)	-	-	165	165
Water (lb/yd^3)	254	254	254	254
w/c	0.39	0.45	0.52	0.64
w/cm	0.39	0.37	0.39	0.37
Coarse Agg. (lb/yd^3)	1890	1890	1890	1890
Fine Agg. (lb/yd^3)	1137	1137	1137	1137
AEA (fl. oz./cwt)	14	14	14	14

Table 3.6 Cement Study Tests

Fresh Concrete	Slump	ASTMiC 143
	Unit Weight	ASTMiC 138
	Air Content	ASTMiC 231
	Time to Set	ASTMiC 403
Hardened Concrete	Compressive Strength	ASTMiC 39
	Elastic Modulus	ASTMiC 469
	Modulus of Rupture	ASTMiC 78
	Split Tensile Strength	ASTMiC 496
	Shrinkage	ASTMiC 157
	Rapid Chloride Ion Permeability	ASTMiC 1202

3.5 POZZOLAN REPLACEMENT FRACTIONS STUDY

This study added further hardened concrete tests to provide a more comprehensive picture of the performance of Class AA concrete containing BFS and/or FA. The same replacement fractions and mixture proportions described above for the Cement Study were used, except the AEA dosages varied between mixture types. Mixture proportions are shown in Table 3.7. All mixtures contained the same Type I cement (Ash Grove from Midlothian, TX). Therefore, in conjunction with the Cement Study results, a large set of data was produced to assess the potential effects of pozzolan replacement.

Since there was overlap between the Cement Study and Pozzolan Replacement Study, full duplicate tests were not performed in the Pozzolan Replacement Study. Instead, for tests that had already been performed in the Cement Study, sufficient data was obtained to verify that the Pozzolan Replacement Study concretes were not substantially different from those batched in the Cement Study.

The following tests were common to both the Cement and Pozzolan Replacement Studies. Fresh concrete tests performed in both studies included slump and air content. Hardened concrete tests included compressive strength (28 day), elastic modulus (28 day), and modulus of rupture (28 day).

New hardened concrete tests performed included creep (loaded at 28 days age), 90 day salt ponding (acid soluble chlorides), freeze-thaw durability (samples submerged in water), and triaxial permeability. Assessing permeability by both the rapid chloride ion penetrability test and the 90 day salt ponding test permitted limited correlation between the two test methods, and facilitated later comparison with silane treated concrete. Very selective permeability tests (two total) were also performed in a triaxial apparatus equipped with permeability measurement in the University of Oklahoma Halliburton Rock Mechanics Laboratory. The triaxial tests were conducted to determine whether another non-standard permeability test method had applicability for concrete. These tests did not produce meaningful results; therefore the results will not be discussed in this report. The additional hardened concrete tests and their designations are shown in Table 3.8.

Table 3.7 Mixture Proportions for Pozzolan Replacement Study

	Mixture Designation			
Material	P	FA	BFS	FB
Cement (lb/yd^3)	658	559	494	395
FA (lb/yd^3)	-	134	-	134
BFS (lb/yd^3)	-	-	165	165
Water (lb/yd^3)	254	254	254	254
w/c	0.39	0.45	0.52	0.64
w/cm	0.39	0.37	0.39	0.37
Coarse Agg. (lb/yd^3)	1890	1890	1890	1890
Fine Agg. (lb/yd^3)	1137	1137	1137	1137
AEA (fl. oz./cwt)	19 to 21	25 to 28	24 to 25	18 to 23

Table 3.8 Additional Tests for Pozzolan Replacement Study

Hardened Concrete	Creep	ASTM C 512
	90 day Salt Ponding	AASHTO T259/T260
	Freeze-Thaw Durability	ASTM C 666
	Triaxial Permeability	-

3.6 MIXING/CURING TEMPERATURE STUDY

This study examined the effects of mixing and curing temperatures on concrete containing BFS and FA. Mixtures were batched and cured at a lowered and elevated temperature to simulate cold and hot weather concreting. The same source of cement (Ash Grove) was used for both curing regimens. Results from the Cement Study (standard curing temperature) for the same cement source provided additional data to get a fairly comprehensive picture of the effects of a broad range of mixing and curing temperatures on pozzolan concrete properties.

To simulate cold weather batching, mixtures were batched at 50 F (10 C) and cured for the first 24 hours at 50 F (10 C). After the initial 24 hours, the concrete was cured at 50 F (10 C) until time of testing. To simulate hot weather batching, the mixtures were batched and cured for the first 12 hours at 95 F (35 C). After the initial 12 hours, the concrete was cured at 83 F (28.3 C). The chosen elevated temperatures represent the average high and mean daily temperature, respectively, for the summer months in Oklahoma.

The four mixture designs described for the Cement Study were tested at both cold and elevated temperature, namely PC control (designated P), 15 percent fly ash replacement (designated FA), 25 percent BFS replacement (designated BFS), and combination of 15 percent FA and 25 percent BFS (designated FB). Additionally, a 50 percent slag replacement rate was tested at elevated and standard temperature only (designated BB). The same coarse and fine aggregate material contents and amount of water were used for all mixtures in the study. The mixture proportions are shown in Table 3.9.

Table 3.9 Mixture Proportions for the Temperature Study

	Mixture Designation				
Material	P	FA	BFS	FB	BB
Cement (lb/yd^3)	658	559	494	395	329
FA (lb/yd^3)	-	134	-	134	-
BFS (lb/yd^3)	-	-	165	165	329
Water (lb/yd^3)	254	254	254	254	254
w/c	0.39	0.45	0.52	0.64	0.77
w/cm	0.39	0.37	0.39	0.37	0.39
Coarse Agg. (lb/yd^3)	1890	1890	1890	1890	1890
Fine Agg. (lb/yd^3)	1137	1137	1137	1137	1137
AEA (fl. oz./cwt)	*	*	*	*	*

* AEA dosage varied for batching temperature

All mixtures were subjected to several tests to determine fresh and hardened properties of concrete. Fresh concrete properties tested included slump, unit weight, air content, and time to set.

Hardened concrete properties tested included compressive strength, tensile strength, modulus of elasticity, modulus of rupture, length change, and rapid chloride ion permeability. The fresh and hardened concrete tests and their ASTM designations are shown in Table 3.10.

Table 3.10 Temperature Study Tests

Fresh Concrete	Slump	ASTM C 143
	Slump Loss	-
	Unit Weight	ASTM C 138
	Air Content	ASTM C 231
	Time to Set	ASTM C 403
Hardened Concrete	Compressive Strength	ASTM C 39
	Elastic Modulus	ASTM C 469
	Modulus of Rupture	ASTM C 78
	Split Tensile Strength	ASTM C 496
	Shrinkage	ASTM C 157
	Rapid Chloride Ion Penetrability	ASTM C 1202

3.7 CLASS A CONCRETE STUDY

In this portion of the research, Class A concrete with pozzolan replacement was studied. The coarse and fine aggregate source materials used were the same as in the preceding three studies, except that the coarse aggregate grading was #57 (instead of #67). Three mixture types were examined. They were PC control (P-A), 15 percent fly ash replacement (FA-A), and 25 percent blast furnace slag replacement (BFS-A). The combination mixture with FA and BFS was not tested. The SSD mixture proportions are shown in Table 3.11.

Fresh and hardened concrete tests conducted are shown in Table 3.12. The compressive strength and the drying shrinkage tests were performed through 90 days. Modulus of elasticity, RCIP and all other strength tests were performed at 28 days.

Table 3.11 Mixture Proportions for Class A Mixtures

	Mixture Designation		
Material	P-A	FA-A	BFS-A
Cement (lb/yd^3)	564	480	423
Fly Ash (lb/yd^3)	0	114	0
BFS (lb/yd^3)	0	0	141
Water (lb/yd^3)	254	254	254
w/c	0.45	0.53	0.60
w/cm	0.45	0.43	0.45
Coarse Agg.(lb/yd^3)	1962	1962	1962
Fine Agg. (lb/yd^3)	1180	1180	1180
Water (lb/yd^3)	254	254	254
AEA (fl.oz/cwt)	1	5 to 6	3 to 6

Table 3.12 Class A Concrete Tests

Fresh Properties	Unit Weight	ASTM C318
	Slump	ASTM C143
	Slump Loss	-
	Air Content	ASTM C231
	Time to Set	ASTM C403
Hardened Properties	Compressive Strength	ASTM C39
	Modulus of Rupture	ASTM C78
	Modulus of Elasticity	ASTM C469
	Drying Shrinkage	ASTM C490
	Splitting Tensile Strength	ASTM C496
	Rapid Chloride Ion Penetrability	ASTM C1202

3.8 HIGH RANGE WATER REDUCER STUDY

This portion of the research program examined the performance of Class AA concrete containing a high range water reducer (HRWR). The HRWR used in the research was Daracem-19 from W.R. Grace & Co. Two goals were examined: a) to increase workability without changing the basic mixture proportions, and b) to produce the same workability (as Class AA concrete with no HRWR) but using a lower w/cm. For this portion of the study, four mixtures were examined. The four mixtures are shown in Table 3.13. For two of the mixtures, a HRWR was added to the same fly ash and slag mixture designs used in the Cement Study. The other two mixtures were identical to the fly ash and slag mixtures except they had less mixing water (w/cm reduced by 0.03) and a higher dosage of HRWR.

All mixtures were subjected to several tests that examined the fresh and hardened properties of concrete. The fresh concrete properties tested included slump and slump loss, unit weight, air content, and time to set. The hardened concrete properties tested included compressive strength (3, 7, and 28 day), tensile strength (28 day), modulus of elasticity (28 day), modulus of rupture (28 day), length change (3, 7, 14, and 28 day), and rapid chloride ion penetrability (28 day). The fresh and hardened concrete tests are shown in Table 3.14.

Table 3.13 Mixture Proportions of Class AA Mixtures for HRWR Study

Material	Mixture Designations			
	FA-H Higher Slump	FA-R Reduced w/cm	BFS-H Higher Slump	BFS-R Reduced w/cm
Cement (lb/yd^3)	559	559	494	494
FA (lb/yd^3)	134	134	-	-
BFS (lb/yd^3)	-	-	165	165
Water (lb/yd^3)	254	237	254	237
w/c	0.45	0.42	0.52	0.48
w/cm	0.37	0.34	0.39	0.36
Coarse Agg. (lb/yd^3)	1890	1890	1890	1890
Fine Agg. (lb/yd^3)	1137	1182	1137	1182
AEA (fl.oz./cwt)	1	2	1	2
HRWR (fl.oz./cwt)	3.5	5	4	5

Table 3.14 HRWR Study Tests

	CONCRETE TESTS	
Fresh Concrete	Slump	ASTM C 143
	Slump Loss	ASTM C 143
	Unit Weight	ASTM C 138
	Air Content	ASTM C 231
	Time to Set	ASTM C 403
Hardened Concrete	Compressive Strength	ASTM C 39
	Elastic Modulus	ASTM C 469
	Modulus Rupture	ASTM C 78
	Split Tensile Strength	ASTM C 496
	Shrinkage	ASTM C 157
	Rapid Chloride Ion Penetrability	ASTM C 1202

3.9 SILANE STUDY

The silane study examined only the Class AA mixtures P (control) and BFS. These were the same mixtures used in previous studies. The materials and mix proportions remained unaltered and can be seen in Table 3.7. In fact, the specimens in this study were extracted from the same batch of specimens used in the Pozzolan Replacement Fractions Study, and then treated with silane. The focus of the research was to ascertain the enhancement ability of silane towards reducing chloride ion permeability of concrete containing blast furnace slag. The 90 day salt ponding test (AASHTO T259/T260) was used to examine this task.

3.10 EXPERIMENTAL METHODS

This section contains a general discussion of procedures used in batching, curing, and testing concrete specimens in this research. Also, variances in procedures from ASTM or AASHTO standards are documented.

3.10.1 Batching and Curing

Prior to batching, the moisture content of aggregates was determined by obtaining representative samples of the aggregates, which were stored in stockpiles in the yard of the laboratory. The samples were then weighed and oven dried to constant weight (ASTM C 566). While obtaining the aggregate samples, a sufficient quantity of the coarse and fine aggregates were separately placed into 5 gal plastic buckets. Each bucket contained 50 lb of coarse or fine aggregate. Lids were then placed on each bucket to prevent any loss of moisture from the time of sampling to the time of batching.

To ensure consistency, twin batches were made for each concrete mixture. The batching was done in a rotating drum mixer with a 6 ft^3 capacity. All batching conformed to ASTM C 192. The procedure for addition of the constituent materials remained the same for all mixtures. When larger batches (around 4.0 ft^3) were required, the batch was charged as if it were two smaller batches. This was done to ensure that the concrete was uniformly mixed. The mixing sequence was as follows. First, one-half of the coarse aggregate was placed into the mixer along with approximately one-third of the mixing water. Then, one-half of the sand and one-half of the cement were gradually added. Once the concrete reached a uniform consistency, the remaining materials were gradually blended into the concrete. For smaller batches (around 2.5 ft^3 or less), all of the coarse aggregate and one-half of the mixing water were first added to the mixer. Then the remaining materials were gradually introduced into the mixer. For all mixtures, the AEA (Daravair 1000, W.R. Grace & Co.) was added to the mixing water to ensure uniform dispersion throughout the concrete.

Different fresh concrete temperatures were required in various portions of the research. For the Cement, Silane, Pozzolan Replacement, Class A and HRWR studies, the desired concrete temperature was 70 F (21 C). When ambient temperatures were too high, crushed ice was added to the mixing water. The Temperature Study required concrete with higher and lower temperatures also. The majority of the hot weather concrete was batched on days with ambient temperatures at or near 90 F (32 C), but on some occasions the ambient temperatures were slightly cooler; therefore warm tap water with a temperature of 90 F (32 C) was used as the mixing water. All of the cold weather concrete was batched during the winter months so there was no need to adjust the temperature of the mixing water.

For the Cement, Pozzolan Replacement, Class A, HRWR , and Silane studies, all concrete specimens were cured at 73.4 ± 3 F (23 ± 1.7 C) and 50 percent relative humidity (RH) for the first 24 hours. Then the specimens were removed from their molds and moist cured in lime-saturated water at 73.4 ± 3 F until time of testing. The length change specimens were cured at 73.4 ± 3 F and 50 percent RH. The only exception was the curing method for creep test specimens. For the first seven days, the creep specimens were covered with wet burlap in a 73.4 ± 3 F environment. From that point on, specimens remained at 73 F and 50 percent relative humidity until time of loading.

For the hot weather concrete, specimens were cured at 95 F (35 C) for the first 12 hours. To obtain the 95 F environment, the specimens were submerged to at least 3/4 of their depth in a bath of 95 F water. The water was heated using a commercial heating element with a thermostat, and a submersible pump was used to circulate the water. After the initial 12 hours, the molds were removed and the specimens were moist cured (ASTM C 192) in lime-saturated water at a temperature of 83 F (28 C) until time of testing. The length change specimens were cured at 74 F and 50 percent RH after the initial 24 hours.

The cold weather concrete was cured at 50 F (10 C) for the first 24 hours. For this portion of the study, stock tanks were placed outside the laboratory on a covered patio. Since the concrete was batched during the winter, the average daily temperature did not rise above 50 F. However, water heaters were used to ensure that the water temperature remained at or near 50 F. After the initial 24 hours, the molds were removed and the specimens were moist cured in lime-saturated water at a temperature of 50 F (10 C) until time of testing. The specimens were cured outdoors in a stock tank. Once the ambient temperature rose above 50 F, ice was added to the water to maintain the temperature. All length change specimens were placed in a 50 percent RH and 73.4 F environment after the initial 24 hours.

3.10.2 Fresh Concrete Tests

A series of tests was performed on concrete mixtures. For the fresh concrete, slump (ASTM C 143), unit weight (ASTM C 136), and air content (ASTM C 231) were determined for each batch. Time to set (ASTM C 403) was also conducted on selected concrete mixtures. For time to set, paste was collected by vibrating the concrete through a #40 screen. After a sufficient amount of paste was collected, the specimens were left in the curing chamber (73 F, 50 percent RH). Periodically, excess bleed water was removed by gently pressing onto the concrete surface with tissue paper. All time to set tests were done using the penetration method. After the concrete paste started to set, one inch deep penetrations were made using varying needle sizes at appropriate time intervals with a device capable of measuring the loads. To determine the initial and final set, the penetration resistance was plotted against time to obtain a curve, or a log-log plot was used to generate a straight line.

The only fresh concrete test that did not follow a particular ASTM standard was the slump loss test. Slump loss is basically the reduction of slump over time. Slump was determined according to ASTM C 143. Consequently, a series of slump tests was performed at roughly fifteen minute intervals for the first one or two hours, depending on the trend of the data. The same concrete fresh sample of at least one cubic foot was used repeatedly and a representative sample was obtained before each slump test.

3.10.3 Hardened Concrete Tests

Compressive strength (ASTM C 39), tensile strength (ASTM C 496), modulus of elasticity (ASTM C 469), modulus of rupture (ASTM C 78), length change (ASTM C 157), creep (ASTM C 512), freeze thaw (ASTM C 666), salt ponding (AASHTO T 259), and rapid chloride ion penetration (ASTM C 1202) were used to examine the hardened properties of concrete mixtures.

Compressive strength was usually tested at 3, 7, 28, 56, and 90 days of age. Typically, three cylinders (4 x 8 in.) from each of two batches were tested at each age, for a total of six cylinders from each mixture. The cylinders were tested using a 600 kip capacity testing machine. The ends of the cylinders were placed on neoprene pads (85 durometer hardness) that were seated in aluminum rings. This testing machine was also used to conduct splitting tensile strength, modulus of rupture (MOR), and modulus of elasticity (MOE) tests.

The splitting tensile strength, modulus of elasticity, and modulus of rupture were tested at 28 and 90 days of age. From each batch, three cylinders (4 x 8 in.) were tested for splitting tensile strength, two cylinders for MOE, and two 6 x 6 x 20 in. concrete beams for MOR. A compressometer jacket equipped with a linear variable differential transformer (LVDT) was used to measure the MOE.

Length change was measured at 3, 7, 28, 56, and 90 days of age. The dimensions of the length change specimens were 3 x 3 x 11.25 in. The length change procedure varied from ASTM C 157. To capture early shrinkage properties, instead of submerging the length change specimens in lime-saturated water after the first 24 hours, the specimens were cured at 50 percent RH for the entire test duration and the specimens were measured at the previously mentioned ages.

The creep test did not vary from ASTM C 512. The creep specimens were four inches in diameter and ten inches in length. Five cylindrical specimens were stacked to form a vertical column; hydrostone was used to fill the joints between the specimens and to provide uniform bearing. The alignment of the columns was cautiously done to avoid eccentric loading. Two unloaded cylinders were used as control.

Creep strains were determined using a mechanical strain gage (8 in. gage length) and external strain gage points. Before loading, each cylinder was instrumented with two pairs of points to allow length change measurements at diametrically opposed locations. The load intensity on the column was

40 percent of the compressive strength at the age of loading (28 days). Strain readings were taken before loading, immediately after loading, two to six hours later, daily for a week, weekly for a month and then monthly until the test was terminated.

The freeze-thaw test conformed to ASTM C 666. Three 4 in. x 4 in. x 15 in. specimens were tested from each mixture. Immediately after normal curing, the specimens were weighed and the dimensions were accurately measured. The fundamental transverse and longitudinal frequency was measured. Then, the specimens were moved into pans in the freeze-thaw chamber. The pans were filled with water so that all specimen surfaces were surrounded by 1/32 to 1/8 in. of water. Before starting the freezing and thawing cycles, care was taken to ensure that the freeze- thaw chamber met the requirements as stated in ASTM C666. For example, the maximum (40 ± 3 F) or minimum (0 ± 3 F) temperature limits of the cycle were not exceeded. Once the test began, measurements of weight and fundamental transverse frequency were taken periodically. Weight and frequency measurements were usually obtained after every 36 ± 2 freeze-thaw cycles. Visual inspection of specimen surfaces was also made and recorded if necessary. The tests were continued to at least 300 cycles.

The salt ponding tests, and sampling and chemical analysis procedures, conformed to AASHTO T259 and AASHTO T260, respectively. The specimen dimensions were 4 x 12 x 12 in. A trowel finish was applied to the top of the specimens within the first hour after mixing.

The salt ponding specimens were cured in a 73 F and 50 percent RH environment. Rubber strips were placed on the specimens' top surface and sealed with silicon to dam the 3 percent sodium chloride (NaCl) solution. The depth of the NaCl solution was maintained at 0.5 inch during ponding. The time schedule for curing, drying, treatment, ponding, and sampling is shown in Table 3.15.

At the conclusion of the ponding period, the specimens were allowed to air dry. Before drilling, the surfaces of the specimens were wire brushed. A rotary percussion drill was used to obtain the powder samples for chemical analysis. Two drill bit sizes were used with the larger bit used to drill the upper half inch. Three holes were drilled from each specimen. Within each hole, two samples were collected from the depths 0.0625 to 0.5 in. and then 0.5 to 1.0 in. To prevent contamination, denatured alcohol was used to clean the drill bits. The Potentiometric Titration method of Procedure A (AASHTO T260) was utilized to determine the acid-soluble chloride ion content.

The rapid chloride ion penetration (RCIP) was tested at 28 and 90 days of age. From each batch, two 4 in. diameter cylinders were tested. Two days prior to testing, the top two inches of the cylinders to be tested were cut off using a masonry saw. The side surface of the cylinders was then

Table 3.15 Salt Ponding Tasks

AGE (days)	TASK
1	Demold specimen / start wet curing
14	End wet curing / start drying
21	Treat specimen with silane (if needed)
29	Place rubber dam around top edges
42	Start ponding of salt solution
132	End ponding / brush off salt buildup / start drying
250+	Drill and pulverize to obtain samples for chemical analysis

covered with epoxy. Once the epoxy dried, the cylinders were placed in a desiccator and subjected to a vacuum of no more than 1mm of mercury (Hg) for three hours. After the three hours, water was introduced into the desiccator with the vacuum pump continuing to run for an additional hour. After the additional hour, the vacuum pump was turned off and the desiccator opened to atmospheric pressure. The cylinders were then ready to test once they had been submerged in water for 18 hours.

End caps, conforming to ASTM C 1202, were manufactured to test the samples. The end caps were then placed on the ends of the prepared specimens. In each of the end caps, sodium hydroxide or sodium chloride was placed. A positive terminal was attached to the cap containing sodium hydroxide and a negative terminal attached to the cap containing sodium chloride. Then a potential of 60 volts was applied to each specimen for six hours. A PC based data acquisition system was used to measure the total coulombs passed through each specimen for the six hour period.

CHAPTER 4

RESULTS

4.1 GENERAL

This chapter contains a presentation of the results and significant observations of the experimental program. Information is first presented for the Cement Study, followed by the Pozzolan Replacement Fractions, Mixing/Curing Temperature, Class A Concrete, use of HRWR, and use of Silane Studies. For each of the major studies, observations are first presented for fresh concrete properties, followed by results of the hardened concrete tests. Properties of the constituent materials were presented in Chapter 3 (section 3.3.1).

Throughout the discussion, the mixture designations presented in Chapter 3 are used. P mixtures were portland cement control mixtures with no pozzolans. FA mixtures contained 15 percent Class C fly ash (replaced as described in Chapter 3), BFS mixtures contained 25 percent slag replacement, and FB mixtures contained the combination of 15 percent fly ash with 25 percent slag.

4.2 CEMENT STUDY

The purpose of the Cement Study was to determine if BFS interacted differently with locally available Type I cements. The study compared the performance of concrete containing BFS to concrete without BFS (control), to concrete containing FA, and to concrete with both FA and BFS. Three different sources of Type I cement were used. These three sources were designated A, B, and C. Source A was Ash Grove (Midlothian, TX), source B was Blue Circle (Tulsa, OK), and source C was Holnam (Ada, OK). Fresh and hardened concrete properties were tested for each concrete mixture. In the mixture designations used in this discussion, the first letter refers to the cement source (A, B, or C). The remaining letters identify the type of mixture (P = control, FA = fly ash, BFS = slag, and FB = fly ash combined with slag).

4.2.1 Fresh Concrete Tests

Five fresh concrete properties were measured for each mixture. The tests performed were slump, fresh concrete temperature, air content, unit weight, and time to set. The results from the fresh concrete property tests are shown in Table 4.1.

Table 4.1 Fresh Concrete Properties for Cement Study

MIXTURE	SLUMP (in.)	AIR CONTENT (%)	UNIT WEIGHT (lb/ft^3)	INITIAL SET (hrs.)	FINAL SET (hrs.)
A-P	3	6.8	141.4	3.4	4.9
A-FA	2.25	6.9	142.0	5.4	7.3
A-BFS	1.25	5.2	144.5	3.5	5.0
A-FB	1.5	5.4	145.2	5.4	7.2
B-P	2.25	5.8	144.0	2.7	4.2
B-FA	3.25	6.6	140.5	5.5	7.6
B-BFS	1	5.2	147.2	2.0	3.3
B-FB	1.75	5.2	144.1	4.8	6.6
C-P	1.75	5.2	144.8	4.9	6.3
C-FA	2.5	6.2	144.4	5.9	8.1
C-BFS	1.5	5.0	146.4	5.1	6.5
C-FB	1.5	5.0	144.5	6.3	8.5

4.2.1.1 Slump. In general, the slump results for each cement followed a similar trend as can be seen in Table 4.1. For most cements, the mixtures containing FA had the greatest slump, whereas the mixtures containing BFS had the least slump. Note the values listed in the table are averages from each of the twin batches.

Of the three cements, cement A produced concrete with slightly more slump for P mixtures. However, the addition of BFS and FA affected the slump. The addition of BFS resulted in a decrease in slump for all cements. The decrease in the slump of the BFS mixtures versus that of the P mixtures ranged from 1.75 in. to 0.25 in. This decrease in slump can be attributed to the higher fineness of the Grade 120 blast furnace slag. The slag was significantly finer (at least 1500 cm^2/g finer) than the Type I portland cements. As the material becomes finer, the water demand increases due to the increase in surface area per unit volume. The increase in water demand of the BFS mixtures expectedly resulted in lower slumps.

Addition of fly ash had the opposite effect on the concrete. Those mixtures containing only fly ash and portland cement generally exhibited increases in slump. For cement B and cement C, the addition of FA increased the slump by 1.0 in. and 0.75 in., respectively. Fly ash, although finer than portland cement, is composed of smooth glassy particles which often reduce water demand and produce better workability. It is not apparent why cement A's FA mixture had less slump than its corresponding P (control) mixture.

When combined together, the addition of both FA and BFS had little effect on slump. For a given cement, slumps of the FB mixtures were generally similar to or greater than those of BFS mixtures. The addition of FA tended to counteract the negative effects of BFS on water demand.

4.2.1.2 Air Content. All mixtures were designed to have a total air content of 7 ± 1.5 percent. The target air content was attained using a commercial air entraining agent (AEA). The AEA dosage was kept constant at 14 fl. oz./cwt. for all mixtures. This dosage rate is significantly more than the manufacturer's recommended dosage of 3/4 to 3 fl. oz/cwt. The results from the air content tests are shown in Table 4.1. The numbers in Table 4.1 represent the average of two tests, one from each of the twin batches.

Similar trends exhibited for the slumps of the mixtures were also observed for the air contents. For each cement, the mixtures containing portland cement with fly ash replacement (mixtures FA) had the greatest air contents. Likewise, the mixtures with only BFS replacement (mixtures BFS) had the lowest air contents. For any given cement, the addition of FA resulted in a slight increase in air content as compared to mixtures containing only PC (mixtures P). The increase in total air content for FA mixtures can be attributed to the increase in workability. The increase in workability allows for a better dispersion of air bubbles, which tends to increase total air content. For this same reason, the BFS mixtures had the least amount of slump, and therefore the lowest total air content.

In general, the different cements produced concrete with similar air contents for like mixtures. However, the control mixture for cement A produced an air content approximately one percent higher than the other control mixtures. Note this mixture (A-P) also exhibited higher slump than the other control mixtures.

4.2.1.3 Concrete Temperature. The concrete temperature for each mixture was taken as a quality control measure. The target concrete temperature was 70 F (21 C) for all mixtures. Since the majority of the mixtures were cast during the summer, crushed ice was added to the mixing water to help lower the concrete temperature. The fresh concrete temperatures ranged from 68 to 76 F (20 to 24 C).

4.2.1.4 Unit Weight. The results from the unit weight tests are given in Table 4.1. The values reported are the average of two unit weight tests, one from each twin batch. The unit weights of the mixtures ranged from 141.4 to 146.4 lb/ft^3 and were affected by the air contents of the mixtures. As expected, the mixtures with the highest total air contents (FA mixtures) generally had the lowest unit weight, and those with the lowest total air contents (BFS mixtures) had the greatest unit weight.

4.2.1.5 Time to Set. The time to set test was performed on concrete made from each cement source for each of the four mixtures. The results from the time to set tests are shown in Table 4.1.

For most mixtures, those containing cement B generally had the earliest initial and final set times. Even though the setting times were different between cements, the time interval between initial and final set for like mixtures was approximately the same. For each cement source, the BFS and P mixtures reached initial and final set in approximately the same amount of time, and the FA and FB mixtures had similar setting times, which were around 1 to 3 hours longer than for the P and BFS mixtures.

4.2.2 Hardened Concrete Tests

Six tests were conducted on the hardened concrete at various ages for each mixture. Compressive strength, splitting tensile strength, modulus of elasticity, modulus of rupture, rapid chloride ion penetrability and length change (shrinkage) were the hardened concrete properties tested.

4.2.2.1 Compressive Strength. The compressive strength of all mixtures was measured at 3, 7, 28, 56, and 90 days of age. For all compressive strength data, the results presented are averages from six cylinders (three from each twin batch). The strength gain curves for each cement source are shown in Figs. 4.1 to 4.3; strength gain curves for each mixture type are shown in Figs. 4.4 to 4.7.

As shown in Figs. 4.1 to 4.3, the BFS mixtures generally had the highest strengths at all ages. The P mixtures had compressive strengths less than those of the BFS mixtures while the FA mixtures had the lowest compressive strength, except for cement B. As expected, the compressive strengths of the FB mixtures fell between the compressive strengths of the FA and BFS mixtures.

Examining Figs. 4.4 to 4.7, it can be seen that for control mixtures, cement C produced concrete with slightly higher strengths than concretes with the other two cements. Cement B interacted better with fly ash than the other cements (Fig. 4.5), while cement A performed better with slag than the other cements (Fig. 4.6). Strengths of all combination (FB) mixtures were very similar (Fig. 4.7).

The compressive strengths of the mixtures were first tested at three days age to determine if the addition of the pozzolans retarded early strength gain. The results are shown in Table 4.2. Also shown in Table 4.2 is the average compressive strength of like mixtures.

Using the averages for like mixtures, the BFS mixture had the greatest compressive strength at three days. The combination mixture (FB) had the lowest compressive strength while mixtures FA and P usually had similar compressive strengths. At three days of age, the BFS mixtures had similar or greater strengths when compared to the P mixtures while the FA mixture's results were varied.

