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UNIVERSITY OF OKLAHOMA

GRADUATE COLLEGE

# INVESTIGATING THE NEED FOR AND EFFECT OF AIR ENTRAINMENT IN HIGH PERFORMANCE CONCRETE

A Dissertation

SUBMITTED TO THE GRADUATE FACULTY

In partial fulfillment of the requirements for the degree of

Doctor of Philosophy

By

Micah Hale

Norman, Oklahoma

2002

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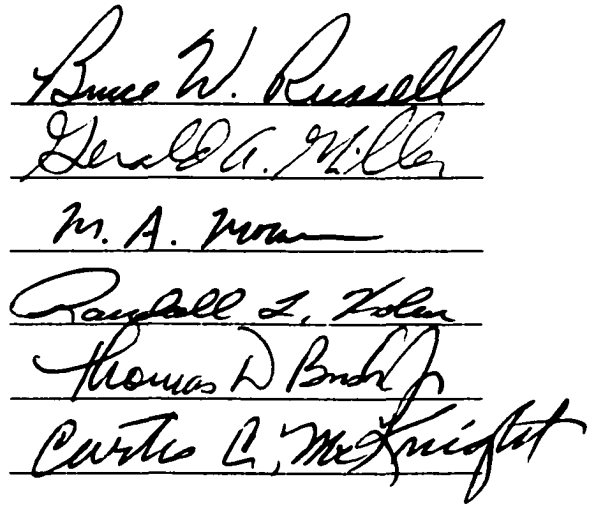
INVESTIGATING THE NEED FOR AND EFFECT OF AIR ENTRAINMENT IN HIGH PERFORMANCE CONCRETE

A Dissertation APPROVED FOR THE SCHOOL OF CIVIL ENGINEERING AND ENVIRONMENTAL SCIENCE

By



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# ABSTRACT

The use of high performance concrete (HPC) in exterior structures has increased in recent years. Its increased strength and durability make HPC very appealing to the prestressed concrete industry, particularly in bridge girders. Due to its increased strength and durability, HPC can reduce the number of girders, increase bridge spans, decrease bridge depth, and improve bridge durability. The research program investigated the need for air entrainment in HPC and its effect on HPC bridge girders. It is necessary to entrain air in some concrete structures that are subjected to freezing and thawing. Current building codes require varying amounts of entrained air depending on the severity of the exposure. Entrained air voids provide air pockets where water can expand and water pressure can be relieved. Without these voids, continuous freeze-thaw cycles will eventually degrade and damage the concrete. A total air content between four and eight percent is generally considered adequate to provide resistance to the freeze-thaw action. Many researchers suggest that entrained air may not be necessary in HPC because of its low permeability, and because of its inherent unsaturated condition. One of the primary objectives of the research program is to determine whether air entrainment is necessary in HPC. Results from the program show that air entrainment may not be necessary for w/cm less 0.36, and a total air content of four percent may be sufficient for w/cm between 0.36 and 0.50.

# CHAPTER 1

# INTRODUCTION

## 1.1 INTRODUCTION

The research program investigated the need for air entrainment in high performance concrete (HPC) and its effect on HPC bridge girder performance. It is necessary to entrain air in some concrete structures that are subjected to freezing and thawing. Entrained air is added to concrete through the use of air entraining agents (AEA). Current building codes require varying amounts of entrained air depending on the severity of the exposure. Entrained air voids provide air pockets where water can expand upon freezing and water pressure can be relieved. Without these voids, continuous freeze-thaw cycles will eventually degrade and damage the concrete. For all concrete structures, a total air content between four and eight percent is generally considered adequate to provide resistance to the freeze-thaw action (Mindess et al, 1981). The Oklahoma Department of Transportation requires a total air content of 5 ± 1.5 percent in bridge girders.

The use of HPC in exterior structures has increased in recent years (Neville et al, 1998). Its increased strength and durability make HPC very appealing to the prestressed concrete industry, particularly in bridge girders. Due to its increased strength and durability, HPC can reduce the number of girders, increase bridge spans, decrease bridge depth, and improve bridge durability (B. Russell, 1994). The

durability and permeability of normal strength concrete has been thoroughly studied over the past century, but the same properties of HPC have not been studied to the same extent. To increase the durability of normal strength concrete, an air-entraining agent is added to the concrete mixture. While the entrained air increases durability, it also decreases concrete strength. For this reason, air entrainment is not commonly used in HPC (Cohen et al, 1992). Many researchers are questioning the need for air entrainment in HPC (Cohen et al, 1992; Hooten et al, 1993; Lessard et al, 1995; Li et al, 1994; Marchand et al, 1995; Mokhtarzadeh et al, 1995; Pigeon et al, 1991). Many of these researchers have concluded that the low permeability of HPC due to its decreased water to cementitious ratio (w/cm) improves its durability (Pigeon et al, 1991; Cohen et al, 1992; Li et al, 1994; Marchand et al, 1995; and Fagerlund, 1994). Accordingly, several researches have developed durable non-air-entrained HPC mixtures (Cohen et al, 1992; Mokhtarzadeh et al, 1995; Fagerlund, 1994; and Hilsdorf, 1994). Despite these indicators, most researchers still recommend the use of air entrainment for durability (Pigeon et al, 1991; Cohen et al, 1992; Marchand et al, 1995; Fagerlund, 1994; Zia et al, 1993; and Aitcin et al, 1993). The objective of this research program is to examine the need of air entrainment in HPC made with materials commonly available.

The use of HPC also has indirect benefits on the environment. The use of HPC can increase the life of concrete structures, reduce maintenance costs, and for bridges reduce the required number of girders. These examples either involve extending the life of a concrete structure or reducing the quantity and sizes of necessary members, thus promoting resource conservation by furthering the supply of

cement. Another environmental benefit of HPC is the incorporation of supplementary materials. Most HPC mixtures incorporate supplementary cementitious materials such as fly ash and blast furnace slag, which are waste products of other manufacturing processes. Fly ash and blast furnace may replace a large percentage of the cement in a concrete mixture thereby reducing the energy required to produce a concrete structure. Prior research at OU examined concrete mixtures where 40 percent of the cement was replaced with fly ash and blast furnace slag (Hale et al, 1999).

Manufacturing cement is very energy intensive. Therefore, reducing the amount of cement in a concrete mixture or extending the life a concrete structure through the use of HPC can have a very beneficial effect on the environment. After aluminum and steel, the "production of portland cement is the third most energy intensive material production process" (Malhotra, 1999). In 1992, cement production accounted for 0.60 percent of the total U.S. energy use and accounted for almost two-thirds of the total energy use in some third world countries (Wilson, 1993). In addition to being very energy intensive, the production of cement also contributes significantly to the quantity of greenhouse gases. For every ton of cement manufactured, one ton of $CO_2$ is released into the atmosphere. Cement production accounts for "approximately seven percent of the total world $CO_2$ production" (Malhotra, 1999). Therefore, not only does the use of HPC have a direct beneficial impact on concrete structures, it also has a very important indirect effect on the environment.

## 1.2 OBJECTIVES

One of the primary goals in the research is to determine whether air entrainment is necessary in HPC. HPC is concrete that has higher strength and lower permeability when compared to normal strength concrete (NSC). The superior qualities are achieved by the low water to cementitious material ratio (w/cm) that is common in HPC. HPC commonly has w/cm equal to or less than 0.45 while NSC commonly has w/cm of 0.45 or greater. Many researchers suggest that AEA might not be necessary in HPC because of its low permeability, and because of its inherent unsaturated condition (Pigeon et al, 1991; Cohen et al, 1992; Li et al, 1994; Marchand et al, 1995; and Fagerlund, 1994).

In addition to investigating the freeze-thaw durability of HPC, the research program will also examine the permeability of HPC by using the Rapid Chloride Ion Penetrability test (RCIP). This portion of the research will examine permeability of mixtures with and without air entrainment and also mixtures with and without pozzolans. Since the RCIP test is a relatively new procedure for measuring permeability, the research program will also provide additional data to ODOT on the effectiveness of the test. Another objective of the research is to examine the prestress losses in concrete with and without air entrainment. This portion of the study will also include investigating the allowable release stress of prestressed concrete girders. The complete list of tasks is shown below.

**Research Objectives**

1. Develop HPC without AEA.

2. Develop HPC with AEA.
3. Investigate the freeze-thaw durability of HPC to determine the necessity of air entrainment in HPC.
4. Investigate the RCIP of HPC with and without AEA.
5. Determine prestress losses of HPC with and without AEA.
6. Investigate the allowable compressive stresses at release to determine whether current allowable stress requirements can be relaxed.

## 1.3 SCOPE

### 1.3.1 Developing High Performance Concrete

This portion of the research program developed HPC without air entrainment. Several HPC mixtures were developed, batched, and tested. With one of the mixtures developed, two prestressed/precast concrete girders were produced. Strength and durability were not the only concerns; the concrete mixtures required sufficient workability and placeability to be used at a local prestressed concrete facility. The mixtures also had to contain the materials and admixtures that were currently in use at the facility. The results of the study showed that a change in the cement source affected the performance of the concrete mixtures, but HPC was still developed using materials native to Oklahoma.

### 1.3.2 Developing High Performance Concrete with Entrained Air

This portion of the research program developed HPC with entrained air. Like the earlier research, two prestressed/precast concrete girders were cast with a mixture developed in the research. A goal of the research program was to produce HPC with entrained air and also to examine the effects of entrained air on the properties of the fresh and hardened concrete, specifically the compressive strength. The research results showed that air entrained HPC is possible using materials native to Oklahoma. However, the research results also showed that trial batching is necessary to determine the appropriate dosage of AEA at w/cm less 0.34.

### 1.3.3 Freeze-Thaw Durability of High Performance Concrete

This section of the experimental program was designed to examine two criteria focused on two objectives. The first objective was to determine if air entrainment is necessary in HPC. The second objective was to determine the maximum w/cm where air entrainment is not needed. Concrete mixtures with varying w/cm were subjected to ASTM C 666 (Procedure A). The variables for the mixtures were total air content and w/cm. The targeted total air contents for the mixtures were 2 percent (entrapped air, no AEA), 4 percent, and 6 percent. The freeze-thaw tests continued until the specimen deteriorated, or the specimen reached 300 freeze thaw cycles. The results from the study show that air entrainment is not required below a specific maximum w/cm for the materials employed.

### 1.3.4 Permeability of High Performance Concrete

This section of the research program investigated the permeability of HPC with and without entrained air. This section of the research program had two tasks. The first task was to examine if there were any differences in the permeability of concrete with and without entrained air. The second task was to provide further information on the validity of the Rapid Chloride Ion Penetrability Test (ASTM C 1202). Concrete mixtures with varying w/cm were subjected to ASTM C 1202. The variables for the mixtures were total air content and w/cm. The targeted total air contents for the mixtures were 2 percent (no air entraining agent), 4 percent, and 6 percent. The results from the research show that entrained air has no noticeable effect on the RCIP of the specimens. The results also further support the view that the RCIP test may not be an adequate test for measuring the permeability of concrete mixtures containing mineral admixtures.

### 1.3.5 Prestress Losses and Allowable Compressive Stresses at Release

This portion of the research examined the prestress losses of non-air entrained and air entrained bridge girders. The main task was focused on determining if the addition of entrained air had any noticeable effects on prestress losses. The measured losses were then compared with the losses calculated using two prevalent methods used for estimating prestress losses. Another objective of the research was to provide additional data with regard to increasing the allowable compressive stress at release. The results of the research show that the addition of entrained air had no noticeable

effect on the prestress losses and that increasing the allowable compressive stresses at release may not be beneficial.

## 1.4 SUMMARY

The dissertation is divided into seven chapters. The first chapter includes an introduction to the six research objectives. The next five chapters are focused on each of the research objectives with the last two research objectives combined into one chapter. Each chapter contains its own literature review, experimental procedures, presentation and discussion of results, and conclusions. The final chapter contains a summary of all the conclusions and recommendations for further research.

# CHAPTER 2

# DEVELOPING HPC WITHOUT ENTRAINED AIR

## 2.1 INTRODUCTION

High Performance Concrete (HPC) does not differ significantly from normal strength concrete (NSC). Both types of concrete are composed from the same basic materials. The differences lie mainly in the proportions and the quantities of the materials. These differences allow HPC to have higher strengths and better durability than NSC. This chapter provides a brief history HPC and its uses, and describes the development of HPC incorporating materials that are native to and commonly used in Oklahoma. The quantity of cement, the water to cementitious material ratio (w/cm), and the type and dosage of admixtures are the variables that were examined. This chapter includes discussion of the literature review, laboratory experiments, and analysis of results.

## 2.2 LITERATURE REVIEW

### 2.2.1 Definitions

The definition of HPC has changed throughout the years. In 1979 the American Concrete Institute (ACI) Committee 363 on High Strength Concrete defined HPC as any concrete having a compressive strength of over 6000 psi (Derucher et al, 1994). In 1997, A.M. Neville in his book *Properties of Concrete*

defined HPC as any concrete with a compressive strength of over 12,000 psi. The Strategic Highway Research Program (SHRP) defined HPC by three requirements. The requirements were a maximum w/cm of 0.35, a minimum durability factor of 80, and a minimum compressive strength of either 3000-psi within four hours of placement, 5000 psi at one day, or 10,000 psi at 28 days (H. Russell, 1999). In 1999, ACI redefined HPC as "concrete meeting special combinations of performance and uniformity requirements that cannot always be achieved routinely using conventional constituents and normal mixing, placing, and curing practices." As one can see, the definition of HPC has changed over the years, and it will continue to change as our knowledge of concrete increases.

### 2.2.2 Background

High Performance Concrete is not necessarily different from normal strength concrete. Both HPC and NSC contain the same basic constituent materials. Those materials are cement, fine aggregate (sand), coarse aggregate (rock), and water. The differences are in the quantities of those materials. HPC may contain as much as or more than 900 lb/yd$^3$ of cement, whereas NSC may contain approximately 500 lb/yd$^3$ of cement. Also, HPC may have a w/cm as low as 0.20 (Neville, 1997) where NSC may have a w/cm of 0.60. However, it should be noted that HPC can contain as little as 600 lb/yd$^3$ of cement.

Another difference between the two types of concretes is the usual addition of chemical and mineral admixtures in HPC that further enhance the fresh and hardened properties of concrete. Chemical admixtures are soluble chemicals that are added to

concrete to improve its properties (Mindess et al, 1981). Chemical admixtures can reduce the water demand, increase or decrease the set time, entrain air, waterproof, and inhibit corrosion (Kosmatka et al, 1988). The advent of the superplasticizer or High Range Water Reducers (HRWR) in 1964 had a dramatic impact on the future of HPC (Derucher 1994). HRWR can reduce the amount of water in a given mixture by as much as 35 percent (Neville, 1997). With HRWR a mixture with a w/cm of about 0.25 can have the same slump as a mixture with a w/cm of about 0.50. The reduction in water content increases the strength and also increases the density of the concrete, which results in concrete with lower permeability.

Mineral admixtures are solids that are added to the concrete to improve its fresh and hardened properties. There are basically two types of mineral admixtures, cementitious and pozzolanic. Cementitious mineral admixtures are solids that have hydraulic cementing properties (along with water the materials will set and harden). Cementitious mineral admixtures include but are not limited to blast furnace slag, natural cements (clayey limestone), and hydraulic lime (Kosmatka et al, 1988). The cementitious mineral admixtures undergo hydration and contribute to concrete strength (Neville, 1997).

Pozzolanic admixtures include silica fume, fly ash, volcanic ash, metakaolin, and rice husk ash. Pozzolanic mineral admixtures (or pozzolans) are composed of natural or artificial materials that contain reactive silica. Pozzolans improve the characteristics of concrete by reacting with products formed during the hydration of cement. Equations 2.1 and 2.2 show the hydration of PC.

$$2C_3S + 6H_2O \rightarrow C_3S_2H_3 + 3CH \qquad (2.1)$$

$$2C_2S + 4H_2O \rightarrow C_3S_2H_3 + CH \quad (2.2)$$

$$CH + S + H_2O \rightarrow C_3S_2H_3 \quad (2.3)$$

The calcium silicate hydrate ($C_3S_2H_3$), which is a dense crystalline structure, is the primary 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, pozzolans contain amorphous silica (S), which reacts (Equation 2.3) with CH to form additional $C_3S_2H_3$, increasing the density of the cement paste matrix thereby improving the strength and permeability of the concrete.

### 2.2.3 History of HPC

The compressive strength and other properties of concrete have improved throughout the 20th Century. In 1903 Van Ornum conducted fatigue tests on concrete. The strength of the concrete specimens tested was between 1200 and 1580 psi. In 1927 McMillan et al published the compressive strengths of several types of mixtures with varying quantities of water. The compressive strengths ranged from a low of approximately 2000 psi to a high of approximately 5300 psi. Then in the 1930s Probst tested concrete with a compressive strength slightly greater than 2000 psi. In 1946 Le Camus tested concrete specimens with compressive strengths of 4600 psi (Bennett et al, 1967). Then Bennett et al tested concrete with a compressive strength of 8700 psi in 1967.

By the early 1960's, HPC was beginning to be used in building projects in the U.S. In 1962, the Outer Drive East Building in Chicago was built using concrete with a compressive strength of 6000 psi. Then in 1976 another Chicago building, the River Plaza Building, contained concrete with compressive strengths of 11,000 psi. One of the latest Chicago buildings to use HPC is the 225 W. Wacker Drive Project. Eighteen of the columns that support the 31-story building were constructed with concrete with compressive strengths of 14,000 psi with one experimental column with a compressive strength in excess of 17,000 psi (Moreno, 1990).

### 2.2.4 Examples of HPC

As previously shown, HPC has been used in the construction of many buildings. The uses of HPC stretch far beyond the construction of skyscrapers. When the entrances to a McDonald's in Quebec needed repairing, HPC was used. HPC was needed to reduce the number of days that the entrances were closed. A compressive strength of 3000 psi was required to allow the entrances to be opened to traffic. If normal strength concrete was used, seven days might have been necessary for the concrete to reach a compressive strength of 3000 psi. Two of the three entrances to the restaurant were to be replaced simultaneously. The entrances were scheduled to be opened to traffic two days later. Due to the high early compressive strength of the concrete, the entrances were reopened 24 hours later. A concrete mixture with a w/cm of 0.30 was used for both entrances. The mixtures attained a compressive strength of over 3000 psi by 24 hours of age (Lessard et al, 1994).

Most structures that utilize HPC do so because of the need for high compressive strengths, which cannot be attained through the use of NSC. However, the increase in modulus of elasticity and decreased permeability also make HPC appealing to designers and engineers. The Interfirst Plaza in Dallas and Two Union Square in Seattle used HPC not because of compressive strength requirements but because of the high modulus of elasticity requirement. The Two Union Square required concrete with a compressive strength of 14,000 psi to carry the loads, but to achieve a modulus of elasticity of 6000 ksi, a concrete mixture with a compressive strength of 19,000 psi was used. The decreased permeability of HPC led the designers of the Lacey V. Murrow bridge in Seattle to choose HPC over NSC (H. Russell, 1997).

Another major use of HPC is in the manufacture of prestressed concrete bridge girders. The use of HPC in bridges can increase the girder spacing and bridge span, produce shallower girders, and increase bridge durability (B. Russell, 1994). Many states have begun using HPC in their bridge girders. HPC bridges have been constructed in Nebraska, New Hampshire, Texas, Virginia, and Washington (H. Russell, 1997).

## 2.3 EXPERIMENTAL PROCEDURES

### 2.3.1. Scope

This portion of the research program sought to develop HPC without air entrainment. Several HPC mixtures were developed, batched, and tested. With one

of the mixtures developed, two prestressed/precast concrete girders were produced. Strength and durability were not the only concerns; the concrete mixtures required sufficient workability and placeability to be used at a local prestressed concrete facility. The mixtures also had to contain the materials and admixtures that were currently in use at the facility.

The quantity of cement, the w/cm, and the type and dosage of admixtures were varied in the research. Earlier research (OCAST research) at OU had developed HPC without air entrainment (Bush et al, 1998), but a change in cement source required that additional testing be done to determine the effects of the change in cement when Holnam ceased production of their Type III Cement during the summer of 1998. This production change resulted in the need for a batching program to identify another suitable cement source to determine if the two cements produced concrete with similar properties. In addition to using a different cement source, earlier research had also used a different HRWR, Daracem 19. During this same time period, many local prestressed concrete facilities were changing from Daracem 19 to a different HRWR. One of the different HRWR is ADVA Flow, which was used in this research. The new HRWR required lower dosages, which reduced retarding effects.

The OCAST research had produced concrete mixtures with one-day compressive strengths of 10,000 psi and 28 day compressive strengths of 15,000 psi using Holnam Type III Cement. A goal of the research was to produce concrete mixtures with similar results. The results of the study showed that changing the

cement source negatively affected the performance of the concrete mixtures, but HPC was still developed using materials native to Oklahoma.

The research program was divided into six sections with the following goals:

1) Determine if the change in cement had an affect on the properties of the concrete mixtures that had been developed through previous research.
2) Determine the effect of the change in HRWR.
3) Determine the optimum cement content and w/cm that produces concrete with most desirable qualities (strength and workability).
4) Determine the optimum dosage of HRWR.
5) Examine the influence of a WR.
6) Examine the influence of an accelerator.

### 2.3.2 Materials

The fine and coarse aggregates were constant for all mixtures. A fine aggregate from Dover, Oklahoma was used. The coarse aggregate was 3/8-in., crushed limestone from Davis, Oklahoma. The gradations for the coarse and fine aggregates are located in Appendix A. The material properties of the fine and coarse aggregates are shown in Table 2.1. Ash Grove Type III Cement from Chanute, KS was used in all but five mixtures. In these five mixtures, Holnam Type III Cement from Midlothian, TX was used. The chemical compositions and blaine fineness of the two cements are shown in Table 2.2. When needed, a water reducer, WRDA with Hycol, and a high range water reducer, ADVA Flow, were added to the mixtures to

provide adequate workability. To increase early age strength, an accelerator, DCI Corrosion Inhibitor, was also added to some mixtures.

Table 2.1 Aggregate Properties

| Property | Fine Aggregate | Coarse Aggregate |
|---|---|---|
| Absorption (SSD) | 0.68 % | 0.86 % |
| Specific Gravity | 2.63 | 2.68 |
| Dry Rodded Unit Weight ($lb/ft^3$) | - | 101.2 |

Table 2.2 Cement Properties

| | Ash Grove | Holnam |
|---|---|---|
| Chemical Compositions (%) | | |
| $SiO_2$ | 20.56 | 19.70 |
| $Al_2O_3$ | 4.74 | 5.80 |
| $Fe_2O_3$ | 3.06 | 2.76 |
| CaO | 64.10 | 61.40 |
| MgO | 2.49 | 0.90 |
| $SO_3$ | 3.14 | 4.15 |
| Compound Compositions (%) | | |
| $C_3S$ | 63.00 | 57.10 |
| $C_2S$ | 12.00 | 13.80 |
| $C_3A$ | 6.00 | 10.50 |
| $C_4AF$ | 9.00 | - |
| | Blaine Air Fineness | |
| Blaine Fineness ($cm^2/g$) | 4740 | 5240 |

### 2.3.3 Variables

**2.3.3.1 Water to Cementitious Material Ratio.** One of the first variables to be examined in the project was the w/cm. The w/cm for the project ranged from 0.24 to 0.30. Mixtures were cast at the following w/cm; 0.24, 0.25, 0.26, 0.27, 0.28, 0.29, and 0.30. Since the goal of the study was to develop HPC, the mixtures were cast at w/cm's between 0.24 and 0.30

**2.3.3.2 Cement Quantity.** Another variable examined was the quantity of cement in each mixture. The quantity of cement was either 800, 900, or 1000 lb/yd$^3$. Ash Grove Type III Cement was used in all but five mixtures. The five mixtures containing Holnam Type III Cement were used to compare the differences, if any, between the two sources of cement.

**2.3.3.3 Admixtures and Dosage.** Since the HRWR might react differently with the two types of cements (Ash Grove and Holnam), the dosages of the HRWR were varied to determine the appropriate quantity. Too much HRWR causes the mixture's set to be delayed, and too little HRWR causes a mixture with poor workability. The HRWR dosage ranged from 5 to 22.5 fluid ounces per 100 lb. of cement (fl oz/cwt). Another variable was the quantity of the water reducer (WR). The dosage rate of the WR was zero, three, or six fl oz/cwt. An accelerator was added to three mixtures to increase the early age strength of the concrete. The dosage of the accelerator was nine gal/yd$^3$. Two mixtures contained Type C Fly Ash.

### 2.3.4 Mixtures

The mixtures proportions were developed to investigate and accomplish the six goals of the research program previously stated. The mixtures proportions examined the effects of the cement source and HRWR source along with the quantity of cement, w/cm, HRWR dosage, WR dosage, and accelerator dosage in the mixtures.

**2.3.4.1 Cement Source.** In the first section of the research, concrete mixtures consisting of Ash Grove Type III Cement were cast using the same mixture designs that had performed well with Holnam Type III Cement. The HRWR and WR used were Daracem 19 and WRDA with Hycol, respectively. The mixtures that were repeated using Ash Grove Cement are shown in Table 2.3. Mixtures 3 and 10 contained only portland cement. In Mixtures 30, 31, and 45, 15 percent of the cement was replaced with fly ash.

Table 2.3. Mixture Proportions from Prior Research Batched w/ Ash Grove Cement.

| Materials | Mixture Designations | | | | |
|---|---|---|---|---|---|
| | 3 | 10 | 30 | 31 | 45 |
| Cement (lb/yd$^3$) | 1096 | 927 | 809 | 742 | 674 |
| Fly Ash (lb/yd$^3$) | 0 | 0 | 202 | 186 | 169 |
| Coarse Aggregate (lb/yd$^3$) | 1790 | 1790 | 1790 | 1790 | 2066 |
| Fine Aggregate (lb/yd$^3$) | 783 | 1102 | 996 | 1129 | 1081 |
| Water (lb/yd$^3$) | 319 | 247 | 253 | 232 | 228 |
| w/cm | 0.30 | 0.28 | 0.26 | 0.26 | 0.28 |
| HRWR (fl oz/cwt) | 22 | 28 | 20 | 17 | 15 |

**2.3.4.2 High Range Water Reducer Source.** In this section of the research, a different HRWR, ADVA Flow, was used with Mixture 3 to determine if the Ash Grove Type III Cement was in fact reacting differently with Daracem 19. For each batch, all variables were held constant except for the HRWR dosage. Mixture 3 was cast four times with HRWR dosages of 6, 8, 10, and 20 fl oz/cwt. The mixture proportions are shown in Table 2.4. The mixtures are designated by the amount of HRWR contained in the mixture. For example, Mixture 3-20 is Mixture 3 with a HRWR dosage rate of 20 fl oz/cwt.

Table 2.4. Mixture Proportions for Examining Effects of HRWR.

| Materials | Mixture Designations | | | |
|---|---|---|---|---|
| | 3-6 | 3-8 | 3-10 | 3-20 |
| Cement (lb/yd$^3$) | 1096 | 1096 | 1096 | 1096 |
| Fly Ash (lb/yd$^3$) | 0 | 0 | 0 | 0 |
| Coarse Aggregate (lb/yd$^3$) | 1790 | 1790 | 1790 | 1790 |
| Fine Aggregate (lb/yd$^3$) | 783 | 783 | 783 | 783 |
| Water (lb/yd$^3$) | 319 | 319 | 319 | 319 |
| w/cm | 0.30 | 0.30 | 0.30 | 0.30 |
| HRWR (fl oz/cwt) | 6 | 8 | 10 | 20 |

**2.3.4.3 Cement Quantity and Water to Cementitious Material Ratio.** The results from the first and second sections of the research showed that there were differences in the two HRWR. The next step was to determine the optimum cement content per cubic yard and w/cm. For all mixtures the coarse aggregate volume was held constant at 65 percent, and the HRWR (ADVA Flow) dosage was 22.5 fl. oz./cwt. The variables in the matrix were cement content and w/cm. The w/cm

varied from 0.24 to 0.30, and the cement content varied from 800 to 1000 pounds per cubic yard. These mixtures are listed in Table 2.5 and Table 2.6. The mixtures are designated by the quantity of cement in each mixture and the w/cm of the mixture. For example, Mixture 9-24 had a w/cm of 0.24 and contained 900 lb. of cement.

Table 2.5. Mixture Proportions for Optimizing w/cm and Cement Content.

| Materials | Mixture Designations | | | | | |
|---|---|---|---|---|---|---|
| | 9-24 | 10-24 | 8-26 | 9-26 | 10-26 | 8-28 |
| Cement (lb/yd$^3$) | 900 | 1000 | 800 | 900 | 1000 | 800 |
| Coarse Aggregate (lb/yd$^3$) | 1790 | 1790 | 1790 | 1790 | 1790 | 1790 |
| Fine Aggregate (lb/yd$^3$) | 1264 | 1118 | 1368 | 1217 | 1065 | 1326 |
| Water (lb/yd$^3$) | 216 | 240 | 208 | 234 | 260 | 224 |
| w/cm | 0.24 | 0.26 | 0.26 | 0.26 | 0.26 | 0.28 |
| HRWR (fl oz/cwt) | 22.5 | 22.5 | 22.5 | 22.5 | 22.5 | 22.5 |

Table 2.6. Mixture Proportions for Optimizing w/cm and Cement Content.

| Materials | Mixture Designations | | | | |
|---|---|---|---|---|---|
| | 9-28 | 10-28 | 8-30 | 9-30 | 10-30 |
| Cement (lb/yd$^3$) | 900 | 1000 | 800 | 900 | 1000 |
| Coarse Aggregate (lb/yd$^3$) | 1790 | 1790 | 1790 | 1790 | 1790 |
| Fine Aggregate (lb/yd$^3$) | 1169 | 1013 | 1284 | 1122 | 960 |
| Water (lb/yd$^3$) | 252 | 280 | 240 | 270 | 300 |
| w/cm | 0.28 | 0.28 | 0.30 | 0.30 | 0.30 |
| HRWR (fl oz/cwt) | 22.5 | 22.5 | 22.5 | 22.5 | 22.5 |

**2.3.4.4 High Range Water Reducer Dosage.** Since the majority of mixtures cast had sufficient workability, the next step was to determine if reducing the HRWR dosage would improve one-day compressive strength without sacrificing workability. The mixture designs are shown in Tables 2.7, 2.8, and 2.9. For most mixtures, the coarse aggregate volume was again held constant at 65 percent, and the cement content was 900 lb/yd$^3$. One mixture contained 800 lb/yd$^3$ of cement while another contained 1000 lb/yd$^3$. The variables were w/cm and HRWR dosage. The w/cm was 0.26, 0.28, and 0.30, and the HRWR dosage ranged from 5 to 18 fl. oz/cwt. These mixtures are also designated by the HRWR in addition to the cement content and w/cm. The last number in the mixture designation is the HRWR dosage.

Table 2.7. Mixture Proportions for Optimizing HRWR Dosage.

| Materials | Mixture Designations | | | | |
|---|---|---|---|---|---|
| | 9-26-18 | 9-28-18 | 9-30-18 | 9-26-15 | 9-28-15 |
| Cement (lb/yd$^3$) | 900 | 900 | 900 | 900 | 900 |
| Coarse Aggregate (lb/yd$^3$) | 1790 | 1790 | 1790 | 1790 | 1790 |
| Fine Aggregate (lb/yd$^3$) | 1217 | 1169 | 1122 | 1217 | 1169 |
| Water (lb/yd$^3$) | 234 | 252 | 270 | 234 | 252 |
| w/cm | 0.26 | 0.28 | 0.30 | 0.26 | 0.28 |
| HRWR (fl oz/cwt) | 18 | 18 | 18 | 15 | 15 |

Table 2.8. Mixture Proportions for Optimizing HRWR Dosage.

| Materials | Mixture Designations | | | | |
|---|---|---|---|---|---|
| | 9-30-15 | 9-26-10 | 9-28-10 | 9-26-5 | 9-28-5 |
| Cement (lb/yd$^3$) | 900 | 900 | 900 | 900 | 900 |
| Coarse Aggregate (lb/yd$^3$) | 1790 | 1790 | 1790 | 1790 | 1790 |
| Fine Aggregate (lb/yd$^3$) | 1122 | 1217 | 1169 | 1217 | 1169 |
| Water (lb/yd$^3$) | 270 | 234 | 252 | 234 | 252 |
| w/cm | 0.30 | 0.26 | 0.28 | 0.26 | 0.28 |
| HRWR (fl oz/cwt) | 15 | 10 | 10 | 5 | 5 |

Table 2.9. Mixture Proportions for Optimizing HRWR Dosage.

| Materials | Mixture Designations | | |
|---|---|---|---|
| | 8-28-15 | 9-28-15 | 10-28-15 |
| Cement (lb/yd$^3$) | 800 | 900 | 1000 |
| Coarse Aggregate (lb/yd$^3$) | 1790 | 1790 | 1790 |
| Fine Aggregate (lb/yd$^3$) | 1326 | 1169 | 1013 |
| Water (lb/yd$^3$) | 224 | 252 | 280 |
| w/cm | 0.28 | 0.28 | 0.28 |
| HRWR (fl oz/cwt) | 15 | 15 | 15 |

**2.3.4.5 High Range Water Reducer and Water Reducer.** In an attempt to decrease HRWR dosage without compromising workability, a water reducer (WR) was introduced into the mixtures. The WR used in all mixtures was WRDA with Hycol. The WR was chosen based on its minimal retarding effects. For these mixtures, the coarse aggregate was again held constant at 65 percent, and the cement content was 900 lb/yd$^3$. The variables were HRWR dosage, WR dosage, and w/cm. The HRWR varied from 5 to 15 fl. oz/ cwt, and the WR was either 3 or 6 fl. oz/cwt. The w/cm for the mixtures was 0.26, 0.28, and 0.30. The mixtures are shown in

Tables 2.10, 2.11, and 2.12. The same system of identification is used except the last numbers represent to the HRWR and WR dosage. For example, Mixture 9-26-5/6 had a w/cm of 0.26, contained 900 lb/yd$^3$ of cement, and the dosages of HRWR and WR were 5 and 6 fl oz/cwt, respectively.

Table 2.10. Mixture Proportions for Optimizing HRWR and WR Dosage.

| Materials | Mixture Designations | | | | |
|---|---|---|---|---|---|
| | 9-26-5/6 | 9-26-5/3 | 9-26-8/6 | 9-26-10/6 | 9-26-10/3 |
| Cement (lb/yd$^3$) | 900 | 900 | 900 | 900 | 900 |
| Coarse Agg. (lb/yd$^3$) | 1790 | 1790 | 1790 | 1790 | 1790 |
| Fine Agg. (lb/yd$^3$) | 1217 | 1217 | 1217 | 1217 | 1217 |
| Water (lb/yd$^3$) | 234 | 234 | 234 | 234 | 234 |
| HRWR (fl oz/cwt) | 5 | 5 | 8 | 10 | 10 |
| WR (fl oz/cwt) | 6 | 3 | 6 | 6 | 3 |
| w/cm | 0.26 | 0.26 | 0.26 | 0.26 | 0.26 |

Table 2.11. Mixture Proportions for Optimizing HRWR and WR Dosage.

| Materials | Mixture Designations | | | | |
|---|---|---|---|---|---|
| | 9-26-10/3 | 9-26-15/3 | 9-28-5/3 | 9-28-10/6 | 9-28-10/3 |
| Cement (lb/yd$^3$) | 900 | 900 | 900 | 900 | 900 |
| Coarse Agg. (lb/yd$^3$) | 1790 | 1790 | 1790 | 1790 | 1790 |
| Fine Agg. (lb/yd$^3$) | 1217 | 1217 | 1169 | 1169 | 1169 |
| Water (lb/yd$^3$) | 234 | 234 | 252 | 252 | 252 |
| HRWR (fl oz/cwt) | 10 | 15 | 5 | 10 | 10 |
| WR (fl oz/cwt) | 3 | 3 | 3 | 6 | 3 |
| w/cm | 0.26 | 0.26 | 0.28 | 0.28 | 0.28 |

Table 2.12. Mixture Proportions for Optimizing HRWR and WR Dosage.

| Materials | Mixture Designations | | | |
|---|---|---|---|---|
| | 9-28-10/3 | 9-28-15/3 | 9-30-10/6 | 9-30-15/3 |
| Cement (lb/yd$^3$) | 900 | 900 | 900 | 900 |
| Coarse Agg. (lb/yd$^3$) | 1790 | 1790 | 1790 | 1790 |
| Fine Agg. (lb/yd$^3$) | 1169 | 1169 | 1122 | 1122 |
| Water (lb/yd$^3$) | 252 | 252 | 270 | 270 |
| HRWR (fl oz/cwt) | 10 | 15 | 10 | 15 |
| WR (fl oz/cwt) | 3 | 3 | 6 | 3 |
| w/cm | 0.28 | 0.28 | 0.30 | 0.30 |

**2.3.4.6 Accelerator.** To improve one-day compressive strength, an accelerator was introduced into several mixtures. For all mixtures the coarse aggregate was held constant at 65 percent, and the dosage rate for the accelerator was nine gallons per cubic yard. There were many variables in this portion of the research. The variables were w/cm, HRWR dosage, WR dosage, and cement content. The w/cm was 0.26, 0.28, or 0.30. The cement content was 800, 900, or 1000 lb/yd$^3$. The HRWR dosage was 10 or 15 fl oz/cwt. The WR dosage was 3 fl oz/cwt. The same system of identification is used as before except for the addition of a "D" to the designation to signify the addition of an accelerator. The mixture proportions are shown in Table 2.13 and 2.14.

Table 2.13. Mixture Proportions for Examining Accelerator Dosage.

| Materials | Mixture Designations | | | | |
|---|---|---|---|---|---|
| | 8-28-15D | 9-28-15D | 10-28-15D | 9-26-10D | 9-28-10D |
| Cement (lb/yd$^3$) | 800 | 900 | 1000 | 900 | 900 |
| Coarse Agg. (lb/yd$^3$) | 1790 | 1790 | 1790 | 1790 | 1790 |
| Fine Agg. (lb/yd$^3$) | 1326 | 1169 | 1013 | 1217 | 1169 |
| Water (lb/yd$^3$) | 224 | 252 | 280 | 234 | 252 |
| HRWR (fl oz/cwt) | 15 | 15 | 15 | 10 | 10 |
| WR (fl oz/cwt) | 0 | 0 | 0 | 0 | 0 |
| Accelerator (gal/yd$^3$) | 9 | 9 | 9 | 9 | 9 |
| w/cm | 0.28 | 0.28 | 0.28 | 0.26 | 0.28 |

Table 2.14. Mixture Proportions for Examining Accelerator Dosage.

| Materials | Mixture Designations | | |
|---|---|---|---|
| | 9-30-10D | 9-28-15/3D | 10-26-10/6D |
| Cement (lb/yd$^3$) | 900 | 900 | 1000 |
| Coarse Agg. (lb/yd$^3$) | 1790 | 1790 | 1790 |
| Fine Agg. (lb/yd$^3$) | 1122 | 1169 | 1065 |
| Water (lb/yd$^3$) | 270 | 252 | 260 |
| HRWR (fl oz/cwt) | 10 | 15 | 10 |
| WR (fl oz/cwt) | 0 | 3 | 6 |
| Accelerator (gal/yd$^3$) | 9 | 9 | 9 |
| w/cm | 0.30 | 0.28 | 0.26 |

### 2.3.5 Batching

Prior to the batching of each mixture, the moisture content of the aggregates was determined. This was accomplished by obtaining representative samples of the aggregates, which were stored in stockpiles outside of the laboratory. The samples were then weighed and oven dried to a constant weight (ASTM C 566). While obtaining the aggregate samples, sufficient quantities of the coarse and fine aggregates were separately placed into 5 gallon 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.

The batching was done in a rotating drum mixer with a 6 $ft^3$ capacity. All of the batching conformed to ASTM C 192 except for the mixing times. The mixtures were mixed until they achieved a uniform consistency. The order and procedure of the addition of the constituent materials remained the same for all mixtures. For all batches, all of the coarse aggregate and one-half of the mixing water were added to the mixer first, before other ingredients. Then the remaining materials were gradually introduced into the mixer. The WR was added to the mixing water whereas the HRWR was added once all the materials had been introduced into the mixer.

For the research program, the desired fresh concrete temperature was between 60 and 70°F. Since the majority of batching was conducted during the summer, crushed ice was added to the mixing water. For those mixtures cast in cooler months, warm tap water was used to increase the fresh concrete temperature.

### 2.3.6 Curing

All the concrete specimens were cured at 73°F and 50 percent relative humidity (RH) for the first 24 hours. The specimens were then removed from their molds and moist cured in lime-saturated water at 73°F until time of testing.

### 2.3.7 Tests

The mixtures were subjected to several tests. The fresh properties examined were concrete temperature and slump (ASTM C 143). The hardened property tested was compressive strength. The compressive strength (ASTM C 39) was tested at one and 28 days of age. At each age, three 4 x 8 in. cylinders were tested. The durability and permeability of the mixtures are examined in Chapters 4 and 5.

## 2.4 PRESENTATION OF RESULTS

### 2.4.1 Fresh Concrete Results

The fresh concrete results are shown below in Tables 2.15, 2.16, 2.17, 2.18, 2.19, and 2.20. The results are separated by the six different sections of the research program. The concrete temperature was between 60 and 70 F for most mixtures. The slumps for the mixtures ranged from zero to 12 inches. Some mixtures would not mix. Those mixtures that did not mix are designated with DNM.

Table 2.15. Fresh Concrete Properties from Examining Cement Source.

| Mixtures | Concrete Temp. (F) | Slump (in.) |
|---|---|---|
| 3 | 62 | 8.75 |
| 10 | 65 | 8.50 |
| 30 | 61 | 5.00 |
| 31 | 63 | 5.50 |
| 45 | 61 | 8.00 |

Table 2.16. Fresh Concrete Properties from Examining Effects of HRWR.

| Mixtures | Concrete Temp. (F) | Slump (in.) |
|---|---|---|
| 3-6 | 60 | 1.00 |
| 3-8 | 62 | 2.00 |
| 3-10 | 61 | 12.00 |
| 3-20 | 61 | 12.00 |

Table 2.17. Fresh Concrete Properties from Optimizing Cement Quantity.

| Mixtures | Concrete Temp. (F) | Slump (in.) |
|---|---|---|
| 9-24 | 60 | 7.50 |
| 10-24 | 63 | 6.00 |
| 8-26 | 68 | 2.50 |
| 9-26 | 63 | 7.00 |
| 10-26 | 62 | 8.25 |
| 8-28 | 58 | 7.50 |
| 9-28 | 59 | 8.25 |
| 10-28 | 58 | 9.50 |
| 8-30 | 71 | 7.50 |
| 9-30 | 72 | 9.00 |
| 10-30 | 70 | 10.0 |

Table 2.18. Fresh Concrete Properties from Optimizing HRWR Dosage.

| Mixtures | Concrete Temp. (F) | Slump (in.) |
|---|---|---|
| 9-26-18 | 60 | 8.25 |
| 9-28-18 | 60 | 10.0 |
| 9-30-18 | 62 | 11.0 |
| 9-26-15 | 63 | 6.50 |
| 9-28-15 | 61 | 7.75 |
| 9-30-15 | 60 | 9.00 |
| 9-26-10 | 65 | 0.50 |
| 9-28-10 | 68 | 2.00 |
| 9-26-5 | - | DNM |
| 9-28-5 | 61 | 7.75 |
| 8-28-15 | 77 | 6.25 |
| 9-28-15 | 77 | 8.25 |
| 10-28-15 | 77 | 7.25 |

Table 2.19. Fresh Concrete Properties from Optimizing HRWR and WR Dosage.

| Mixtures | Concrete Temp. (F) | Slump (in.) |
|---|---|---|
| 9-26-5/6 | 60 | DNM |
| 9-26-5/3 | 60 | DNM |
| 9-26-8/6 | 59 | 2.00 |
| 9-26-10/6 | 59 | 3.25 |
| 9-26-10/3 | 55 | 1.50 |
| 9-26-10/3 | 63 | 4.00 |
| 9-26-15/3 | 65 | 7.00 |
| 9-28-5/3 | 60 | 0.50 |
| 9-28-10/6 | 65 | 4.00 |
| 9-28-10/3 | 58 | 2.50 |
| 9-28-10/3 | 65 | 6.00 |
| 9-28-15/3 | 71 | 8.25 |
| 9-30-10/6 | 65 | 8.25 |
| 9-30-15/3 | 65 | 9.50 |

Table 2.20. Fresh Concrete Properties from Examining Accelerator Dosage.

| Mixtures | Concrete Temp. (F) | Slump (in.) |
|---|---|---|
| 8-28-15D | 72 | 0.00 |
| 9-28-15D | 71 | 4.25 |
| 10-28-15D | 72 | 6.00 |
| 9-26-10D | - | DNM |
| 9-28-10D | - | 0.25 |
| 9-30-10D | 73 | 0.25 |
| 9-28-15/3D | 74 | 7.00 |
| 10-26-10/6D | - | DNM |

### 2.4.2 Hardened Concrete Results.

The compressive strength at one and 28 days was the only hardened concrete property tested for this portion of the research. Each compressive strength result is the average of three 4 x 8 in. cylinders. The individual cylinder tests, standard deviations, and confidence intervals are shown in Appendix A. The durability and permeability are examined in later chapters. The test results are shown in Table, 2.21, 2.22, 2.23, 2.24, 2.25 and 2.26.

Table 2.21. Compressive Strength Results from Examining Cement Source.

| Mixtures | Average One Day (psi)[1] | Average 28 Day (psi)[1] |
|---|---|---|
| 3 | 5500 | 12,110 |
| 10 | 3690 (2 d) | 6040 |
| 30 | 5550 | 12,630 |
| 31 | 4640 | 12,890 |
| 45 | 7670 | 12,120 |

1) Average compressive strength of three tests.
2) Individual tests and statistical data are shown in Appendix A.

Table 2.22. Compressive Strength Results from Examining Effects of HRWR.

| Mixtures | Average One Day (psi)[1] | Average 28 Day (psi)[1] |
|---|---|---|
| 3-6 | 6370 | 10,920 |
| 3-8 | 7240 | 10,920 |
| 3-10 | 6350 | 11,280 |
| 3-20 | 4220 | 11,800 |

1) Average compressive strength of three tests.
2) Individual tests and statistical data are shown in Appendix A.

Table 2.23. Compressive Strength Results from Optimizing Cement Quantity.

| Mixtures | Average One Day (psi) [1] | Average 28 Day (psi) [1] |
|---|---|---|
| 9-24 | 7190 | 11,805 |
| 10-24 | 8390 | 13,750 |
| 8-26 | 8210 | 12,450 |
| 9-26 | 7450 | 11,950 |
| 10-26 | 6840 | 12,050 |
| 8-28 | 7440 | 12,300 |
| 9-28 | 6940 | 11,410 |
| 10-28 | 5250 | 11,550 |
| 8-30 | 4750 | 10,480 |
| 9-30 | 3890 | 10,050 |
| 10-30 | 2780 | 9510 |

1) Average compressive strength of three tests.
2) Individual tests and statistical data are shown in Appendix A.

Table 2.24. Compressive Strength Results from Optimizing HRWR Dosage.

| Mixtures | Average One Day (psi) [1] | Average 28 Day (psi) [1] |
|---|---|---|
| 9-26-18 | 6660 | 11,540 |
| 9-28-18 | 6980 | 12,210 |
| 9-30-18 | 5460 | 12,840 |
| 9-26-15 | 7930 | 12,140 |
| 9-28-15 | 6180 | 12,540 |
| 9-30-15 | 5710 | 11,575 |
| 9-26-10 | 8990 | 11,930 |
| 9-28-10 | 8280 | 12,390 |
| 9-26-5 | DNM | DNM |
| 9-28-5 | 6990 | PC* |
| 8-28-15 | 7430 | 13,010 |
| 9-28-15 | 7595 | 13,540 |
| 10-28-15 | 6240 | 10,090 |

1) Average compressive strength of three tests.
2) Individual tests and statistical data are shown in Appendix A.
3) PC = Poor Cylinders, due to poor workability the remaining cylinders were not properly consolidated.
4) DNM = concrete mixtures that did not mix.

Table 2.25. Compressive Strength Results from Optimizing HRWR and WR Dosage.

| Mixtures | Average One Day (psi) [1] | Average 28 Day (psi) [1] |
|---|---|---|
| 9-26-5/6 | DNM | DNM |
| 9-26-5/3 | DNM | DNM |
| 9-26-8/6 | 8560 | 13,250 |
| 9-26-10/6 | 9000 | 14,120 |
| 9-26-10/3 | 8830 | PC |
| 9-26-10/3 | 9290 | 13,150 |
| 9-26-15/3 | 8520 | 13,370 |
| 9-28-5/3 | 7900 | PC |
| 9-28-10/6 | 9100 | 12,870 |
| 9-28-10/3 | 8460 | 12,570 |
| 9-28-10/3 | 7920 | 11,650 |
| 9-28-15/3 | 7420 | 13,500 |
| 9-30-10/6 | 7830 | 11,980 |
| 9-30-15/3 | 7850 | 12,150 |

1) Average compressive strength of three tests.
2) Individual tests and statistical data are shown in Appendix A.
3) PC = Poor Cylinders, due to poor workability the remaining cylinders were not properly consolidated.
4) DNM = concrete mixtures that did not mix.

Table 2.26. Compressive Strength Results from Examining Accelerator Dosage.

| Mixtures | Average One Day (psi) [1] | Average 28 Day (psi) [1] |
|---|---|---|
| 8-28-15D | 7920 | PC |
| 9-28-15D | 8960 | 13,240 |
| 10-28-15D | 9100 | 13,870 |
| 9-26-10D | DNM | DNM |
| 9-28-10D | 8780 | PC |
| 9-30-10D | 8400 | PC |
| 9-28-15/3D | 8630 | 12,880 |
| 10-26-10/6D | DNM | DNM |

1) Average compressive strength of three tests.
2) Individual tests and statistical data are shown in Appendix A.
3) PC = Poor Cylinders, due to poor workability the remaining cylinders were not properly consolidated.
4) DNM = concrete mixtures that did not mix.

## 2.5 DISCUSSION OF RESULTS

### 2.5.1 Fresh Concrete Results

**2.5.1.1 Cement Source.** The source of cement had little effect on the workability of the mixtures. The slumps of the mixtures are shown in Figure 2.1. This is expected because there was little difference between the two cements. Both cements had finenesses within 500 $cm^2/g$ of each other. Higher cement fineness increases the amount of surface area, which would increase the water demand, but the difference in fineness was not that great.

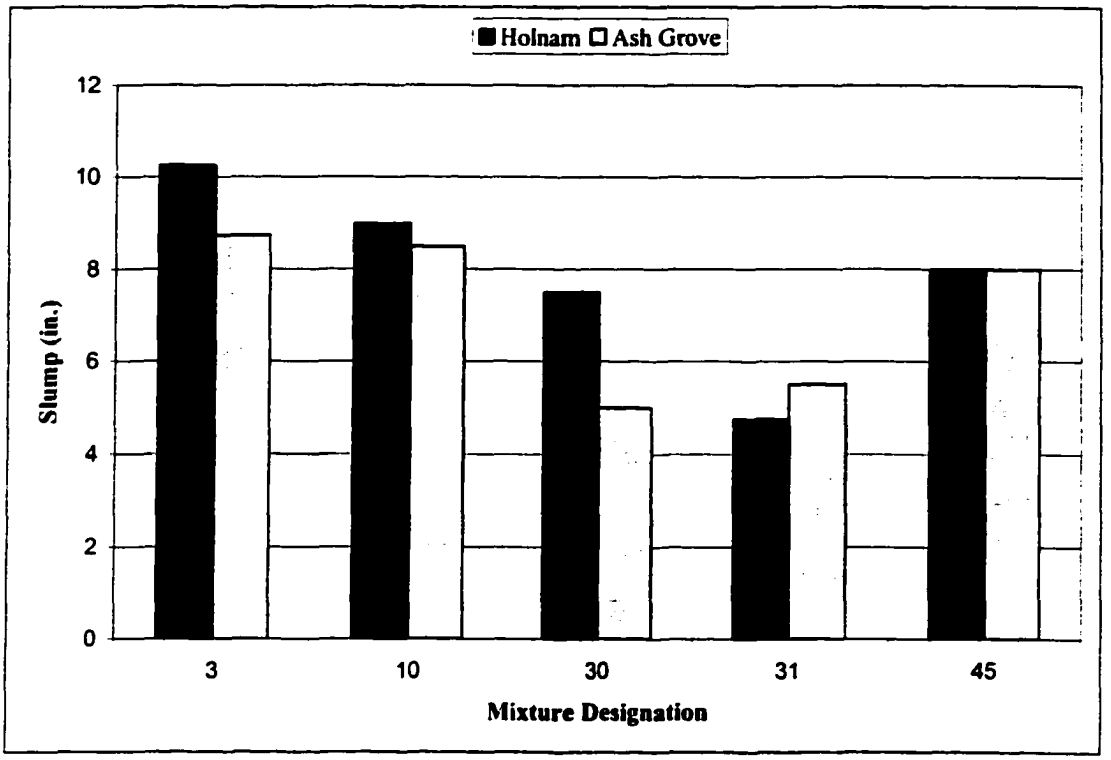


Figure 2.1 Slumps of Ash Grove and Holnam Mixtures.

**2.5.1.2 High Range Water Reducer Source.** For this portion of the research, Mixture 3 was batched five times with either Daracem 19 or ADVA Flow. All mixtures contained Ash Grove Type III Cement. The results of the slump tests are shown in Figure 2.2. Once again, the last number in the mixtures designations is the dosage rate of HRWR in fl oz/cwt. From the figure, it is evident that the dosage rates for the two HRWR are different. At equal dosage rates, mixtures containing ADVA Flow had greater slumps than mixtures cast with Daracem 19. Furthermore, to produce concrete with similar slumps the dosage rate for mixtures containing ADVA Flow was less than half of that for mixtures cast with Daracem 19.

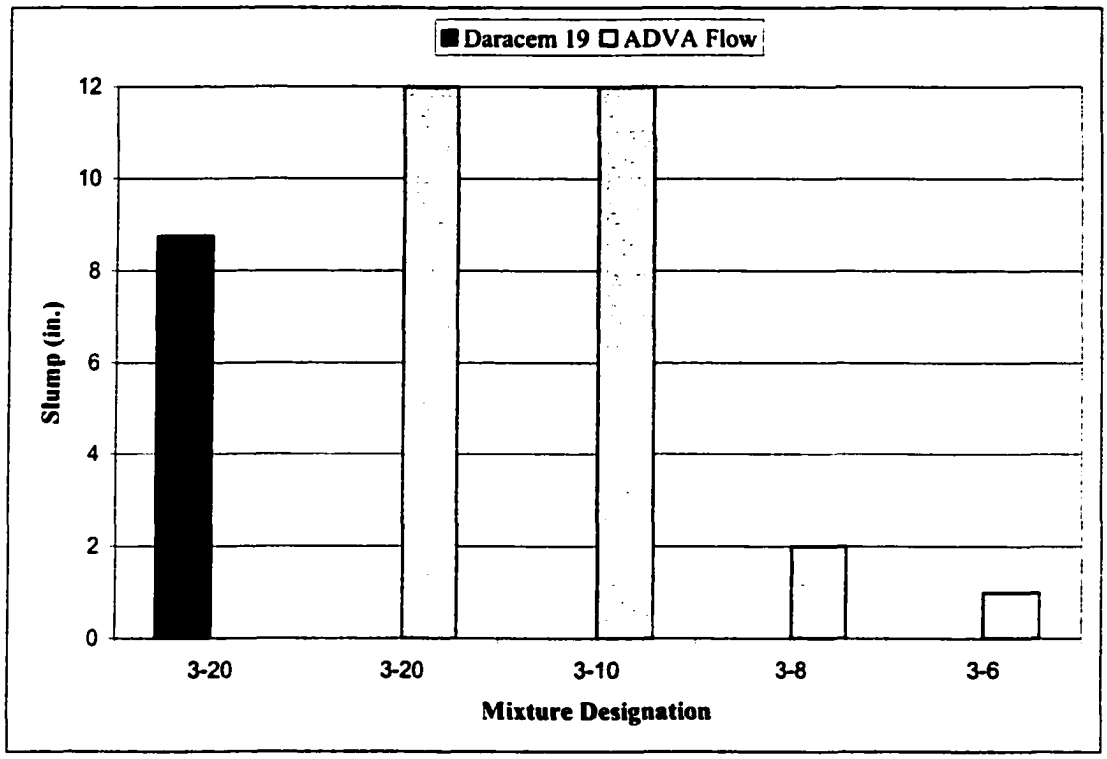


Figure 2.2 Comparisons of ADVA Flow and Daracem 19.

**2.5.1.3 Cement Quantity and Water to Cementitious Material Ratio.** The goal of the next phase in the research program was to determine the optimum cement content and w/cm. The results are shown in Figure 2.3. All mixtures were cast with Ash Grove Type III Cement and contained ADVA Flow at a dosage rate of 22.5 fl oz/cwt. The cement content for the mixtures was 800, 900, or 1000 lb/yd$^3$. The w/cm for the mixtures was 0.24, 0.26, 0.28, or 0.30. For all but one mixture, increases in w/cm resulted in increases in slumps, which was expected. Also, for all mixtures except one, increases in cement content resulted in greater slumps for mixtures of the same w/cm, which was also expected. Since adequate workability was a requirement, mixtures with a w/cm greater than 0.26 and cement content equal to and greater than 900 lb/yd$^3$ were further examined in the research program. Also, the results from the slump tests showed that reducing the dosage of ADVA Flow might be possible due to

the fact that most mixtures had slumps greater than seven inches. From the slump data, a preliminary design aid (Table 2.27) was developed to show the relationship of w/cm, cementitious material content, and slump. When combined with additional research results, the table could be used as a design aid to assist engineers in developing concrete mixtures.

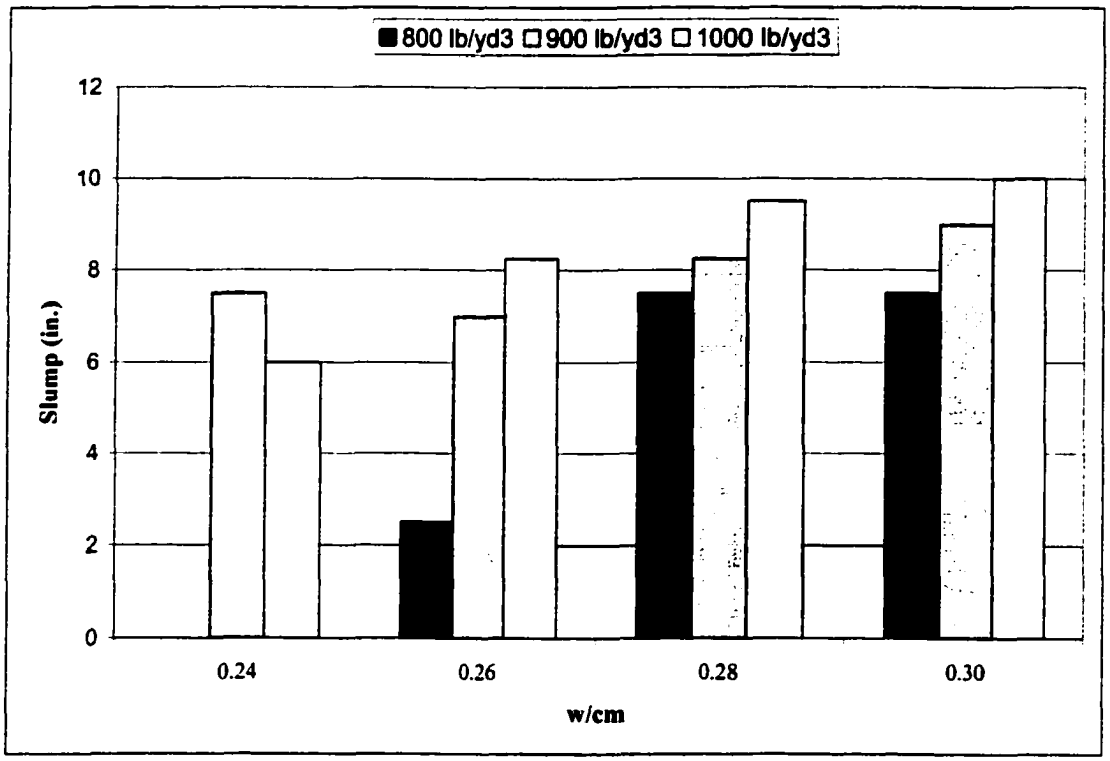


Figure 2.3. Slumps for Determining Cement Content and w/cm.

Table 2.27. Design Aid for Determining Slumps (in.) Based on Mixture Properties.

| w/cm | Cementitious Material Content | | |
|---|---|---|---|
| | 800 | 900 | 1000 |
| 0.26 | 2.50 | 7.00 | 8.25 |
| 0.28 | 7.50 | 8.25 | 9.50 |
| 0.30 | 7.50 | 9.00 | 10.00 |

**2.5.1.4 High Range Water Reducer Dosage.** The goal of this phase of the research was to determine the optimum HRWR dosage. The HRWR dosage was varied from 5 to 18 fl oz/cwt. All mixtures contained 900 lb/yd$^3$ of cement, and the HRWR used was ADVA Flow. The results of the study are shown in Figure 2.4. As expected, the HRWR dosage did affect the slumps of the mixtures. Increases in the quantity of HRWR resulted in increases in slump and workability. Also, increases in w/cm resulted in increases in slumps, which was also expected. For mixtures containing 900 lb/ft$^3$ of cement, the results shown in Figure 2.4 indicate that a minimum HRWR dosage of 15 fl oz/cwt is necessary to produce concrete with adequate workability.