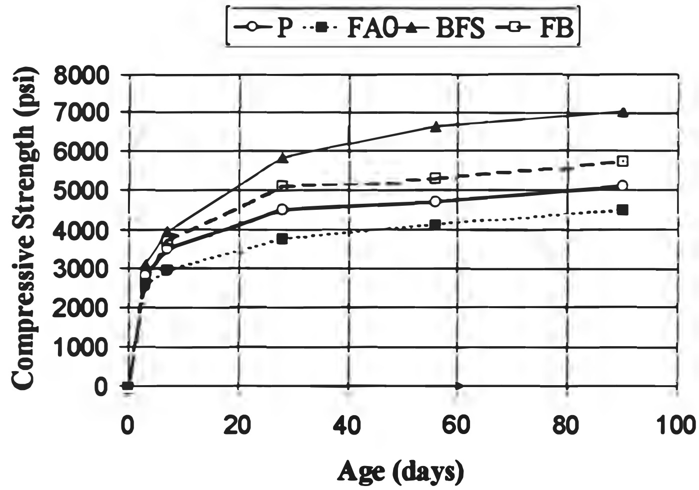


Fig. 4.1 Strength Gain for Cement A Mixtures

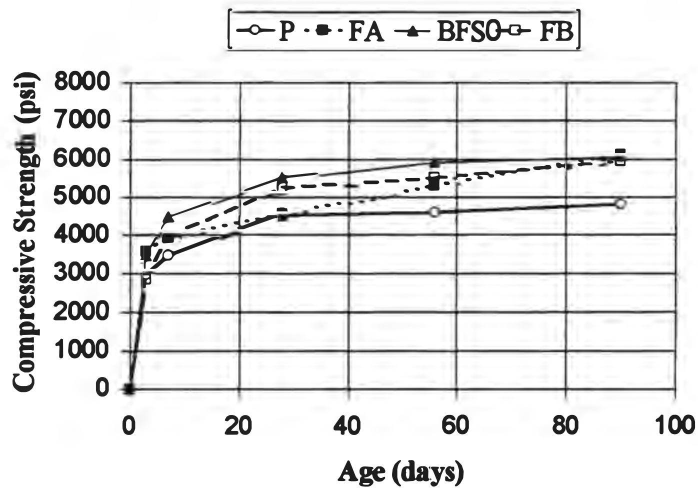


Fig. 4.2 Strength Gain for Cement B Mixtures

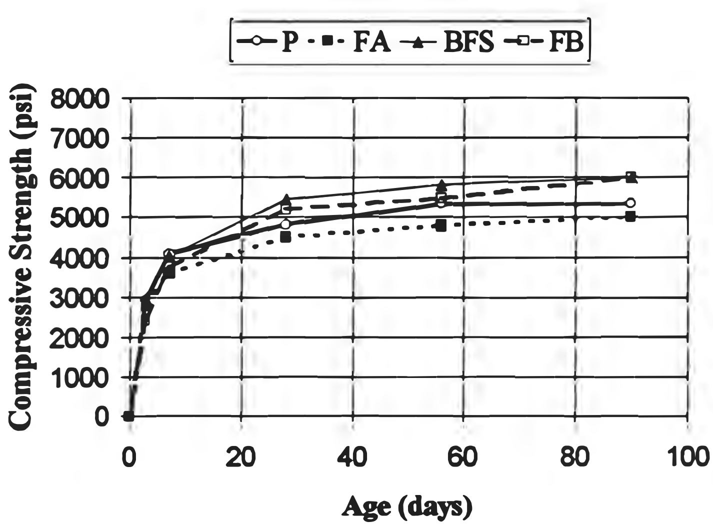


Fig. 4.3 Strength Gain for Cement C Mixtures

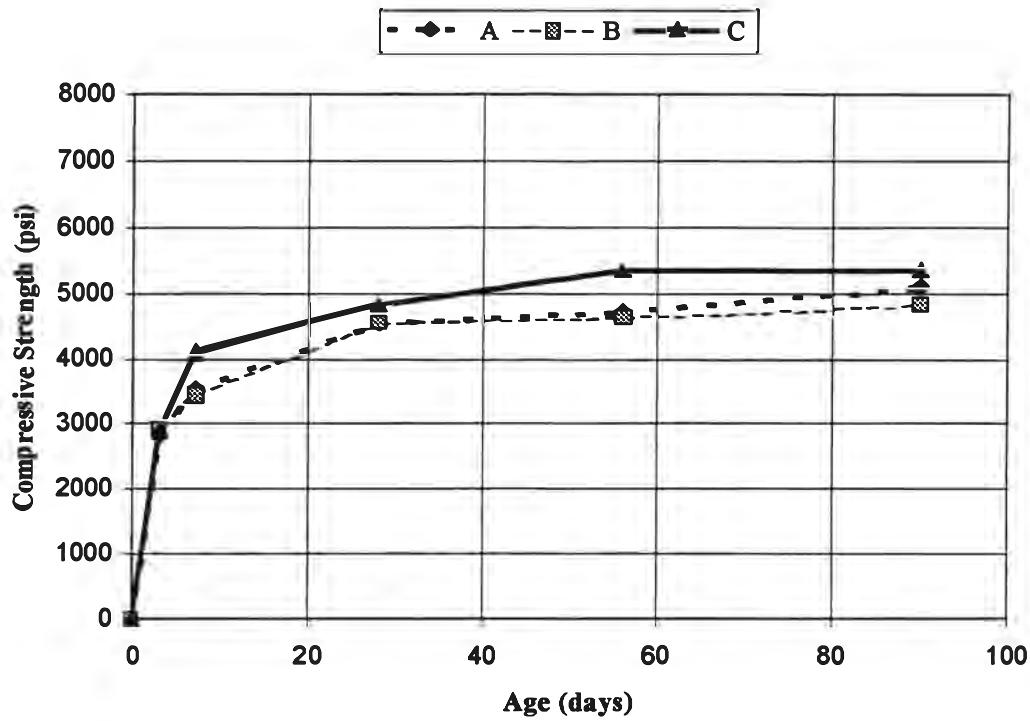


Fig. 4.4 Strength Gain for P Mixtures

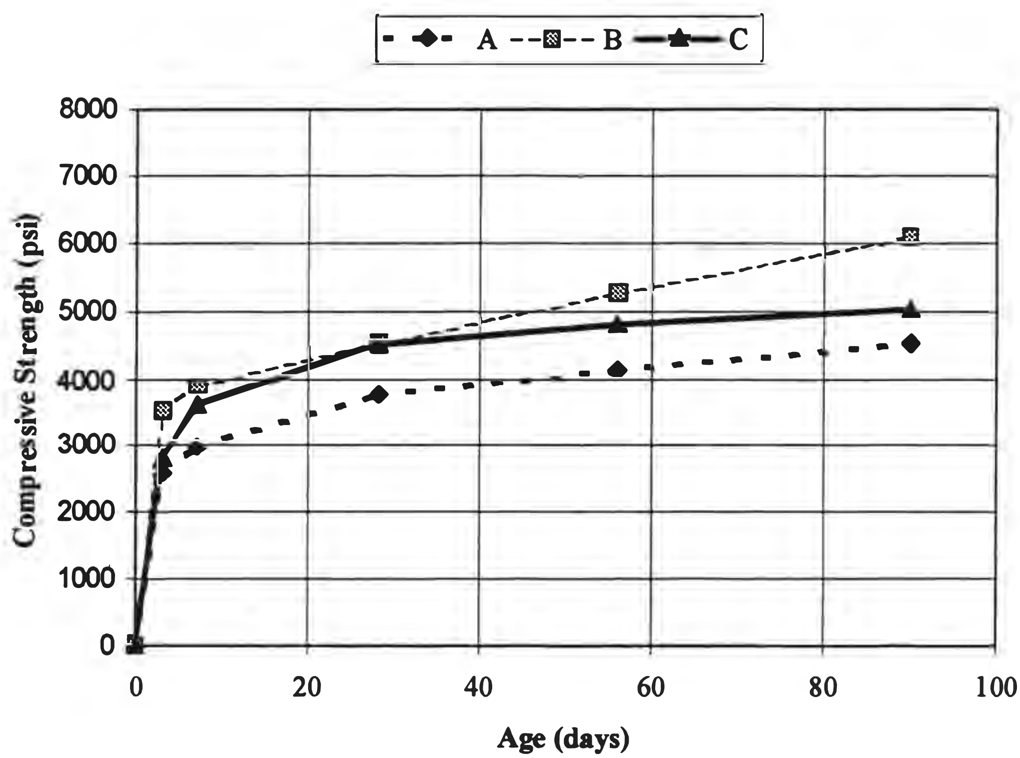


Fig. 4.5 Strength Gain for FA Mixtures

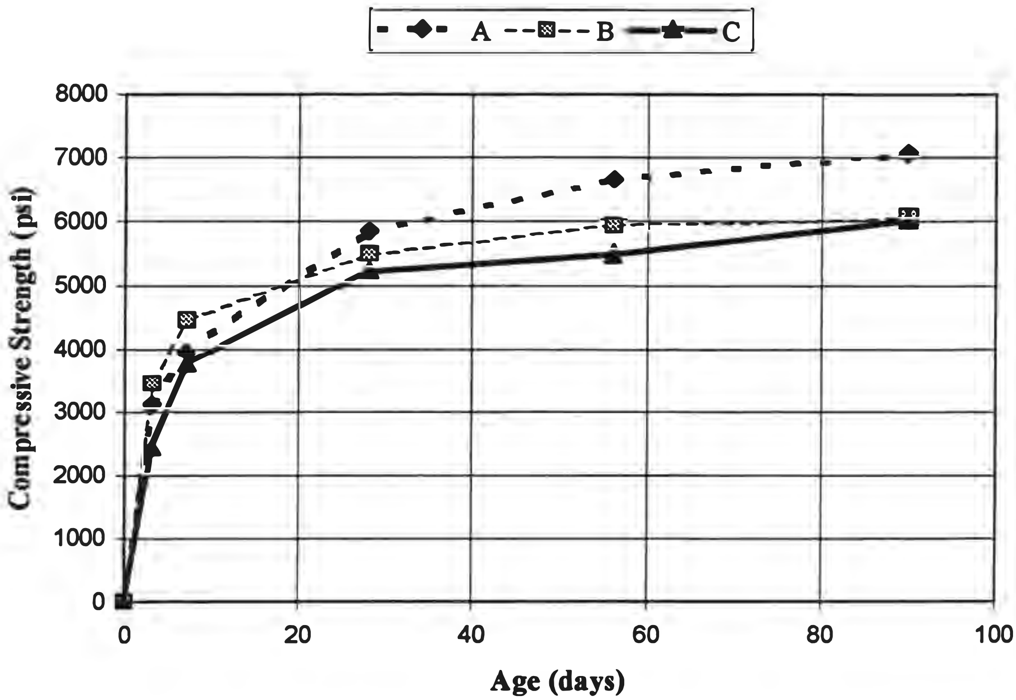


Fig. 4.6 Strength Gain for BFS Mixtures

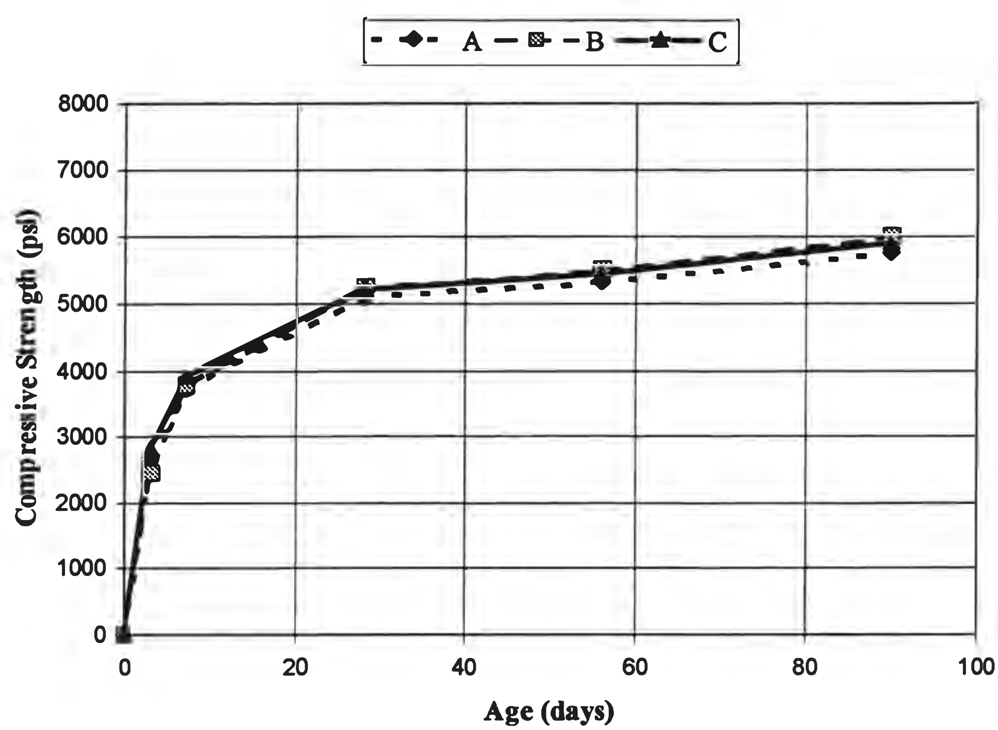


Fig. 4.7 Strength Gain for FB Mixtures

Table 4.2 Compressive Strength (psi) at Three Days, Cement Study

	Mixture			
Cement	P	FA	BFS	FB
A	2820	2570	3100	2610
B	2910	3510	3420	2790
C	2900	2800	2950	2420
Average	*2880*	*2960*	*3160*	*2610*

At three days of age, the compressive strength for all the mixtures for all three cements fell within a range of 1000 psi and the source of cement had little effect on the compressive strength. The compressive strength of mixtures A-P, B-P, and C-P fell within a very small range of 100 psi. Addition of BFS improved strengths of cement A and B mixtures at three days of age. The compressive strengths of mixture A-BFS and mixture B-BFS were almost 300 psi and 500 psi greater than their respective control mixtures (A-P and B-P). There was no significant difference in the compressive strength of mixtures C-P and C-BFS.

The addition of FA decreased the compressive strength of mixtures containing cements A and C when compared to their respective control mixtures. The compressive strength of mixture A-FA was 250 psi less than that of the control mixture (A-FA), and the compressive strength of mixture C-FA was 100 psi less than that of its control mixture (C-P). However, for cement B the FA mixture (B-FA) had the highest compressive when compared to all other mixtures at three days age. The compressive strength of fly ash mixture B-FA was 600 psi greater than that of its control mixture (B-P).

The results from the compressive strength tests at seven days are shown in Table 4.3. Also shown in the table is the average compressive strength of like mixtures.

Table 4.3 Compressive Strength (psi) at Seven Days, Cement Study

	Mixture			
Cement	P	FA	BFS	FB
A	3500	2960	3940	3700
B	3410	3870	4430	3900
C	4070	3590	4030	3750
Average	*3660*	*3470*	*4130*	*3780*

Using the averages for like mixtures, the BFS mixtures once again had the greatest compressive strength at seven days. However, the combination mixture (FB) now had the second highest compressive strength instead of the lowest. The P mixtures and FA mixtures, which had similar compressive strengths at three days, were beginning to separate at seven days. At seven days of age, the BFS mixtures had similar or greater strengths when compared to the P mixtures, while the FA mixtures' strengths were generally lower than those of the P mixtures (except for cement B's FA mixture).

The results from the compressive strength tests at 28 days are shown in Table 4.4. Also shown is the average compressive strength of like mixtures. For like mixtures, the BFS mixtures once again had the greatest compressive strength (5580 psi) at 28 days. By 28 days the compressive strength of the FB mixtures was 5170 psi compared to 4530 psi for P mixtures and 4450 for FA mixtures. Cement B's FA mixture was the only FA mixture to achieve a compressive strength greater than its respective control mixture (B-P).

Table 4.4 Compressive Strength (psi) at 28 Days, Cement Study

	Mixture			
Cement	P	FA	BFS	FB
A	4510	3750	5820	5090
B	4280	5080	5470	5220
C	4810	4510	5450	5200
Average	*4530*	*4450*	*5580*	*5170*

At 28 days age, the control mixture with cement C still had greatest compressive strength when compared to the other cement sources. The compressive strength of mixture C-P was 300 psi greater than that of mixture A-P and over 500 psi greater than the strength of mixture B-P.

For cement A (Fig. 4.1), mixture A-BFS had the greatest compressive strength (5820 psi). The strength of mixture A-BFS was 1300 psi greater than the control mixture (A-P), over 2000 psi greater than the FA mixture (A-FA), and over 700 psi greater than the FB mixture (A-FB). Mixture A-BFS had the highest compressive strength of all mixtures and all cement sources at 28 days. The compressive strength of mixture A-FA was almost 800 psi less than that of its control (A-P) whereas the compressive strength of mixture A-FB was over 500 psi greater than the strength of the control.

For cement B (Fig. 4.2), the BFS mixture also had the highest compressive strength (5470 psi). The compressive strength of mixture B-BFS was almost 1200 psi greater than that of the control mixture (B-P) and 250 psi greater than the strength of mixture B-FB. The FA mixture for cement B performed particularly well (5080 psi) when compared to the other FA mixtures (3750 psi for A-FA and 4510 psi for C-FA).

For cement C (Fig. 4.3), the compressive strength of mixture C-BFS was over 600 psi greater than for mixture C-P, 250 psi greater than for mixture C-FB, and almost 1000 psi greater than for mixture C-FA. The compressive strengths of cement C mixtures were all within 1000 psi of each other.

At 28 days of age significant differences were becoming apparent in the different mixtures. The compressive strength of the BFS mixtures were on average over 20 percent greater than the compressive strength of the P mixtures. Cement A benefitted the most from the addition of slag. Cement A's BFS mixture was almost 30 percent stronger than its control mixture. Cement B benefitted the most from the addition of fly ash. While the addition of fly ash decreased the compressive strength of cement A and cement C's mixtures, the addition of fly ash increased the compressive strength of cement B's FA mixture by 19 percent. The compressive strengths of mixtures with the combination of fly ash and slag (FB) were on average 14 percent higher than those of the control mixtures.

The results from the compressive strength tests at 56 days are shown in Table 4.5. Also shown in the table is the average compressive strength of like mixtures. At 56 days, like 28 days, the BFS mixtures had the highest compressive strength (6120 psi) followed by the FB mixtures (5400 psi), P mixtures (4880 psi), and finally the FA mixtures (4720 psi).

Table 4.5 Compressive Strength (psi) at 56 Days, Cement Study

	Mixture			
Cement	P	FA	BFS	FB
A	4700	4120	6640	5290
B	4600	5240	5910	5430
C	5330	4790	5810	5480
Average	*4880*	*4720*	*6120*	*5400*

At 56 days, cement C still had the highest compressive strength (5330 psi) when compared to the other control mixtures (A-P and B-P), as can be seen in Fig. 4.4. The compressive strength of mixture C-P was about 700 psi greater than the strengths of mixtures A-P and B-P, whose strengths were similar.

For cement A, mixture A-BFS still had the highest compressive strength (6640 psi) of all mixtures tested. The compressive strength of mixture A-BFS was almost 2000 psi greater than that of the control mixture (A-P) and over 1200 psi greater than the strength of mixture A-FB. The FA mixture's strength was considerably lower than those of the other mixtures. The compressive strength of the FA mixture (4120 psi) was almost 600 psi lower than for the control mixture and over 2500 psi lower than the strength of mixture A-BFS.

Of cement B mixtures, mixture B-BFS had the highest compressive strength (5910 psi). However, differences in strength between mixture types were not as pronounced as for cement A. Also, the FA mixture of cement B was still performing better than the other fly ash mixtures. The compressive strength of mixture B-BFS was over 1300 psi greater than that of the control mixture (B-P), over 600 psi greater than the strength of mixture B-FA, and over 400 psi greater than mixture B-FB's strength.

Cement C's mixtures followed the same trend as cement A's mixtures. The trend was that the BFS mixture had the greatest compressive strength followed by the FB mixture, the P mixture, and finally the FA mixture. The compressive strength of mixture C-BFS was over 400 psi greater than that of its control (C-P), over 300 psi greater than that of mixture C-FB, and almost 1000 psi greater than the strength of the FA mixture.

The differences previously observed at 28 days became more apparent at 56 days of age. The compressive strength of the BFS mixtures were on average now over 25 percent greater than the compressive strengths of their respective P mixtures. Cement A benefitted the most from the addition of BFS. Cement A's BFS mixture strength was over 40 percent greater than that of its control mixture. On the other hand, cement B benefitted the most from the addition of FA. While the addition of FA decreased the compressive strength of cement A and cement C mixtures, the addition of FA increased the compressive strength of cement B's FA mixture by 14 percent. The compressive strengths of mixtures with the combination of FA and BFS (FB) were on average 11 percent higher than those of the control mixtures.

The results from the compressive strength tests at 90 days of age are shown in Table 4.6. Also shown is the average compressive strength of like mixtures. At 90 days, like 56 days, the BFS mixtures had the highest compressive strength (6360 psi) followed by the FB mixtures (5860 psi), the FA mixtures (5190 psi), and finally the P mixtures (5080 psi).

At 90 days of age, cement C's control still had the highest compressive strength when compared to the other control mixtures. Although its average strength did not change from 56 days, its compressive strength was still over 200 psi greater than that of mixture A-P and over 500 psi greater than that of mixture B-P.

Table 4.6 Compressive Strength (psi) at 90 Days, Cement Study

	Mixtures			
Cement	P	FA	BFS	FB
A	5090	4490	7040	5720
B	4820	6060	6050	5880
C	5330	5010	5990	5990
Average	*5080*	*5190*	*6360*	*5860*

For cement A, mixture A-BFS had a compressive strength of 7040 psi which was the highest compressive strength of all mixtures tested in the Cement Study. The compressive strength of mixture A-BFS was almost 2000 psi greater than for mixture A-P, over 1300 psi greater than that of mixture A-FB, and over 2500 psi greater than the strength of the FA mixture.

For cement B at 90 days of age, the compressive strength of mixture B-FA (6060 psi) was as high as that of mixture B-BFS (6050 psi). The strengths of pozzolan mixtures (B-FA, B-BFS, and B-FB) all fell within a range of 200 psi. The pozzolan mixtures of cement B all possessed strengths at least 1000 psi greater than that of the control mixture (B-P).

For cement C, the mixtures containing BFS had the highest compressive strength. At 90 days of age mixture C-BFS and mixture C-FB had the same compressive strength (5990 psi). The compressive strength of those mixtures was over 600 psi greater than that of the control (C-P) and over 900 psi greater than the strength of the FA mixture (C-FA).

At 90 days of age, the compressive strengths of the mixtures containing BFS were significantly higher than the strengths of the control mixtures. For cement A, the addition of BFS increased the compressive strength by 38 percent when compared to the control mixture (A-P). Cement B's FA mixture was the only FA mixture that exhibited strength increase as compared to the strength of the corresponding control mixture. The compressive strength of cement B's FA mixture was 25 percent greater than its control mixture's strength. The strength gain curves (Figs. 4.1 to 4.7) show that the mixtures containing FA and/or BFS were still gaining strength at 90 days of age whereas the rate of strength gain for P mixtures began to slow down at 28 days of age. Mixtures A-BFS and B-FA appeared to have a greater rate of strength gain than the other FA and BFS mixtures.

The results from the compressive tests indicate that cement A interacted differently with the slag by producing concrete with greater compressive strength. Also, the results show that as compared to P mixtures, the mixtures containing slag had higher compressive strengths at seven days of age and later. This increase in compressive strength is due to the pozzolanic reaction mentioned earlier in Chapter 2. The BFS reacts with the normal byproducts of the cement hydration to form addition $C_3S_2H_3$ that improves the density of the concrete paste matrix thereby improving strength. Theoretically, this same process should occur in the FA mixtures; however, improved strengths were only observed for fly ash mixtures with cement B. Currently there is no explanation for why the fly ash mixtures of cement A and cement C did not perform as well. It is unclear whether this observation is due to variability in the fly ash, true differences in interaction with the cements, or some other cause.

In putting the compressive strength results into perspective, it should be noted that air contents for the mixtures were not the same. It is well known that increases in air content are accompanied by decreases in compressive strength. However, it does not appear that the air content differences are a primary explanation for the observed differences in compressive strength. For example, all BFS mixtures had air contents within a tight range of 5.0 to 5.2 percent, yet mixture A-BFS clearly achieved higher strength than the slag mixtures containing the other two cements. Also, mixture B-FA produced higher compressive strength than its control (B-P) even though the fly ash mixture had a total air content nearly one percent higher than that of the control mixture.

4.2.2.2 Modulus of Rupture. The modulus of rupture (MOR) was tested at 28 days age. Four 6 in. x 6 in. x 20 in. specimens were tested from each mixture, two specimens from each of the twin batches. The results from the MOR tests are shown in Table 4.7. The data in the table represent the average of four specimens. Also shown in Table 4.7 are the averages for like mixtures. The averages indicate that for all cements the mixtures containing slag (BFS and FB) had the highest MOR. As can be seen in Table 4.7, the MOR results fell within a range of 670 to 930 psi.

Table 4.7 Modulus of Rupture (psi), Cement Study

	Mixture			
Cement	P	FA	BFS	FB
A	705	675	920	835
B	780	790	930	785
C	670	670	790	830
Average	*720*	*710*	*880*	*815*

The source of cement had little effect on the MOR of the mixtures. Examination of 90 percent confidence intervals of the MOR results from the P mixtures (A-P, B-P, and C-P) indicated that there was statistically no difference in the mixtures' flexural strength.

However, the addition of slag affected flexural strengths of the mixtures. For cement A, the addition of slag resulted in an increase of 215 psi over the strength of its control mixture (A-P). Similarly, as compared to their control mixtures, slag mixtures with cements B and C attained strength increases of 70 psi and 120 psi, respectively. Ninety percent confidence intervals confirmed that flexural strengths of control mixtures were statistically different from those of slag mixtures.

There were no statistically significant flexural strength differences between P, FA, and FB mixtures for any cement, except cement A. For cement A, the combination fly ash and slag mixture (A-FB) achieved a flexural strength 169 psi higher than its control (A-P).

The results of the MOR tests are plotted versus the square root of the 28 day compressive strength of the respective mixtures in Fig. 4.8. Also plotted on the graph is the line $f_r = 7.5*\sqrt{f'c}$ (psi). This equation is commonly used to estimate the MOR of concrete based on its 28 day compressive strength. From Fig. 4.8, it can be seen that flexural strengths of all the mixtures plot above this line. This means that the equation can be used to conservatively estimate the MOR for all mixtures tested.

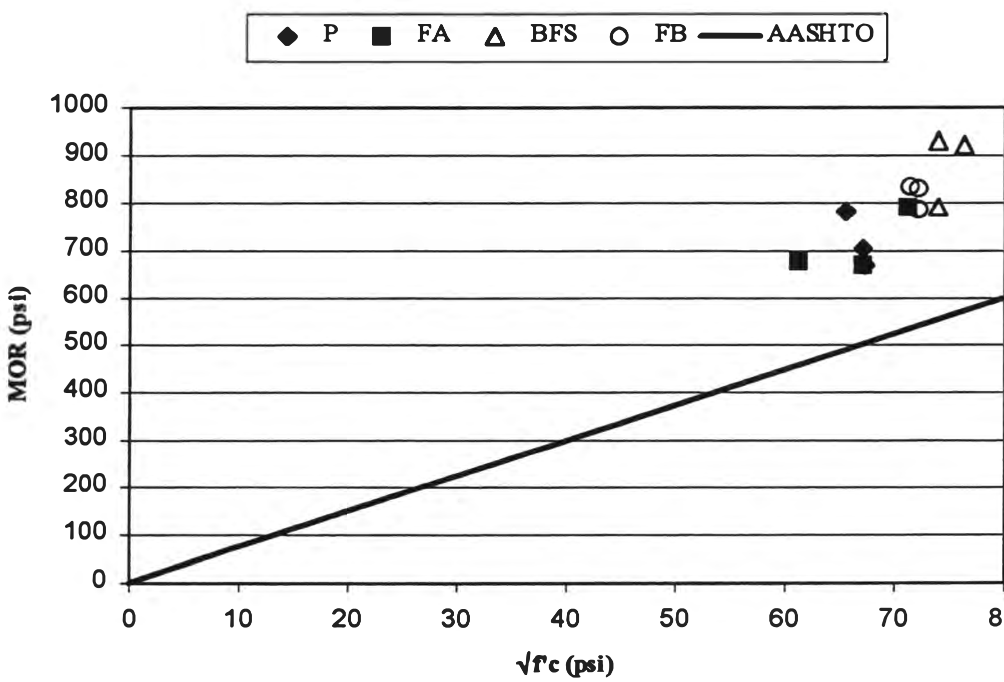


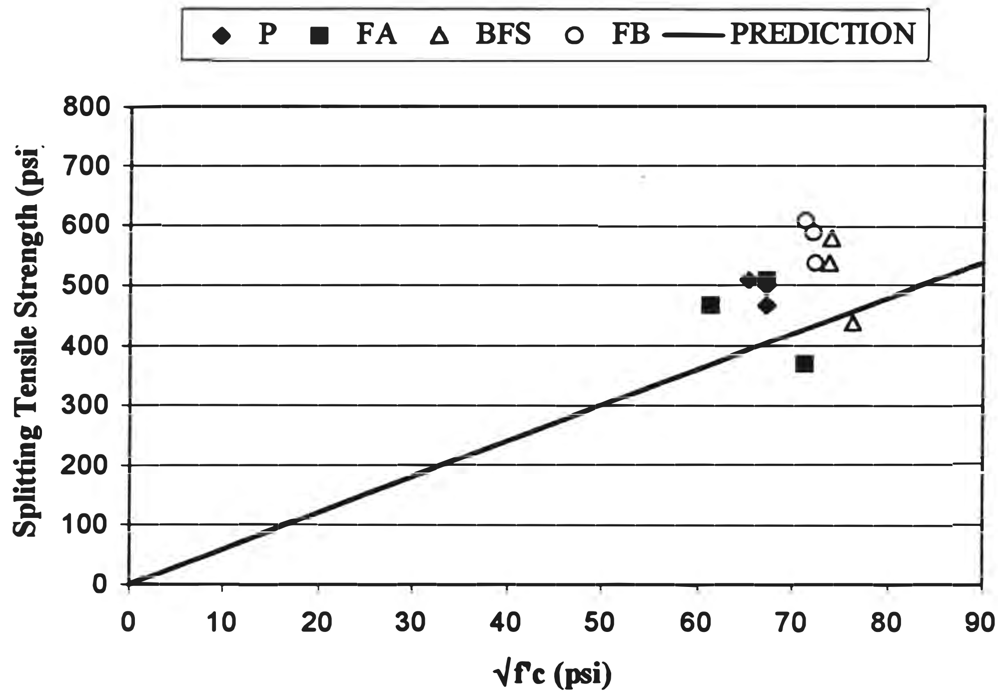
Fig. 4.8 Modulus of Rupture Results and AASHTO Equation, Cement Study

4.2.2.3 Splitting Tensile Strength. The splitting tensile strength of the mixtures was measured at 28 days and 90 days of age. Six cylinders were tested from each mixture, three cylinders from each of the twin batches. Results from the 28 day and 90 day splitting tensile strength tests are shown in Table 4.8. The numbers shown represent the averages of six cylinders. Also shown is the average splitting tensile strength of like mixtures. These averages generally infer that mixtures containing slag (BFS and FB) tended to have higher splitting tensile strength at 28 days and 90 days of age. However, 90 percent confidence intervals showed no statistical difference in splitting tensile strength due to cement source or presence (or absence) of pozzolans. The lack of statistical difference is attributed to the larger scatter in splitting tensile strength data as compared to MOR data.

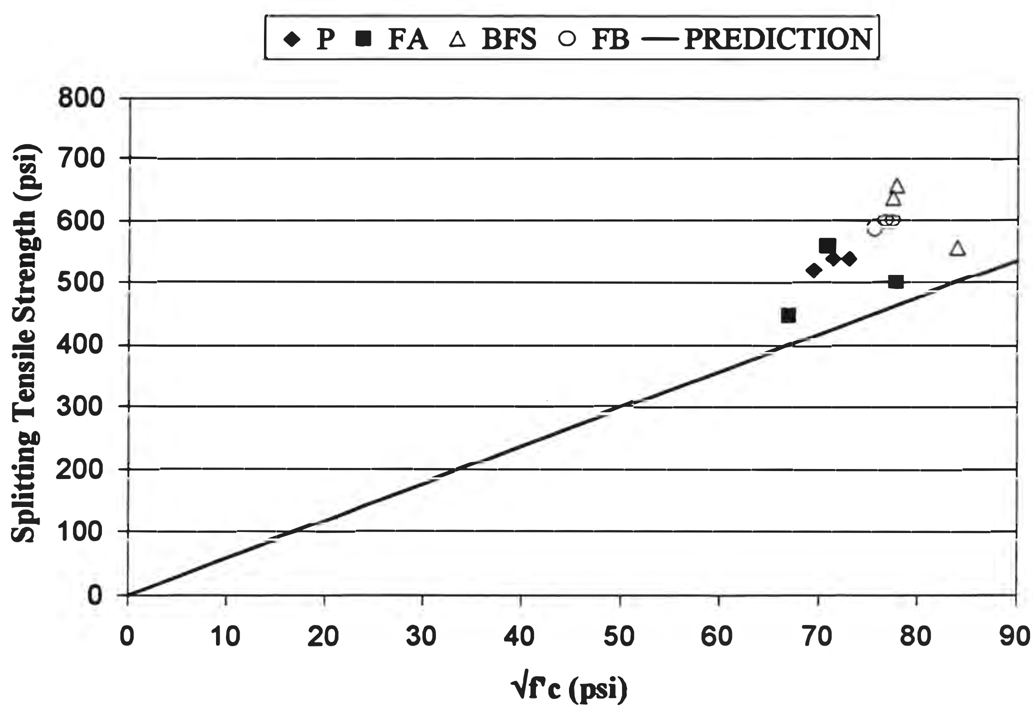
The splitting tensile strengths are plotted versus the square root of the 28 day compressive strength of each mixture in Fig. 4.9. Also plotted on the graph is the equation $f_t = 6*\sqrt{f'_c}$ (psi), which is often used to predict split tensile strength from compressive strength. At 28 days of age, all but two mixtures plot above the prediction equation line, and at 90 days of age all the mixtures plot above the line. Thus the prediction equation produces a reasonable estimate of the splitting tensile strength based on the mixtures' compressive strengths at 28 and 90 days.

Table 4.8 Splitting Tensile Strength (psi) at 28 and 90 Days, Cement Study

		Mixture			
	Cement	P	FA	BFS	FB
28 Day	A	470	470	440	610
	B	510	370	580	540
	C	500	510	540	590
	Average	*490*	*450*	*520*	*580*
90 Day	A	540	450	560	590
	B	520	500	660	600
	C	540	560	640	600
	Average	*530*	*500*	*620*	*600*



(a) 28 Day



(b) 90 Day

Fig. 4.9 Splitting Tensile Strength with Prediction Equation, Cement Study

4.2.2.4 Modulus of Elasticity. The modulus of elasticity (MOE) was tested at 28 and 90 days age, with results shown in Table 4.9. Data shown in the table are the averages of four cylinders.

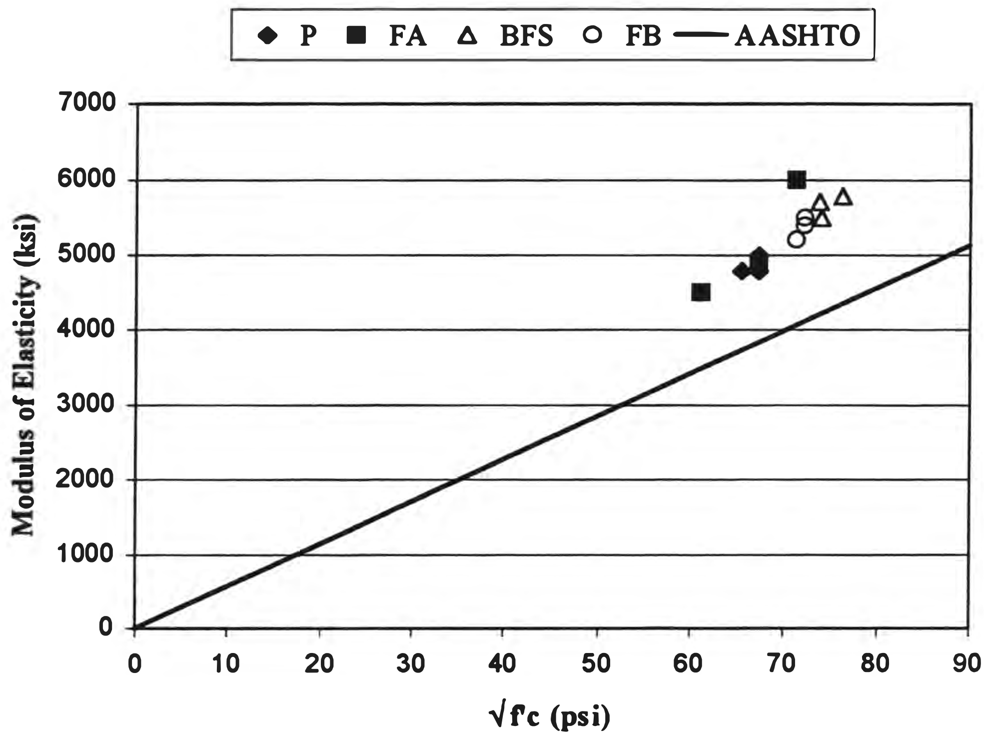
Table 4.9 Modulus of Elasticity (ksi), Cement Study

		Mixture			
	Cement	P	FA	BFS	FB
28 Day	A	4800	4500	5800	5200
	B	4800	6000	5500	5500
	C	5000	4900	5700	5400
	Average	*4900*	*5100*	*5700*	*5400*
90 Day	A	5000	5000	5900	5700
	B	5400	5700	5900	5700
	C	5500	5100	5900	5900
	Average	*5300*	*5300*	*5900*	*5800*

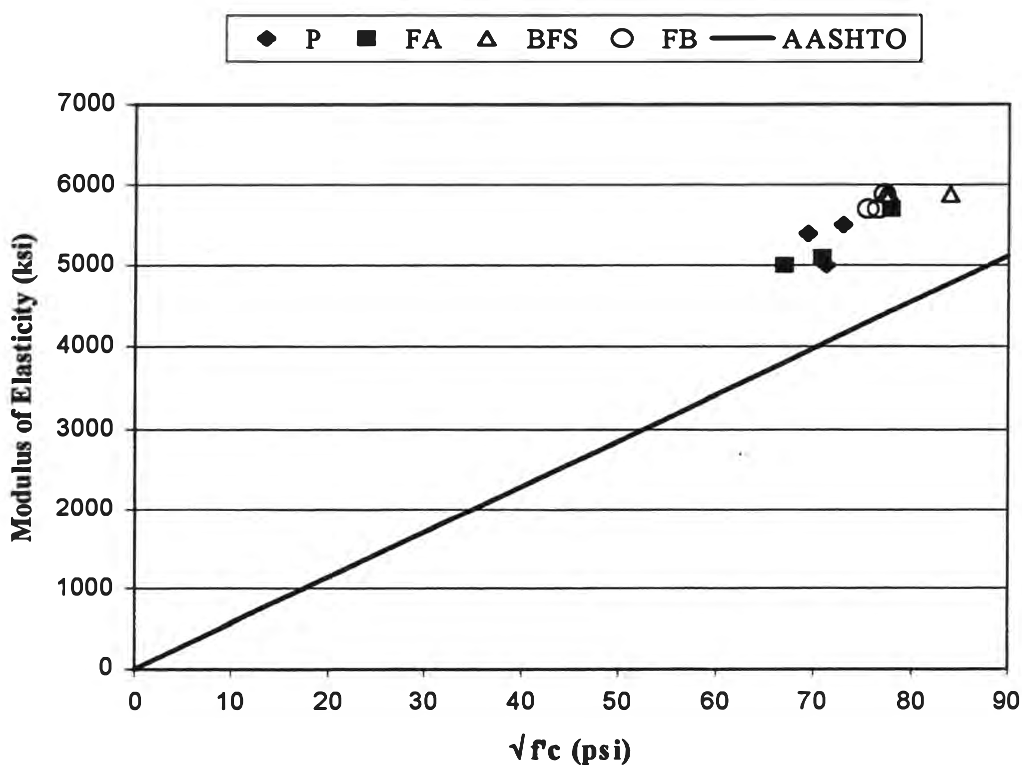
At 28 and 90 days age, the source of cement did not affect the MOE of like mixtures. The results of the tests generally indicate that the MOE for like mixtures are similar. The only exception is the FA mixture for cement B, which also had considerably higher compressive strength as compared to the other FA mixtures. The MOE of Mixture B-FA was 20 to 30 percent higher than the MOE of the other FA mixtures (A-FA and C-FA).

For a given cement, some differences were observed between mixture types. For all cements, the mixtures containing slag (mixtures BFS and FB) had higher MOE than their corresponding control mixtures at 28 and 90 days of age. Examination of ninety percent confidence intervals confirmed this observation. For cements A and C, the FA mixtures had MOE values statistically similar to those of their respective P mixtures. However, for cement B, the MOE of the FA mixture was 25 percent higher than for its P mixture. In fact, ninety percent confidence intervals indicated that for cement B, the MOE of the FA mixture was similar to those of the BFS and FB mixtures, which were in turn statistically different from the MOE of the control mixture.

The MOE of each mixture at 28 days of age and 90 days of age was plotted versus the square root of each mixture's 28 day and 90 day compressive strength (Fig. 4.10). Also plotted on the graphs is the equation $E_c = 57{,}000\sqrt{f'_c}$ (psi). As seen in Fig. 4.10, the results of the 28 day and 90 day MOE plot above the AASHTO line, meaning the equation can be used to conservatively estimate the MOE of the mixtures tested.



(a) 28 Day



(b) 90 Day

Fig. 4.10 Modulus of Elasticity Results and AASHTO Equation, Cement Study

4.2.2.5 Shrinkage. The drying shrinkage of the mixtures was measured at 3, 7, 28, 56, and 90 days of age. Four specimens were measured from each mixture, two specimens from each of the twin batches. The results from the drying shrinkage tests are shown in Table 4.10. Also shown in Figs. 4.11, 4.12, and 4.13 are the shrinkage curves for each cement.

The source of cement had little effect on the shrinkage. The 90 day drying shrinkage for all three control mixtures (A-P, B-P, and C-P) fell within a range from 460 to 505 microstrains. The shrinkage curves show that for a given cement, mixtures containing BFS (mixtures BFS and FB) had less shrinkage than the control mixtures. The shrinkage curves also show that the shrinkage of the FA mixtures was generally similar to that of the P mixtures.

Through examination of the shrinkage curves, it is evident that the majority of shrinkage occurred before 28 days of age. After 56 days of age, the rate of shrinkage was minimal.

Table 4.10 Drying Shrinkage (microstrains), Cement Study

	Age (days)				
Mixture	3	7	28	56	90
A-P	95	220	360	430	460
A-FA	90	20	385	450	450
A-BFS	80	130	290	290	290
A-FB	85	145	295	335	335
B-P	140	220	380	440	475
B-FA	125	235	410	480	490
B-BFS	130	225	365	415	430
B-FB	115	230	360	410	425
C-P	105	225	385	500	505
C-FA	125	205	345	410	425
C-BFS	85	150	290	365	375
C-FB	80	160	280	330	345

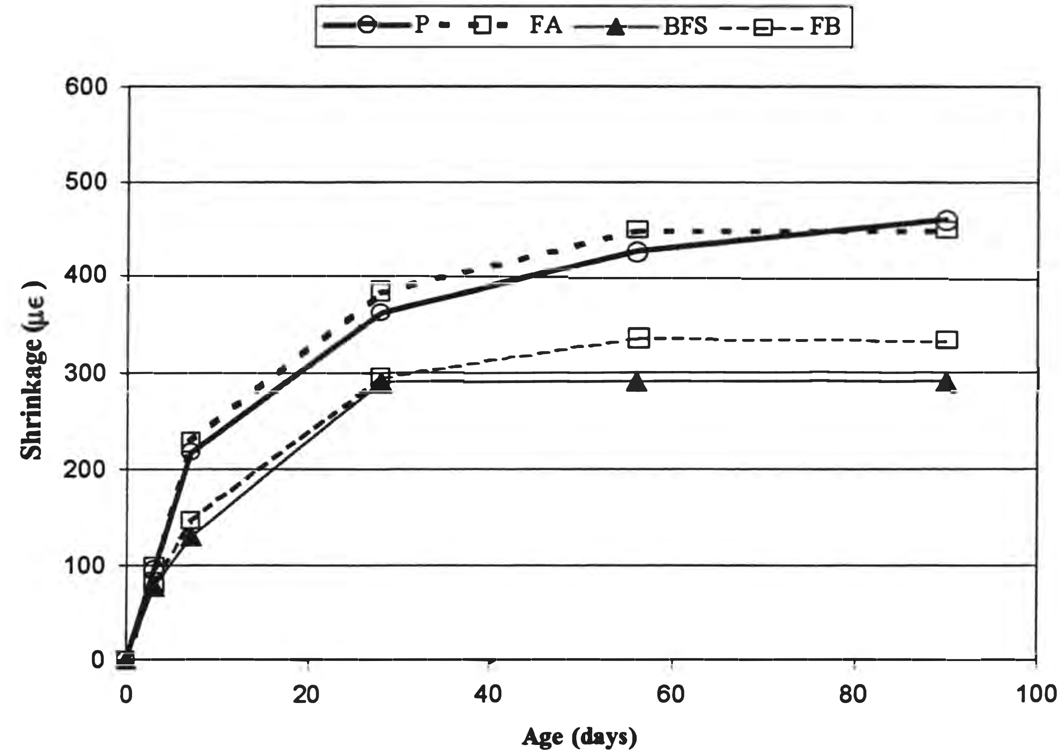


Fig. 4.11 Shrinkage Curves for Cement A Mixtures

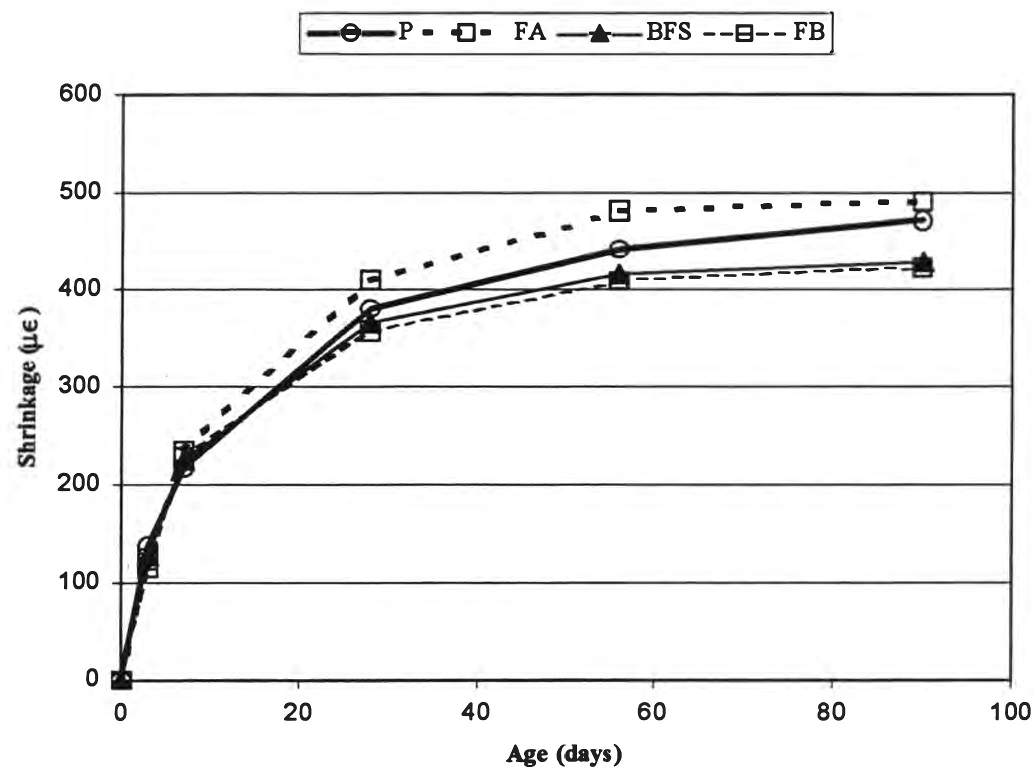


Fig. 4.02 Shrinkage Curves for Cement B Mixtures

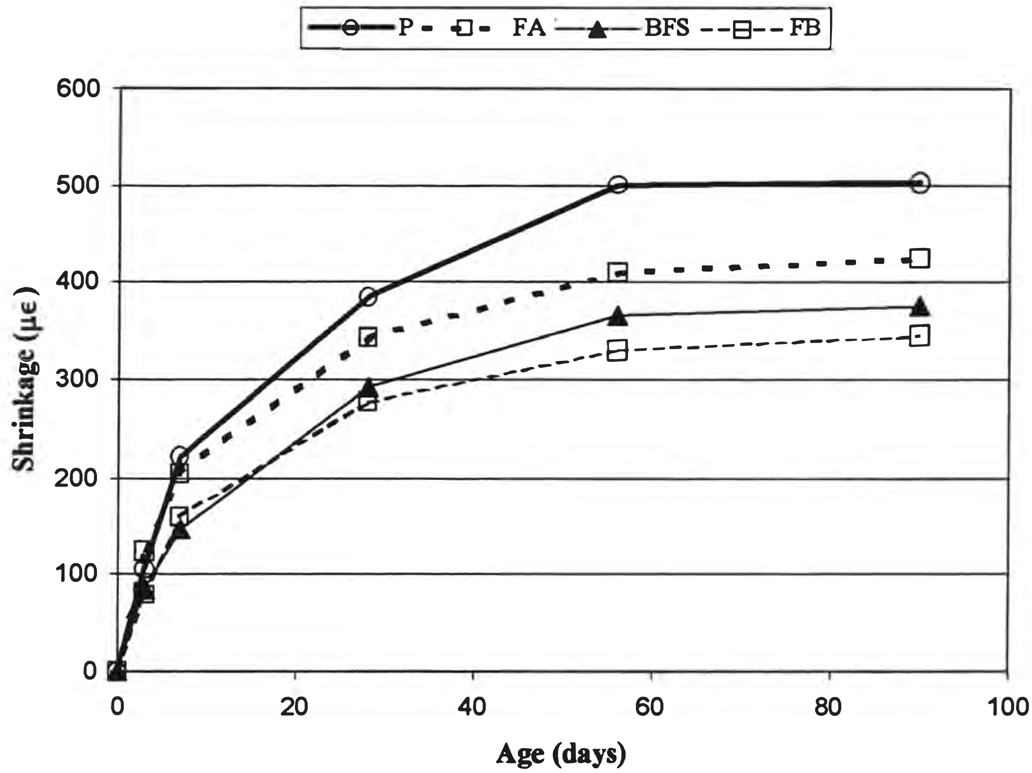


Fig. 4.13 Shrinkage Curves for Cement C Mixtures

4.2.2.6 Rapid Chloride Ion Penetrability. Results of 28 day and 90 day Rapid Chloride Ion Penetrability (RCIP) tests for the mixtures are shown in Table 4.11 and Figs. 4.14 and 4.15. Each data point represents the average of four tests (two samples from each of the twin batches). Variations associated with the cement used were not large, although cement C's FA mixture passed higher coulombs at 28 days of age than did the other two FA mixtures. By 90 days of age there were no substantial variations associated with the cement source. However, substantial differences were seen for any given cement with the addition of FA and/or BFS.

Considering 28 days results, P (control) mixtures averaged 4240 coulombs passed with a range of averages of 570 coulombs. However, FA mixtures passed 50 to 100 percent more coulombs than their control mixtures. In contrast, BFS mixtures averaged 2170 coulombs passed, or about one half the coulombs passed by the control mixtures. The FB mixtures had slightly lower coulombs passed than the control mixtures, with an average of 3820 coulombs passed.

Rapid chloride ion penetrability reduced from 28 to 90 days; however the same trends were also observed at 90 days. The P, BFS, and FB mixtures passed about 20 to 25 percent fewer coulombs at 90 days than at 28 days. However, a greater percent reduction was seen for the FA mixtures, which passed about half the number of coulombs at 90 days than at 28 days.

According to ASTM C1202, at 28 days the P and FA mixtures would be rated to have high chloride penetrability (>4000 coulombs passed), and the BFS and FB mixtures would classify as having moderate chloride penetrability (2000 to 4000 coulombs). At age 90 days, these ratings would change to moderate for the P, FA, and FB mixtures, and low for the BFS mixtures. Researchers (Pfeifer et al. 1994) suggest that these ratings should be applied with caution since the RCIP test is primarily an indication of the concrete's resistivity. Reasons for the concrete containing 20 percent Class C fly ash's better conductivity (leading to higher coulombs passed) have not been established. However, the results were consistent for all cements tested.

Table 4.11 Rapid Chloride Ion Penetrability Results (Coulombs), Cement Study

		Mixture			
	Cement	PC	FA	BFS	FB
28 Day	A	4130	6350	1820	3900
	B	4580	6860	2380	3300
	C	4010	8860	2310	4260
	Average	*4240*	*7360*	*2170*	*3820*
90 Day	A	3500	3670	1285	2770
	B	2670	4230	1930	2280
	C	3560	4225	1660	3025
	Average	*3235*	*4070*	*1630*	*2690*

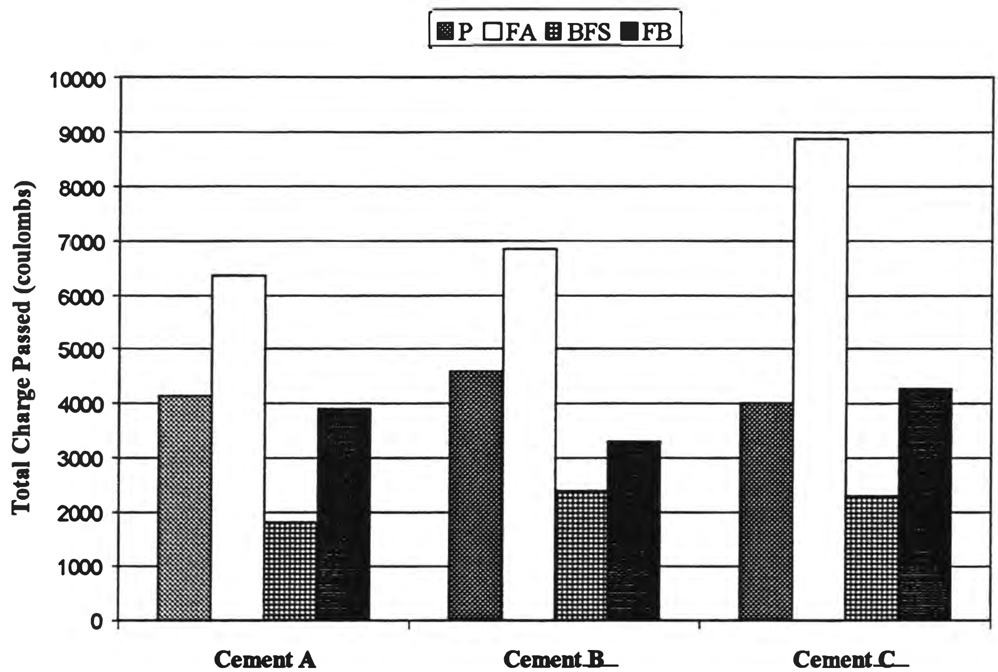


Fig. 4.14 28 Day Rapid Chloride Ion Penetrability, Cement Study

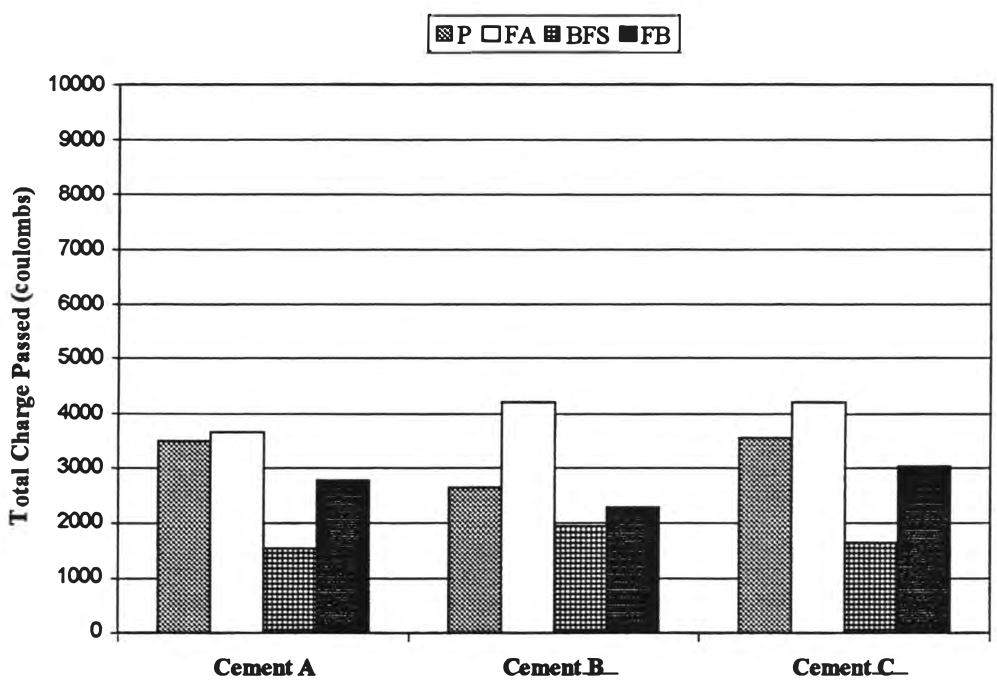


Fig. 4.15 90 Day Rapid Chloride Ion Penetrability, Cement Study

4.3 POZZOLAN REPLACEMENT FRACTIONS STUDY

In this study, a single Type I cement was used with various pozzolan replacements. Some tests common to the Cement Study were performed to verify that the concretes were similar. Additional hardened property tests performed exclusively for this study included creep, freeze thaw durability and chloride ion penetration. Four Class AA mixtures were used: portland cement alone (P), 15 percent Class C fly ash replacement (FA), 25 percent slag replacement (BFS), and both 15 percent fly ash and 25 percent slag replacement (FB). The cement used was Type I from source A (Ash Grove).

4.3.1 Fresh Properties

Table 4.12 contains concrete properties of creep test mixtures; Table 4.13 contains concrete properties of the freeze thaw and salt ponding test mixtures. Slumps for pozzolan concretes used to fabricate creep, freeze thaw, and salt ponding specimens were generally similar to those observed earlier in the Cement Study (for cement A). However, slumps for the control mixtures were lower for the present study than for the Cement Study (1 to 1.5 in. vs. 3 in.). Air contents are not directly comparable between the two studies. A constant AEA dosage was used for the Cement Study; AEA dosage was varied with mixture type in the present study. However, the range of total air contents was similar for both studies. These slumps and air contents complied with ODOT Class AA concrete standards which require 2 ± 1 in. slump and 7 ± 1.5 percent air.

Table 4.12 Concrete Properties of Class AA Mixtures for Creep Test

	Mixture			
Property	P	FA	BFS	FB
Air Contentd(%)	5.5	8	5.5	7
Slump (in.)	1.5	2.5	1.5	1.5
f_c @ 28d (psi)	4840	3880	4900	4940
E_c @ 28d (ksi)	5780	4360	4980	5160

Table 4.13 Fresh Properties of Class AA Mixtures for Freeze Thaw and Salt Ponding Tests

	Mixture			
Property	P	FA	BFS	FB
Air Content (%)	7.1	6.5	5.7	6.6
Slump (in.)	1	2.5	1	2

4.3.2 Hardened Properties

Table 4.12 also contains the average compressive strength and modulus of elasticity of creep specimens at 28 days (age at which loading was applied.) Strengths of the creep specimens were similar except for the fly ash mixture, which was about 1000 psi lower than the others. Similarly, the modulus of elasticity was lowest for the FA mixture.

4.3.2.1 Creep. Tables 4.14 and 4.15 contain the total creep at the end of test, and the rate of creep during and after 60 days, respectively. Fig. 4.16 is a plot of creep versus time for the mixtures. For this test, seven test specimens per mixture were utilized. Two unloaded specimens were used as controls. The other five specimens were stacked into a vertical column and subjected to continuous, constant load. The solid curves in Fig. 4.16 represent the average creep for each mixture while the data points are the creep values for individual specimens. Note that the individual data points are not shown prior to 60 days so that differences in the curves can be distinguished.

As seen in Table 4.14 the total creep of P concrete (no pozzolans) was roughly twice that of the other mixtures. Comparatively, the FA, FB and BFS mixtures had 44, 47 and 50 percent less creep, respectively, than the P mixture at the end of the test. The variation in total creep of the three mixtures with pozzolans was in the range of 5 to 12 percent which is small in comparison to the overall creep magnitudes.

Most of the difference in creep between mixtures occurred in the first two months of loading. Beyond that two month period, the rate of creep was almost identical for all four mixtures. This can be seen in the creep versus time plot of Fig. 4.16 and in Table 4.14, where most of the difference in slope occurred in the first 60 days.

In summary, creep for the mixtures <u>containing</u> BFS, FA, and their combination was similar. The total magnitude of creep for all pozzolan mixtures was about half that exhibited by the control (non-pozzolan) mixture.

Table 4.14 Total Creep at End of Test

	Mixture			
	P	FA	BFS	FB
Duration of Test (months)	8.5	8.4	8.5	8.6
Creep (microstrains)	1597	889	794	842

Table 4.15 Comparison of Creep During First Two Months and Remaining Six Months

	Mixture			
	P	FA	BFS	FB
First Duration of Test (days)	64	64	63	66
Creep (microstrains)	1405	765	615	654
Next Duration of Test (days)	188	188	191	191
Creep (microstrains)	192	124	179	188

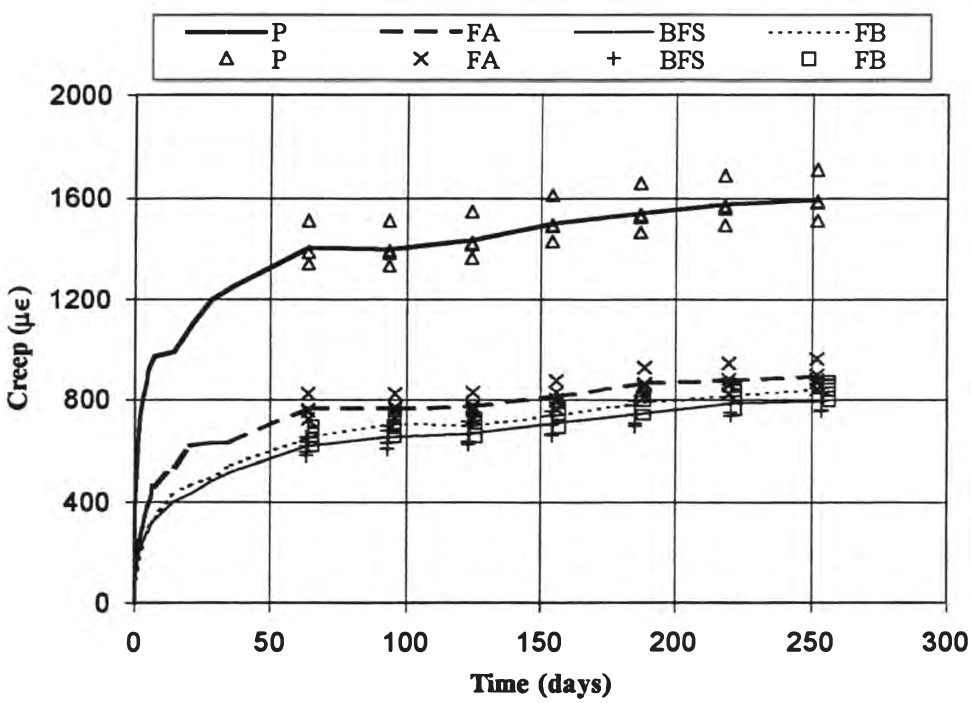


Fig. 4.16 Creep of Class AA Mixtures Over Time

4.3.2.2 Freeze Thaw Durability. Freeze thaw tests were conducted on all four Class AA mixtures. Testing commenced at the age of fourteen days after moist curing in the environmental chamber. Twelve specimens (three specimens per mixture) were immersed in water and then exposed to at least 300 cycles of freezing and thawing. Table 4.16 contains weight loss, dynamic modulus, and durability factors, and the dynamic modulus (as determined from transverse frequency) is plotted versus number of freeze thaw cycles in Fig. 4.17.

Weight loss over time was very small. The largest weight loss was about 2.2 percent for the mixture containing 15 percent FA replacement. This weight loss was basically the result of minor deterioration of some smooth surfaces during the freezing-thawing process and did not contribute to the depletion of dynamic elastic modulus. Side surfaces deteriorated faster and to a greater extent than the top and bottom surfaces. This tendency may have been affected by the placement of the heating elements, which were attached to both sides of the pans in the freeze thaw chamber. Most top surfaces of the specimens were unchanged.

The overall performance of all four mixtures was very similar. From Fig. 4.17 it can be seen that all four mixtures exhibited little or no loss in dynamic modulus over the duration of the test. The lowest durability factor was measured for the BFS mixture, which also had the lowest total air content. In general, performance was very good with durability factors equal to or exceeding 94 percent, as shown in Table 4.16. For the range of air contents tested, similar excellent freeze thaw resistance was exhibited by all mixtures.

Table 4.16 Weight Loss and Dynamic Modulus of Elasticity

	Mixture			
Property	P	FA	BFS	FB
Air Content (%)	7.1	6.5	5.5	6.6
Weight Loss (%)	0.75	2.21	1.48	0.00
Initial Dynamic Modulus (ksi)	5465	5090	6120	5815
Final Dynamic Modulus (ksi)	5545	5060	5935	5820
Durability Factor (%)	100	99	94	100

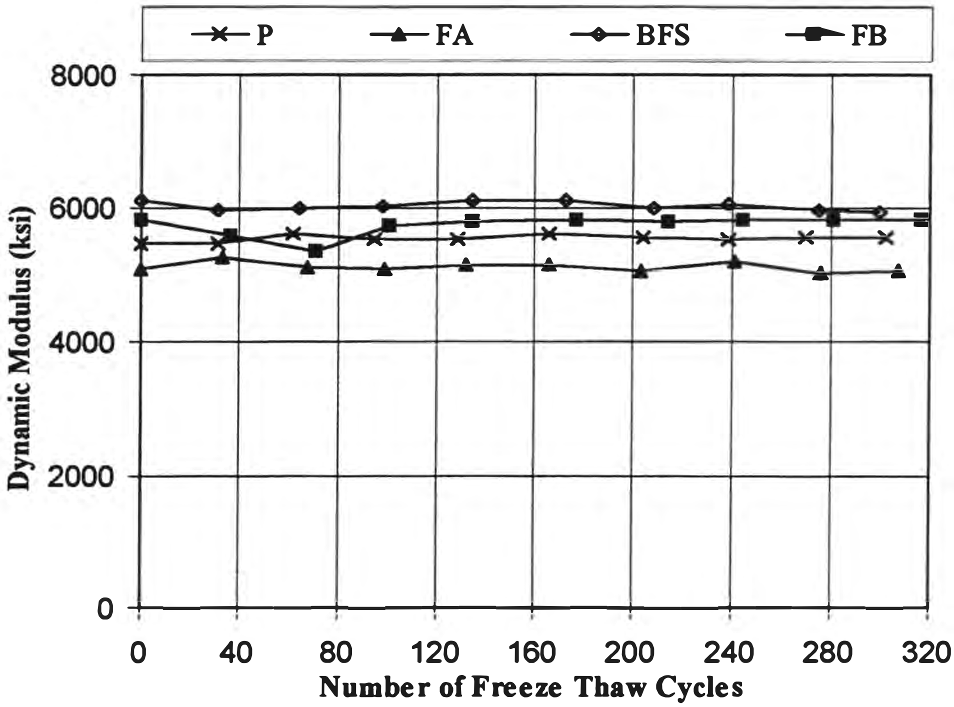


Figure 4.17 Effect of Number of Freeze Thaw Cycles on Dynamic Modulus

4.3.2.3 Salt Ponding. Salt ponding tests were conducted on all four Class AA mixtures. For each mixture, there were three ponded specimens and an unponded specimen used as control. Three evenly spaced holes were drilled into each specimen to extract a total of six samples (three from the upper half inch and three from the lower half inch). Chloride contents from the corresponding unponded specimen were subtracted from those of the ponded specimens to determine the total chlorides (acid soluble) absorbed. The values reported are the average of nine samples (3 holes for each of 3 specimens at each depth). Absorbed chlorides are reported in parts per million (note that 1 lb/yd^3 is equivalent to 255 ppm).

Figure 4.18 contains absorbed chlorides at the upper half inch of the four mixtures, while results for the lower half inch can be seen in Fig. 4.19. Since variability in absorbed chloride results can be substantial, 90 percent confidence intervals are shown in both figures. Note that the scale is different for the two figures.

As can be seen in Fig. 4.18 the averages of the salt ponding test results at the upper half inch indicated that the FA mixture absorbed the most chlorides followed by the P, FB and BFS mixtures in descending order. However, statistical results indicate that the performance of the P, FA, and FB mixtures was similar (their 90 percent confidence intervals overlapped). Absorbed chlorides in the

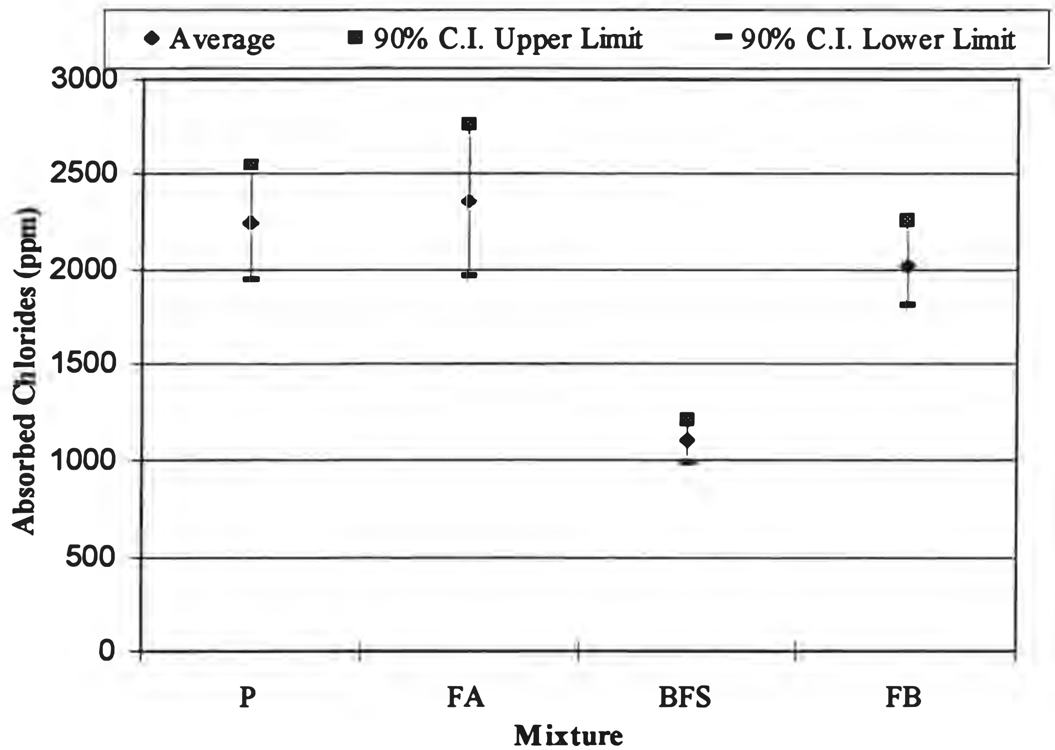


Fig. 4.18 Absorbed Chlorides in the Upper Half Inch

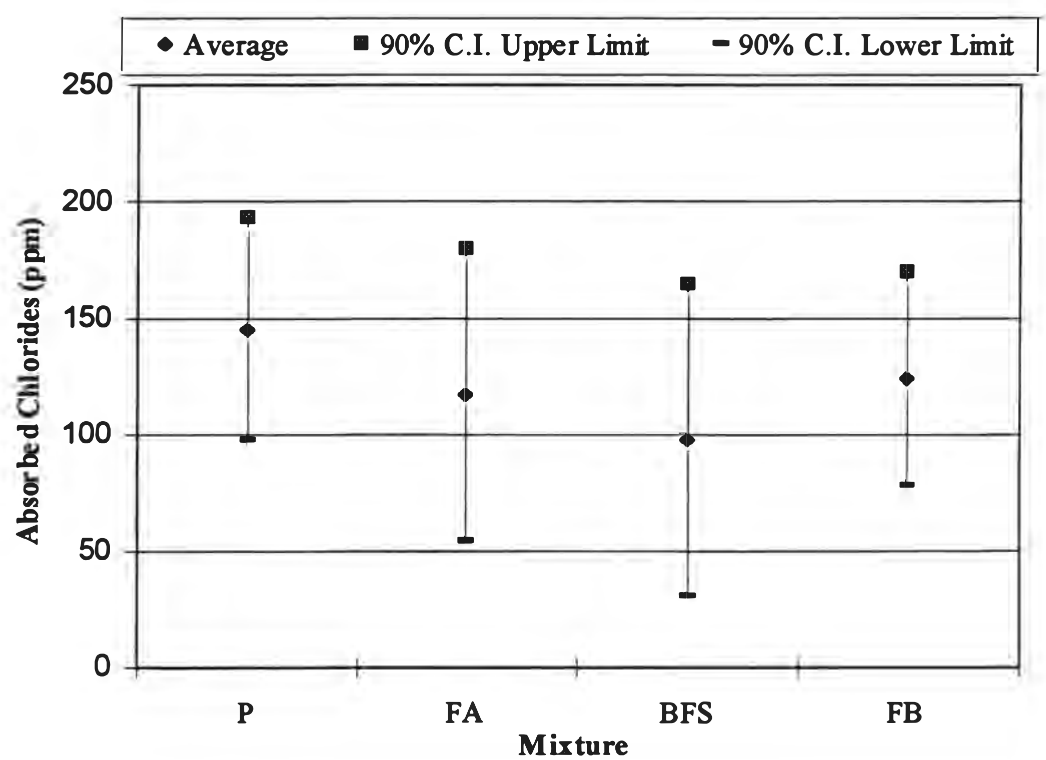


Fig. 4.19 Absorbed Chlorides in the Lower Half Inch

upper half inch were on the order of 8 to 9 lb/yd^3 for these three mixtures. On the other hand, the BFS mixtures absorbed about 50 percent less chlorides than the other mixtures in the upper half inch, and the BFS mixture's confidence interval did not overlap the others.

Comparing absorbed chlorides in the upper and lower half inch it can be seen that much higher chloride levels resulted in the upper half inch. Of the total chlorides absorbed through one inch of concrete, chlorides in the lower half inch constituted less than ten percent. Absorbed chlorides were very low (0.4 to 0.6 lb/yd^3) for all mixtures in the lower half inch depth. The overlapping confidence intervals indicate that performance of all mixtures was similar at the lower half inch depth (Fig. 4.19). In general, BFS mixtures consistently performed better than the P mixture with averages differing by 51% (upper half inch) and 33% (lower half inch).

Figure 4.20 is a bar chart containing 90 day salt ponding results (at both depths) and results of the RCIP test for concretes at 90 days age. The vertical scale should be read as ppm for salt ponding test results and coulombs for RCIP test results. Remarkably similar trends can be seen between 90 day RCIP results and absorbed chlorides at the first depth from the salt ponding test. Both tests clearly indicated that the BFS mixture had the highest resistance to chloride ion penetration. Table 4.17, contains the results and percentage difference as compared to the control P mixture for both tests. Within the same mixture, the percentage differences from the corresponding P mixtures were quite close. In a sense, this similar relationship confirmed the validity of both tests to investigate relative permeability differences between concretes.

Based on statistical results of both salt ponding and RCIP tests, it can be concluded that BFS substantially reduced the chloride ion penetration of Class AA concrete, while FA had little effect on permeability. The FB mixture yielded statistically similar results as the P mixture in the salt ponding test but showed slightly better performance in the RCIP test.