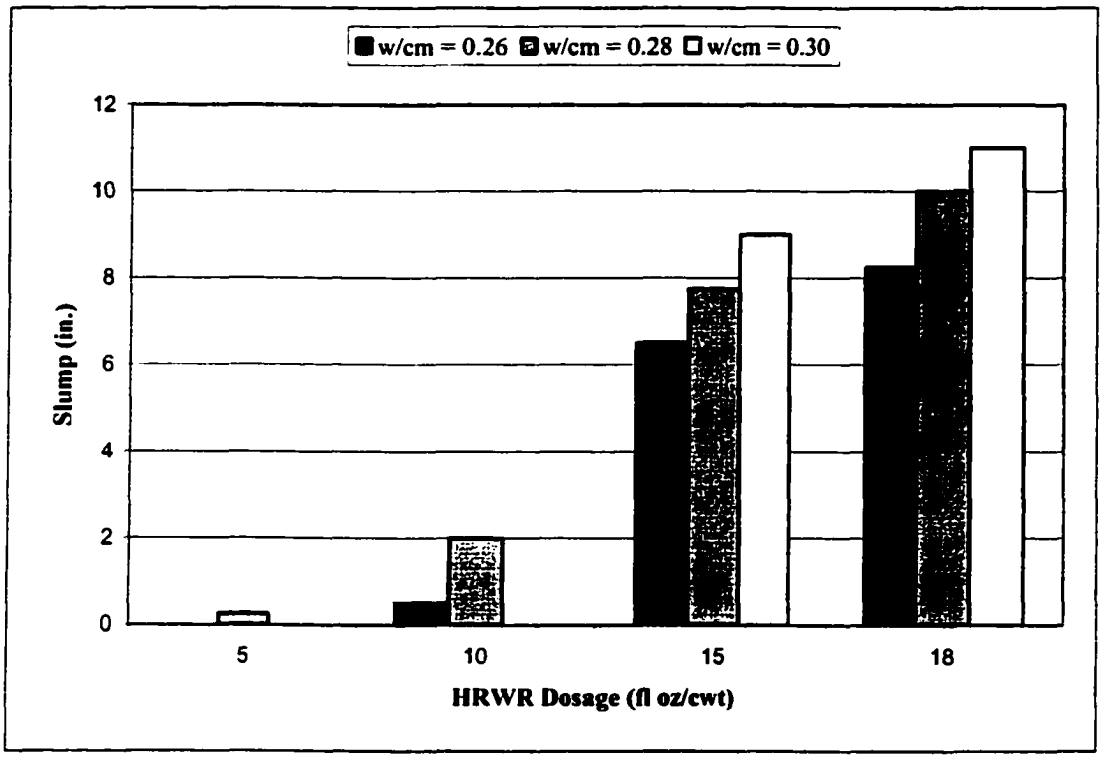


Figure 2.4. Slumps for Determining HRWR Dosage.

**2.5.1.5 High Range Water Reducer and Water Reducer.** The next phase of the research examined whether the addition of a WR could reduce the HRWR dosage. All mixtures contained 900 lb/yd$^3$ of cement. The WR and HRWR used was WRDA with Hycol and ADVA Flow, respectively. The results are shown in Figure 2.5. To produce concrete with sufficient workability, a HRWR dosage of 15 fl oz/cwt was still necessary for concrete mixtures with a w/cm of 0.26. Lower dosages of HRWR were possible at higher w/cm, but the increase in w/cm decreased compressive strength which will be shown later in the chapter.

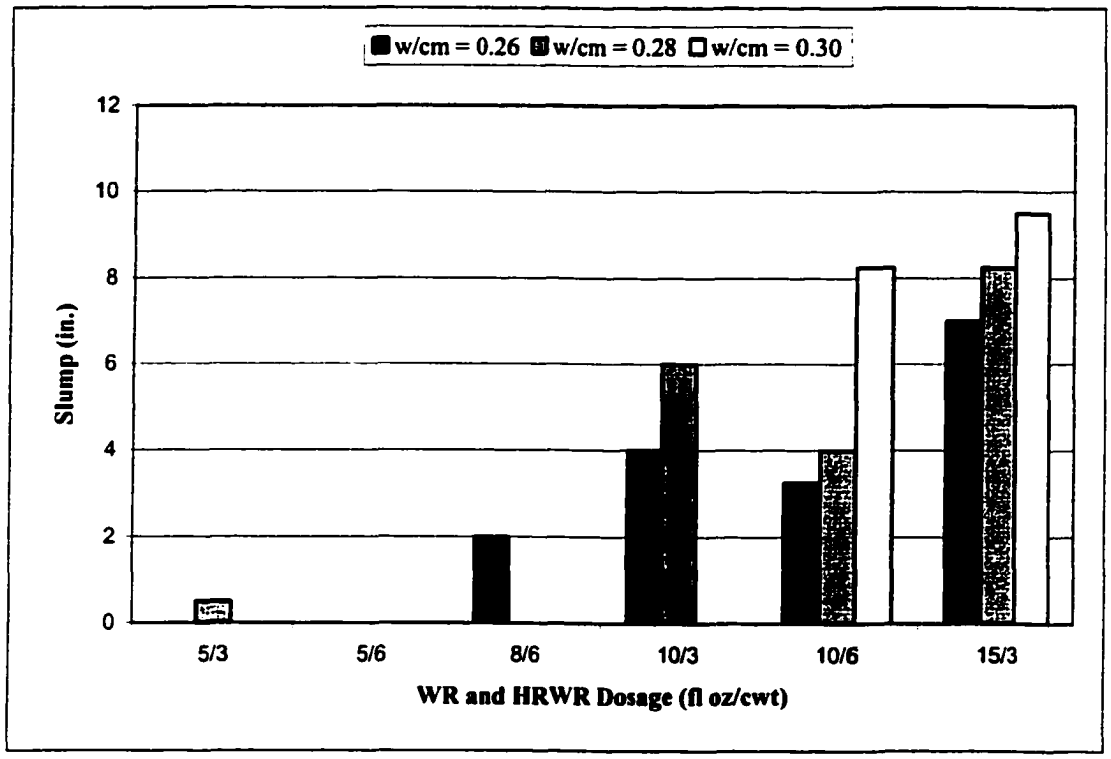


Figure 2.5. Slumps for Determining WR and HRWR Dosage.

**2.5.1.6 Accelerator.** The final phase of this section investigated the addition of an accelerator to increase the compressive strength at one day of age. Accelerators are added to concrete to reduce the set times and increase early age strength. The results from the study were shown in Table 2.20. The addition of the accelerator reduced the workability of most mixtures. Most importantly, the accelerator greatly increased the slump loss. Many mixtures began to set before all the specimens could be cast. This is an important factor in the research because with the mixtures developed, beams were cast. The mixtures must be fluid for a sufficient period of time to allow the beams to be cast.

### 2.5.2 Hardened Concrete Results

**2.5.2.1 Cement Source.** Concrete mixtures containing Ash Grove Type III Cement were cast using the same mix designs that performed well with Holnam Type III Cement. Other than cement source, the remaining quantities and types of materials remained the same for each pair of mixtures. The HRWR used for all mixtures was Daracem 19. Comparisons of the compressive strengths of the two cements are shown in Table 2.28.

With the exception of mixture 45, concrete mixtures made with Ash Grove cement did not perform as well as concrete mixtures made with Holnam Type III Cement. Not only did the Ash Grove mixtures have significantly less strength (3000 to 5000 psi at one day), the cement appeared to react differently with the HRWR, Daracem 19. For instance, the set time was delayed for Mixture 10. Mixture 10 had a one-day compressive strength of 10,050 psi when made with Holnam III, whereas the same mixture made with Ash Grove III had not reached final set at 24 hours and had a two-day compressive strength of only 3690 psi. This evidence along with the decrease in one-day compressive strength suggested that Daracem 19 might have been reacting differently with Ash Grove III.

Table 2.28. Compressive Strengths of Ash Grove and Holnam Mixtures.

| Mixture | 1 Day (psi) | | 28 Day (psi) | |
|---|---|---|---|---|
| | Holnam | Ash Grove | Holnam | Ash Grove |
| 3 | 9690 | 5500 | 14,240 | 12,110 |
| 10 | 10,050 | 3690 (2d) | 14,600 | 6040 |
| 30 | 7930 | 5550 | 14,670 | 12,630 |
| 31 | 7990 | 4640 | 14,210 | 12,890 |
| 45 | 7350 | 7670 | 13,750 | 12,120 |

**2.5.2.2 High Range Water Reducer Source.** A different HRWR, ADVA Flow, was used with Mixtures 3 and 10 to determine if Ash Grove III was in fact reacting differently with Daracem 19. The results of the one-day compressive strength tests are shown in Figure 2.6. Also shown in Figure 2.6 are the mixtures cast with Holnam III and Daracem 19 and then subsequent mixtures cast with Ash Grove III and various dosages of either Daracem 19 or ADVA Flow. The dosages of the HRWR are listed directly below the type of HRWR.

The use of ADVA Flow produced concrete with greater strengths and greater slumps than like mixtures cast with Daracem 19. However, the best performing Ash Grove mixtures had strengths over 2000 psi less than similar Holnam mixtures at one day of age. Mixture 10, which had not reached final set at 24 hours when made with Daracem 19, achieved a one day compressive strength of 7650 psi when cast with ADVA Flow at a dosage rate of 12 fl oz/cwt. Even with the increase in strength, Mixture 10 when made with ADVA Flow was still significantly less (2500 psi) than the same Holnam III mixture at one day of age. The results from these tests suggest that Ash Grove Cement may have been reacting differently with Daracem 19, but it appears that Holnam Cement was of a higher quality than the other cement.

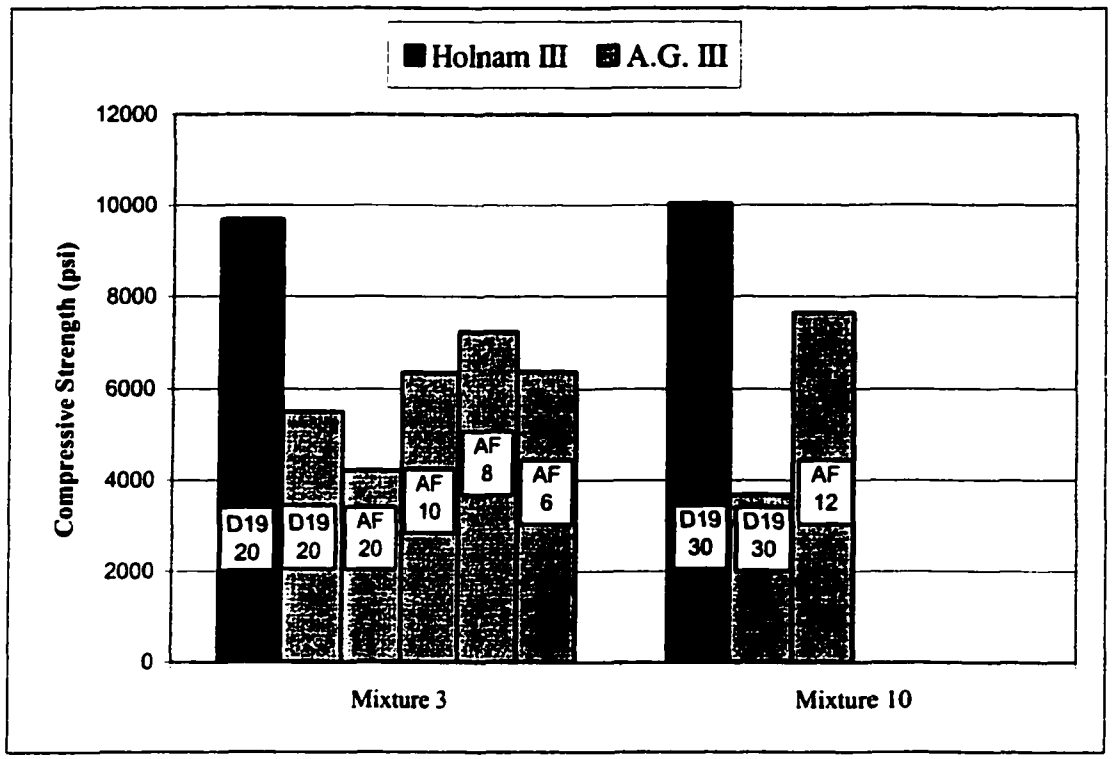


Figure 2.6. One-Day Compressive Strengths of AG III and Holnam III Mixtures.

**2.5.2.3 Cement Quantity and Water to Cementitious Material Ratio.** The goal of the next phase in the research program was to determine the optimum cement content and w/cm. The results are shown in Figures 2.7 and 2.8. All mixtures were cast with Ash Grove Type III Cement and contained ADVA Flow at a dosage rate of 22.5 fl oz/cwt. The cement content for the mixtures was 800, 900, or 1000 lb/yd$^3$. The w/cm for the mixtures was 0.24, 0.26, 0.28, or 0.30.

The results from the tests showed that increases in w/cm decreased the compressive strength at both ages, which was expected. Also, increases in cement content decreased one-day strengths, which are statistically different at 90 percent confidence intervals (Appendix A, Figure A.1). By 28 days of age the differences in the compressive strength of mixtures with like w/cm were becoming less pronounced.

Except for mixtures with a w/cm of 0.24, examination of the 90 percent confidence intervals in Figure A.2 (Appendix A) shows that mixtures with identical w/cm did not have statistically different strengths at 28 days of age. The mixtures with w/cm of 0.24 did not follow the same trend as the other mixtures. It is not clear why the 0.24 mixtures did not follow the same trend. The mixtures had sufficient workability to be mixed and placed properly.

The one-day strengths from these mixtures ranged from 2780 psi to 8390 psi. The slumps of the mixtures were between 3.5 in. to 10.0 in. The results from these mixtures showed that a cement content of 900 pounds per cubic yard of concrete showed the most promise because of its workability (slumps greater than 7 in.) and compressive strength (one day strengths greater than 7000 psi).

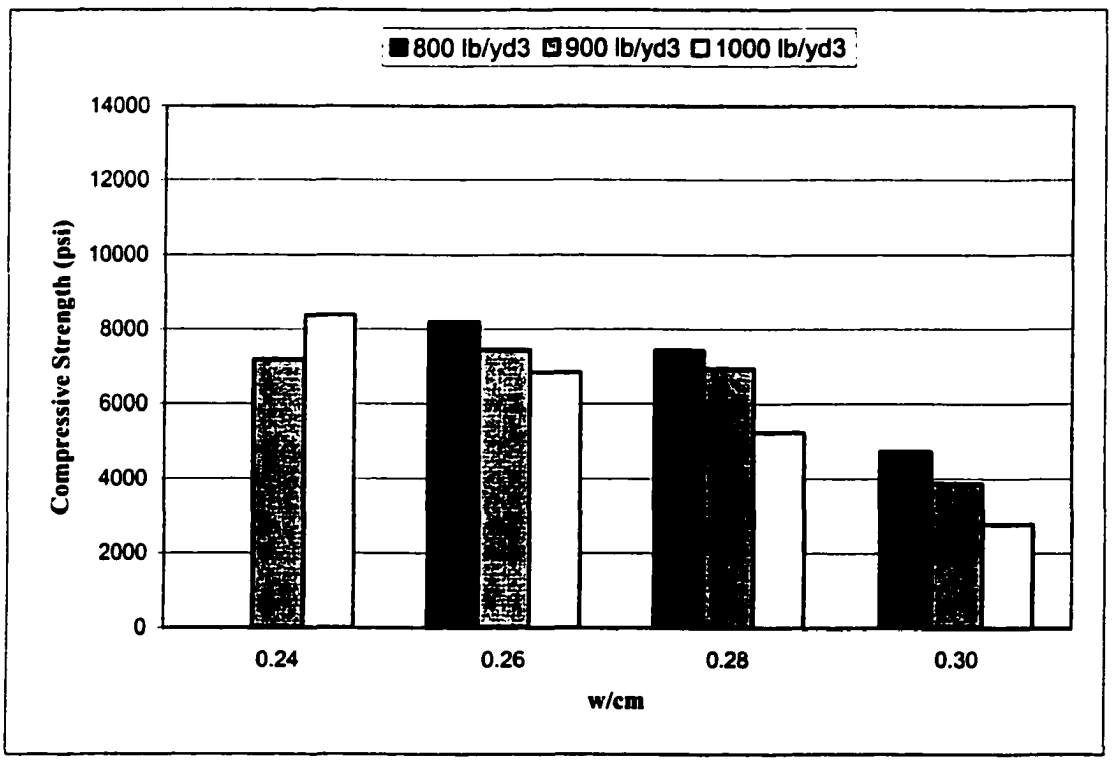


Figure 2.7. One Day Compressive Strengths for Optimizing Cement Content & w/cm.

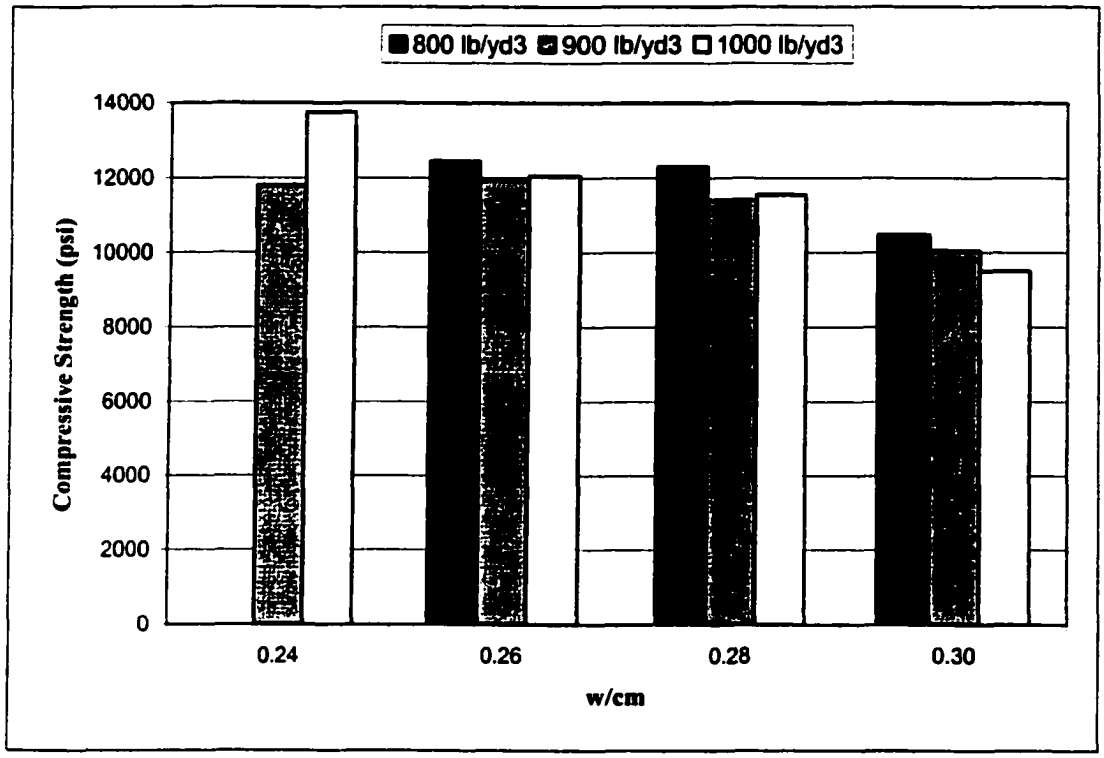


Figure 2.8. 28-Day Compressive Strengths for Optimizing Cement Content & w/cm.

**2.5.2.4 High Range Water Reducer Dosage.** As stated earlier, most mixtures previously cast had slumps of at least six inches. The objective of this phase of the research program was to determine the optimum HRWR dosage. The HRWR dosage was varied from 5 to 18 fl oz/cwt. All mixtures contained 900 lb/yd$^3$ of cement, and the HRWR used was ADVA Flow. The results from the compressive strength tests at one day are shown in Figure 2.9.

Based on compressive strength results alone, a HRWR dosage of 10 fl oz/cwt produced concrete with highest compressive strength at one day and near the highest compressive strength at 28 days of age. However, a HRWR dosage of 10 fl oz/cwt did not provide enough workability to allow a beam to be cast. At one day, the retarding effects of the HRWR can be seen in Figure 2.9. With the exception of the

one mixture cast with 5 fl oz/cwt of HRWR, the mixtures containing smaller dosages of HRWR had higher compressive strengths. Examination of the 90 percent confidence intervals in Figure A.3 (Appendix A) shows that there are significant differences between the one-day compressive strengths of mixtures with w/cm of 0.26 and 0.28 at HRWR dosages of 10 and 15 fl oz/cwt. This trend is also evident between mixtures with HRWR dosages of 10 and 18 fl oz/cwt. For example, reducing the HRWR dosage from 18 fl oz/cwt to 10 fl ox/cwt increased the one-day compressive by 2330 psi for mixtures with a w/cm of 0.26.

By 28 days of age, the difference in compressive strength of all mixtures was less than 1500 psi. The compressive strengths for five of the eight mixtures were not statistically different (Figure A.4 in Appendix 4). This was expected because by 28 days of age the retarding effects of the HRWR are minimized. Based on workability and compressive strength, mixtures with a w/cm of 0.26 and HRWR of 15 fl oz/cwt displayed the most promise of producing concrete with the highest compressive with sufficient workability.

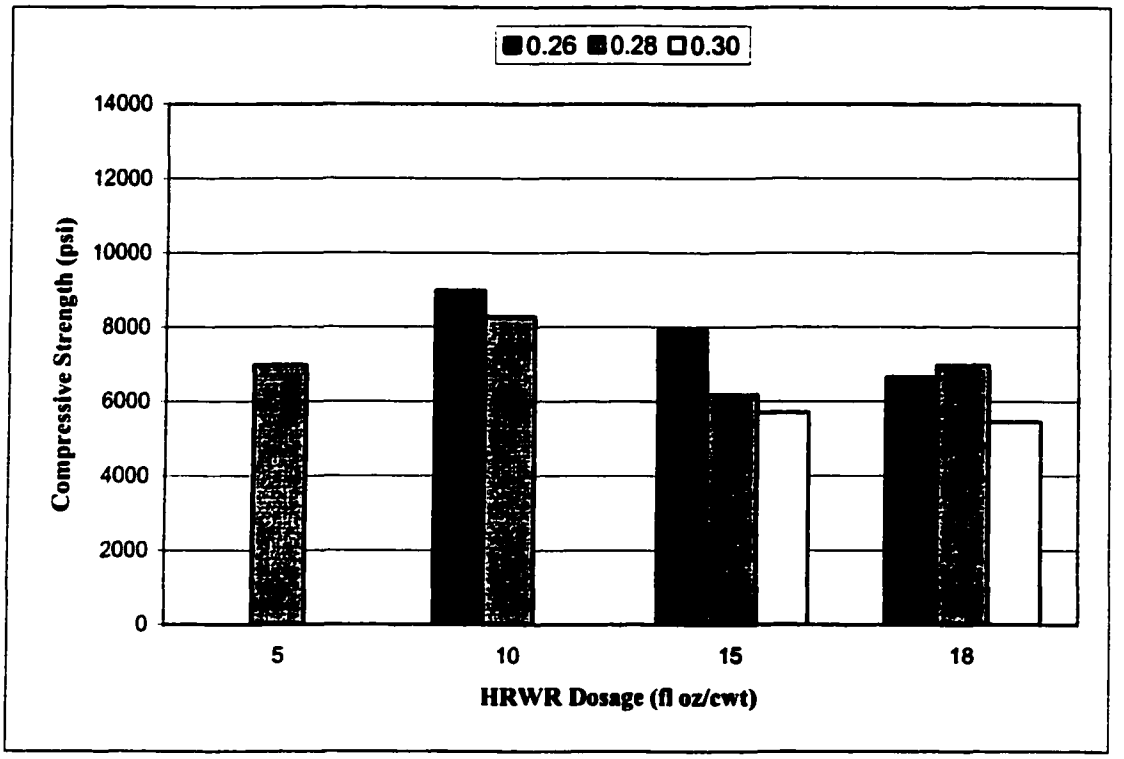


Figure 2.9. One-Day Compressive Strength for Optimizing HRWR Dosage.

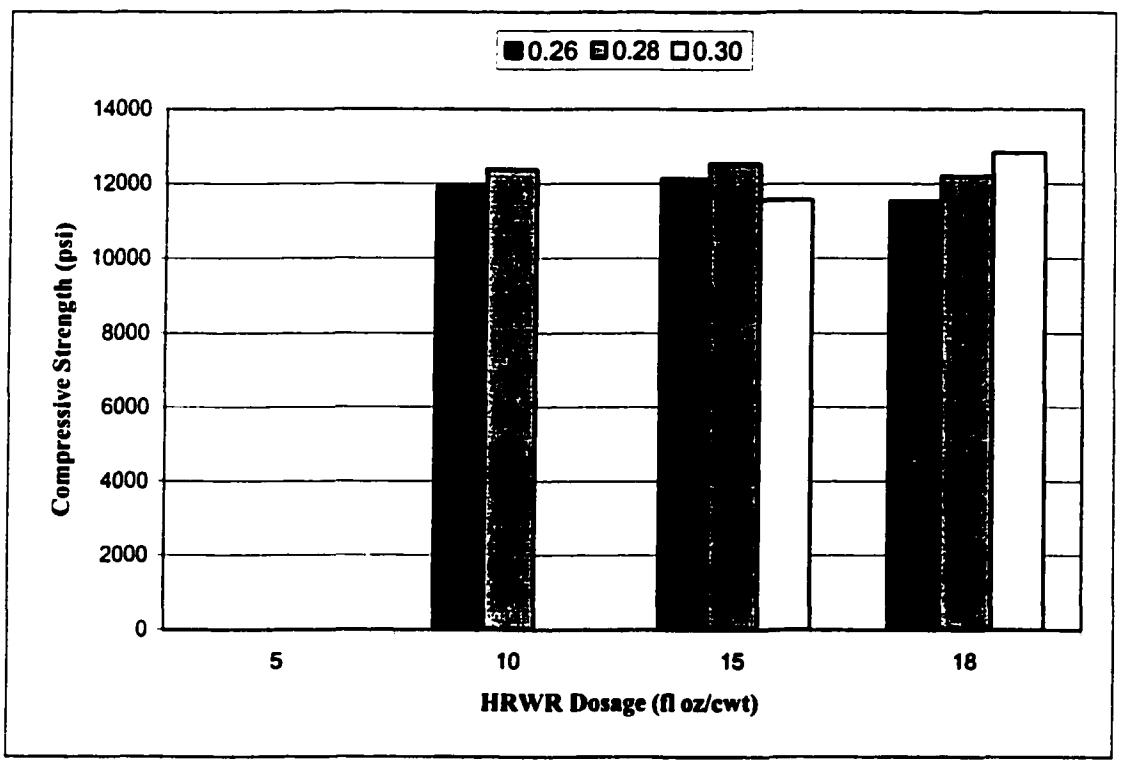


Figure 2.10. 28-Day Compressive Strength for Optimizing HRWR Dosage.

**2.5.2.5 High Range Water Reducer and Water Reducer.** The next phase of the research examined whether the addition of a WR could reduce the HRWR dosage. All mixtures contained 900 lb/yd$^3$ of cement. The compressive strength results at one day of age are shown in Figure 2.11. Once again, the mixtures with a HRWR dosage of 10 fl oz/cwt produced concrete with the greatest compressive strength at one day of age (9250 psi), which is statistically different through examination of the 90 percent confidence intervals (Figure A.5 in Appendix A). Even though the addition of a WR allowed for the reduction in the HRWR dosage, the slump or workability was too low to reduce the HRWR dosage below 15 fl oz/cwt. Lower dosages of HRWR were possible at higher w/cm, but the increase in w/cm decreased compressive strength at one day and 28 days of age.

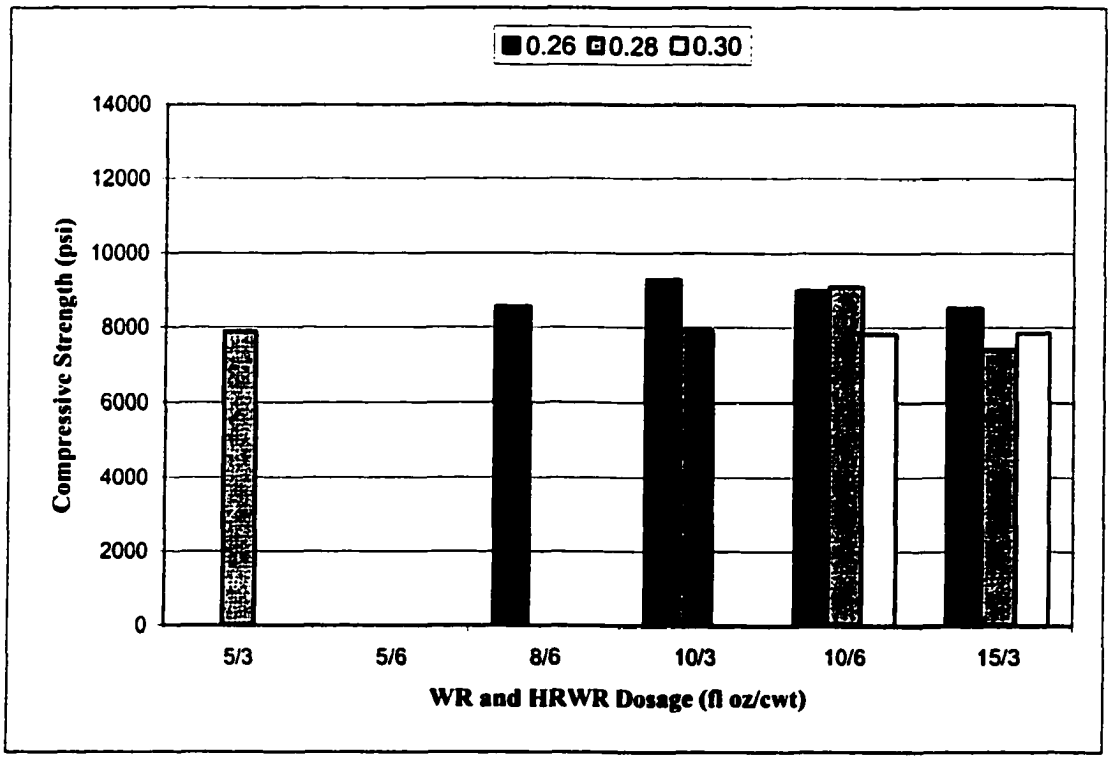


Figure 2.11. One-Day Compressive Strength for Optimizing HRWR and WR Dosage.

**2.5.1.6 Accelerator.** The final phase of this section of the research investigated the addition of an accelerator to increase the compressive strength at one day of age. The results from the study were listed in Table 2.26 and are shown in Figure 2.12. For all mixtures, the addition of the accelerator increased the one-day compressive strength. The differences for all mixtures except for 9-28-10 and 9-28-10D were statistically significant (Figure A.7 in Appendix A). For most mixtures, the increase in compressive strength was between 500 and 1500 psi. Even though all mixtures benefited from the addition of the accelerator, the substantial slump loss proved to be too great to benefit from the use of an accelerator.

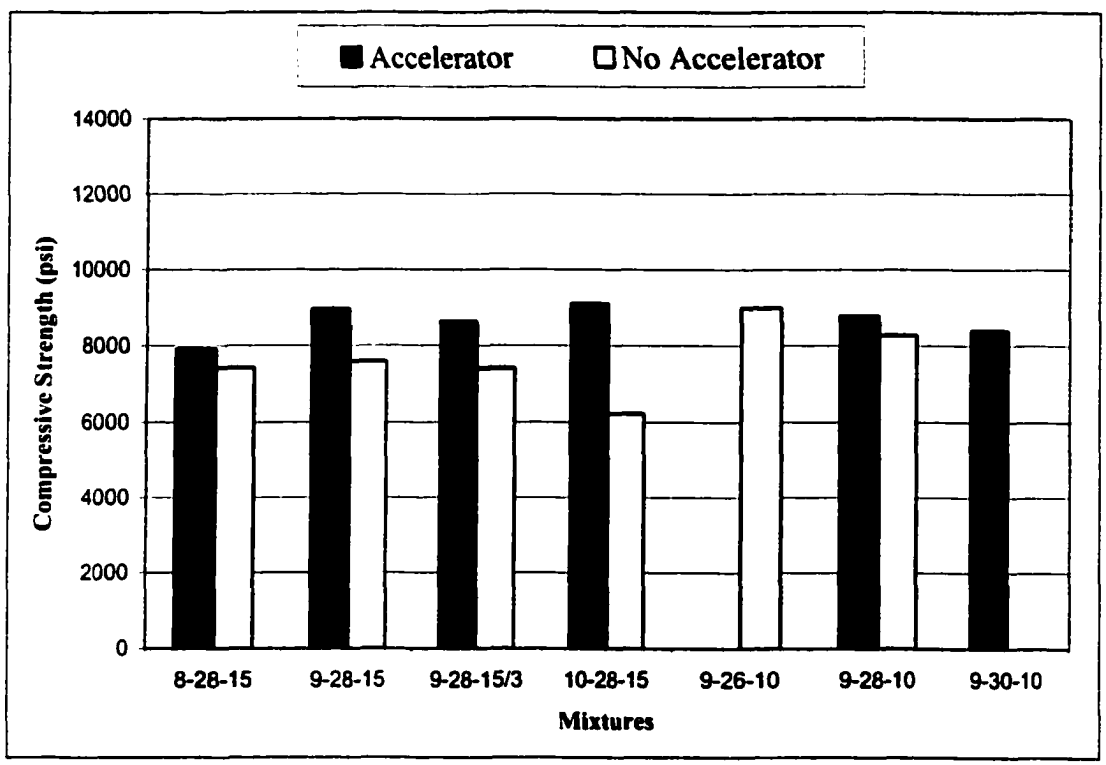


Figure 2.12. One-Day Compressive Strength Results for Examining Accelerator Dosage.

## 2.6 CONCLUSIONS

The results of the research program showed that HPC can be produced with materials that are native to Oklahoma. All materials used in the research program are currently being used by batch plants and prestressing facilities in the area. The research program determined that Holnam Type III Cement produced higher strengths than Ash Grove Type III Cement. However, concrete mixtures were cast with Ash Grove cement that achieved a one-day compressive strength of more than 9000 psi and a 28-day compressive strength of more than 14,000 psi, but the compressive strength of the Ash Grove mixture was still approximately 1000 psi less at both ages than the best performing Holnam mixture. A minimum w/cm of 0.26 and a maximum HRWR dosage of 15 fl oz/cwt were established as the lower and upper limits needed to produce concrete mixtures with sufficient workability. Extensive slump loss negated the use of an accelerator. The findings of this section of the research program are summarized below.

1. The cement source had little effect on the workability of the mixtures, which was expected because both cements had similar fineness. However, there were differences in the compressive strength. Concrete mixtures made with Ash Grove cement did not perform as well as concrete mixtures made with Holnam cement. Not only did the Ash Grove mixtures have significantly less strength (3000 to 5000 psi at one day), the cement appeared to react differently with the HRWR, Daracem 19. It is not clear

as to why Holnam cement produced concrete with greater compressive strengths.

2. For most mixtures, increases in cement content resulted in greater slumps for mixtures with like w/cm. The results showed that a minimum cement content of 900 lb/yd$^3$ was necessary for a concrete mixture with a w/cm equal to and less than 0.26 to have sufficient workability. For the mixtures tested, cement contents of 800 lb/yd$^3$ and greater produced workable concrete at w/cm of 0.28 and greater. Results from these mixtures showed that a cement content of 900 pounds per cubic yard of concrete showed the most promise because of its workability (slumps greater than 7 in.) and compressive strength (one day strengths greater than 7000 psi).
3. The addition of HRWR increased workability. Too much HRWR delayed set times and decreased early age strength. At w/cm between 0.26 to 0.30, a dosage rate of 15 fl oz/cwt was necessary to produce concrete with sufficient workability. Lower dosages of HRWR were possible with the use of a WR but only at higher w/cm. Based on workability and compressive strength, mixtures with a w/cm of 0.26 and HRWR of 15 fl oz/cwt displayed the most promise of producing concrete with the highest compressive strength with sufficient workability.
4. The addition of an accelerator increased the one-day compressive strength. For most mixtures, the increase in compressive strength was between 500 and 1500 psi. Even though all mixtures benefited from the addition of the

accelerator, the substantial slump loss proved to be too great to benefit from the use of an accelerator.

5. Based on compressive strength and workability, the results of research program indicated that for the aggregates and cements tested, the optimum cement content was 900 lb/yd$^3$. The optimum w/cm was 0.26 and the optimum coarse aggregate content was 1790 lb/yd$^3$. This mix proportion will be used to cast the precast/prestressed bridge girders that will be examined in later phases of the research program.

# CHAPTER 3

# DEVELOPING HPC WITH ENTRAINED AIR

## 3.1 INTRODUCTION

The second phase in the research program developed High Performance Concrete (HPC) with entrained air. It is necessary entrain air in some concrete structures that are subjected to freezing and thawing cycles. Entrained air is added to concrete through the use of air entraining agents (AEA). Current building codes require varying amounts of entrained air depending on the severity of the exposure. Entrained air voids provide air pockets where water can expand and water pressure can be relieved. Without these voids, continuous freeze/thaw cycles will eventually degrade and damage the concrete. A total air content between four and eight percent is generally considered adequate to provide resistance to the freeze/thaw action (Mindess et al, 1981).

The chapter will show the development of HPC with entrained air and also the effects of entrained air on the fresh and hardened properties of concrete. As with the mixtures developed in Chapter 2, mixtures will be cast that incorporate materials that are native to and commonly used in Oklahoma. Based on this material work, two prestressed concrete girders were cast with one of the mixtures developed during this portion of the research. The water to cementitious material ratio (w/cm), air content, and the type and dosage of admixtures are all variables that were examined.

## 3.2 LITERATURE REVIEW

There are two types of air voids in concrete, entrapped air and entrained air. Entrapped air voids become entrapped in the concrete during the mixing of the concrete. These voids typically have a diameter of 0.04 in. or larger (Kosmatka et al, 1994). They are randomly spaced throughout out the concrete. Entrapped air voids normally make up approximately one to two percent of the total volume of a concrete mixture. Entrained air voids are introduced into the concrete through the use of chemical admixtures called air-entraining agents (AEA). The AEA are commercial, chemical admixtures that when added to the concrete during mixing produce tiny air bubbles in the concrete. There may be as many as 300 billion bubbles in a cubic yard of concrete with a total air content of four to six percent by volume (Kosmatka et al, 1994). Entrained air voids generally have a diameter of about 0.002-in. (Neville, 1997) and are evenly distributed throughout the concrete. Entrained air voids are typically spaced within 0.008 in. of each other (Derucher et al, 1994).

It is necessary to add AEA to some concrete structures that are subjected to freezing and thawing. The Building Code Requirements for Structural Concrete and Commentary requires varying amounts of entrained air depending on the severity of exposure and nominal maximum aggregate size. Entrained air voids provide air pockets where water can expand and water pressure can be relieved. Without these voids, continuous freeze/thaw cycles will eventually degrade and damage the concrete. For all concrete structures, a total air content between four and eight

percent is generally considered adequate to provide resistance to the freeze/thaw action (Mindess et al, 1981).

Although the addition of entrained air improves the concrete's freeze/thaw durability, entrained air has a negative effect on strength. Entrained air decreases the compressive strength of both NSC and HPC. As a rule of thumb, an increase in the total air content of one percent decreases compressive strength two to five percent (Mindess et al, 1981). For example, a concrete mixture with a total air content of seven percent may have a compressive strength that is 25 percent less than an identical mixture with a total air content of two percent.

## 3.3 EXPERIMENTAL PROCEDURES

### 3.3.1 Scope

This portion of the research program developed HPC with entrained air. With one of the mixtures developed, two prestressed/precast concrete girders were produced. Therefore, strength and durability were not the only concern; the concrete mixtures must have sufficient workability. The mixtures required enough workability to be used at a local prestressed concrete facility. Another necessity was the need for the mixtures to contain the materials and admixtures that were currently in use at the facility. The total air content, w/cm, and the type and dosage of admixtures were varied in the research. A goal of the research program was to produce HPC with entrained air and also to examine the effects of entrained air on the properties of the fresh and hardened concrete, specifically the compressive strength. The research

results showed that air entrained HPC is possible using materials native to Oklahoma. However, the research results also showed that trial batching is necessary to determine the appropriate dosage of AEA at w/cm less 0.34.

### 3.3.2 Materials

The type of fine and coarse aggregate was constant for all mixtures. A fine aggregate from Dover, Oklahoma was used. The coarse aggregate was 3/8-in., crushed limestone from Davis, Oklahoma. The material properties of the fine and coarse aggregates are shown in Table 2.1 of Chapter 2. Ash Grove Type III Cement from Chanute, KS was used in all mixtures. The chemical compositions and blaine fineness of the cement are shown in Table 2.2 of Chapter 2. When needed, a water reducer, WRDA with Hycol, and a high range water reducer, ADVA Flow, were added to the mixtures to provide adequate workability. To achieve the necessary amounts of entrained air, an air-entraining agent (AEA), DARAVAIR 1000 was added to the mixtures.

### 3.3.3 Variables

The variables examined in the research were the w/cm, admixture dosage, and the total air content. The w/cm examined were 0.26, 0.28, 0.30, 0.34, 0.36, 0.42, and 0.50. When needed a WR and/or a HRWR were added to the mixtures to provide sufficient workability. The targeted total air content was 2, 4, and 6 percent at each w/cm.

### 3.3.4 Mixtures

The mixture designs are shown in Tables 3.1 through Table 3.9. Each mixture is designated by the quantity of cement in the mixture, the w/cm of the mixture, and the measured total air content of the fresh concrete. For example, Mixture 9-26-1.8 contains 900 lb/yd$^3$ of cement and has a w/cm of 0.26. The measured air content of the fresh concrete was 1.8 percent.

The targeted total air contents for the mixtures were 2, 4, and 6 percent. Many mixtures required several trial batches in order to achieve the desired air content. Mixtures were cast until the measured air content was within ± 0.5 percent of the desired air content. Mixtures with air contents out of this range were discarded.

Table 3.1. Mixture Proportions.

| Materials | Mixture Designations | | | | |
|---|---|---|---|---|---|
| | 9-26-1.8 | 9-26-2.1 | 9-26-2.4 | 9-26-3.1 | 9-26-3.3 |
| Cement (lb/yd$^3$) | 900 | 900 | 900 | 900 | 900 |
| Coarse Agg. (lb/yd$^3$) | 1790 | 1790 | 1790 | 1790 | 1790 |
| Fine Agg. (lb/yd$^3$) | 1217 | 1128 | 1217 | 1040 | 1040 |
| Water (lb/yd$^3$) | 234 | 234 | 234 | 234 | 234 |
| HRWR (fl oz/cwt) | 15 | 15 | 15 | 15 | 15 |
| WR (fl oz/cwt) | 3 | 3 | 3 | 3 | 3 |
| AEA (fl oz/cwt) | 0 | 4 | 0 | 10 | 15 |
| Calculated Air Content (%) | 2 | 4 | 2 | 6 | 6 |
| w/cm | 0.26 | 0.26 | 0.26 | 0.26 | 0.26 |

Table 3.2. Mixture Proportions Continued.

| Materials | Mixture Designations | | | | |
|---|---|---|---|---|---|
| | 9-26-3.5 | 9-26-3.8 | 9-26-3.9 | 9-26-4.5 | 9-26-5.6 |
| Cement (lb/yd$^3$) | 900 | 900 | 900 | 900 | 900 |
| Coarse Agg. (lb/yd$^3$) | 1790 | 1790 | 1790 | 1790 | 1790 |
| Fine Agg. (lb/yd$^3$) | 1040 | 1128 | 1128 | 1040 | 1040 |
| Water (lb/yd$^3$) | 234 | 234 | 234 | 234 | 234 |
| HRWR (fl oz/cwt) | 15 | 15 | 15 | 15 | 15 |
| WR (fl oz/cwt) | 3 | 3 | 3 | 3 | 3 |
| AEA (fl oz/cwt) | 15 | 10 | 10 | 17.5 | 15 |
| Calculated Air Content (%) | 6 | 4 | 4 | 6 | 6 |
| w/cm | 0.26 | 0.26 | 0.26 | 0.26 | 0.26 |

Table 3.3. Mixture Proportions Continued.

| Materials | Mixture Designations | | | |
|---|---|---|---|---|
| | 9-26-5.9 | 9-26-9.1 | 9-26-13 | 9-26-13 |
| Cement (lb/yd$^3$) | 900 | 900 | 900 | 900 |
| Coarse Agg. (lb/yd$^3$) | 1790 | 1790 | 1790 | 1790 |
| Fine Agg. (lb/yd$^3$) | 1040 | 1040 | 1040 | 1040 |
| Water (lb/yd$^3$) | 234 | 234 | 234 | 234 |
| HRWR (fl oz/cwt) | 15 | 15 | 15 | 15 |
| WR (fl oz/cwt) | 3 | 3 | 3 | 3 |
| AEA (fl oz/cwt) | 15 | 20 | 30 | 17 |
| Calculated Air Content (%) | 6 | 6 | 6 | 6 |
| w/cm | 0.26 | 0.26 | 0.26 | 0.26 |

Table 3.4. Mixture Proportions Continued.

| Materials | Mixture Designations | | | | |
|---|---|---|---|---|---|
| | 9-26-17 | 9-28-1.9 | 9-28-4.1 | 9-28-5.8 | 9-30-1.1 |
| Cement (lb/yd$^3$) | 900 | 900 | 900 | 900 | 900 |
| Coarse Agg. (lb/yd$^3$) | 1790 | 1790 | 1790 | 1790 | 1790 |
| Fine Agg. (lb/yd$^3$) | 1040 | 1169 | 1081 | 992 | 1122 |
| Water (lb/yd$^3$) | 234 | 252 | 252 | 252 | 270 |
| HRWR (fl oz/cwt) | 15 | 15 | 15 | 12 | 10 |
| WR (fl oz/cwt) | 3 | 3 | 3 | 3 | 3 |
| AEA (fl oz/cwt) | 20 | 0 | 8 | 12 | 0 |
| Calculated Air Content (%) | 6 | 2 | 4 | 6 | 2 |
| w/cm | 0.26 | 0.28 | 0.28 | 0.28 | 0.30 |

Table 3.5. Mixture Proportions Continued.

| Materials | Mixture Designations | | | | |
|---|---|---|---|---|---|
| | 9-30-2.1 | 9-30-4.5 | 9-30-4.9 | 9-30-5.7 | 9-30-6.8 |
| Cement (lb/yd$^3$) | 900 | 900 | 900 | 900 | 900 |
| Coarse Agg. (lb/yd$^3$) | 1790 | 1790 | 1790 | 1790 | 1790 |
| Fine Agg. (lb/yd$^3$) | 1122 | 1034 | 1034 | 945 | 1034 |
| Water (lb/yd$^3$) | 270 | 270 | 270 | 270 | 270 |
| HRWR (fl oz/cwt) | 12 | 8 | 4 | 10 | 10 |
| WR (fl oz/cwt) | 3 | 3 | 3 | 3 | 3 |
| AEA (fl oz/cwt) | 0 | 0.25 | 1 | 1 | 6 |
| Calculated Air Content (%) | 2 | 4 | 4 | 6 | 4 |
| w/cm | 0.30 | 0.30 | 0.30 | 0.30 | 0.30 |

Table 3.6. Mixture Proportions Continued.

| Materials | Mixture Designations | | | | |
|---|---|---|---|---|---|
| | 9-30-9.1 | 9-30-11 | 9-30-15 | 9-34-2.2 | 9-34-3 |
| Cement (lb/yd$^3$) | 900 | 900 | 900 | 900 | 900 |
| Coarse Agg. (lb/yd$^3$) | 1790 | 1790 | 1790 | 1790 | 1790 |
| Fine Agg. (lb/yd$^3$) | 1034 | 1034 | 1034 | 1028 | 939 |
| Water (lb/yd$^3$) | 270 | 270 | 270 | 306 | 306 |
| HRWR (fl oz/cwt) | 12 | 8 | 8 | 8 | 2 |
| WR (fl oz/cwt) | 3 | 3 | 3 | 3 | 3 |
| AEA (fl oz/cwt) | 4 | 4 | 2 | 0 | 0.25 |
| Calculated Air Content (%) | 4 | 4 | 4 | 2 | 4 |
| w/cm | 0.30 | 0.30 | 0.30 | 0.34 | 0.34 |

Table 3.7. Mixture Proportions Continued.

| Materials | Mixture Designations | | | | |
|---|---|---|---|---|---|
| | 9-34-5.1 | 9-34-11 | 9-34-13 | 9-34-17 | 9-36-2.6 |
| Cement (lb/yd$^3$) | 900 | 900 | 900 | 900 | 900 |
| Coarse Agg. (lb/yd$^3$) | 1790 | 1790 | 1790 | 1790 | 1790 |
| Fine Agg. (lb/yd$^3$) | 939 | 939 | 939 | 939 | 980 |
| Water (lb/yd$^3$) | 306 | 306 | 306 | 306 | 324 |
| HRWR (fl oz/cwt) | 2 | 8 | 5 | 5 | 2.5 |
| WR (fl oz/cwt) | 3 | 3 | 3 | 3 | 3 |
| AEA (fl oz/cwt) | 0.5 | 4 | 1 | 3 | 0 |
| Calculated Air Content (%) | 4 | 4 | 4 | 4 | 2 |
| w/cm | 0.34 | 0.34 | 0.34 | 0.34 | 0.36 |

Table 3.8. Mixture Proportions Continued.

| Materials | Mixture Designations | | | | |
|---|---|---|---|---|---|
| | 9-36-3.8 | 9-36-6.2 | 9-42-2.1 | 9-42-1.8 | 9-42-3.5 |
| Cement (lb/yd$^3$) | 900 | 900 | 900 | 900 | 900 |
| Coarse Agg. (lb/yd$^3$) | 1790 | 1790 | 1790 | 1790 | 1790 |
| Fine Agg. (lb/yd$^3$) | 892 | 803 | 839 | 839 | 750 |
| Water (lb/yd$^3$) | 324 | 324 | 378 | 378 | 378 |
| HRWR (fl oz/cwt) | 3 | 3 | 0 | 0 | 0 |
| WR (fl oz/cwt) | 3 | 3 | 3 | 0 | 3 |
| AEA (fl oz/cwt) | 1.0 | 1.5 | 0 | 0 | 0.25 |
| Calculated Air Content (%) | 4 | 6 | 2 | 2 | 4 |
| w/cm | 0.36 | 0.36 | 0.42 | 0.42 | 0.42 |

Table 3.9. Mixture Proportions Continued.

| Materials | Mixture Designations | | | | |
|---|---|---|---|---|---|
| | 9-42-4.4 | 9-42-5.9 | 9-50-0.9 | 9-50-3.6 | 9-50-6.6 |
| Cement (lb/yd$^3$) | 900 | 900 | 900 | 900 | 900 |
| Coarse Agg. (lb/yd$^3$) | 1790 | 1790 | 1790 | 1790 | 1790 |
| Fine Agg. (lb/yd$^3$) | 750 | 662 | 650 | 561 | 473 |
| Water (lb/yd$^3$) | 378 | 378 | 450 | 450 | 450 |
| HRWR (fl oz/cwt) | 0 | 0 | 0 | 0 | 0 |
| WR (fl oz/cwt) | 0 | 0 | 0 | 0 | 0 |
| AEA (fl oz/cwt) | 1.0 | 1.25 | 0 | 0.5 | 0.75 |
| Calculated Air Content (%) | 4 | 6 | 2 | 4 | 6 |
| w/cm | 0.42 | 0.42 | 0.50 | 0.50 | 0.50 |

### 3.3.5 Batching

The batching of the mixtures followed the same procedures and sequences that were described in Chapter 2. For these mixtures, the AEA was added to the mixtures once they achieved a uniform consistency

For the research program, the desired fresh concrete temperature was 70°F. Since the majority of batching was conducted during the summer, crushed ice was added to the mixing water. For those mixtures cast in cooler months, warm tap water was used to increase the fresh concrete temperature.

### 3.3.6 Curing

All the concrete specimens were cured at 73°F and 50 percent relative humidity (RH) for the first 24 hours. The specimens were then removed from their molds and moist cured in lime-saturated water at 73°F until time of testing.

### 3.3.7 Tests

The mixtures were subjected to several tests. The fresh properties examined were concrete temperature (ASTM C 1064), air content (ASTM C 231) and slump (ASTM C 143). The compressive strength was the hardened property tested. The compressive strength (ASTM C 39) was tested at one, seven, 28, and 56 days of age. At each age, three 4 x 8 in. cylinders were tested. The durability and permeability of the mixtures are examined in Chapters 4 and 5.

## 3.4 PRESENTATION OF RESULTS

### 3.4.1 Fresh Concrete Results

The fresh concrete results are shown below in Tables 3.10, 3.11, and 3.12. The fresh concrete temperature was between 70 and 80 F for most mixtures. The slumps for the mixtures ranged from 1.50 to 12 inches. The measured air contents of the fresh concrete ranged from 0.9 to 17 percent.

Table 3.10. Fresh Concrete Results.

| Mixtures | Concrete Temp. (F) | AEA Dosage (fl oz/cwt) | Air Content (%) | Slump (in.) |
|---|---|---|---|---|
| 9-26-1.8 | 80 | 0 | 1.8 | 9.00 |
| 9-26-2.1 | 75 | 4.0 | 2.1 | 9.00 |
| 9-26-2.4 | 74 | 0 | 2.4 | 6.50 |
| 9-26-3.1 | 71 | 10.0 | 3.1 | 5.50 |
| 9-26-3.3 | 75 | 15.0 | 3.3 | 7.25 |
| 9-26-3.5 | 74 | 15.0 | 3.5 | 9.00 |
| 9-26-3.8 | 77 | 10.0 | 3.8 | 8.00 |
| 9-26-3.9 | 70 | 10.0 | 3.9 | 8.50 |
| 9-26-4.5 | 85 | 17.5 | 4.5 | 4.50 |
| 9-26-5.6 | 75 | 15.0 | 5.6 | 4.25 |
| 9-26-5.9 | 71 | 15.0 | 5.9 | 8.75 |
| 9-26-9.1 | 70 | 20.0 | 9.1 | 11.00 |
| 9-26-13 | 70 | 30.0 | 13.0 | 8.25 |
| 9-26-13 | 72 | 17.0 | 13.0 | 12.00 |
| 9-26-17 | 74 | 20.0 | 17.0 | 12.00 |

Table 3.11. Fresh Concrete Results Continued.

| Mixtures | Concrete Temp. (F) | AEA Dosage (fl oz/cwt) | Air Content (%) | Slump (in.) |
|---|---|---|---|---|
| 9-28-1.9 | 81 | 0 | 1.9 | 9.00 |
| 9-28-4.1 | 75 | 8.0 | 4.1 | 11.00 |
| 9-28-5.8 | 71 | 12.0 | 5.8 | 9.50 |
| 9-30-1.1 | 73 | 0 | 1.1 | 10.00 |
| 9-30-2.1 | 80 | 0 | 2.1 | 8.00 |
| 9-30-4.5 | 77 | 0.25 | 4.5 | 1.50 |
| 9-30-4.9 | 74 | 1 | 4.9 | 2.25 |
| 9-30-5.7 | 72 | 1.0 | 5.7 | 10.75 |
| 9-30-6.8 | 71 | 6.0 | 6.8 | 9.75 |
| 9-30-9.1 | 75 | 4.0 | 9.1 | 11.50 |
| 9-30-11 | 69 | 4.0 | 11.0 | 9.50 |
| 9-30-15 | 70 | 2.0 | 15.0 | 10.25 |
| 9-34-2.2 | 81 | 0 | 2.2 | 8.50 |
| 9-34-3 | 78 | 0.25 | 3.0 | 4.25 |
| 9-34-5.1 | 74 | 0.5 | 5.1 | 4.50 |
| 9-34-11 | 75 | 4.0 | 11.0 | 11.00 |
| 9-34-13 | 69 | 1.0 | 13.0 | 11.00 |
| 9-34-17 | 70 | 3.0 | 17.0 | 11.00 |

Table 3.12. Fresh Concrete Results Continued.

| Mixtures | Concrete Temp. (F) | AEA Dosage (fl oz/cwt) | Air Content (%) | Slump (in.) |
|---|---|---|---|---|
| 9-36-2.6 | 75 | 0 | 2.6 | 2.50 |
| 9-36-3.8 | 71 | 1.0 | 3.8 | 3.50 |
| 9-36-6.2 | 75 | 1.5 | 6.2 | 2.00 |
| 9-42-2.1 | 71 | 0 | 2.1 | 5.00 |
| 9-42-1.8 | 71 | 0 | 1.8 | 3.25 |
| 9-42-3.5 | 74 | 0.25 | 3.5 | 9.25 |
| 9-42-4.4 | 80 | 1.0 | 4.4 | 3.75 |
| 9-42-5.9 | 70 | 1.25 | 5.9 | 4.00 |
| 9-50-0.9 | 65 | 0 | 0.9 | 6.25 |
| 9-50-3.6 | 75 | 0.5 | 3.6 | 9.50 |
| 9-50-6.6 | 71 | 0.75 | 6.6 | 10.00 |

### 3.4.2 Hardened Concrete Results

The compressive strength was tested at one, seven, 28, and 56 days. Each compressive strength result is the average of three 4 x 8 in. cylinders tests. The individual tests, standard deviations, and confidence intervals are reported in Appendix B. Mixtures with air contents out of the specified range were not tested. The durability and permeability are examined in later chapters. The test results are shown in Tables 3.13, 3.14, and 3.15.

Table 3.13. Compressive Strength Results.

| Mixtures | Average Compressive Strength (psi) | | | |
|---|---|---|---|---|
| | 1 Day[1] | 7 Day[1] | 28 Day[1] | 56 Day[1] |
| 9-26-1.8 | 6010 | 11,630 | 12,520 | 13,900 |
| 9-26-2.1 | 6470 | 10,790 | 11,590 | - |
| 9-26-2.4 | 6830 | 11,040 | 12,190 | 12,960 |
| 9-26-3.1 | - | - | - | - |
| 9-26-3.3 | - | - | - | - |
| 9-26-3.5 | - | - | - | - |
| 9-26-3.8 | 4830 | 10,440 | 11,270 | 12,090 |
| 9-26-3.9 | 6740 | 10,590 | 12,160 | 12,030 |
| 9-26-4.5 | - | - | - | - |
| 9-26-5.6 | 4560 | 9270 | 10,560 | 11,290 |
| 9-26-5.9 | 6670 | 9920 | 11,380 | 12,080 |
| 9-26-9.1 | - | - | - | - |
| 9-26-13 | - | - | - | - |
| 9-26-13 | - | - | - | - |
| 9-26-17 | - | - | - | - |

1) Average compressive strength of three tests.
2) Individual tests and statistical data are shown in Appendix B.

Table 3.14. Compressive Strength Results Continued.

| Mixtures | Average Compressive Strength (psi) | | | |
|---|---|---|---|---|
| | 1 Day[1] | 7 Day[1] | 28 Day[1] | 56 Day[1] |
| 9-28-1.9 | 5540 | 10,650 | 11,870 | 12,460 |
| 9-28-4.1 | 6410 | 9140 | 10,770 | 11,570 |
| 9-28-5.8 | 6360 | 9520 | 10,080 | 10,940 |
| 9-30-1.1 | 6150 | 10,050 | 12,190 | 13,600 |
| 9-30-2.1 | 5580 | 9060 | 10,430 | 11,480 |
| 9-30-4.5 | 5610 | 8650 | 9960 | 11,000 |
| 9-30-4.9 | 4580 | 7290 | 8340 | 8880 |
| 9-30-5.7 | 6000 | 9130 | 10,270 | 11,030 |
| 9-30-6.8 | 5720 | 8490 | 9830 | 10,090 |
| 9-30-9.1 | - | - | - | - |
| 9-30-11 | - | - | - | - |
| 9-30-15 | - | - | - | - |
| 9-34-2.2 | 5160 | 8760 | 9940 | 10,530 |
| 9-34-3 | 4450 | 7090 | 8640 | 8840 |
| 9-34-5.1 | 4130 | 6740 | 7540 | 8120 |
| 9-34-11 | - | - | - | - |
| 9-34-13 | - | - | - | - |
| 9-34-17 | - | - | - | - |

1) Average compressive strength of three tests.
2) Individual tests and statistical data are shown in Appendix B.

Table 3.15. Compressive Strength Results Continued.

| Mixtures | Average Compressive Strength (psi) | | | |
|---|---|---|---|---|
| | 1 Day[1] | 7 Day[1] | 28 Day[1] | 56 Day[1] |
| 9-36-2.6 | 4220 | 7210 | 9180 | 9620 |
| 9-36-3.8 | 4580 | 6960 | 8340 | 9040 |
| 9-36-6.2 | 3660 | 6790 | 7700 | 8450 |
| 9-42-2.1 | 3050 | 5940 | 7480 | 7540 |
| 9-42-1.8 | 2690 | 6760 | 8691 | 9050 |
| 9-42-3.5 | 2950 | 5390 | 6490 | 6770 |
| 9-42-4.4 | 2750 | 4940 | 6470 | 6860 |
| 9-42-5.9 | 2640 | 4900 | 6110 | 6710 |
| 9-50-0.9 | 2020 | 4730 | 6220 | 6990 |
| 9-50-3.6 | 1560 | 5220 | 6340 | 6760 |
| 9-50-6.6 | 1650 | 4320 | 5560 | 6150 |

1) Average compressive strength of three tests.
2) Individual tests and statistical data are shown in Appendix B.

## 3.5 DISCUSSION OF RESULTS

### 3.5.1 Fresh Concrete Results

For mixtures with a w/cm equal to or less than 0.36, WR and HRWR were used to achieve adequate workability. As expected, higher dosages of HRWR were required at lower w/cm. The addition of AEA was observed to increase the workability of concrete. This is because the entrained air behaves as "small ball bearings" that help lubricate the mixture. The slumps of mixtures with w/cm of 0.26, 0.34, and 0.50 did increase as the total air content increased, but the slumps of the remaining mixtures did not necessarily increase with increases in air content.

At lower w/cm, higher dosages of AEA were required to achieve the targeted total air contents. Shown in Figures 3.1 and 3.2 are the dosages of AEA necessary to attain the targeted air contents of four and six percent. From the figures, it is evident that mixtures below a w/cm of 0.30 require higher dosages of AEA to achieve the desired air contents. Below a w/cm of 0.30, 12 and 15 fl oz/cwt of AEA were necessary to attain an air content of six percent. This dosage rate is significantly more than the manufacturer's recommended dosage rate of 3/4 to 3 fl. oz/cwt. At w/cm greater than 0.30, the dosage rates required were within the manufacturer's recommendation. The higher dosage rates were necessary due to insufficient amounts of water in mixtures with w/cm of 0.26 and 0.28.

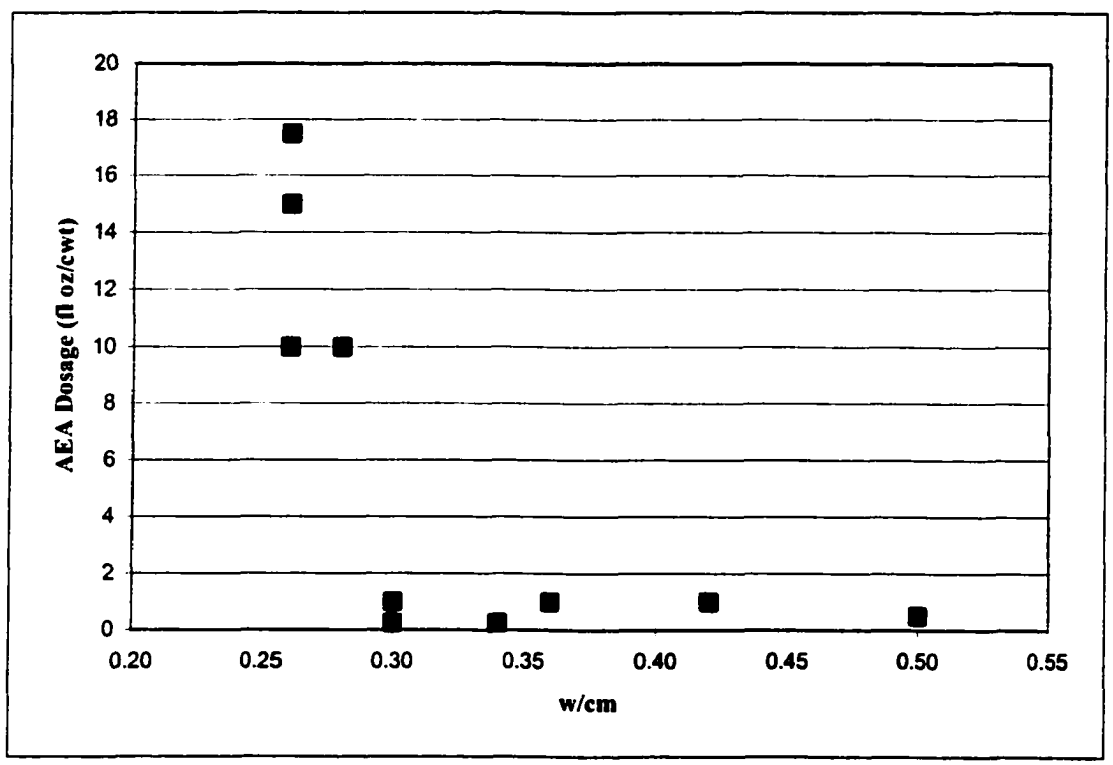


Figure 3.1. AEA Dosage for 4 percent Total Air Content.

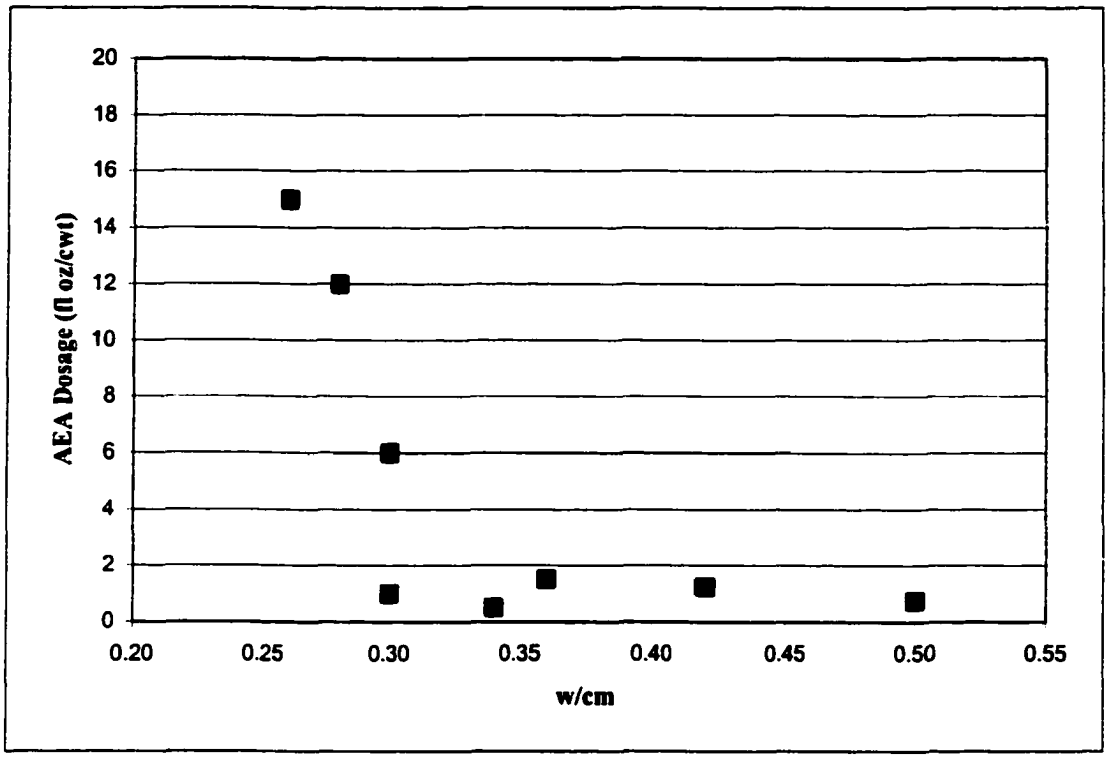


Figure 3.2. AEA Dosage for 6 percent Total Air Content.

As previously stated, many mixtures were cast several times in order to achieve the targeted total air contents of four and six percent. Mixtures with w/cm of 0.26 and 0.30 were repeated numerous times. Shown in Figure 3.3 are the dosages of AEA and the measured air contents of several mixtures. All mixtures contained the same quantity of cement and coarse aggregate, and all mixtures had a w/cm of 0.26. Also, all mixtures were mixed for approximately the same length of time in the same concrete mixer. The only variable in the mixtures was the concrete temperature. The fresh concrete temperature ranged from 70 to 85 F. The manufacturer's specifications warn that as temperatures increase, the admixture loses its air entraining abilities. They also warn that increases in mixing time cause higher air contents. These reasons may account for some of the variations in air content but not all. Some mixtures were cast twice with the same AEA dosage (17.5 and 20 fl

oz/cwt) and had significant differences in measured air content (greater than 7 percent difference in air content at each w/cm). The results from the tests further reinforce the need for trial batching. At low w/cm, trial batching is necessary examine the fresh concrete properties such as workability and air content and to determine the correct dosages of admixtures.

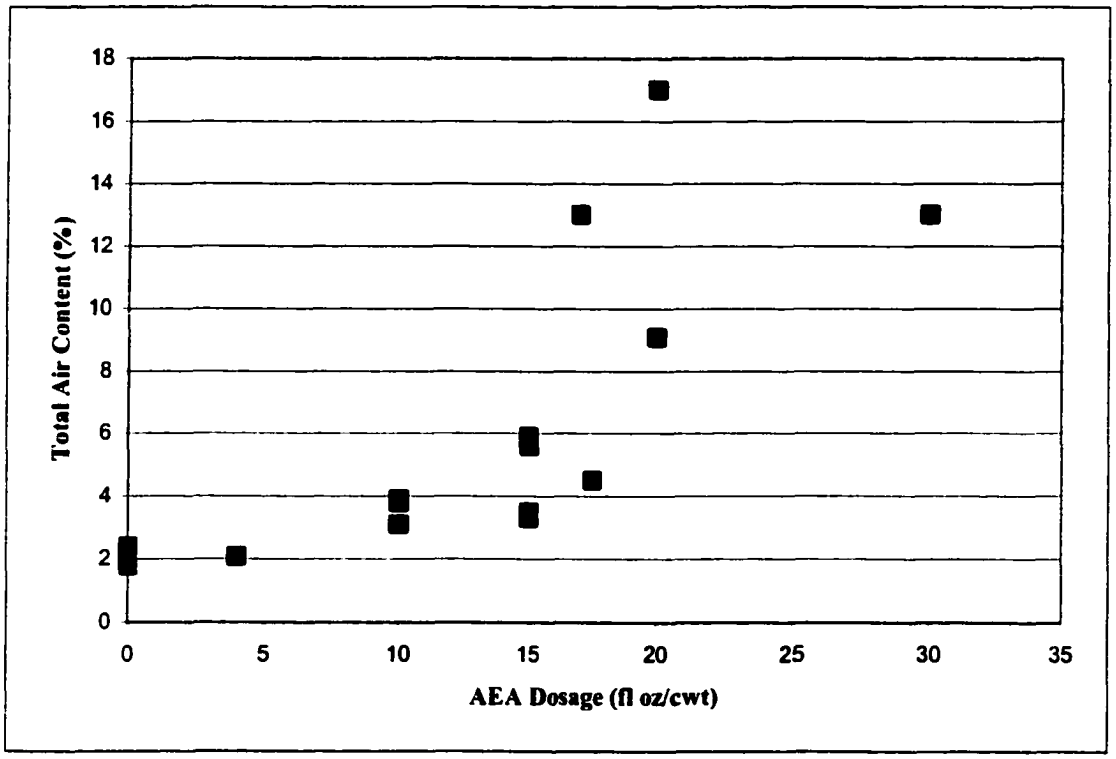


Figure 3.3. AEA Dosage versus Total Air Content for w/cm of 0.26.

### 3.5.2 Compressive Strength Results

The addition of entrained air decreases the compressive strength of concrete. This is because air is concrete. The decrease in compressive strength normally ranges from two to five percent for every one percent increase in entrained air. Therefore, a mixture with an air content of six percent may have a compressive strength that is 20 percent less than an identical mixture with no entrained air (2 percent air). The

compressive strength results are shown in Figures 3.4, 3.5, and 3.6. Where there were multiple mixtures at a given air content, the results shown in the figures are of the mixtures whose measured air content was closest to the targeted air content.

At one day of age, the compressive strength results followed a general trend that is substantiated by examination of the 90 percent confidence intervals in Figure B.1 (Appendix B). Increases in w/cm resulted in decreases in compressive strength, which was expected. However, one would also expect that increases in air content (for mixtures with like w/cm) would decrease compressive strength. This was not the trend for most mixtures. For example, the mixture with the greatest air content had the highest compressive strength at one day for mixtures cast at a w/cm of 0.30. The confidence intervals (Figure B.1 in Appendix B) overlap for most mixtures at each w/cm, which means that the differences between mixtures are not statistically significant. It is unclear as to why the mixtures did not follow the expected trends at one day of age. But, by 28 and 56 days of age, the expected trend (the lower the air content, the greater the compressive strength) became apparent.

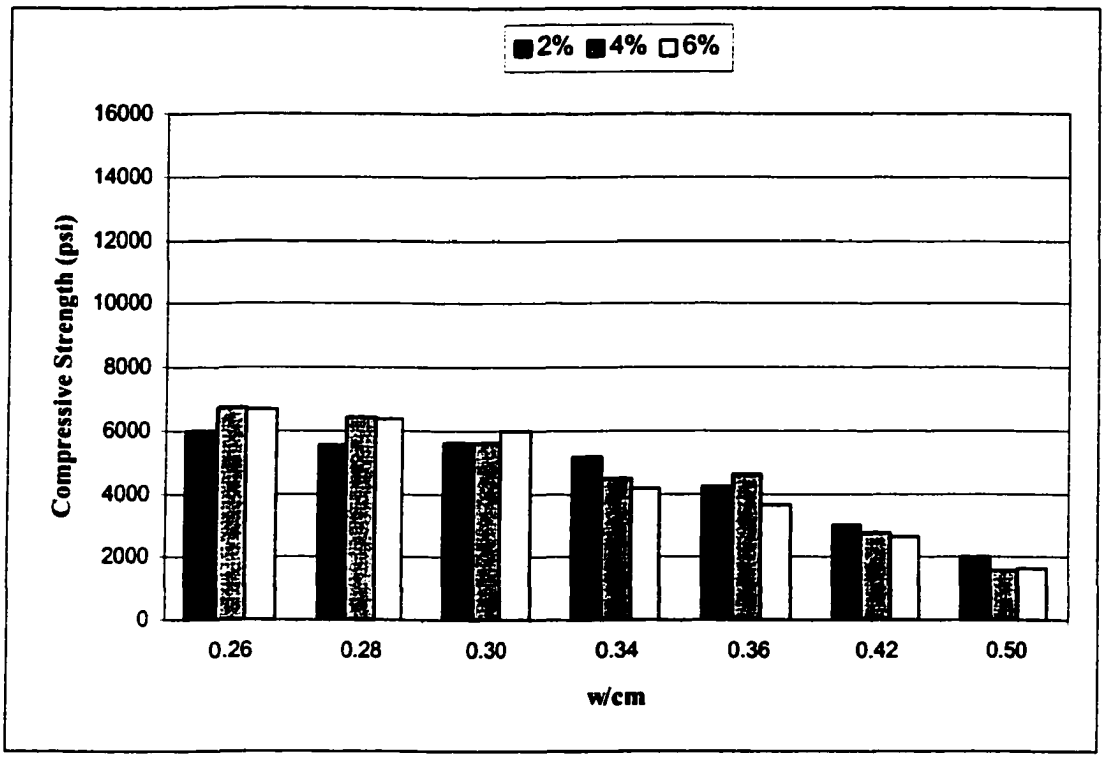


Figure 3.4. Compressive Strength Results at One Day.

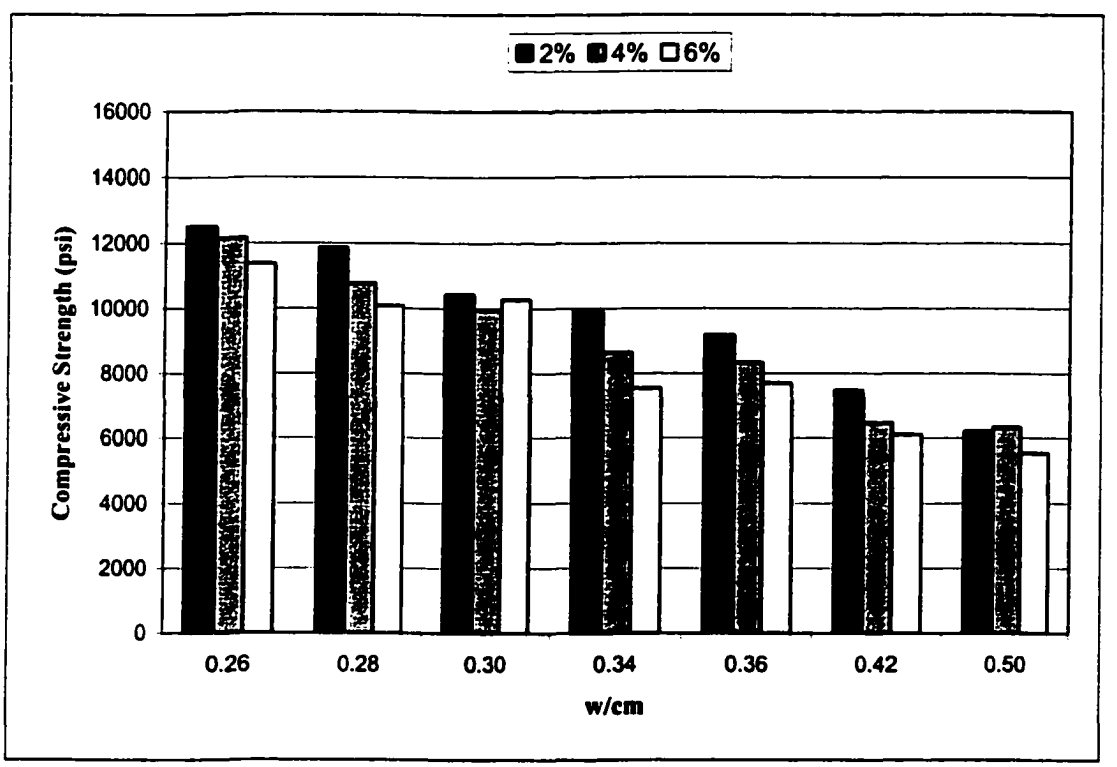


Figure 3.5. Compressive Strength Results at 28 Days.

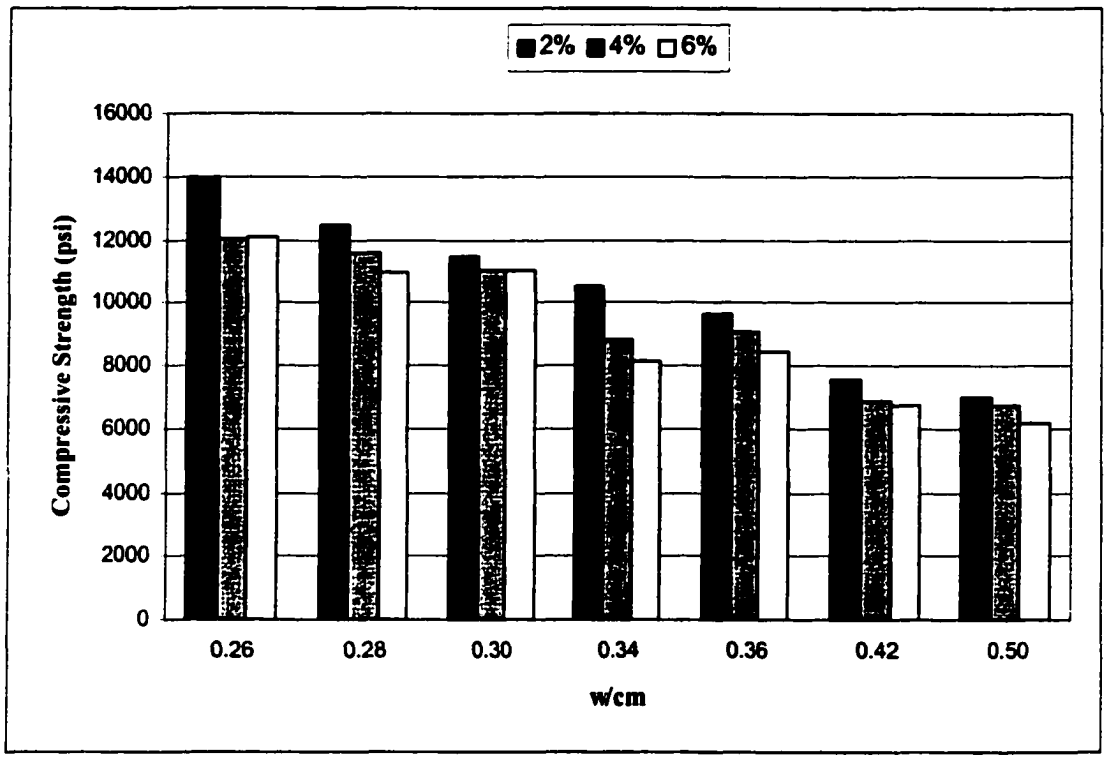


Figure 3.6. Compressive Strength Results at 56 Days.

By 56 days of age, the expected trends become visible. For mixtures of the same w/cm, mixtures without entrained air (two percent air) had the greatest compressive strength. For most mixtures, the mixtures with a nominal air content of two percent had the greater compressive strength and the six percent mixture had the least strength. This trend is validated through examination of the 90 percent confidence intervals (Figure B.3 in Appendix). Figure B.3 shows that there are significant differences between mixtures with nominal air contents of two and six percent for most w/cm, but there is some overlap between either the two and four percent mixtures or the four and six percent mixtures.

Shown in Table 3.16 is the decrease in compressive strength for every one percent increase in entrained air for mixtures with a nominal air content of six

percent. At one day of age, half of the mixtures did not follow the " 2 –5 percent decrease in compressive strength for every one percent increase in entrained air" rule of thumb. But, by 28 and 56 days of age, the decrease in compressive strength was well within this range for most mixtures (Figure 3.7). The results further reinforce that the rule of thumb is an adequate predictor in the decreases in compressive strength that result from increases in entrained air.

Table 3.16. Decrease in Compressive Strength (%) per 1% Increase in Entrained Air

| w/cm | Concrete Age | | | |
|---|---|---|---|---|
| | 1 day | 7 days | 28 days | 56 days |
| 0.26 | -2.7 | 3.6 | 2.2 | 3.2 |
| 0.28 | -3.8 | 2.7 | 3.9 | 3.1 |
| 0.30 | -2.1 | -0.2 | 0.4 | 1.1 |
| 0.34 | 6.9 | 8.0 | 8.3 | 7.9 |
| 0.36 | 3.7 | 1.6 | 4.5 | 3.4 |
| 0.42 | 3.5 | 4.6 | 4.8 | 2.9 |
| 0.50 | 3.2 | 1.5 | 1.9 | 2.1 |

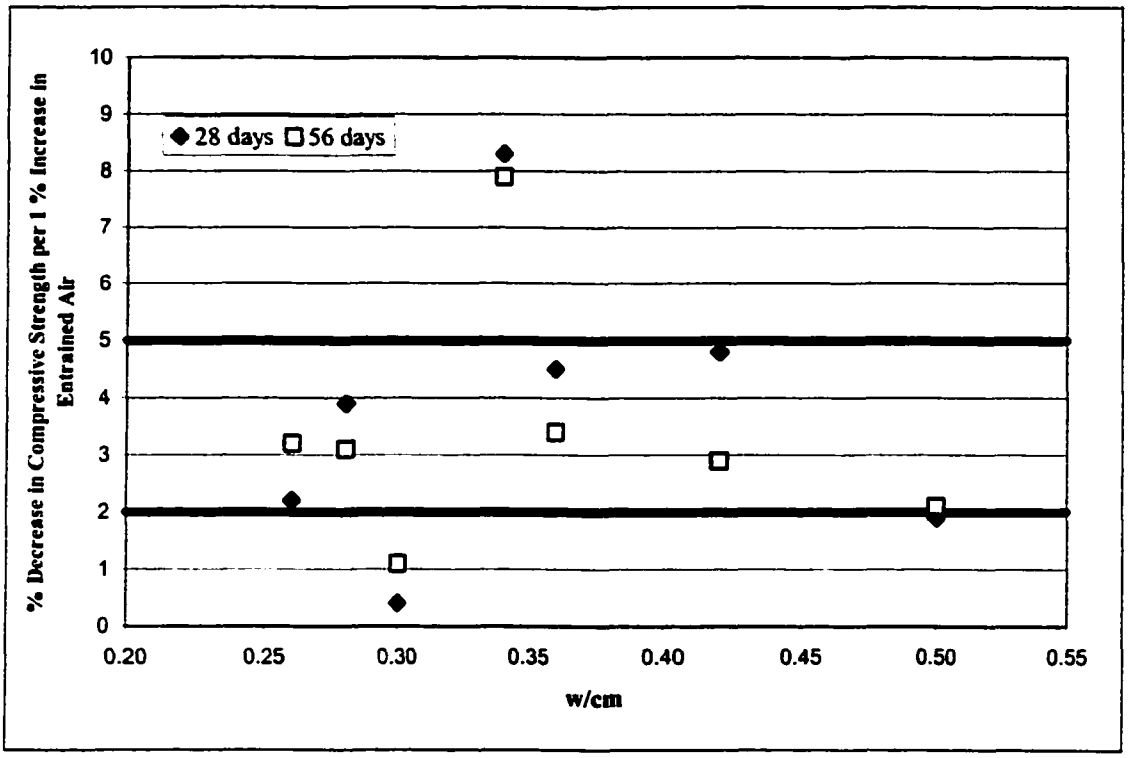


Figure 3.7. Decrease in Compressive Strength per Increase in Entrained Air.

## 3.6 CONCLUSIONS

This portion of the research focused on the development of HPC with air entrainment using locally available materials. With one of the mixtures developed, two prestressed concrete beams were cast. Once again, not only were the mixtures to have high compressive strength, they must also be cast with local materials and must have enough workability to be placed. Another task of the research was to document the effects of air entrainment of the compressive strength of the concrete. The findings of the research are summarized below.

1. Much higher dosages of AEA are required at w/cm below 0.30 when compared to w/cm above 0.30. At w/cm greater than 0.30, the dosage rates required were within the manufacturer's recommendation. The higher dosage rates were necessary due to insufficient amounts of water in mixtures with w/cm of 0.26 and 0.28. Trial batching is recommended at lower w/cm to determine the optimum dosages of admixtures.
2. For most w/cm, the compressive strength decreased as the total air content increased. By 56 days of age, most mixtures followed the "2 – 5 percent decrease in compressive strength for every 1 percent increase in entrained air" rule of thumb.
3. Air entrained HPC mixtures with adequate workability and high compressive strength can be developed using locally available materials.
4. Based on compressive strength and workability, the results indicated that for the aggregates and cements tested, the optimum cement content was 900 lb/yd$^3$. The optimum w/cm was 0.26 and the optimum coarse aggregate content was 1790 lb/yd$^3$. This mix proportion was used to cast the precast/prestressed bridge girders that will be examined in later phases of the research program.

# CHAPTER 4

# EXAMINING THE FREEZE THAW DURABILITY OF HPC

## 4.1 INTRODUCTION

This section of the research program investigated the need for air entrainment in high performance concrete (HPC). Entrained air is required to ensure the durability of some concretes that are subjected to freezing and thawing. Entrained air is added to concrete through the use of air entraining agents (AEA). Current building codes require varying amounts of entrained air depending on the severity of the exposure. Entrained air voids provide small air pockets where water can expand when freezing and where water pressure can be relieved. There may be as many as 300 billion entrained air voids in a cubic yard of concrete with a total air content of four to six percent by volume (Kosmatka et al, 1994). The voids generally have a diameter of about 0.002-in. (Neville, 1997) and are evenly distributed throughout the concrete. Entrained air voids are typically spaced within 0.008 in. of each other (Derucher et al, 1994). Without these voids, continuous freeze-thaw cycles will eventually degrade and damage the concrete. A total air content between four and eight percent is generally considered adequate to provide resistance to the freeze/thaw action (Mindess et al, 1981). The Oklahoma Department of Transportation requires a total air content of 5 ± 1.5 percent in bridge girders.

The experimental program was designed to examine two objectives. The first objective was to determine if air entrainment is necessary for freeze-thaw durability in HPC. The second objective was to determine the maximum w/cm where air entrainment is not needed. Concrete mixtures with varying water to cementitious material ratios (w/cm) were subjected to ASTM C 666 (Procedure A). The variables for the mixtures were total air content and w/cm. The targeted total air contents for the mixtures were 2 percent (entrapped air, no air entraining agent added), 4 percent, and 6 percent. The freeze-thaw tests continued until the specimen deteriorated, or the specimen reached 300 freeze thaw cycles. The results from the study show that air entrainment is not required below a specific maximum w/cm for the materials employed.

## 4.2 LITERATURE REVIEW

### 4.2.1 Introduction

For the purposes of this study, the researchers defined HPC using ACI's 1999 definition which states that HPC is "concrete meeting special combinations of performance and uniformity requirements that cannot always be achieved routinely using conventional constituents and normal mixing, placing, and curing practices." Also, normal strength concrete (NSC) is defined as all other concretes that do not fall within ACI's definition of HPC. The use of HPC in exterior structures has increased in recent years (Neville et al, 1998). Its increased strength and durability make HPC very appealing to the prestressed concrete industry, particularly in bridge girders. Due to its increased strength and durability, HPC can reduce the number of girders, increase bridge

spans, decrease bridge depth, and increase bridge durability (B. Russell, 1994). The durability and permeability of NSC has been thoroughly studied over the past century, but the same properties of HPC have not been studied to the same extent. To increase the durability of normal strength concrete, an air-entraining agent is added to the concrete mixture. While the entrained air increases durability, it also decreases concrete strength. For this reason, air entrainment is not commonly used in HPC (Cohen et al, 1992). Many researchers are questioning the need for air entrainment in HPC (Cohen et al, 1992; Hooten et al, 1993; Lessard et al, 1995; Li et al, 1994; Marchand et al, 1995; Mokhtarzadeh et al, 1995; Pigeon et al, 1991). Many of these researchers have concluded that the low permeability of HPC due to its decreased water to cementitious ratio (w/cm) improves its durability (Pigeon et al, 1991; Cohen et al, 1992; Li et al, 1994; Marchand et al, 1995; and Fagerlund, 1994). Accordingly, several researches have developed durable non-air-entrained HPC mixtures (Cohen et al, 1992; Mokhtarzadeh et al, 1995; Fagerlund, 1994; and Hilsdorf, 1994). Despite these indicators, most researchers still recommend the use of air entrainment for durability (Pigeon et al, 1991; Cohen et al, 1992; Marchand et al, 1995; Fagerlund, 1994; Zia et al, 1993; and Aitcin et al, 1993). The objective of this research program is to examine the need of air entrainment in HPC made with materials commonly available.

### 4.2.2 Freeze-Thaw Mechanism

It is common knowledge that water freezes at 32°F, and when water freezes there is a nine percent increase in volume as water turns to ice. However, water that is trapped within the capillary pores of concrete does not necessarily freeze at 32°F. The

temperature at which water freezes in the capillary pores is a function of the size of the pores and pore chemistry. As pore sizes decrease, the temperature required to freeze the water also decreases. For example, in pores with a diameter of 10 nm, the water will not freeze until 23°F, and for pores with a diameter of 3.5 nm, the water will not freeze until -4°F (Mindess et al. 1981).

While the freezing of water damages the concrete paste, it is not the main contributor to the freeze-thaw deterioration of concrete. The major cause of damage is due to the increase in hydraulic pressure within the pore spaces. As water freezes within a capillary pore, the ice that is formed compresses the unfrozen water within the pore. If the water can escape into an occupied void, the hydraulic pressure is relieved. However, if the distance to a void is too great and the hydraulic pressure cannot be relieved, the water pressure will expand the pores causing tensile stresses in the surrounding concrete paste. In saturated concrete, the tensile stresses will eventually exceed the tensile capacity of the paste and cracking will occur. Entrained air is added to the concrete to provide the voids necessary to relieve the hydraulic pressure (Mindess et al, 1981).

### 4.2.3 Freeze-Thaw Tests Procedure

The American Society for Testing and Materials (ASTM) developed a test procedure for examining the freeze-thaw durability of concrete, ASTM C 666 Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing. ASTM C 666 requires that the specimens are moist cured for 14 days prior to testing. The specimens are then subjected to 300 freeze-thaw cycles at temperatures ranging from 0°F to 40°F. The dynamic modulus is measured prior to testing and during testing. Changes in the

dynamic modulus provide a measure of damage to the concrete. Within ASTM C 666 are two different procedures, Procedure A and Procedure B. For Procedure A, the specimens are frozen and thawed in water, and for Procedure B, the specimens are thawed in water and frozen in air. After 300 cycles, the durability factor of the specimens is reported. The durability factor is the percent change in the dynamic modulus of elasticity. For example, a concrete mixture with a durability factor of 60 has a dynamic modulus that is 60 percent of what it was prior to testing. Acceptable freeze-thaw durability is defined as concrete having a durability factor greater than 60 or a spacing factor less than 0.008 inches (Marchand et al, 1995, and Mokhtarzadeh et al, 1995).

Many researchers suggest that ASTM C 666 Procedure A does not adequately simulate field conditions (Aitcin et al, 1993; Cohen et al, 1992; Kucharska, 1994; Lessard et al, 1995; Marchand et al, 1995; Mokhtarzadeh et al, 1995; and Pigeon et al, 1991). Many concrete structures are not subjected to freeze-thaw conditions as early as 14 days after casting nor are the structures completely saturated with water which is required by ASTM C 666. Aitcin et al (1993), Lessard et al (1995), and Pigeon et al (1991) believed that ASTM C 666 would required air entrainment in concrete structures that would otherwise have adequate freeze-thaw durability for outdoor exposures. Another concern is the possible temperature gradient within individual specimens (Kucharska, 1994 and Galeota et al, 1991). Even with these faults, most researchers still recommend the use of the test to examine the freeze-thaw durability of concrete.

### 4.2.4 Air Content

There are two types of air voids in concrete, entrapped and entrained air voids. Entrapped air voids result from air that is trapped in the concrete during mixing. Entrapped air normally accounts for approximately two percent of the volume of the concrete mixture. Entrained air voids are intentionally placed in the concrete through the use of AEA (Mindess et al, 1981). AEA are chemical admixtures composed of animal or vegetable fats, alkali salts of wood resins, or alkali salts of sulfated and sulfonated organic compounds (Neville, 1997). Entrained air voids have a diameter of approximately 0.002 inches (0.05mm.) and are evenly distributed throughout the concrete mixture, whereas entrapped air voids are much larger (can be up to several millimeters in diameter) and are randomly distributed throughout the concrete (Neville, 1997, and Popovics, 1998).

If exposed to freezing and thawing, normal strength concrete requires a total air content of four to seven percent (Mindess et al, 1981). Of this four to seven percent air, normally two percent is entrapped air and the remaining two to five percent is entrained air. Due to the reduced permeability of HPC, researchers have suggested that the air content of HPC can be reduced (Lessard et al, 1995). Fagerlund (1995) used a closed container model to determine the minimum air contents required for HPC to have acceptable freeze-thaw durability. The model assumed a spherical shape with solid, impermeable materials along the outside of the sphere with the freezable water in the center. From his model, Fagerlund determined that an entrained air content of 0.2 percent would be sufficient in HPC, but in normal strength concrete 7.5 percent would be necessary.

Experimental results have proven that the total air content required for HPC to have acceptable freeze-thaw durability is less than that for normal strength concrete. Acceptable freeze-thaw durability is defined as concrete having a durability factor greater than 60 or a spacing factor less than 0.008 inches (Marchand et al, 1995, and Mokhtarzadeh et al, 1995). Several researchers have developed HPC mixtures with low air contents that have acceptable freeze-thaw durability (Hooten, 1993, Kriesel et al, 1995, Pigeon et al, 1991, and Pinto et al, 2001). However, several researchers have also developed HPC mixtures with low air contents that did not have acceptable freeze-thaw durability (Cohen et al, 1992, Galeota et al, 1991, Hooten et al, 1993, Kriesel et al, 1993, and Li et al, 1994).

### 4.2.5 Air Void System

In addition to the total air content, the specific surface and spacing factor of air voids are crucial factors that play a major role in the freeze-thaw durability of concrete. The surface area of air voids per unit volume is expressed as specific surface. The specific surface is expressed in terms of square inches per cubic inches. For concrete with acceptable freeze-thaw durability, the specific surface is typically between 400 to 600 $in^2/in^3$ or $in^{-1}$. The specific surface for concrete containing only entrapped air is normally less than 300 $in^{-1}$ (Neville, 1997).

The spacing factor is defined as the "average maximum distance from any point in the paste to the edge of a void." A spacing factor of 0.008 inch or less is generally considered adequate to ensure freeze-thaw durability (Aitcin et al, 1994, Attigobe et al,

1992, and Mindess et al, 1981). However, Marchland et al (1995) developed durable, low w/cm concrete mixtures with spacing factors as high as 0.030 inch.

### 4.2.6 Water to Cementitious Material Ratio

In 1956 Hubert Woods suggested that as an alternative to air entrainment, concrete mixtures could be cast at or below a water to cement ratio (w/c) of 0.40. His reasoning was that at low w/c (below 0.40), well cured concrete mixtures would not contain water "that would freeze under natural conditions." He also suggested that the reduced permeability of low w/c concrete would aid in preventing the natural saturation of the concrete. Woods recommended that experimental testing be conducted to verify this theory (Woods, 1956). Years later, Francis Young and Sidney Mindess (1981) theorized that for completely hydrated cement pastes, air entrainment may not be necessary at w/c equal to or less than 0.36. Cohen et al (1992) theorized that low w/cm concrete containing silica fume is relatively impermeable to water. Because of this impermeability, the concrete would never become saturated in natural, outdoor exposures. Therefore, air entrainment would not be necessary. But if there were a possibility for saturation, air entrainment would still be required. Marchland et al (1995), Hooten (1993), and Pigeon et al (1991) all believed that at low w/cm, the concrete consumes available water during hydration, which reduces the freezable water in concrete and increases its durability.

Several researchers have developed low w/cm mixtures that had acceptable freeze-thaw durability without the aid of air entrainment. Pigeon et al (1991) developed freeze-thaw durable mixtures at w/cm of 0.30 at lower. With the use of silica fume,

Hooten (1993) achieved good durability at w/cm of 0.35 and lower. Pinto and Hover (2001) achieved durability factors of 101 at w/cm of 0.35 using a modified version of ASTM C 666 (14 day drying period before testing). Mokhtarzadeh et al (1995) developed durable mixtures with w/cm of 0.29 and 0.31. Whereas Li et al (1994) had acceptable durability at w/cm of 0.24 and lower.

However, for each of the durable non-air entrained mixtures developed by the previous researchers, there are similar mixtures that did not have acceptable durability. Kriesel et al (1995) and Cohen et al (1992) examined concrete mixtures with a w/cm of 0.30 that had poor durability. Li et al (1994) tested mixtures with w/cm of 0.24 to 0.33 that were not durable. Without the aid of silica fume, concrete mixtures investigated by Hooten (1993) were not durable at a w/cm of 0.35. From these results, one cannot exclusively determine a w/cm where air entrainment is not required. Many other factors such as aggregate type, cement type, and curing conditions of the concrete also affect the durability of concrete (Mokhtarzadeh et al, 1995).

### 4.2.7 Aggregate Type

The type of aggregate plays an important role in the freeze-thaw durability of concrete. Certain types of aggregates are susceptible to freeze-thaw damage. The porosity of the coarse aggregates is vital to the concrete's durability. Some limestones and granites have little porosity and a low permeability. However due to their low permeability, these aggregates are not normally saturated in concrete and contain voids (since they seldom become saturated) where hydraulic pressure can be relieved. On the other hand, sandstones have a high permeability, but are very porous and may be prone to

saturation. Their high porosity allows water to escape during freezing which reduces the hydraulic pressure. These aggregates are not usually susceptible to freeze-thaw damage. Problems arise when the aggregates have high porosity and low permeability. The high porosity is achieved by extremely fine pores within the aggregates. If these aggregates become saturated, the distance the water must flow to relieve the hydraulic pressure is too great. The water then freezes within the aggregate and fracture of the aggregate occurs. Aggregates that are most susceptible to freeze-thaw damage are fine-grained rocks, such as cherts or shales (Mindess et al, 1981).

Researchers have investigated the freeze-thaw durability of concrete mixtures containing various types of coarse aggregates. Pigeon et al (1991) found acceptable durability with concrete mixtures containing either limestone or granite. Aitcin et al (1994) had acceptable durability with concrete containing either crushed diorite or crushed granite. Kriesel et al (1996) and Mokhtarzadeh et al (1995) determined that concrete containing low absorption limestone performed the best. Both researchers determined that round gravel, partially crushed granite, and crushed granite were unacceptable. Even though some researchers found that limestone was the best performing aggregate, Cohen et al (1992) and Li et al (1994) had poor results with limestone.

The freeze-thaw durability of aggregates can be investigated by two main methods. The aggregates can be tested indirectly using ASTM C 666 (tests in concrete) or tested directly using ASTM C 682, Standard Practice for Evaluation of Frost Resistance of Coarse Aggregate in Air Entrained Concrete by Critical Dilation Process.

The results from the previous researchers suggest that durability of the aggregate should be known before its use in a harsh environment.

The size of the aggregate also plays a role in the required air content. Depending on the nominal maximum aggregate (NMA) size and environmental conditions, the required total air contents range from 3.5 to 7.5 percent (ACI 318-99). This is because less paste is required for concrete containing larger aggregates to be workable (Mindess and Young, 1981). For example, concretein severe exposure containing coarse aggregate with a NMA size of 3 in. requires a total air content of 4.5 percent, but concrete containing 3/8 in. NMA size requires 7.5 percent.

### 4.2.8 Curing

The age, curing temperature, and curing regimen all affect the freeze-thaw durability of concrete. Water within the capillary pores freeze at lower temperatures as the concrete ages. As the concrete cures, the concentration of salts within the pores increases, which lowers the freezing temperature of the solution. For example, the temperature must be lower than 30°F in the capillary pores for water to freeze at 3 days of age but at 28 days of age the freezing temperature decreases to 23°F (Neville, 1997).

Not only does the length of curing affect the freeze-thaw durability, the temperature of the curing regimen can also have an effect. In the prestressed concrete industry, steam curing is used to increase the one-day compressive strength. The steam curing increases the initial hydration. This results in a "less uniform distribution of hydration products within the paste" which alters the pore size distribution (Mindess et al, 1981). The change in pore distribution may result in a slightly higher permeability. The

increase in permeability allows more water into the concrete making the specimen more susceptible to freeze-thaw damage.

Kriesel et al (1996) and Mokhtarzadeh et al (1995) determined that the curing regimen was an important factor affecting the freeze-thaw durability of concrete. Kriesel et al (1996) determined that moist cured specimens had higher durability factors than heat cured specimens. They also found that moist cured specimens absorbed less water than heat-cured specimens which indicates reduced permeability for moist cured specimens.

### 4.2.9 Conclusions

As the Literature Review reveals, many factors affect the freeze-thaw durability of concrete. The w/cm, air content, aggregate type, and curing regimens are some of the factors that affect the durability of concrete. While many researchers developed durable non-air entrained mixtures, other researchers were unable to produce similar results. For now, most researchers still recommend the use of air entrainment in HPC subjected to a harsh environment. The use of air entrainment can assure the freeze-thaw durability of HPC. Further research needs to be conducted on the durability of non-air entrained concrete.

## 4.3 EXPERIMENTAL PROCEDURES

### 4.3.1 Scope

The experimental program was designed to examine two objectives. The first objective was to determine if air entrainment is necessary for freeze-thaw durability in

HPC. The second objective is to determine the maximum w/cm where air entrainment is not needed. Several different concrete mixtures with varying w/cm and varying total air contents were subjected to the freeze-thaw durability test (ASTM C 666, Procedure A). The testing matrix is shown in Table 4.1. The w/cm ranged from 0.26 to 0.50. The targeted total air contents were 2, 4, and 6 percent.

Table 4.1. Testing Matrix

| Target Total Air Content (%) | w/cm | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 0.26 | 0.30 | 0.32 | 0.34 | 0.36 | 0.42 | 0.45 | 0.50 |
| 2 | X | X | - | X | X | X | - | X |
| 4 | X | X | X | - | X | X | X | X |
| 6 | X | X | - | - | X | X | - | X |
| X = indicates batching and testing of these variables | | | | | | | | |

### 4.3.2 Materials

Ash Grove Type III Cement was used in all mixtures. The coarse aggregate was 3/8 inch (ASTM # 8), crushed limestone from Davis, Oklahoma. The fine aggregate was washed river sand from Dover, Oklahoma. The material properties of the cement and aggregates are listed in Chapter 2. To provide adequate workability a water reducer (WR) and/or a high range water reducer (HRWR) was used. The WR used was WRDA with Hycol, and the HRWR used was ADVA Flow. An air entraining agent (AEA), DARAVAIR 1000, was used to attain the required target total air contents.

### 4.3.3 Mixtures

All mixtures contained 900 lb/yd$^3$ of cement and 1790 lb/yd$^3$ of coarse aggregate. The w/cm were 0.26, 0.30, 0.32, 0.34, 0.36, 0.42, 0.45, and 0.50. The quantity of fine aggregate was dependent on the w/cm and total air content. Mix proportioning was done by the Absolute Volume Method. In this method sand is used to replace the same volume whenever water and air are reduced. For example, as the w/cm increased, the quantity of fine aggregate decreased. Likewise, as the air contents increased for mixtures with the same w/cm, the quantity of sand decreased. The mixture proportions are shown in Tables 4.2 through Table 4.6.

Mixture designations, or batch numbers, were determined by three properties. The first number in the designation is the quantity of cement in each mixture. Since all the mixture contained 900 lb/yd$^3$, the first number for all the mixtures is nine. The second number is the w/cm of the mixture. The third number is the measured total air content for the mixture. For example, mixture 9-26-2.4 contained 900 lb/yd$^3$ of cement. The mixture also had a w/cm of 0.26 and a measured total air content of 2.4 percent.

Table 4.2 Mixture Proportions.

| Materials | Mixture Designations | | | | |
|---|---|---|---|---|---|
| | 9-26-2.4 | 9-26-3.8 | 9-26-5.6 | 9-30-1.1 | 9-30-4.5 |
| Cement (lb/yd$^3$) | 900 | 900 | 900 | 900 | 900 |
| Coarse Agg. (lb/yd$^3$) | 1790 | 1790 | 1790 | 1790 | 1790 |
| Fine Agg. (lb/yd$^3$) | 1217 | 1128 | 1040 | 1122 | 1034 |
| Water (lb/yd$^3$) | 234 | 234 | 234 | 270 | 270 |
| HRWR (fl oz/cwt) | 15 | 15 | 15 | 10 | 10 |
| WR (fl oz/cwt) | 3 | 3 | 3 | 3 | 3 |
| AEA (fl oz/cwt) | 0 | 10 | 15 | 0 | 0.25 |
| Targeted Air Content (%) | 2 | 4 | 6 | 2 | 4 |
| Calculated Unit Weight (lb/yd$^3$) | 153.4 | 150.1 | 146.8 | 151.2 | 147.9 |
| w/cm | 0.26 | 0.26 | 0.26 | 0.30 | 0.30 |

Table 4.3. Mixture Proportions.

| Materials | Mixture Designations | | | | |
|---|---|---|---|---|---|
| | 9-30-5.7 | 9-32-4.1 | 9-34-2.0 | 9-36-2.6 | 9-36-3.8 |
| Cement (lb/yd$^3$) | 900 | 900 | 900 | 900 | 900 |
| Coarse Agg. (lb/yd$^3$) | 1790 | 1790 | 1790 | 1790 | 1790 |
| Fine Agg. (lb/yd$^3$) | 945 | 986 | 1028 | 980 | 892 |
| Water (lb/yd$^3$) | 270 | 288 | 306 | 324 | 324 |
| HRWR (fl oz/cwt) | 10 | 10 | 8 | 2.5 | 3 |
| WR (fl oz/cwt) | 3 | 3 | 3 | 3 | 3 |
| AEA (fl oz/cwt) | 1 | 0.25 | 0 | 0 | 1.0 |
| Targeted Air Content (%) | 6 | 4 | 2 | 2 | 4 |
| Calculated Unit Weight (lb/yd$^3$) | 144.6 | 146.8 | 149.0 | 147.9 | 144.7 |
| w/cm | 0.30 | 0.32 | 0.34 | 0.36 | 0.36 |

Table 4.4. Mixture Proportions.

| Materials | Mixture Designations | | | |
|---|---|---|---|---|
| | 9-36-6.2 | 9-42-1.8 | 9-42-2.2FA | 9-42-2.4SF |
| Cement (lb/yd$^3$) | 900 | 900 | 765 | 855 |
| Fly Ash (lb/yd$^3$) | 0 | 0 | 135 | 0 |
| Silica Fume (lb/yd$^3$) | 0 | 0 | 0 | 45 |
| Coarse Agg. (lb/yd$^3$) | 1790 | 1790 | 1790 | 1790 |
| Fine Agg. (lb/yd$^3$) | 803 | 839 | 817 | 822 |
| Water (lb/yd$^3$) | 324 | 378 | 378 | 378 |
| HRWR (fl oz/cwt) | 3 | 0 | 0 | 0 |
| WR (fl oz/cwt) | 3 | 0 | 0 | 3 |
| AEA (fl oz/cwt) | 1.5 | 0 | 0 | 0 |
| Targeted Air Content (%) | 6 | 2 | 2 | 2 |
| Calculated Unit Weight (lb/yd$^3$) | 141.5 | 144.7 | 143.9 | 142.4 |
| w/cm | 0.36 | 0.42 | 0.42 | 0.42 |

Table 4.5. Mixture Proportions.

| Materials | Mixture Designations | | | |
|---|---|---|---|---|
| | 9-42-4.4 | 9-42-5.9 | 9-45-4.1 | 9-50-0.9 |
| Cement (lb/yd$^3$) | 900 | 900 | 900 | 900 |
| Coarse Agg. (lb/yd$^3$) | 1790 | 1790 | 1790 | 1790 |
| Fine Agg. (lb/yd$^3$) | 750 | 662 | 679 | 650 |
| Water (lb/yd$^3$) | 378 | 378 | 405 | 450 |
| HRWR (fl oz/cwt) | 0 | 0 | 0 | 0 |
| WR (fl oz/cwt) | 0 | 0 | 0 | 0 |
| AEA (fl oz/cwt) | 1 | 1.25 | 0.75 | 0 |
| Targeted Air Content (%) | 4 | 6 | 4 | 2 |
| Calculated Unit Weight (lb/yd$^3$) | 141.4 | 138.1 | 139.8 | 140.4 |
| w/cm | 0.42 | 0.42 | 0.45 | 0.50 |

Table 4.6. Mixture Proportions.

| Materials | Mixture Designations | | | |
|---|---|---|---|---|
| | 9-50-1.5FA | 9-50-2.2SF | 9-50-3.6 | 9-50-6.6 |
| Cement (lb/yd$^3$) | 765 | 855 | 900 | 900 |
| Fly Ash (lb/yd$^3$) | 135 | 0 | 0 | 0 |
| Silica Fume (lb/yd$^3$) | 0 | 45 | 0 | 0 |
| Coarse Agg. (lb/yd$^3$) | 1790 | 1790 | 1790 | 1790 |
| Fine Agg. (lb/yd$^3$) | 628 | 633 | 561 | 473 |
| Water (lb/yd$^3$) | 450 | 450 | 450 | 450 |
| HRWR (fl oz/cwt) | 0 | 0 | 0 | 0 |
| WR (fl oz/cwt) | 0 | 0 | 0 | 0 |
| AEA (fl oz/cwt) | 0 | 0 | 0.5 | 0.75 |
| Targeted Air Content (%) | 2 | 2 | 4 | 6 |
| Calculated Unit Weight (lb/yd$^3$) | 139.6 | 138.1 | 137.1 | 133.8 |
| w/cm | 0.50 | 0.50 | 0.50 | 0.50 |

### 4.3.4 Tests

All mixtures were subjected to several tests. The fresh concrete properties tested were slump (ASTM C 143), unit weight (ASTM C 138), and air content (ASTM C 231). The hardened properties tested were compressive strength (ASTM C 39) at one, seven, twenty-eight, and fifty-six days of age and freeze-thaw durability (ASTM C 666, Procedure A).

The only deviation from the ASTM test procedures occurred in the freeze-thaw tests. ASTM C 666 states that the specimens be submerged in water for 14 days and then placed in the freeze-thaw chamber. For this program, the specimens were submerged in water for 56 days and then placed in the chamber. The additional 42 days allowed the concrete mixtures to attain higher compressive strengths and greater maturity.

## 4.4 RESULTS

### 4.4.1 Fresh Properties

The results of the fresh property tests are shown in Table 4.7. The air contents for all the mixtures were near the targeted total air contents. Not all the mixtures that were cast fell into one of the targeted zones. Several mixtures had to be discarded because the total air contents were much higher than the targeted air content. If the measured total air content was outside this range (± 0.5 percent), the concrete was discarded and no tests were performed.

Table 4.7. Fresh Concrete Properties

| Mixture | Slump (in.) | Total Air Content (%) | Unit Weight (lb/ft$^3$) |
|---|---|---|---|
| 9-26-2.4 | 6.50 | 2.4 | 152.3 |
| 9-26-3.8 | 8.00 | 3.8 | 149.3 |
| 9-26-5.6 | 4.25 | 5.6 | 147.2 |
| 9-30-1.1 | 10.00 | 1.1 | 150.9 |
| 9-30-4.5 | 1.50 | 4.5 | 147.5 |
| 9-30-5.7 | 10.75 | 5.7 | 146.2 |
| 9-32-4.1 | 6.50 | 4.1 | 147.2 |
| 9-34-2.0 | 11.50 | 2.0 | 150.6 |
| 9-36-2.6 | 2.50 | 2.6 | 147.8 |
| 9-36-3.8 | 3.50 | 3.8 | 146.8 |
| 9-36-6.2 | 2.00 | 6.2 | 139.6 |
| 9-42-1.8 | 3.25 | 1.8 | 145.8 |
| 9-42-2.2FA | 2.00 | 2.2 | 145.9 |
| 9-42-2.4SF | 1.00 | 2.4 | 143.8 |
| 9-42-4.4 | 3.75 | 4.4 | 142.7 |
| 9-42-5.9 | 4.00 | 5.9 | 139.1 |
| 9-45-4.1 | 5.50 | 4.1 | 140.3 |
| 9-50-0.9 | 6.25 | 0.9 | 143.4 |
| 9-50-1.5FA | 8.00 | 1.5 | 142.3 |
| 9-50-2.2SF | 3.25 | 2.2 | 140.4 |
| 9-50-3.6 | 9.50 | 3.6 | 135.1 |
| 9-50-6.6 | 10.00 | 6.6 | 133.4 |

25.4 mm = 1 inch
16.01 kg/m$^3$ = 1 lb/ft$^3$

### 4.4.2 Hardened Properties

The results of the hardened property tests are shown in Tables 4.8 and 4.9. The results from the compressive strength tests are shown in Table 4.8. Shown in Table 4.9 is the durability factor (DF) of the specimens at 300 freeze-thaw cycles. The compressive strength results are the average of three compressive strength tests, and the durability factors are the average of four specimens. The individual results and statistical data for the compressive strength tests and durability factors are shown in Appendix C.

Table 4.8. Compressive Strength Results.

| Mixtures | Average Compressive Strength (psi) | | | |
|---|---|---|---|---|
| | 1 day[1] | 7 days[1] | 28 days[1] | 56 days[1] |
| 9-26-2.4 | 6830 | 11,040 | 12,190 | 12,960 |
| 9-26-3.8 | 4830 | 10,440 | 11,270 | 12,090 |
| 9-26-5.6 | 4560 | 9270 | 10,560 | 11,290 |
| 9-30-1.1 | 6150 | 10,050 | 12,190 | 13,600 |
| 9-30-4.5 | 5610 | 8650 | 9960 | 11,010 |
| 9-30-5.7 | 6000 | 9130 | 10,270 | 11,030 |
| 9-32-4.1 | 5730 | 8320 | 9650 | 10,700 |
| 9-34-2.0 | 4700 | 9080 | 10,250 | 11,200 |
| 9-36-2.6 | 4220 | 7210 | 9180 | 9620 |
| 9-36-3.8 | 4580 | 6960 | 8340 | 9040 |
| 9-36-6.2 | 3660 | 6790 | 7700 | 8450 |
| 9-42-1.8 | 2690 | 6760 | 8690 | 9050 |
| 9-42-2.2FA | 2830 | 6840 | 8680 | 9100 |
| 9-42-2.4SF | 4070 | 6290 | 7770 | 8240 |
| 9-42-4.4 | 2750 | 4940 | 6470 | 6860 |
| 9-42-5.9 | 2640 | 4900 | 6110 | 6710 |
| 9-45-4.1 | 2600 | 4900 | 6110 | 6980 |
| 9-50-0.9 | 2020 | 4730 | 6220 | 6990 |
| 9-50-1.5FA | 1970 | 6020 | 7360 | 7870 |
| 9-50-2.2SF | 2110 | 4390 | 6100 | 6380 |
| 9-50-3.6 | 1560 | 5220 | 6340 | 6760 |
| 9-50-6.6 | 1650 | 4320 | 5560 | 6150 |

1) Average compressive strength of three tests.
2) Individual tests and statistical data are shown in Appendix C.

Table 4.9. Freeze-Thaw Results.

| Mixture | Freeze-Thaw | |
|---|---|---|
| | Number of Cycles | Average Durability Factor[1] |
| 9-26-2.4 | 300 | 97.5 |
| 9-26-3.8 | 300 | 97.7 |
| 9-26-5.6 | 300 | 99.3 |
| 9-30-1.1 | 300 | 100.6 |
| 9-30-4.5 | 300 | 98.9 |
| 9-30-5.7 | 300 | 95.6 |
| 9-32-4.1 | 300 | 94.4 |
| 9-34-2.0 | 300 | 94.2 |
| 9-36-2.6 | 300 | 77.6 |
| 9-36-3.8 | 300 | 94.4 |
| 9-36-6.2 | 300 | 100.9 |
| 9-42-1.8 | 300 | 20.8 |
| 9-42-2.2FA | 300 | 30.5 |
| 9-42-2.4SF | 300 | 13.4 |
| 9-42-4.4 | 300 | 100.2 |
| 9-42-5.9 | 300 | 93.2 |
| 9-45-4.1 | 300 | 91.3 |
| 9-50-0.9 | 141 | 17.3 |
| 9-50-1.5FA | 300 | 21.5 |
| 9-50-2.2SF | 300 | 22.4 |
| 9-50-3.6 | 300 | 91.3 |
| 9-50-6.6 | 300 | 93.1 |

1) Average durability factor of four tests.
2) Individual tests and statistical data are shown in Appendix C.

## 4.5 DISCUSSION OF RESULTS

### 4.5.1 Fresh Properties

The results from the total air content test and the unit weight test directly correlated. While this result is expected, the literature does not contain a lot of information on this subject. Increases in total air content resulted in decreases in unit weight for mixtures of like w/cm, which was expected. For mixtures with the same w/cm, the unit weight decreased as the total air content increased, which was expected (Figure 4.1). Also, the unit weights of mixtures with like total air contents decreased as the w/cm increased, which was also expected (Figure 4.2).

The unit weight test served as a check for the total air content. The check was necessary to be certain that the air meter was working correctly and as an independent quality control technique. Shown in Table 4.10 is a comparison of the calculated unit weights and the measured unit weights of the mixtures. Also in Table 4.10 is the calculated unit weight based on the measured air content. The differences between the two air contents are also shown. The average differences between the measured and the calculated unit weights (for the targeted and actual air contents) were +0.67 lb.ft$^3$ and +0.61 lb/ft$^3$, respectively. The standard deviation for both differences was 1.36 lb/ft$^3$. Overall, the differences between the measured and calculated unit weights were not significant, and the minimal differences show that no errors occurred during the batching of the concrete mixture. The minimal differences also show that the unit weight test would be a good quality control tool to use on the job site.