Table 4.17 Comparison of Salt Ponding Test Results and RCIP Test Results

Mixture	Salt Ponding Absorbed Cl, Upper Half Inch (ppm)	Difference (%)	RCIP @ 90 days Charge Passed (Coulombs)	Difference (%)
P	2230		3501	
FA	2351	5	3671	5
BFS	1094	-51	1552	-56
FB	2020	-9	2769	-21

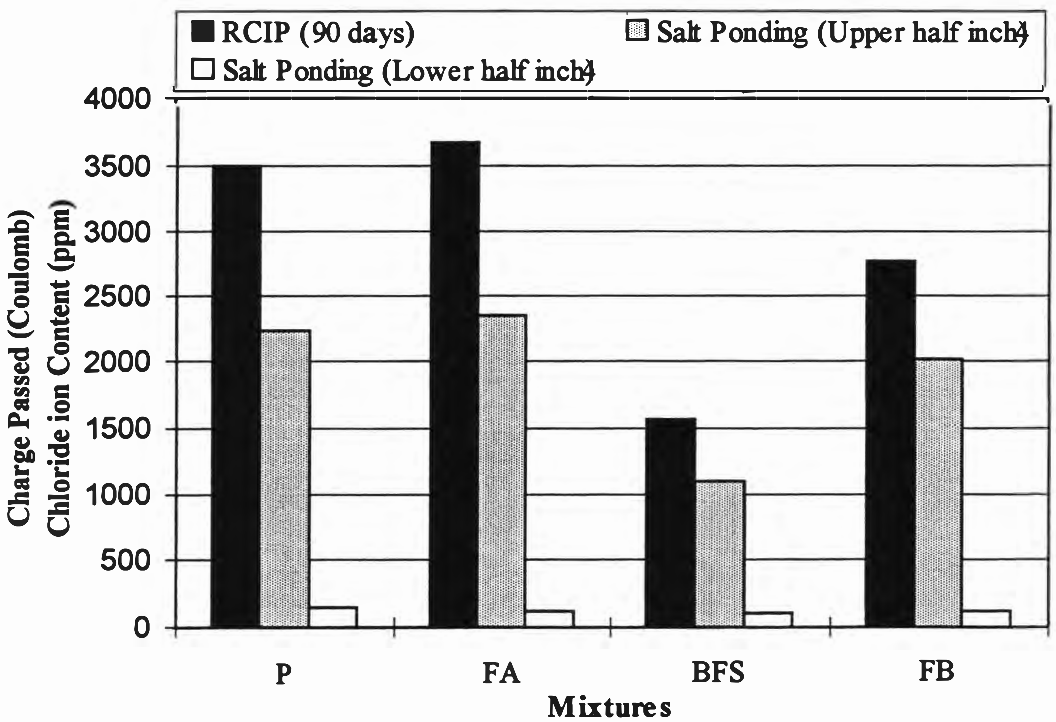


Fig. 4.20 Comparison of Salt Ponding and RCIP Test Results

4.4 MIXING/CURING TEMPERATURE STUDY

The purpose of this study was to determine how different batching and curing temperatures affected mixtures with slag and/or Class C fly ash. A single Type I cement (Ash Grove) was used for this study. The same four mixtures tested in the Cement Study were tested in the Temperature Study; one additional mixture type containing 50 percent BFS replacement (designated BB) was also tested.

Three different casting and curing temperatures were examined. As mentioned in Chapter 3, the batching and curing temperatures were chosen to be representative of hot and cold weather conditions in Oklahoma (in addition to standard conditions). The standard regimen mixtures were cast near 70 F, and cured at 73 F and 100 percent relative humidity. For the hot weather regimen, the mixtures were cast at 90 F, and cured at 83 F and 100 percent humidity. Finally, for the cold weather regimen, the mixtures were cast at 50 F, and cured at 50 F and 100 percent humidity. Mixture BB (with 50 percent BFS replacement) was studied only for the hot weather and standard regimens.

4.4.1 Fresh Concrete Tests

Five fresh concrete properties were measured for each mixture. The tests performed were slump, fresh concrete temperature, total air content, unit weight, and time to set. The results from the fresh concrete property tests are shown in Table 4.18.

4.4.1.1 Slump. In general, the results from the different temperature regimens follow a similar trend as can be seen in Table 4.18. For the standard and cold weather regimens, those mixtures containing slag (mixtures BFS, FB, and BB) generally had less slump, while mixtures FA and P generally had the most slump. For like mixtures, there were only slight differences between the slumps of the standard and cold weather mixtures. However, the elevated mixing temperature reduced the slumps of all mixtures.

For the standard and cold weather regimens, the addition of BFS decreased slumps. The decrease in slump was 1.75 in. and 1.50 in. for the standard and cold weather mixtures, respectively. Slumps of FA mixtures were fairly similar to those of the control (P) mixtures for standard and cold weather mixtures. The slumps of FB (combination of fly ash and slag) mixtures for the standard and cold weather mixtures were between those of the BFS and FA mixtures. As expected the slumps of the BB mixtures (50 percent slag replacement) were less than those of the control mixtures and BFS mixtures (25 percent slag replacement).

The hot weather regimen reduced the slumps of all mixtures, which was expected. The slumps of all mixtures were between 0.50 in., and 1.00 in. Since the slumps fell within a total range of ½ in., it is difficult to draw any conclusions regarding pozzolan addition from these results.

Table 4.18 Fresh Concrete Properties for Mixing/Curing Temperature Study

MIXTURE	SLUMP (in)	AIR CONTENT (%)	UNIT WEIGHT (lb/ft³)	INITIAL SET (hr.)	FINAL SET (hr.)
Hot Weather					
P	0.75	5.1	147.1	2.8	3.7
FA	0.75	5.6	143.8	3.4	4.7
BFS	1	5.2	148.1	2.9	3.7
FB	0.5	5.6	148.5	3.6	4.5
BB	1	4.2	147.8	3.0	3.9
Standard					
P	3	6.8	141.4	3.4	4.9
FA	2.25	6.9	142.0	5.4	7.3
BFS	1.25	5.2	144.5	3.5	5.0
FB	1.5	5.4	145.2	5.4	7.2
BB	0.5	3.4	150.2	2.8	5.2
Cold Weather					
P	2.5	9.[illegible]	140.9	6.7	9.4
FA	3	8.9	141.8	9.7	12.9
BFS	1	6.1	145.8	6.8	9.9
FB	1.75	7.7	143.7	11.3	15.2

4.4.1.2 Air Content. The results from the air content tests are shown in Table 4.18. The numbers represent the average of two tests (one from each twin batch). All mixtures were designed to have a total air content of 7 ± 1.5 percent. The AEA dosage for the standard and hot weather mixtures was held constant at 17 fl. oz./cwt and 40 fl. oz./cwt, respectively. The dosage rate for the cold weather mixtures ranged from 20 to 30 fl. oz./cwt (the lower rate being used for the P and FA mixtures). The dosage rates used for all the curing regimens were significantly higher than the manufacturer's recommended dosage rate of 0.75 to 3 fl. oz./cwt.

The hot weather mixtures required more than twice the AEA dosage of the standard mixtures. This required dosage increase was due to the decreased workability of the mixtures. Also, the manufacturer's guidelines suggest that the effectiveness of the AEA is diminished when the concrete temperature rises above 80 F. This same principle is true for the cold weather mixtures. As the concrete temperature decreases, the AEA's air entraining efficiency diminishes.

The air contents of the BB mixtures were significantly less than those of the other mixtures due to the BB mixture's low workability. Furthermore, the decrease in air content was also affected by the use of a constant AEA dosage within the hot weather and standard regimens. However, it is doubtful that the BB mixture could have attained 5 percent total air content even at a much higher AEA dosage. A constant dosage was used for all the standard temperature mixtures to show how increases in BFS content would affect the total air content.

4.4.1.3 Concrete Temperature. For standard mixtures the target concrete temperature was 70 F. Most standard mixtures were cast during the summer so crushed ice was added to the mixing water to lower the concrete temperature. Measured fresh concrete temperatures for the standard mixtures ranged from 68 to 76 F. For the hot weather mixtures the target fresh concrete temperature was 95 F. Warm mixing water was used to attain the necessary temperature. Measured fresh concrete temperatures for these mixtures ranged from 90 F to 94 F. The target fresh concrete temperature of the cold weather mixtures was 50 F. Most of these mixtures were batched when the ambient temperature was near 50 F; therefore, no additional measures were needed to attain the required temperature. Fresh concrete temperatures for the cold weather mixtures ranged from 51 F to 56 F.

4.4.1.4 Unit Weight. The results from the unit weight tests are shown in Table 4.18. The values reported are the average of two unit weight tests (one from each of the twin batches). The unit weights of the mixtures ranged from 140.9 to 150.2 lb/ft^3. Slightly higher unit weights were often observed for hot weather mixtures (even at similar air contents as standard mixtures). This may be related to water evaporation at the higher mixing temperature. No significant trends were expected, nor observed, as a result of using different batching temperatures.

4.4.1.5 Time to Set. Time to initial and final set is shown in Table 4.18. The time to set was performed on each mixture and for each temperature regimen. For like mixtures, the time to initial and final set was shortened with increase in concrete temperature, as expected. This effect was most pronounced when comparing the standard and cold weather mixtures. The cold weather mixtures' initial set times were about double those of corresponding standard mixtures. Furthermore, the time interval from initial to final set also increased with decreasing temperature. The time interval between initial and final set was on the order of one hour for hot weather mixtures; corresponding time intervals for cold weather mixtures ranged from about three to four hours.

Within a given temperature regimen, mixtures P, BFS, and BB had similar set times which were less than those for mixtures containing fly ash (FA and FB). As expected, the FA and FB mixtures had extended set times. The increase in setting times was expected for all pozzolan mixtures since pozzolan addition normally retards set times. However, mixtures with only BFS replacement (no fly ash) exhibited setting times very close to those of the control (P) mixtures at all temperatures.

4.4.2 Hardened Concrete Property Tests

Six tests were conducted on the hardened concrete at various ages for each mixture. Compressive strength, splitting tensile strength, modulus of elasticity, modulus of rupture, rapid chloride ion penetrability, and length change were the hardened concrete properties tested.

4.4.2.1 Compressive Strength. The compressive strength was measured at 3, 7, 28, 56, and 90 days of age. Six cylinders were tested from each mixture, three from each twin batch. Strength gain curves for mixtures at each temperature regimen are shown in Figs. 4.21 to 4.23. Figures 4.24 to 4.28 contain strength gain curves for each temperature regimen broken out by mixture type.

For all mixture types, the hot weather mixtures had the highest compressive strengths as expected. The cold weather mixtures had the lowest compressive strengths at all ages. For each temperature regimen, the BB mixtures (BFS mixtures for the cold curing) had the highest compressive strengths at seven days age and beyond. The P mixtures had compressive strengths less than those of the BFS mixtures while the FA mixtures had the least compressive strength. The compressive strength of the FB mixtures was between those of the BFS mixtures and the FA mixtures.

Compressive strengths were first determined at three days of age to determine the early effects of the curing regimens. Results from the three day compressive strength tests are shown in Table 4.19. The three day strengths for all cold cured mixtures were significantly lower than for their standard cured counterparts. Three of the four cold weather mixtures had strengths that were over 50 percent less than those of like standard cured mixtures. The mixtures subjected to the hot weather regimen had compressive strengths that were 6 to 33 percent greater than for like standard cured mixtures. Generally, the BB or BFS mixtures had the highest or near highest strength for all curing regimens.

The elevated temperature curing of the hot weather regimen increased the compressive strength of all mixtures. The P mixture benefitted most from the elevated temperature curing, exhibiting compressive strengths 33 percent higher than those of the standard cured specimens. The cold curing regimen significantly decreased the compressive strength of all mixtures. The compressive strengths of all the mixtures ranged from 1200 to 1460 psi which was approximately 50 percent less than the strengths of their standard cured counterparts.

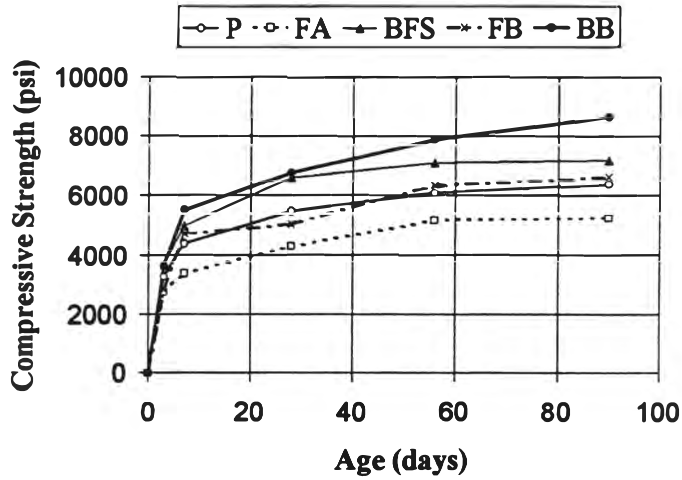


Fig. 4.21 Compressive Strength for Hot Weather Mixtures

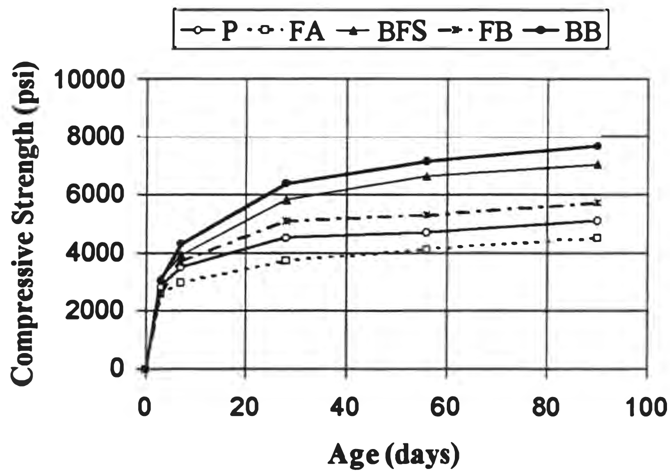


Fig. 4.22 Compressive Strength for Standard Mixtures

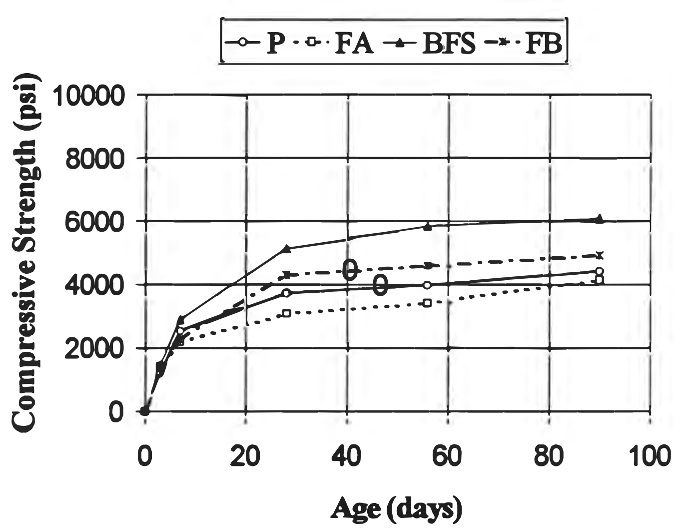


Fig. 4.23 Compressive Strength for Cold Weather Mixtures

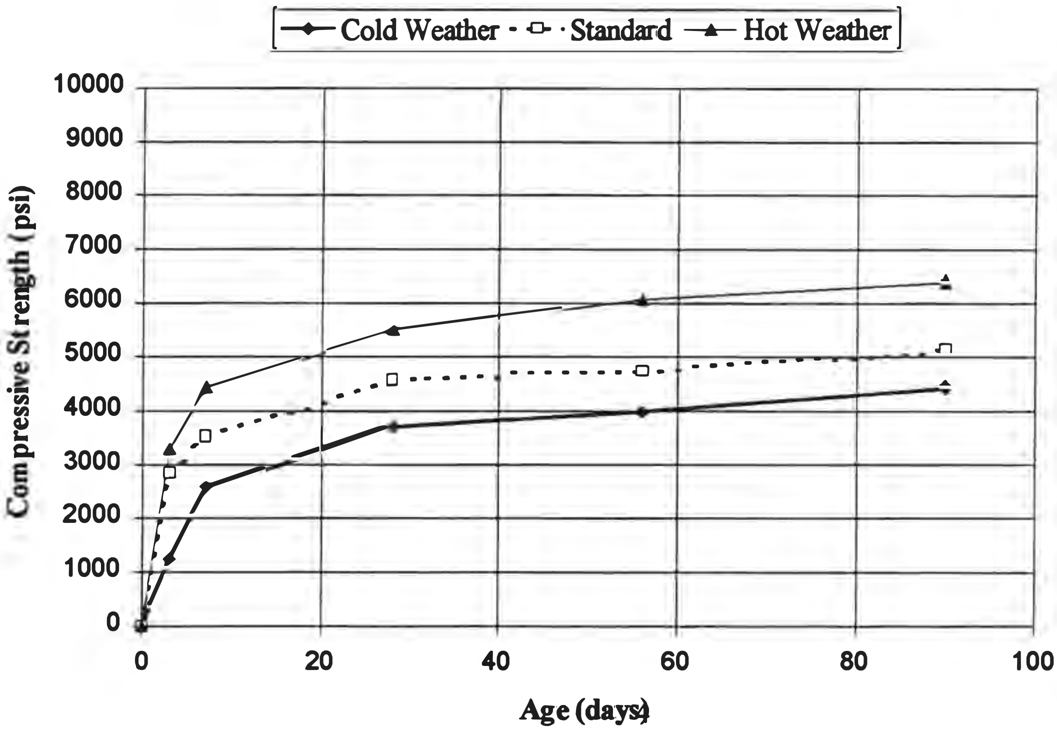


Fig. 4.24 Compressive Strength for P Mixtures, Temperature Study

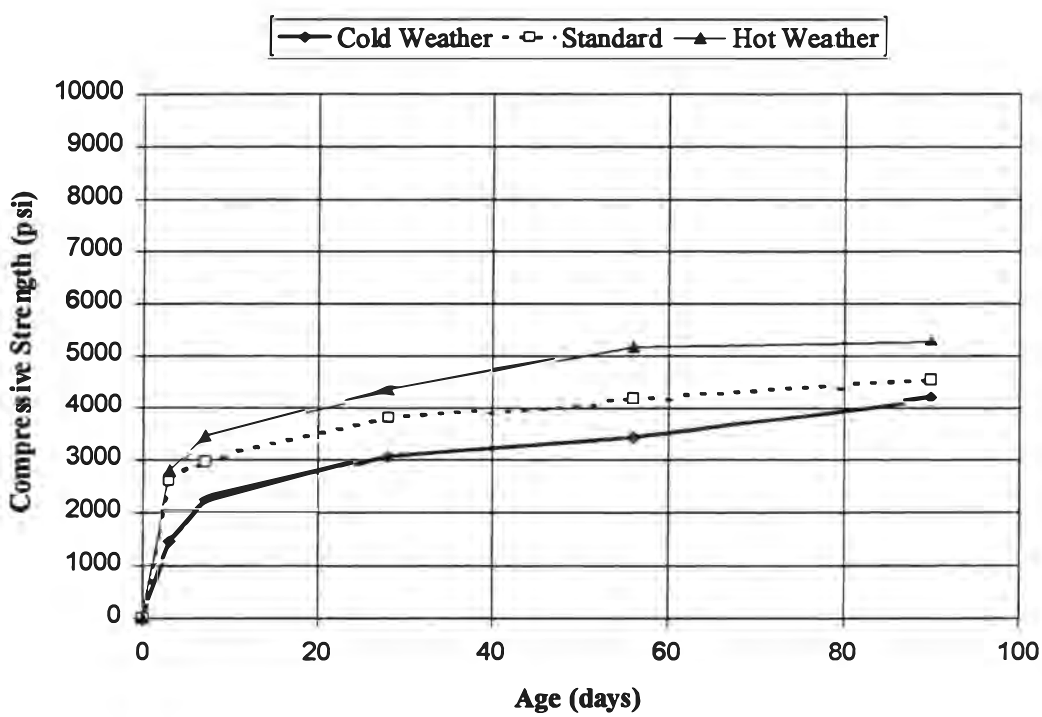


Fig. 4.25 Compressive Strength for FA Mixtures, Temperature Study

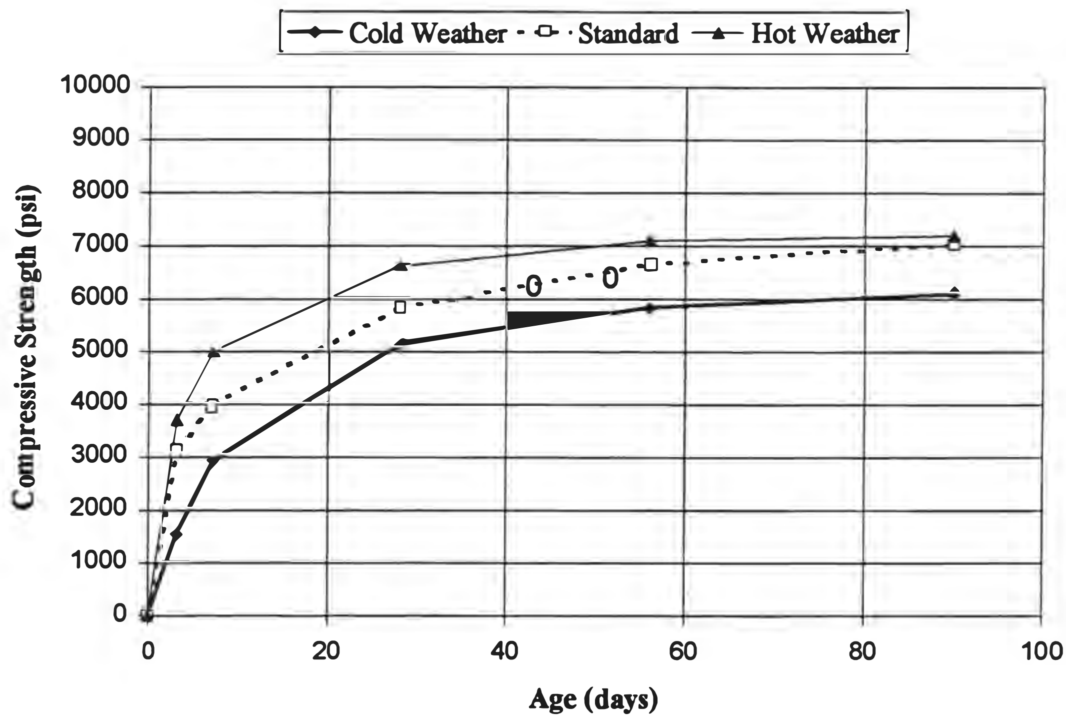


Fig. 4.26 Compressive Strength for BFS Mixtures, Temperature Study

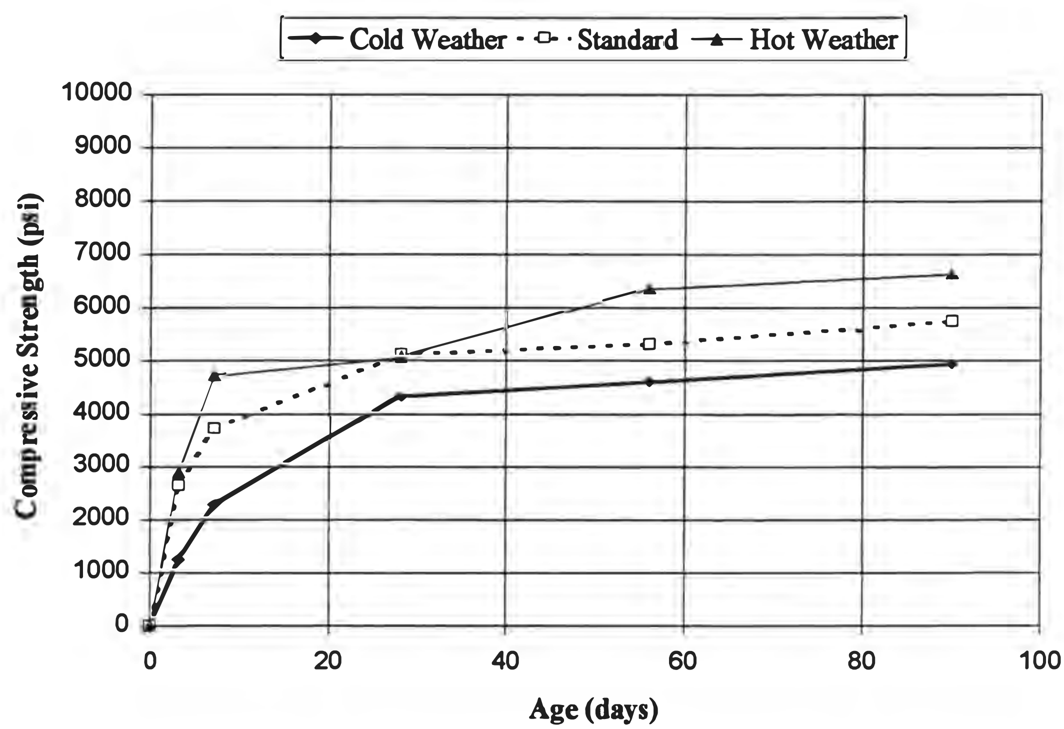


Fig. 4.27 Compressive Strength for FB Mixtures, Temperature Study

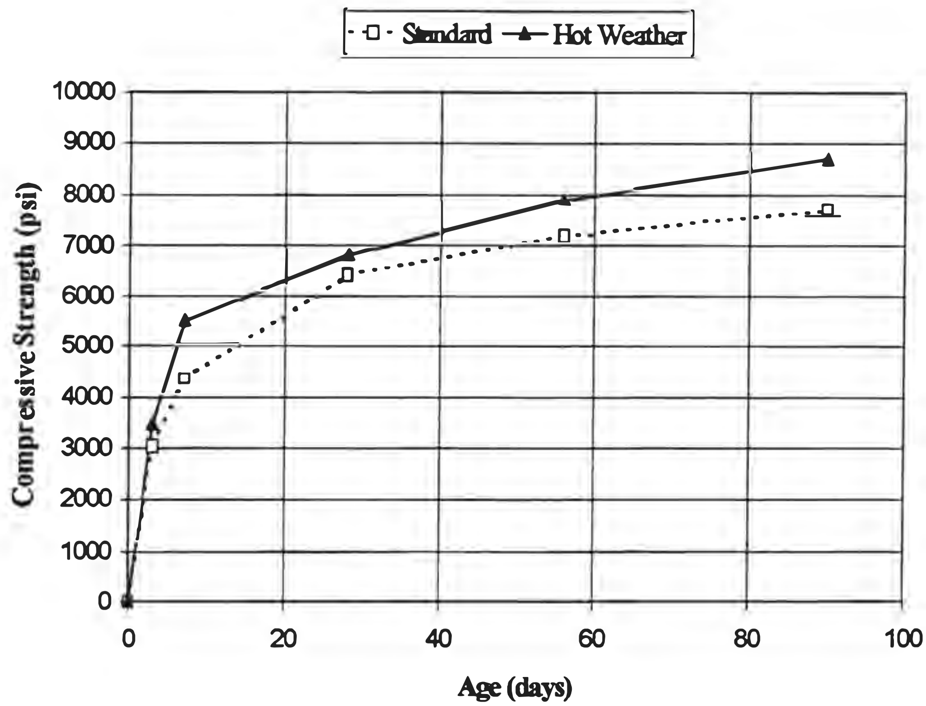


Fig. 4.28 Compressive Strength for BB Mixtures, Temperature Study

Table 4.19 Compressive Strength (psi) at Three Days Age, Temperature Study

	Mixture				
Temperature Regimen	P	FA	BFS	FB	BB
Hot Weather	3760	2740	3670	2860	3470
Standard	2820	2570	3100	2610	3050
Cold Weather	1200	1410	1500	1210	-

The results from the compressive strength tests from seven days of age are shown in Table 4.20. At seven days age, the hot weather regimen produced the concrete with the highest compressive strength, and the mixtures subjected to the cold weather regimen had the least compressive strength. The compressive strengths of the hot weather mixtures were 15 to 27 percent higher than those of corresponding standard cured mixtures. The compressive strengths of cold weather mixtures were 25 to 40 percent less than those of standard cured mixtures. For each curing regimen, the BB mixtures (BFS for the cold curing) possessed the highest compressive strength while the FA mixtures had the lowest strength.

Table 4.20 Compressive Strength (psi) at Seven Days Age, Temperature Study

	Mixture				
Temperature Regimen	P	FA	BFS	FB	BB
Hot Weather	4380	3400	4990	4710	5500
Standard	3500	2960	3940	3700	4310
Cold Weather	2520	2190	2900	2250	-

The compressive strength results of the 28 day tests are shown in Table 4.21. At 28 days of age, all mixtures subjected to elevated curing except for one (mixture FB) reached compressive strengths greater than their standard cured counterparts. For each curing regimen, the BFS or BB mixtures had the highest compressive strength. The compressive strengths of the cold cured specimens were still less than those of the standard cured mixtures.

Table 4.21 Compressive Strength (psi) at 28 Days Age, Temperature Study

	Mixture				
Temperature Regimen	P	FA	BFS	FB	BB
Hot Weather	5460	4300	6610	5060	6780
Standard	4510	3750	5820	5090	6390
Cold Weather	3700	3060	5140	4310	-

The results from the compressive strength tests at 56 days are shown in Table 4.22. At 56 days of age, the mixtures subjected to elevated curing had the highest compressive strength, and the mixtures subjected to the cold curing had the lowest compressive strength. Once again, the BFS or BB mixtures had the highest compressive strength for all curing regimens, and the FA mixtures had the lowest compressive strength.

Table 4.22 Compressive Strength (psi) at 56 Days Age, Temperature Study

	Mixture				
Temperature Regimen	P	FA	BFS	FB	BB
Hot Weather	6070	5180	7110	6350	7570
Standard	4700	4120	6640	5290	7150
Cold Weather	3980	3400	5835	4590	-

The results of the compressive strength tests at 90 days of age are shown in Table 4.23. At 90 days of age, the compressive strengths of the mixtures subjected to elevated curing were greater than those of their respective standard cured mixtures. The control (P) mixture exhibited a 25 percent increase; pozzolan mixtures had strength increases on the order of 7 percent (BFS) to 17 percent (FA). The strength gain curves also show that the rate of strength gain had decreased more for the elevated curing mixtures than for the other curing regimens. Once again, the cold cured mixtures had the lowest compressive strength (10 to 13 percent lower than standard cured mixtures). For all curing regimens, the BFS or BB mixtures had the highest compressive strengths; the FA mixtures had the lowest strengths.

Table 4.23 Compressive Strength (psi) at 90 Days Age, Temperature Study

	Mixture				
Temperature Regimen	P	FA	BFS	FB	BB
Hot Weather	6380	5270	7200	6630	8660
Standard	5090	4490	7040	5720	7670
Cold Weather	4560	4150	6100	4940	-

The results from the compressive strength tests show that for each curing regimen the BFS or BB mixtures had the greatest compressive strength. This is due to the pozzolanic reaction previously mentioned. Again, the FA mixtures should have benefitted from the pozzolanic reaction also, but for unexplainable reasons they (FA mixtures) did not. The combination of BFS and FA produced concrete that had compressive strengths less than the BFS mixture, more than the FA mixtures, and at later ages more than the P mixtures. Note that the BB mixtures had total air contents that were one to two percent less than those of the other mixtures. This reduction in total air content also contributes to the increases in compressive strength.

All mixtures benefitted from the introduction of elevated curing, as expected. The benefit was most notable at early ages. Curing specimens under the cold weather regimen decreased the compressive strength of all mixtures by about 10 to 15 percent at later ages. The decrease in compressive strengths was also most noticeable at early ages (approximately 50 percent at three days). For all curing regimens, the BB or BFS mixtures had the greatest compressive strength followed by the FB, P, and FA mixtures.

4.4.2.2 Modulus of Rupture. The modulus of rupture (MOR) was tested at 28 days of age. Four 6 in. x 6 in. x 20 in. specimens were tested from each mixture (two specimens from each twin batch). The results from the MOR tests are shown in Table 4.24. The values in the table represent the average strength of four specimens.

The only trend that appeared in the MOR results was that the BFS or BB mixtures had the greatest MOR for each of the different temperature regimens. The MOR was not consistently affected by the temperature regimens as shown in Fig. 4.29.

Table 4.24 Modulus of Rupture (psi), Temperature Study

	Mixture				
Temperature Regimen	P	FA	BFS	FB	BB
Hot Weather	790	750	895	790	975
Standard	705	675	920	835	995
Cold Weather	720	680	905	740	-

The results of the MOR tests are plotted versus the square root of the 28 day compressive strength of the respective mixtures in Fig. 4.30. Also plotted on the graph is the line $f_r = 7.5 * \sqrt{f'_c}$ (psi), commonly used to estimate the MOR of concrete based on its compressive strength. It can be seen from Fig. 4.30 that data points from all mixtures plot above this line; thus the equation can be used to conservatively estimate the MOR for all mixtures tested.

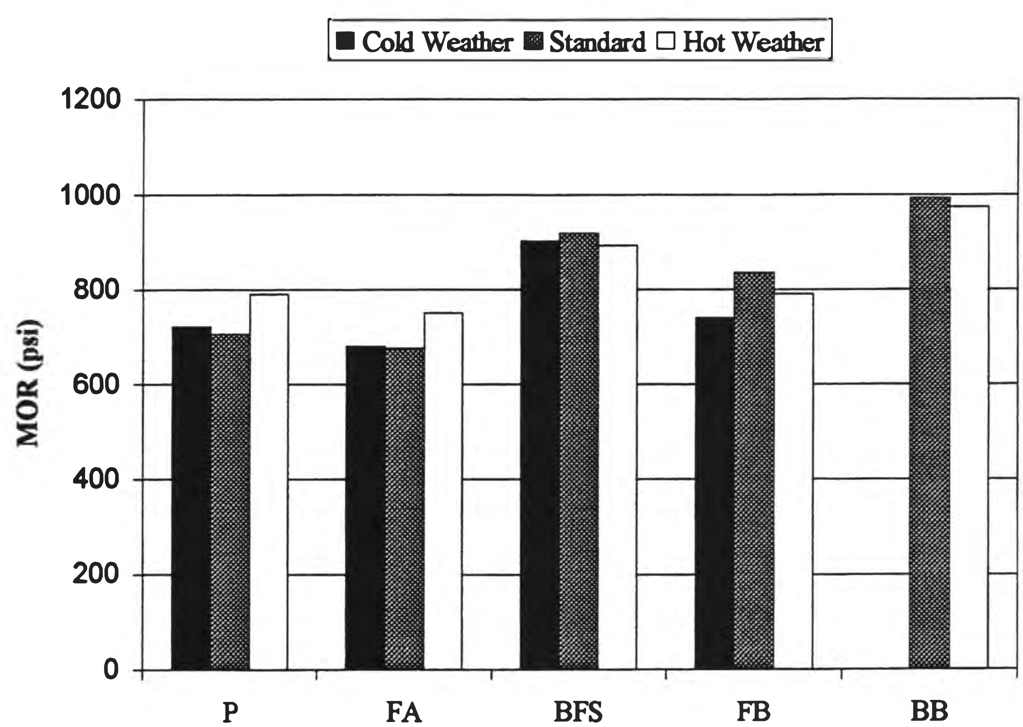


Fig. 4.29 Modulus of Rupture, Temperature Study

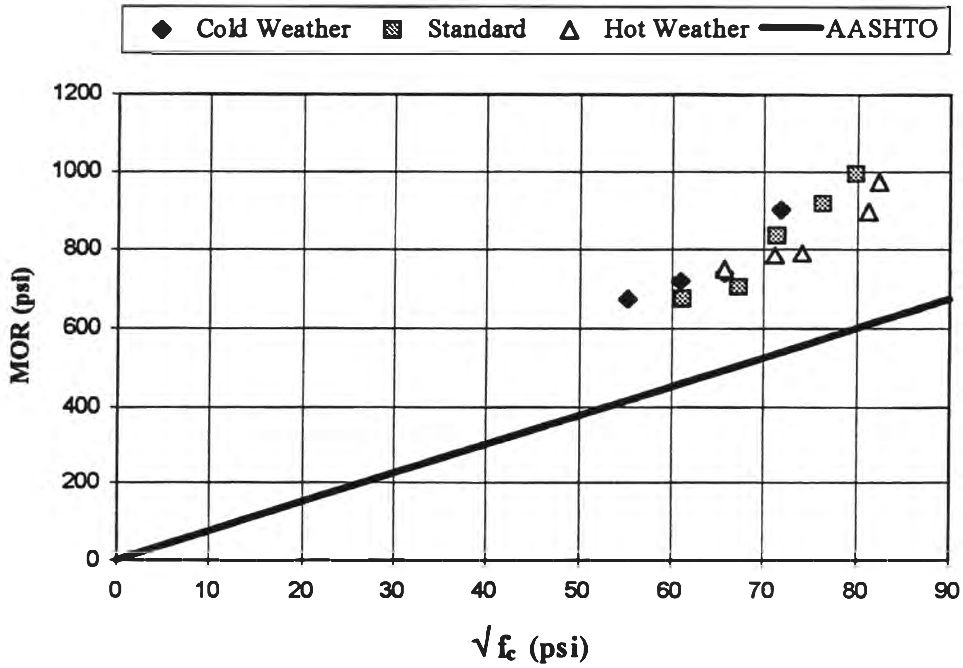


Fig. 4.30 Modulus of Rupture and AASHTO Equation, Temperature Study

4.4.2.3 Splitting Tensile Strength. The splitting tensile strength of the mixtures was measured at 28 days and 90 days of age. Six cylinders were tested from each mixture, three cylinders from each of the twin batches. Figures 4.31 and 4.32 contain bar graphs of splitting tensile strength at 28 and 90 days of age. Results from the 28 day and 90 day splitting tensile strength tests are also shown in Table 4.25. The values shown represent the average of six cylinders.