Table 4.10. Comparison of Calculated and Measured Unit Weights.

| Mixture Designation | Unit Weights ($lb/ft^3$) | | | | |
|---|---|---|---|---|---|
| | Calculated based (2, 4, or 6 %) | Measured | Difference | Calculated based on actual air content | Difference |
| 9-26-2.4 | 153.4 | 152.3 | -1.1 | 152.7 | -0.4 |
| 9-26-3.8 | 150.1 | 149.3 | -0.8 | 150.4 | -1.1 |
| 9-26-5.6 | 146.8 | 147.2 | +0.4 | 147.5 | -0.3 |
| 9-30-1.1 | 151.2 | 150.9 | -0.3 | 152.7 | -1.8 |
| 9-30-4.5 | 147.9 | 147.5 | -0.4 | 147.1 | +0.4 |
| 9-30-5.7 | 144.6 | 146.2 | +1.6 | 145.1 | +1.1 |
| 9-32-4.1 | 146.8 | 147.2 | +0.4 | 146.7 | +0.5 |
| 9-34-2.0 | 149.0 | 150.6 | +1.6 | 149.0 | +1.6 |
| 9-36-2.6 | 147.9 | 147.8 | -0.1 | 147.0 | +0.8 |
| 9-36-3.8 | 144.7 | 146.8 | +2.1 | 145.0 | +1.8 |
| 9-36-6.2 | 141.2 | 139.6 | -1.6 | 141.1 | -1.5 |
| 9-42-1.8 | 144.7 | 145.8 | +1.1 | 145.0 | +0.8 |
| 9-42-2.2FA | 143.9 | 145.9 | +2.0 | 143.6 | +2.3 |
| 9-42-2.4SF | 142.4 | 143.8 | +1.4 | 141.8 | +2.0 |
| 9-42-4.4 | 141.4 | 142.7 | +1.3 | 140.8 | +1.9 |
| 9-42-5.9 | 138.1 | 139.1 | +1.0 | 138.3 | +0.8 |
| 9-45-4.1 | 139.8 | 140.3 | +0.5 | 139.6 | +0.7 |
| 9-50-0.9 | 140.4 | 143.4 | +3.0 | 142.2 | +1.2 |
| 9-50-1.5FA | 139.6 | 142.3 | +2.7 | 140.3 | +2.0 |
| 9-50-2.2SF | 138.1 | 140.4 | +2.3 | 137.8 | +2.6 |
| 9-50-3.6 | 137.1 | 135.1 | -2.0 | 137.7 | -2.6 |
| 9-50-6.6 | 133.8 | 133.4 | -0.4 | 132.8 | +0.6 |
| | Average Differences ($lb/ft^3$) | | +0.67 | | +0.61 |
| | Standard Deviation ($lb/ft^3$) | | 1.36 | | 1.36 |

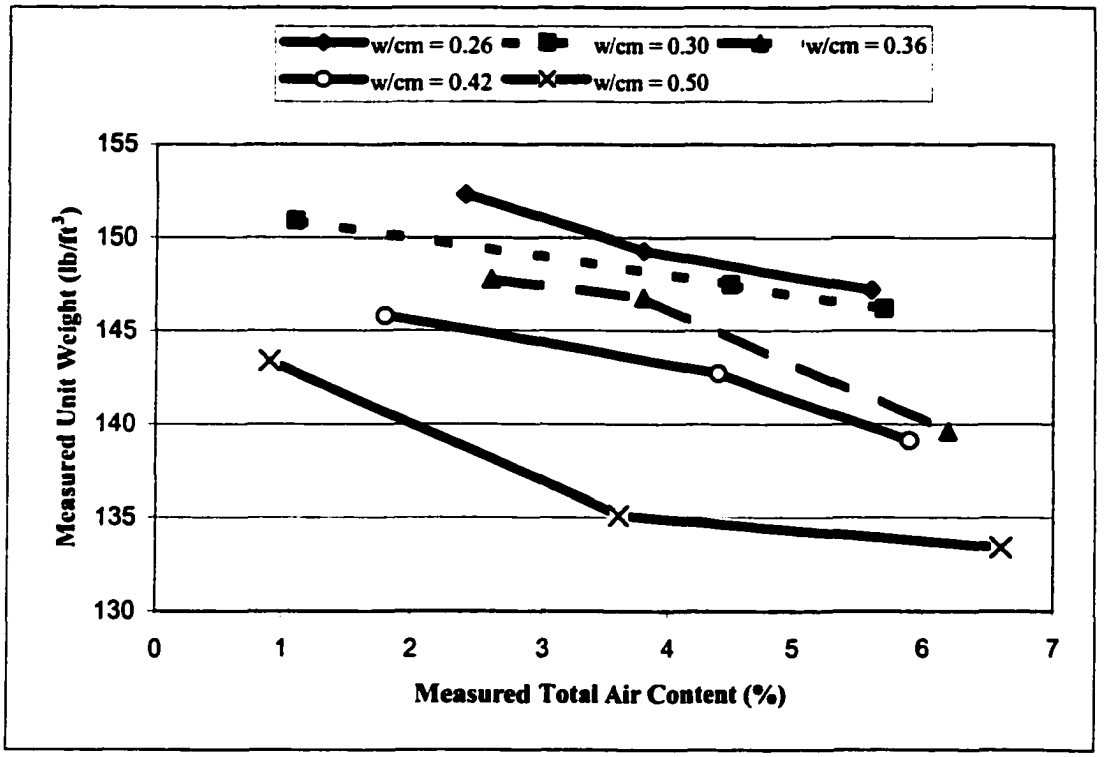


Figure 4.1. Measured Unit Weight versus Measured Air Content.

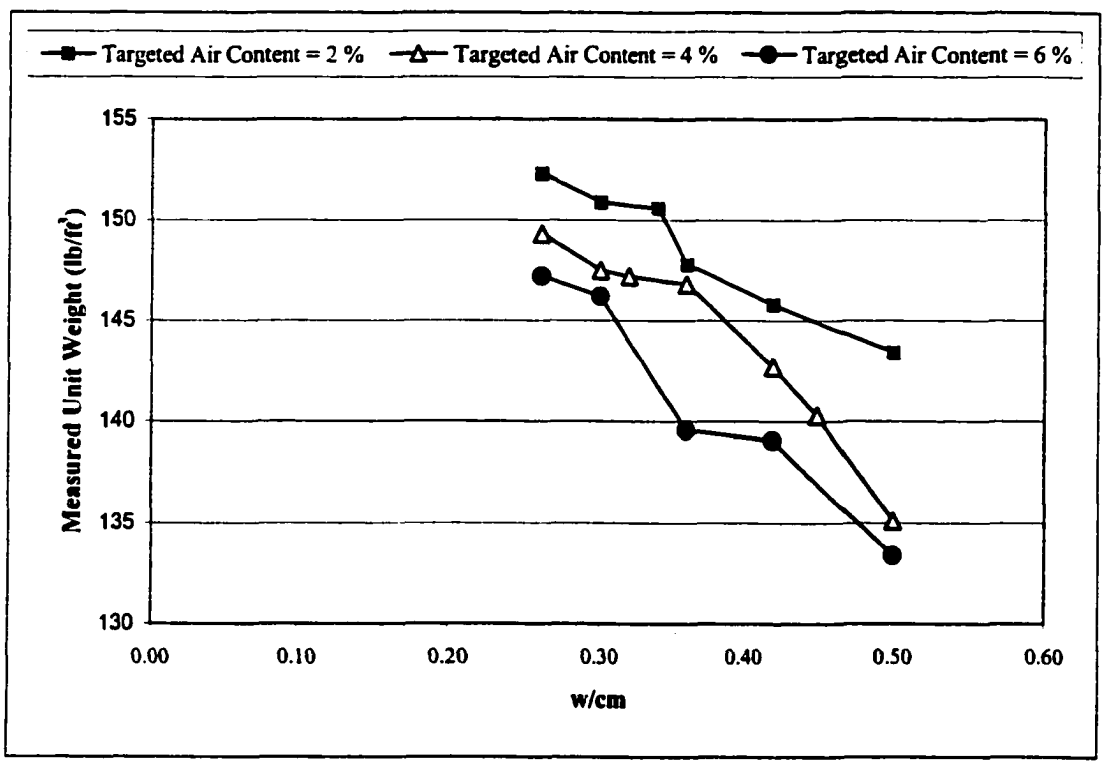


Figure 4.2. Measured Unit Weight versus w/cm.

### 4.5.2 Hardened Properties

**4.5.2.1 Compressive Strength.** The compressive strength tests for the mixtures followed an expected trend. As the w/cm decreased, the compressive strengths increased. These trends were validated through examination of the 90 percent confidence intervals shown in Figure C.4 in Appendix C. Also, for mixtures with like w/cm, the increase in total air content resulted in a decrease in compressive strength (Figure 4.3). In Chapter 3, the decrease in compressive strength per increase in air content was examined for the mixtures. The decreases in compressive strength generally followed the "2 – 5 percent decrease in compressive strength for every 1 percent increase in total air content" rule of thumb. The effects of air entrainment on the mixtures were discussed in more detail in Chapter 3.

**4.5.2.2 Freeze-Thaw Durability.** The results from the freeze-thaw tests indicate that air entrainment may not be needed in concrete mixtures with a w/cm less than 0.36. Also, the results show that between a w/cm of 0.36 and 0.50 only four percent air is necessary for freeze-thaw durability. The durability factors are shown in Figure 4.4. From Figure 4.4, it appears that mixtures with a w/cm less than 0.36 do not require air entrainment. Pinto and Hover (2001) also found acceptable durability at w/cm less than 0.35 for non-air entrained mixtures. At w/cm greater than 0.35, they achieved durability factors greater than 98 with a nominal air content of 4 percent. The results of the freeze-thaw tests are further discussed in the following sections.

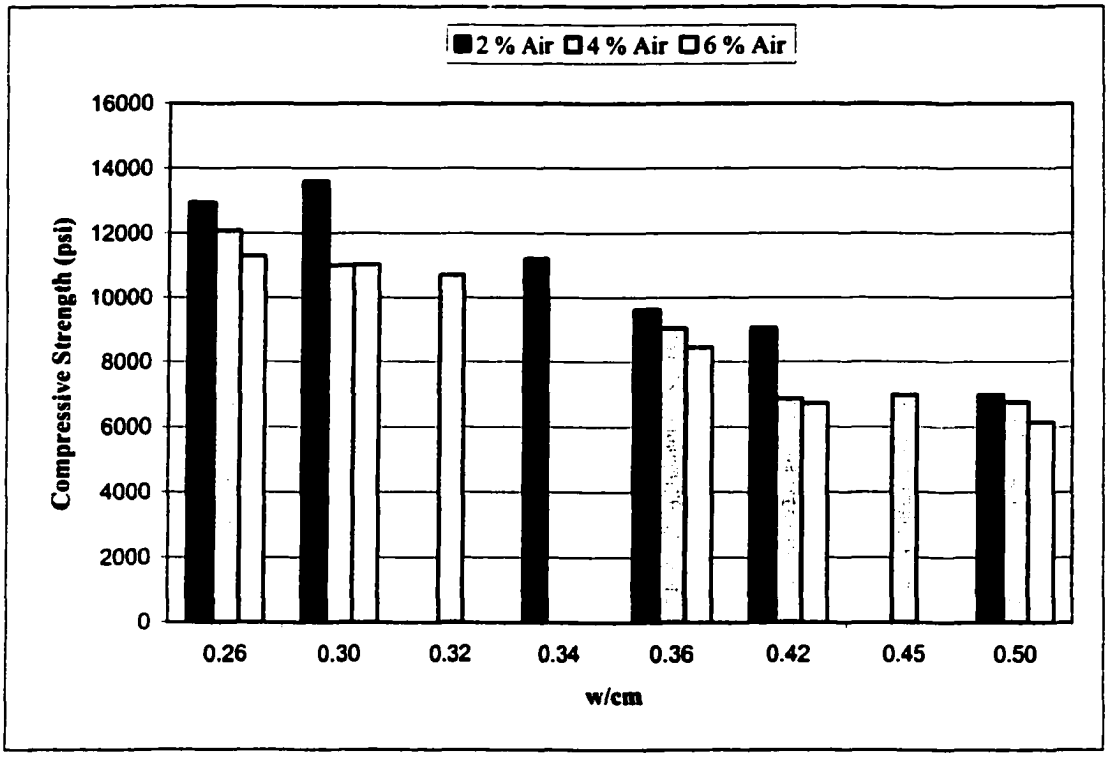


Figure 4.3. 56-Day Compressive Strength versus w/cm.

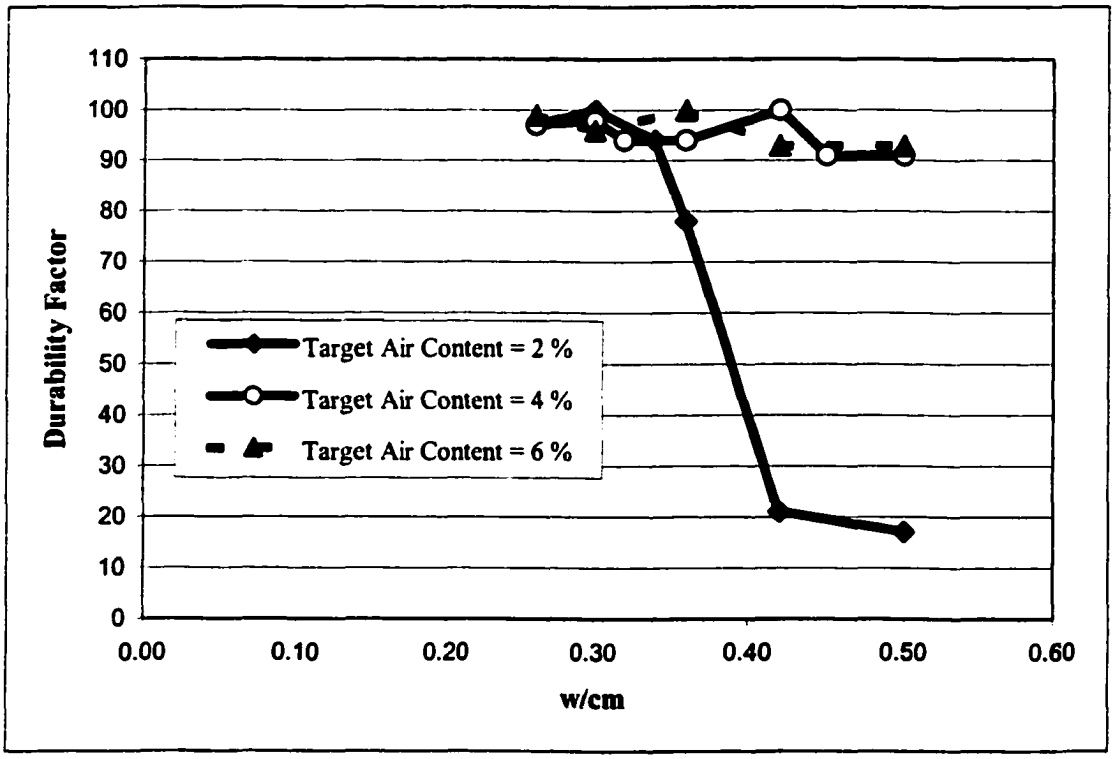


Figure 4.4. Durability Factors versus w/cm.

The mixtures that had unacceptable durability (unacceptable durability is defined as a durability factor below 60 by ASTM C 666) were the non-air entrained mixtures at w/cm of 0.42 and 0.50. Specimens from these mixtures are shown in Figures 4.5 through 4.10. Mixture 9-50-0.9, which had a total air content of 0.9, had deteriorated by 141 freeze-thaw cycles as shown in Figure 4.5. Also, mixture 9-42-1.8 (Figure 4.8), which had a total air content of 1.8 percent, had a durability factor of 21. By 300 freeze-thaw cycles all four specimens had fractured into two pieces.

In an attempt to improve their durability, fly ash or silica fume was added to the mixtures. At each w/cm, 15 percent of the cement was replaced with fly ash (Mixtures 9-42-2.2FA and 9-50-1.5FA), or 5 percent of the cement was replaced with silica fume (Mixtures 9-42-2.4SF and 9-50-2.2SF). Results show that the addition of silica fume and fly ash did not improve the mixtures' durability (Table 4.9). At a w/cm of 0.50, both mixtures (9-50-1.5FA and 9-50-2.2SF) had durability factors of 22 compared to the durability factor of 17 for the mixtures without pozzolans. However, there was a difference in the appearance of the specimens. Mixture 9-50-0.9 had deteriorated by 141 freeze-thaw cycles (Figure 4.5), but with the addition of fly ash and silica fume, the specimens did not completely deteriorate as evident in Figures 4.6 and 4.7.

Fly ash and silica fume were also added to the mixtures with a w/cm of 0.42 (Mixtures 9-42-2.2FA and 9-42-2.2SF). As with the mixtures with a w/cm of 0.50, the pozzolans did not significantly increase the concrete's freeze-thaw durability (Figures 4.9 and 4.10). Without pozzolans, Mixture 9-42-1.8 had a durability factor of 21. The addition of fly ash increased the durability factor to 31, and silica fume reduced the durability factor to 13.

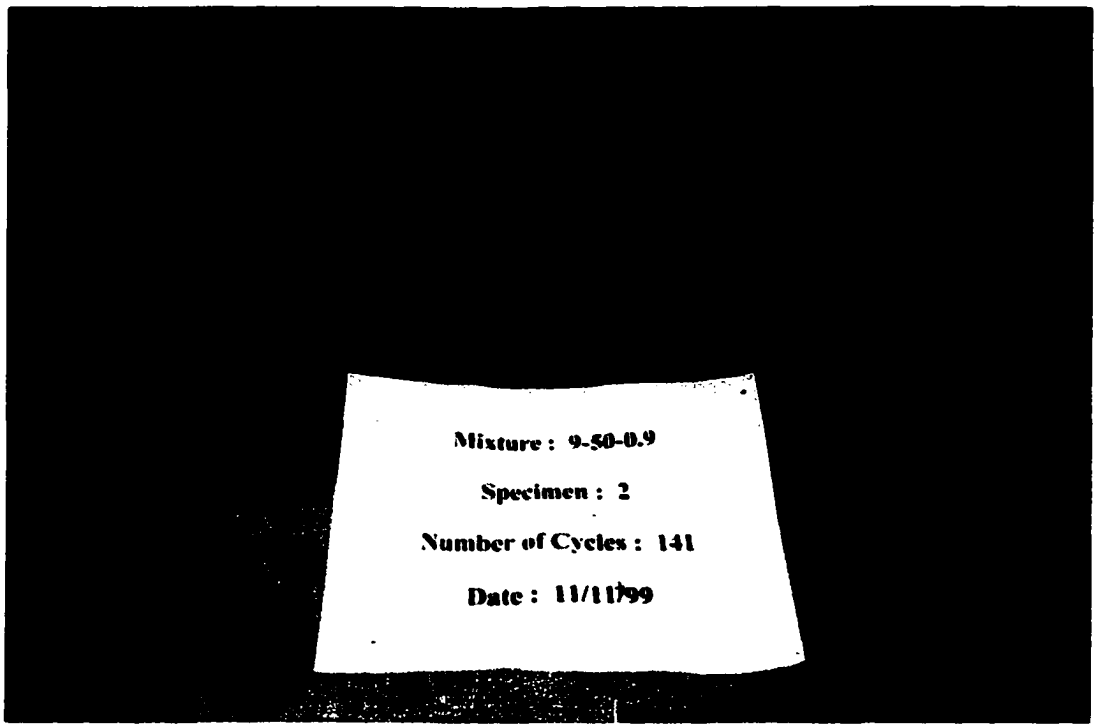


Figure 4.5. Mixture 9-50-0.9 with a Durability Factor of 17.

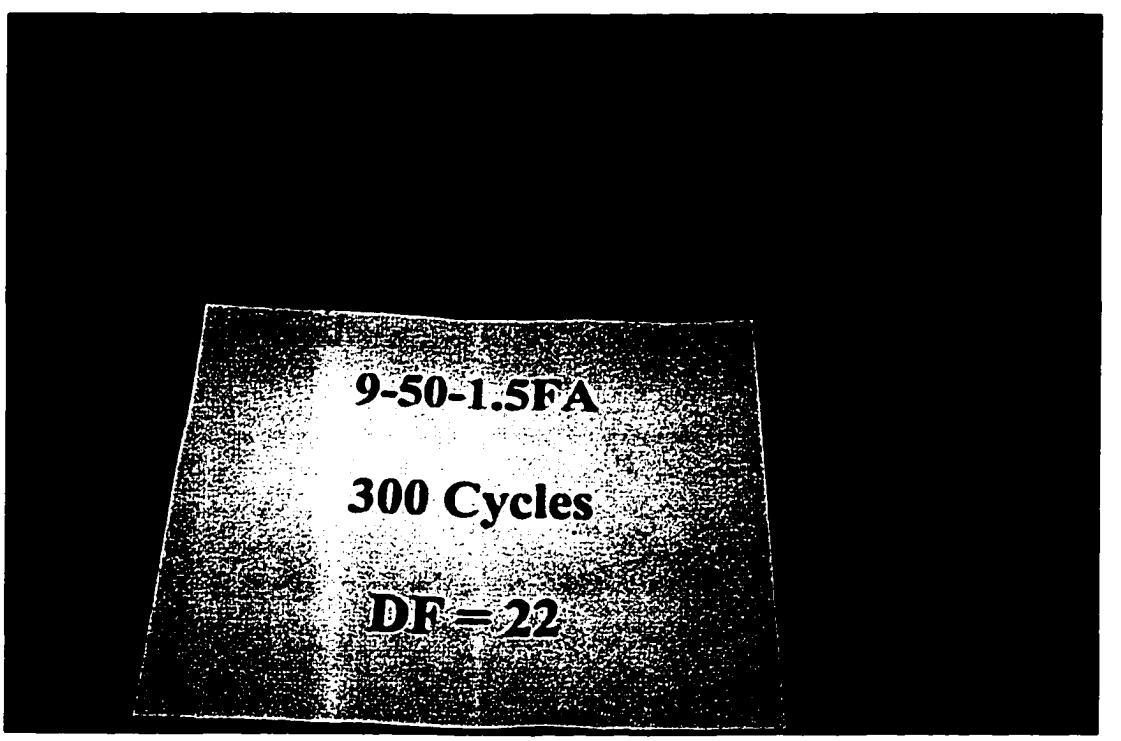


Figure 4.6. Mixture 9-50-1.5FA with a Durability Factor of 22.

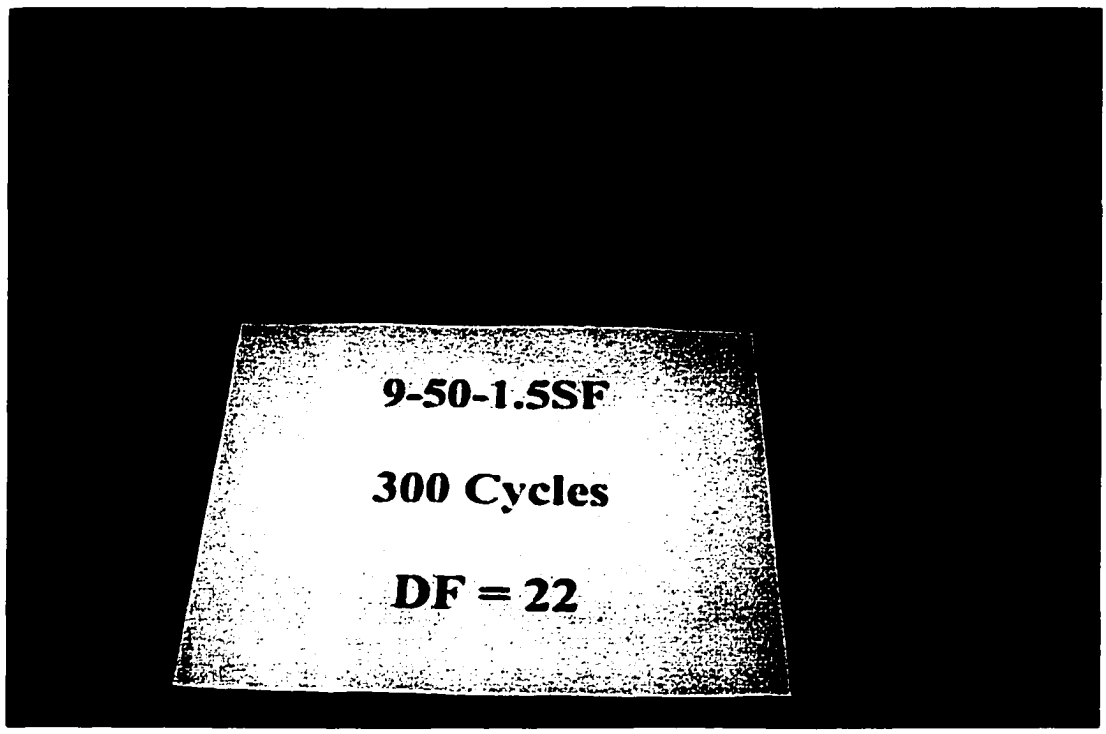


Figure 4.7. Mixture 9-50-1.5SF with a Durability Factor of 22.

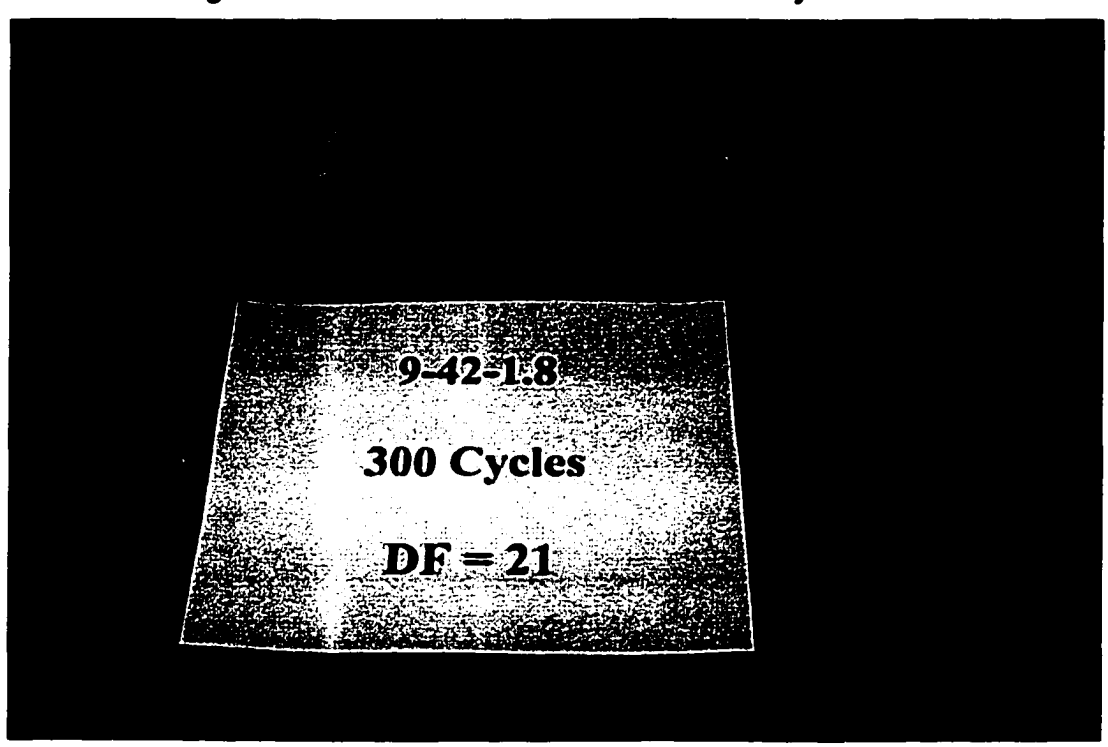


Figure 4.8. Mixture 9-42-1.8 with a Durability Factor of 21.

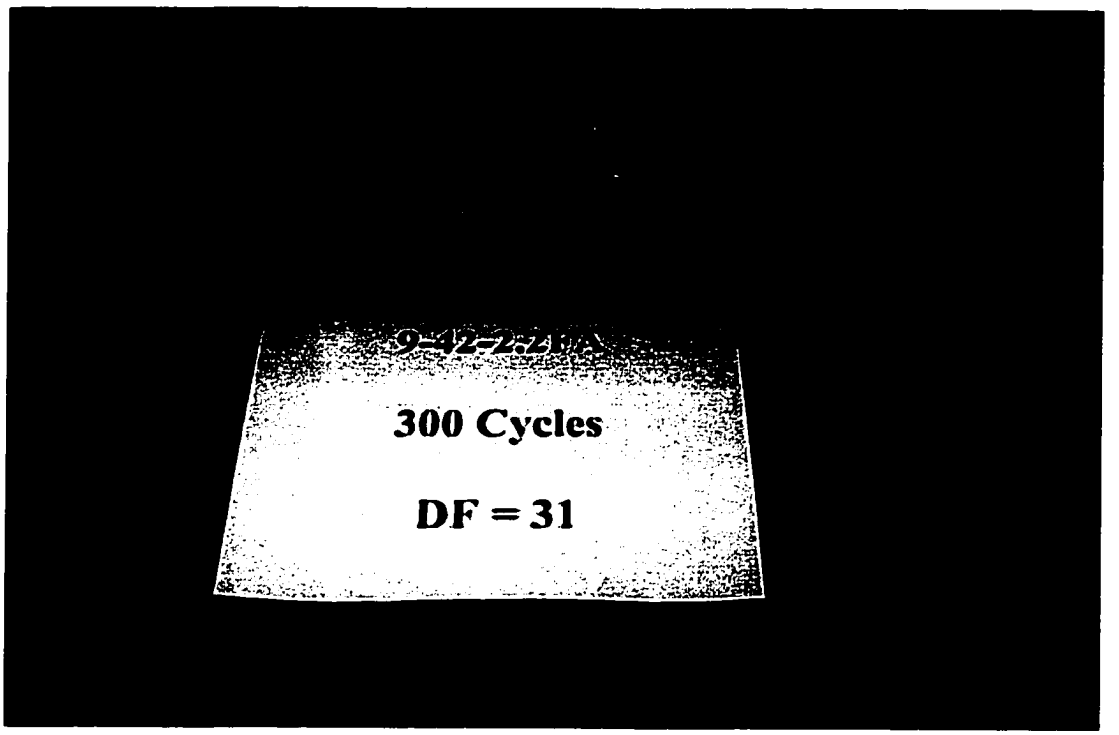


Figure 4.9. Mixture 9-42-2.2FA with a Durability Factor of 31.

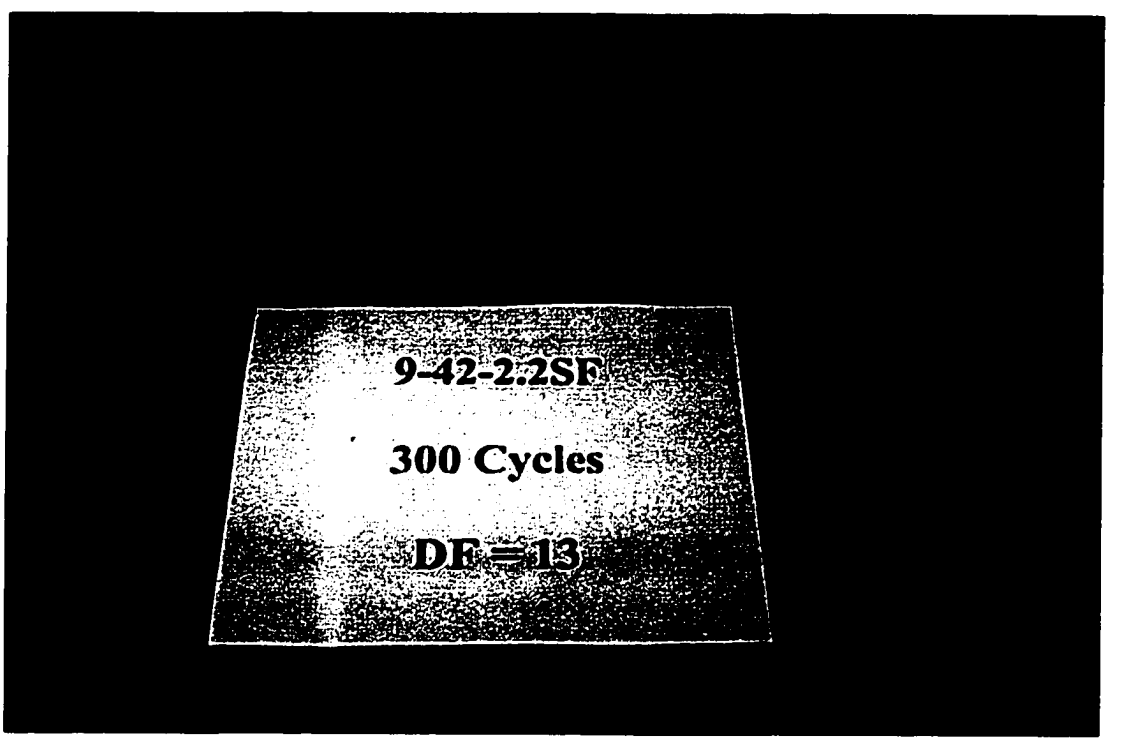


Figure 4.10. Mixture 9-42-2.2SF with a Durability Factor of 13.

The results from the research show that a total air content of four percent is sufficient to protect the concrete against freeze-thaw damage for concrete mixtures with a w/cm between 0.36 and 0.50. All mixtures containing a nominal air content of four percent had a durability factor of at least 91. Examination of the 90 percent confidence intervals (Figure C.5 in Appendix C) shows that 14 of the 15 mixtures with a targeted air content of four or six percent plot above a durability factor of 90 percent. Photographs of the tested specimens are shown in Figures 4.11 through 4.13. Without air entrainment, the mixture 9-50-0.9 had deteriorated by 141 cycles, but with addition of air entrainment, Mixture 9-50-3.7 (Figure 4.11) had a durability factor 91. At a w/cm of 0.42, mixtures had either fractured (Figure 4.8 and Figure 4.10) or had begun to deteriorate (Figure 4.9). But with 4.4 percent air, Mixture 9-42-4.4 had a durability factor of 100. Pinto and Hover (2001) also found acceptable durability with a nominal air content of 4 percent for mixtures with w/cm between 0.36 and 0.50.

For the mixtures in this study, a total air content of four percent is equal to an air content of 6.9 percent in the mortar (cement, fine aggregate, and water). This is still less than the mortar air content of 8.7 percent that is recommended for concrete containing 3/8 in. coarse aggregate (Mindess and Young, 1981). As explained in the literature review, the type, size, and quantity of coarse aggregate can affect the freeze-thaw durability of concrete (Neville, 1997). The conclusions from this research are limited to the mixtures and materials tested in the study. Decreasing the aggregate content would increase mortar content, which in turn increases the required air content of the mortar to be resistant to freeze-thaw cycles. Simply stated, as the mortar content increases, the air content required for the specimen to have sufficient freeze-thaw durability also increases.

If larger aggregates were used, additional paste would be required for workability, which would increase the required total air content when compared to a similar mix with less paste/mortar. Finally, using aggregates that are susceptible to freeze-thaw damage might also affect the need for air entrainment.

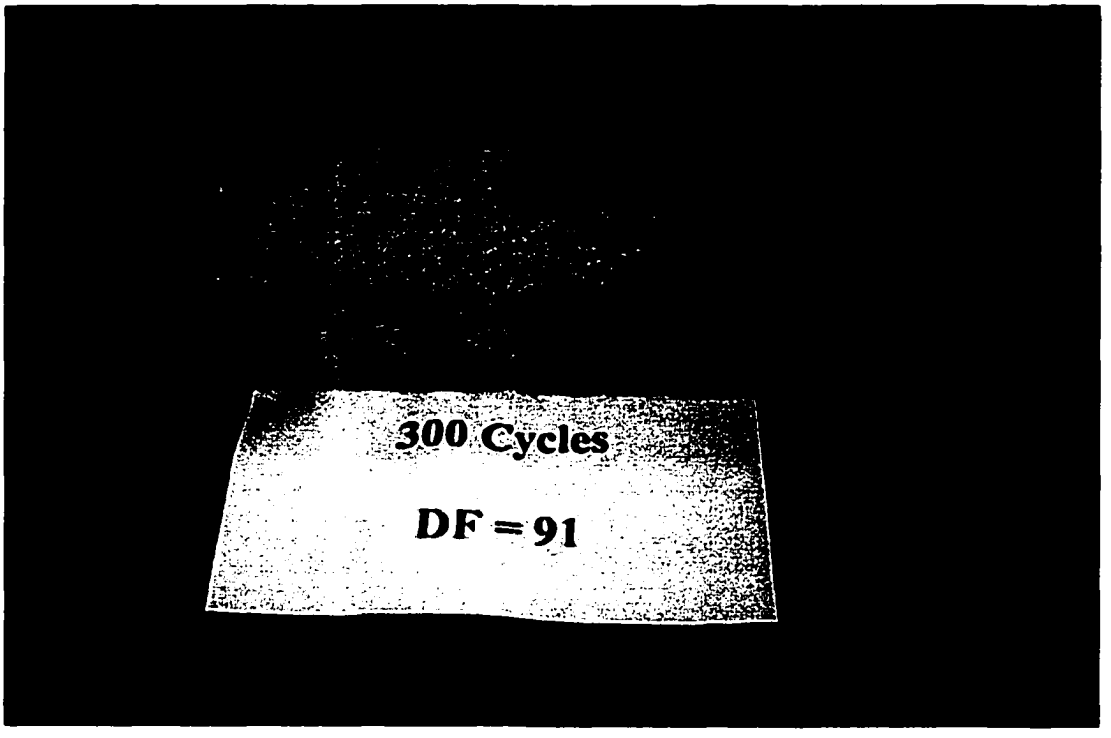


Figure 4.11. Mixture 9-50-3.7 with a Durability Factor of 91.

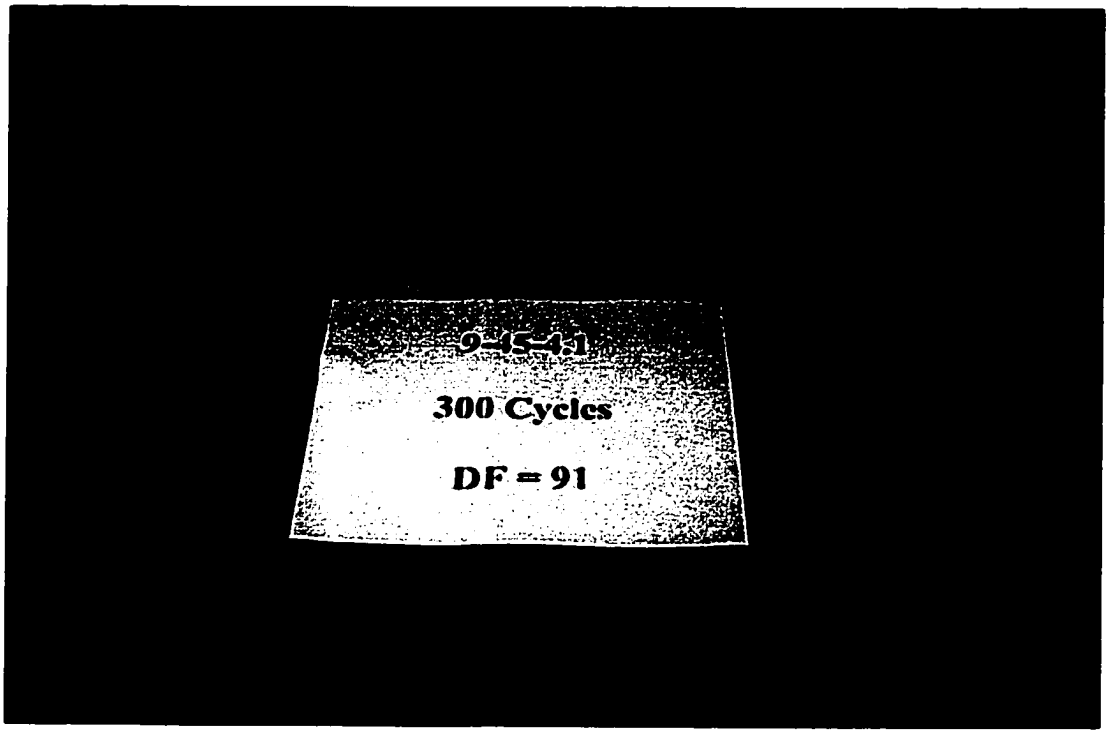


Figure 4.12. Mixtures 9-45-4.1 with a Durability Factor of 91.

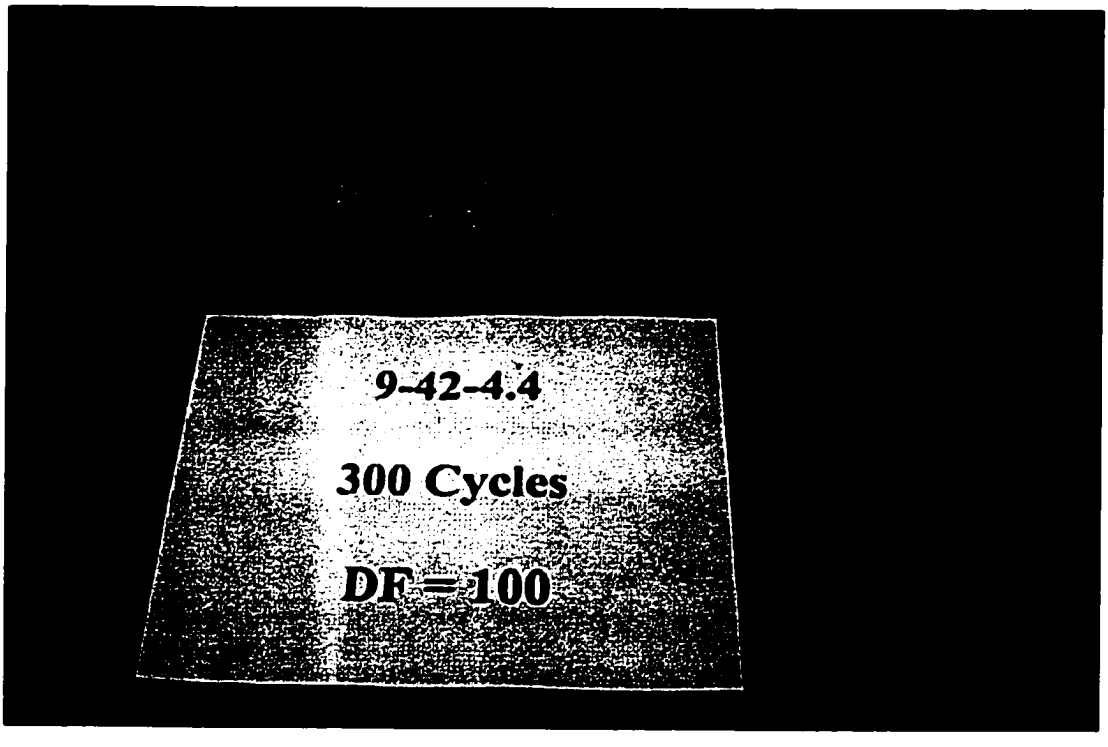


Figure 4.13. Mixtures 9-42-4.4 with a Durability Factor of 100.

At a w/cm of 0.36 and below, all non-air entrained mixtures had durability factors of 78 or greater. The freeze-thaw specimens are shown in Figures 4.14 through 4.17. The results indicate that air entrainment may not be necessary at w/cm equal to and less than 0.36. Once again these results are similar to Pinto and Hover (2001) whose non-air entrained mixture at a w/cm of 0.36 had a durability factor of 98. Also, a w/cm of 0.36 was the limit at which Mindess and Young (1981) theorized that air entrainment might not be necessary. Many researchers were able to produce durable non-air entrained mixtures, but Pinto and Hover (2001) and Hooten (1993) were the only researchers to produce durable non-air entrained mixtures at a w/cm of 0.35. Pigeon et al (1991) developed freeze-thaw durable mixtures at w/cm of 0.30 at lower. Mokhtarzadeh et al (1995) developed durable mixtures with w/cm of 0.29 and 0.31. Whereas Li et al (1994) had acceptable durability at w/cm of only 0.24 and lower.

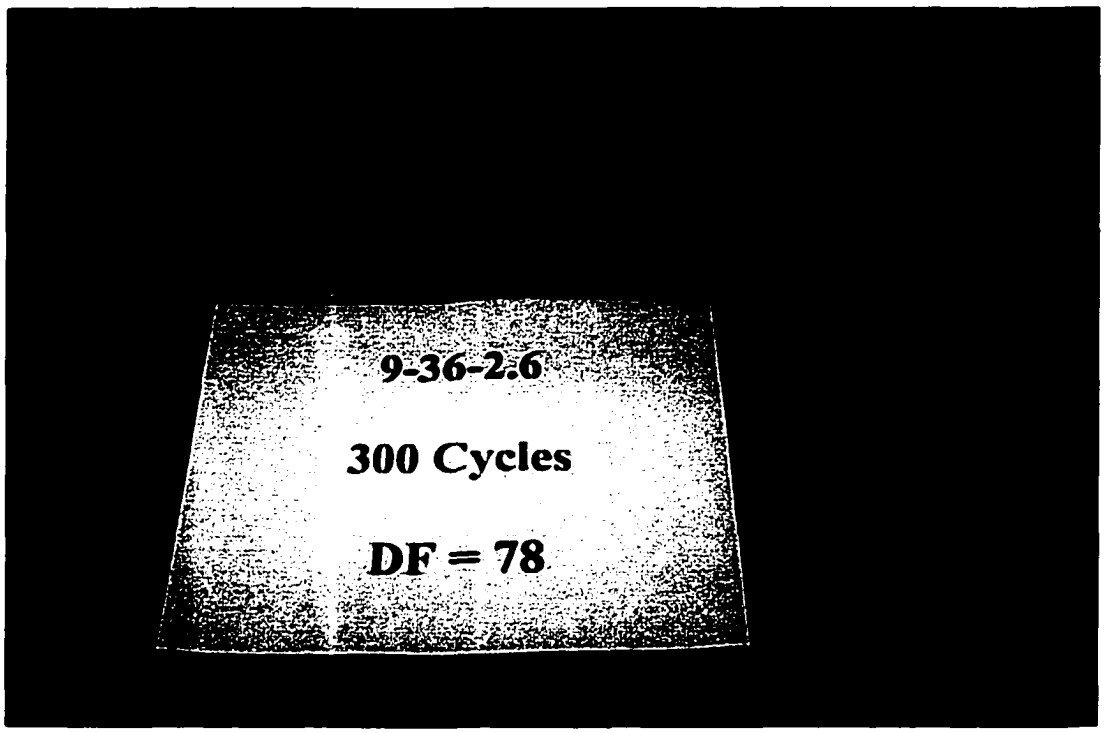


Figure 4.14. Mixture 9-36-2.6 with a Durability Factor of 78.

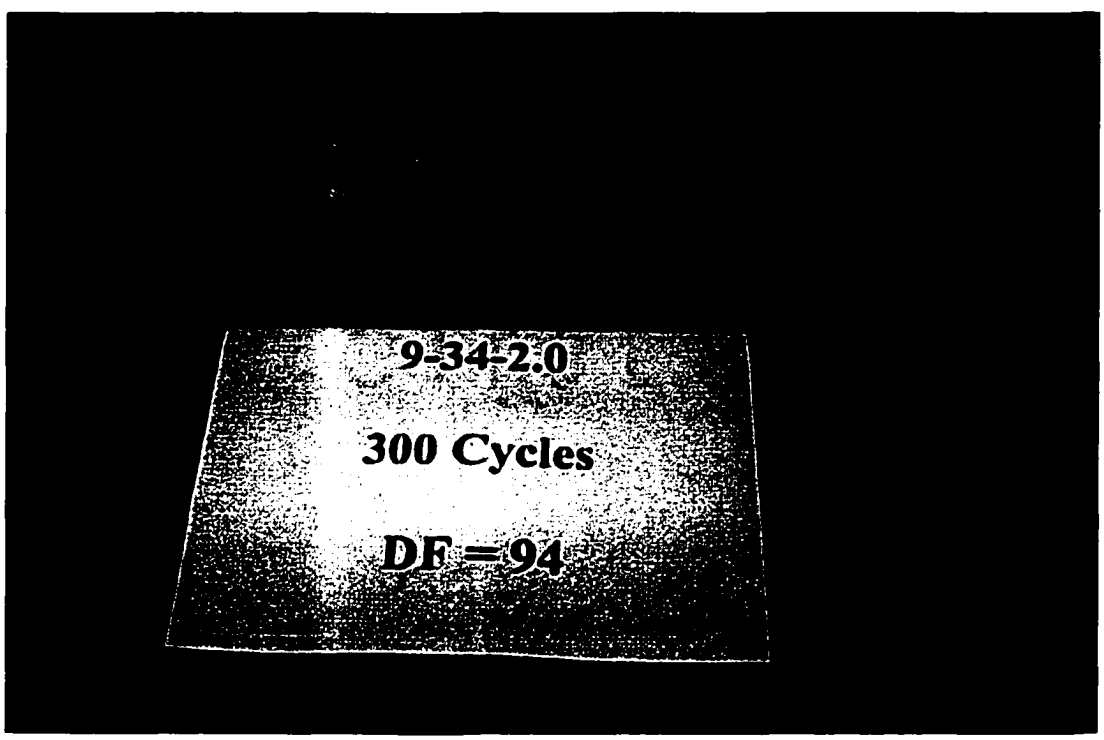


Figure 4.15. Mixture 9-34-2.0 with a Durability Factor 94.

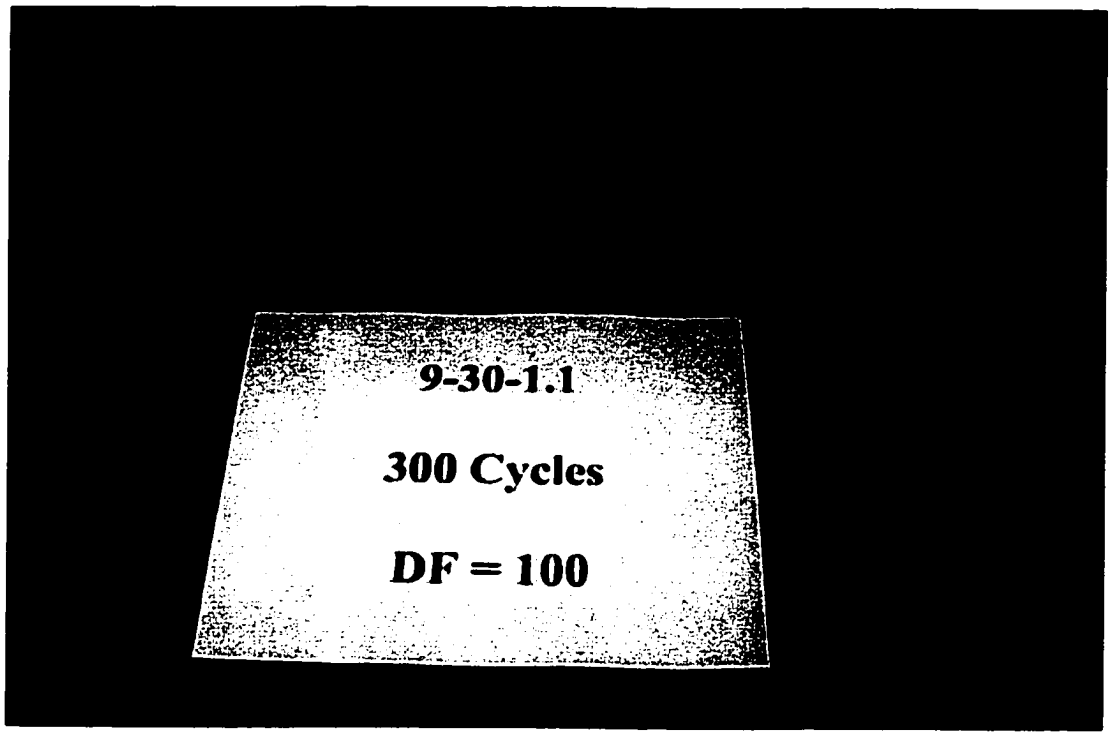


Figure 4.16. Mixture 9-30-1.1 with a Durability Factor of 100.

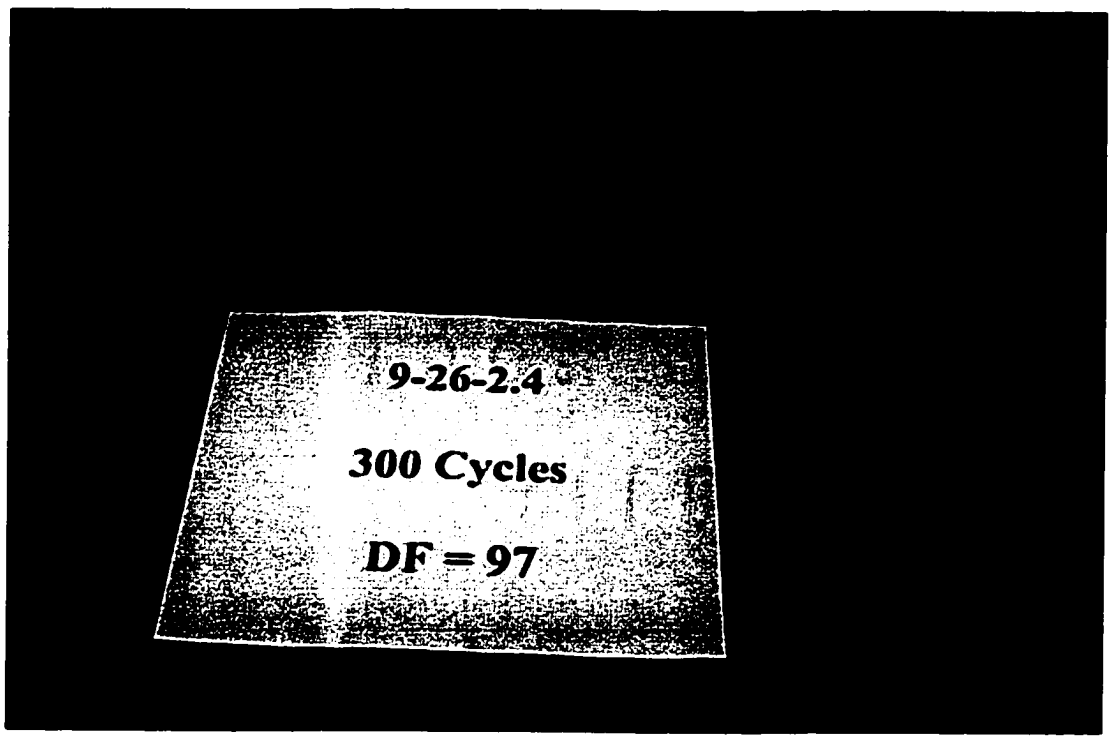


Figure 4.17. Mixture 9-26-2.4 with a Durability Factor of 97.

## 4.6 CONCLUSIONS

Results from the research show that air entrainment may not be necessary to achieve adequate freeze-thaw durability for concrete mixtures with w/cm less than 0.36. From the results in Table 4.9, it also appears that a total air content of 4 percent is enough to provide freeze-thaw durability for mixtures with a w/cm between 0.36 and 0.50. The findings of this research are very similar to those of Pinto and Hover (2001) who also developed non-air entrained, freeze-thaw durable mixtures at w/cm less than 0.36 and who also determined that a total air content of 4 percent was adequate for w/cm between 0.36 and 0.50.

However, all mixtures examined in the research contained the same type of coarse aggregate, which was known not to be susceptible to effects of freezing and thawing. The results from this research apply only to the materials used in the research. Mixtures containing aggregates with poor freeze-thaw durability may not perform as well as the mixtures tested in this research program. Before one can specify non-air entrained concrete in a harsh environment, specimens containing the materials to be used in the concrete should to be tested to determine its freeze-thaw durability. If freeze-thaw testing is not available, air entrainment should be employed in the concrete.

# CHAPTER 5

# INVESTIGATING THE PERMEABILITY OF HPC WITH AND WITHOUT ENTRAINED AIR

## 5.1 INTRODUCTION

This section of the research program investigated the permeability of high performance concrete (HPC) with and without entrained air. The previous chapter examined the freeze-thaw durability of HPC. Decreasing the amount of water entering a concrete structure can reduce the damage caused by freeze-thaw cycles. Therefore, reducing the permeability would increase the durability of concrete structures. This section of the research program had two tasks. The first task was to examine if there were any differences in the permeability of concrete with and without entrained air. The second task was to provide further information on the validity of the Rapid Chloride Ion Penetrability Test (ASTM C 1202) as a permeability measuring technique. Many researchers believe the RCIP test measures the concrete's conductivity not necessarily the permeability (Shi et al, 1998). Since the test procedure is relatively new, the results of the research will also provide the Oklahoma Department of Transportation (ODOT) information on the effectiveness of the test.

Concrete mixtures with varying water to cementitious material ratios (w/cm) were subjected to ASTM C 1202. The variables for the mixtures were total air content and w/cm. The targeted total air contents for the mixtures were 2 percent (no air entraining agent), 4 percent, and 6 percent. The results from the research show that entrained air has

no noticeable effect on the RCIP of the specimens. The results also further support the view that the RCIP test may not be an adequate test for measuring the permeability of concrete mixtures containing mineral admixtures.

## 5.2 LITERATURE REVIEW

The longevity of a concrete structure is influenced by the permeability of the concrete. If the amount of water entering a concrete structure can be reduced, the life of the structure can be extended. As discussed in Chapter 4, the presence of water in hardened concrete can eventually deteriorate the concrete through continuous freeze-thaw cycles. To combat the harmful effects of freeze-thaw cycles, entrained air is added to the concrete. Entrained air voids provide air pockets where water can expand and water pressure can be relieved. Without these voids, continuous freeze-thaw cycles will eventually degrade and damage the concrete. With the help of entrained air voids, highly permeable concrete can be resistant to freeze-thaw damage. However, damage from freeze-thaw cycles is not the only concern of highly permeable concrete. Water can also carry harmful chemicals (such as deicing salts) into the structure, which can lead to the corrosion of the reinforcement and loss of the structural capacity of the member. Therefore, to produce durable concrete structures, the permeability of the concrete must be considered.

Like any other material, the permeability of concrete is influenced by the pore system of the concrete paste. The porosity of concrete is the measure of the total volume of pores within the concrete. The size, spacing, distribution, and continuity of the pores

all have an effect on the permeability of concrete. Also of importance is the area around the aggregates known as the interface zone. This area is the interface between the paste and the aggregates. The interface area is known to have a different pore system than the remaining paste and is the location for early microcracking, but the "significance of the interface zone with respect to permeability remains uncertain (Neville, 1997)." To increase permeability, pores must be interconnecting to provide a path for water to flow. The addition of entrained air has little or no effect on the permeability of concrete. This is due to the fact that the entrained air bubbles are distributed evenly throughout the concrete and the pores do not connect (Mindess et al, 1981; Neville, 1997; Kosmatka et al, 1994).

Pozzolans such as fly ash, blast furnace slag, and silica fume also have an effect on the permeability of concrete. Pozzolans react with the byproducts of the cement hydration reaction to form additional calcium silicate hydrate (C-S-H). The additional C-S-H decreases the porosity of the cement paste, which in turn reduces the permeability (Mindess et al, 1981 and Neville, 1997).

There are several different standardized tests that measure the permeability of concrete. Many of the tests require a significant amount of time to measure the concrete's permeability. In 1991 a test was adopted by American Society for Testing and Materials (ASTM) that measured the concrete's permeability in six hours. This test is known as the Rapid Chloride Ion Penetrability Test (RCIP). Theoretically, the test measures the number of chloride ions that pass through a sample of concrete in a six-hour period of time. In general, the lower the permeability of the concrete the lower the

amount of coulombs passed. Therefore, concrete with a high permeability will pass more coulombs.

Some researchers believe that the Rapid Chloride Ion Penetrability Test (ASTM C 1202) measures the concrete's conductivity but not necessarily the concrete's permeability (Shi et al, 1998). The addition of mineral admixtures such as fly ash, blast furnace slag, and silica fume may alter the concrete's conductivity by altering the pH of the pore solution, which could either increase or decrease the RCIP value. The pore fluid of hardened concrete consists mainly of Na, K, and OH ions. Shi et al (1998) reported that the addition of mineral admixtures might increase or decrease the concentrations of these ions. They reported that BFS decreases the concentration of the OH and K ions, but increases the Na concentration. Shi et al (1998) also reported that the replacement of cement with 5 percent silica fume "can lead to order of magnitude reductions in Na, K, and OH ion concentrations." They also reported that the addition of fly ash might either increase or decrease the Na and K concentrations.

It is theorized that these changes in concentrations of the pore fluid result in changes in the concretes' specific conductivity. When compared to the control mixture (100 percent portland cement), the addition of 50 percent BFS reduced the concrete's specific conductivity by 3.25 percent at 28 days and up to 24 percent by 730 days. A specific conductivity of a concrete mixture containing 5 percent silica saw a reduction of 70.6 percent at 28 days. Shi et al (1998) concluded that "it was not correct" to use the RCIP test to evaluate the rapid chloride penetrability of concrete containing mineral admixtures.

Zhao et al (1999) also examined the pore chemicals in concretes with mineral admixtures. They measured the concretes' resistivity and its RCIP. They also found that the concretes' resistivity increased with the addition of mineral admixtures and as the concretes' resistivity increased its RCIP values decreased. These findings are similar to the results of a study conducted by Wee et al (2000).

Pfiefer et al (1994) examined the correlation of the RCIP test to the 90-day salt ponding test (AASHTO T259). They, like Shi et al, also state that the addition of silica fume can substantially reduce the number of coulombs passed. Pfiefer et al states that typical concrete "may have a 5- to 10-fold decrease in coulombs passed when 7 percent silica fume is added, while the actual chloride ingress after 90-day ponding tests may decrease only one to two times." For selecting materials for low permeability concretes, Pfiefer et al recommended that the selection should based on the 90-day salt ponding tests (AASHTO T259) not the RCIP test (ASTM C 1202). Scanlon et al (1996) also examined the correlation between the 90-day ponding test (AASHTO T259) and the RCIP test (ASTM C 1202) for concretes containing fly ash and/or silica fume. They too concluded that there were inconsistencies between the permeability determined by the RCIP test and the permeability measured by the 90-day ponding test. Scanlon et al stated that the correlation between coulomb values and chloride ingress given in AASHTO T277 or ASTM C 1202 "appears invalid for use with concretes containing silica fume, fly ash or a HRWRA."

## 5.3 EXPERIMENTAL PROCEDURES

### 5.3.1 Scope

The research program had two tasks. The first task was to examine if there were any differences in the permeability of concrete with and without entrained air. The second task was to provide further information on the validity of the Rapid Chloride Ion Penetrability test (ASTM C 1202). Several different concrete mixtures with varying w/cm and varying total air contents were subjected to the RCIP test (ASTM C 1202). The testing matrix is shown in Table 5.1. The w/cm ranged from 0.26 to 0.50. The targeted total air contents were 2, 4, and 6 percent.

Table 5.1. Testing Matrix

| Target Total Air Content (%) | w/cm | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 0.26 | 0.30 | 0.32 | 0.34 | 0.36 | 0.42 | 0.45 | 0.50 |
| 2 | X | X | - | X | X | X | - | X |
| 4 | X | X | X | - | X | X | X | X |
| 6 | X | X | - | - | X | X | - | X |
| X = indicates batching and testing of these variables | | | | | | | | |

### 5.3.2 Materials

Ash Grove Type III Cement was used in all mixtures. The coarse aggregate was 3/8 inch, crushed limestone from Davis, Oklahoma. The fine aggregate was washed river sand from Dover, Oklahoma. The material properties of the cement and aggregates are listed in Chapter 2. To provide adequate workability, a water reducer (WR) and/or a high range water reducer (HRWR) was used. The WR used was WRDA with Hycol, and the

HRWR used was ADVA Flow. An air entraining agent (AEA), DARAVAIR 1000, was used to attain the required target total air contents. Two mixtures contained Class C fly ash, and two mixtures also contained silica fume.

### 5.3.3 Mixtures

The same mixtures used to examine the freeze-thaw durability of HPC in Chapter 4 were also used to examine the permeability of HPC mixtures. The mixtures proportions are located in Table 4.2 through 4.6 of Chapter 4.