As was the case for the MOR data, there was no consistent trend of the effect of mixing/curing temperature on splitting tensile strength. Generally, the introduction of elevated curing increased the splitting tensile strength when compared to the standard cured specimens. However, the lower curing temperature did not always decrease splitting tensile strength. These general observations can be attributed to the fact that tensile strength is not linearly related to compressive strength, and to the scatter in the data.

Within any given temperature regimen, the addition of FA and/or BFS (mixtures BFS or BB) affected the splitting tensile strength. The BB mixtures had the greatest splitting tensile strength at 28 days and 90 days of age. The FB or BFS mixtures were usually second strongest while the P or FA mixtures were the weakest.

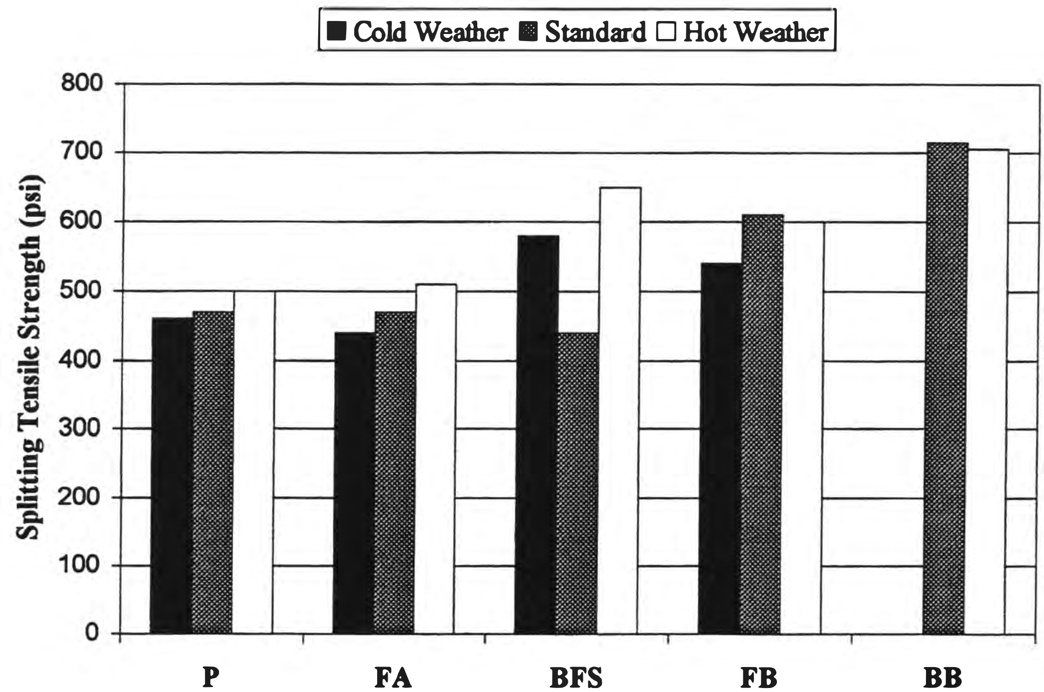


Fig. 4.31 Splitting Tensile Strength at 28 Days, Temperature Study

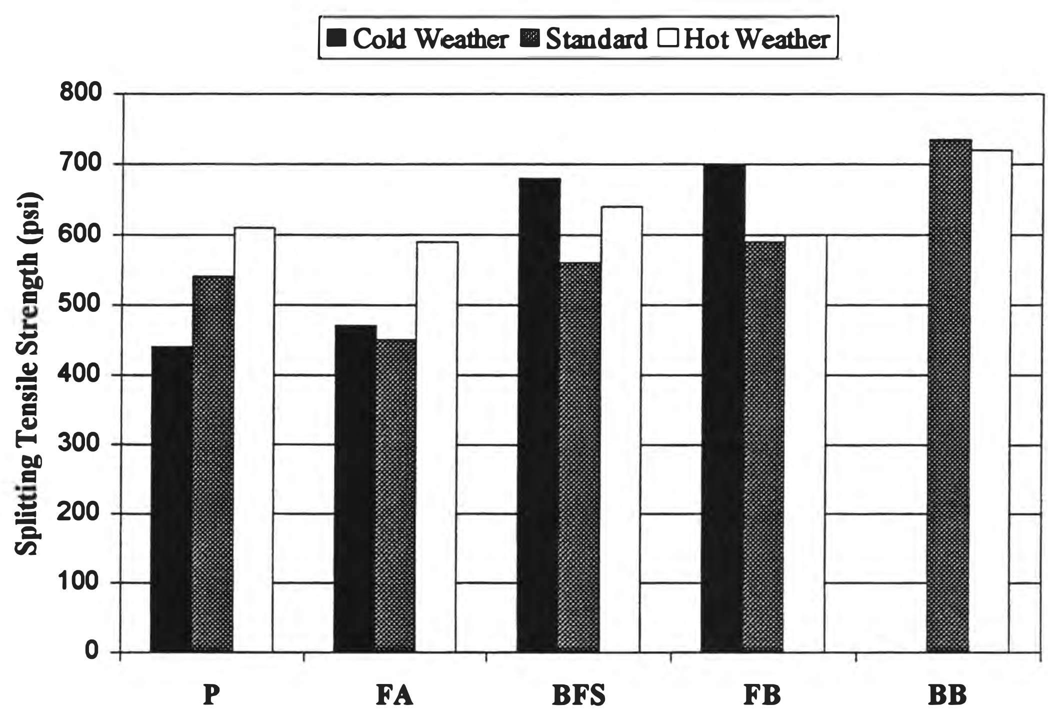


Fig.4.32 Splitting Tensile Strength at 90 Days, Temperature Study

The splitting tensile strengths are plotted versus the square root of the compressive strengths of each mixture in Fig. 4.33. Also plotted on the graph is the prediction line $f_t = 6*\sqrt{f_c}$ (psi). Data for all but one mixture plotted above the line; thus, the prediction equation produces a reasonable estimate of the splitting tensile strength based on the compressive strength at 28 and 90 days age

Table 4.25 Splitting Tensile Strength (psi) at 28 and 90 Days, Temperature Study

		Mixture				
	Temperature Regimen	P	FA	BFS	FB	BB
28 Day	Hot Weather	500	510	650	600	705
	Standard	470	470	440e	610e	715
	Cold Weather	460	440e	580	540	-
90 Day	Hot Weather	610e	590	640	600	720
	Standard	540	450	560	590	735
	Cold Weather	440	470	680	700	-

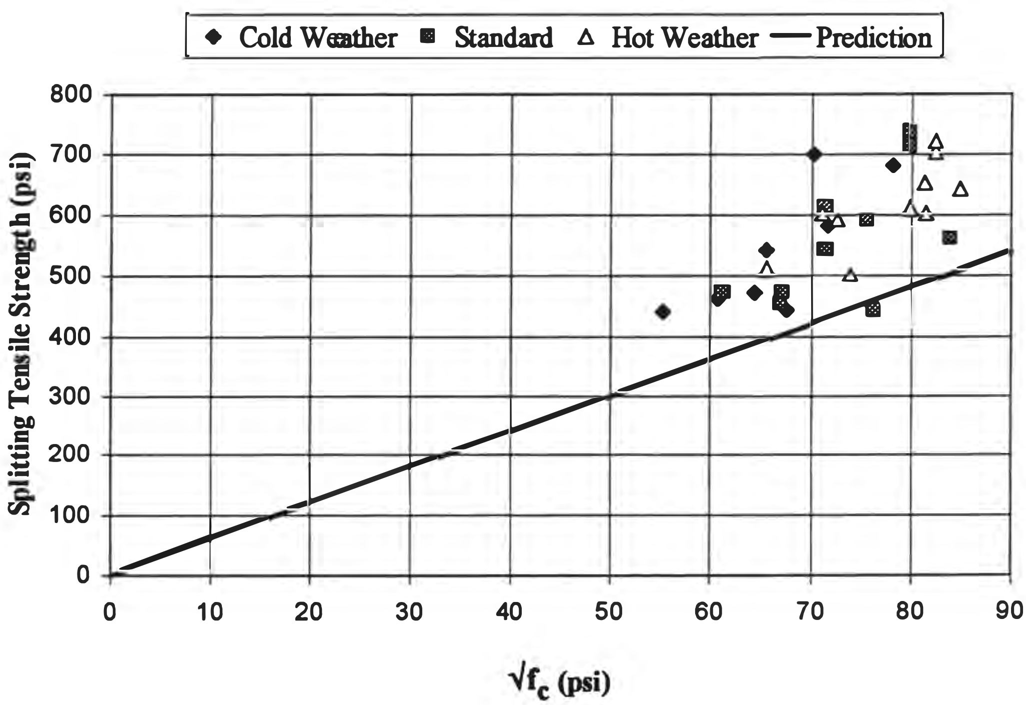


Fig. 4.33 Splitting Tensile Strength and Prediction Equation, Temperature Study

4.4.2.4 Modulus of Elasticity. The modulus of elasticity (MOE) was tested at 28 and 90 days of age. The results from the 28 day and 90 day tests are contained in Table 4.26. Each value shown in the table represents the average MOE of four cylinders. The results of the MOE tests are also shown in Figs. 4.34 and 4.35.

At 28 and 90 days age, the mixtures subjected to the hot weather regimen generally had higher MOE values than like standard cured mixtures. Also, the mixtures subjected to the cold weather regimen generally had MOE values less than their standard cured counterparts.

The mixtures containing slag (mixtures BFS, FB, and BB) had the greatest MOE at 28 and 90 days of age, while mixtures P and FA had lower MOE. The differences in MOE between the slag and non-slag mixtures became less pronounced with increasing mixing/curing temperature.

The MOE of each mixture at 28 and 90 days of age was plotted versus the square root of each mixture's compressive strength (Fig. 4.36). Also plotted on the graph is the line, MOE = $57{,}000 * \sqrt{f'c}$ (psi). As seen in Fig. 4.36, the results from the 28 day and 90 day MOE tests plot above this line, meaning the equation can be used to conservatively estimate the MOE of the mixtures tested based on their compressive strength.

Table 4.26 Modulus of Elasticity (ksi) at 28 and 90 Days, Temperature Study

		Mixture				
	Temperature Regimen	P	FA	BFS	FB	BB
28 Day	Hot Weather	5600	5200	5700	6100	6300
	Standard	4800	4500	5800	5200	6100
	Cold Weather	5000	4100	5400	5300	-
90 Day	Hot Weather	5700	6000	6300	6400	6500
	Standard	5000	5000	5900	5700	6400
	Cold Weather	4200	4400	5700	5700	-

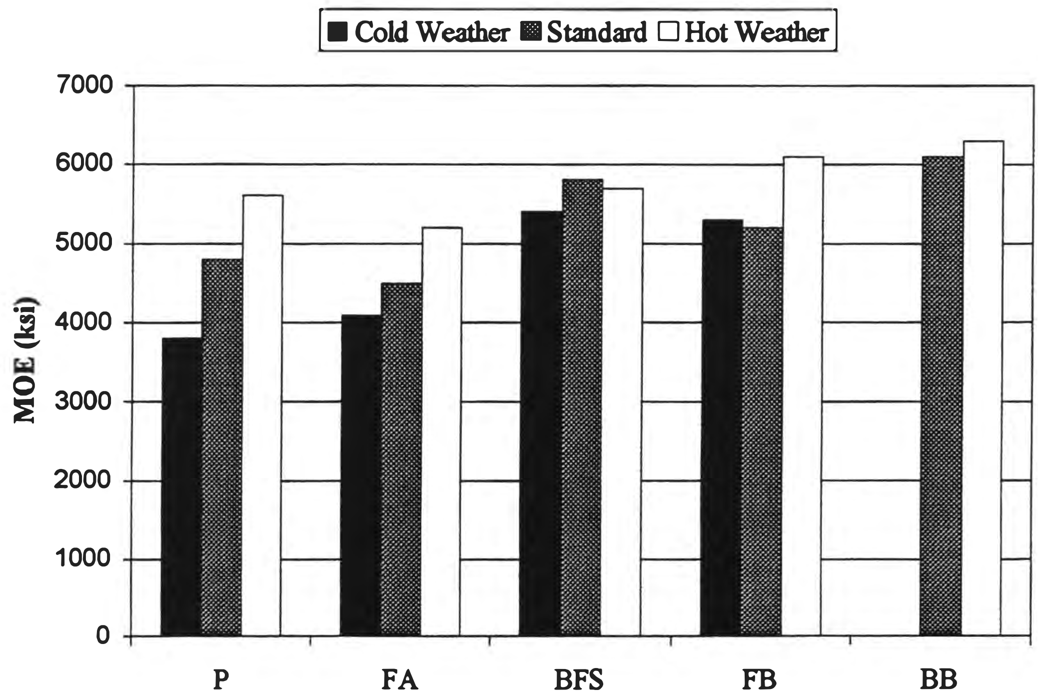


Fig. 4.34 Modulus of Elasticity at 28 Days, Temperature Study

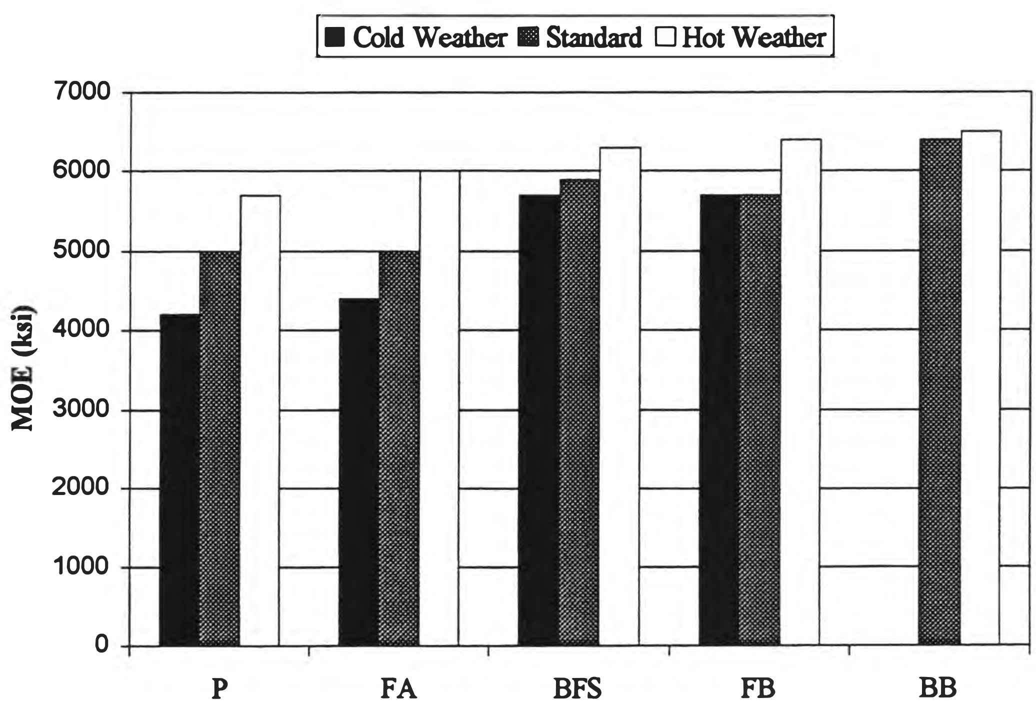


Fig. 4.35 Modulus of Elasticity at 90 Days, Temperature Study

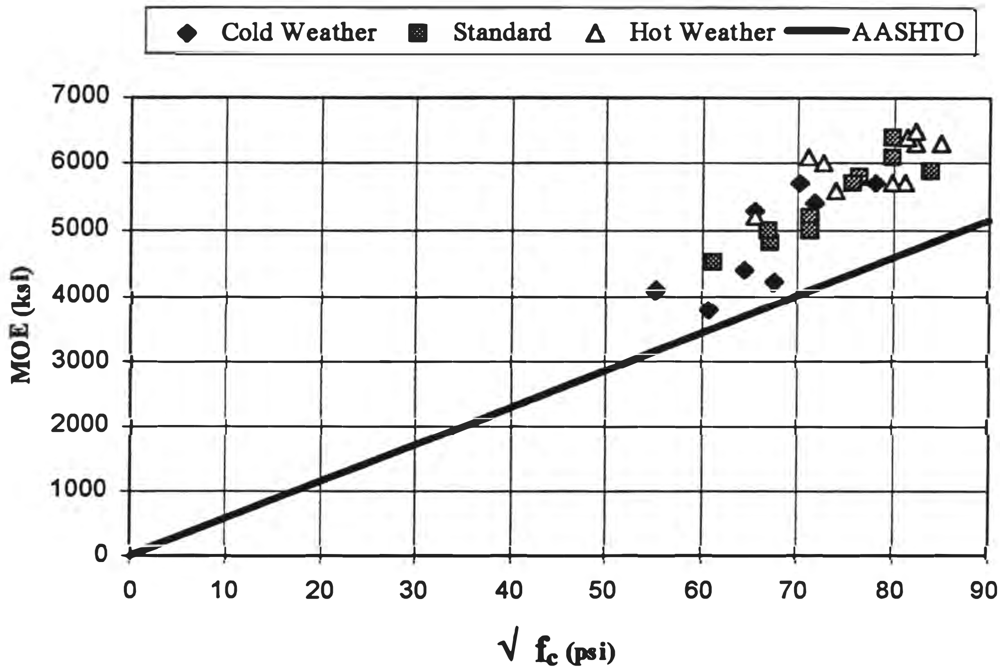


Fig. 4.36 Modulus of Elasticity and AASHTO Equation, Temperature Study

4.4.2.5 Shrinkage. The drying shrinkage of the mixtures was measured at 3, 7, 28, 56, and 90 days of age. Data was collected using four specimens from each mixture (two specimens from each of the twin batches). The average results from the drying shrinkage tests are shown in Table 4.27. Also shown in Figs. 4.37 to 4.39 are the shrinkage curves for each temperature regimen.

The different curing regimens did not substantially affect the drying shrinkage at 90 days of age. The 90 day drying shrinkage for all mixtures ranged from 290 to 460 microstrains. The drying shrinkage values for the mixtures subjected to the hot weather regimen were within 90 microstrains of one another. Therefore, little can be determined from the slight differences in the drying shrinkage. The rate of shrinkage was greatly reduced for nearly all specimens by 56 days of age.

Table 4.27 Drying Shrinkage (microstrains), Temperature Study

Mixture	Age (days)				
	3	7	28	56	90
Hot Weather					
P	100	175	320	400	410
FA	95	180	410	450	450
BFS	100	210	365	410	420
FB	55	180	315	355	365
BB	45	165	305	355	360
Standard					
P	95	220	360	430	460
FA	90	200	385	450	450
BFS	80	130	290	290	290
FB	85	145	295	335	335
BB	95	150	260	330	340
Cold Weather					
P	45	165	410	435	435
FA	20	210	335	360	365
BFS	90	170	295	330	345
FB	30	125	270	290	320

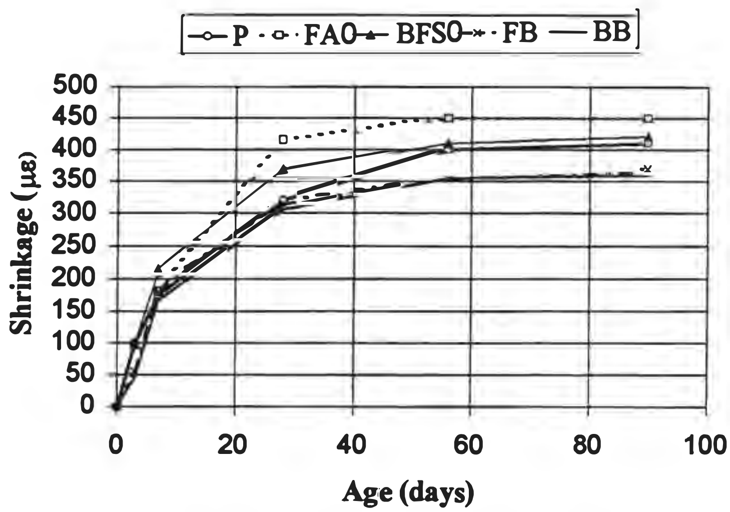


Fig. 4.37 Shrinkage Curves for Hot Weather Mixtures

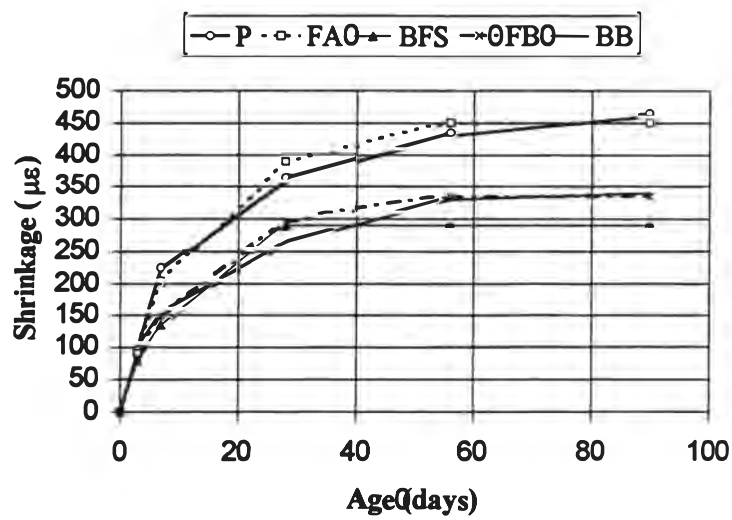


Fig. 4.38 Shrinkage Curves for Standard Mixtures

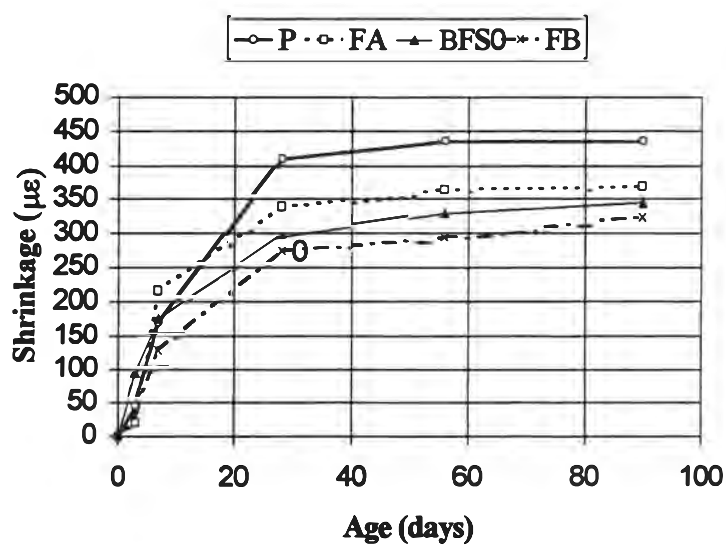


Fig. 4.39 Shrinkage Curves for Cold Weather Mixtures

4.4.2.6 Rapid Chloride Ion Penetrability. Results from the 28 day and 90 day Rapid Chloride Ion Penetrability (RCIP) tests for the mixtures are shown in Table 4.28. Each data point represents the average of four tests (two samples from each of the twin batches). The averages are also plotted in Figs. 4.40 and 4.41. In general, the total charge passed reduced with increase in mixing/curing temperature. These observations are consistent with compressive strength results. The same mixtures that exhibited higher compressive strengths had lower penetrability, since both are typically related to density of the hardened concrete. Also, within each curing regimen, as compared to P mixtures, the addition of BFS decreased the RCIP values, while the addition of FA increased the RCIP values.

At 28 days of age, the hot weather regimen reduced the RCIP values of all but one mixture (BB). For the hot weather mixtures, the BB mixture had the lowest RCIP (1142 coulombs) followed by the BFS mixture (1705 coulombs) and FB mixture (1998 coulombs). All the mixtures except for mixture FA had RCIP values less than the P mixture (2737 coulombs). The FA mixture had the highest RCIP (4184 coulombs). The cold weather mixtures followed the same trend as the hot weather mixtures.

Rapid chloride ion penetrability reduced from 28 to 90 days; the same trends seen at 28 days were also observed at 90 days. At 90 days of age, the RCIP values of the majority of the hot weather mixtures decreased slightly from 28 days. Mixtures P, BFS, FB, and BB saw minimal to moderate decreases (about 10 to 25 percent) in total charge passed from 28 to 90 days of age. At 90 days of age the RCIP value of mixture FA was less than one-half of its 28 day value. However, the coulombs passed for cold weather mixtures significantly decreased from 28 to 90 days. The FB mixture decreased 62 percent. The P, FA, and BFS mixtures decreased 34, 39, and 33 percent, respectively. This observation is consistent with the fact that the reduced curing temperature slowed earlier hydration to a greater extent than long term hydration. With time, the cold weather specimens were able to "catch up," to some degree, to the standard cured specimens.

For each curing regimen and for all ages, the FA mixtures had either the highest or second highest RCIP values. The P mixtures were generally next, followed by the FB mixtures, then the BFS mixtures, and finally the BB mixtures. The P and FA mixtures benefitted the most from the elevated curing, but they also suffered the most from the cold weather regimen. The BFS and BB mixtures were relatively unaffected by changes in the curing regimen.

According to ASTM C1202, all the FA mixtures at 28 days would be rated to have high penetrability (> 4000 coulombs passed). The cold weather and standard P mixtures would also be rated as having high penetrability. The hot weather P mixture would be rated to have moderate chloride ion penetrability (2000 to 4000 coulombs). The cold weather BFS mixture, along with cold weather and standard FB mixtures, would also be classified as having moderate penetrability. The remaining mixtures (standard and hot BFS, hot FB, and standard and hot BB) would be classified as having low penetrability (1000 to 2000 coulombs).

At 90 days, the cold weather P and FA mixtures would still be classified as having high penetrability. The hot weather and standard P and FA mixtures would be now classified as having moderate penetrability, along with the standard FB mixture. All the BFS mixtures and the standard BB mixture would be rated as having low penetrability at 90 days of age. The hot and cold weather FB mixtures would also be classified as having low penetrability. The hot weather BB mixture would classify as having very low penetrability (100 to1000 coulombs).

Table 4.28 RCIP (coulombs passed) at 28 and 90 Days, Temperature Study

		Mixtures				
	Temperature Regimen	P	FA	BFS	FB	BB
28 Day	Hot Weather	2737	4184	1705	1998	1142
	Standard	4130	6350	1820	3900	1053
	Cold Weather	6216	7310	2101	3045	-
90 Day	Hot Weather	2151	2073	1239	1703	791
	Standard	3500	3670	1285	2770	1128
	Cold Weather	4131	4470	1399	1157	-

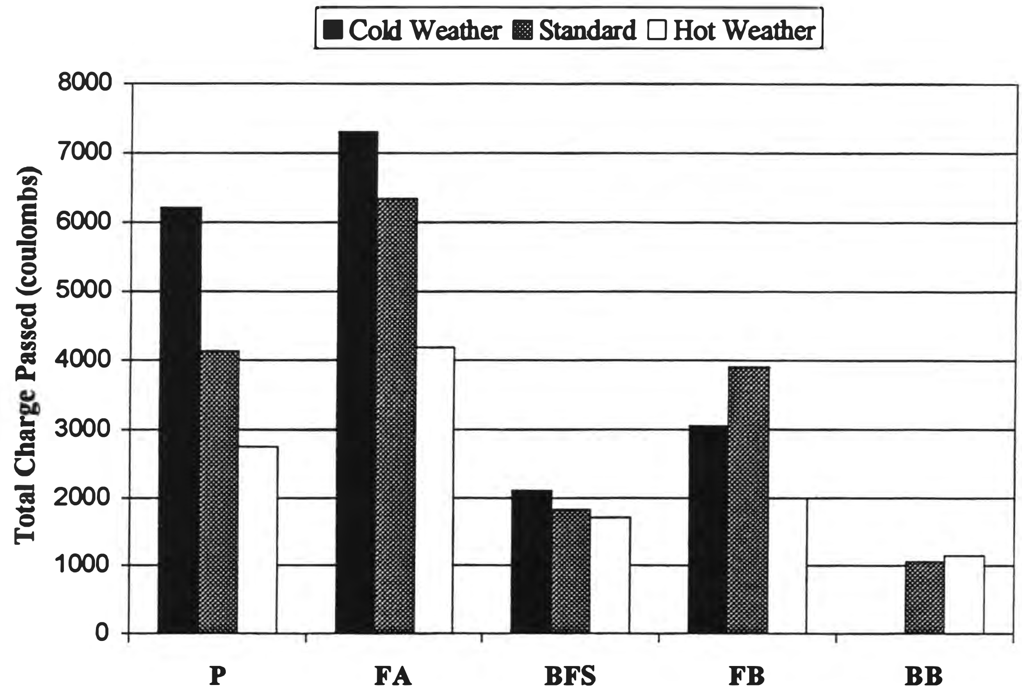


Fig. 4.40 RCIP at 28 Days, Temperature Study

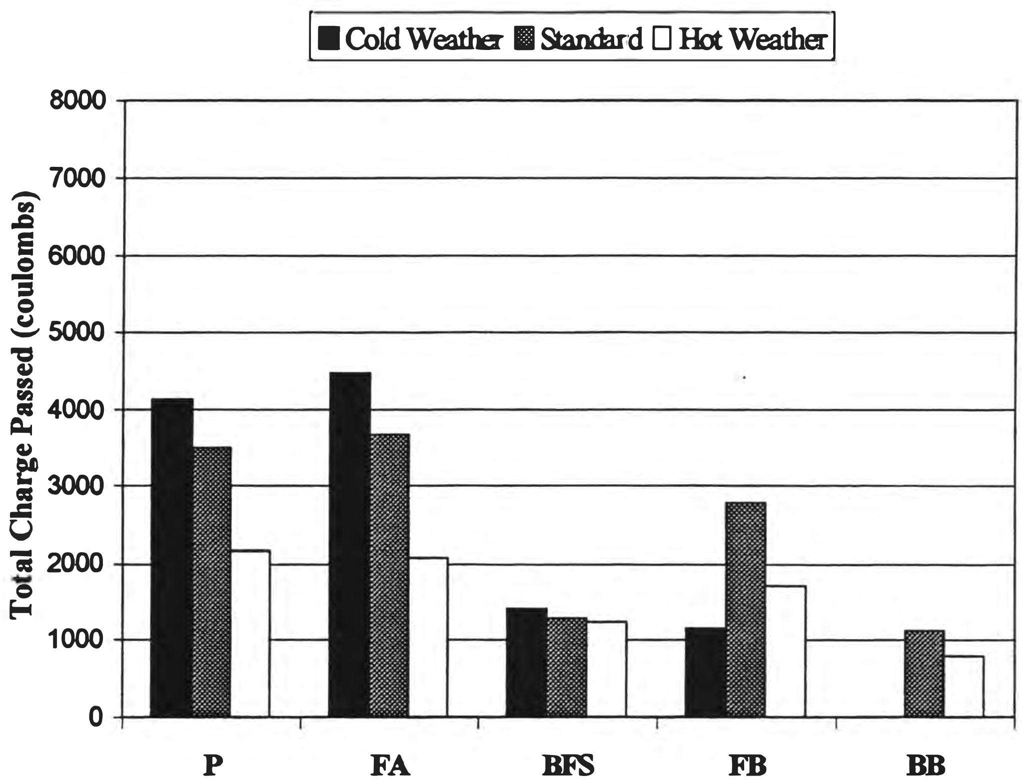


Fig. 4.41 RCIP at 90 Days, Temperature Study

4.5 CLASS A CONCRETE STUDY

This section focuses on the examination of the effect of pozzolan replacement on Class A concrete. Comparisons are made between mixtures within Class A concrete and where appropriate, to results of tests on Class AA concrete that used the same cement (Ash Grove). It should be realized that Class A and AA concrete have different mixture designs and specifications. Thus, differences in properties of Class A and Class AA concrete were affected by a number of factors, for example, relative differences in the amount of paste, water demand, water to cementitious materials ratio, cementitious materials content and total air content. In this study, the mixtures tested included: 1) Control (P-A), 2) 15 percent Class C fly ash replacement (FA-A), and 3) 25 percent blast furnace slag replacement (BFS-A). Note that the mixture designations are identical to those used previously, with the suffix "-A" added to indicate Class A concrete. The combination of FA and BFS was not investigated.

4.5.1 Fresh Properties

Fresh properties of Class A concrete examined included the slump, slump loss, total air content, unit weight, and time to set. Table 4.29 contains fresh concrete properties of Class A mixtures. The values reported are averages of twin batches.

Table 4.29 Fresh Properties of Class A Concrete

Mixture	P-A	FA-A	BFS-A
AEA (fl. oz/cwt)	4.5	1	5.5
Slump (in.)	2.4	2.7	2.4
Air Content (%)	7.4	5.4	6.9
Unit Weight (lb/ft^3)	141.2	144.7	142.8
Initial Set (hr)	5.6	6.9	6.5
Final Set (hr)	7.2	8.5	8.4
Concrete Temp. (°F)	70.5	69.7	69.0

4.5.1.1 Slump and Slump Loss. Considering the scatter of the data, there was little difference in slumps within Class A mixtures. Slumps of all individual batches were within the range of 2 to 2.75 in. with overlapping data between mixtures. Therefore, there was no distinct conclusion regarding the effect of pozzolan addition on the slumps of Class A concrete.

On the other hand, a consistent difference existed between slumps of Class A and AA mixtures. In general, all Class A concrete had greater slumps than Class AA, sometimes twice as much. This was due to the lower cement content, larger coarse aggregate size and slightly higher coarse to fine aggregate ratio (0.072 higher by weight) for Class A concrete which reduced the water demand. In other words, Class A concrete had more "free" mixing water to facilitate workability even though the total amount of water used in Class A and AA mixtures was the same.

Figure 4.42 is a plot of slump vs. time for Class AA (broken lines) and Class A (solid lines) mixtures. The rate of slump loss of the three Class A mixtures was almost identical, as indicated by the slope of the lines. There were no significant changes due to the presence of either fly ash or blast furnace slag. During the first 90 minutes, slump loss for Class A mixtures was around 2 in. as compared to about 2.5 in. for Class AA mixtures. This suggests that Class A mixtures had a slightly lower rate of slump loss than Class AA mixtures. However, the ambient temperature was 5 F higher for the Class AA test, and the operators were different for the two tests. Therefore, the rate of slump loss could be considered similar for the two mixture classes. However, it should be recognized that slump loss under laboratory conditions may not be representative of slump loss experienced under field conditions.