### 5.3.4 Tests

All mixtures were subjected to several tests. The fresh concrete properties tested were slump (ASTM C 143), unit weight (ASTM C 138), and air content (ASTM C 231). The hardened properties tested were compressive strength (ASTM C 39) at one, seven, twenty-eight, and fifty-six days of age, freeze-thaw durability (ASTM C 666, Procedure A), and the rapid chloride ion penetrability test (RCIP, ASTM C 1202) at 28 and 56 days of age. The compressive strength was discussed in detail in Chapters 2 and 3. The freeze-thaw durability was discussed in Chapter 4. This chapter will mainly focus on the permeability of the mixtures measured by the RCIP test.

The RCIP was tested at 28 and 56 days of age. Four specimens were tested from each mixture. Two days prior to testing, the top two inches of the cylinders to be tested were cut off using a masonry saw. The sides of the cylinders were then covered with epoxy (Figure 5.1). Once the epoxy dried, the cylinders were placed in a vacuum of no more than 1mm of Hg for three hours. After the three hours, water was introduced into

the container with the vacuum pump continuing to run for an additional hour. After the additional hour, the vacuum pump was turned off and the container was 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 end of the prepared specimens (Figure 5.2). In each of the end caps, sodium hydroxide or sodium chloride was placed. A positive terminal was then attached to the cap containing 0.3 N NaOH solution and a negative terminal attached to the cap containing 3.0 percent NaCl. 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 (Figure 5.3).

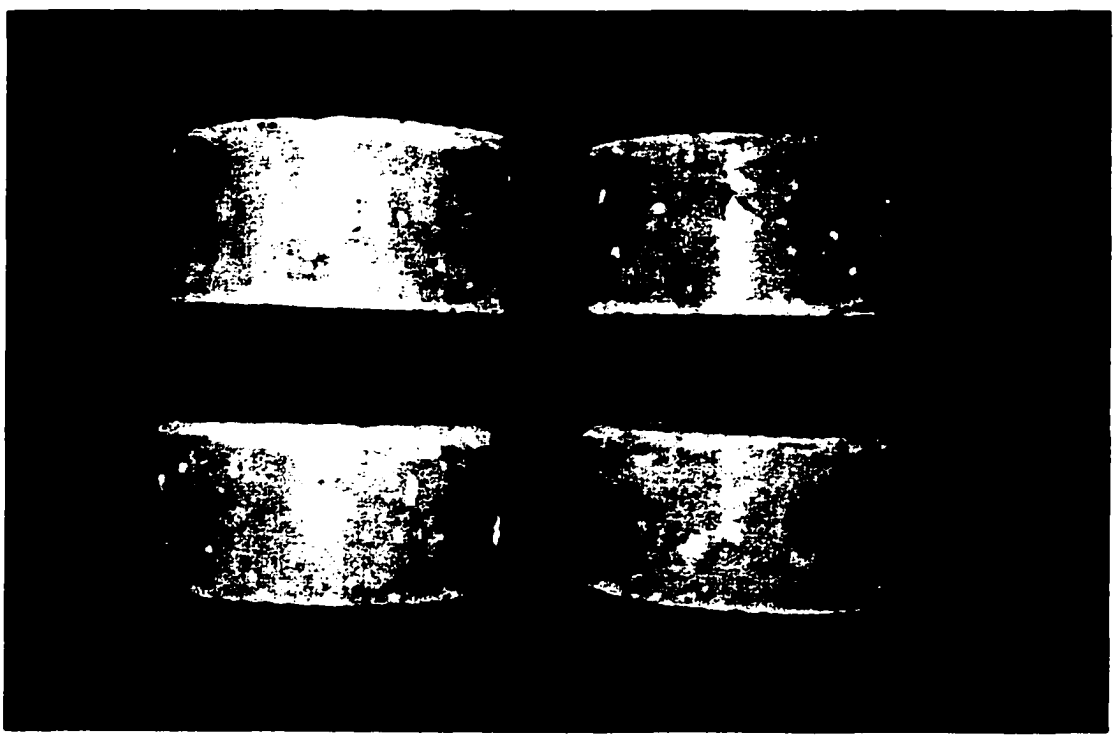

Figure 5.1. Epoxy Coated Test Specimens.

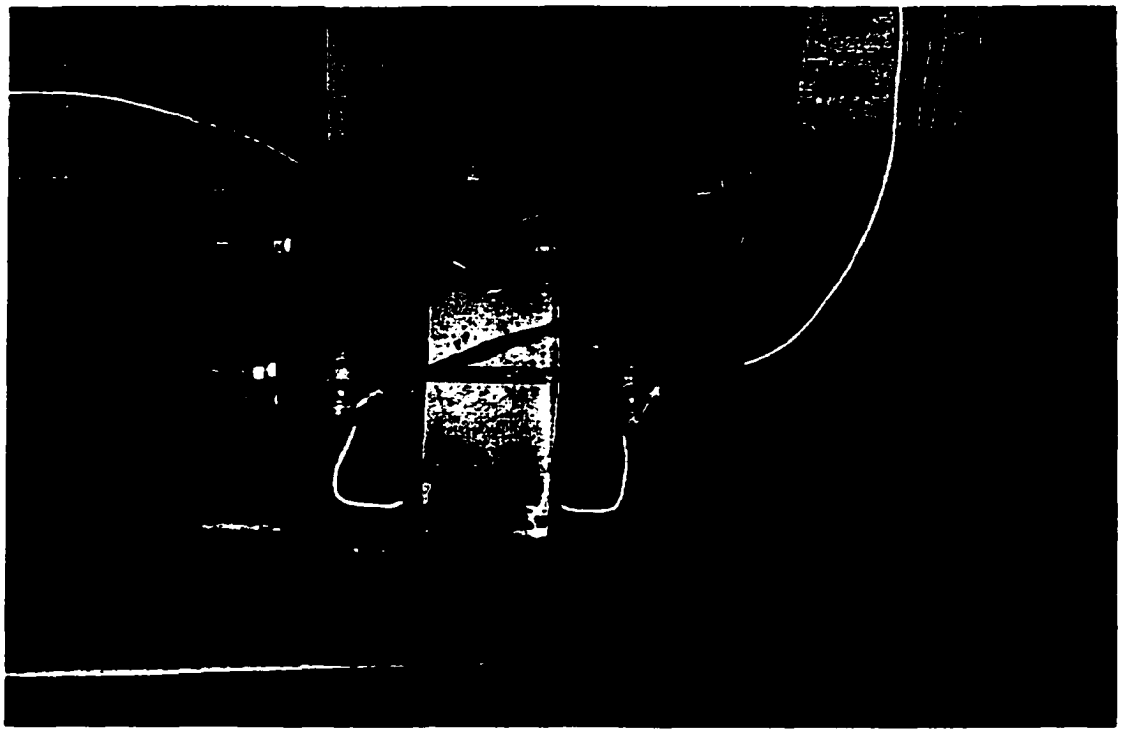

Figure 5.2. End Caps for RCIP Test.

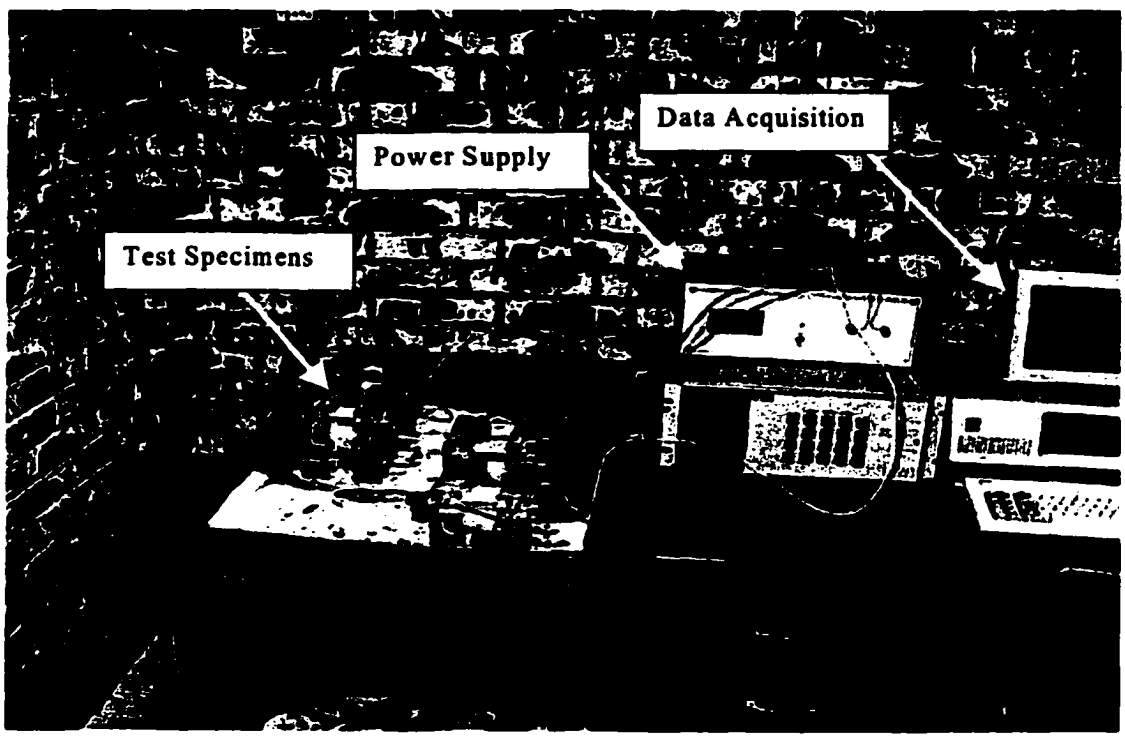


Figure 5.3. RCIP Test Set-up.

## 5.4 RESULTS

### 5.4.1 Fresh Properties

The results of the fresh property tests are shown in Table 5.2. The air contents for all the mixtures were near the targeted total air contents.

Table 5.2. Fresh Concrete Properties

| Mixture | Slump (in.) | Total Air Content (%) | Unit Weight (lb/ft$^3$) |
|---|---|---|---|
| 9-26-2.4 | 6.50 | 2.4 | 152.3 |
| 9-26-3.8 | 8.00 | 3.8 | 149.3 |
| 9-26-5.6 | 4.25 | 5.6 | 147.2 |
| 9-30-1.1 | 10.00 | 1.1 | 150.9 |
| 9-30-4.5 | 1.50 | 4.5 | 147.5 |
| 9-30-5.7 | 10.75 | 5.7 | 146.2 |
| 9-32-4.1 | 6.50 | 4.1 | 147.2 |
| 9-34-2.0 | 11.50 | 2.0 | 150.6 |
| 9-36-2.6 | 2.50 | 2.6 | 147.8 |
| 9-36-3.8 | 3.50 | 3.8 | 146.8 |
| 9-36-6.2 | 2.00 | 6.2 | 139.6 |
| 9-42-1.8 | 3.25 | 1.8 | 145.8 |
| 9-42-2.2FA | 2.00 | 2.2 | 145.9 |
| 9-42-2.4SF | 1.00 | 2.4 | 143.8 |
| 9-42-4.4 | 3.75 | 4.4 | 142.7 |
| 9-42-5.9 | 4.00 | 5.9 | 139.1 |
| 9-45-4.1 | 5.50 | 4.1 | 140.3 |
| 9-50-0.9 | 6.25 | 0.9 | 143.4 |
| 9-50-1.5FA | 8.00 | 1.5 | 142.3 |
| 9-50-2.2SF | 3.25 | 2.2 | 140.4 |
| 9-50-3.6 | 9.50 | 3.6 | 135.1 |
| 9-50-6.6 | 10.00 | 6.6 | 133.4 |

### 5.4.2 Hardened Properties

The results of the hardened property tests are shown in Tables 5.3 and 5.4. The results from the compressive strength tests are shown in Table 5.3. Shown in Table 5.4 are the number of coulombs passed at both 28 and 56 days of age. Also shown in Table 5.4 is the ASTM permeability classification based on the number of coulombs passed. The compressive strength results are the average of three compressive strength tests, and for most mixtures the RCIP results are the average of four specimens. The individual compressive strength tests and the individual RCIP tests are listed in Appendix C and Appendix D, respectively. The statistical data for the RCIP results are also located in Appendix D.

Table 5.3. Compressive Strength Results.

| Mixtures | Average Compressive Strength (psi) | | | |
|---|---|---|---|---|
| | 1 day[1] | 7 days[1] | 28 days[1] | 56 days[1] |
| 9-26-2.4 | 6830 | 11,040 | 12,190 | 12,960 |
| 9-26-3.8 | 4830 | 10,440 | 11,270 | 12,090 |
| 9-26-5.6 | 4560 | 9270 | 10,560 | 11,290 |
| 9-30-1.1 | 6150 | 10,050 | 12,190 | 13,600 |
| 9-30-4.5 | 5610 | 8650 | 9960 | 11,010 |
| 9-30-5.7 | 6000 | 9130 | 10,270 | 11,030 |
| 9-32-4.1 | 5730 | 8320 | 9650 | 10,700 |
| 9-34-2.0 | 4700 | 9080 | 10,250 | 11,200 |
| 9-36-2.6 | 4220 | 7210 | 9180 | 9620 |
| 9-36-3.8 | 4580 | 6960 | 8340 | 9040 |
| 9-36-6.2 | 3660 | 6790 | 7700 | 8450 |
| 9-42-1.8 | 2690 | 6760 | 8690 | 9050 |
| 9-42-2.2FA | 2830 | 6840 | 8680 | 9100 |
| 9-42-2.4SF | 4070 | 6290 | 7770 | 8240 |
| 9-42-4.4 | 2750 | 4940 | 6470 | 6860 |
| 9-42-5.9 | 2640 | 4900 | 6110 | 6710 |
| 9-45-4.1 | 2600 | 4900 | 6110 | 6980 |
| 9-50-0.9 | 2020 | 4730 | 6220 | 6990 |
| 9-50-1.5FA | 1970 | 6020 | 7360 | 7870 |
| 9-50-2.2SF | 2110 | 4390 | 6100 | 6380 |
| 9-50-3.6 | 1560 | 5220 | 6340 | 6760 |
| 9-50-6.6 | 1650 | 4320 | 5560 | 6150 |

1) Average compressive strength of three tests.
2) Individual tests and statistical data are shown in Appendix C.

Table 5.4. RCIP Results.

| Mixture | Average Number of Coulombs Passed | | ASTM Classification at 56 Days |
|---|---|---|---|
| | 28 days[1] | 56 Days[1] | |
| 9-26-2.4 | 710 | 520 | Very Low |
| 9-26-3.8 | 671 | 660 | Very Low |
| 9-26-5.6 | 956 | 799 | Very Low |
| 9-30-1.1 | 1270 | 849 | Very Low |
| 9-30-4.5 | 1789 | 1281 | Low |
| 9-30-5.7 | 1222 | 756 | Very Low |
| 9-32-4.1 | 1534 | 811 | Very Low |
| 9-34-2.0 | 2471 | 1739 | Low |
| 9-36-2.6 | 2453 | 2319 | Moderate |
| 9-36-3.8 | 3416 | 2949 | Moderate |
| 9-36-6.2 | 3500 | 2166 | Moderate |
| 9-42-1.8 | 4546 | 4551 | High |
| 9-42-2.2FA | 4639 | 3514 | Moderate |
| 9-42-2.4SF | 1343 | 1134 | Low |
| 9-42-4.4 | 5905 | 5110 | High |
| 9-42-5.9 | 5430 | 4216 | High |
| 9-45-4.1 | 5969 | 5143 | High |
| 9-50-0.9 | 9450 | 7410 | High |
| 9-50-1.5FA | 8624 | 5491 | High |
| 9-50-2.2SF | 1868 | 1484 | Low |
| 9-50-3.6 | 8057 | 7549 | High |
| 9-50-6.6 | 8623 | 8467 | High |

1) Average RCIP value of four tests.
2) Individual tests and statistical data are shown in Appendix D.

## 5.5 DISCUSSION OF RESULTS

### 5.5.1 Fresh Properties

The results from the total air content test and the unit weight test directly correlated. Increases in total air content resulted in decreases in unit weight for mixtures of like w/cm, which was expected. For mixtures with the same w/cm, the unit weight decreased as the total air content increased, which was expected. Also, the unit weights of mixtures with like total air contents decreased as the w/cm increased, which was also expected. The results were discussed in more detail in Chapter 4.

### 5.5.2 Hardened Properties

**5.5.2.1 Compressive Strength.** The compressive strength tests for the mixtures followed an expected trend. As the w/cm decreased, the compressive strengths increased. This trend is verified through examination of the 90 percent confidence intervals in Appendix C. Also, for mixtures with like w/cm, the increase in total air content resulted in a decrease in compressive strength. In Chapter 3, the decrease in compressive strength per increase in air content was examined for the mixtures. The decreases in compressive strength generally followed the "2 – 5 percent decrease in compressive strength for every 1 percent increase in total air content" rule of thumb.

**5.5.2.1 Permeability.** From examination of Figures 5.4 and 5.5, it is apparent that increases in w/cm increased the number of coulombs passed for mixtures containing only portland cement. This trend is also evident by examination of the 90 percent

confidence intervals in Figures D.1 and D.2 of Appendix D. This increase in the number of coulombs passed was expected. The effect of the w/cm on the permeability of concrete has been well documented (Neville, 1997; Mindess et al, 1981). A decrease in the w/cm reduces the porosity of the concrete, which results in a more impermeable concrete.

At 28 days of age, the total charge passed ranged from 671 coulombs for mixture 9-26-3.8 to 9450 coulombs for mixture 9-50-0.9 (mixtures containing only portland cement). At 56 days of age, the RCIP value decreased for most mixtures. By this age, mixtures with a w/cm equal to or less than 0.34 had low permeability based on ASTM C 1202 classifications. These findings are similar to the findings of Pinto et al (2001) who also found that to achieve low permeability without the use of supplementary cementitious materials, a w/cm of 0.35 or lower would be necessary. Mixtures (containing only portland cement) with a w/cm of 0.42 or greater would be classified as having high permeability.

The addition of fly ash had little affect on the chloride penetrability when compared to identical mixtures without fly ash. At a w/cm of 0.42, mixture 9-42-2.2FA passed approximately the same number of coulombs at 28 days of age as mixture 9-42-1.8 (4546 versus 4639 coulombs). Both mixtures would be classified as having high permeability. But, by 56 days of the addition of fly ash reduced the number of coulombs by more than 20 percent. At 56 days of age, mixture 9-42-1.8 would still be classified as having high permeability, but mixture 9-42-2.2FA would now be classified as having moderate permeability.

For mixtures with a w/cm of 0.50, the addition of fly ash decreased the number of coulombs passed by approximately 10 and 25 percent at 28 and 56 days of age, respectively. Even though the addition of fly ash reduced the total number of coulombs, all four mixtures would still be classified as having high permeability. These results are consistent with the report of Shi et al who stated that fly ash could either increase or decrease the Na and K concentrations of the pore fluid which could result in higher or lower chloride penetrability as classified by ASTM C 1202.

Mixtures 9-42-2.4SF and 9-50-2.2SF contained silica fume at a replacement rate of 5 percent. Figures 5.4 and 5.5 show the dramatic effect that the addition of silica fume has on the rapid chloride ion penetrability of the concrete. At 28 and 56 days of age, the total coulombs passed for the silica fume mixtures was more than 75 percent less than that of identical mixtures (9-42-1.8 and 9-50-0.9) without silica fume. The differences are statistically significant through examination of the 90 percent confidence intervals in Figures D.1 and D.2 in Appendix D. These results are consistent with Shi et al who reported that the replacement of cement with 5 percent silica fume "can lead to order of magnitude reductions in Na, K, and OH ion concentrations" which would greatly reduce the number of coulombs passed.

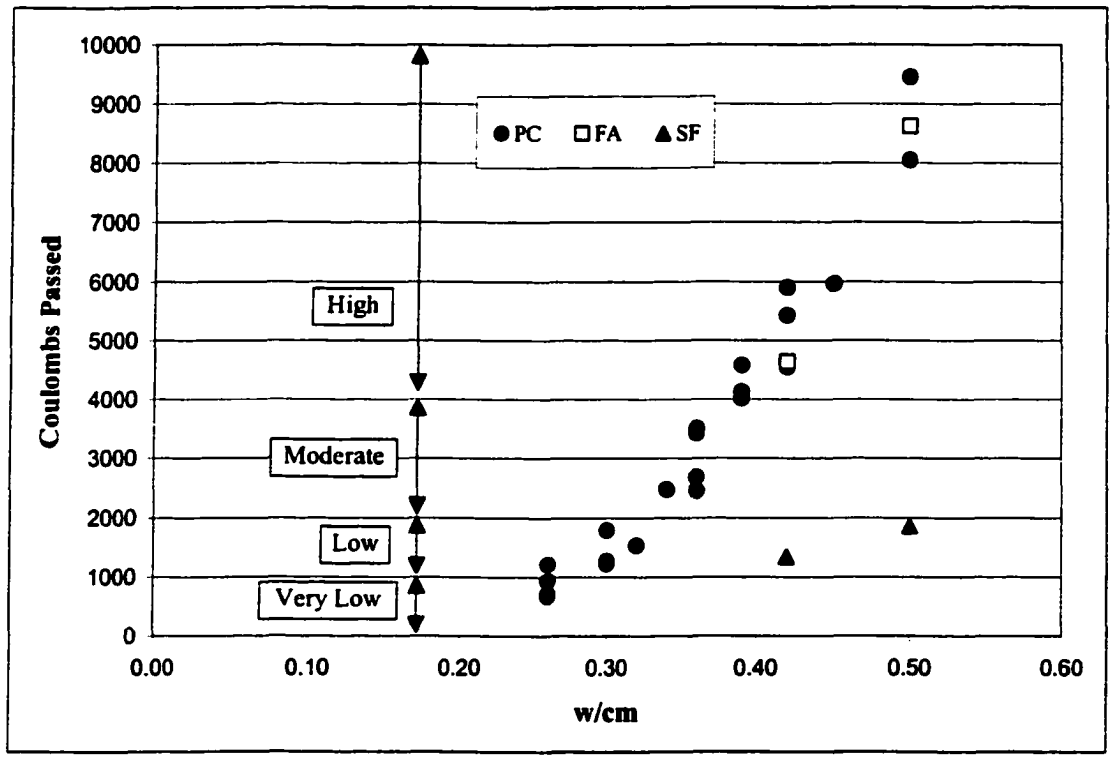


Figure 5.4. 28-Day RCIP Results and ASTM C 1202 Permeability Classifications.

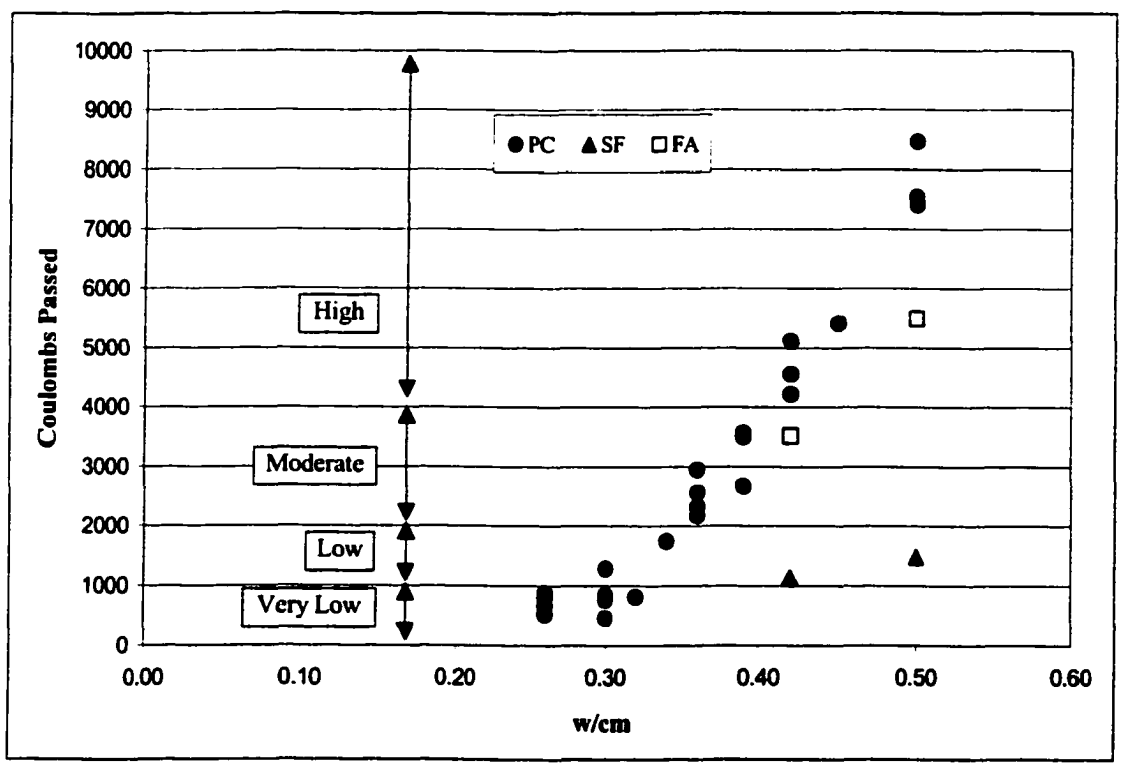


Figure 5.5. 56-Day RCIP Results and ASTM C 1202 Permeability Classifications.

The effect of entrained air on the RCIP is shown in Figures 5.6 and 5.7. As shown in the figures, the quantity of entrained air had no consistent effect on the RCIP. For example, the number of coulombs increased as the total air content increased for mixtures with a w/cm of 0.50 (at 56 days of age), while there was no consistent effect at other w/cm. Even though there were inconsistencies at most w/cm, the addition of entrained air did not affect the ASTM C 1202 permeability classifications. As an example, for mixtures with a w/cm of 0.36 (at 56 days), the addition of approximately two percent entrained air (mixture 9-36-3.8) increased the number of coulombs passed to 2949 coulombs when compared to the control mixture (mixture 9-36-2.6) without entrained air, which passed 2319 coulombs. However, the mixture with four percent entrained air (9-36-6.2) passed the least amount of coulombs (2116) of the three mixtures. Even though the total number of coulombs passed for these mixtures ranged from 2166 to 2949, they would all still be classified as having moderate permeability. These results are similar to the findings of Myers et al (1997) who found that entrained air had no "appreciable effect on the permeability of high performance concrete."

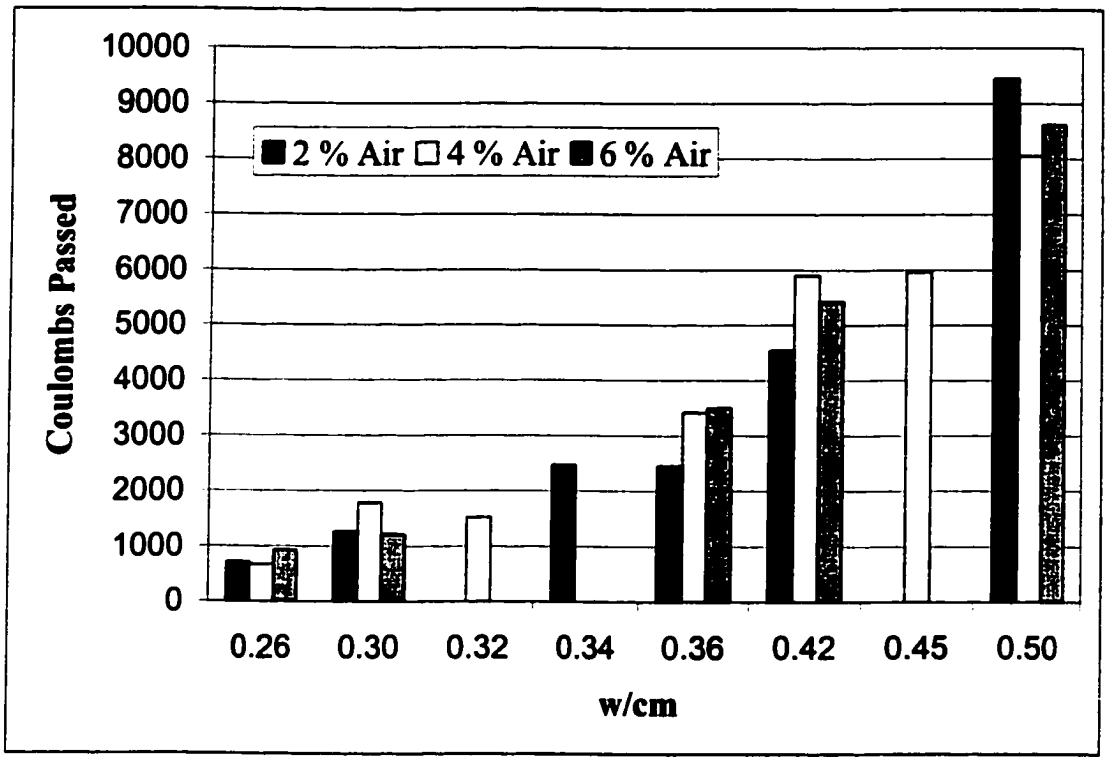


Figure 5.6. Effect of Entrained Air on 28-Day RCIP.

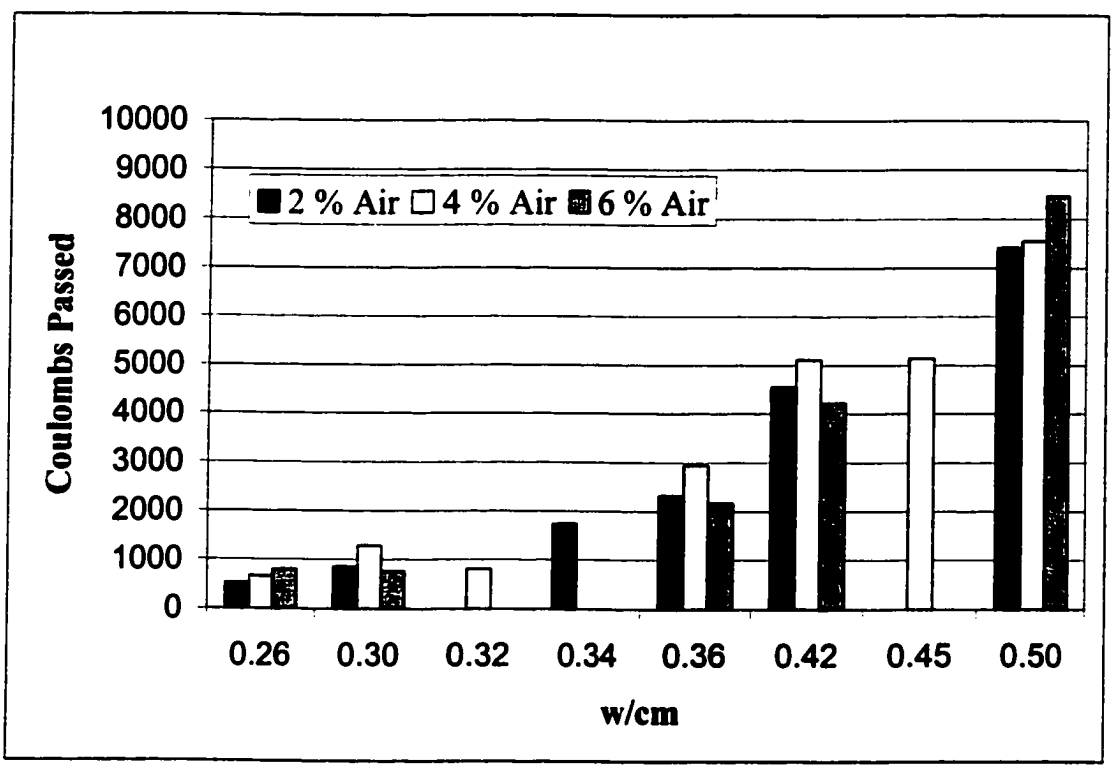


Figure 5.7. Effect of Entrained Air on 56-Day RCIP.

## 5.6 CONCLUSIONS

The purpose of the research program was to examine the permeability of air entrained concretes and to provide additional data on the effectiveness of the RCIP Test (ASTM C 1202) as a means to measure concrete penetrability. The findings of the research are summarized below.

1. The addition of entrained air had no noticeable effect the permeability of the mixtures. The findings are consistent with those of other researchers (Mindess et al, 1981; Neville, 1997; Kosmatka et al, 1994).
2. The permeability (measured by ASTM C 1202) increased as w/cm increased for mixtures containing only portland cement which was expected. These results are similar to those of other researchers (Mindess et al, 1981; Neville, 1997; Kosmatka et al, 1994) who state that increases in w/cm result in greater permeability.
3. To achieve low permeability concrete (based on ASTM C 1202 classifications), mixtures should be cast at a w/cm equal to or less than 0.34. The results are similar with Pinto et al (2001) who found that a w/cm of 0.35 was necessary to produce concrete with low permeability based on ASTM C 1202.
4. For mixtures not containing any mineral admixtures, the RCIP test appears to be effective in measuring concrete's chloride ion penetrability. As shown in Figure 5.4 and 5.5, the concrete's penetrability increases as the w/cm increase,

which is expected. All mixtures containing only portland cement follow this trend.

5. Once mineral admixtures are introduced, this trend is no longer valid. When compared to similar control mixtures, silica fume reduced the chloride ion penetrability by more than 75 percent. These conclusions are similar to the findings of other researchers (Shi et al, 1998; Zhao et al, 1999; Pfiefer et al, 1994; Scanlon et al, 1996) who question the use of the RCIP test when testing concrete that contains mineral admixtures.
6. Since the RCIP test does not directly measure permeability, other factors can influence the parameter the test actually does measure, which is concrete resistivity. Therefore, other factors (such as pore fluid chemistry) may influence the parameter actually measured, leading to a basic need for users to understand what the test actually measures so that results can be put into proper perspective. When testing concrete containing mineral admixtures, one should compare the results to an identical mixture without mineral admixtures. This comparison with mixtures containing only portland cement may provide a better idea as to the true permeability of the concrete.

# CHAPTER 6

# EXAMINING THE PRESTRESS LOSSES AND ALLOWABLE COMPRESSIVE STRESS AT RELEASE OF BRIDGE GIRDERS WITH AND WITHOUT AIR ENTRAINMENT

## 6.1 INTRODUCTION

This portion of the research examined the prestress losses of non-air entrained and air entrained bridge girders. The main task was focused on determining if the addition of entrained air had any noticeable effects on the prestress losses. The measured losses were then compared with the losses calculated using two prevalent methods used for estimating prestress losses. Another objective of the research was to provide additional data with regard to increasing the allowable compressive stress at release. The results of the research show that the addition of entrained air had no noticeable effect on the prestress losses and that increasing the allowable compressive stresses at release may not be beneficial.

## 6.2 LITERATURE REVIEW

### 6.2.1 Prestress Losses

Over time the initial prestressing force that is applied to a member decreases in magnitude. During a period of approximately five years, a prestressed member may lose an estimated 25 percent of the initial prestress force (Nawy, 1996, and Lin and Burns,

1981). Elastic shortening, creep, shrinkage, and relaxation are the four major contributors to prestress losses. Of the four major losses in pretensioned structures, elastic shortening is the only loss that is not time dependent and is independent of the others. Elastic shortening is the loss of prestress force that occurs when the strands are released (at transfer of the prestress force). At transfer, the strands are cut and this force, which is applied to the concrete through the strands, shortens the concrete. The strands also shorten with the concrete thereby reducing the initial prestress force (Lin and Burns, 1981). The loss due to elastic shortening occurs only once and is not affected by time.

The remaining losses (creep, shrinkage, and relaxation) are time dependent and dependent on one another. Creep is defined as the deformation of concrete due to sustained loads. As the girders deform or shorten due to the prestress force, the length of the strands shortens which results in a loss of prestress force. The loss due to creep may account for approximately 25 percent of the total losses. The majority of this loss occurs within the first year. Creep studies have shown that 60 to 83 percent of the total creep occurs during the first year (Lin and Burns, 1981). A similar loss occurs in the prestressing strands. Steel relaxation is the loss of prestress due to constant strain in the prestressing strands.

Another time dependent loss is shrinkage. Concrete decreases in volume when it loses water through evaporation. Drying, plastic, carbonation, and autogenous are all different types of shrinkage. Drying shrinkage occurs in the hardened concrete and is a result of moisture loss. Plastic shrinkage occurs in fresh concrete and is the loss of water from the paste of concrete. Carbonation shrinkage occurs when the cements paste reacts chemically with carbon dioxide. Autogenous shrinkage is a type of drying shrinkage that

is caused by the internal consumption of water during hydration (Mindess and Young, 1981). Like creep and elastic shortening, as the concrete shortens, the prestress strands also shorten which results in a loss of prestress force. The loss due to shrinkage accounts for estimated 28 percent of the total losses. As with creep, approximately 80 percent of the total shrinkage will occur within the first year (Lin and Burns, 1981).

There are many methods used to estimate the effective prestress force (prestress force existing after all losses). Two widely accepted methods are the American Association of State Highway and Transportation Officials (AASHTO) and the Precast/Prestressed Concrete Institute (PCI) equations. Research is now being conducted to determine the accuracy of these equations when measuring the losses of HPC bridge girders.

Roller et al (1995) examined the prestress losses in HPC bridge girders. Along with prestress losses, creep and shrinkage of the concrete used to cast the girders were also measured. The girders tested were 70 ft. long and 54 in. deep. Four girders were cast, but the losses were reported for only Girder 3 and Girder 4. The two girders were subjected to two different curing regimens. Girder 3 was steam cured for 24 hours at 140°F and after an additional 10 hours the forms were removed. Girder 4 was not steam cured, but cured under a waterproof tarpaulin for 10 hours and the forms were removed 12 hours after casting.

Concrete mixtures with a w/cm of 0.27 and 0.28 were used to cast the girders. Girder 3 had a release strength and 28-day compressive strength of 8920 and 9930 psi, respectively. Girder 4 had release and 28 day compressive strengths of 6960 and 8830 psi, respectively. The prestress losses were measured using internal strain meters. The

results of their research showed the AASHTO equations overestimated the losses by approximately 50 percent at 18 months for Girder 3. However, the researchers report that the steam curing of Girder 3 may have affected the early age prestress losses. When compared to Girder 4 (non-steam cured), the early age losses of Girder 3 were significantly lower. The results also showed that the AASHTO equations for estimating creep and shrinkage "may be overly conservative for high strength concrete". The researchers recommend further study in the creep and shrinkage behavior of HPC to determine if the AASHTO equations can be modified.

Roller et al (2000) again examined the prestress losses, but this research program examined the losses of a bridge built by the Louisiana Department of Transportation and Development. Construction of the bridge was completed in October 1999. The bridge consisted of five 73 ft. spans. The compressive strength of the girders was 7020 psi at release (39 hours) and 10,100 psi at 56 days of age. The prestress losses were reported for 12 months. The measured losses were approximately 35 percent less than the calculated losses. These results are consistent with Roller et al's earlier research.

Pessiki et al (1996) examined the effective prestress force in bridge girders that were 28 years old. The girders were I-beams with dimensions of 24 x 60 in. and a length of 90 ft. 5 in. The girders were removed from a seven span bridge on I-80 in Pennsylvania. Load tests were performed on the girders to determine the decompression load. Visual observations, strain gauges, and displacement transducers were used in obtaining the decompression loads. The average prestress loss for both girders were 18 percent compared a loss of 33 percent predicted by the AASHTO equations. Azizinamini et al (1996) also examined the available prestress in an existing bridge girder. These

researchers investigated the effective prestress force in a 25-year-old girder. The girder was removed from a bridge on I-80 in Nebraska. The length of the girder was 54 ft. 10 in. The testing of the girder showed that the prestress loss after 25 years of service was 20.7 percent, which is less than the 25.7 percent, predicted by the AASHTO equations.

Idriss (2001) measured the prestress losses in bridge girders during construction and during service. The bridge has spans of 96 and 101 ft. The beams were cast with HPC with compressive strengths of 7330 psi at three days of age and 10,150 psi at 56 days of age. Deformation sensors were placed in the girders to measure the prestress losses. After five months of service, the measured losses were less than the losses predicted by AASHTO and PCI. The AASHTO equations predicted losses of 28 percent and the PCI equations predicted losses of 22.6, which are both greater than the measured losses of 11 percent. However, it must be noted that the losses reported are after five months service. The girders will continue to lose additional prestress force over the next five years. Many researchers have shown that the AASHTO equations overestimate the total prestress losses, but most researchers agree that more testing needs to be done before the prediction equations are modified.

### 6.2.2 Allowable Compressive Stress at Release

The AASHTO Bridge Specifications, the American Concrete Institute (ACI) Building Code, and PCI Design Handbook limit the allowable compressive stress imposed on the concrete by the prestress force to 60 percent of the compressive strength at release ($0.6f_{ci}$). The purpose of the limit was to control creep deformation and prevent crushing due to prestress force (Huo et al, 1995). However, researchers are examining if

this limit can be raised. Raising the limit would reduce the number of unbonded strands in the end regions of girders, increase production time, increase capacity of a member, and eliminate the need for steam curing (Huo and Tadros, 1997).

There is little data available regarding the effects of increasing the allowable compressive stress at release. Even though there is minimal published data, it appears that many prestressed/precast concrete manufacturers regularly release at stresses of 75 percent of the concrete strength at release. The PCI Standard Design Practice states, "no problems have been reported by allowing compression as high as $0.75f'_{ci}$ (PCI, 1996)." There has been some work on allowable stresses done at The University of Oklahoma. Pang (1997) investigated the effects of large compressive stresses on the hardened properties of concrete. Pang conducted creep tests on concrete cylinders loaded to $0.6f_{ci}$, $0.7f_{ci}$, and $0.8f_{ci}$. He concluded that the creep at higher stress levels was "not excessive and was similar to creep experienced by concrete stressed at lower levels." Pang also concluded that allowable compressive limit could be raised to at least $0.7f_{ci}$.

Noppakunwijai (2001) conducted one of the few experimental programs that examined the effects of high release stresses on prestressed/precast girders. Two 33 ft. girders with a span to depth ratio of 32 were cast. The concrete stress at release was $0.79f_{ci}$ and $0.84f_{ci}$. The prestress losses of the girders were measured. Noppakunwijai et al (2001) concluded that higher release stresses had no negative impact on the test specimen. The amount of literature on the release stresses of prestressed concrete is very limited, particularly experimental data on bridge girders. The justification for increasing the allowable compressive stress limit at release appears to be based on common practices in the prestressed/precast concrete industry (PCI, 1996). Even though there

appears to be no negative impact caused by this practice, research should be conducted to examine the effects of release stresses greater than $0.6f_{ci}$.

## 6.3 EXPERIMENTAL PROGRAM

### 6.3.1 Scope

The research program examined the prestress losses in bridge girders with and without air entrainment. The purpose of the study was to determine: (1) What the prestress losses are and (2) if there are any differences in the prestress losses of air entrained concrete when compared to non-air entrained concrete. Four prestressed girders were cast. Two girders had a targeted total air content of two percent, and two had a targeted total air content of six percent. The girders were cast using concrete mixtures developed during the second (Mixture 9-26-15/3, Table 2.11) and third (Mixture 9-26-5.9, Table 3.3) phases of the research. The measured prestress losses were compared with estimated losses calculated from the AASHTO Guidelines and the PCI equations to determine the accuracy of the prediction equations.

The research program also examined the allowable compressive stresses at release for prestressed beams. Currently the AASHTO Bridge Design Specifications permits the concrete compressive stress at release to be 60 percent or less of the concrete compressive strength at release ($0.60f_{ci}$). Researchers are investigating whether this limit can be increased beyond $0.60f_{ci}$. The research results will provide additional data to examine the efficacy of various proposals. Two of the beams had a targeted release stress

of 60 percent, and two of the beams had a targeted release stress of 75 percent. The research program is shown in Table 6.1.

Table 6.1. Research Program.

| Beam | Targeted Allowable Compressive Stresses ($f_{bot}$ / $f_{ci}$) | | Targeted Total Air Content (%) | |
|---|---|---|---|---|
| | 0.60 | 0.75 | 2 | 6 |
| 1 | - | X | X | - |
| 2 | - | X | - | X |
| 3 | X | - | - | X |
| 4 | X | - | X | - |

### 6.3.2 Materials

Ash Grove Type III Cement was used in all mixtures. The coarse aggregate was 3/8 inch, crushed limestone from Davis, Oklahoma. The fine aggregate was washed river sand from Dover, Oklahoma. The material properties of the cement and aggregates are listed in Chapter 2. To provide adequate workability, a water reducer (WR) and/or a high range water reducer (HRWR) was used. The WR used was WRDA with Hycol, and the HRWR used was ADVA Flow. An air entraining agent (AEA), DARAVAIR 1000, was used to attain the required target total air contents. The girders contained 0.60 in. diameter, low relaxation prestressing strand and Grade 60 mild reinforcement.

### 6.3.3 Mixtures

The mixtures used to cast the girders were developed in the first and second phases of the research program (Chapters 2 and 3). The mixtures were chosen based on workability and strength. The chosen mixtures are shown in Table 6.2. Girders 1 and 4 were cast with the same mixture, and girders 2 and 3 contained the same mixture. The only difference in the two mixtures was the targeted total air content and quantity of sand. Girders 1 and 4 had a targeted total air content of two percent, and girders 2 and 3 had a targeted total air content of six percent.

Table 6.2. Mixture Designs.

| | Girder 1 | Girder 2 | Girder 3 | Girder 4 |
|---|---|---|---|---|
| Cement ($lb/yd^3$) | 900 | 900 | 900 | 900 |
| Coarse Aggregate | 1790 | 1790 | 1790 | 1790 |
| Fine Aggregate | 1217 | 1040 | 1040 | 1217 |
| Water | 254 | 254 | 254 | 254 |
| w/cm | 0.26 | 0.26 | 0.26 | 0.26 |
| Targeted Total Air Content (%) | 2.0 | 6.0 | 6.0 | 2.0 |
| Calculated Unit Weight ($lb/ft^3$) | 153.4 | 146.8 | 146.8 | 153.4 |

### 6.3.4 Girder Design

Four prestressed girders were cast as part of the research program. The girders were cast at Coreslab Structures, Inc, of Oklahoma City. All four girders had the same cross-sectional properties. The girders had a depth of 24 inches and a length of 24 feet.

The moment of inertia and area of the girders were 12,370 $in^4$ and 163.25 $in^2$, respectively. The dimensions and cross-sections of the girders are shown in Figures 6.1 through 6.4.

Girders 1 and 2 were designed to have allowable compressive stresses at release of $0.75f_{ci}$. Girders 3 and 4 were designed to have allowable compressive stresses at release of $0.60f_{ci}$. All four girders contained 10 prestressing strands, however some of girders contained debonded strands. Since Girders 1 and 4 required the same concrete but different compressive stresses at release, two strands in Girder 4 were debonded to lower the compressive stresses at release. Girder 1 contained 10 bonded prestressing strands, and Girder 4 contained eight bonded strands. Girders 2 and 3 also required some debonding to achieve the desired compressive stresses at release. Girder 2 contained nine bonded prestressing strands and one unbonded strand, whereas Girder 3 contained eight bonded strands and two unbonded strands. Girders 1 and 4 contained no air entrainment, while Girders 2 and 3 were targeted to have a total air content of six percent.

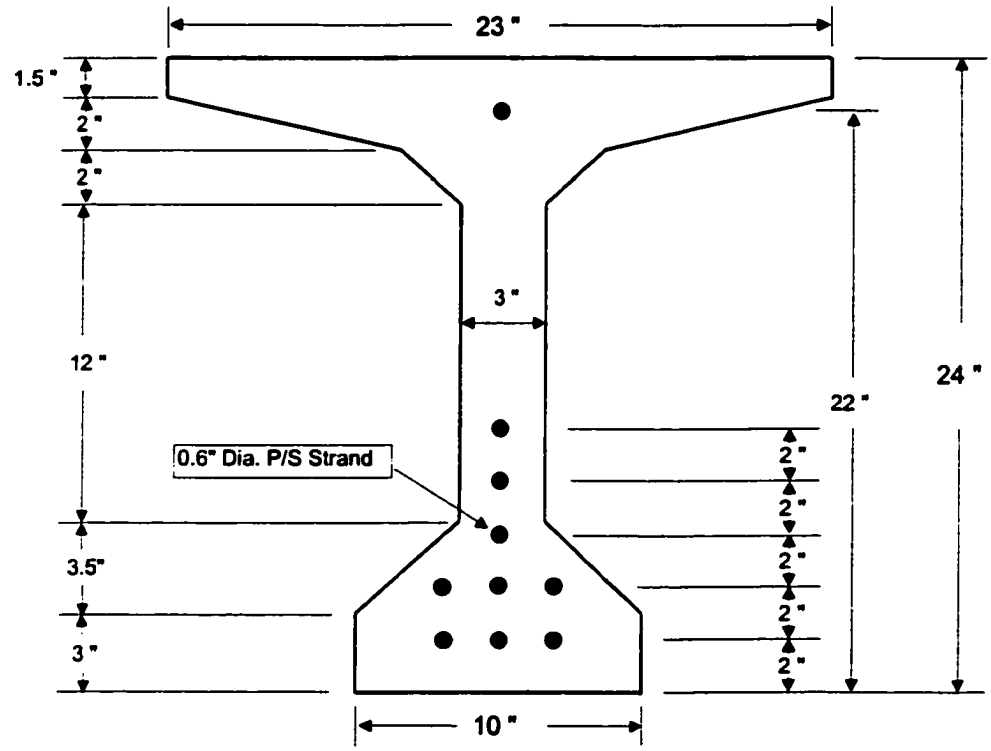


Figure 6.1. Cross-section of Girder 1.

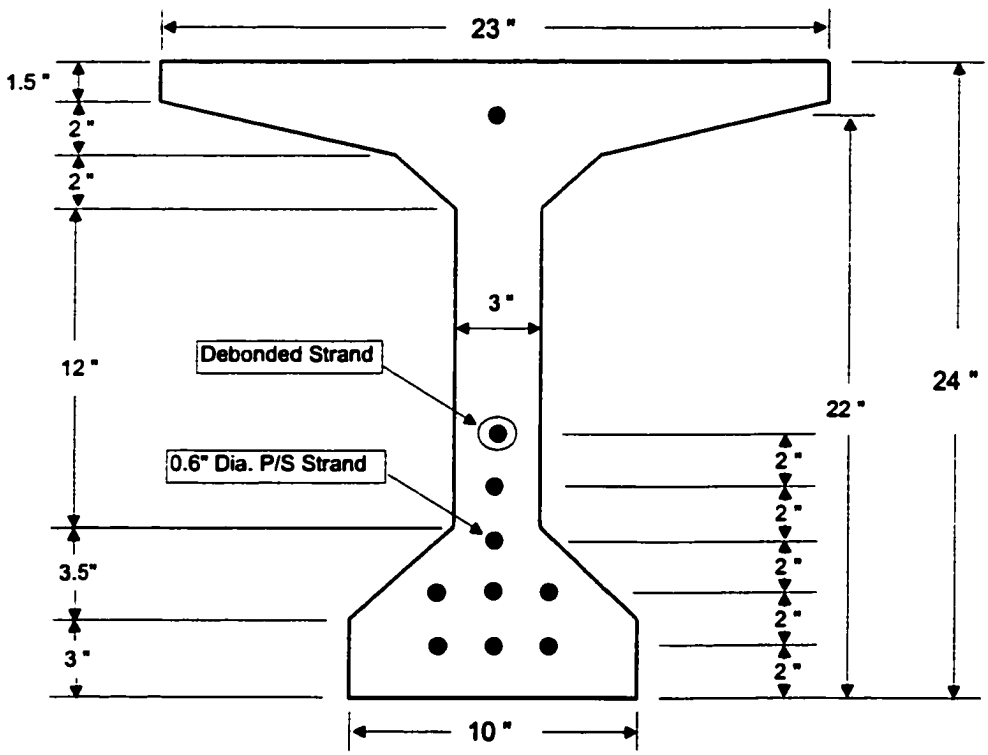


Figure 6.2. Cross-section of Girder 2.

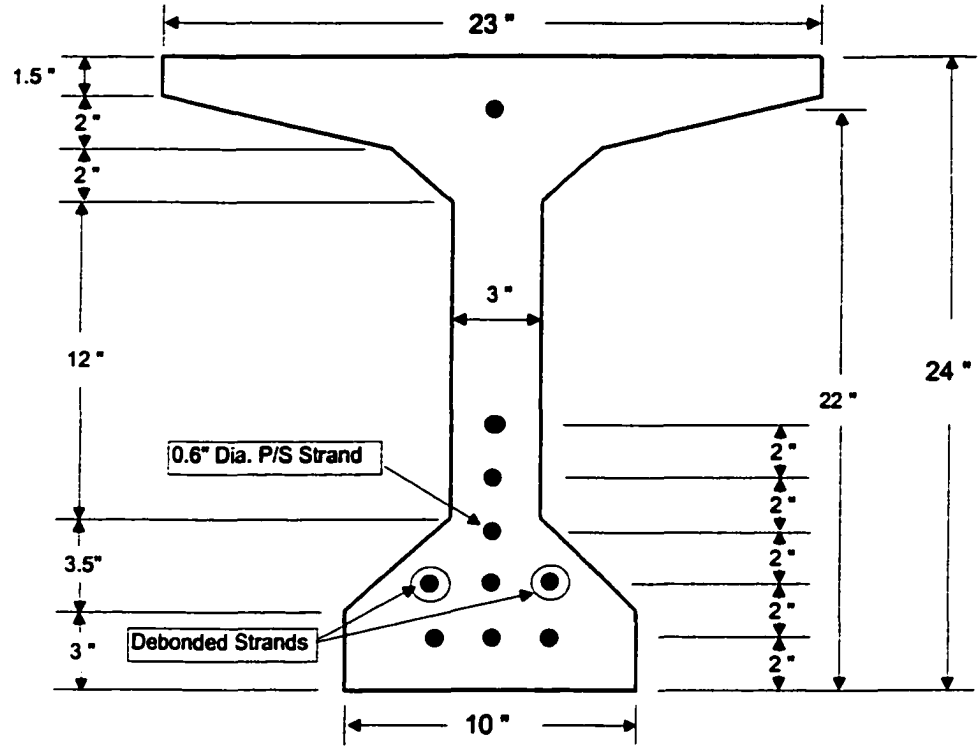


Figure 6.3. Cross-section of Girder 3.

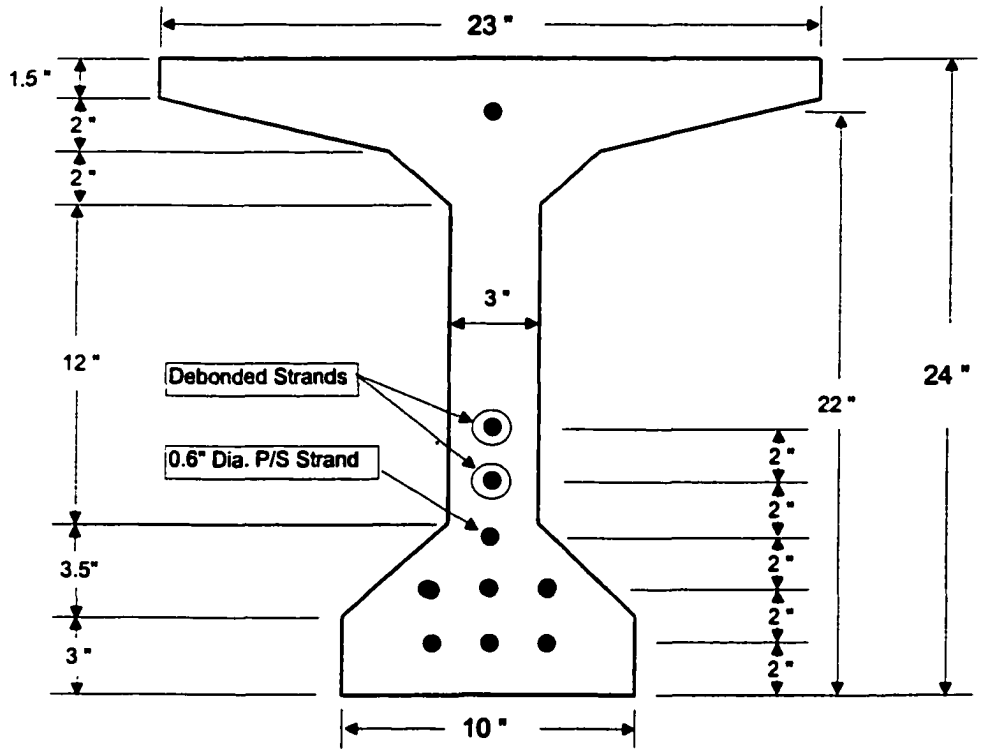


Figure 6.4. Cross-section of Girder 4.

### 6.3.5 Batching

As mentioned earlier, the mixture designs for the girders were chosen from earlier phases of the research program. The mixtures were chosen based on workability and strength. Prior to the casting of the girders, several trial batches were cast at Coreslab Structures in Oklahoma City. The selected mixtures were developed at Fears Structural Engineering Laboratory (FSEL) using a 6-$ft^3$ rotary concrete mixer, but at Coreslab a much larger mixer (4 $yd^3$) was used to batch the concrete. The trial batches were necessary to determine appropriate dosages of water reducers and air entraining agents. Shown in Table 6.3 is a comparison of mixture proportions (particularly admixture dosages) between the mixtures cast at FSEL and the mixtures cast at Coreslab. The main difference between the mixtures cast at FSEL and at Coreslab was the dosage of AEA. At FSEL, a dosage of 15 fl oz/cwt was required to attain approximately six percent air, but at Coreslab only 0.65 fl oz/cwt was necessary. Higher dosages of AEA were required at FSEL because the smaller mixer was not as efficient in agitating the fresh concrete as well as the larger mixer used by Coreslab.

Table 6.3. Comparison of FSEL and Coreslab Mixtures.

| | FSEL | Coreslab | FSEL | Coreslab |
|---|---|---|---|---|
| Cement (lb/yd$^3$) | 900 | 900 | 900 | 900 |
| Coarse Aggregate | 1790 | 1790 | 1790 | 1790 |
| Fine Aggregate | 1217 | 1217 | 1040 | 1040 |
| Water | 254 | 254 | 254 | 254 |
| w/cm | 0.26 | 0.26 | 0.26 | 0.26 |
| Targeted Total Air Content (%) | 2.0 | 2.0 | 6.0 | 6.0 |
| Calculated Unit Weight (lb/ft$^3$) | 153.4 | 153.4 | 146.8 | 146.8 |
| WR (fl oz/cwt) | 3 | 3 | 3 | 3 |
| HRWR (fl oz/cwt) | 15 | 18 | 15 | 18 |
| AEA (fl oz/cwt) | 0 | 0 | 15 | 0.65 |

### 6.3.6 Instrumentation

After the girders were cast and the forms removed, detachable mechanical strain gauge (DEMEC) targets were glued onto the beams. The DEMEC targets were placed along the side of the bulbs and along the top of the girders. The targets were placed 60, 68, and 76 inches from each end and also at 144, 152, and 160 inches. The placement of the targets along the bulb of the girders is shown in Figure 6.5. The distances between the DEMEC targets were measured using a DEMEC dial gauge. A close-up view of the targets along the bulb and on the top of the girders is shown in Figures 6.6 and 6.7, respectively. Readings were taken before the cutting of the prestressing strands, and immediately (within one to two hours) after cutting the strands. By evaluating the changes in length between DEMEC targets, the concrete strain was calculated.

Measurements were taken periodically until December 2001 and at that time the beams were one year old.

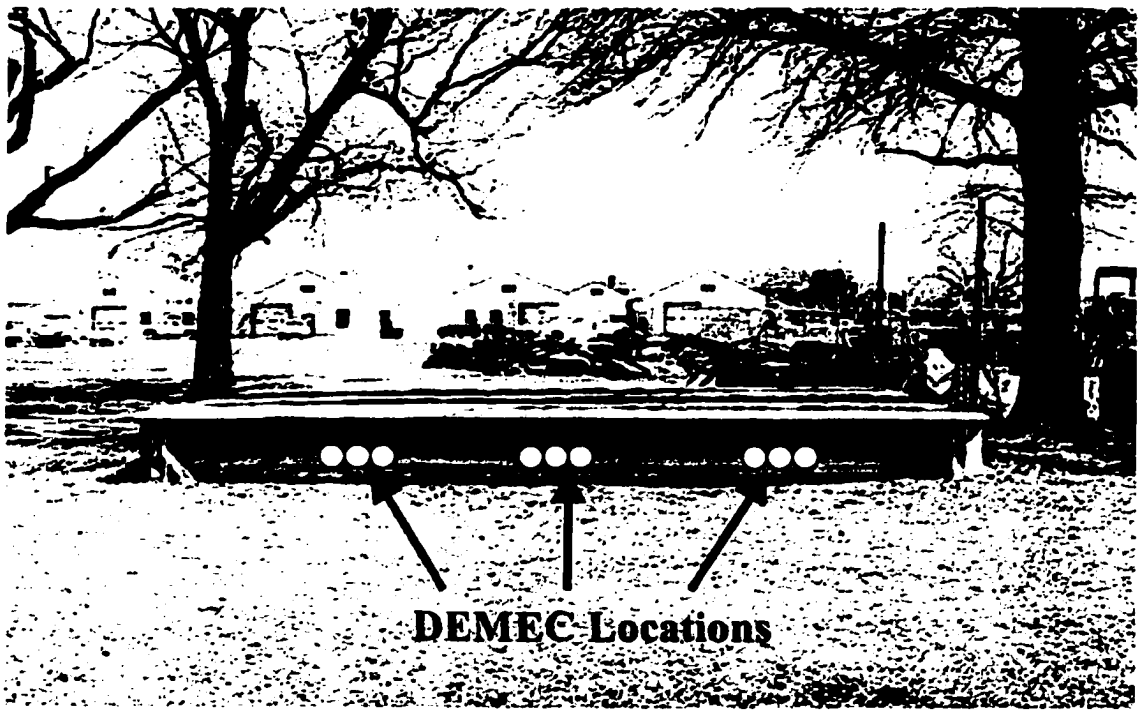


Figure 6.5. DEMEC Locations Along the Side of the Girders.

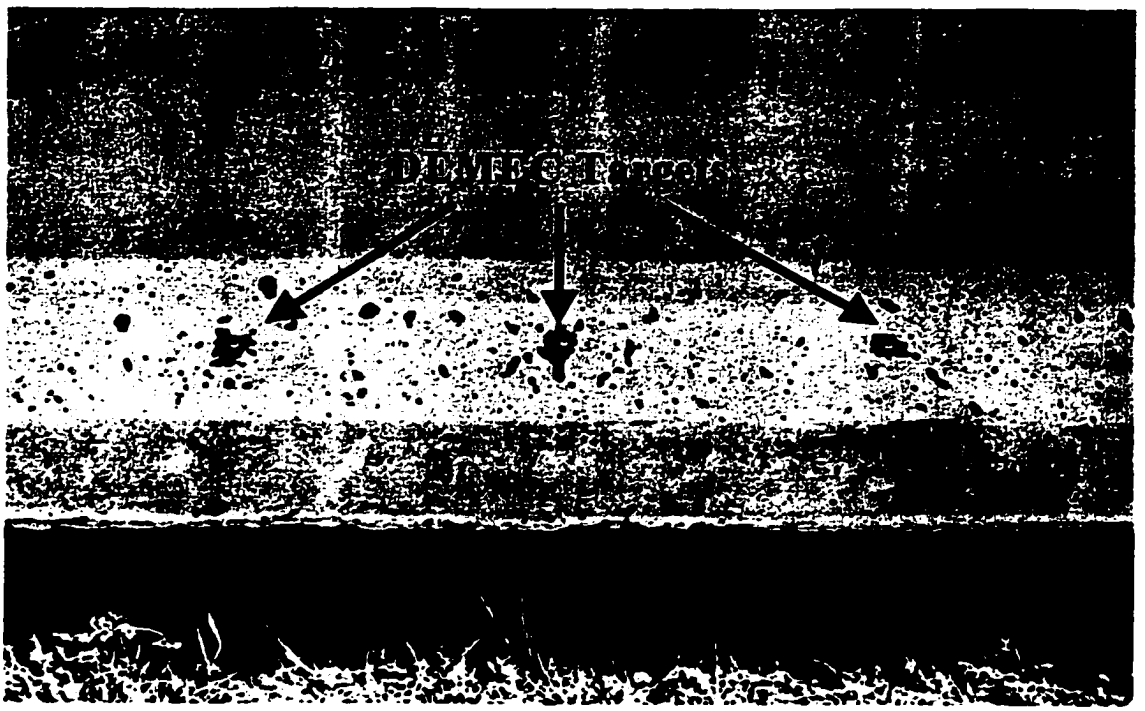

Figure 6.6. DEMEC Targets on the Bulb of the Girder.



Figure 6.7. DEMEC Targets on the Top of the Girder.

### 6.3.7 Tests

The two mixtures were subjected to several tests. The fresh concrete properties tested were slump (ASTM C 143), unit weight (ASTM C 138), and air content (ASTM C 231). The hardened properties tested were compressive strength (ASTM C 39), length change (ASTM C 157), and modulus of elasticity (ASTM C 469). The prestress losses were also measured for a period of one year.

Earlier research (Johnson 2001) had examined the creep (ASTM C 512) and shrinkage of the mixtures. To examine the creep of the mixtures, five 4 x 10 in. concrete cylinders were loaded in a test frame. The 4 x 10 in. cylinders were chosen for the creep test (instead of the standard 4 x 8 in. cylinders) because the larger length allowed for the use of an eight-inch gauge length versus a four-inch gauge length. Prior research at

FSEL had shown that an eight-inch gauge length produced more consistent data than the four-inch gauge lengths. Prior to loading, DEMEC targets were glued onto the front and rear of each cylinder. The targets were placed one inch from the top and bottom of the cylinders. Using a hydraulic pump, the cylinders were loaded to 45 percent of their one-day compressive strength. DEMEC readings were taken before and after loading. Readings were also taken periodically over a period of 56 days as described by ASTM C 512. A diagram of the creep test set up is shown in Figure 6.8.

The shrinkage of the mixtures was also measured using the 4 x 10 inch cylinders. Companion, unloaded cylinders were stored with the creep specimens. These specimens also had DEMEC targets attached in the same positions as the creep specimens. Readings were taken on the shrinkage specimens at the same time as the creep specimens. The shrinkage specimens were used to determine the creep of the concrete. The amount of shrinkage was subtracted from the change in length of the loaded cylinders. The difference between the two readings is the change in length due only to creep.

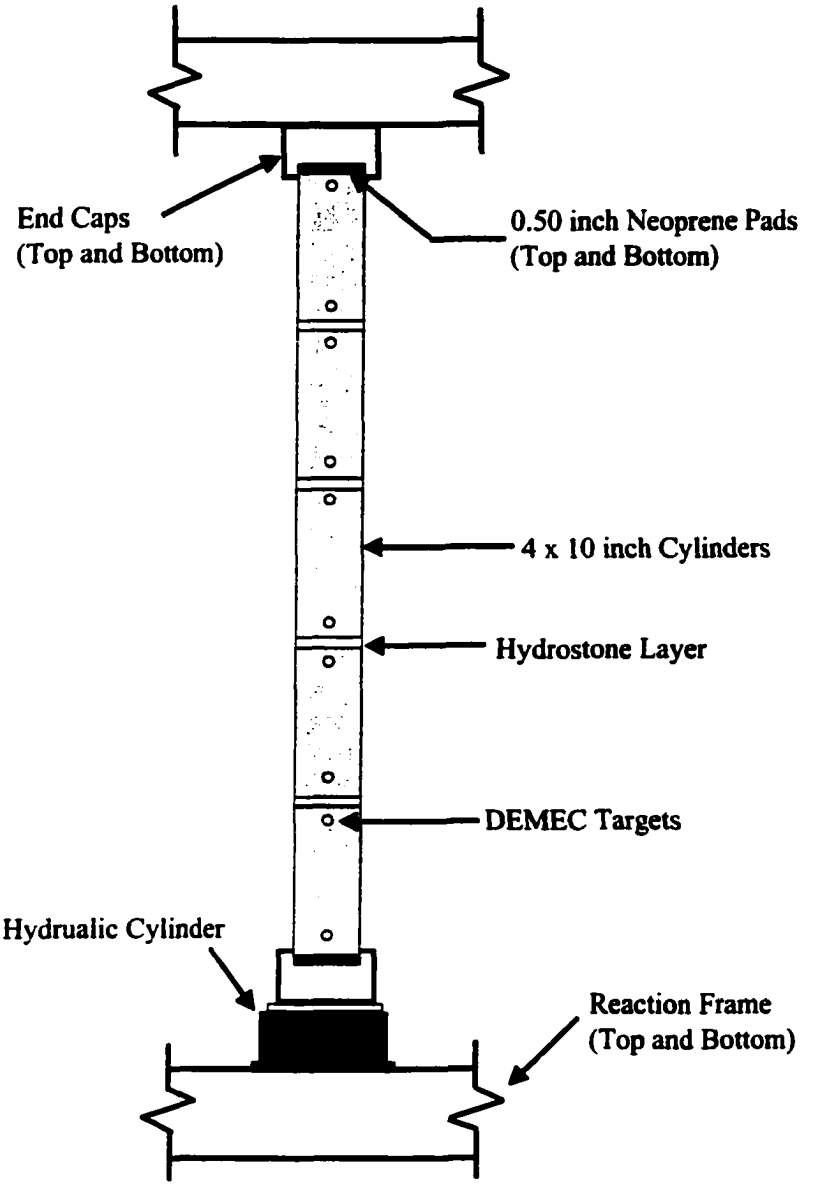


Figure 6.8. Creep Test Set-up.

## 6.4 PRESENTATION OF RESULTS

### 6.4.1 Concrete and Girder Properties

The results from the fresh concrete tests are shown in Table 6.4. Also shown in the table are the fresh concrete properties of identical mixtures cast at FSEL. The compressive strength and modulus of elasticity of the girders are shown in Table 6.5. The creep results from Johnson's research are shown in Table 6.6. A comparison of the compressive strength between the FSEL mixtures and the Coreslab mixtures is shown in Table 6.7. The compressive strength, modulus of elasticity, and shrinkage reported are the averages of at least three individual tests. The individual tests and statistical data are reported in Appendix E.

The measured prestress losses at the north and south ends of the girders are shown in Tables 6.8 and 6.9, respectively. The average losses of both ends of the girders are reported in Table 6.10. The measured prestress losses at the center of the girders are listed in Table 6.11. All prestress losses reported are the losses at the center of gravity for the prestressing strand. The losses are the average of four readings (two reading from each side of the girder). Also in the tables are the locations where the girders were stored. The girders were stored outside at Coreslab (superscript 1), inside at FSEL (superscript 2), and outside at FSEL (superscript 3).

Table 6.4. Fresh Concrete Properties.

| Fresh Concrete Properties | Girders 1 & 4 | 9-26-2.4 | Girders 2 & 3 | 9-26-5.6 |
|---|---|---|---|---|
| Batch Location | Coreslab | FSEL | Coreslab | FSEL |
| Fresh Concrete Temp. (F) | 68 | 74 | 60 | 75 |
| Slump (in.) | 10.0 | 6.50 | 9.75 | 4.25 |
| Air Content (%) | 2.3 | 2.4 | 6.2 | 5.6 |
| Unit Weight ($lb/ft^3$) | 151.1 | 152.3 | 146.9 | 147.2 |
| Air Temperature (F) | 36 | 91 | 35 | 91 |
| Date Batched | 12/19/00 | 8/2/99 | 12/21/00 | 7/29/00 |

Table 6.5. Hardened Concrete Properties of the Girders.

| | Girder 1 | Girder 2 | Girder 3 | Girder 4 |
|---|---|---|---|---|
| Average Compressive Strength (psi)[1] | | | | |
| 1 day | 8700 | 6130 | 6130 | 8700 |
| 14 days | 10,190 | 7110 | 7110 | 10,190 |
| 28 days | 11,060 | 8390 | 8390 | 11,060 |
| 56 days | 12,440 | 9200 | 9200 | 12,440 |
| 180 days | 14,460 | 10,850 | 10,850 | 14,460 |
| 360 days | 15,610 | 11,460 | 11,460 | 15,610 |
| Average Modulus of Elasticity (ksi)[1] | | | | |
| 1 day | 5600 | 4700 | 4700 | 5600 |
| 14 days | 5800 | 4900 | 4900 | 5800 |
| 28 days | 6000 | 5500 | 5500 | 6000 |
| 56 days | 6300 | 5400 | 5400 | 6300 |
| 180 days | 6800 | 5500 | 5500 | 6800 |
| 360 days | 6900 | 6000 | 6000 | 6900 |

1. Reported values are the average of three tests.
2. Individual tests and statistical data are located in Appendix E.

Table 6.6. Creep Results from Johnson.

| Age at Testing (days) | Creep Strain ($10^{-6}$ in./in.) | |
|---|---|---|
| | 9-26-2.4 | 9-26-5.6 |
| 2 | 206.69 | 241.11 |
| 3 | 254.75 | 291.06 |
| 4 | 316.17 | 303.75 |
| 5 | 333.32 | 311.58 |
| 6 | 341.01 | 326.27 |
| 7 | 357.21 | 336.15 |
| 14 | 402.17 | 410.13 |
| 21 | 433.62 | 454.14 |
| 28 | 446.04 | 463.46 |
| 56 | 534.06 | 506.52 |

Table 6.7. Compressive Strength of FSEL and Coreslab Mixtures.

| | Beams 1 & 4 | 9-26-2.4 | Beams 2 & 3 | 9-26-5.6 |
|---|---|---|---|---|
| Batch Location | Coreslab | FSEL | Coreslab | FSEL |
| 1 day (psi) | 8700 | 6830 | 6130 | 4560 |
| 7 day | - | 11,040 | - | 9270 |
| 14 day | 10,190 | - | 7110 | - |
| 28 day | 11,060 | 12,190 | 8390 | 10,560 |
| 56 day | 12,440 | 12,960 | 9200 | 11,290 |

Table 6.8. Measured Prestress Losses at the North End.

| Beam Age (days) | Temperature (F) | Prestress Losses at the North End (ksi)[4] | | | |
|---|---|---|---|---|---|
| | | Girder 1 | Girder 2 | Girder 3 | Girder 4 |
| | | Air = 2.3% | Air = 6.2% | Air = 6.2% | Air = 2.3% |
| | | $f_{bot}/f_{ci}$ = 66.0 | $f_{bot}/f_{ci}$ = 86.9 | $f_{bot}/f_{ci}$ = 71.4 | $f_{bot}/f_{ci}$ = 55.4 |
| 1 (at release) | 36 [1] | 28.98 | 33.88 | 23.70 | 25.29 |
| 16 | 40 [1] | 40.65 | 52.05 | 40.84 | 36.33 |
| 29 | 65 [2] | 41.32 | 55.00 | 42.38 | 37.22 |
| 43 | 65 [3] | 47.34 | 62.90 | 49.18 | 42.43 |
| 60 | 51 [3] | 45.93 | 59.31 | 45.66 | 39.75 |
| 84 | 63 [3] | 47.99 | 64.22 | 49.31 | 42.47 |
| 120 | 71 [3] | 49.70 | 65.62 | 50.25 | 44.28 |
| 180 | 90 [3] | 53.91 | 70.35 | 56.93 | 48.22 |
| 360 | 63 [3] | 58.22 | 72.97 | 59.46 | 50.81 |

1 = Cured outside at Coreslab Structures.
2 = Cured inside at FSEL.
3 = Cured outside at FSEL.
4 = Strain measurements are located in Appendix E.

Table 6.9. Measured Prestress Losses at the South End.

| Beam Age (days) | Temperature (F) | Prestress Losses at the South End (ksi)[4] | | | |
|---|---|---|---|---|---|
| | | Girder 1 | Girder 2 | Girder 3 | Girder 4 |
| | | Air = 2.3% | Air = 6.2% | Air = 6.2% | Air = 2.3% |
| | | $f_{bot}/f_{ci}$ = 66.0 | $f_{bot}/f_{ci}$ = 86.9 | $f_{bot}/f_{ci}$ = 71.4 | $f_{bot}/f_{ci}$ = 55.4 |
| 1 (at release) | 36 [1] | 26.45 | 31.67 | 25.16 | 25.77 |
| 16 | 40 [1] | 38.6 | 50.36 | 41.65 | 36.86 |
| 29 | 65 [2] | 39.09 | 52.66 | 42.17 | 37.28 |
| 43 | 65 [3] | 44.61 | 60.51 | 49.06 | 43.1 |
| 60 | 51 [3] | 43.35 | 58.95 | 47.11 | 41.35 |
| 84 | 63 [3] | 44.59 | 61.73 | 49.74 | 43.76 |
| 120 | 71 [3] | 46.22 | 63.16 | 50.76 | 44.77 |
| 180 | 90 [3] | 50.78 | 67.76 | 55.69 | 48.51 |
| 360 | 63 [3] | 54.93 | 70.93 | 58.98 | 51.5 |

1 = Cured outside at Coreslab Structures.
2 = Cured inside at FSEL.
3 = Cured outside at FSEL.
4 = Strain measurements are located in Appendix E.

Table 6.10. Average Prestress Losses at Both Ends.

| Beam Age (days) | Temperature (F) | Average Prestress Losses at Ends (ksi)[4] | | | |
|---|---|---|---|---|---|
| | | Girder 1 | Girder 2 | Girder 3 | Girder 4 |
| | | Air = 2.3% | Air = 6.2% | Air = 6.2% | Air = 2.3% |
| | | $f_{bot}/f_{ci}$ = 66.0 | $f_{bot}/f_{ci}$ = 86.9 | $f_{bot}/f_{ci}$ = 71.4 | $f_{bot}/f_{ci}$ = 55.4 |
| 1 (at release) | 36 [1] | 27.72 | 32.78 | 24.43 | 25.53 |
| 16 | 40 [1] | 39.63 | 51.21 | 41.25 | 36.60 |
| 29 | 65 [2] | 40.21 | 53.83 | 42.28 | 37.25 |
| 43 | 65 [3] | 45.98 | 61.71 | 49.12 | 42.77 |
| 60 | 51 [3] | 44.64 | 59.13 | 46.39 | 40.55 |
| 84 | 63 [3] | 46.29 | 62.98 | 49.53 | 43.12 |
| 120 | 71 [3] | 47.96 | 64.39 | 50.51 | 44.53 |
| 180 | 90 [3] | 52.35 | 69.06 | 56.31 | 48.34 |
| 360 | 63 [3] | 56.78 | 71.95 | 59.22 | 51.56 |

1 = Cured outside at Coreslab Structures.
2 = Cured inside at FSEL.
3 = Cured outside at FSEL.
4 = Strain measurements are located in Appendix E.

Table 6.11. Prestress Losses at Center (ksi).

| Beam Age (days) | Temperature (F) | Prestress Losses at Center (ksi)[4] | | | |
|---|---|---|---|---|---|
| | | Girder 1 | Girder 2 | Girder 3 | Girder 4 |
| | | Air = 2.3% | Air = 6.2% | Air = 6.2% | Air = 2.3% |
| | | $f_{bot}/f_{ci}$ = 66.0 | $f_{bot}/f_{ci}$ = 86.9 | $f_{bot}/f_{ci}$ = 71.4 | $f_{bot}/f_{ci}$ = 55.4 |
| 1 (at release) | 36 [1] | 27.83 | 33.58 | 23.44 | 24.86 |
| 16 | 40 [1] | 39.92 | 51.93 | 40.19 | 35.67 |
| 29 | 65 [2] | 40.17 | 55.32 | 41.35 | 36.87 |
| 43 | 65 [3] | 46.08 | 62.45 | 48.58 | 42.60 |
| 60 | 51 [3] | 44.14 | 60.25 | 45.99 | 40.71 |
| 84 | 63 [3] | 45.96 | 64.27 | 48.56 | 43.73 |
| 120 | 71 [3] | 47.57 | 65.94 | 50.55 | 45.21 |
| 180 | 90 [3] | 49.71 | 71.53 | 55.09 | 49.30 |
| 360 | 63 [3] | 53.30 | 74.03 | 58.46 | 51.80 |

1 = Cured outside at Coreslab Structures.
2 = Cured inside at FSEL.
3 = Cured outside at FSEL.
4 = Strain measurements are located in Appendix E.

## 6.5 DISCUSSION OF RESULTS

### 6.5.1 Fresh Concrete Properties

As mentioned in earlier chapters, one goal of the research was to develop a HPC mixture that could be easily used in the local prestressed industry. The slumps of the mixtures used in casting the girders were 9.75 and 10 inches. Both mixtures had sufficient workability to produce the girders. As can be seen in Figures 6.9 and 6.10, the girders had a smooth finish and there were no "honeycombed" areas.

Girders 1 and 4 had a targeted air content of two percent, and Girders 2 and 3 had a targeted air content of six percent. Both mixtures were within ± 0.50 percent of the targeted air contents. The first batch of concrete for Girders 2 and 3 had to be discarded due to an air content of 9.6 percent. The unit weights of the mixtures inversely correlated to the air contents of the mixtures. The mixture for Girders 1 and 4 had a higher unit weight than the concrete mixture for Girders 2 and 3, which was expected.

The unit weights of the mixtures cast at FSEL and at Coreslab are shown in Table 6.12. The calculated unit weights and the percent difference between the calculated and measured unit weights are also shown in Table 6.12. All mixtures were within 1.5 percent of the calculated unit weight. The difference between the measured and calculated unit weights was considered acceptable. This is a testament to the quality control procedures employed by Coreslab. The mixtures cast at FSEL were smaller mixtures (approximately 2.2 $ft^3$) and the materials were weighed using a digital scale. The materials were weighed to the nearest hundredth of a pound. At Coreslab, the mixtures were much larger (approximately 2.5 $yd^3$ or 67.5 $ft^3$) and the materials were

weighed using a weight and balance system and mixed in a concrete mixer that had been in use since the 1926. The minimal differences between the measured and calculated unit weights (1.5 percent and less) and the use of a mixer that was built in 1926 confirms that HPC can be produced at most facilities that are currently casting concrete.

Table 6.12. Comparison of Unit Weights.

| Location | 9-26-2.4 | Measured / Calculated | 9-26-5.6 | Measured / Calculated |
|---|---|---|---|---|
| Unit Weight - Coreslab ($lb/ft^3$) | 151.1 | 98.5 % | 146.9 | 100.1 % |
| Unit Weight – FSEL ($lb/ft^3$) | 152.3 | 99.3 % | 147.2 | 100.3 % |
| Unit Weight – Calculated ($lb/ft^3$) | 153.4 | 100.0 % | 146.8 | 100.0 % |

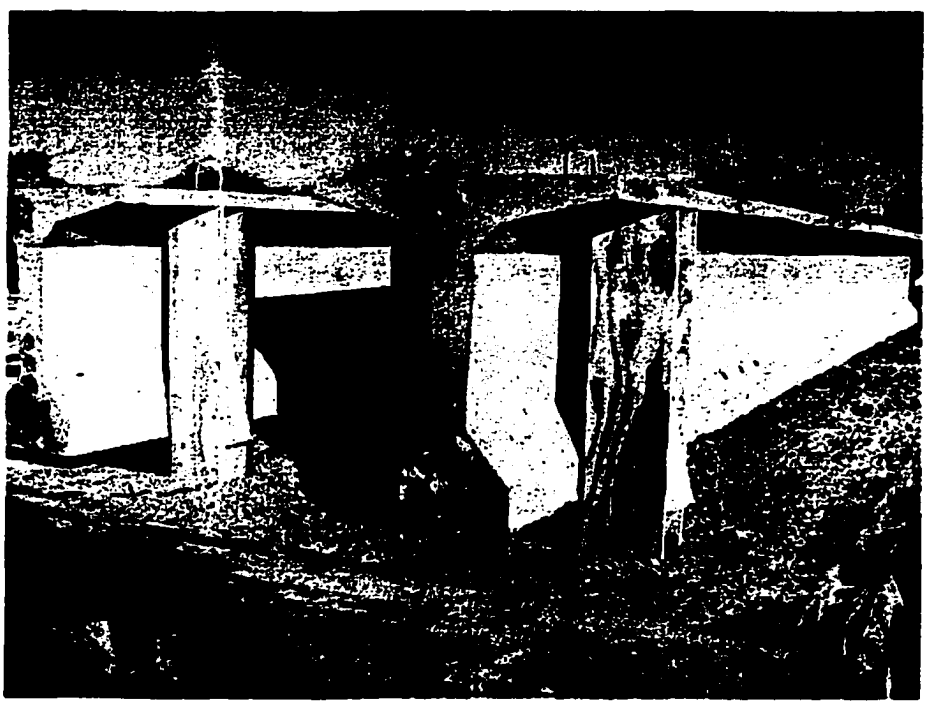

Figure 6.9. Photograph of Girders.

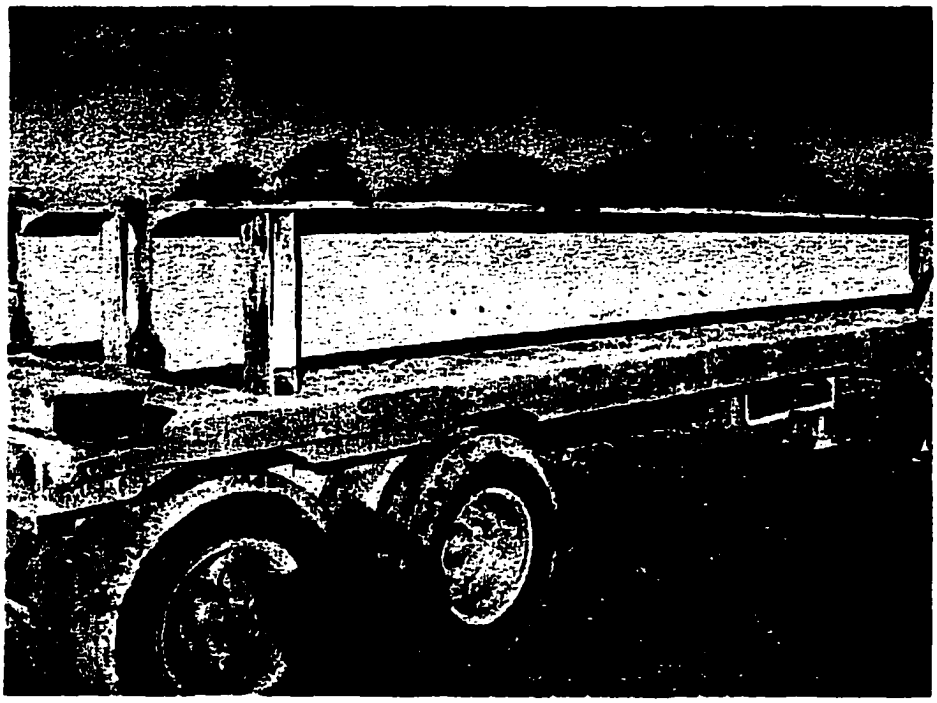

Figure 6.10. Photograph of Girders.

### 6.5.2 Hardened Concrete Properties

**6.5.2.1 Compressive Strength.** A comparison of the FSEL and Coreslab mixtures are shown in Figures 6.11 and 6.12. The difference between the mixtures was the curing regimen. The cylinders cast at Coreslab were steam cured for approximately 12 hours (overnight) with the girders and then cured with the girders outside in ambient temperatures. The FSEL cylinders were cured at 73°F and 50 percent relative humidity for 24 hours and then cured at 73°F and 100 percent relative humidity until tested. The use of heat curing increased the one-day compressive strengths of the Coreslab mixtures, but decreased their long term compressive strength, which is shown in Figures 6.11 and 6.12. Steam curing increases early age strength by increasing the initial hydration. This results in a "less uniform distribution of hydration products within the paste" which decreases the ultimate strength of concrete (Mindess et al, 1981). This is evident in

Figure 6.11 and 6.12 where the compressive strength of the Coreslab mixtures was approximately 30 percent greater than the FSEL mixtures at one day of age, but by 28 days of age, the FSEL achieved compressive strengths that were greater than the steam cured Coreslab mixtures.

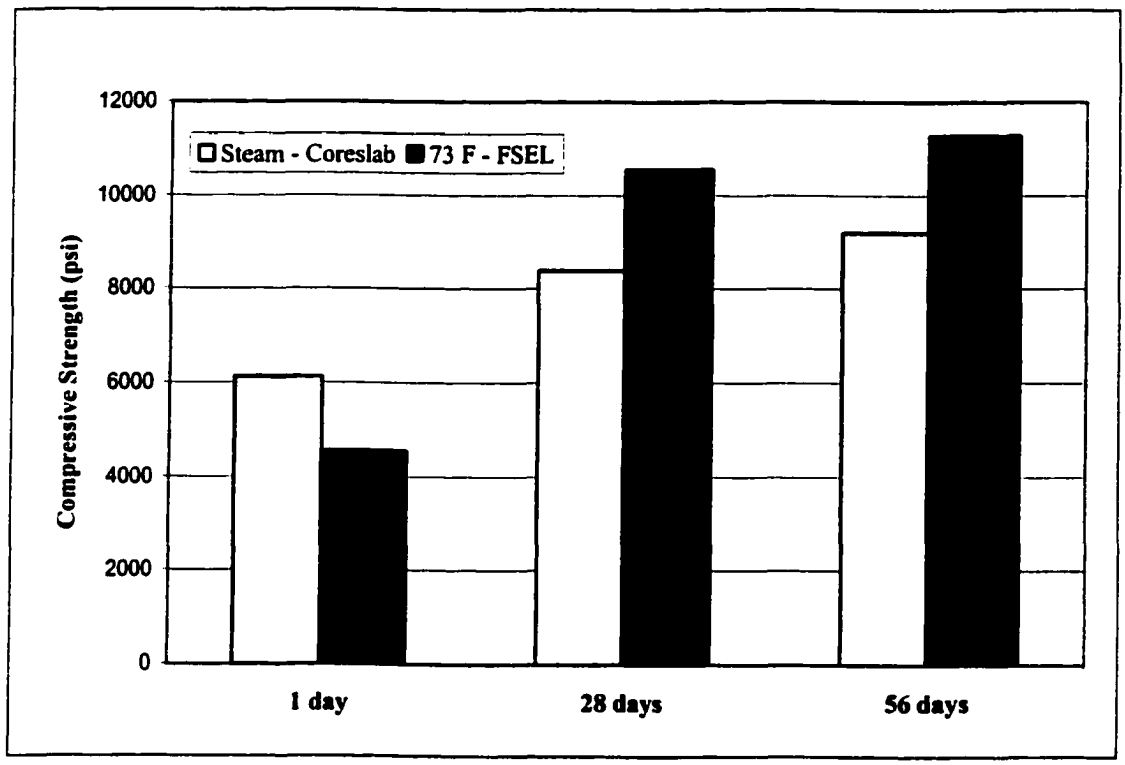


Figure 6.11. Comparison of One-day Compressive Strengths (psi).

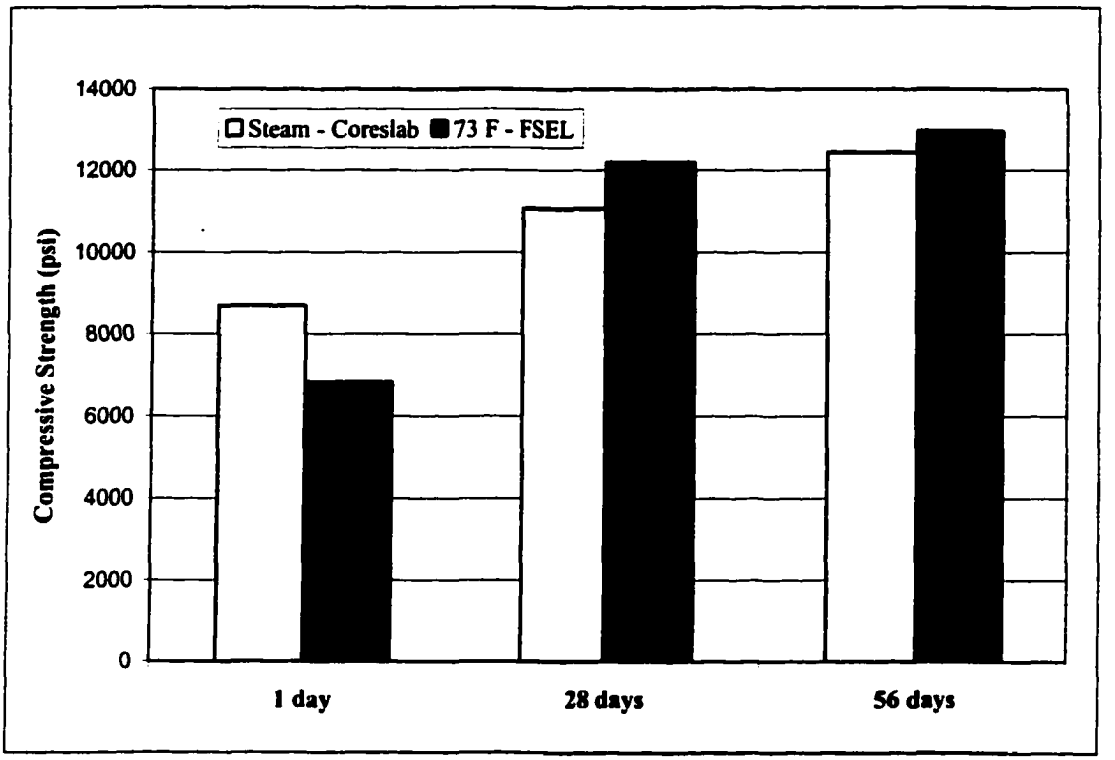


Figure 6.12. Comparison of 28-day Compressive Strengths (ksi).

The strength gain of the two mixtures cast at Coreslab is shown in Figure 6.13. The difference between the two mixtures is the total air content. One mixture contained no entrained air (air content of 2.3 percent) and the other contained 6.2 percent air (approximately 4 percent entrained air). The effects of the entrained air are shown in Figure 6.13. The rate of strength gain for the two mixtures is almost identical, but for each age tested the addition of entrained air reduced the compressive strength by roughly 30 percent.

The decrease in compressive strength due to the addition of air entrainment was discussed Chapter 3. The addition of one percent of entrained air normally decreases the compressive strength by two to five percent (Mindess et al, 1981). The decrease in compressive strength per increase in entrained air is shown in Table 6.13 for each age

tested. The decrease in compressive strength per one percent increase in entrained air ranged from 6.2 to 7.8 percent. This is slightly more than the "2 to 5 percent decrease" suggested by many books, but still within an acceptable and expected range.

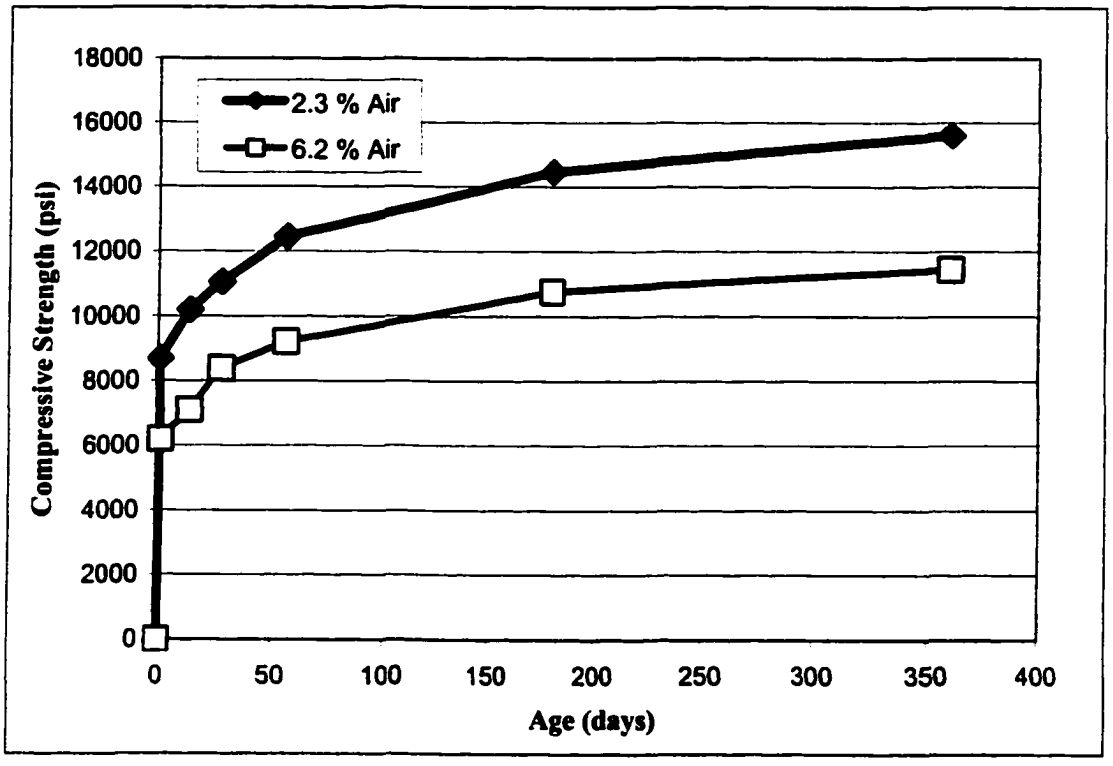


Figure 6.13. Strength Gain for the Coreslab Mixtures.

Table 6.13. Decrease in Compressive Strength due to Entrained Air.

| Age (days) | Girder 1 | Girder 2 | % Decrease in Compressive Strength per One % Increase in Entrained Air |
|---|---|---|---|
| 1 | 8700 | 6130 | 7.60 |
| 14 | 10,190 | 7110 | 7.80 |
| 28 | 11,060 | 8390 | 6.20 |
| 56 | 12,440 | 9200 | 6.70 |
| 180 | 14,460 | 10,850 | 6.40 |
| 360 | 15,610 | 11,460 | 6.80 |

**6.5.2.2 Modulus of Elasticity.** The modulus of elasticity (MOE) is a measure of the stiffness of the concrete. The MOE of concrete is seldom measured for design; instead ACI318-99 provides two prediction equations (Eqns. 6.1 and 6.2) that can be used to determine the MOE. As can be seen in the equations, the compressive strength and unit weight are the major factors that influence the MOE of concrete. Increases in both compressive strength and unit weight result in higher MOE. These trends exist in the results of the mixtures examined in this research. Increases in compressive strength resulted in increases in MOE.

The MOE of the mixtures are plotted in Figure 6.14 versus the square root of the compressive strength. Also plotted on the graph are equations 6.1 and 6.2. As shown in Figure 6.14, the MOE of the mixtures plot near the prediction equations, meaning the equations can be used when estimating the MOE based on their compressive strength.

$$E_c = 57{,}000 * \sqrt{f'_c} \qquad \text{Eqn. 6.1}$$

Where
$f'_c$ = compressive strength (lb/in$^2$)

$$E_c = 33 w_c^{1.5} * \sqrt{f'_c} \qquad \text{Eqn. 6.2}$$

Where
$f'_c$ = compressive strength (lb/in$^2$)
$w_c$ = unit weight of the concrete (lb/ft$^3$)

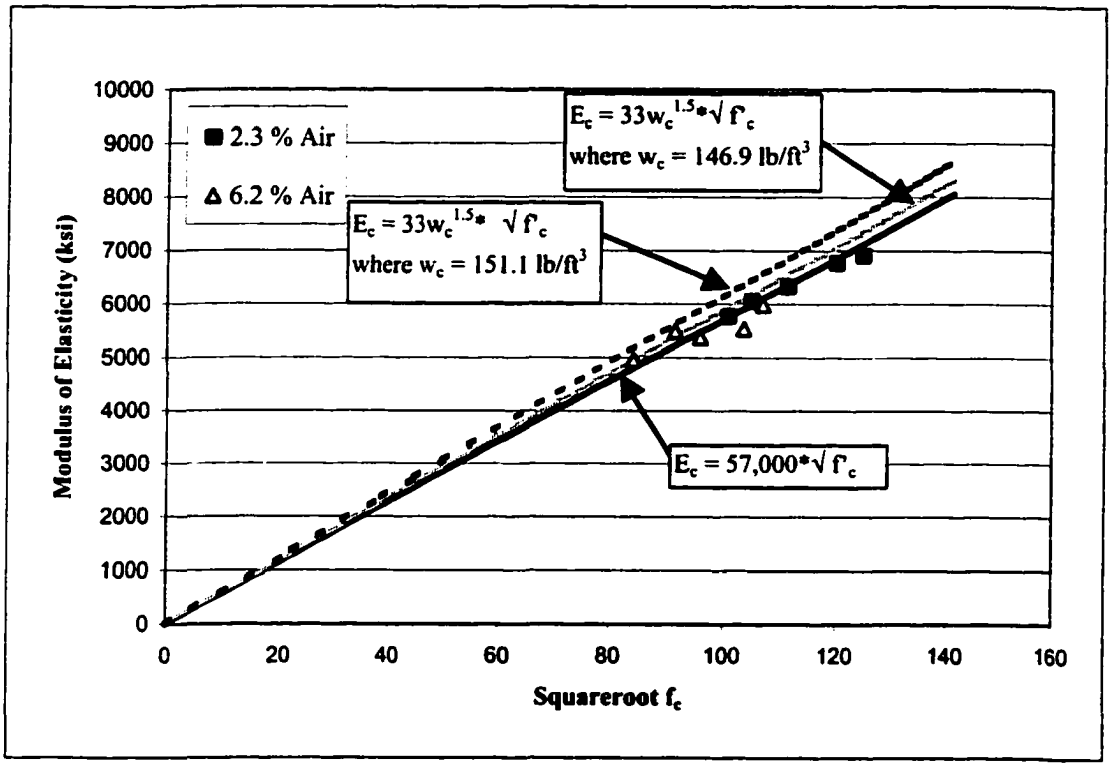


Figure 6.14. MOE and Prediction Equations.

**6.5.2.3 Creep.** Earlier research by Johnson (2001) examined the differences between the creep of air entrained and non-air entrained mixtures. Creep is the deformation of concrete due to sustained loads. The creep of concrete is affected by the strength, age at loading, curing conditions, aggregate content, and modulus of elasticity of the concrete mixture (Mindess et al, 1981). The mixtures examined by Johnson were the identical to the mixtures (mixtures 9-26-2.3 and 9-26-6.2) used to cast the girders for this research.

The results of Johnson's research are shown in Figure 6.15. As shown in the graph, the addition of entrained air has little or no effect on the creep of concrete, which was expected. Both mixtures were cured at the same temperature and relative humidity, and the quantity of coarse aggregate was also equal in both mixtures. Even though the compressive strengths were different, both mixtures were loaded to 40 percent of their one-day compressive strength. Johnson's results show that the creep of concrete is not directly affected by the addition of entrained air. The creep is indirectly affected by entrained air due to the reduction of strength caused by the addition of entrained air. The results of Johnson's research show that air entrained and non-air entrained prestressed girders will exhibit similar creep behavior.

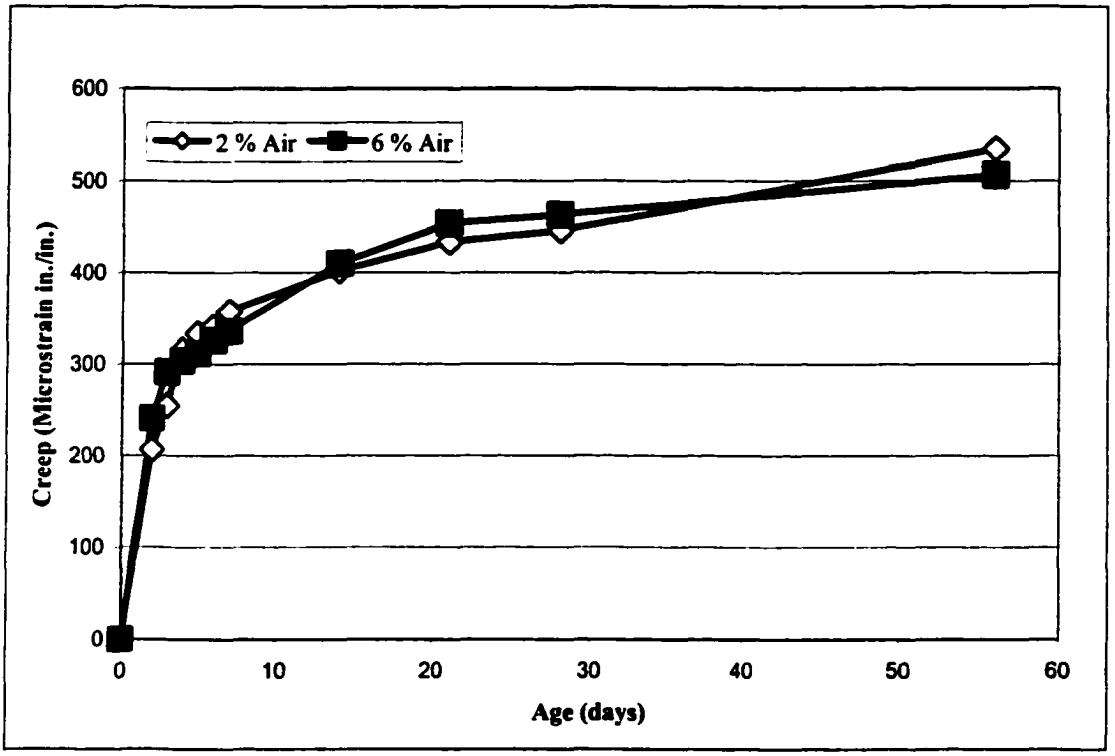


Figure 6.15. Creep Results from Johnson's Research.

**6.5.2.4 Shrinkage.** The shrinkage or length change of the mixtures used to cast the girders was measured for one year. Shrinkage specimens were cast from the same concrete mixtures that were used in casting the girders (mixtures 9-26-2.3 and 9-26-6.2). The shrinkage curves for the mixtures are shown in Figure 6.16.

Shrinkage is caused by the loss of moisture in the concrete. The major contributors to shrinkage are the w/cm, the volume of paste, and the volume and type of coarse aggregate. Since the paste content was approximately the same for both mixtures and the coarse aggregate was the same for both mixtures, the shrinkage would also have been expected to be approximately the same. As shown in Figure 6.16, the shrinkage curves for the two mixtures were similar. The shrinkage at one year of age was 680 and 740 microstrains for mixtures 9-26-2.3 and 9-26-6.2, respectively. The results are typical

of concrete mixtures containing high quantities of cement (Ramseyer, 1999). Like the creep results, the results from the shrinkage tests were also used in the analysis of the prestress losses.

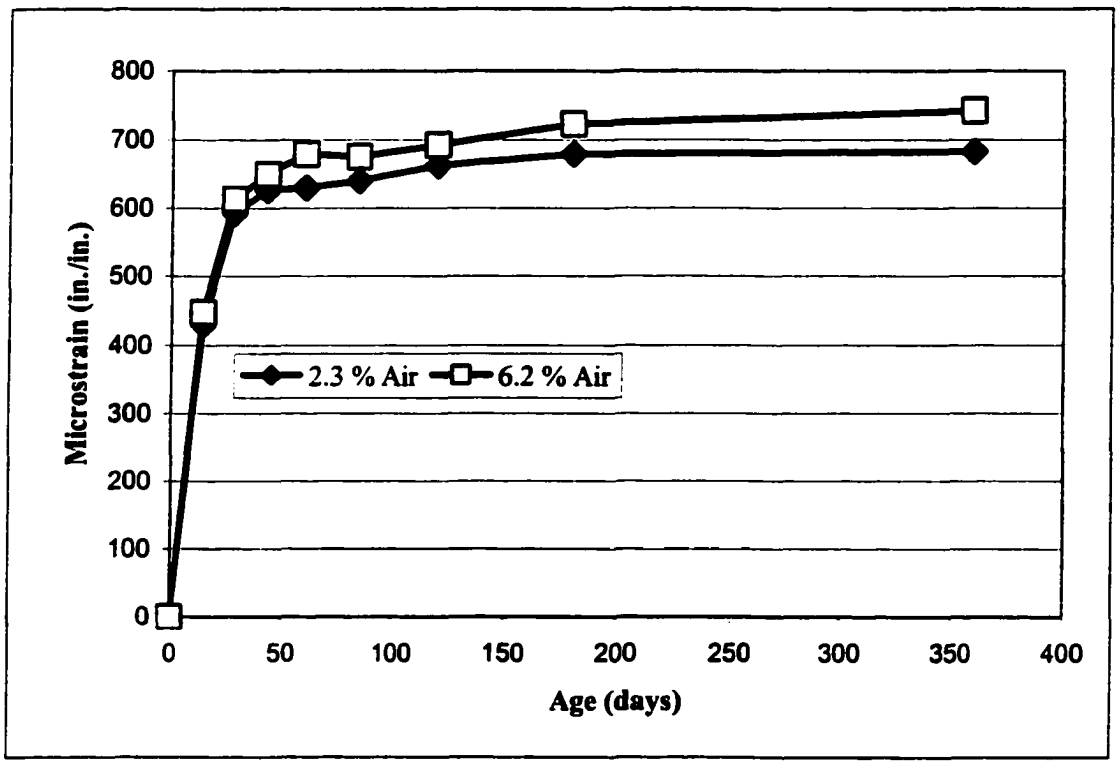


Figure 6.16. Shrinkage Curves.

### 6.5.3 Prestress Losses

**6.5.3.1 Elastic Shortening.** Elastic shortening is the loss of prestress force that occurs when the strands are released (at transfer of the prestress force). At transfer, the strands are cut and this force, which is applied to the concrete through the strands, shortens the concrete. The strand length also shortens as the length of concrete shortens thereby reducing the initial prestress force.

The loss due to elastic shortening was determined by measuring the distance between DEMEC points before transfer and after transfer of the prestress force. The elastic shortening was also calculated using equations developed by AASHTO and PCI (equations 6.3 and 6.4). The AASHTO and PCI equations are almost identical. The difference being that the concrete stress due to the prestressing strands is multiplied by the Kcir factor in the PCI equation. The Kcir factor is equal 0.90 for pretensioned girders. This term represents a 10 percent loss of prestress force due to elastic shortening. Researchers suggest that the 10 percent loss assumption will provide sufficient accuracy for most prestensioned members (Lin and Burns, 1981). For the calculations in this research, a "modified" Kcir factor was used to reflect the actual losses due to elastic shortening. The "modified" Kcir factor was determined through an iterative process. The "modified" factors ranged from 0.89 to 0.91. The calculations for the Kcir factors and the elastic shortening losses are shown in Appendix E.

The measured and predicted values are shown in Table 6.14. The two prediction equations produced results that were very similar which was expected. The calculations for the elastic shortening losses are shown in Appendix E. For each beam, the AASHTO equations predicted elastic shortenings losses that were approximately two ksi (or 11 percent) greater than the PCI equations. Once again, this is due to the addition of the Kcir factor in the PCI equations, which reduces the concrete stress by approximately 10 percent.

Table 6.14. Prestress Losses Due to Elastic Shortening.

| Girders | Location | Prestress Losses Due to Elastic Shortening (KSI) | | |
|---|---|---|---|---|
| | | Measured | AASHTO Predicted | PCI Predicted |
| 1 | Ends | 27.72 | 23.67 | 20.35 |
| | Center | 27.83 | 23.22 | 19.91 |
| 2 | Ends | 32.78 | 26.30 | 22.09 |
| | Center | 33.58 | 25.75 | 21.54 |
| 3 | Ends | 24.43 | 20.73 | 18.24 |
| | Center | 23.44 | 20.25 | 17.77 |
| 4 | Ends | 25.53 | 20.41 | 17.96 |
| | Center | 24.86 | 19.93 | 17.48 |

However, both equations underestimated the elastic shortening losses (Figure 6.17). The AASHTO equations predicted losses that were four to eight ksi (15 to 30 percent) less than the measured losses whereas as the PCI equations predicted losses which were six to ten ksi (or 30 to 45 percent) less. The losses for Girders 1, 3, and 4 were approximately four ksi greater than the losses predicted by the AASHTO equations and seven ksi greater than the losses predicted by the PCI equations. The elastic shortening losses for Girder 2 were seven and 10 ksi greater than those predicted by the AASHTO and PCI equations, respectively. The higher than expected measured elastic shortening losses in Girder 2 can be attributed to high compressive stress at release of $0.87f_{ci}$. At approximately 70 percent of the ultimate strength, the stress-strain curve of concrete begins to "bend over" (Neville, 1997). At stresses greater than 70 percent of

ultimate, the slope of the stress-strain curves begins to decreases, which reduces the modulus of elasticity. Girders 2 had a release stress of 0.87fci. At this level of stress the modulus of elasticity is most likely less than the measured values (4700 ksi at one day) used in the calculations. The lower modulus of elasticity would increase the elastic shortening losses predicted by both PCI and AASHTO equations which would bring the predicted and measured values closer.

The differences between the measured and predicted elastic shortening losses might also be due to the changes in concrete temperature between readings (before and after transfer). The thermal expansion for the concrete and strand was taken as $6 \times 10^{-6}$ in./in./degree F (MacGregor, 1999). When the strands were released, the morning temperatures were near 15°F with daily high temperatures of approximately 45°F. The temperature of the girders was approximately 100°F when the forms were removed and the DEMEC points were being glued onto the girders. A 20 °F change in concrete temperature would result in a loss of 3.40 ksi and a 30 °F difference in concrete temperature would result in a loss of 5.10 ksi. The potential losses due to changes in concrete temperature lower the measured elastic shortening losses into the range of losses predicted by the AASHTO equations. The calculations for the losses due to temperature changes are also shown in Appendix E.

One can not be certain as to why the measured losses were greater than those predicted by AASHTO and PCI. However, the changes in concrete temperature and the allowable compressive stress at release greater than $0.60f_{ci}$ contributed to the greater than expected elastic shortening losses.

$\Delta f_{pES} = (E_p/E_{ci})f_{cgp}$ **(AASHTO)** Eqn. 6.3

where;

$E_p$ = modulus of elasticity of prestressing steel (ksi)

$E_{ci}$ = modulus of elasticity of concrete at transfer (ksi)

$f_{cgp}$ = sum of concrete stresses at the center of gravity of prestressing tendons due to the prestressing force at transfer and the self-weight of the at the sections of maximum moment (ksi)

$ES = K_{es}E_s f_{cir}/E_{ci}$ **(PCI)** Eqn. 6.4

where;

$K_{es}$ = 1.0 for pretensioned members

$E_s$ = modulus of elasticity of prestressing steel (ksi)

$E_{ci}$ = modulus of elasticity of concrete at transfer (ksi)

$f_{cir}$ = net compressive stress in concrete at the center of gravity of tendons immediately after the prestress has been applied to the concrete (ksi).

$f_{cir}$ = $K_{cir}(P_i/A_g + P_i e^2/I_g) - M_g e/I_g$

where:

$K_{cir}$ = 0.9 for pretensioned members

$P_i$ = initial prestress force

e = eccentricity of center of gravity of tendons with respect to center of gravity of concrete at the cross section considered.

$A_g$ = area of gross concrete section at the cross section considered

$I_g$ = moment of inertia of gross concrete section at the cross section considered

$M_g$ = bending moment due to dead weight of prestressed member and any other permanent loads in place at time of prestressing

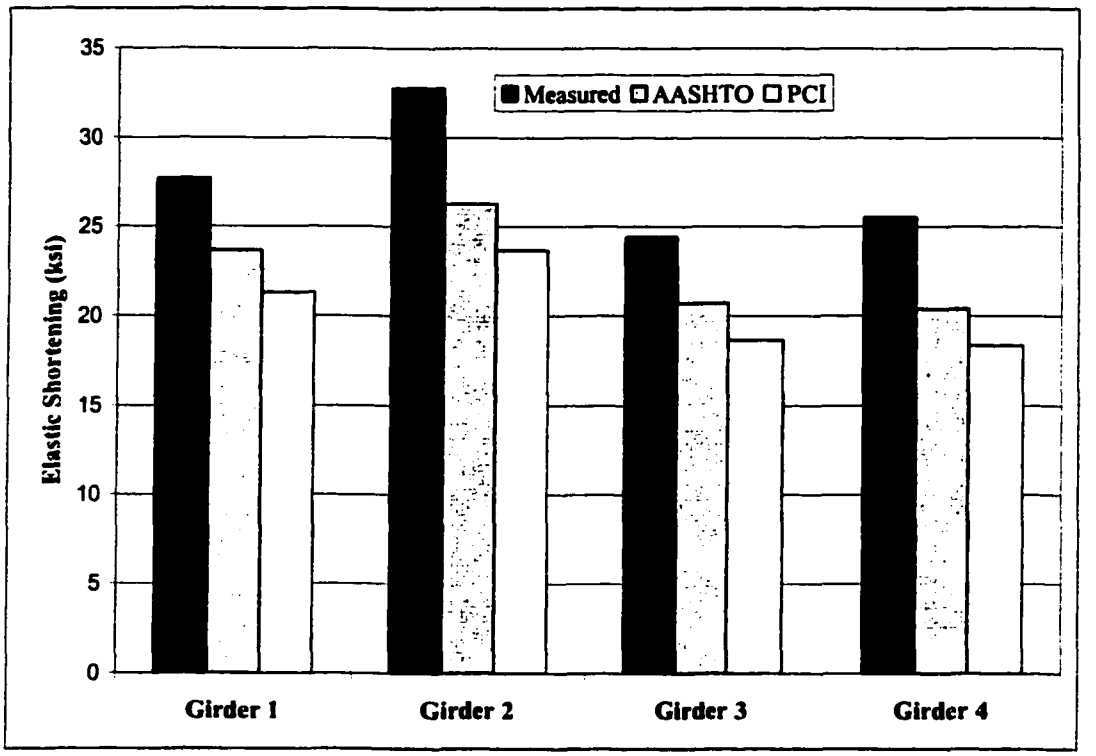


Figure 6.17. Comparison of Predicted and Measured E.S. Losses.

**6.5.3.2 Creep.** Creep is defined as the deformation of concrete due to sustained loads. As the girders deform or shorten due to the prestress force, the length of the strands shortens which results in a loss of prestress force. Creep is a major contributor to the loss of prestress force. The loss due to creep normally accounts for approximately 24 percent of the total losses (Lin and Burns, 1981).

The AASHTO and PCI predictions equations are shown in Equations 6.5 and 6.6, respectively. The results from the prediction equations are shown in Table 6.15. The calculations for the creep losses are shown in Appendix E. Unlike the results from the elastic shortening equations, there are major differences between the predicted values of the two equations. The AASHTO equations predicted creep losses that were between 22 to 29 percent greater than the PCI equations. However, there are some similarities

between the equations. Both equations include the difference between the concrete stress at transfer and the concrete stress due to permanent dead loads. Also, by rearranging the PCI equation (Eqn. 6.7) and assuming a modular ratio of six, the Kcr(Es/Ec) terms becomes 12 which is similar to the AASHTO equation. The use of HPC in these girders resulted in a modulus of elasticity of 6000 ksi at 28 days of age. The greater modulus of elasticity reduced the modular ratio to 4.75 making the $K_{cr}(E_s/E_c)$ equal to 9.50 instead of 12. This decreased the creep losses predicted by the PCI equations when compared to the AASHTO equations. This is the most likely reason as to why the AASHTO equation predicted creep losses that were greater than the PCI equation.

$$\Delta f_{pCR} = 12.0 f_{cgp} - 7.0 \Delta f_{cdp} \qquad \textbf{(AASHTO)} \quad \text{Eqn. 6.5}$$

where:

$f_{cgp}$ = concrete stress at the center of gravity of prestressing steel at transfer (KSI)

$\Delta f_{cdp}$ = change in concrete stress at the center of gravity of prestressing steel due to permanent loads, except the load acting at the time the prestressing force is applied. Values of $\Delta f_{cdp}$ should be calculated at the same section or sections for which $f_{cgp}$ is calculated (KSI)

$$CR = K_{cr}(E_s/E_c)(f_{cir}-f_{cds}) \qquad \textbf{(PCI )} \quad \text{Eqn. 6.6}$$

where:

$K_{cr}$ = 2.0 for normal weight concrete

$f_{cir}$ = net compressive stress in concrete at the center of gravity of tendons immediately after the prestress has been applied to the concrete (ksi).

$f_{cds}$ = stress in concrete at center of gravity of tendons due to all superimposed permanent dead loads that are applied to the member after it had been prestressed

$E_c$ = modulus of elasticity of concrete at 28 days

$f_{cds} = M_{sd}(e)/I_g$

$M_{sd}$ = moment due to all superimposed permanent dead loads applied after prestressing

$CR = 12.0(f_{cir}-f_{cds})$ **(PCI-Rearranged)** Eqn. 6.7

Table 6.15. Estimated Losses Due to Creep.

| Girders | Location | Prestress Losses Due to Creep (KSI) | |
|---|---|---|---|
| | | AASHTO Predicted | PCI Predicted |
| 1 | Ends | 55.81 | 39.54 |
| | Center | 54.75 | 38.71 |
| 2 | Ends | 52.04 | 39.82 |
| | Center | 50.96 | 38.88 |
| 3 | Ends | 41.02 | 32.24 |
| | Center | 40.08 | 31.43 |
| 4 | Ends | 48.13 | 34.67 |
| | Center | 46.98 | 33.76 |

**6.5.3.3 Shrinkage.** Concrete decreases in volume when it loses water through evaporation. Like creep and elastic shortening, as the concrete shortens, the prestress strands also shorten which results in a loss of prestress force. The shrinkage of the girders was determined by measuring the length change (ASTM C 157) of concrete prisms cast with the same concrete as the girders. The measured and predicted shrinkage losses are shown in Table 6.16. The shrinkage losses were 19.40 ksi for Girders1 and 4 and 21.10 ksi for Girders 2 and 3. The measured losses were calculated by using Hooke's Law. The measured losses were then compared to the losses predicted by the AASHTO (Eqn. 6.8) and PCI (Eqn. 6.9) equations. The calculations for the shrinkage losses are shown in Appendix E. Both equations estimated shrinkage losses that were over 50 percent less than those measured from the shrinkage prisms.

It must be noted that the measured shrinkage losses were determined from 2 x 2 x 11 in. concrete prisms cast with the same concrete as the girders. This may account for the differences between the measured and predicted losses due to shrinkage. Unlike the girders, the shrinkage prisms did not contain any reinforcement, which would restrain the concrete and reduce shrinkage. The addition of reinforcement would assist in preventing the girders from shrinking as much as the non-reinforced shrinkage prisms. Another possible explanation for the differences between the predicted and measured shrinkage is the quantity of cement used in the production of the girders. Neither equation (AASHTO or PCI) accounts for the quantity of cement used in the girders. As the quantity of cement in the mixture increases, the amount of shrinkage also increases (Mindess and Young, 1981). The AASHTO and PCI equations were developed based on mixtures with

lower quantities of cement, but with the introduction of HPC more girders are being cast with greater cement quantities (at or near 1000 lb/yd$^3$).