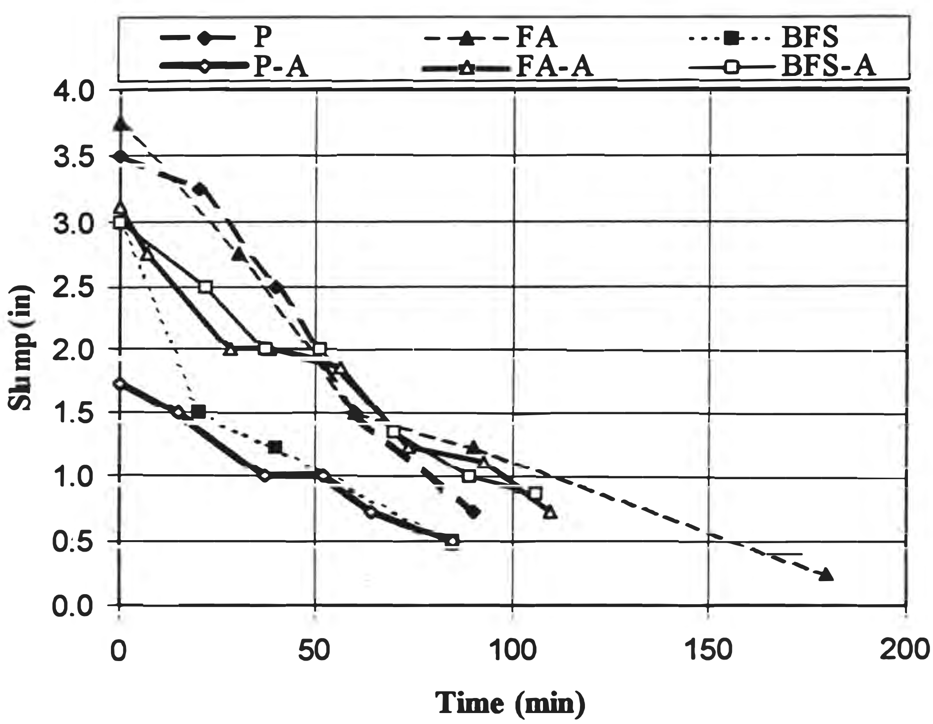


Fig. 4.42 Slump Loss of Class A and Class AA Concrete

4.5.1.2 Air Content. The air contents of individual batches ranged from 5.3 to 7.8 percent. By comparing the amount of air entrainment agent (AEA) used to achieve these air contents, trends can be detected. The FA-A mixture required comparatively less AEA (1 fl.oz./cwt) to generate the required air content. This tendency was partially due to the slightly higher slumps of the FA replacement mixtures owing to the smooth glassy nature of the fly ash particles. In contrast, considerably more AEA (about 5 fl.oz./cwt) was used for the BFS-A and P-A mixtures with little noticeable difference in total air content between them. The implication of this observation is that the air entraining ability of the 15 percent FA replacement (FA-A) mixture was better than both the 25 percent slag replacement (BFS-A) and control (P-A) mixtures.

Since there was more free water and better workability for Class A mixtures, the effectiveness of the AEA was also improved. For example, Class AA mixtures required much more AEA (about 14 oz./cwt) than Class A mixtures to achieve target air contents only one percent higher than those of Class A concrete. While the specific observation above was affected by the mixing energy imparted by the laboratory mixer, a similar (although less pronounced) trend should also be expected for field batches.

4.5.1.3 Unit Weight. Unit weights of individual Class A batches ranged from 140.7 to 145.7 lb/ft^3. As seen in Table 4.29, the unit weight varied inversely to the air content. Comparisons with Class AA mixtures indicate these unit weights were within the same range, but conclusions can't be drawn due to differences in total air content.

4.5.1.4 Time to Set. Figure 4.43 contains a summary of times to initial and final set for Class A and AA mixtures. The three pairs of bars in the left side of the figure represent setting times for Class A mixtures. The time interval between the initial and final set for all six mixtures remained virtually constant (1.5 to 2 hours). Time to initial set for Class A mixtures was about 5.5 to 7 hours, as compared to around 3 to 5 hours for Class AA mixtures. The longer set times for Class A mixtures is consistent with the lower heat of hydration generated by their reduced total cementitious materials content. For both mixture classes, pozzolan addition tended to increase setting time as compared to their respective control mixtures (due to the reduced early reactivity of FA and BFS as compared to portland cement). However, the set delay for BFS mixtures was more pronounced for Class A concrete than for Class AA.

4.5.2 Hardened Properties

4.5.2.1 Compressive Strength. Compressive strength gain curves for both Class A and Class AA concretes are shown in Fig. 4.44. In the figure, the solid lines represent strength gain for Class

A mixtures. Each data point of the FA mixture represents the average of six cylinders (three for each of the twin batches). The data points of the BFS and control mixtures are averages of three test specimens. Also included in the figure are strength gain curves for Class AA mixtures which used the same cement type and source (dashed lines).

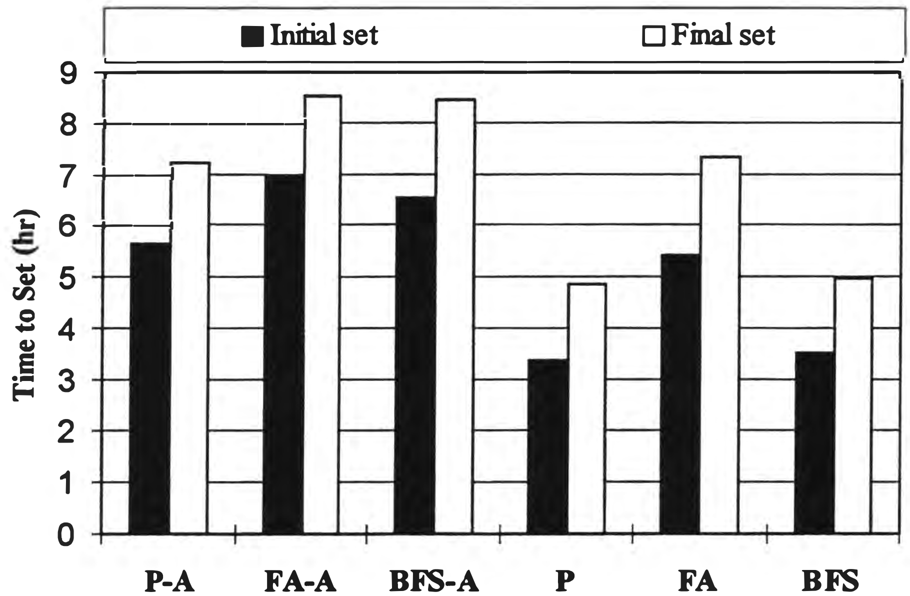


Fig. 4.43 Setting Times of Class A and Class AA Concrete

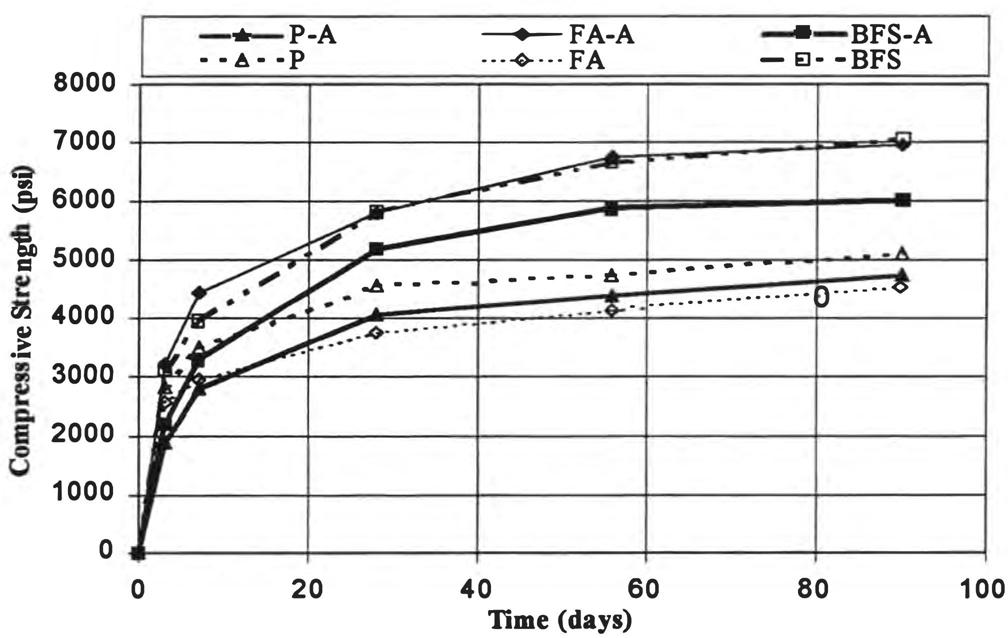


Fig. 4.44 Strength Gain Curves of Class A and AA Concrete

Comparing Class A mixtures, the average strength enhancement of the pozzolan mixtures compared to the control (P-A) at 28 days was about 50 percent for FA-A and 20 percent for BFS-A. At three and seven days, the pozzolan replacement mixtures performed well. Both exceeded the strength of the control mixture which contained no pozzolans. For the FA-A mixture, its three and seven days strength exceeded the control's corresponding strength by approximately 70 percent and 60 percent, respectively. The strength increase for the BFS-A mixture was in the range of 15 to 20 percent at three and seven days. As was also observed for Class AA mixtures, pozzolan mixtures had comparable or higher strengths than control mixtures at three and seven days age.

Comparing like mixtures between Class A and AA, the three day compressive strength of the Class AA control (P) was greater than that of the Class A control (P-A) by about 50 percent. At 28 days, P exceeded P-A by about 10 percent. Likewise, for the BFS replacement mixtures, strengths of Class AA (BFS) mixtures at 3 and 28 days were greater than those of corresponding Class A (BFS-A) mixtures by about 40 and 10 percent, respectively. On the contrary, the Class AA FA replacement mixture (FA) had less compressive strength than Class A (FA-A) by 20 percent at 3 days and 35 percent at 28 days.

When evaluating strengths between like mixtures of Class A and Class AA concretes, it must be realized that differences in air content affect strength comparisons. For like mixtures with the same air content, Class AA concretes are expected to exhibit higher strengths due to the larger cementitious materials content and lower water to cementitious materials ratio. For the mixtures depicted in Fig. 4.44, the control Class A and AA mixtures possessed air contents within 0.5 percent of one another and as expected the Class AA mixture was stronger (about 300 psi at 28 and 90 days). For BFS mixtures, the Class A mixture's air content was about 1.5 percent higher than that of the Class AA mixture, and the AA mixture's strength was about 1000 psi higher at 90 days.

On the other hand, the FA Class A mixture had an air content approximately 1.5 percent lower than the Class AA mixture, and the Class A concrete exceeded the Class AA mixture's strength by over 2500 psi at 28 days. A rule of thumb often used in strength comparisons is each 1 percent increase in air is accompanied by a strength decrease of 3 to 5 percent. Coupled with the fact that the Class A fly ash mixture had lower cementitious materials content and higher w/cm than Class AA a reversal in strength would not be expected to such a large degree. At this point it is an open question as to why the FA mixture performed so well with Class A concrete, when the opposite behavior was exhibited by Class AA concrete made using the same cement source (as well as with another cement source).

4.5.2.2 Modulus of Rupture. Figure 4.45 contains flexural strengths (28 days age) for Class A (dark bars) and Class AA (white bars) mixtures. The values presented are the average of four test specimens (two from each twin batch) except for Class A BFS replacement (BFS-A) and Class A control (P-A) mixtures which had only two specimens. The 25 percent BFS replacement Class A (BFS-A) mixture had the highest flexural strength, followed by the 15 percent FA replacement Class A (FA-A) mix with the second highest and the control (P-A) mix with the lowest flexural strength. The relationship between the two mixture classes was that Class A concrete generally exhibited less overall flexural strength than Class AA concrete as expected. Flexural strengths of FA mixtures were similar due to the unexplained better performance of FA in Class A as compared to Class AA.

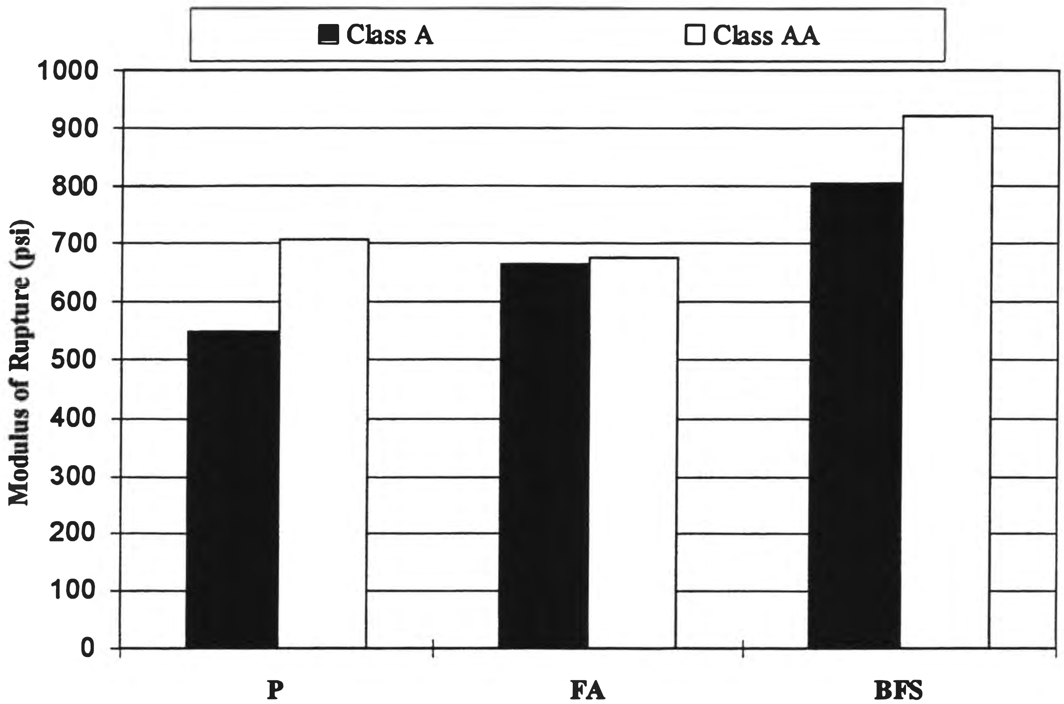


Fig. 4.45 Flexural Strength of Class A and Class AA Mixture

Examination of 90 percent confidence intervals indicated that flexural strengths of fly ash mixtures (both Class A and Class AA) and the Class AA control mixture were statistically similar. However, it should be realized that there were only two data values for Class A control and BFS mixtures which diminished the feasibility of using 90 percent confidence interval to examine scatter. The rest of the data were tight enough for their average values to be used for comparison. Although the data is limited, the Class A BFS mixture seems to have performed better than the Class A control.

Flexural strength is plotted versus the square root of compressive strength in Fig. 4.46. The solid line represents the AASHTO prediction equation, $f_r = 7.5 \sqrt{f_c}$ (psi). As can be seen in this figure, the prediction equation was conservative for the data obtained.

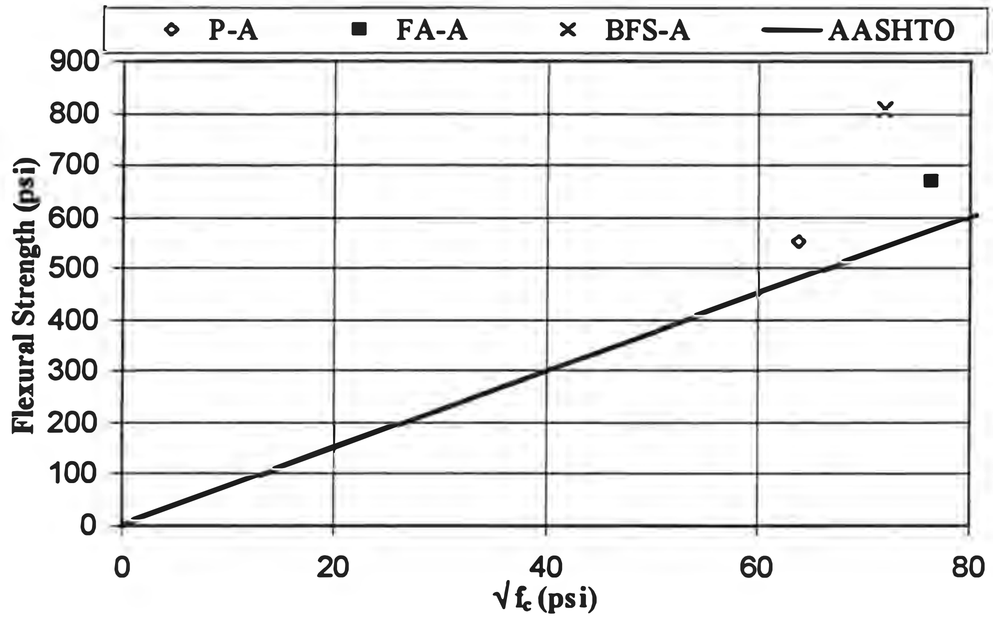


Fig. 4.46 Flexural Strength of Class A Concrete at 28 days

4.5.2.3 Splitting Tensile Strength. Figure 4.47 contains splitting tensile strengths (28 days age) for Class A and Class AA mixtures. The values presented are the averages of six cylinders (three from each twin batch) except for BFS Class A and P Class A which used the average of three cylinders. For Class A concrete, the averages infer that pozzolan replacement increased splitting tensile strength, with the BFS mixture producing the highest strength. Comparing between mixture classes, the control mixture in Class AA performed better than Class A as expected. The FA and BFS mixtures in Class AA (for the same cement source as Class A) did not perform as well as their corresponding mixtures in Class A. However, Class AA FA and BFS mixtures which used other cement sources had splitting tensile strengths more comparable to the Class A mixtures (see Table 4.8, section 4.2.2.3). The FA mixture in Class A performed better than Class AA in other areas as well (compressive and flexural strengths).

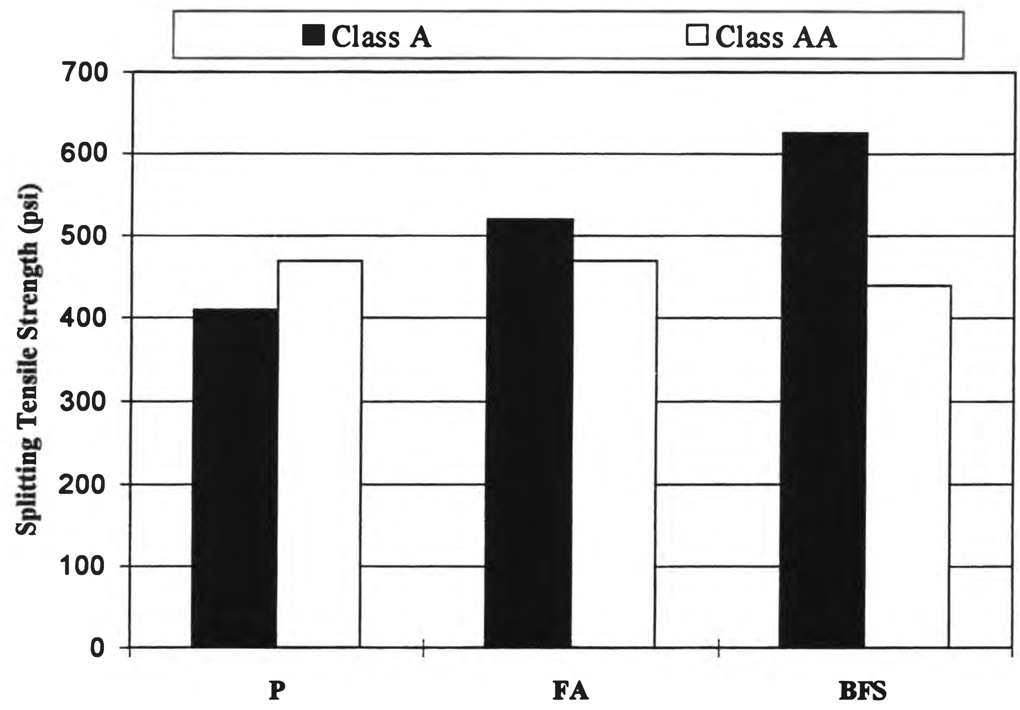


Fig. 4.47 Splitting Tensile Strength of Class A and AA Mixtures

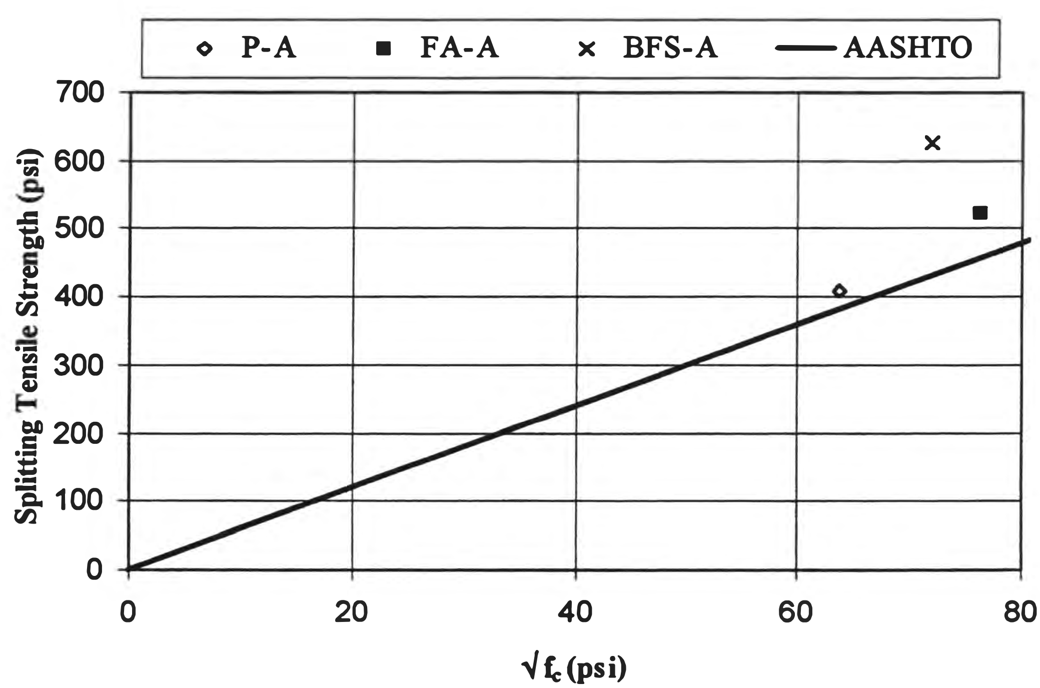


Fig. 4.48 Splitting Tensile Strength of Class A Concrete (28 days)

Splitting tensile strength is plotted versus the square root of compressive strength in Fig. 4.48. The solid line represents the standard prediction equation, $f_t = 6\sqrt{f_c}$ (psi). As was the case for Class AA concrete, the prediction equation produces a reasonable estimate for splitting tensile strength from compressive strength.

4.5.2.4 Modulus of Elasticity. Figure 4.49 contains the elastic modulus (28 days age) for Class A and Class AA mixtures. The values presented are the averages of six test specimens (three from each twin batch) except for Class A slag replacement and Class A control mixtures which had only three specimens.

The average modulus of elasticity (MOE) of all the Class A concrete mixtures were within the range of 5500 to 4900 ksi with the 15 percent FA replacement mixture having the highest MOE, the 25 percent BFS replacement mixture in between and the control mixture having the lowest MOE. However, the 90 percent confidence intervals overlapped between mixtures within Class A except for the control and FA mixture. In general, the pozzolan mixtures had similar or slightly higher MOE than the control mixture.

The average MOE from Fig. 4.49 infer that the Class AA mixture with BFS performed better than Class A, which is consistent with its higher compressive strength. The Class AA FA mixture's MOE was lower than that of the Class A mixture, which is also consistent with the higher compressive strength of FA in Class A. The control mixtures had similar MOE for the two classes of concrete.

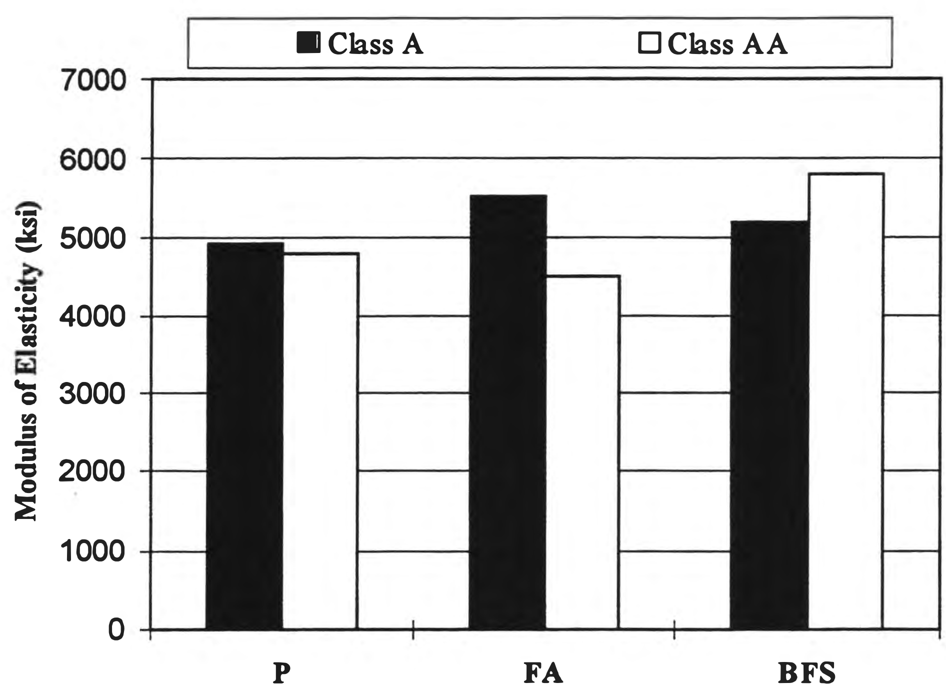


Fig. 4.49 Modulus of Elasticity of Class A and Class AA Mixtures

Figure 4.50 is a plot of modulus of elasticity versus the square root of compressive strength (both at twenty eight days). The solid line represents the standard prediction equation, $E_c = 57000\sqrt{f'_c}$ (psi). Again, as was the case for Class AA concrete, all points plotted above the prediction line; hence, the prediction equation is conservative for estimating modulus of elasticity.

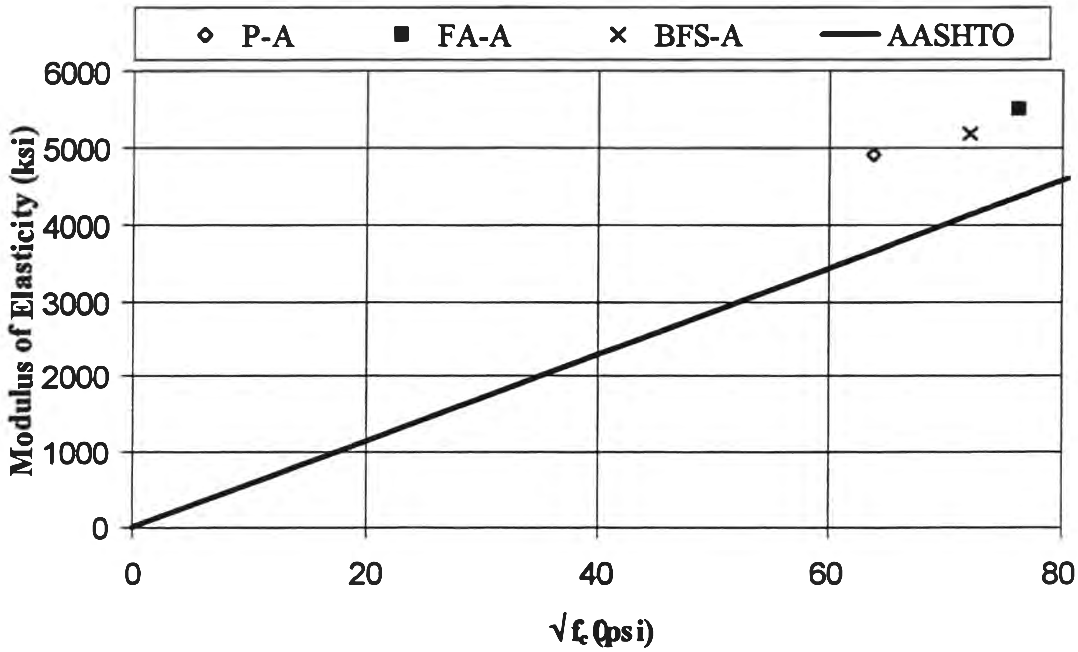


Fig. 4.50 Modulus of Elasticity of Class A Concrete at 28 days

4.5.2.5 Drying Shrinkage. Figure 4.51 is a plot of drying shrinkage for Class A and Class AA mixtures. The solid lines represent shrinkage for Class A mixtures while the broken lines are for Class AA. The values presented in the figure are averages from four test specimens (two for each twin batch) except for PC-A and BFS-A, which had two specimens each.

Within Class A, examination of the average shrinkage inferred that introduction of pozzolans slightly reduced drying shrinkage. However, the scatter and 90 percent confidence intervals of the data suggested that there was no statistical difference in shrinkage between Class A mixtures.

As expected from the fact that Class A mixtures had less paste (2.5 percent less), Class A concrete had slightly less drying shrinkage than Class AA concrete after twelve weeks. The only exception was the BFS mixtures which had basically identical shrinkage for both mixture classes. In general, most of the difference in shrinkage between Class A and AA mixtures occurred during the first 28 days as seen from the slope differences in Fig. 4.51.

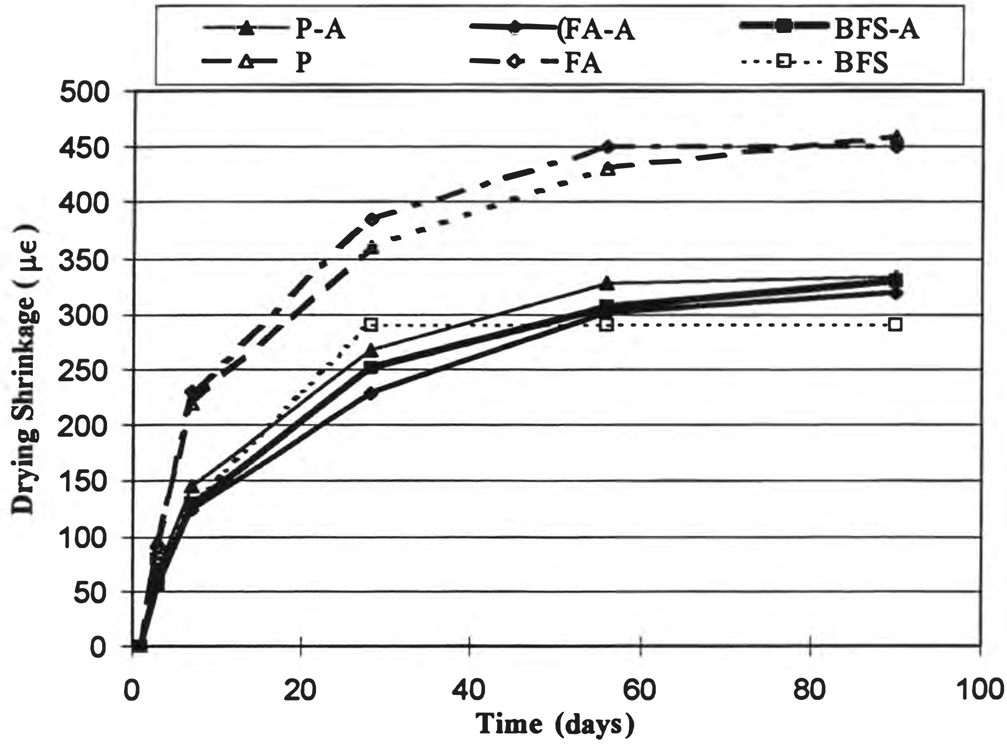


Fig. 4.51 Drying Shrinkage of Class A and Class AA Mixtures

4.5.2.6 Rapid Chloride Ion Penetrability. Figure 4.52 is a bar chart of rapid chloride ion penetrability for Class A and AA mixtures at 28 and 90 days.(Designations ending with "-A" represent Class A mixtures. The data is grouped by mixture class at each age; i.e., the first three bars are for Class A mixtures and the second group for Class AA mixtures (at 28 days). Similar data for 90 day results are presented in the right hand portion of the figure. The values presented in the chart are averages of four test specimens except FA-A which had eight specimens.

For Class A mixtures, large reductions in coulombs passed were observed at both 28 and 90 days for mixtures with pozzolans. At 28 days, BFS-A and FA-A were about 60 percent and 40 percent less penetrable, respectively, than the control (P-A). At 90 days, the penetrabilities of the same two mixtures were about 60 and 30 percent less than the control. As expected, penetrabilities at 90 days were lower than those at 28 days.

When comparing Class A mixtures vs. Class AA mixtures, differences were observed. Mixtures containing BFS passed similarly low values of charge at 28 and 90 days (both would classify as "moderate" at 28 days and "low" at 90 days). At 28 days, the test results indicated the control Class A mixture had considerably higher penetrability than the Class AA control (although both would classify as "high" by ASTM C 1202). By 90 days, these two mixtures had similar penetrabilities (each would classify as "moderate"). However, large differences were observed between the two fly ash mixtures, especially at 28 days. The Class A fly ash mixture passed about 1/3 less coulombs than the corresponding Class AA mixture (although both would classify as having "high" penetrability). This observation is consistent with their unexpected reversal in relative compressive strengths. By 90 days age, the differences between the two mixtures was less pronounced, although the unexpected trend was still present. At 90 days age, both fly ash mixtures would classify as having "moderate" penetrability.

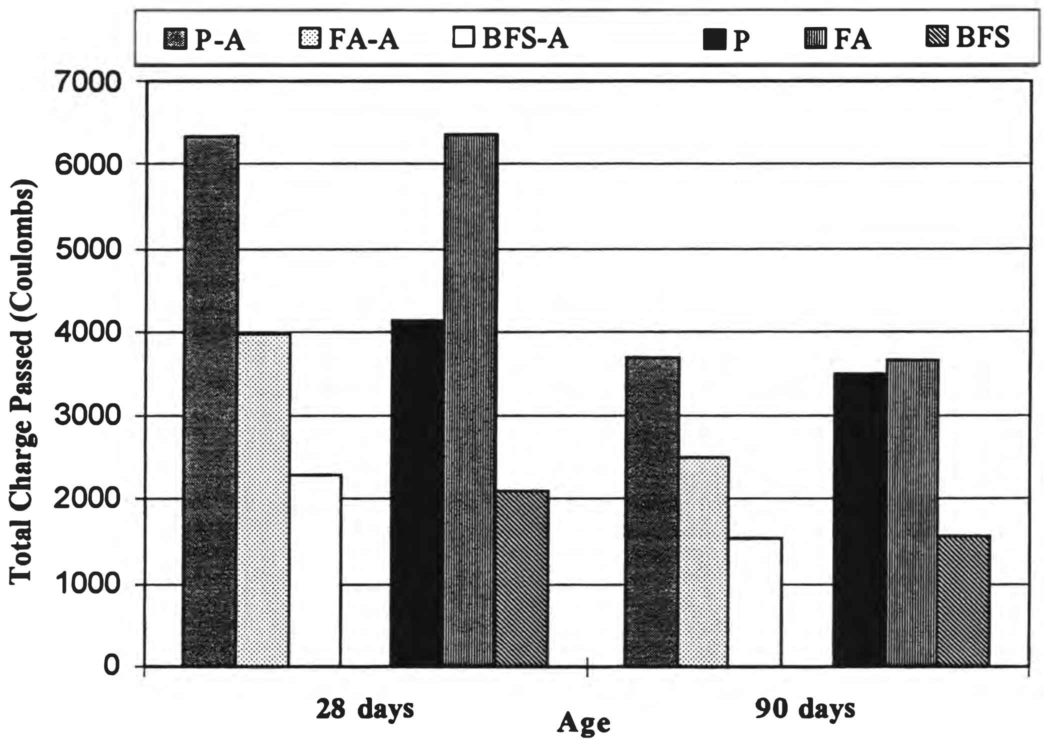


Fig. 4.52 Rapid Chloride Ion Penetrability of Class A and Class AA Mixtures

4.6 USE OF HIGH RANGE WATER REDUCER

This study examined the effects of using a high range water reducer (HRWR) on Class AA concrete with pozzolan replacement. The HRWR was used in two ways: 1) to increase the workability of mixtures with otherwise unchanged mixture proportions, 2) to produce mixtures with workability similar to those without HRWR but with lower w/cm. For the first goal, HRWR dosages were determined to increase the slump of Class AA mixtures to approximately six inches. For the second goal, concretes were produced with w/cm reduced by 0.03 (as compared to normal Class AA mixtures) but with slumps in the 1 to 3 in. range. Comparisons were made between the HRWR mixtures and with Class AA mixtures without HRWR that contained the same cement (Ash Grove). Only two types of mixtures were studied: 1) 15 percent Class C fly ash replacement and 2) 25 percent slag replacement. Designations used for mixtures with the first (higher slump) goal contain the suffix "-H" (FA-H and BFS-H). Mixtures with the second (reduced w/cm) goal have designations with the suffix "-R" (FA-R(and BFS-R). Class AA mixtures without HRWR are designated FA and BFS as before.

4.6.1 Fresh Properties

The effects of HRWR on the slump, slump loss, air content, unit weight, and time to set of Class AA concrete were examined. Table 4.30 contains the amounts of chemical admixtures used and the average fresh concrete properties of Class AA mixtures containing HRWR.

Table 4.30 Average Fresh Properties of Class AA Concrete with HRWR

Mixture	FA-H Higher Slump	FA-R Reduced w/cm	BFS-H Higher Slump	BFS-R Reduced w/cm
w/cm	0.37	0.34	0.39	0.36
HRWR (fl.oz./cwt)	3.5	5	4	5
Slump	5.9	2.7	6.2	2.25
AEA (fl.oz./cwt)	1	2	1	2
Air Content (%)	5.9	5.7	5.6	5.3
Unit Weight (lb/ft^3)	146.0	146.6	146.4	148.3
Initial Set (hr)	5.5	5.5	5.1	5.0
Final Set (hr)	6.9	7.0	6.6	6.5
Concrete Temp.(°F)	74	7.0	71	70

4.6.1.1 Slump and Slump Loss. Approximately 4 fl.oz./cwt of HRWR was required to increase slump from the usual 1 to 3 inch range to about 6 inches. About 5 fl. oz./cwt of HRWR was required to produce similar slump as previous mixtures without HRWR while reducing the water to cementitious material ratio by 0.03. All in all, the average slumps between higher slump mixtures FA-H and BFS-H were similar and close to the target slump of six inches. In this case, it should be realized that the amount of HRWR used to produce the corresponding slump was different for the two mixtures (0.5 fl. oz./cwt less for the mixture with FA). On the other hand, the average slump of BFS-R was 15 percent less than that of FA-R even though both mixtures used the same amount of HRWR. Thus, the observation that FA decreased the amount of HRWR required to obtain the same slump, or increased the slump with the same HRWR quantity, conformed with previous observations where FA improved workability of concrete.

Figure 4.53 contains slump loss of mixtures with and without HRWR. Little difference in the rate of slump loss was observed between the reduced w/cm HRWR mixtures and the non-HRWR mixtures. Both types of mixtures lost about 2 in. of slump in the first hour.

The rate of early slump loss of high slump mixtures with HRWR was faster than for the reduced w/cm HRWR mixtures and the non-HRWR mixtures. For mixtures with initial slump of about six inches, the slump decreased to approximately three inches within 15 minutes. Once slump decreased to about two inches, rates of slump loss between the two types of HRWR mixtures became similar to each other (and to that of the non-HRWR mixtures). Between the fly ash and slag mixtures, there were little differences in the rate of slump loss.

The above observations imply that high slump mixtures will require earlier HRWR redosage in order to take advantage of the increased short term workability. It should also be noted that rate of slump loss in the field would be influenced by a number of factors, namely, temperature, wind, and relative humidity.

4.6.1.2 Air Content. Total air contents for all batches ranged from 5.0 to 6.2 percent. The amount of air entraining agent (AEA) used for the FA and BFS mixtures with HRWR were the same for each slump class. The AEA dosage was 1 fl. oz./cwt for the increased slump HRWR mixtures and 2 fl. oz./cwt for the HRWR mixtures with about 2.5 in. slump but reduced w/cm. This inferred that higher workability facilitates better air entraining ability.

As compared to the same mixtures without HRWR, the amount of AEA used for the HRWR mixtures was significantly less (HRWR mixtures used 1 to 2 fl. oz./cwt of AEA while non-HRWR mixtures used about 14 fl.oz./cwt). Thus, HRWR mixtures had considerably better air entraining ability than mixtures without HRWR.

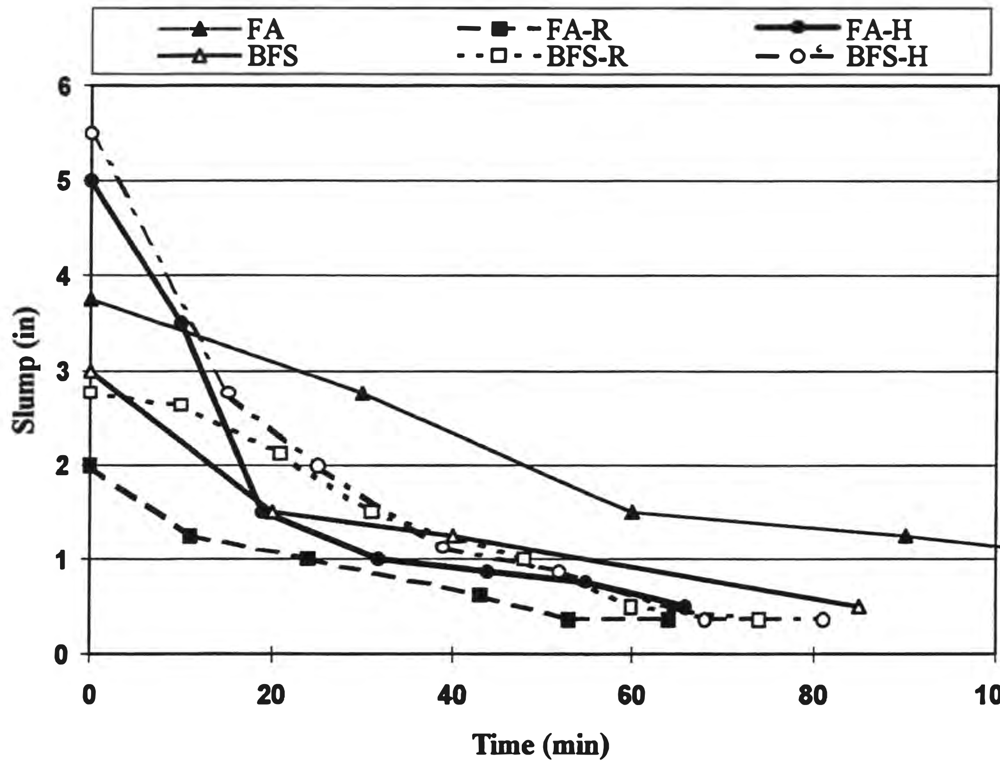


Fig. 4.53 Slump Loss of Class AA Concrete With and Without HRWR

4.6.1.3 Unit Weight. Average unit weights of the HRWR batches ranged from 146.0 to 148.3 lb/ft^3. No conclusive trends regarding unit weights were observed other than unit weights tended to vary inversely with total air content.

4.6.1.4 Time to Set. Figure 4.54 contains setting times for Class AA mixtures with and without HRWR. Only the fly ash replacement and slag replacement mixtures are presented and compared. The dark bars represent results from standard mixtures without HRWR. The empty bars represent the HRWR mixtures with normal slumps and reduced w/cm (R) and the lighter bars represent HRWR mixtures with 6 in. slump (H). The first two groups of bars represent results for fly ash mixtures.

Time to set of the Class AA mixtures with HRWR ranged from 5.0 to 5.5 hours for initial set and from 6.5 to 7.0 hours for final set. Considering only mixtures containing HRWR (first two bars in each group of Fig. 4.54), setting times were virtually identical (for like mixtures) regardless of the initial goal for using HRWR. This is consistent with the fact that very similar HRWR dosages were used in both cases. Furthermore, fly ash mixtures containing HRWR had setting times very close to those of fly ash mixtures without HRWR. On the other hand, initial and final set of BFS mixtures were retarded approximately 1.5 hours with the addition of HRWR.

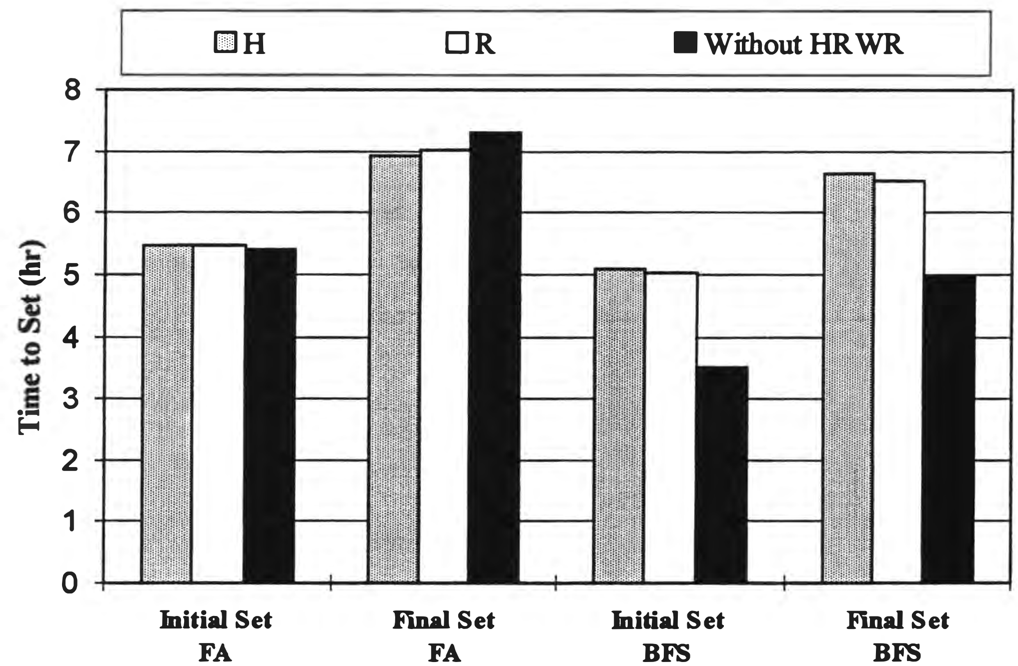


Fig. 4.54 Time to Set for Class AA Mixtures With and Without HRWR

4.6.2 Hardened Properties

4.6.2.1 Compressive Strength. Figure 4.55 is a plot of compressive strength gain over time through 28 days age. The solid lines represent mixtures with 15 percent fly ash replacement while the broken lines represent mixtures with 25 percent slag replacement. Designations ending with H represent HRWR mixtures with 6 in. slump while designations ending with R depict HRWR mixtures with 2.5 in slump but reduced w/cm. Results presented are averages of typically six test specimens, three specimens from each twin batch.

Considering BFS mixtures, introduction of HRWR resulted in enhanced compressive strengths (as compared to the BFS mixture with no HRWR) at seven days age and beyond. This observation was also confirmed through examination of 90 percent confidence intervals. Furthermore, the reduced w/cm HRWR mixture had slightly higher strengths than the high slump HRWR mixture (BFS-H).

For fly ash concrete, the HRWR mixtures also had considerably higher compressive strengths than the FA mixture without HRWR. However, the very large differences in strength between FA

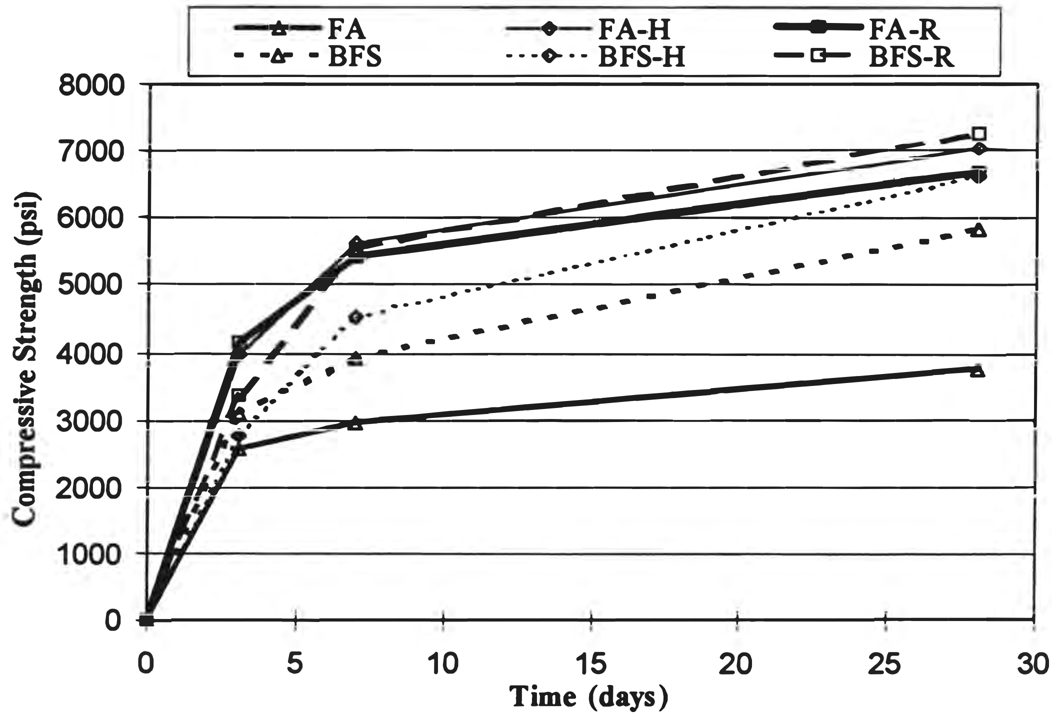


Fig. 4.55 Strength Gain of Class AA Concrete With and Without HRWR

mixtures with and without HRWR are likely not solely attributable to the addition of HRWR. The standard FA mixture results presented in the figure are from mixtures made in the Cement Study, where introduction of FA tended to reduce compressive strengths. However, other portions of the research (for example, the Class A Study) produced results contrary to that trend. The variability in observed FA mixture results casts doubt as to the degree of improvement caused by addition of HRWR, although it is reasonable that some strength enhancement should occur.

Therefore, the general conclusions that can be drawn are that HRWR introduction tended to enhance compressive strength. This is generally recognized to be caused by the improved dispersion of cementitious material particles in the fresh concrete, allowing better access to water for hydration. Also, reduction in w/cm tended to improve compressive strength, as expected.

4.6.2.2 Modulus of Rupture. Figure 4.56 contains 28 day flexural strengths of Class AA mixtures with and without HRWR. The dark bars represent mixtures with FA and the empty bars represent mixtures with BFS. A total of two test specimens (one from each twin batch) were used to test MOR for HRWR mixtures; four specimens each were used for mixtures without HRWR.

For BFS mixtures (open bars), addition of HRWR tended to slightly increase flexural strength as compared to the standard BFS mixture; however, data was insufficient to confirm this statistically.

As before, observations concerning FA mixtures with HRWR are inconclusive due to variability observed in these mixtures.

The average 28 day modulus of rupture of the various mixtures was plotted against the square root of the compressive strength as shown in Fig. 4.57. As can be seen in the figure, the AASHTO equation $f_r = 7.5\sqrt{f_c}$ (psi) produced conservative estimates of the modulus of rupture.

4.6.2.3 Splitting Tensile Strength. A chart of the splitting tensile strength for the Class AA mixtures with and without HRWR is shown in Figure 4.58. The dark bars represent mixtures with fly ash while the empty bars represent mixtures with blast furnace slag.

The FA-H mixture had splitting tensile strengths ranging from 610 to 790 psi while the FA-R mixture's splitting tensile strengths ranged from 660 to 725 psi. The range of splitting tensile strengths was 540 to 710 psi for BFS-H and 695 to 800 psi for BFS-R. All mixtures with HRWR had higher splitting tensile strengths than their corresponding mixtures without HRWR. For mixtures with BFS, their averages in splitting tensile strength of Fig. 4.58 indicated that HRWR improved the tensile strength, and the reduced w/cm further increased the strength. These observations were supported by their 90 percent confidence intervals as no overlapping occurred. For mixtures with FA, the 90 percent confidence intervals of FA-H and FA-R overlapped, inferring that there was no statistical difference between them. Comparisons between FA mixtures with HRWR and FA mixtures without HRWR were inconclusive due to variabilities mentioned earlier. Note that the general trend of splitting tensile strength was consistent with that of flexural strength.

Figure 4.59 is a plot of 28 day splitting tensile strength versus square root of the compressive strength. All the splitting tensile strengths plotted above the prediction equation, $f_t = 6\sqrt{f_c}$ (psi). Thus, the prediction equation was conservative as compared to the splitting tensile strength data.

4.6.2.4 Modulus of Elasticity. Figure 4.60 contains modulus of elasticity for the Class AA mixtures with and without HRWR. The dark bars represent mixtures with Class C fly ash while the empty bars represent mixtures with blast furnace slag. Six test specimens (three specimens per twin batch) were used for each series of MOE tests.

For the slag mixtures, BFS (no HRWR) and BFS-H had similar modulus of elasticity (90 percent confidence intervals overlapped), but BFS-R had MOE slightly higher (approximately 10 percent more, with no overlapping of 90 percent confidence intervals) than the other two as expected. For the FA mixtures, there was no statistical difference between the two HRWR mixtures, regardless of w/cm. Due to variabilities seen throughout this research, it is inconclusive as to whether improved strength resulting from addition of HRWR increased the modulus of elasticity of FA mixtures.

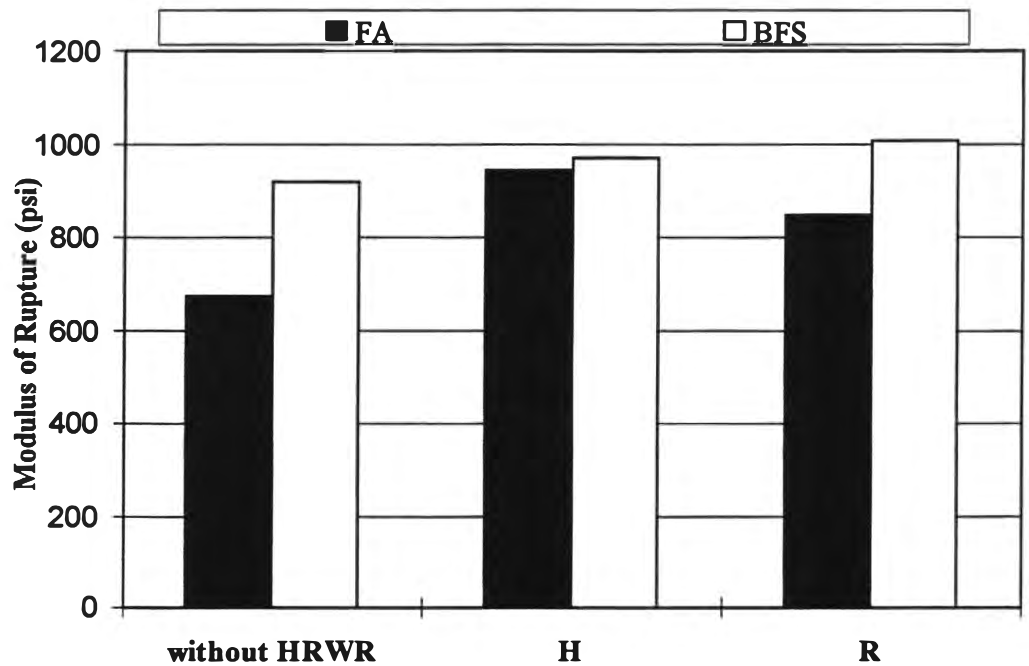


Fig. 4.56 Flexural Strength of Class AA Concrete With and Without HRWR

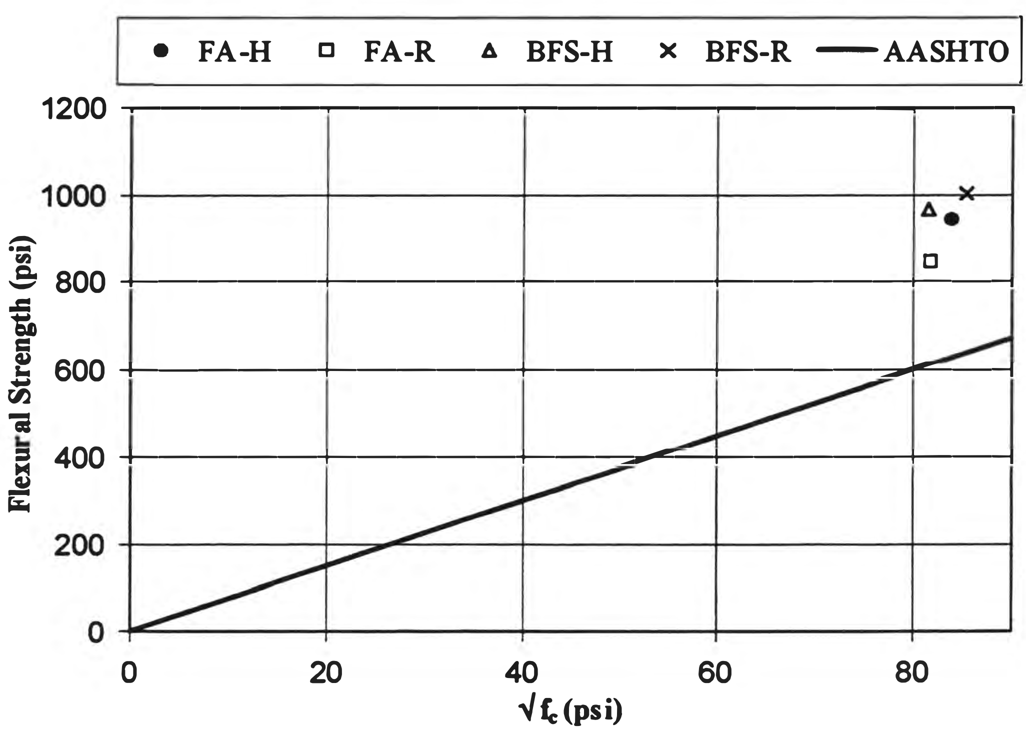


Fig. 4.57 28 Day Flexural Strength of Class AA Concrete with HRWR

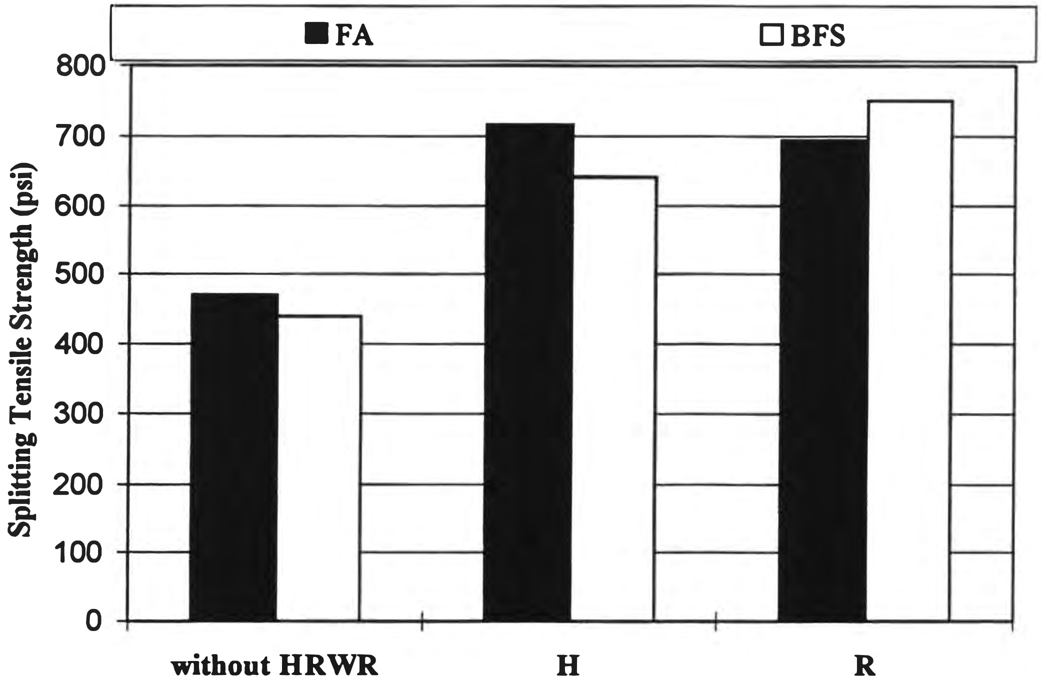


Fig. 4.58 Splitting Tensile Strength of Class AA Concrete With and Without HRWR

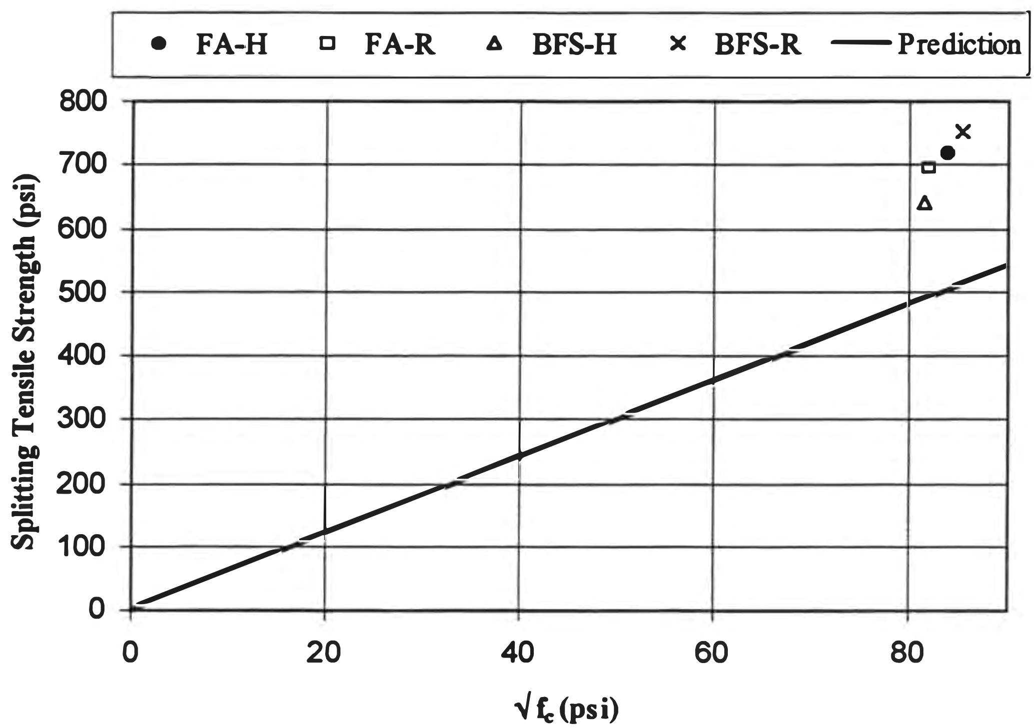


Fig. 4.59 28 Day Splitting Tensile Strength of Class AA Concrete With HRWR

Figure 4.61is a plot of 28 day modulus of elasticity versus square root of compressive strength. The modulus of elasticity of all mixtures plotted above the AASHTO prediction equation, $E_c = 57000\sqrt{f'_c}$ (psi), inferring that the equation was conservative.

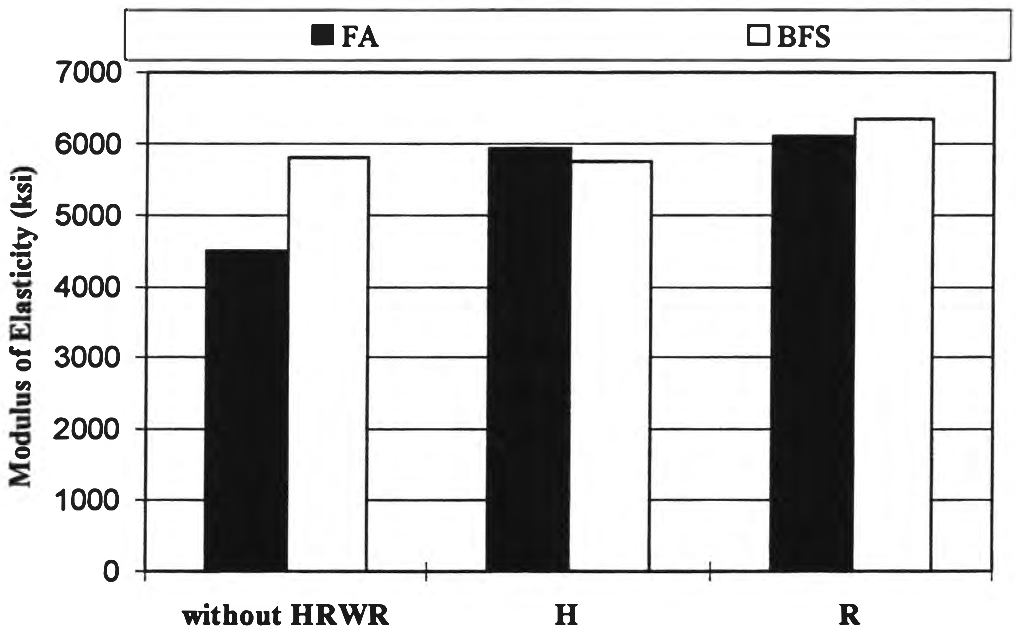


Fig. 4.60 Modulus of Elasticity of Class AA Concrete With and Without HRWR

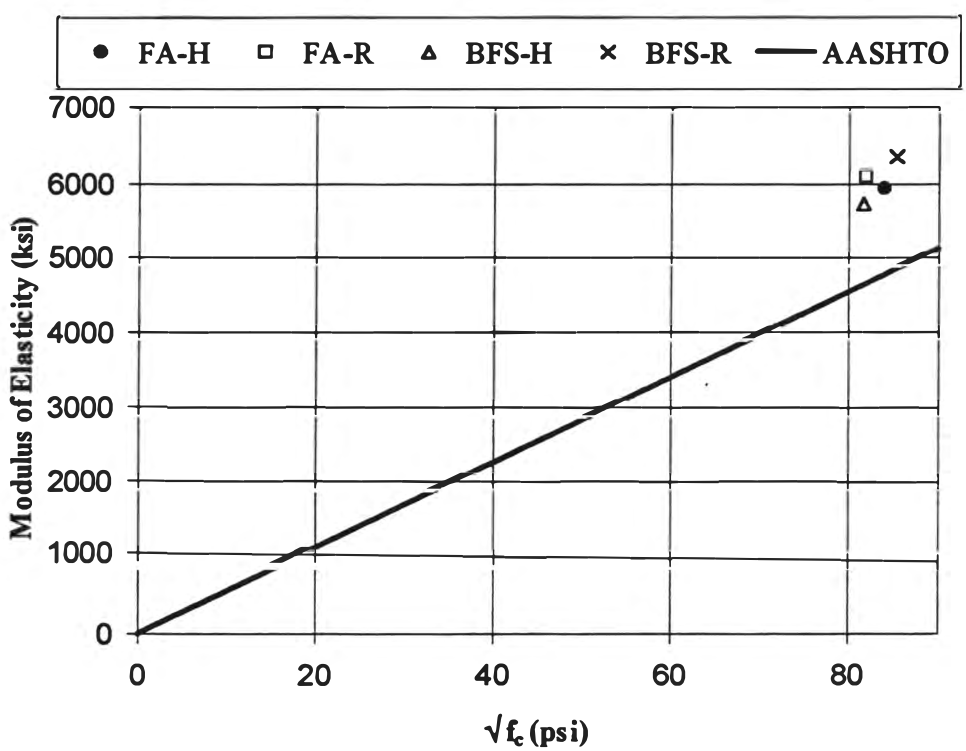


Fig. 4.61 28 Day Modulus of Elasticity of Class AA Concrete with HRWR

4.6.2.5 Drying Shrinkage. Figure 4.62 is a plot of the drying shrinkage over time for Class AA mixtures with and without HRWR. The solid lines represent fly ash mixtures and the broken lines represent blast furnace slag mixtures.

The drying shrinkage was similar regardless of w/cm within the same mixtures with HRWR. It should be noted that the reduction in w/cm by 0.03 did not result in a large change in the amount of paste. Shrinkage values were within about 100 microstrains of one another for all mixtures. Although addition of HRWR tended to slightly reduce shrinkage, the performance of all mixtures could be considered similar.

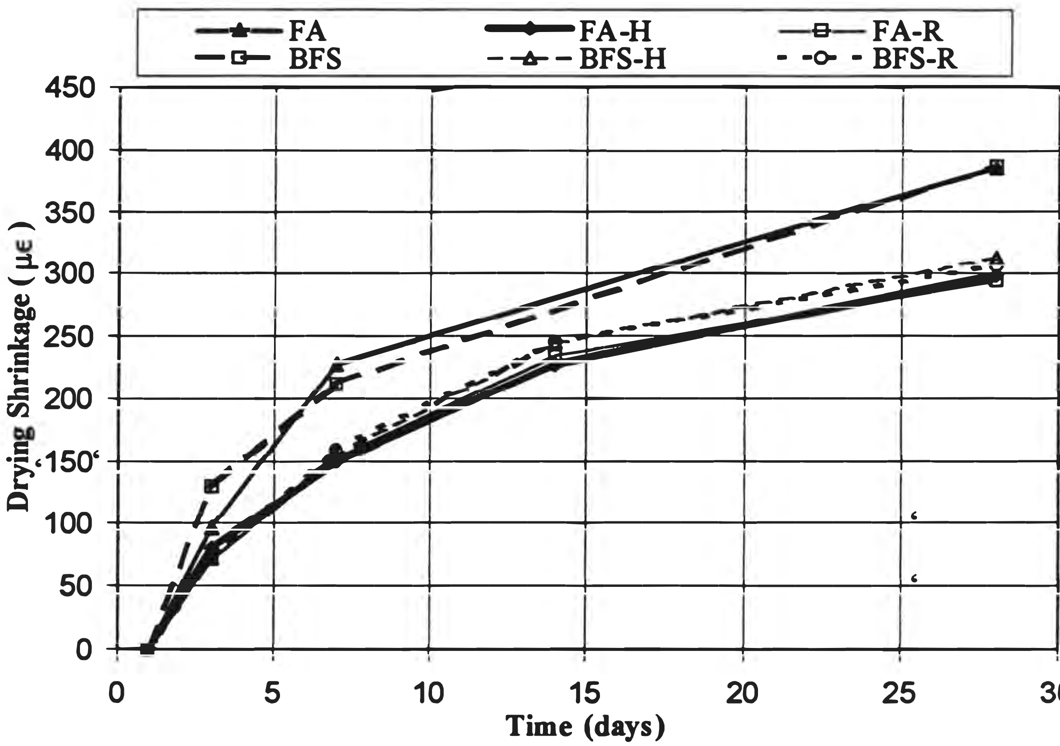


Fig. 4.62 Drying Shrinkage of Class AA Concrete With and Without HRWR

4.6.2.6 Rapid Chloride Ion Penetrability. Figure 4.63 contains the rapid chloride ion penetrability (total charge passed) of Class AA concrete with and without HRWR. The dark bars represent mixtures with fly ash while the empty bars represent mixtures with blast furnace slag. Four test specimens (two from each twin batch) was used in each RCIP test.