$\Delta f_{pSR} = (17.0 - 0.150\ H)$ **(AASHTO)** Eqn. 6.8

where:

H = average ambient relative humidity

$SH = (8.2 \times 10\text{-}6)K_{sh}E_s \times (1 - 0.06V/S)(100 - R.H.)$ **(PCI)** Eqn 6.9

where:

$K_{sh}$ = 1.0 for pretensioned members

V/S = volume to surface ratio

R.H. = average ambient relative humidity

Table 6.16. Prestress Losses Due to Shrinkage.

| Girder | Prestress Losses Due to Shrinkage (KSI) | | |
|---|---|---|---|
| | Measured (1 year) | AASHTO Predicted | PCI Predicted |
| 1 | 19.40 | 7.25 | 7.36 |
| 2 | 21.10 | 7.25 | 7.36 |
| 3 | 21.10 | 7.25 | 7.36 |
| 4 | 19.40 | 7.25 | 7.36 |

**6.5.3.4 Relaxation.** Relaxation of the steel strand is similar to creep in concrete. Steel relaxation is the loss of prestress due to the constant strain AASHTO provides two different equations (Eqns. 6.10 and 6.11) for measuring the relaxation of the strands. The losses due to relaxation are calculated at transfer and after transfer. PCI developed one equation to predict relaxation losses (Eqn. 6.12).

The predicted losses due to relaxation are shown in Table 6.17. For all girders, the loss due to relaxation ranged 0.68 to 2.79 ksi. The calculations for relaxation losses are shown in Appendix E. As shown in Table 6.17, there are some differences between the predicted values between the two equations. For all girders, the AASHTO equations predicted losses that were less than those predicted by the PCI equations. The differences between the losses can be attributed to the greater creep losses predicted by the AASHTO equations.

$\Delta f_{pR1} = (\log (24.0t)/40.0)[f_{pj}/f_{py} - 0.55]\, f_{pj}$ at transfer (**AASHTO**) Eqn. 6.10

where:

t = time estimated in days from stressing to transfer (days)

$f_{pj}$ = initial stress in the tendon at the end of stressing (ksi)

$f_{py}$ = specified yield strength of prestressing steel (ksi)

$\Delta f_{pR2} = 0.30[20.0 - 0.4\Delta f_{pES} - 0.2(\Delta f_{pSR} + \Delta f_{pCR})]$ **(AASHTO)** Eqn. 6.11

where:

$\Delta f_{pES}$ = loss due to elastic shortening (ksi)

$\Delta f_{pSR}$ = loss due to shrinkage (ksi)

$\Delta f_{pCR}$ = loss due creep of the concrete (ksi)

$RE = [K_{re} - J(SH + CR + ES)]C$ **(PCI)** Eqn. 6.12

where Kre, J, and C are taken from tables

ES = loss due to elastic shortening (ksi)

SH = loss due to shrinkage (ksi)

CR = loss due creep of the concrete (ksi)

Table 6.17. Predicted Losses Due to Relaxation.

| Girders | Location | Prestress Losses Due to Relaxation (KSI) | |
|---|---|---|---|
| | | AASHTO Predicted | PCI Predicted |
| 1 | Ends | 0.84 | 2.39 |
| | Center | 0.95 | 2.44 |
| 2 | Ends | 0.68 | 2.18 |
| | Center | 0.81 | 2.24 |
| 3 | Ends | 1.96 | 2.53 |
| | Center | 2.07 | 2.58 |
| 4 | Ends | 1.69 | 2.70 |
| | Center | 1.82 | 2.76 |

**6.5.3.5 Total Losses.** The measured total losses and the predicted total losses are shown below in Table 6.18. For all beams, the AASHTO equations predicted losses that were greater than the measured losses. Once again, the differences between the predicted losses of the two equations can be attributed to the higher creep losses estimated by the AASHTO equations.

The measured losses for all girders are also shown in Figure 6.18. As shown in Figure 6.18, it appears that the majority of the losses occur by 180 days of age and afterward the rate of prestress loss decreases. Also, in the graph each curve has a noticeable "jump" in losses at 43 days of age. Moving the girders from the inside of FSEL to the outside of FSEL probably caused the increase in losses. This seems to be the most logical explanation. Prior to the readings taken at day 43, the girders had been stored inside at FSEL and then were moved outside of FSEL. The girders were loaded onto a trailer by the use of a spreader beam and then hauled outside where they were removed from the trailer by a forklift. The noticeable increases in losses were most likely caused by stresses imposed on the girder while they were being lifted by the spreader beam and forklift. Even though there was a noticeable jump in losses at 43 days of age, the next readings were more inline with the remaining data (Figure 6.18).

Table 6.18. Total Prestress Losses.

| Girders | Location | Total Prestress Losses (KSI) | | |
|---|---|---|---|---|
| | | Measured (1 year) | AASHTO Predicted | PCI Predicted |
| 1 | Ends | 56.78 | 87.56 | 70.48 |
| | Center | 53.30 | 86.17 | 69.25 |
| 2 | Ends | 71.95 | 86.26 | 72.66 |
| | Center | 74.03 | 84.76 | 71.24 |
| 3 | Ends | 59.22 | 70.96 | 61.00 |
| | Center | 58.46 | 69.66 | 59.75 |
| 4 | Ends | 51.86 | 77.48 | 63.32 |
| | Center | 51.80 | 75.97 | 61.98 |

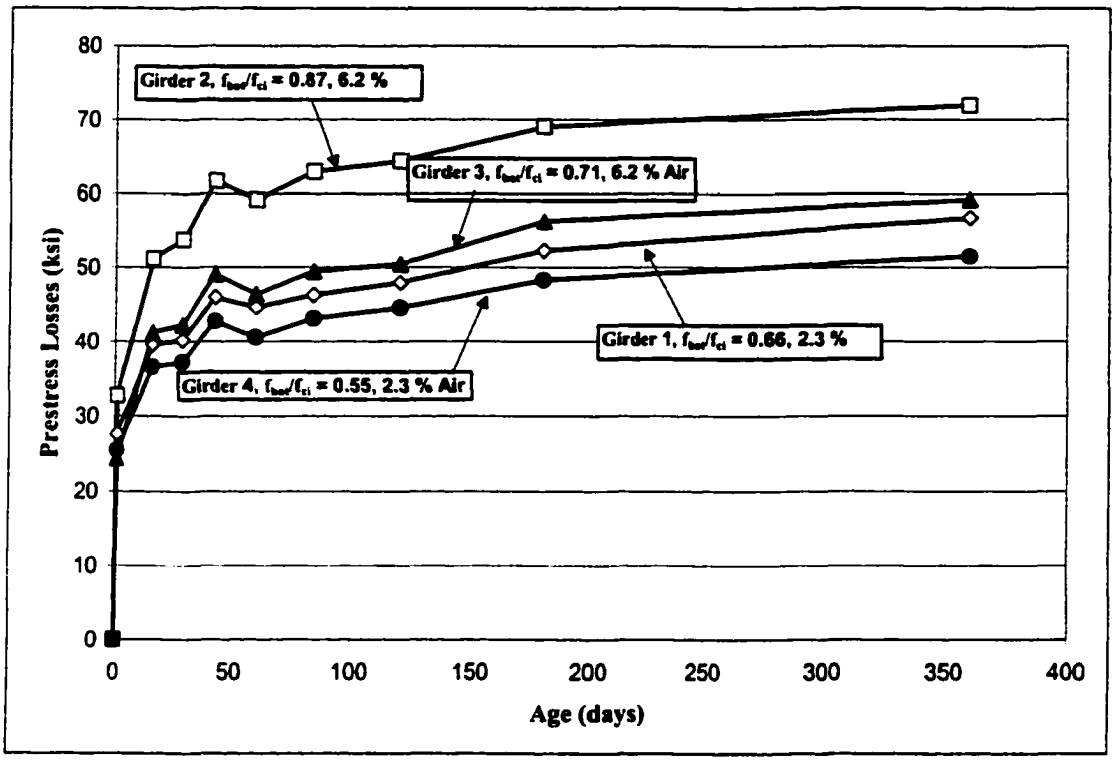


Figure 6.18. Measured Total Losses for the Girders.

### 6.5.4 Allowable Compressive Stress

The research program also investigated the allowable compressive stress at release. Currently the AASHTO Bridge Design Specifications and the Building Requirements for Structural Concrete (ACI 318-99) limits the compressive stress at release to be 60 percent or less of the concrete compressive strength at release ($0.60f_{ci}$). Researchers are investigating whether this limit can be increased beyond $0.60f_{ci}$. The lower release limit of $0.60f_{ci}$ causes the need for steam curing in many instances to achieve strengths. Steam curing increases the rate of strength gain in the concrete, allowing the concrete to achieve greater compressive strengths at earlier ages. However, steam curing has negative side effects. Steam curing reduces the ultimate strength and increases the permeability of steam-cured concrete when compared to concrete that is not

steam cured (Neville, 1997 and Mindess and Young, 1981). By raising the allowable compressive stress to 75 percent, the need for steam curing might be eliminated which could result in concrete of higher quality. The research results will provide additional data to examine the efficacy of various proposals. The testing matrix is shown in Table 6.19.

Table 6.19. Testing Matrix.

| Beam | Targeted Allowable Compressive Stresses ($f_{bot}$ / $f_{ci}$) | | Targeted Total Air Content (%) | |
|---|---|---|---|---|
| | 0.60 | 0.75 | 2 | 6 |
| 1 | - | X | X | - |
| 2 | - | X | - | X |
| 3 | X | - | - | X |
| 4 | X | - | X | - |

The targeted allowable stresses of 0.60 and 0.75 were not attained due to higher and lower than expected one-day compressive strengths. Girders 3 and 4 had a targeted release stress of 60 percent, and girders 1 and 2 had a targeted release stress of 75 percent. The one-day compressive strength of Girders 1 and 4 was expected to be near 8000 psi based on trial batching at FSEL and Coreslab. However, the compressive strength of Girders 1 and 4 was 8700 psi at one day. The 700 psi increase was due to the steam curing used by Coreslab. The increase in the one-day compressive strength for Girders 1 and 4 resulted in the targeted allowable compressive stress not being attained. Girder 1 was designed to have an allowable compressive stress at release of 0.75, but due to the unexpectedly high one-day compressive strength, this ratio was only 0.66. The

same can be said for Girder 4. Girder 4 was designed to have allowable compressive stress of 0.60, but this ratio was only 0.55.

The lower than expected one-day compressive strengths of Girders 2 and 3 resulted in higher compressive stresses at release. Girder 2 was designed to have an allowable compressive stress at release of 0.75, but due to the low compressive strength, this ratio was 0.87. Girder 3 was designed to have an allowable compressive stress at release of 0.60, but the stress was 0.71. The low one-day compressive strength was most likely the result of the extremely low temperature the previous night, which prevented the steam in the prestressing beds from attaining its normal temperature. Girders 2 and 3 were cast on Thursday, December 21, and the prestressing strands were released on Friday, December 23. Due to the holiday weekend (Christmas), Coreslab was closing early so waiting for the concrete to reach higher compressive strengths was not an option.

Even though the targeted allowable stresses were not attained, three of the four girders had allowable compressive stresses at release greater than 0.60. The high release stresses did not appear to have any noticeable detrimental effects on the girders. The only possible effect of the high compressive stress at release occurred on the south of Girder 2. As shown in Figure 6.19 and 6.20, a portion of concrete fractured along the web of the girder. It is uncertain to whether this fracture is due to the high release stress or due to other factors such as low minimum cover throughout the web of the girder (less than 1.5 inches). Girder 2 did have the highest stress at release of 87.0 percent, which is 45 percent greater than that allowed by AASHTO and ACI. The remaining girders did not have any major cracks or other signs of failure.

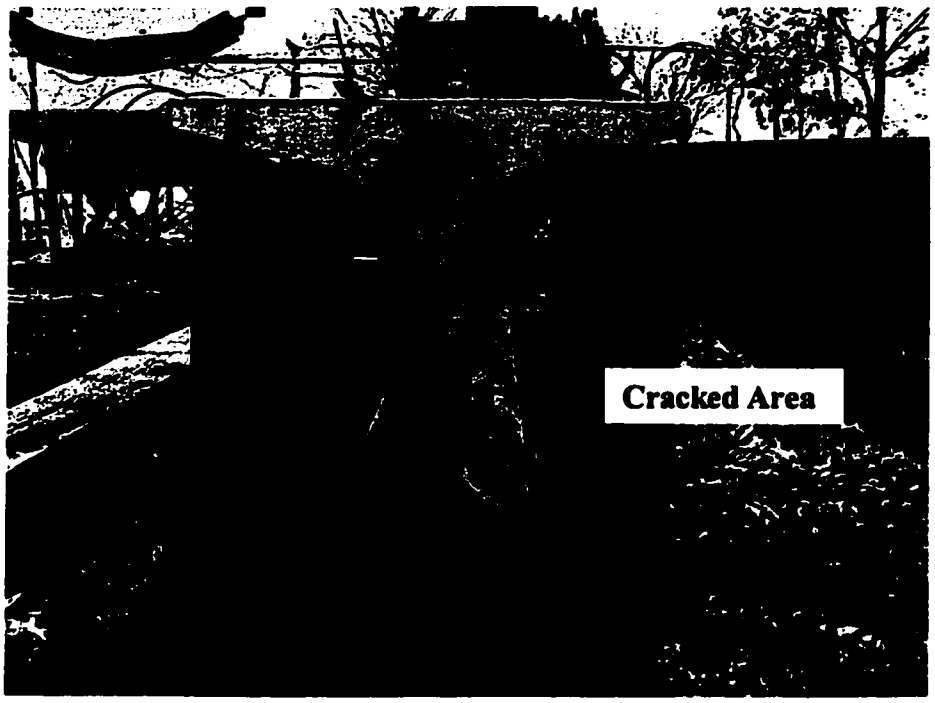


Figure 6.19. Photograph of Girder 2.

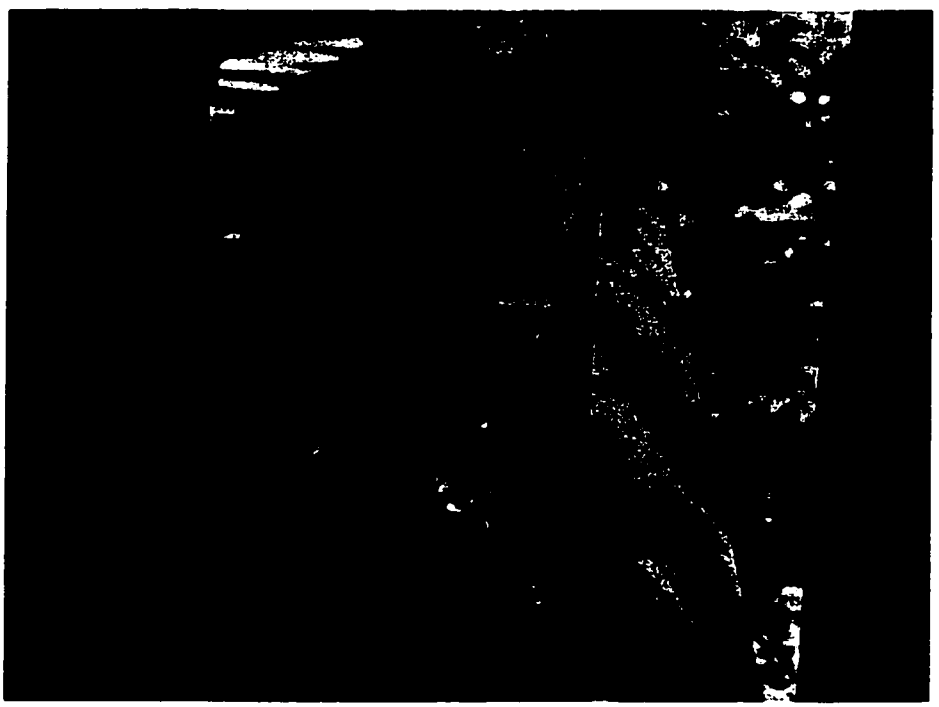

Figure 6.20. Photograph of Fractured Area of Girder 2.

Although the high release stresses did not appear to have any effect on the appearance of the girders, they did affect the amount of prestress losses. The total measured losses for the four girders and the allowable compressive stress at release are shown in Table 6.20. As shown in Figure 6.21, the girders with the greatest release stress had the highest amount of prestress loss. Girder 2 which had the highest stress of 0.87 had the most losses followed in descending order of release stress.

Even though the two girders with the greatest losses (Girders 2 and 3) contained entrained air, the increase in losses is most likely due to the high release stress. Earlier in the research program the shrinkage of the girders was examined. Shrinkage prisms cast from the concrete used in both girders had similar shrinkage losses (19.40 and 21.10 ksi at one year). Johnson (2000) examined the creep of the mixtures. His results showed that addition of entrained air should not have affected the creep behavior of the girders (Figure 6.15). The elastic shortening losses were higher for Girder 2, which was expected because of the high release stress of 0.87, but the losses for the remaining girders fell within a range of 24 to 28 ksi. The results from this research and Johnson's (2001) research show that entrained air does not have any affect on the prestress losses other than those losses affected by the reduction in compressive strength caused by entrained air. Therefore, the increase in losses shown in Figure 6.21 is most likely due to the increase in the allowable compressive stress at release.

Further examination of Figure 6.21 shows that there is a point where the increase in release stress has a greater effect on the prestress losses. It appears that Girders 1, 3, and 4 show increases in prestress losses that are consistent with their increase in release stress. However, the losses for Girder 2 do not follow the same trend. Shown in Table

6.21 is the change in prestress losses due to the percent change in release stress. Each girder is used as a reference to show the change in losses due to the change in release stress. Excluding Girder 2, a one percent increase in release stress resulted in a 0.45 or 0.46 ksi increase in prestress losses. Girder 2 which had a release stress of 0.87 did not follow this trend. Depending on which girder is being referenced, the change in the prestress losses per increase in release stress ranged from 0.64 to 0.82 ksi for Girder 2 which is approximately 50 to 90 percent greater than the rate of Girders 1, 3, and 4. These results show that above a release stress of 0.71 there is a point where the increase in release stress versus the increase in prestress losses is no longer linear. Even though there was no significant damage to Girder 2 caused by the high release stress of 0.87, the increase in total losses of at least 20 percent when compared to the remaining girders would deter most engineers and researchers from raising allowable stress limit as high as 0.87.

Table 6.20. Compressive Stress at Release and Measured Losses.

| Girders | Location | Total Prestress Losses (KSI) | | | |
|---|---|---|---|---|---|
| | | $f_{bot}/f_{ci}$ | Measured (1 year) | AASHTO Predicted | PCI Predicted |
| 1 | Ends | 66.0 | 56.78 | 87.56 | 70.48 |
| | Center | | 53.30 | 86.17 | 69.25 |
| 2 | Ends | 86.9 | 71.95 | 86.26 | 72.66 |
| | Center | | 74.03 | 84.76 | 71.24 |
| 3 | Ends | 71.4 | 59.22 | 70.96 | 61.00 |
| | Center | | 58.46 | 69.66 | 59.75 |
| 4 | Ends | 55.4 | 51.86 | 77.48 | 63.32 |
| | Center | | 51.80 | 75.97 | 61.98 |

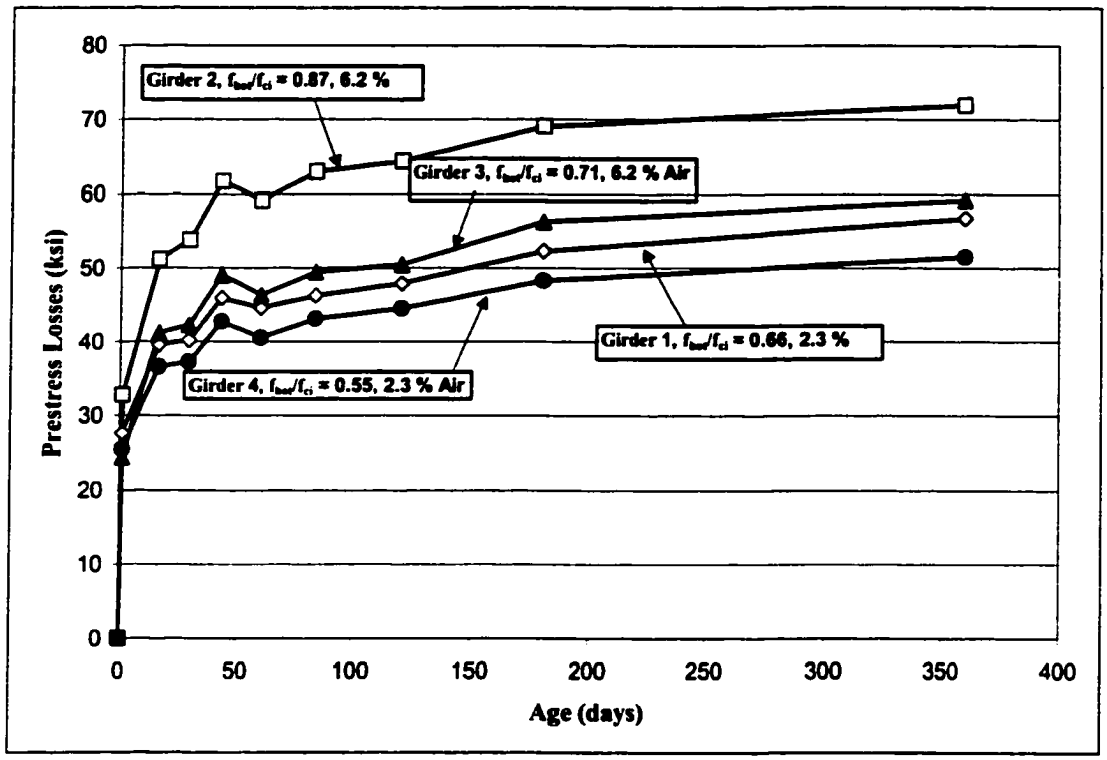


Figure 6.21. Measured Total Losses.

Table 6.21. Change in Prestress Losses (ksi) per Increase in Release Stress.

| Girders | $f_{bot}/f_{ci}$ | Measured Losses (1 year) | Change in Prestress Losses per Percent Change in Release Stress | | | |
|---|---|---|---|---|---|---|
| | | | Reference to Girder 4 | Reference to Girder 3 | Reference to Girder 2 | Reference to Girder 1 |
| 1 | 66.0 | 56.78 | 0.46 | 0.45 | 0.73 | 0.00 |
| 2 | 86.9 | 71.95 | 0.64 | 0.82 | 0.00 | 0.72 |
| 3 | 71.4 | 59.22 | 0.46 | 0.00 | 0.82 | 0.45 |
| 4 | 55.4 | 51.86 | 0.00 | 0.46 | 0.64 | 0.46 |

# 6.0 CONCLUSIONS

One of main objects of the research program was to demonstrate that the use HPC is possible in the local prestressed concrete industry. Girders were cast with mixtures that had a w/cm of 0.26. The mixtures attained an early strength of 8700 psi (for Girders 1 and 4) and reached over 15,000 psi at one year (for Girders 1 and 4). It must be noted that these mixtures did not contain any special chemical or mineral admixtures. The girders were cast with materials that Coreslab uses in their normal day-to-day operations. The casting of the girders also reemphasized the detrimental effects that air entrainment has on the compressive strength of concrete. At one day of age, the difference between the two mixtures was over 2500 psi, and at later ages (14, 28, and 56 days of age) this difference was approximately 3000 psi.

Another task of the research program was to examine the prestress losses of girders with and without air entrainment. Other than the increase in losses due to the decrease in compressive strength, entrained air did not have any noticeable effect on the prestress losses. Increasing the allowable compressive at release was also investigated. Current codes limit the release stress to $0.60f_{ci}$. Another goal of the research was to provide additional data to determine of this limit could be raised. Based on the results, the allowable compressive stress limit can be raised, but the prestress losses would increase. The results from the research support increasing the limit to $0.71f_{ci}$, but somewhere between $0.71f_{ci}$ and $0.87f_{ci}$ the increase in prestress losses becomes too great to merit an increase beyond $0.71f_{ci}$. Additional findings of this section of the research program are summarized below.

1. With good quality control measures, most precast/prestressed concrete facilities have the capabilities to produce to HPC. HPC was produced using locally available materials and produced using a concrete mixer that was manufactured in 1926.
2. Other than the reduction in compressive strength, the addition of entrained air did not affect the prestress losses when compared to similar non-air entrained girders.
3. The AASHTO prediction equations over estimated the total losses for all girders. The AASHTO equations predicted losses that were approximately 50 percent greater than the measured losses for Girders 1 and 4. For all girders, the PCI equations estimated losses that were more accurate than the AASHTO equations. Pessiki et al (1996), Roller et al (1995), Roller et al (2000), and Idriss (2001) reported that the AASHTO prediction equations overestimate the prestress losses.
4. For all girders, the AASHTO equations underestimated the losses due to elastic shortening. The overestimation was most likely due to changes in concrete temperature between readings and the high release stress and lower modulus of elasticity for girders with release stresses greater than $0.70f_{ci}$.
5. For all girders, the AASHTO equations underestimated the losses due to shrinkage. However, these measured losses may not truly represent the shrinkage losses of the girders. The losses were measured from 2 x 2 x 11 in. concrete prisms. Unlike the girders, the shrinkage prisms did not contain any reinforcement, which would restrain the concrete and reduce shrinkage. The

addition of reinforcement would assist in preventing the girders from shrinking as much as the non-reinforced shrinkage prisms. Another possible explanation for the differences between the predicted and measured shrinkage is the quantity of cement used in the production of the girders. The AASHTO equation does not account for the quantity of cement used in the girders.

6. When compared to the PCI equations, the AASHTO equations predicted creep losses that were much greater (22 to 29 percent). The AASHTO equations do not account for the modulus of elasticity. This is the main reason as to why the AASHTO equations estimated losses that were greater than those predicted by the PCI equations.
7. Increasing the allowable compressive stress at release resulted in greater prestress losses. For all girders, the prestress losses increased with raising the release stress. The results support increasing the release limit to $0.71f_{ci}$, but benefits of a higher release stress might be negated by greater prestress losses.

# CHAPTER 7

# CONCLUSIONS AND RECOMMENDATIONS

## 7.1 INTRODUCTION

As stated in Chapter 1, the research program investigated the need for air entrainment in high performance concrete (HPC) and its effect on HPC bridge girders. In addition to investigating the freeze-thaw durability of HPC, the research program also examined the permeability of HPC by using the Rapid Chloride Ion Penetrability test (RCIP). This portion of the research examined the permeability of mixtures with and without air entrainment and also mixtures with and without pozzolans. Another objective of the research examined the prestress losses in concrete with and without air entrainment. This portion of the study also included investigating the allowable release stress of prestressed concrete girders. The significant findings of each portion of the research program are summarized in the following sections.

## 7.2 DEVELOPING HIGH PERFORMANCE CONCRETE

The results of this section of the research program showed that HPC can be produced with materials that are native to Oklahoma. All materials used in the research program are currently being used by batch plants and prestressing facilities

in the area. Concrete mixtures were cast that achieved a one-day compressive strength of more than 9000 psi and a 28-day compressive strength of more than 14,000 psi. A minimum w/cm of 0.26 and a maximum HRWR dosage of 15 fl oz/cwt were established as the lower and upper limits needed to produce concrete mixtures with sufficient workability. The amount of slump loss negated the use of an accelerator. The findings of this section of the research program are summarized below.

1. There were some differences observed between cement manufacturers. Cements intended for use in HPC should be used in trial batching before use in the concrete structure.
2. For most mixtures increases in cement content resulted in greater slumps for mixtures with like w/cm. The results showed that a minimum cement content of 900 lb/yd$^3$ was necessary for a concrete mixture with a w/cm equal to and less than 0.26 to have sufficient workability. For the mixtures tested, cement contents of 800 lb/yd$^3$ and greater produce workable concrete at w/cm of 0.28 and greater. Results from these mixtures showed that a cement content of 900 pounds per cubic yard of concrete showed the most promise because of its workability (slumps greater than 7 in.) and compressive strength (one day strengths greater than 7000 psi).
3. The addition of HRWR increased workability (Figure 2.4 of Chapter 2). Too much HRWR delayed set times and decreased early age strength (Figure 2.9 of Chapter 2). At w/cm between 0.26 and 0.30, a dosage rate

of 15 fl oz/cwt was necessary to produce concrete with sufficient workability. Lower dosages of HRWR were possible with the use of a WR but only at higher w/cm. Based on workability and compressive strength, mixtures with a w/cm of 0.26 and HRWR of 15 fl oz/cwt displayed the most promise of producing concrete with the highest compressive with sufficient workability.

4. The addition of a calcium nitrite accelerator increased the one-day compressive strength. For most mixtures, the increase in compressive strength was between 500 and 1500 psi. Even though all mixtures benefited from the addition of the accelerator (calcium nitrite accelerator), the substantial slump loss proved to be too great to benefit from the use of a calcium nitrite accelerator.
5. Based on compressive strength and workability, the results of research program indicated that for the aggregates and cements tested, the optimum cement content was 900 lb/yd$^3$ (results found in section 2.5.2.3). The optimum w/cm was 0.26. This mix proportion will be used to cast the precast/prestressed bridge girders that will be examined in later phases of the research program.

## 7.3 DEVELOPING HIGH PERFORMANCE CONCRETE WITH ENTRAINED AIR

This portion of the research focused on the development of HPC with air entrainment using locally available materials. With one of the mixtures developed, two prestressed concrete beams were cast. Once again, not only were the mixtures to have high compressive strength, they must also be cast with local materials and must have enough workability to be placed. Another task of the research was to document the effects of air entrainment of the compressive strength of the concrete. The findings of the research are summarized below.

1. Higher dosages of AEA are required at w/cm below 0.30 (Figure 3.2). At w/cm greater than 0.30, the dosage rates required were within the manufacturer's recommendation. Mixtures with w/cm of 0.26 and 0.28 required additional mixing time to achieve the desired air contents. Trial batching is recommended at lower w/cm to determine the correct dosages of admixtures.
2. For most w/cm, the compressive strength decreased as the total air content increased. By 56 days of age, most mixtures followed the "2 – 5 percent decrease in compressive strength for every 1 percent increase in entrained air" rule of thumb (Table 3.16).
3. Air entrained HPC mixtures with adequate workability and high compressive strength can be developed using locally available materials.

4. Based on compressive strength and workability, the results of research program indicated that for the aggregates and cements tested, the optimum cement content was 900 lb/yd$^3$. The optimum w/cm was 0.26 (results can be found in section 3.5.2 of Chapter 3). This mix proportion will be used to cast the precast/prestressed bridge girders that will be examined in later phases of the research program.

## 7.4 EXAMINING THE FREEZE-THAW DURABILITY OF HIGH PERFORMANCE CONCRETE

The experimental program was designed to examine two objectives. The first objective was to determine if air entrainment is necessary for freeze-thaw durability in HPC. The second objective is to determine the maximum w/cm where air entrainment is not needed. Results from the research show that air entrainment may not be necessary to achieve adequate freeze-thaw durability for concrete mixtures with w/cm less than 0.36. From the results in Table 4.9 from Chapter 4, it also appears that a total air content of 4 percent is enough to provide freeze-thaw durability for mixtures with a w/cm between 0.36 and 0.50. However, all mixtures examined in the research contained the same type of coarse aggregate, which was known to have adequate durability. The results from this research apply only to the materials used in the research. Mixtures containing aggregates with poor freeze-thaw durability may not perform as well as the mixtures tested in this research program. Before one can specify non-air entrained concrete in a harsh environment, specimens

containing the materials to be used in the concrete should to be tested to determine its freeze-thaw durability. If freeze-thaw testing is not available, air entrainment should be employed in the concrete.

## 7.5 EXAMINING THE PERMEABILITY OF HIGH PERFORMANCE CONCRETE WITH AND WITHOUT ENTRAINED AIR

This section of the research program investigated the permeability of high performance concrete (HPC) with and without entrained air. Another purpose was to additional data on the effectiveness of the RCIP Test (ASTM C 1202) as a means to measure concrete penetrability. The findings of the research are summarized below.

1. The addition of entrained air had no noticeable effect the permeability of the mixtures. The findings are consistent with those of other researchers (Mindess et al, 1981; Neville, 1997; Kosmatka et al, 1994).
2. To achieve low permeability concrete (based on ASTM C 1202 classifications), mixtures should be cast at a w/cm equal to or less than 0.34. The results are similar with Pinto et al (2001) who found the a w/cm of 0.35 was necessary to produce with low permeability based on ASTM C 1202.
3. For mixtures not containing any mineral admixtures, the RCIP test appears to be effective in measuring concrete's chloride ion penetrability. As shown in Figure 5.4 and 5.5, the concrete's penetrability increases as the

w/cm increase, which is expected. All mixtures containing only portland cement follow this trend.

4. Once mineral admixtures are introduced, this trend is no longer valid. When compared to similar control mixtures, silica fume reduced the chloride ion penetrability by more than 75 percent.
5. Since the RCIP test does not directly measure permeability, other factors can influence the parameter the test actually does measure, which is concrete resistivity. Therefore, other factors (such as pore fluid chemistry) may influence the parameter actually measured, leading to a basic need for users to understand what the test actually measures so that results can be put into proper perspective. When testing concrete containing mineral admixtures, one should compare the results to an identical mixture without mineral admixtures. This comparison with mixtures containing only portland cement may provide a better idea as to the true permeability of the concrete.

## 7.6 EXAMINING THE PRESTRESS LOSSES AND ALLOWABLE COMPRESSIVE STRESS AT RELEASE OF BRIDGE GIRDERS WITH AND WITHOUT AIR ENTRAINMENT

One objective of the research program was to demonstrate that the use HPC is possible in the local prestressed concrete industry. Girders were cast with mixtures that had a w/cm of 0.26. The mixtures attained a one day strength of 8700 psi (for Girders 1 and 4) and reached over 15,000 psi at one year (for Girders 1 and 4). It must be noted that these mixtures did not contain any special chemical or mineral admixtures. The girders were cast with materials that Coreslab uses in their normal day-to-day operations. The casting of the girders also re-emphasized the effects that air entrainment has on reducing the compressive strength of concrete. At one day of age, the difference between the two mixtures was over 2500 psi, and at later ages (14, 28, and 56 days of age) this difference was approximately 3000 psi.

Another task of the research program was to examine the prestress losses of girders with and without air entrainment. Other than the increase in losses due to the decrease in compressive strength, entrained air did not have any noticeable effect on the prestress losses. Increasing the allowable compressive at release was also investigated. Current codes limit the release stress to $0.60f_{ci}$. Another goal of the research was to provide additional data to determine of this limit could be raised. Based on the results, the allowable compressive stress limit can be raised, but the prestress losses would increase. The results from the research support increasing the limit to $0.71f_{ci}$, but somewhere between $0.71f_{ci}$ and $0.87f_{ci}$ the increase in prestress

losses becomes too great to merit an increase beyond $0.71f_{ci}$. Additional findings of this section of the research program are summarized below.

1. With good quality control measures, most precast/prestressed concrete facilities have the capabilities to produce to HPC. HPC was produced using locally available materials and produced using a concrete mixer that was manufactured in 1926.
2. The addition of entrained air decreased the modulus of elasticity at all ages when compared to the non-air entrained mixture (Table 6.5). Prediction equations can be used to estimate the modulus of elasticity based on the compressive strength of the concrete.
3. Other than the reduction in compressive strength and modulus of elasticity, the addition of entrained air did not affect the prestress losses when compared to similar non-air entrained girders.
4. The AASHTO prediction equations over estimated the total losses for all girders. The AASHTO equations predicted losses that were approximately 50 percent greater than the measured losses for Girders 1 and 4. For all girders, the PCI equations estimated losses that were more accurate than the AASHTO equations.
5. For all girders, the AASHTO equations underestimated the losses due to elastic shortening (Table 6.14).. The overestimation was most likely due to changes in concrete temperature between readings and the high release stress.

6. For all girders, the AASHTO equations underestimated the losses due to shrinkage (Table 6.16). However, these measured losses may not truly represent the shrinkage losses of the girders. The losses were measured from 2 x 2 x 11 in. concrete prisms. Unlike the girders, the shrinkage prisms did not contain any reinforcement, which would restrain the concrete and reduce shrinkage. The addition of reinforcement would assist in preventing the girders from shrinking as much as the non-reinforced shrinkage prisms. Another possible explanation for the differences between the predicted and measured shrinkage is the quantity of cement used in the production of the girders. The AASHTO equation does not account for the quantity of cement used in the girders.
7. When compared to the PCI equations, the AASHTO equations predicted creep losses that were much greater (22 to 29 percent). The AASHTO equations do not account for the modulus of elasticity. This is the main reason as to why the AASHTO equations estimated losses that were greater than those predicted by the PCI equations.
8. Increasing the allowable compressive stress at release resulted in greater prestress losses. For all girders, the prestress losses increased with raising the release stress. The results support increasing the release limit to $0.71f_{ci}$, but benefits of a higher release stress might be negated by greater prestress losses.

## 7.7 RECOMMENDATIONS

Further research needs to examine the freeze-thaw durability of concrete containing aggregates that are known to have poor freeze-thaw durability. For the aggregates used in this research program, the results have shown that air entrainment is not required at w/cm equal to and less than 0.36. Is this statement still valid for concretes containing poor aggregates? Further research should also be done to determine if a total air content of four percent provides adequate freeze-thaw durability at w/cm greater than 0.50. The air void system of the hardened concrete should also be examined to determine the spacing factors and the air contents of the hardened concrete.

Additional research in the area of prestress losses and allowable compressive stresses at release is needed. The results from this research show that AASHTO prediction equations overestimate the prestress losses of girders with release stresses at or near $0.6f_{ci}$. Further research is needed to investigate the prestress losses of members with release stresses greater than $0.6f_{ci}$. Finally, HPC bridge girders should be cast and instrumented to monitor the prestress losses over the life of the structure.

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# APPENDIX A

Appendix A includes the individual test results and statistical data for the results from Chapter 2. Appendix A also includes plots of the 90 percent confidence intervals.

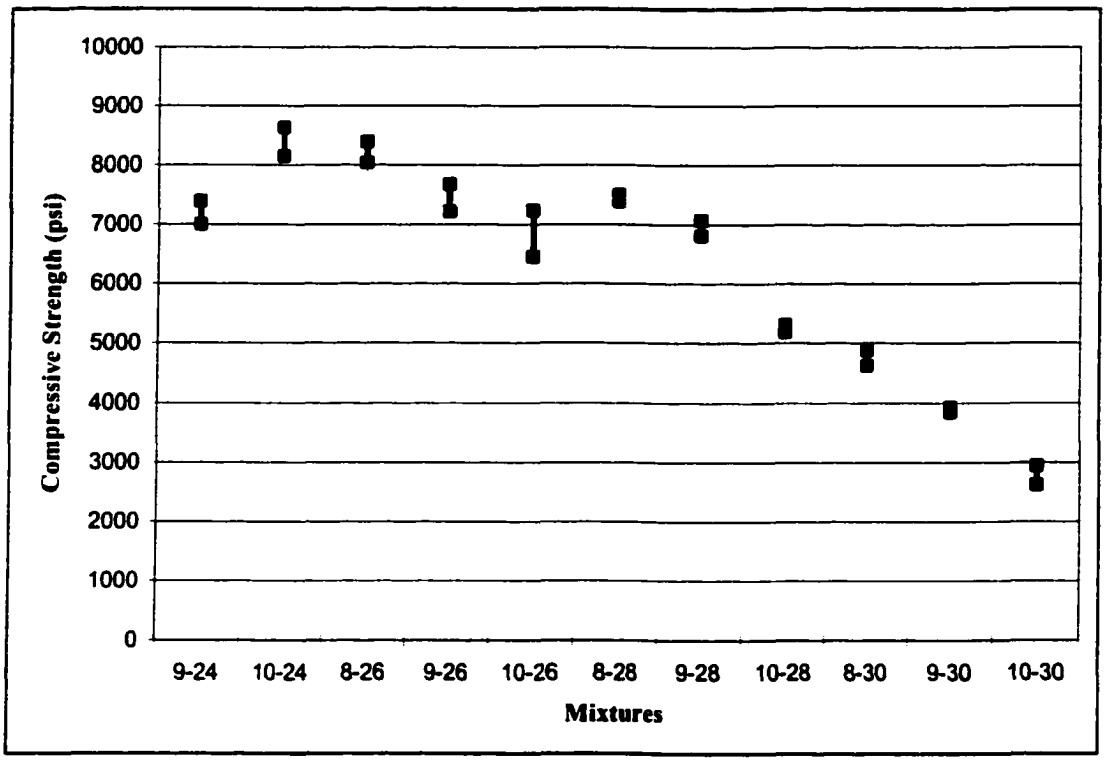


Figure A.1 One-Day Compressive Strengths for Optimizing Cement Content &w/cm.

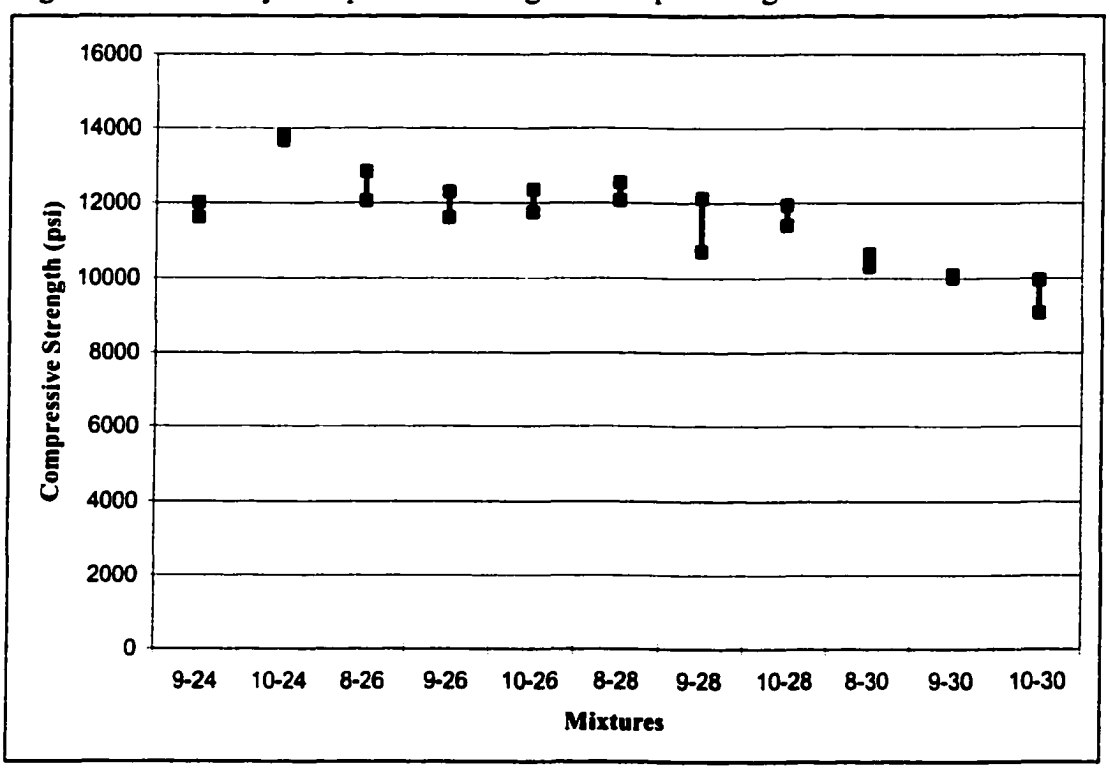


Figure A.2 28 Day Compressive Strengths for Optimizing Cement Content & w/cm.

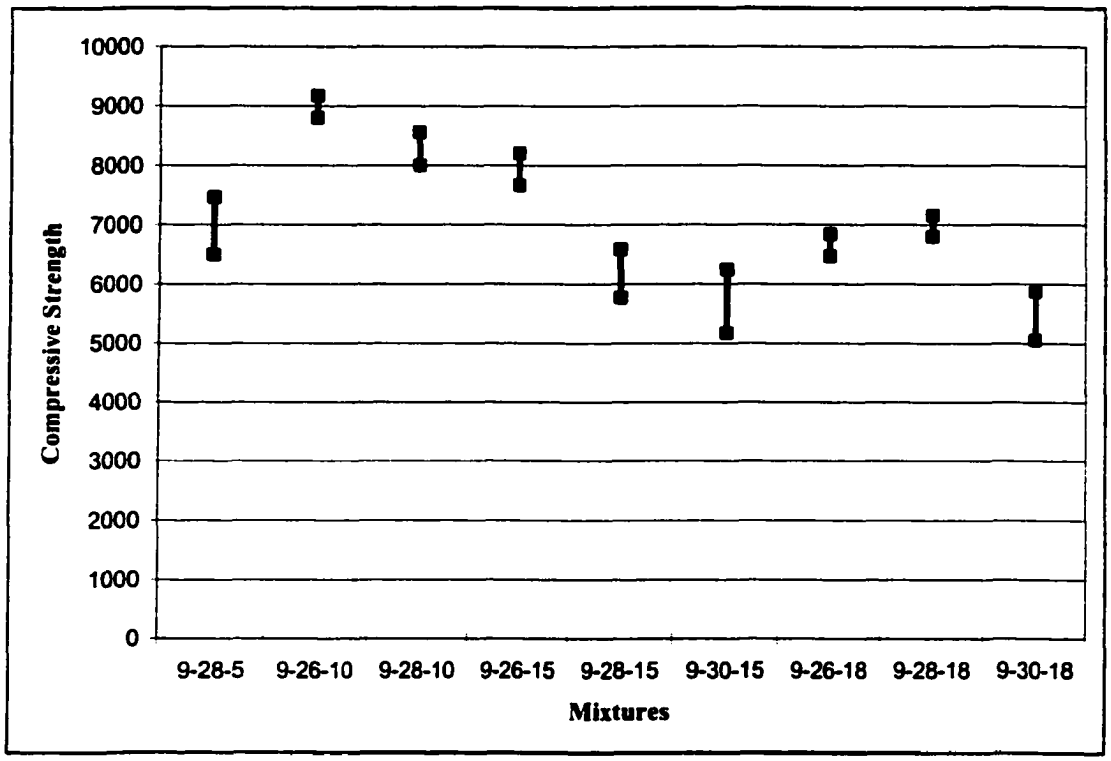


Figure A.3 One-Day Compressive Strength for Optimizing HRWR Dosage.

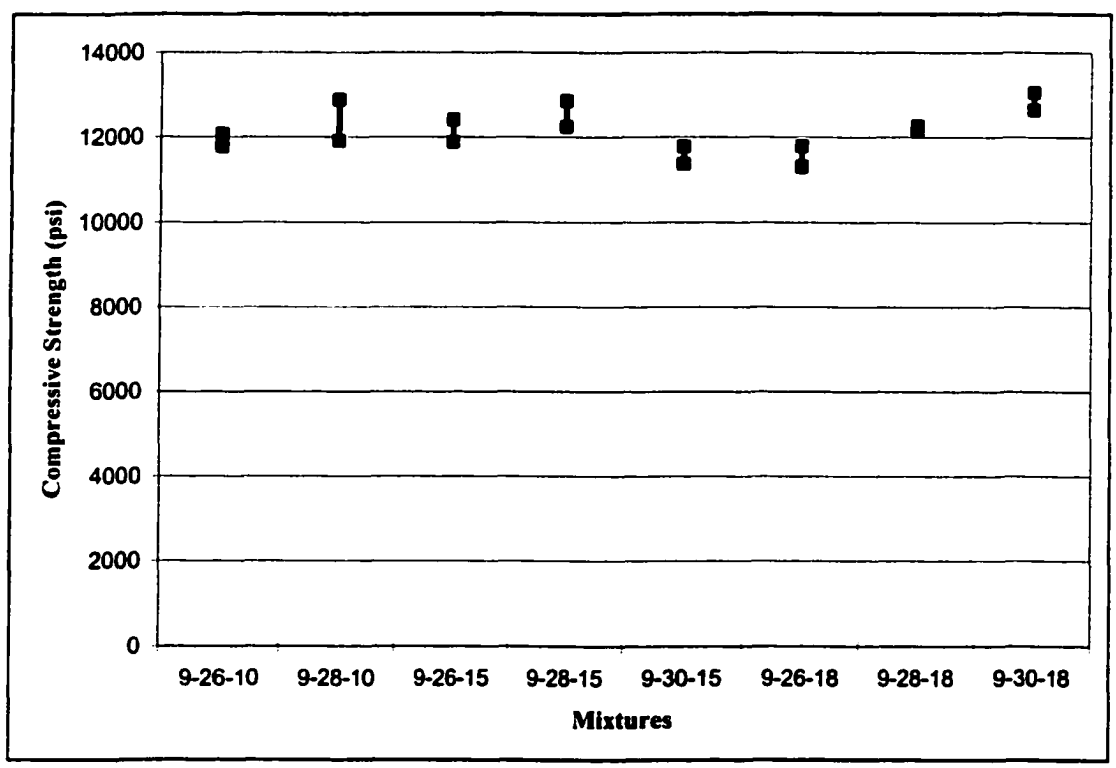


Figure A.4 28-Day Compressive Strength for Optimizing HRWR Dosage.

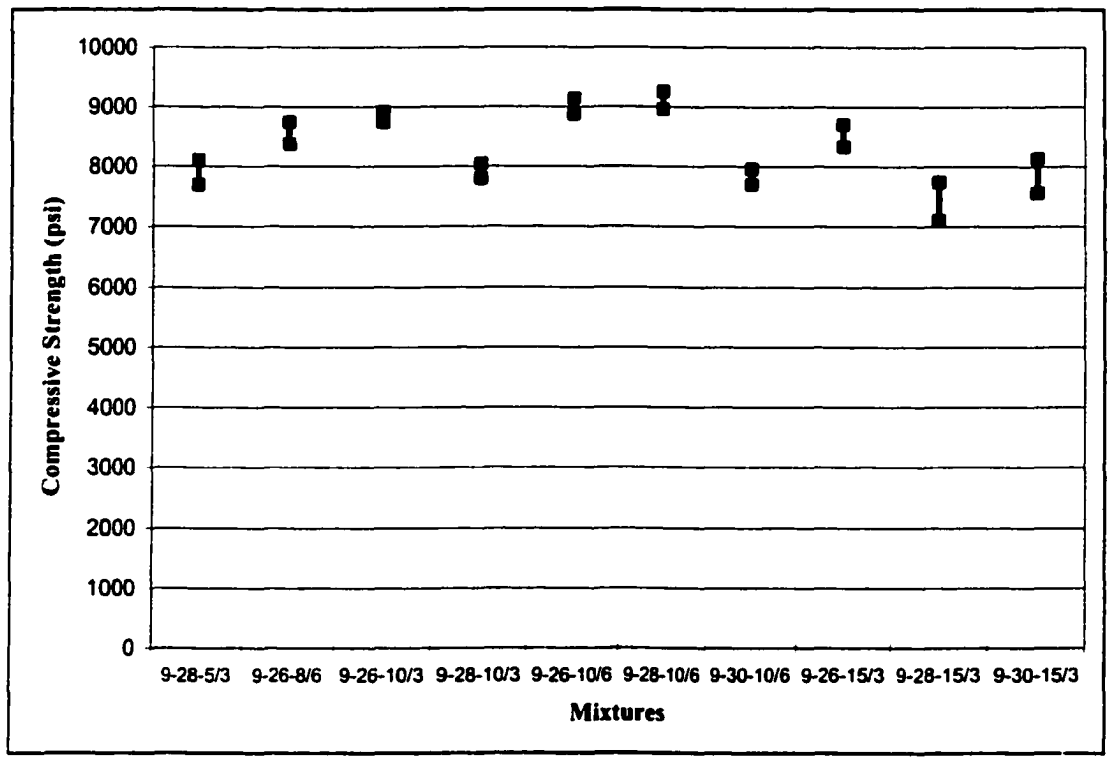


Figure A.5 One-Day Compressive Strength for Optimizing HRWR and WR Dosage.

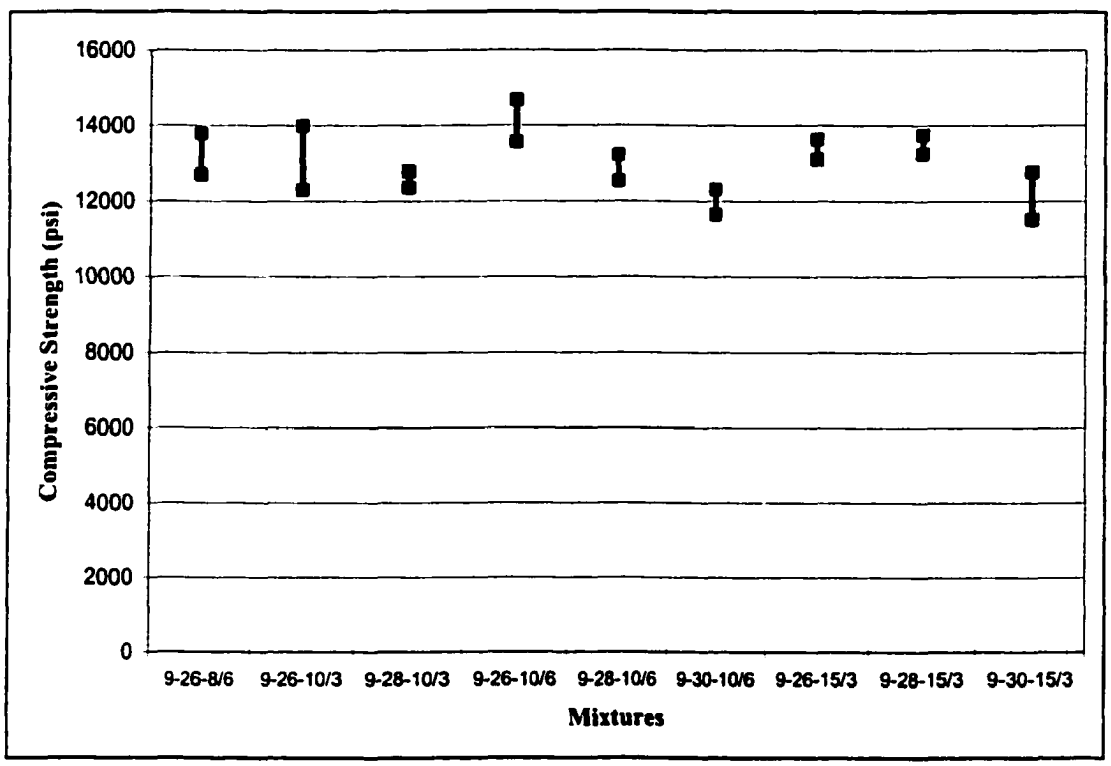


Figure A.6 28-Day Compressive Strength for Optimizing HRWR and WR Dosage.

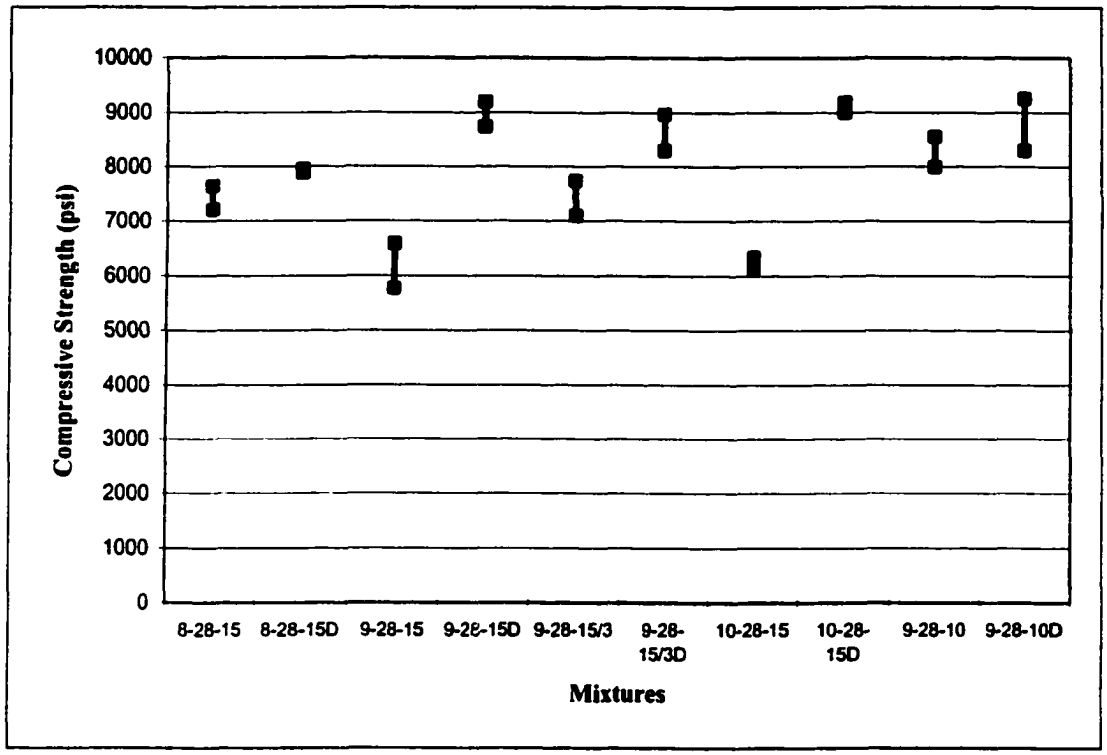


Figure A.7 One-Day Compressive Strength Results for Examining Accelerator Dosage.