Considering BFS mixtures, the total charge passed was similar for mixtures with and without HRWR. These mixtures would classify as having moderate to low penetrability according to ASTM C 1202(.

FA mixtures with HRWR had penetrabilities similar to each other (both would classify as "moderate") and lower than the penetrability of the non-HRWR fly ash mixture. It is inconclusive as to the effect of including HRWR with FA mixtures, owing to the large differences in compressive strength between the mixtures with and without HRWR.

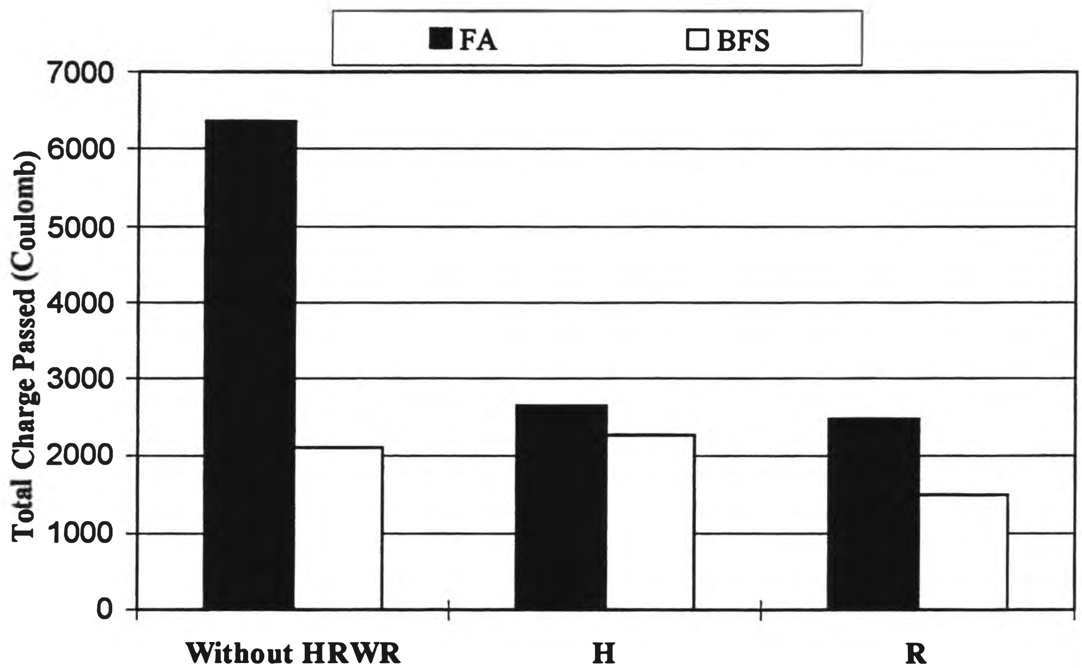


Fig. 4.63 28 day RCIP of Class AA Mixtures With and Without HRWR

4.7 USE OF SILANE

This section deals with the effect of silane treatment on permeability of concrete containing blast furnace slag. The salt ponding test was conducted for this study. The RCIP test was not performed because it includes a vacuum saturation step. Silane sealers cannot withstand a large hydrostatic head, so the RCIP test may produce questionable results. Two mixtures (BFS and P) were treated with silane on the top specimen surfaces at the age of 21 days. The amount of silane used (162.5 ft^2/gal) complied with manufacturer's recommendation. Other procedures remained the same as for the regular salt ponding test. Each mixture had three treated specimens (ponded) and a control (unponded) specimen. Within each specimen, six samples (three from the upper half inch and three from the next half inch) were collected from three holes. Mixture designations ending with the suffix "-T" indicate specimens treated with silane.

Fresh properties of the mixtures can be seen in Table 4.31. Basically, the slumps of the mixtures were the same and the air contents were within 1.5 percent of one another. These specimens were from the same batches as salt ponding specimens from the Pozzolan Replacement Fractions Study (section 4.3).

Table 4.31 Fresh Properties of Class AA Mixtures for Silane Study

Mixture	Air Content (%)	Slump (in.)
P and P-T	7.0	1
BFS and BFS-T	5.7	1

Figure 4.64 contains the average absorbed chlorides in the upper half inch of P and BFS mixtures (treated and untreated). Also shown are their 90 percent confidence intervals. Figure 4.65 contains corresponding values at the next half inch depth of the specimens. Note that the scales of the two figures are different.

At the upper half inch, treated and untreated specimens produced absorbed chlorides that were statistically different from each other. As expected, silane treatment drastically reduced the absorbed chlorides. For both P-T and BFS-T, absorbed chlorides were reduced to about ten percent of their corresponding untreated specimens. For untreated specimens, introduction of 25 percent blast furnace slag resulted in a 50 percent decrease in absorbed chlorides as compared to the control (P) mixture. However, for treated specimens the control and slag concretes had statistically similar absorbed chlorides in the upper half inch. This implied that the pozzolan played a secondary role to the silane in reducing chloride ion absorption of treated concrete.

For the lower half inch, the average absorbed chlorides of the treated specimens were less than those of untreated specimens of the same mixture; however, no statistical difference (90 percent C.I.'s overlapped) in absorbed chlorides was detected between treated mixtures.

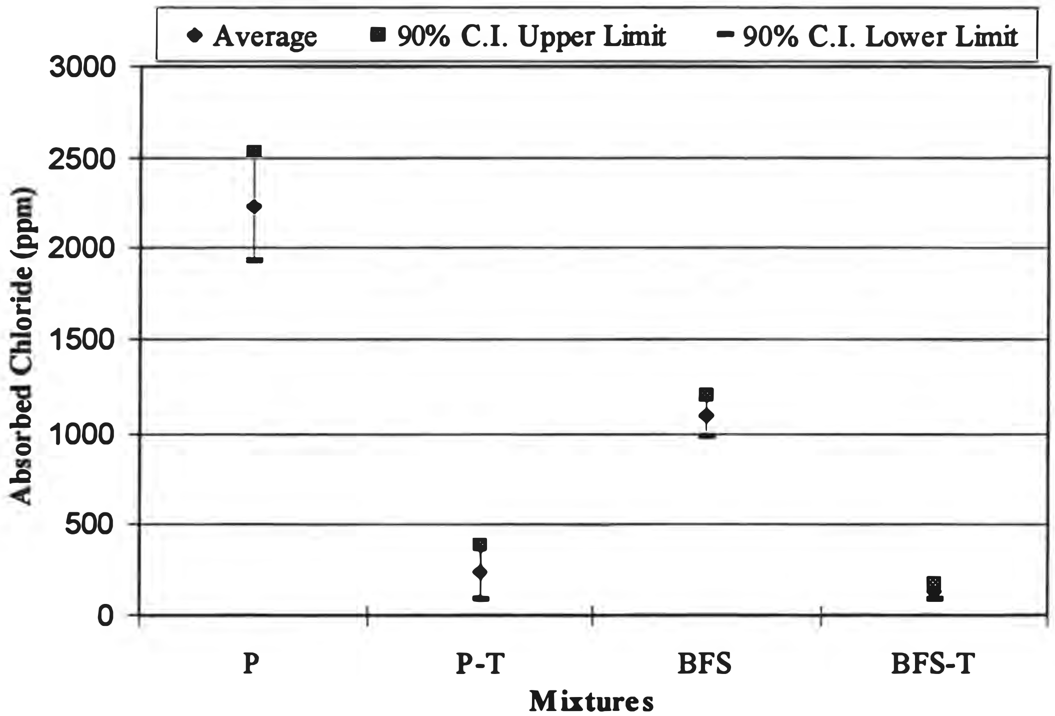


Fig. 4.64 Absorbed Chlorides in the Upper Half Inch, Silane Study

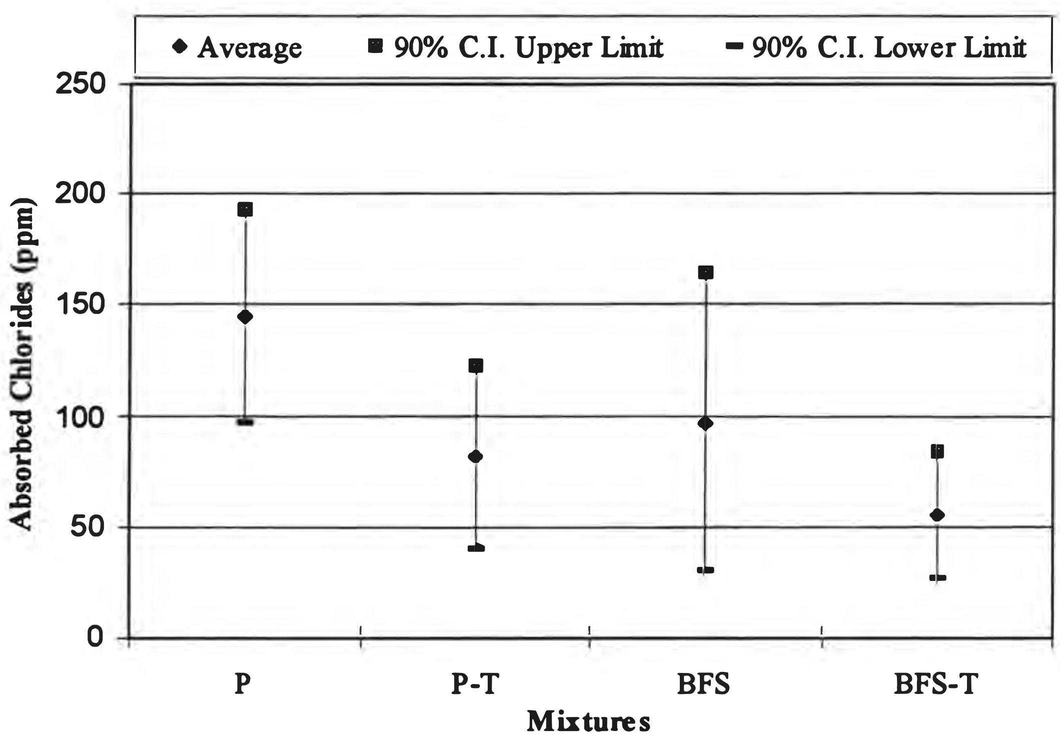


Fig. 4.65 Absorbed Chlorides in the Lower Half Inch, Silane Study

Silane penetration depth measured at the conclusion of the salt ponding tests indicated no difference between control mixtures and mixtures containing blast furnace slag.. The average penetration was 0.10 in. for both mixtures (average of 40 measurements taken at random locations on each broken and wetted specimen). It should be noted that the ad-hoc penetration measurements were conducted on specimens treated at their natural moisture content (similar for both). Silane penetration depth is known to be inversely related to the substrate moisture content at time of treatment.

4.8'SUMMARY

The data generated in this study verifies that performance of Oklahoma concretes can indeed be improved through the use of pozzolans, especially ground granulated blast furnace slag. The maximum blast furnace slag replacement rate used for the majority of tests in this research was 25 percent (as compared to much higher limits examined in the literature, and 40 to 50 percent replacement rates used in several field applications). Blast furnace slag replacement was found to cause slight reductions in workability and air entrainment. Examining hardened concrete properties as compared to those of ordinary portland cement concrete (no pozzolans), at this replacement rate mixtures containing Grade 120 blast furnace slag possessed higher compressive, flexural, and tensile strengths, lower permeability (greatly reduced RCIP values and chloride ion absorption in the upper half inch depth), less creep, and higher or similar elastic modulus. Setting times, freeze thaw resistance, shrinkage, and chloride ion absorption when treated by silane, were found similar for concrete with blast furnace slag and ordinary portland cement concrete. The overall consistency and rationality of data trends for blast furnace slag concretes lend further confidence in the ability of blast furnace slag to improve concrete performance.

On the other hand, performance of concretes containing Class C fly ash was found to be variable. In particular, strengths (compressive, flexural, and tensile) were sometimes increased, and sometimes decreased with the introduction of fly ash. Permeability of fly ash concrete, as compared to ordinary portland cement concrete, was usually found to be similar or slightly higher (but not in all cases). It is not appropriate to interpret these observations as a generalization that concrete containing Class C fly ash is inferior to ordinary portland cement concrete. Instead, the data raises questions as to causes for the observations. Possible factors could range from variability in the fly ash material itself, to problems in the way the fly ash was sampled, stored or handled, to operator error in batching, mixing, and/or testing. However, the consistent nature of the blast furnace slag data makes operator error seem unlikely to be a major factor.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 OVERVIEW

A laboratory testing program was undertaken to evaluate the performance of Class AA and Class A concretes utilizing partial replacement of portland cement (PC) with ground granulated blast furnace slag (BFS) and/or Class C fly ash (FA). Several studies were conducted to examine performance aspects related to constituent materials (types and amounts used) as well as to construction/field issues. Conclusions and recommendations drawn from these studies are presented below.

The pozzolan replacement rates listed are in the context of specifications that were in effect when the research was initiated (and presented in Chapter 3). Blast furnace slag was used to replace portland cement on a 1:1 basis by weight. However, per the specification, Class C fly ash replaced portland cement at a 1.35:1 ratio, i.e., 1.35 lb. of fly ash replaced 1.0 lb. of portland cement. Therefore, a "15 percent fly ash replacement rate" is very similar to replacing 20 percent (on a direct weight basis) of the cement with fly ash.

5.2 CONCLUSIONS

5.2.1 Interaction of FA and BFS with Type I Cements

Three Type I cements were evaluated in Class AA concrete to determine their interaction with Grade 120 BFS and Class C FA. For each cement, mixtures included a PC control, 15 percent FA replacement, 25 percent BFS replacement, and the combination of 15 percent FA plus 25 percent BFS. The following observations were made:

1. Introduction of 15 percent FA generally led to slightly increased slumps and higher air contents (for the same AEA dosage) as compared to PC control mixtures. Introduction of 25 percent BFS caused moderate slump reduction and slightly lower air contents (for the same AEA dosage).
2. As a group, setting times for mixtures <u>containing</u> one cement were slightly shorter than for the other two cements. For all cements tested, mixtures with 25 percent BFS replacement had

similar setting times to those of their corresponding PC control mixtures. Fly ash and combination mixtures exhibited slightly increased (by 1 to 3 hr.) setting times.

3. With regard to compressive strength, Type I cements generally interacted similarly with BFS and/or Class C FA in concrete mixtures, although some differences were observed. As compared to PC mixtures, all cements achieved strength increases when combined with 25 percent BFS; BFS mixtures with one cement possessed 90 day compressive strengths 1000 psi higher than for mixtures with the other two cements. A different cement achieved a 25 percent strength increase when using the 15 percent Class C FA replacement rate, whereas the other two other cements had strength decreases up to 15 percent.
4. Using a 25 percent replacement rate of BFS, compressive strengths were increased approximately 25 percent at 28 and 90 days as compared to control PC mixtures. Significantly, permeabilities as measured by the Rapid Chloride Ion Penetration (RCIP) test were reduced by half.
5. On average for the three cements tested, using a 15 percent replacement rate of Class C FA tended to slightly reduce compressive strengths as compared to control PC mixtures. Rapid chloride ion penetrabilities were up to double those of control mixtures without FA.
6. As compared to control PC mixtures, using a replacement rate of 25 percent blast furnace slag *combined* with 15 percent Class C fly ash resulted in similar compressive strengths at 7 days age, and higher compressive strengths at 28 days and beyond for the three cements tested. RCIP tests also indicated similar or better performance as compared to control PC mixtures.
7. Shrinkage was fairly similar for all mixtures, irrespective of cement source and pozzolan replacement.
8. For all cements, flexural and splitting tensile strengths tended to be highest for mixtures with 25 percent BFS.

5.2.2 Pozzolan Replacement Fractions

Additional tests were conducted on Class AA mixtures containing the same cement and aggregates, with only the pozzolan replacement varying. Mixtures included a PC control, 15 percent FA replacement, 25 percent BFS replacement, and the combination of 15 percent FA plus 25 percent BFS.

1. Mixtures containing BFS and/or FA exhibited substantially less creep than the PC control. Creep deformations of the pozzolan mixtures were only 40 to 50 percent of those experienced

by the control PC mixture. While creep of all pozzolan mixtures could be considered similar, the BFS mixture exhibited slightly less creep than the FA mixture.

2. All mixtures exhibited similar (very good) freeze thaw performance at the air contents tested (approximately 5.5 to 7 percent). At the end of 300 cycles, all durability factors were larger than 94 percent, and the largest weight loss exhibited by any mixture was only 2.2 percent.

3. Absorbed chlorides in the upper half inch (90 day salt ponding test) were about 50 percent lower for the 25 percent BFS replacement mixture than for the other three mixtures (which behaved similarly). Absorbed chlorides were similar and very low for all mixtures at the second depth. Average absorbed chlorides in the upper half inch were found to correlate well with average 90 day RCIP results.

5.2.3 Mixing/Curing Temperature

Tests were conducted to assess the potential effects of cold and hot weather batching and curing on concretes containing pozzolans. All mixtures contained the same cement and aggregates. A PC control and the aforementioned pozzolan replacement rates were used; also, a mixture containing 50 percent BFS replacement was included for the hot and standard temperature regimes.

1. At the high temperature (90 F), all mixtures had similar (lower) slumps within the range of 0.5 to 1 inches. Slumps at standard (73 F) and low (50 F) temperatures ranged from 1 to 3 inches. Substantially higher AEA dosages were required to achieve target air contents at the high temperature, particularly for BFS mixtures. Increased AEA dosages were also required for the cold weather mixtures.

2. Time to setting of 25 and 50 percent BFS, and PC control, mixtures were generally similar to each other, and less than those of mixtures containing FA. Setting times of all mixtures were increased as the fresh concrete temperature decreased. Cold weather mixtures had setting times about double those of standard temperature mixtures.

3. As expected, compressive strengths were reduced for the low curing temperature (50 F) and increased for the high (83 F) curing temperature for all mixtures. As a percentage of strength at standard curing, the PC mixture received the largest benefit from elevated temperature curing. For all curing regimes, mixtures containing 25 (or 50) percent BFS had the highest strengths; by 3 days age these mixtures had comparable or higher strengths than the PC control for all temperatures. BFS mixtures had 10 to 20 percent higher strength than the PC control for 83 F curing, and 30 to 40 percent higher strength for 50 and 73 F curing. Mixtures with 15 percent FA had the least strengths for all temperatures.

4. Permeabilities, as indicated by the RCIP test, were reduced with increasing curing temperature. Mixtures containing either 25 or 50 percent BFS had the least total coulombs passed for all temperatures, and were least affected by differences in curing temperature.

5.2.4 Class A Concrete

Class A concretes used the same pozzolan replacement rates listed previously, except that the combination mixture (15 percent FA plus 25 percent BFS) was not tested.

1. Class A mixtures had more free mixing water available than Class AA mixtures, resulting in larger slumps on average (about 2 ½ in. for all mixtures). For these larger slumps, pozzolan addition had little effect on workability. Air was also more easily entrained in Class A concrete.
2. Class A PC control and BFS mixtures had 28 day strengths about 500 to 700 psi lower than those of corresponding Class AA mixtures. On the contrary, Class A fly ash mixtures were stronger at 28 days than Class AA fly ash mixtures.
3. Shrinkages of Class A mixtures were similar to each other, and in turn, lower than those of Class AA mixtures (due to the lower total cementitious materials content of Class A).
4. RCIP results at 28 and 90 days were fairly similar for Class A and Class AA mixtures, although FA mixtures were slightly less penetrable for Class A than for Class AA. Slag mixtures had the least penetrability of all mixtures at both 28 and 90 days.

5.2.5 Use of HRWR

Two goals were examined for high range water reducer (HRWR) use in Class AA concrete: 1) increase slump to around 6 in. without changing mixture proportions, and 2) maintain the same slump (1 to 3 in.) with reduced w/cm. The two mixture types tested included 15 percent FA replacement and 25 percent BFS replacement.

1. Similar HRWR dosages were used to achieve both goals; however, early slump loss was greater for mixtures with high (6 in.) slump. AEA dosages needed to achieve target air contents were greatly reduced for HRWR mixtures as compared to non HRWR mixtures.
2. Setting times for FA and BFS mixtures with HRWR were similar to one another. As compared to their companion mixtures with no HRWR, the BFS mixtures were retarded by about 1.5 hr. with inclusion of HRWR; FA mixtures were relatively unaffected. However, in the absence of HRWR, set times of FA mixtures were already longer than those of BFS mixtures.

3. Use of HRWR generally improved compressive, flexural, and tensile strengths (to varying degrees), even for mixtures with unchanged w/cm.

5.2.6 Use of Silane

The 90 day salt ponding test was performed on two Class AA mixtures treated with silane: PC control, and 25 percent BFS replacement.

1. Absorbed chlorides at the upper half inch depth were similarly low for both types of concrete when treated with silane. The pozzolan (BFS) likely played a secondary role to the silane in reducing absorbed chlorides. These results demonstrate that concrete containing BFS can still receive benefit from silane treatment (although the relative benefit is less than for an ordinary PC concrete).
2. Absorbed chlorides at the second depth were very low, and essentially the same, regardless of silane treatment or presence of BFS.

5.2.7 Observations Common to All Studies

1. The AASHTO equation for elastic modulus, $E_c = 57{,}000\ \sqrt{f_c}$ (psi), was conservative for all mixtures tested.
2. The prediction equation for estimating flexural strength, (f_r= $7.5\ \sqrt{f_c}$ (psi), was conservative for all mixtures.
3. The prediction equation, $f_t = 6\ \sqrt{f_c}$ (psi), produced a reasonable (and nearly always conservative) estimate of splitting tensile strength.

5.3 RECOMMENDATIONS

1. Current specifications permit replacement of about 45 percent total of the portland cement with pozzolans (approximately 20 percent fly ash combined with 25 percent blast furnace slag). Mixtures were tested in this study with as much as 50 percent blast furnace slag, and good performance was demonstrated. The data supports permitting an increased replacement rate for blast furnace slag of up to 50 percent (when used alone).
2. This research did not address total limits on pozzolan replacement. Therefore, the upper limit on total pozzolans should remain at 45 to 50 percent at present, and the current maximum limit on fly ash should be retained. However, further benefits can be realized by permitting

higher slag contents than 25 percent (while retaining the current, or a slightly increased, upper limit on total pozzolans).

3. Additional study is needed on performance of concrete with Class C fly ash. Variability of fly ash material (from source to source, and over time), and of concrete made using the fly ash, should be assessed. Also, the merits of increasing the limit on fly ash replacement should be studied.
4. Further study should be conducted to assess the effects of limits on individual pozzolans, their combinations, amount of total pozzolans, and use of pozzolans in conjunction with blended cements, on concrete performance.

5.4 GUIDELINES FOR USE OF FLY ASH AND BLAST FURNACE SLAG IN CLASS AA AND CLASS A MIXTURES

ODOT has broad experience with use of Class C fly ash in concrete mixtures. However, blast furnace slag has not yet been implemented in field projects. Therefore, this section expands more on aspects related to use of BFS, but also includes observations pertinent to use of Class C FA. An excellent source containing guidelines for use of BFS is the ACI document *Ground Granulated Blast-Furnace Slag as a Cementitious Constituent in Concrete* (ACI Comm. 233). Some general information from the Comm. 233 report, and observations from the research, are presented below.

5.4.1 General Benefits and Drawbacks

As compared to control portland cement concrete, beneficial effects of using Grade 120 BFS at the replacement rate tested included:

1. Increased compressive, flexural, and tensile strengths (typically by 7 days for compressive strength).
2. Substantially lower permeability (greatly reduced RCIP values and chloride ion absorption in the upper half inch depth).
3. Reduced creep, similar or slightly higher elastic modulus.
4. Consistent nature (trends) of performance.

Blast furnace slag replacement (Grade 120) was also found to cause:

1. Slight reductions in workability (Class AA concrete affected more than Class A).

2. Reduced effectiveness in entraining air when workability was decreased, or with low or elevated casting temperature.

Setting times, freeze thaw resistance, shrinkage, and chloride ion absorption when treated by silane, were found similar for concrete with blast furnace slag and ordinary portland cement concrete.

5.4.2 Potential for Use in Bridge Decks and Other Applications

The data generated in this study verifies that performance of Oklahoma concretes can indeed be improved through the use of pozzolans, especially ground granulated blast furnace slag. The maximum blast furnace slag replacement rate used for the majority of tests in this research was 25 percent (as compared to much higher limits examined in the literature, and 40 to 50 percent replacement rates used in field applications in other areas). Even at this fairly low replacement rate, reductions in chloride ion penetrability were substantial. Coupled with the good rate of strength gain of Grade 120 BFS (equal or exceeding 7 day strengths of PC control concrete), these characteristics make Grade 120 BFS a highly suitable pozzolan for use in bridge decks. Grade 100 BFS would be expected to lead to similar reductions in permeability, although rate of strength gain should be expected to be slower.

Improved durability of BFS concrete would also enhance the performance of other structures. Rigid pavements are ideal candidates for use of BFS owing to the better durability, and possibly even higher tensile strengths that can be achieved. Piers, abutments, or applications where early strength gain is not essential would benefit also.

5.4.3 Guidelines for Use of BFS

1. **Storage and Handling.** Procedures similar to those used for portland cement should be followed. Because BFS has somewhat similar fineness and color to portland cement, adequate labeling is necessary to avoid confusing the materials.
2. **Batching.** BFS should replace portland cement on a one-to-one basis by weight. This material should be introduced to the mixer at the same time as the portland cement.
3. **Proportioning.** The amount of pozzolan used should reflect the concrete's intended purpose and expected curing temperature. Also, the grade (activity) of BFS will affect the amount used. Volume calculations should take into account the differences in specific gravity between BFS, FA, and portland cement. BFS and FA should be included in the calculation of water to cementitious materials ratio. Some differences were seen in how various Type I cements

interacted with BFS and/or Class C FA. Therefore, final mixture proportions should be based on results of trial batches conducted with the actual materials (cement, pozzolan(s), aggregates, and chemical admixtures) to be used on the job.

4. **Use of Admixtures.** Admixture effects should be similar, in general, to effects on portland cement concrete. For concrete with lower workability, higher dosages of air entraining agents (AEA) may be required if BFS is present. Also, high or low temperature may negatively impact the effectiveness of AEA for BFS concrete. A HRWR reducer can be used to increase slump (for the same w/cm) or increase strength (for the same slump). Improved workability attributed to a HRWR also encourages more effective air entrainment.

5. **Curing.** Proper curing procedures are equally important for concrete whether or not pozzolans are present. Adequate exposure to moisture is necessary for proper curing. Concretes containing BFS and/or FA respond similarly to portland cement if curing temperatures are lowered or elevated. Set times may be increased, and rate of strength gain retarded, more for FA or Grade 100 BFS concrete than for PC control concrete. Concrete with Grade 120 BFS at 25 percent replacement responded to altered curing temperatures similarly to control portland cement concrete. Limitations on use of BFS in cool weather, similar to those in place for use of Class C FA, seem most appropriate for BFS replacement rates of more than 25 percent, or Grade 100 BFS. The data supports that such limitations could be relaxed, to some degree, if Grade 120 BFS is used at a replacement rate of no more than 25 percent.

6. **Color of Hardened Concrete.** Concrete containing BFS can be expected to be somewhat lighter in color than concrete containing portland cement alone. A blue-green tint may be observed at early ages, but diminishes on the surface with time (the concrete's interior may retain the darker color for a considerable period of time). Early application of sealers or continuous application of water may extend the period of blue-green color.

REFERENCES

ACI Committee 233 (1995). *Ground Granulated Blast-Furnace Slag as a Cementitious Constituent in Concrete*, American Concrete Institute, Detroit.

American Association of State Highway and Transportation Officials (1986a). Standard Method of Test for Resistance of Concrete to Chloride Ion Penetration, AASHTO Designation T 259-80, Washington, D.C.

American Association of State Highway and Transportation Officials (1986b). Standard Test Method for Sampling and Testing for Total Chloride Ion In Concrete and Concrete Raw Materials, AASHTO Designation T 260-84, Washington, D.C.

American Society for Testing and Materials (1995a). Air Content of Freshly Mixed Concrete by the Pressure Method (C 231), Vol. 4.02, Philadelphia, 1995, pp. 134-141.

American Society for Testing and Materials (1995b). Creep of Concrete in Compression (C 512), Vol. 4.02, Philadelphia, 1995, pp. 272-275.

American Society for Testing and Materials (1995c). Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration (C 1202), Vol. 4.02, Philadelphia, 1995, pp. 624-629.

American Society for Testing and Materials (1995d). Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading) (C 78), Vol. 4.02, Philadelphia, 1995, pp. 31-33.

American Society for Testing and Materials (1995e). Fineness of Hydraulic Cement by Air Permeability Apparatus (C 204), Vol. 4.01, Philadelphia, pp. 161-169.

American Society for Testing and Materials (1995f). Length Change of Hardened Hydraulic Cement Concrete (C 157), Vol. 4.02, Philadelphia, 1995, pp. 101-106.

American Society for Testing and Materials (1995g). Making and Curing Concrete Test Specimens in the Laboratory (C 192), Vol. 4.02, Philadelphia, pp. 116-122.

American Society for Testing and Materials (1995h). Resistance of Concrete to Rapid Freezing and Thawing (C 666), Vol. 4.02, Philadelphia, 1995, pp. 320-325.

American Society for Testing and Materials (1995i). Sieve Analysis of Fine and Coarse Aggregates (C 136), Vol. 4.02, Philadelphia, 1995, pp. 78-82.

American Society for Testing and Materials (1995j). Slump of Hydraulic Cement Concrete (C 143), Vol. 4.02, Philadelphia, 1995, ppe 88-90.

American Society for Testing and Materials (1995k). Specific Gravity and Absorption of Coarse Aggregate (C 127), Vol. 4.02, Philadelphia, 1995, pp. 64-68.

American Society for Testing and Materials (1995l). Specific Gravity and Absorption of Fine Aggregate (C 128), Vol. 4.02, Philadelphia, 1995, pp. 69-73.

American Society for Testing and Materials (1995m). Splitting Tensile Strength of Cylindrical Concrete Specimens (C 496), Vol. 4.02, Philadelphia, 1995, pp. 266-269.

American Society for Testing and Materials (1995n). Static Modulus of Elasticity of Concrete in Compression (C 469), Vol. 4.02, Philadelphia, 1995, pp. 241-244.

American Society for Testing and Materials (1995o). Time of Setting of Concrete Mixtures by Penetration Resistance (C 403), Vol. 4.02, Philadelphia, 1995, pp. 217-221.

American Society for Testing and Materials (1995p). Total Moisture Content of Aggregate by Drying (C 566), Vol. 4.02, Philadelphia, 1995, pp. 282-283.

American Society for Testing and Materials (1995q). Unit Weight and Voids in Aggregate (C 29), Vol. 4.02, Philadelphia, 1995, pp. 1-4.

American Society for Testing and Materials (1995r). Unit Weight, Yield, and Air Content of Concrete (C 138), Vol. 4.02, Philadelphia, 1995, pp. 83-85.

Al-Moudi, O. S. B., Rasheeduzzafar, M. M., and Al-Mana, A. I. (1993). "Prediction of Long-Term Corrosion Resistance of Plain and Blended Cement Concretes," *ACI Materials Journal*, November-December, pp. 564-570.

Baalbaki, M., Sarker, S. L., Aiticin, P. C., and Isabella, H. (1992). "Properties and Microstructures of High-Performance Concretes Containing Silica Fume, Slag, and Fly Ash," *Fly Ash, Silica Fume, Slag, and Natural Pozzolans in Concrete,* Volume II, pp. 921-942.

Campbell, G. M., and Detwiler, R. J. (1993), "Development of Mix Designs for Strength and Durability of Steam Cured Concrete," *Concrete International*, July, pp. 37-39.

Chern, J.C., and Chan, Y.W. (1989). "Deformations of Concretes Made with Blast-Furnace Slag Cement and Ordinary Portland Cement," *ACI Materials Journal*, July - September, pp. 372-382.

Douglas, E., and Branstetr, J. (1990). "A Preliminary Study on the Alkali Activation of Ground Granulated Blast-Furnace Slag," *Cement and Concrete Research*, Vol. 20, pp. 746-756.

Douglas, E., Bilodeau, A., Brandstetr, J., and Malhotra, V.M. (1991). "Alkali Activated Ground Granulated Blast-Furnace Slag Concrete: Preliminary Investigation," *Cement and Concrete Research*, Vol. 21, pp. 101-108.

Douglas, E., and Pouskouleli, G. (1991). "Prediction of Compressive Strength of Mortars Made With Portland Cement - Blast - Furnace Slag + Fly Ash Blends," *Cement and Concrete Research*, Vol. 21, pp. 523-534.

Frearson, J.P.H., and Higgins, D.D. (1992). "Sulfate Resistance of Mortars Containing Ground Granulated Blast Furnace Slag with Variable Alumina Content," *Fly Ash, Silica Fume, Slag, and Natural Pozzolans in Concrete*, Volume II, pp. 1525-1542.

Gifford, P.M., and Gillott, J.E. (1996). "Alkali-Silica Reaction (ASR) and Alkali-Carbonate Reaction (ACR) in Activated Blast Furnace Slag Cement (ABFSC) Concrete," *Cement and Concrete Research*, Vol. 26, No. 1, pp. 21-26.

Hamling, J.W. and Kriner, R.W. (1992). "Evaluation of Granulated Blast Furnace Slag as a Cementitious Admixture-A Case Study," *Cement, Concrete, and Aggregates*, Vol. 14, No. 1, Summer, pp. 13-20.

Hogan, F.J., and Meusel, J.W. (1981). "Evaluation for Durability and Strength Development of a Ground Granulated Blast Furnace Slag," *Cement, Concrete and Aggregates*, Summer, pp. 40-52.

Mangat, P.S., and Khatib, J.M. (1995). "Influence of Fly Ash, Silica Fume, and Slag on Sulfate Resistance of Concrete," *ACI Materials Journal*, September-October, pp. 542-552.

Mehta, P.K. (1986). *Concrete - Structure, Properties, and Materials*, Prentice-Hall, Englewood Cliffs, New Jersey.

Mindess, S., and Young, J.F. (1988). *Concrete*, Prentice-Hall, Englewood Cliffs, New Jersey.

Pfeifer, D.W., McDonald, D.B, Krauss, P.D. (1994). "The Rapid Chloride Permeability Test and Its Correlation to the 90-Day Chloride Ponding Test," *PCI Journal*, Vol. 39, No. 1, January - February, pp. 38-47.

Rose, J., "The Effect of Cementitious Blast Furnace Slag on Chloride Permeability of Concrete," Corrosion, Concrete, and Chlorides, V.M, Malhotra, Ed., *SP-102*, American Concrete Institute, Detroit, pp. 107-125.

Sakai, K., Watanabe, H., Suzuki, M., and Hamazaki, K. (1992). "Properties of Granulated Blast Furnace Slag Cement Concrete," *Fly Ash, Silica Fume, Slag, and Natural Pozzolans in Concrete*, Volume II, pp. 1367-1400.

Sivasundaram, V. and Malhotra, V.M. (1992). "Properties of Concrete Incorporating Low Quantity of Cement and High Volumes of Ground Granulated Slag," *ACI Materials Journal*, November-December, pp. 554-563.

Togawa, K., and Nakamoto, J. (1992). "Study on the Effects of Blast Furnace Slag on Properties of No-Slump Concrete Mixtures," *Fly Ash, Silica Fume, Slag, and Natural Pozzolans in Concrete*, Volume II, pp. 1401-1412.

Tomisawa, T., Chikada, T., and Nagao, Y. (1992). "Properties of Super Low Heat Cement Incorporating Large Amounts of Ground Granulated Blast Furnace Slag of High Fineness," *Fly Ash, Silica Fume, Slag, and Natural Pozzolans in Concrete*, Volume II, pp. 1385-1392.