Table A.1 Individual Results & Statistical Data for 1 day Compressive Strength Tests.

| Mixture Designation | One Day Compressive Strength (psi) | | | Average (psi) | Std. Dev. (psi) | 90 Percent Confidence Intervals | | Coefficient of Variation |
|---|---|---|---|---|---|---|---|---|
| | Cylinder 1 | Cylinder 2 | Cylinder 3 | | | Lower Limit | Upper Limit | |
| 9-24 | 7432 | 6928 | 7220 | 7193 | 207 | 6997 | 7390 | 2.87 |
| 10-24 | 8654 | 8467 | 8041 | 8387 | 257 | 8144 | 8631 | 3.06 |
| 8-26 | 8015 | 8159 | 8465 | 8213 | 188 | 8035 | 8391 | 2.28 |
| 9-26 | 7524 | 7119 | 7698 | 7447 | 243 | 7217 | 7677 | 3.26 |
| 10-26 | 6258 | 7146 | 7123 | 6842 | 413 | 6450 | 7235 | 6.04 |
| 8-28 | 7384 | 7501 | | 7443 | 59 | 7374 | 7511 | 0.79 |
| 9-28 | 6755 | 7077 | 6983 | 6938 | 135 | 6810 | 7067 | 1.95 |
| 10-28 | 5308 | 5184 | | 5246 | 62 | 5174 | 5318 | 1.18 |
| 8-30 | 4678 | 4632 | 4934 | 4748 | 133 | 4622 | 4874 | 2.80 |
| 9-30 | 3946 | 3847 | 3865 | 3886 | 43 | 3845 | 3927 | 1.11 |
| 10-30 | 2645 | 2687 | 3015 | 2782 | 165 | 2625 | 2939 | 5.95 |
| 9-26-18 | 6800 | 6800 | 6387 | 6662 | 195 | 6477 | 6847 | 2.92 |
| 9-28-18 | 6739 | 7168 | 7040 | 6982 | 180 | 6812 | 7153 | 2.58 |
| 9-30-18 | 4859 | 5849 | 5678 | 5462 | 432 | 5052 | 5872 | 7.91 |
| 9-26-15 | 7842 | 7639 | 8313 | 7931 | 282 | 7663 | 8199 | 3.56 |
| 9-28-15 | 5715 | 6081 | 6755 | 6184 | 431 | 5775 | 6593 | 6.97 |
| 9-30-15 | 5818 | 4968 | 6347 | 5711 | 568 | 5172 | 6250 | 9.95 |
| 9-26-10 | 9257 | 8789 | 8919 | 8988 | 197 | 8801 | 9176 | 2.19 |
| 9-28-10 | 8157 | 8680 | 7998 | 8278 | 291 | 8002 | 8555 | 3.52 |
| 9-28-5 | 7682 | 6773 | 6501 | 6985 | 505 | 6506 | 7465 | 7.23 |
| 8-28-15 | 7506 | 7654 | 7115 | 7425 | 227 | 7209 | 7641 | 3.06 |
| 10-28-15 | 6207 | 6391 | 6127 | 6242 | 111 | 6137 | 6347 | 1.77 |
| 9-26-8/6 | 8584 | 8306 | 8776 | 8555 | 193 | 8372 | 8739 | 2.26 |
| 9-26-10/6 | 8821 | 9145 | 9036 | 9001 | 135 | 8873 | 9129 | 1.50 |
| 9-26-10/3 | 8949 | 8750 | 8776 | 8825 | 88 | 8741 | 8909 | 1.00 |
| 9-26-10/3 | 8821 | 9145 | 9036 | 9001 | 135 | 8873 | 9129 | 1.50 |
| 9-26-15/3 | 8241 | 8624 | 8684 | 8516 | 196 | 8330 | 8703 | 2.30 |
| 9-28-5/3 | 7914 | 8152 | 7628 | 7898 | 214 | 7695 | 8101 | 2.71 |
| 9-28-10/6 | 9055 | 9314 | 8941 | 9103 | 156 | 8955 | 9252 | 1.71 |
| 9-28-10/3 | 7764 | 7921 | 8075 | 7920 | 127 | 7799 | 8041 | 1.60 |
| 9-28-10/3 | 8812 | 8758 | 7801 | 8457 | 464 | 8016 | 8898 | 5.49 |
| 9-28-15/3 | 7653 | 6951 | 7666 | 7423 | 334 | 7106 | 7741 | 4.50 |
| 9-30-10/6 | 7820 | 7673 | 7996 | 7830 | 132 | 7704 | 7955 | 1.69 |
| 9-30-15/3 | 7771 | 8243 | 7522 | 7845 | 299 | 7561 | 8129 | 3.81 |
| 8-28-15D | 7950 | 7896 | | 7923 | 27 | 7892 | 7954 | 0.34 |
| 9-28-15D | 8659 | 9246 | 8984 | 8963 | 240 | 8735 | 9191 | 2.68 |
| 10-28-15D | 9016 | 9043 | 9228 | 9096 | 94 | 9006 | 9185 | 1.04 |
| 9-28-10D | 8273 | 8598 | 9460 | 8777 | 501 | 8301 | 9253 | 5.71 |
| 9-30-10D | 8080 | 8750 | 8364 | 8398 | 275 | 8137 | 8659 | 3.27 |
| 9-28-15/3D | 8325 | 8448 | 9118 | 8630 | 348 | 8299 | 8961 | 4.04 |

Table A.2 Individual Results & Statistical Data for 28 D Compressive Strength Tests.

| Mixture Designation | 28 Day Compressive Strength (psi) | | | Average (psi) | Std. Dev. (psi) | 90 Percent Confidence Intervals | | Coefficient of Variation |
|---|---|---|---|---|---|---|---|---|
| | Cylinder 1 | Cylinder 2 | Cylinder 3 | | | Lower Limit | Upper Limit | |
| 9-24 | 12045 | 11847 | 11538 | 11810 | 209 | 11612 | 12008 | 1.77 |
| 10-24 | 13846 | 13741 | 13651 | 13746 | 80 | 13670 | 13822 | 0.58 |
| 8-26 | 12487 | 11925 | 12938 | 12450 | 414 | 12056 | 12844 | 3.33 |
| 9-26 | 12058 | 12320 | 11459 | 11946 | 360 | 11603 | 12288 | 3.02 |
| 10-26 | 12021 | 12456 | 11683 | 12053 | 316 | 11753 | 12354 | 2.63 |
| 8-28 | 12002 | 12617 | 12291 | 12303 | 251 | 12065 | 12542 | 2.04 |
| 9-28 | 11519 | 12267 | 10453 | 11413 | 744 | 10706 | 12120 | 6.52 |
| 10-28 | 11846 | 11262 | 11895 | 11668 | 288 | 11395 | 11941 | 2.46 |
| 8-30 | 10536 | 10664 | 10243 | 10481 | 176 | 10314 | 10648 | 1.68 |
| 9-30 | 10025 | 10026 | 10108 | 10053 | 39 | 10016 | 10090 | 0.39 |
| 10-30 | 9469 | 10102 | 8963 | 9511 | 466 | 9069 | 9954 | 4.90 |
| 9-26-18 | 11654 | 11201 | 11778 | 11544 | 248 | 11309 | 11780 | 2.15 |
| 9-28-18 | 12280 | 12215 | 12120 | 12205 | 66 | 12143 | 12267 | 0.54 |
| 9-30-18 | 13004 | 12984 | 12540 | 12843 | 214 | 12639 | 13046 | 1.67 |
| 9-26-15 | 11938 | 12540 | 11954 | 12144 | 280 | 11878 | 12410 | 2.31 |
| 9-28-15 | 12550 | 12934 | 12149 | 12544 | 320 | 12240 | 12849 | 2.55 |
| 9-30-15 | 11874 | 11369 | 11484 | 11576 | 216 | 11370 | 11781 | 1.87 |
| 9-26-10 | 12143 | 11847 | 11788 | 11926 | 155 | 11778 | 12074 | 1.30 |
| 9-28-10 | 12984 | 12458 | 11740 | 12394 | 510 | 11910 | 12878 | 4.11 |
| 8-28-15 | 13161 | 12479 | 13403 | 13014 | 391 | 12643 | 13386 | 3.01 |
| 9-28-15 | 13309 | 13393 | 13903 | 13535 | 262 | 13286 | 13784 | 1.94 |
| 10-28-15 | 10209 | 9973 | | 10091 | 118 | 9954 | 10228 | 1.17 |
| 9-26-8/6 | 13156 | 12598 | 13987 | 13247 | 571 | 12705 | 13789 | 4.31 |
| 9-26-10/6 | 13457 | 14875 | 14012 | 14115 | 583 | 13561 | 14669 | 4.13 |
| 9-26-10/3 | 13984 | 13548 | 11918 | 13150 | 889 | 12306 | 13994 | 6.76 |
| 9-26-15/3 | 13647 | 12987 | 13478 | 13371 | 280 | 13105 | 13637 | 2.09 |
| 9-28-10/6 | 12983 | 12385 | 13239 | 12869 | 358 | 12529 | 13209 | 2.78 |
| 9-28-10/3 | 12631 | 12809 | 12273 | 12571 | 223 | 12359 | 12783 | 1.77 |
| 9-28-10/3 | 11021 | 11743 | 12182 | 11649 | 479 | 11194 | 12103 | 4.11 |
| 9-28-15/3 | 13365 | 13259 | 13871 | 13498 | 267 | 13245 | 13752 | 1.98 |
| 9-30-10/6 | 12064 | 12361 | 11519 | 11981 | 349 | 11650 | 12312 | 2.91 |
| 9-30-15/3 | 11253 | 12841 | 12356 | 12150 | 664 | 11519 | 12781 | 5.47 |
| 9-28-15D | 12786 | 13511 | 13428 | 13242 | 324 | 12934 | 13549 | 2.45 |
| 10-28-15D | 13616 | 13971 | 14029 | 13872 | 183 | 13699 | 14045 | 1.32 |
| 9-28-15/3D | 12819 | 12687 | 13129 | 12878 | 185 | 12702 | 13054 | 1.44 |

Table A.3. Gradation for Fine Aggregate.

| Sieve Size | Percent Passing by Weight |
|---|---|
| 3/8 in. | 100.0 |
| No. 4 | 99.1 |
| No. 8 | 94.0 |
| No. 16 | 81.5 |
| No. 30 | 55.3 |
| No. 50 | 22.9 |
| No. 100 | 4.8 |

Table A.4. Gradation for Coarse Aggregate.

| Sieve Size | Percent Passing by Weight |
|---|---|
| 1/2 in. | 100.0 |
| 3/8 in. | 94.2 |
| No. 4 | 16.4 |
| No. 8 | 3.6 |
| No. 16 | 1.1 |
| No. 100 | 0.6 |

# APPENDIX B

Appendix B contains the individual test results and statistical data of Chapter 3. Appendix B also includes plots of the 90 percent confidence intervals.

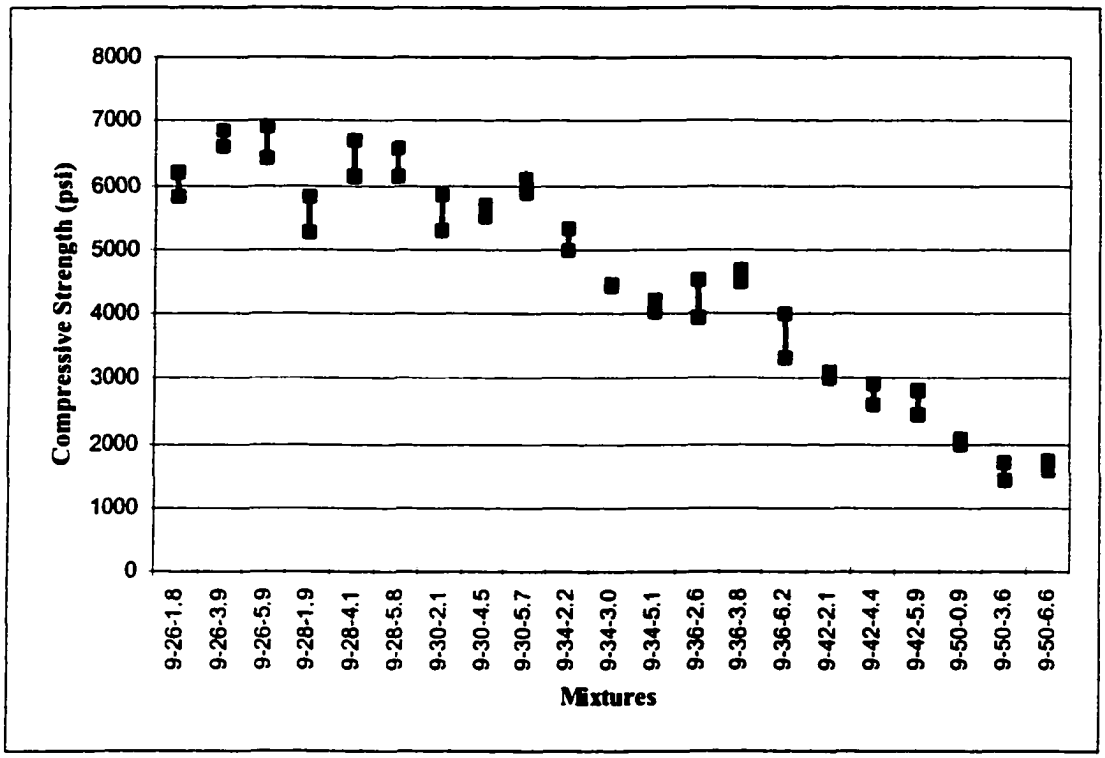


Figure B.1 90 % C.I. for One Day Compressive Strength Results.

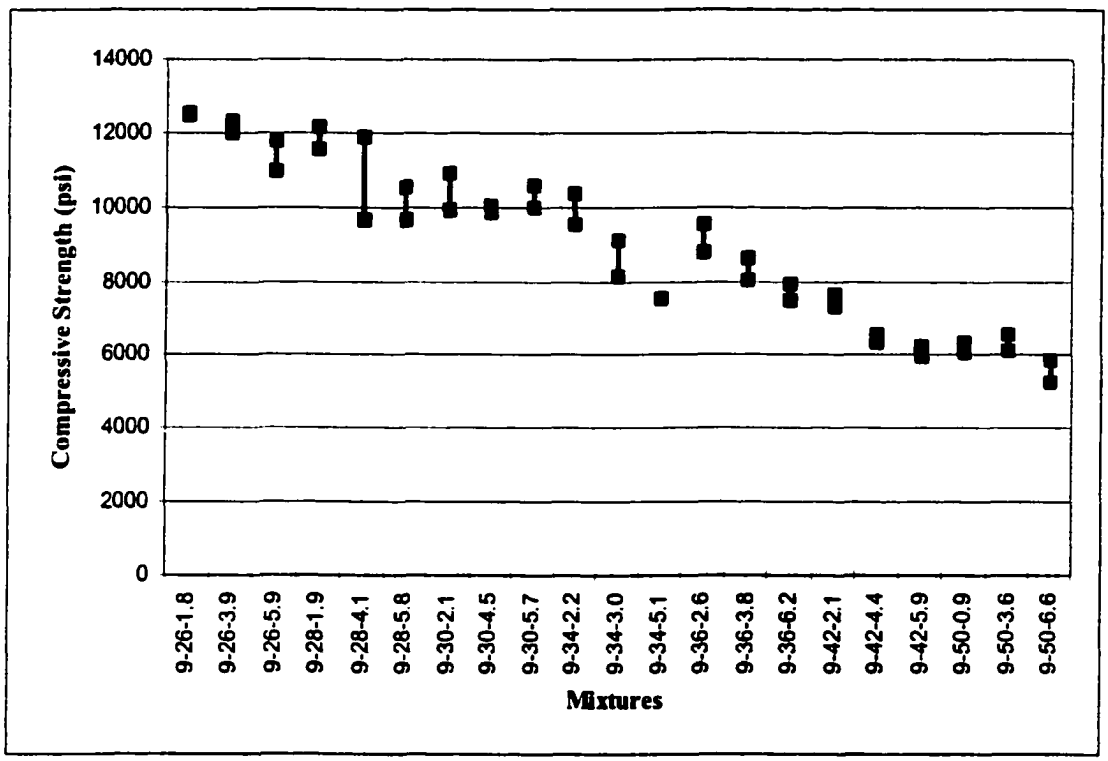


Figure B.2 90 % C.I. for 28-Day Compressive Strength Results.

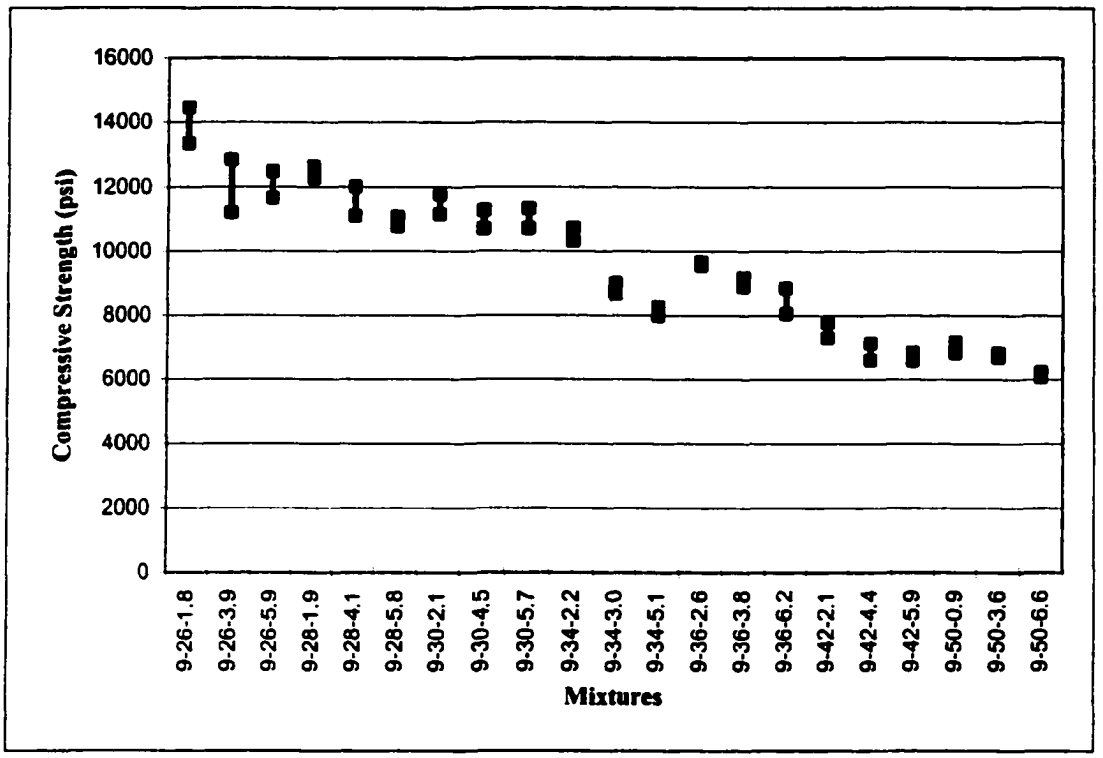


Figure B.3 90 % C.I. for 56-Day Compressive Strength Results.

Table B.1 Individual Results & Statistical Data for 1 day Compressive Strength Tests.

| Mixture Designation | One Day Compressive Strength (psi) | | | Average (psi) | Std. Dev. (psi) | 90 Percent Confidence Intervals | | Coefficient of Variation |
|---|---|---|---|---|---|---|---|---|
| | Cylinder 1 | Cylinder 2 | Cylinder 3 | | | Lower Limit | Upper Limit | |
| 9-26-1.8 | 5986 | 6263 | 5787 | 6012 | 195 | 5827 | 6197 | 3.25 |
| 9-26-2.1 | 6568 | 6082 | 6761 | 6470 | 286 | 6199 | 6742 | 4.42 |
| 9-26-2.4 | 6884 | 6778 | 6817 | 6826 | 44 | 6785 | 6868 | 0.64 |
| 9-26-3.8 | 4678 | 5096 | 4722 | 4832 | 188 | 4654 | 5010 | 3.88 |
| 9-26-3.9 | 6553 | 6824 | 6831 | 6736 | 129 | 6613 | 6859 | 1.92 |
| 9-26-5.6 | 4397 | 4659 | 4617 | 4558 | 115 | 4449 | 4667 | 2.52 |
| 9-26-5.9 | 6369 | 6664 | 6987 | 6673 | 252 | 6434 | 6913 | 3.78 |
| 9-28-1.9 | 5823 | 5653 | 5142 | 5539 | 289 | 5265 | 5814 | 5.22 |
| 9-28-4.1 | 6268 | 6813 | 6162 | 6414 | 285 | 6143 | 6685 | 4.45 |
| 9-28-5.8 | 6104 | 6322 | 6657 | 6361 | 227 | 6145 | 6577 | 3.58 |
| 9-30-1.1 | 5685 | 6303 | 6465 | 6151 | 336 | 5832 | 6470 | 5.46 |
| 9-30-2.1 | 5917 | 5596 | 5221 | 5578 | 284 | 5308 | 5848 | 5.10 |
| 9-30-4.5 | 5687 | 5460 | 5693 | 5613 | 108 | 5510 | 5716 | 1.93 |
| 9-30-4.9 | 4735 | 4555 | 4449 | 4580 | 118 | 4468 | 4692 | 2.58 |
| 9-30-5.7 | 6127 | 5996 | 5882 | 6002 | 100 | 5907 | 6097 | 1.67 |
| 9-30-6.8 | 5493 | 5771 | 5882 | 5715 | 164 | 5560 | 5871 | 2.86 |
| 9-34-2.2 | 5416 | 5074 | 4994 | 5161 | 183 | 4988 | 5335 | 3.55 |
| 9-34-3.0 | 4458 | 4450 | 4446 | 4451 | 5 | 4447 | 4456 | 0.11 |
| 9-34-5.1 | 4275 | 4038 | 4070 | 4128 | 105 | 4028 | 4227 | 2.54 |
| 9-36-2.6 | 3798 | 4506 | 4362 | 4222 | 306 | 3932 | 4512 | 7.24 |
| 9-36-3.8 | 4461 | 4571 | 4715 | 4582 | 104 | 4484 | 4681 | 2.27 |
| 9-36-6.2 | 3786 | 4019 | 3170 | 3658 | 358 | 3318 | 3998 | 9.79 |
| 9-42-2.1 | 3107 | 2990 | 3043 | 3047 | 48 | 3001 | 3092 | 1.57 |
| 9-42-1.8 | 2606 | 2576 | 2883 | 2688 | 138 | 2557 | 2820 | 5.14 |
| 9-42-3.5 | 2855 | 3006 | 3001 | 2954 | 70 | 2887 | 3021 | 2.37 |
| 9-42-4.4 | 2947 | 2753 | 2547 | 2749 | 163 | 2594 | 2904 | 5.94 |
| 9-42-5.9 | 2897 | 2620 | 2392 | 2636 | 206 | 2440 | 2832 | 7.83 |
| 9-50-0.9 | 2026 | 1970 | 2078 | 2025 | 44 | 1983 | 2067 | 2.18 |
| 9-50-3.6 | 1761 | 1462 | 1459 | 1561 | 142 | 1426 | 1695 | 9.08 |
| 9-50-6.6 | 1554 | 1638 | 1750 | 1647 | 80 | 1571 | 1724 | 4.87 |

Table B.2 Individual Results & Statistical Data for 7 day Compressive Strength Tests.

| Mixture Designation | Seven Day Compressive Strength (psi) | | | Average (psi) | Std. Dev. (psi) | 90 Percent Confidence Intervals | | Coefficient of Variation (%) |
|---|---|---|---|---|---|---|---|---|
| | Cylinder 1 | Cylinder 2 | Cylinder 3 | | | Lower Limit | Upper Limit | |
| 9-26-1.8 | 11938 | 11644 | 11297 | 11626 | 262 | 11378 | 11875 | 2.25 |
| 9-26-2.1 | 11038 | 10492 | 10835 | 10788 | 225 | 10574 | 11002 | 2.09 |
| 9-26-2.4 | 11432 | 11040 | 10646 | 11039 | 321 | 10735 | 11344 | 2.91 |
| 9-26-3.8 | 10282 | 10664 | 10381 | 10442 | 162 | 10289 | 10596 | 1.55 |
| 9-26-3.9 | 10716 | 10680 | 10373 | 10590 | 154 | 10444 | 10736 | 1.45 |
| 9-26-5.6 | 9169 | 9623 | 9013 | 9268 | 259 | 9023 | 9514 | 2.79 |
| 9-26-5.9 | 9732 | 9960 | 10072 | 9921 | 141 | 9787 | 10056 | 1.43 |
| 9-28-1.9 | 11082 | 10646 | 10227 | 10652 | 349 | 10320 | 10983 | 3.28 |
| 9-28-4.1 | 9542 | 9494 | 8382 | 9139 | 536 | 8630 | 9648 | 5.86 |
| 9-28-5.8 | 9685 | 9284 | 9587 | 9519 | 171 | 9357 | 9681 | 1.79 |
| 9-30-1.1 | 10146 | 9515 | 10484 | 10048 | 402 | 9667 | 10430 | 4.00 |
| 9-30-2.1 | 9222 | 8742 | 9200 | 9055 | 221 | 8845 | 9265 | 2.44 |
| 9-30-4.5 | 8347 | 8012 | 9580 | 8646 | 674 | 8006 | 9287 | 7.80 |
| 9-30-4.9 | 7137 | 7287 | 7458 | 7294 | 131 | 7169 | 7419 | 1.80 |
| 9-30-5.7 | 8767 | 9500 | 9136 | 9134 | 299 | 8850 | 9419 | 3.28 |
| 9-30-6.8 | 8728 | 8506 | 8541 | 8592 | 97 | 8499 | 8684 | 1.13 |
| 9-34-2.2 | 8672 | 8656 | 8948 | 8759 | 134 | 8631 | 8886 | 1.53 |
| 9-34-3.0 | 7237 | 6958 | 7075 | 7090 | 114 | 6981 | 7199 | 1.61 |
| 9-34-5.1 | 6682 | 6973 | 6560 | 6738 | 173 | 6574 | 6903 | 2.57 |
| 9-36-2.6 | 6866 | 7422 | 7336 | 7208 | 244 | 6976 | 7440 | 3.39 |
| 9-36-3.8 | 6942 | 6836 | 7117 | 6965 | 116 | 6855 | 7075 | 1.66 |
| 9-36-6.2 | 6613 | 6810 | 6950 | 6791 | 138 | 6660 | 6922 | 2.04 |
| 9-42-2.1 | 5979 | 5953 | 5879 | 5937 | 42 | 5897 | 5977 | 0.71 |
| 9-42-1.8 | 6761 | 6967 | 6544 | 6757 | 173 | 6593 | 6921 | 2.56 |
| 9-42-3.5 | 5086 | 5582 | 5508 | 5392 | 218 | 5185 | 5599 | 4.05 |
| 9-42-4.4 | 4628 | 4880 | 5306 | 4938 | 280 | 4672 | 5204 | 5.67 |
| 9-42-5.9 | 4720 | 4707 | 4501 | 4643 | 100 | 4547 | 4738 | 2.16 |
| 9-50-0.9 | 4762 | 4623 | 4794 | 4726 | 74 | 4656 | 4797 | 1.57 |
| 9-50-3.6 | 5114 | 5133 | 5418 | 5222 | 139 | 5090 | 5354 | 2.66 |
| 9-50-6.6 | 4169 | 4245 | 4548 | 4321 | 164 | 4165 | 4476 | 3.79 |

Table B.3 Individual Tests & Statistical Data for 28 day Compressive Strength Tests.

| Mixture Designation | 28 Day Compressive Strength (psi) | | | Average (psi) | Std. Dev. (psi) | 90 Percent Confidence Intervals | | Coefficient of Variation (%) |
|---|---|---|---|---|---|---|---|---|
| | Cylinder 1 | Cylinder 2 | Cylinder 3 | | | Lower Limit | Upper Limit | |
| 9-26-1.8 | 12473 | 12498 | 12579 | 12517 | 45 | 12474 | 12560 | 0.36 |
| 9-26-2.1 | 10971 | 11767 | 12019 | 11586 | 447 | 11162 | 12010 | 3.86 |
| 9-26-2.4 | 11945 | 12187 | 12434 | 12189 | 200 | 11999 | 12378 | 1.64 |
| 9-26-3.8 | 11515 | 11150 | 11140 | 11268 | 174 | 11103 | 11434 | 1.55 |
| 9-26-3.9 | 12302 | 12245 | 11931 | 12159 | 163 | 12004 | 12314 | 1.34 |
| 9-26-5.6 | 10725 | 10593 | 10368 | 10562 | 147 | 10422 | 10702 | 1.40 |
| 9-26-5.9 | 11134 | 11984 | 11010 | 11376 | 433 | 10965 | 11787 | 3.81 |
| 9-28-1.9 | 11972 | 12167 | 11453 | 11864 | 301 | 11578 | 12150 | 2.54 |
| 9-28-4.1 | 9339 | 12151 | 10811 | 10767 | 1148 | 9676 | 11858 | 10.67 |
| 9-28-5.8 | 10474 | 10308 | 9460 | 10081 | 444 | 9659 | 10502 | 4.41 |
| 9-30-1.1 | 12790 | 12301 | 11481 | 12191 | 540 | 11678 | 12704 | 4.43 |
| 9-30-2.1 | 10554 | 10970 | 9767 | 10430 | 499 | 9957 | 10904 | 4.78 |
| 9-30-4.5 | 9830 | 10052 | 10003 | 9962 | 95 | 9871 | 10052 | 0.96 |
| 9-30-4.9 | 8019 | 8642 | 8345 | 8335 | 254 | 8094 | 8577 | 3.05 |
| 9-30-5.7 | 10491 | 9826 | 10499 | 10272 | 315 | 9972 | 10572 | 3.07 |
| 9-30-6.8 | 9732 | 9802 | 9953 | 9829 | 92 | 9741 | 9917 | 0.94 |
| 9-34-2.2 | 9437 | 9879 | 10491 | 9936 | 432 | 9525 | 10346 | 4.35 |
| 9-34-3.0 | 7943 | 9139 | 8826 | 8636 | 506 | 8155 | 9117 | 5.86 |
| 9-34-5.1 | 7570 | 7516 | 7534 | 7540 | 22 | 7519 | 7561 | 0.30 |
| 9-36-2.6 | 8640 | 9564 | 9321 | 9175 | 391 | 8804 | 9546 | 4.26 |
| 9-36-3.8 | 8720 | 7986 | 8323 | 8343 | 300 | 8058 | 8628 | 3.60 |
| 9-36-6.2 | 7411 | 7835 | 7857 | 7701 | 205 | 7506 | 7896 | 2.67 |
| 9-42-2.1 | 7712 | 7367 | 7358 | 7479 | 165 | 7322 | 7636 | 2.20 |
| 9-42-1.8 | 8434 | 8765 | 8875 | 8691 | 187 | 8513 | 8869 | 2.16 |
| 9-42-3.5 | 6785 | 6569 | 6107 | 6487 | 283 | 6218 | 6756 | 4.36 |
| 9-42-4.4 | 6313 | 6525 | 6564 | 6467 | 110 | 6363 | 6572 | 1.71 |
| 9-42-5.9 | 6039 | 6280 | 6009 | 6109 | 121 | 5994 | 6225 | 1.99 |
| 9-50-0.9 | 6201 | 6417 | 6028 | 6215 | 159 | 6064 | 6366 | 2.56 |
| 9-50-3.6 | 6443 | 6563 | 6015 | 6340 | 235 | 6117 | 6564 | 3.71 |
| 9-50-6.6 | 5806 | 5765 | 5098 | 5556 | 325 | 5248 | 5865 | 5.84 |

Table B.4 Individual Tests & Statistical Data for 56 day Compressive Strength Tests.

| Mixture Designation | 56 Day Compressive Strength (psi) | | | Average (psi) | Std. Dev. (psi) | 90 Percent Confidence Intervals | | Coefficient of Variation (%) |
|---|---|---|---|---|---|---|---|---|
| | Cylinder 1 | Cylinder 2 | Cylinder 3 | | | Lower Limit | Upper Limit | |
| 9-26-1.8 | 14218 | 14399 | 13080 | 13899 | 584 | 13345 | 14453 | 4.20 |
| 9-26-2.4 | 13140 | 12993 | 12754 | 12962 | 159 | 12811 | 13113 | 1.23 |
| 9-26-3.8 | 12174 | 12165 | 11927 | 12089 | 114 | 11980 | 12197 | 0.95 |
| 9-26-3.9 | 10854 | 12352 | 12875 | 12027 | 856 | 11214 | 12840 | 7.12 |
| 9-26-5.6 | 10976 | 11670 | 11232 | 11293 | 287 | 11021 | 11565 | 2.54 |
| 9-26-5.9 | 11674 | 12662 | 11889 | 12075 | 424 | 11672 | 12478 | 3.51 |
| 9-28-1.9 | 12223 | 12679 | 12463 | 12455 | 186 | 12278 | 12632 | 1.50 |
| 9-28-4.1 | 12153 | 10989 | 11573 | 11572 | 475 | 11120 | 12023 | 4.11 |
| 9-28-5.8 | 10901 | 10767 | 11151 | 10940 | 159 | 10789 | 11091 | 1.45 |
| 9-30-1.1 | 13221 | 13971 | 13597 | 13596 | 306 | 13306 | 13887 | 2.25 |
| 9-30-2.1 | 11676 | 11735 | 11020 | 11477 | 324 | 11169 | 11785 | 2.82 |
| 9-30-4.5 | 10587 | 11312 | 11094 | 10998 | 304 | 10709 | 11286 | 2.76 |
| 9-30-4.9 | 8883 | 8899 | 8844 | 8875 | 23 | 8853 | 8897 | 0.26 |
| 9-30-5.7 | 10908 | 10713 | 11476 | 11032 | 324 | 10725 | 11340 | 2.93 |
| 9-30-6.8 | 10002 | 10101 | 10169 | 10091 | 69 | 10026 | 10156 | 0.68 |
| 9-34-2.2 | 10403 | 10363 | 10831 | 10532 | 212 | 10331 | 10733 | 2.01 |
| 9-34-3.0 | 9054 | 8861 | 8603 | 8839 | 185 | 8664 | 9015 | 2.09 |
| 9-34-5.1 | 8314 | 7972 | 8080 | 8122 | 143 | 7986 | 8258 | 1.76 |
| 9-36-2.6 | 9616 | 9695 | 9547 | 9619 | 60 | 9562 | 9677 | 0.63 |
| 9-36-3.8 | 9169 | 8832 | 9122 | 9041 | 149 | 8899 | 9183 | 1.65 |
| 9-36-6.2 | 8208 | 9044 | 8106 | 8453 | 420 | 8054 | 8852 | 4.97 |
| 9-42-2.1 | 7320 | 7411 | 7876 | 7536 | 244 | 7304 | 7767 | 3.23 |
| 9-42-1.8 | 8943 | 9065 | 9140 | 9049 | 81 | 8972 | 9126 | 0.90 |
| 9-42-3.5 | 6689 | 6833 | 6774 | 6765 | 59 | 6709 | 6821 | 0.87 |
| 9-42-4.4 | 7253 | 6627 | 6706 | 6862 | 278 | 6598 | 7126 | 4.06 |
| 9-42-5.9 | 6655 | 6577 | 6895 | 6709 | 135 | 6580 | 6838 | 2.02 |
| 9-50-0.9 | 6926 | 6821 | 7234 | 6994 | 175 | 6827 | 7160 | 2.51 |
| 9-50-3.6 | 6662 | 6767 | 6837 | 6755 | 72 | 6687 | 6824 | 1.06 |
| 9-50-6.6 | 6073 | 6260 | 6102 | 6145 | 82 | 6067 | 6223 | 1.34 |

# APPENDIX C

Appendix C contains the individual test results and statistical data of Chapter 4. Appendix C also includes plots of the 90 percent confidence intervals.

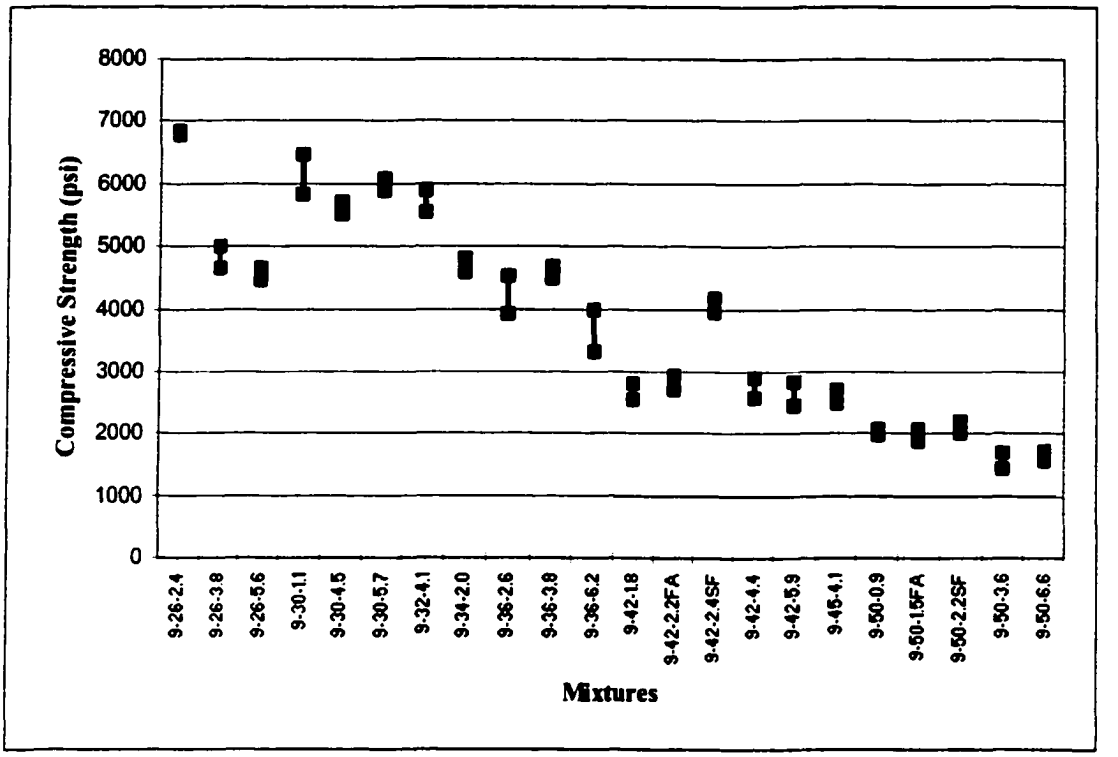


Figure C.1 90 Percent Confidence Intervals for One Day Compressive Strength.

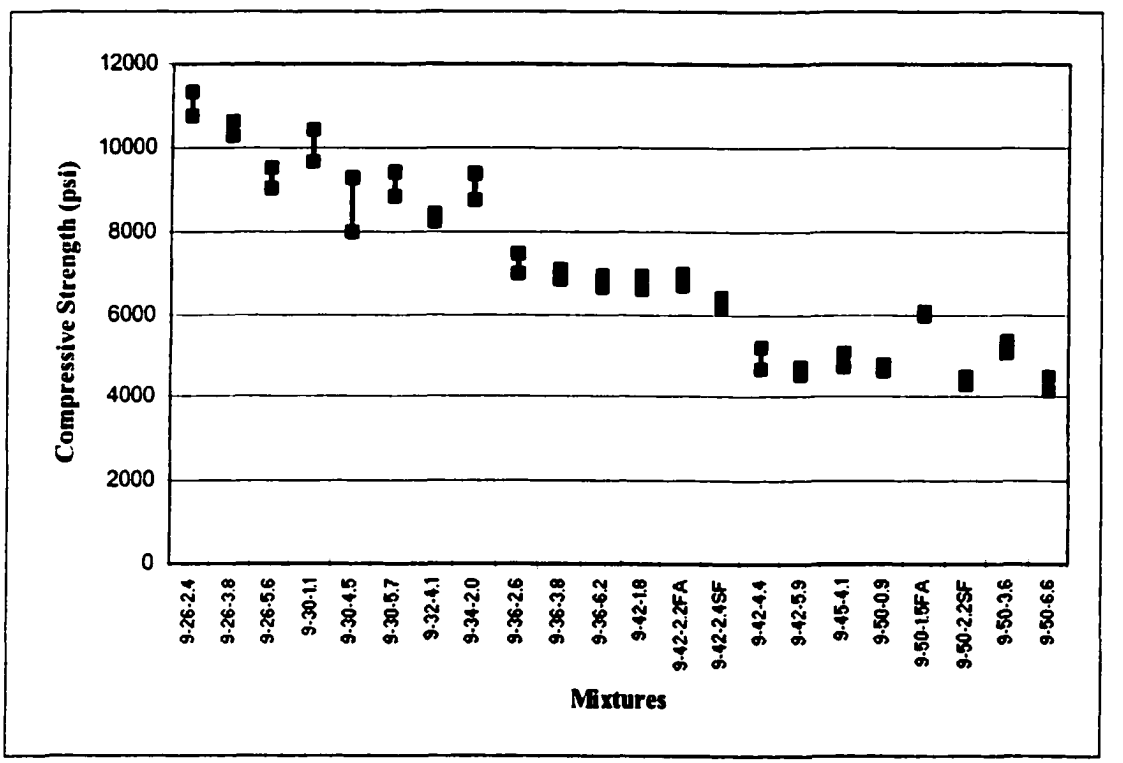


Figure C.2 90 Percent Confidence Intervals for Seven Day Compressive Strength.

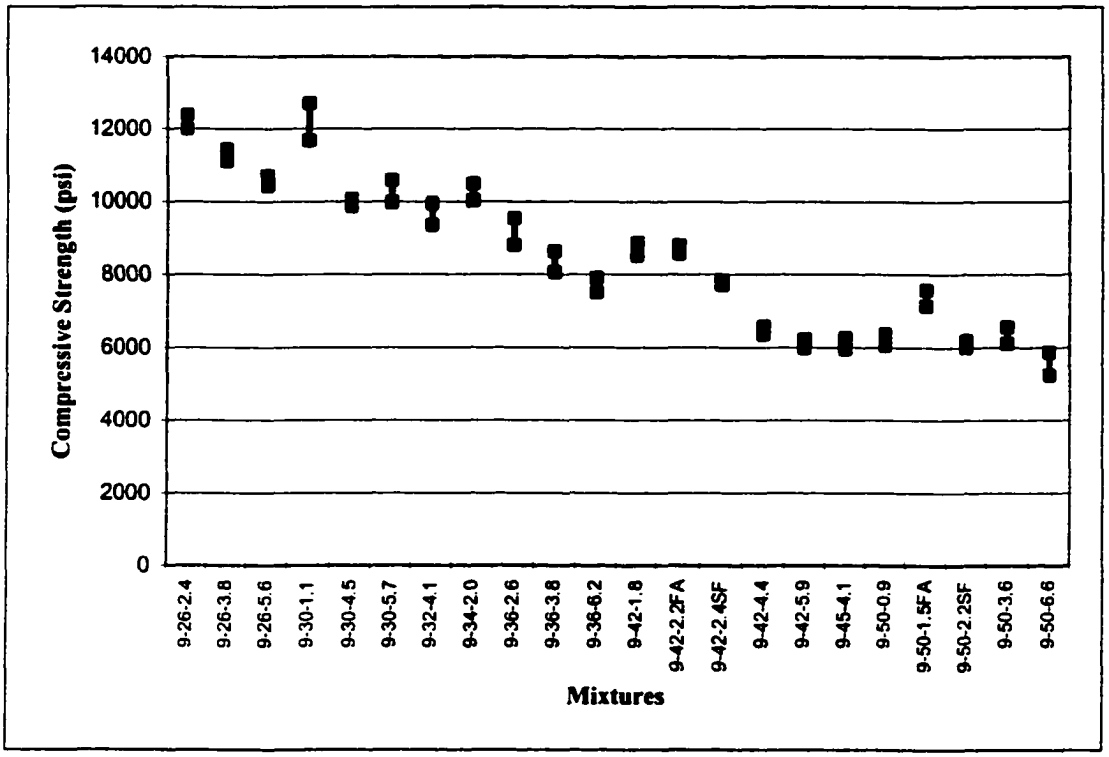


Figure C.3 90 Percent Confidence Intervals for 28 Day Compressive Strength.

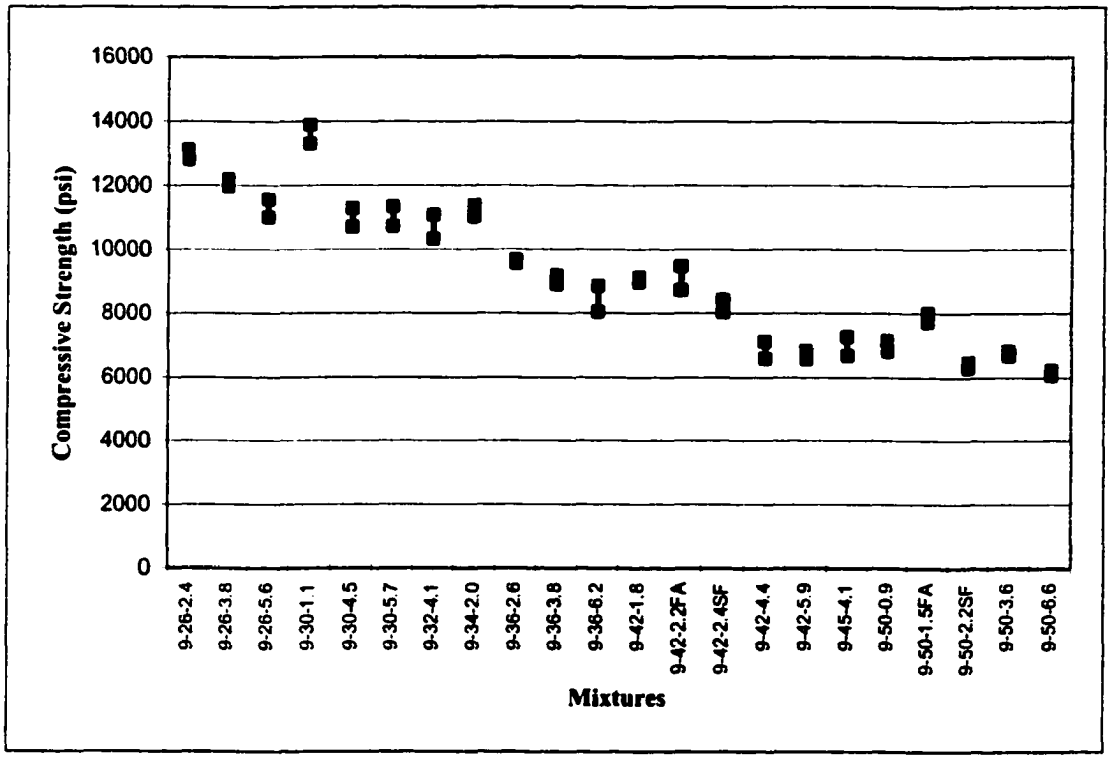


Figure C.4 90 Percent Confidence Intervals for 56 Day Compressive Strength.

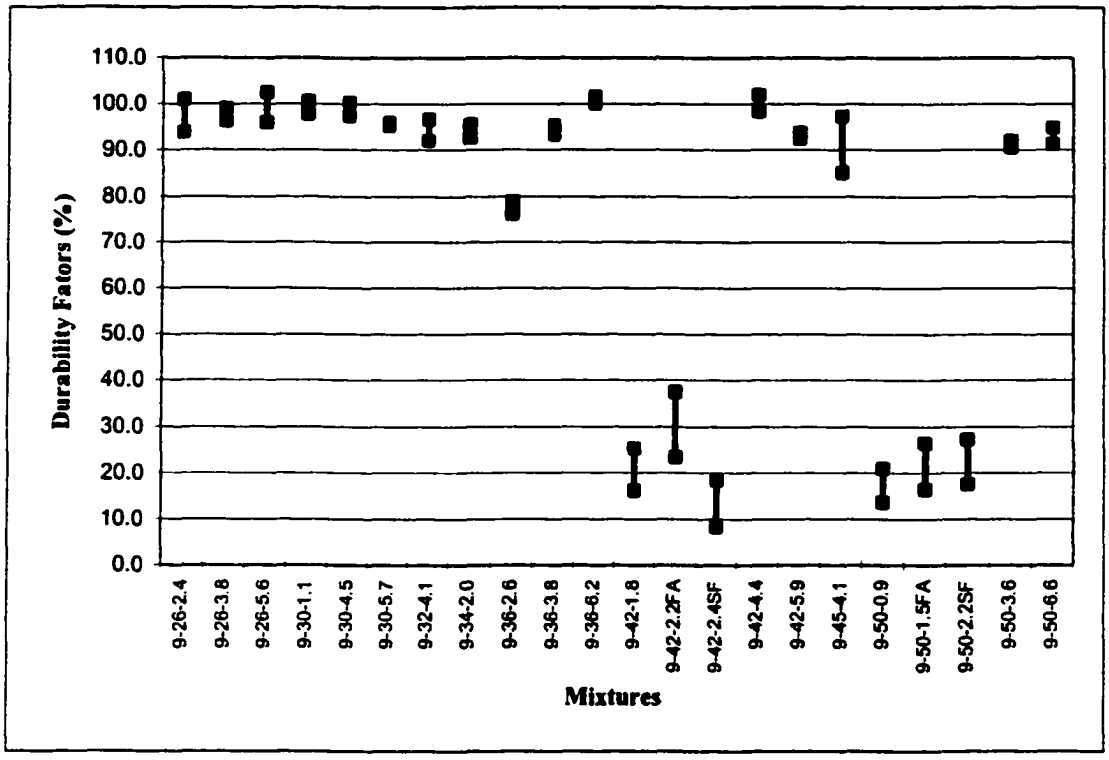


Figure C.5 90 Percent Confidence Intervals for Durability Factors.

Table C.1 Individual Results and Statistical Data for One Day Compressive Strength Tests.

| Mixture Designation | One Day Compressive Strength (psi) | | | Average (psi) | Std. Dev. (psi) | 90 Percent Confidence Intervals | | Coefficient of Variation |
|---|---|---|---|---|---|---|---|---|
| | Cylinder 1 | Cylinder 2 | Cylinder 3 | | | Lower Limit | Upper Limit | |
| 9-26-2.4 | 6884 | 6778 | 6817 | 6826 | 44 | 6785 | 6868 | 0.64 |
| 9-26-3.8 | 4678 | 5096 | 4722 | 4832 | 188 | 4654 | 5010 | 3.88 |
| 9-26-5.6 | 4397 | 4659 | 4617 | 4558 | 115 | 4449 | 4667 | 2.52 |
| 9-30-1.1 | 5685 | 6303 | 6465 | 6151 | 336 | 5832 | 6470 | 5.46 |
| 9-30-4.5 | 5687 | 5460 | 5693 | 5613 | 108 | 5510 | 5716 | 1.93 |
| 9-30-5.7 | 6127 | 5996 | 5882 | 6002 | 100 | 5907 | 6097 | 1.67 |
| 9-32-4.1 | 5978 | 5557 | 5640 | 5725 | 182 | 5552 | 5898 | 3.18 |
| 9-34-2.2 | 4540 | 4727 | 4839 | 4702 | 123 | 4585 | 4819 | 2.62 |
| 9-36-2.6 | 3798 | 4506 | 4362 | 4222 | 306 | 3932 | 4512 | 7.24 |
| 9-36-3.8 | 4461 | 4571 | 4715 | 4582 | 104 | 4484 | 4681 | 2.27 |
| 9-36-6.2 | 3786 | 4019 | 3170 | 3658 | 358 | 3318 | 3998 | 9.79 |
| 9-42-1.8 | 2606 | 2576 | 2883 | 2688 | 138 | 2557 | 2820 | 5.14 |
| 9-42-2.2FA | 2973 | 2787 | 2720 | 2827 | 107 | 2725 | 2928 | 3.79 |
| 9-42-2.4SF | 3951 | 4226 | 4039 | 4072 | 115 | 3963 | 4181 | 2.82 |
| 9-42-4.4 | 2947 | 2753 | 2547 | 2749 | 163 | 2594 | 2904 | 5.94 |
| 9-42-5.9 | 2897 | 2620 | 2392 | 2636 | 206 | 2440 | 2832 | 7.83 |
| 9-45-4.1 | 2614 | 2729 | 2451 | 2598 | 114 | 2490 | 2706 | 4.39 |
| 9-50-0.9 | 2026 | 1970 | 2078 | 2025 | 44 | 1983 | 2067 | 2.18 |
| 9-50-1.5FA | 2091 | 1844 | 1987 | 1974 | 101 | 1878 | 2070 | 5.13 |
| 9-50-2.2SF | 2015 | 2238 | 2069 | 2107 | 95 | 2017 | 2198 | 4.51 |
| 9-50-3.6 | 1761 | 1462 | 1459 | 1561 | 142 | 1426 | 1695 | 9.08 |
| 9-50-6.6 | 1554 | 1638 | 1750 | 1647 | 80 | 1571 | 1724 | 4.87 |

Table C.2 Individual Results and Statistical Data for Seven Day Compressive Strength Tests.

| Mixture Designation | Seven Day Compressive Strength (psi) | | | Average (psi) | Std. Dev. (psi) | 90 Percent Confidence Intervals | | Coefficient of Variation (%) |
|---|---|---|---|---|---|---|---|---|
| | Cylinder 1 | Cylinder 2 | Cylinder 3 | | | Lower Limit | Upper Limit | |
| 9-26-2.4 | 11432 | 11040 | 10646 | 11039 | 321 | 10735 | 11344 | 2.91 |
| 9-26-3.8 | 10282 | 10664 | 10381 | 10442 | 162 | 10289 | 10596 | 1.55 |
| 9-26-5.6 | 9169 | 9623 | 9013 | 9268 | 259 | 9023 | 9514 | 2.79 |
| 9-30-1.1 | 10146 | 9515 | 10484 | 10048 | 402 | 9667 | 10430 | 4.00 |
| 9-30-4.5 | 8347 | 8012 | 9580 | 8646 | 674 | 8006 | 9287 | 7.80 |
| 9-30-5.7 | 8767 | 9500 | 9136 | 9134 | 299 | 8850 | 9419 | 3.28 |
| 9-32-4.1 | 8348 | 8446 | 8162 | 8319 | 118 | 8207 | 8431 | 1.42 |
| 9-34-2.0 | 8748 | 8957 | 9530 | 9078 | 331 | 8764 | 9392 | 3.64 |
| 9-36-2.6 | 6866 | 7422 | 7336 | 7208 | 244 | 6976 | 7440 | 3.39 |
| 9-36-3.8 | 6942 | 6836 | 7117 | 6965 | 116 | 6855 | 7075 | 1.66 |
| 9-36-6.2 | 6613 | 6810 | 6950 | 6791 | 138 | 6660 | 6922 | 2.04 |
| 9-42-1.8 | 6761 | 6967 | 6544 | 6757 | 173 | 6593 | 6921 | 2.56 |
| 9-42-2.2FA | 6914 | 6961 | 6637 | 6837 | 143 | 6702 | 6973 | 2.09 |
| 9-42-2.4SF | 6361 | 6096 | 6406 | 6288 | 137 | 6158 | 6418 | 2.18 |
| 9-42-4.4 | 4628 | 4880 | 5306 | 4938 | 280 | 4672 | 5204 | 5.67 |
| 9-42-5.9 | 4720 | 4707 | 4501 | 4643 | 100 | 4547 | 4738 | 2.16 |
| 9-45-4.1 | 4746 | 4830 | 5121 | 4899 | 161 | 4746 | 5052 | 3.28 |
| 9-50-0.9 | 4762 | 4623 | 4794 | 4726 | 74 | 4656 | 4797 | 1.57 |
| 9-50-1.5FA | 6077 | 6021 | 5983 | 6027 | 39 | 5990 | 6064 | 0.64 |
| 9-50-2.2SF | 4443 | 4251 | 4481 | 4392 | 101 | 4296 | 4487 | 2.29 |
| 9-50-3.6 | 5114 | 5133 | 5418 | 5222 | 139 | 5090 | 5354 | 2.66 |
| 9-50-6.6 | 4169 | 4245 | 4548 | 4321 | 164 | 4165 | 4476 | 3.79 |

Table C.3 Individual Results and Statistical Data for 28 Day Compressive Strength Tests.

| Mixture Designation | 28 Day Compressive Strength (psi) Cylinder 1 | Cylinder 2 | Cylinder 3 | Average (psi) | Std. Dev. (psi) | 90 Percent Confidence Intervals Lower Limit | Upper Limit | Coefficient of Variation (%) |
|---|---|---|---|---|---|---|---|---|
| 9-26-2.4 | 11945 | 12187 | 12434 | 12189 | 200 | 11999 | 12378 | 1.64 |
| 9-26-3.8 | 11515 | 11150 | 11140 | 11268 | 174 | 11103 | 11434 | 1.55 |
| 9-26-5.6 | 10725 | 10593 | 10368 | 10562 | 147 | 10422 | 10702 | 1.40 |
| 9-30-1.1 | 12790 | 12301 | 11481 | 12191 | 540 | 11678 | 12704 | 4.43 |
| 9-30-4.5 | 9830 | 10052 | 10003 | 9962 | 95 | 9871 | 10052 | 0.96 |
| 9-30-5.7 | 10491 | 9826 | 10499 | 10272 | 315 | 9972 | 10572 | 3.07 |
| 9-32-4.1 | 9311 | 9583 | 10046 | 9647 | 303 | 9359 | 9935 | 3.15 |
| 9-34-2.0 | 10428 | 10398 | 9919 | 10248 | 233 | 10027 | 10470 | 2.28 |
| 9-36-2.6 | 8640 | 9564 | 9321 | 9175 | 391 | 8804 | 9546 | 4.26 |
| 9-36-3.8 | 8720 | 7986 | 8323 | 8343 | 300 | 8058 | 8628 | 3.60 |
| 9-36-6.2 | 7411 | 7835 | 7857 | 7701 | 205 | 7506 | 7896 | 2.87 |
| 9-42-1.8 | 8434 | 8765 | 8875 | 8691 | 187 | 8513 | 8869 | 2.16 |
| 9-42-2.2FA | 8545 | 8665 | 8840 | 8683 | 121 | 8568 | 8798 | 1.39 |
| 9-42-2.4SF | 7696 | 7786 | 7839 | 7774 | 59 | 7718 | 7830 | 0.76 |
| 9-42-4.4 | 6313 | 6525 | 6564 | 6467 | 110 | 6363 | 6572 | 1.71 |
| 9-42-5.9 | 6039 | 6280 | 6009 | 6109 | 121 | 5994 | 6225 | 1.99 |
| 9-45-4.1 | 5912 | 6138 | 6280 | 6110 | 152 | 5966 | 6254 | 2.48 |
| 9-50-0.9 | 6201 | 6417 | 6028 | 6215 | 159 | 6064 | 6366 | 2.56 |
| 9-50-1.5FA | 7078 | 7354 | 7645 | 7359 | 232 | 7139 | 7579 | 3.15 |
| 9-50-2.2SF | 5961 | 6174 | 6170 | 6102 | 99 | 6007 | 6196 | 1.63 |
| 9-50-3.6 | 6443 | 6563 | 6015 | 6340 | 235 | 6117 | 6564 | 3.71 |
| 9-50-6.6 | 5806 | 5765 | 5098 | 5556 | 325 | 5248 | 5865 | 5.84 |

Table C.4 Individual Results and Statistical Data for 56 Day Compressive Strength Tests.

| Mixture Designation | 56 Day Compressive Strength (psi) | | | Average (psi) | Std. Dev. (psi) | 90 Percent Confidence Intervals | | Coefficient of Variation (%) |
|---|---|---|---|---|---|---|---|---|
| | Cylinder 1 | Cylinder 2 | Cylinder 3 | | | Lower Limit | Upper Limit | |
| 9-26-2.4 | 13140 | 12993 | 12754 | 12962 | 159 | 12811 | 13113 | 1.23 |
| 9-26-3.8 | 12174 | 12165 | 11927 | 12089 | 114 | 11980 | 12197 | 0.95 |
| 9-26-5.6 | 10976 | 11670 | 11232 | 11293 | 287 | 11021 | 11565 | 2.54 |
| 9-30-1.1 | 13221 | 13971 | 13597 | 13596 | 306 | 13306 | 13887 | 2.25 |
| 9-30-4.5 | 10587 | 11312 | 11094 | 10998 | 304 | 10709 | 11286 | 2.76 |
| 9-30-5.7 | 10908 | 10713 | 11476 | 11032 | 324 | 10725 | 11340 | 2.93 |
| 9-32-4.1 | 10763 | 10188 | 11160 | 10704 | 399 | 10325 | 11083 | 3.73 |
| 9-34-2.0 | 11152 | 11006 | 11446 | 11201 | 183 | 11028 | 11375 | 1.63 |
| 9-36-2.6 | 9616 | 9695 | 9547 | 9619 | 60 | 9562 | 9677 | 0.63 |
| 9-36-3.8 | 9169 | 8832 | 9122 | 9041 | 149 | 8899 | 9183 | 1.65 |
| 9-36-6.2 | 8208 | 9044 | 8106 | 8453 | 420 | 8054 | 8852 | 4.97 |
| 9-42-1.8 | 8943 | 9065 | 9140 | 9049 | 81 | 8972 | 9126 | 0.90 |
| 9-42-2.2FA | 9389 | 8538 | 9360 | 9096 | 395 | 8721 | 9470 | 4.34 |
| 9-42-2.4SF | 8511 | 8026 | 8150 | 8229 | 206 | 8034 | 8424 | 2.50 |
| 9-42-4.4 | 7253 | 6627 | 6706 | 6862 | 278 | 6598 | 7126 | 4.06 |
| 9-42-5.9 | 6655 | 6577 | 6895 | 6709 | 135 | 6580 | 6838 | 2.02 |
| 9-45-4.1 | 6978 | 7371 | 6603 | 6984 | 314 | 6686 | 7282 | 4.49 |
| 9-50-0.9 | 6926 | 6821 | 7234 | 6994 | 175 | 6827 | 7160 | 2.51 |
| 9-50-1.5FA | 8062 | 7827 | 7723 | 7871 | 142 | 7736 | 8005 | 1.80 |
| 9-50-2.2SF | 6500 | 6391 | 6263 | 6385 | 97 | 6293 | 6477 | 1.52 |
| 9-50-3.6 | 6662 | 6767 | 6837 | 6755 | 72 | 6687 | 6824 | 1.06 |
| 9-50-6.6 | 6073 | 6260 | 6102 | 6145 | 82 | 6067 | 6223 | 1.34 |

Table C.5 Individual Results and Statistical Data for the Freeze-Thaw Tests.

| Mixture Designation | Durability Factor (%) Specimens 1 | 2 | 3 | 4 | Average DF (%) | Std. Dev. (%) | 90 Percent Confidence Intervals Lower Limit | Upper Limit | Coefficient of Variation (%) |
|---|---|---|---|---|---|---|---|---|---|
| 9-26-2.4 | 96.0 | 104.7 | 95.5 | 93.7 | 97.5 | 4.3 | 94.0 | 101.0 | 4.37 |
| 9-26-3.8 | 100.1 | 97.6 | 95.4 | 97.7 | 97.7 | 1.7 | 96.3 | 99.1 | 1.70 |
| 9-26-5.6 | 96.1 | 96.4 | 98.7 | 105.8 | 99.3 | 3.9 | 96.0 | 102.5 | 3.94 |
| 9-30-1.1 | 100.7 | 99.7 | 96.4 | 99.9 | 99.2 | 1.6 | 97.8 | 100.5 | 1.66 |
| 9-30-4.5 | 97.6 | 96.8 | 100.8 | 100.3 | 98.9 | 1.7 | 97.5 | 100.3 | 1.73 |
| 9-30-5.6 | 96.0 | 95.2 | 95.6 | | 95.6 | 0.3 | 95.3 | 95.9 | 0.34 |
| 9-32-4.1 | 89.5 | 96.5 | 95.7 | 95.8 | 94.4 | 2.8 | 92.0 | 96.7 | 3.00 |
| 9-34-2.0 | 94.4 | 94.6 | 91.5 | 96.3 | 94.2 | 1.7 | 92.8 | 95.6 | 1.83 |
| 9-36-2.6 | 75.0 | 79.4 | 78.1 | 77.8 | 77.6 | 1.6 | 76.3 | 78.9 | 2.07 |
| 9-36-3.8 | 94.2 | 96.3 | 93.0 | 94.0 | 94.4 | 1.2 | 93.4 | 95.4 | 1.27 |
| 9-36-6.2 | 100.6 | 100.6 | 99.9 | 102.3 | 100.9 | 0.9 | 100.1 | 101.6 | 0.88 |
| 9-42-1.8 | 16.5 | 18.3 | 17.9 | 30.3 | 20.8 | 5.6 | 16.2 | 25.3 | 26.77 |
| 9-42-2.2FA | 18.5 | 27.5 | 41.7 | 34.2 | 30.5 | 8.5 | 23.4 | 37.5 | 28.04 |
| 9-42-2.4SF | 4.5 | 18.8 | 19.3 | 10.8 | 13.4 | 6.1 | 8.3 | 18.4 | 45.86 |
| 9-42-4.4 | 101.5 | 96.8 | 102.4 | 100.1 | 100.2 | 2.1 | 98.5 | 101.9 | 2.12 |
| 9-42-5.9 | 94.2 | 93.4 | 92.0 | 93.0 | 93.2 | 0.8 | 92.5 | 93.8 | 0.85 |
| 9-45-4.1 | 99.5 | 79.4 | 93.1 | 93.1 | 91.3 | 7.3 | 85.2 | 97.3 | 8.04 |
| 9-50-0.9 | 10.2 | 19.6 | 17.2 | 22.2 | 17.3 | 4.5 | 13.6 | 21.0 | 25.81 |
| 9-50-1.5FA | 26.7 | 26.1 | 21.6 | 11.5 | 21.5 | 6.1 | 16.5 | 26.5 | 28.34 |
| 9-50-2.2SF | 28.5 | 27.9 | 18.3 | 15.0 | 22.4 | 5.9 | 17.6 | 27.3 | 26.29 |
| 9-50-3.6 | 90.1 | 91.0 | 92.4 | 91.8 | 91.3 | 0.9 | 90.6 | 92.0 | 0.95 |
| 9-50-6.6 | 92.4 | 94.9 | 95.1 | 89.9 | 93.1 | 2.1 | 91.3 | 94.8 | 2.28 |

# APPENDIX D

Appendix D includes individual tests results and statistical data from Chapter 5. Appendix D also contains plots of the 90 percent confidence intervals.

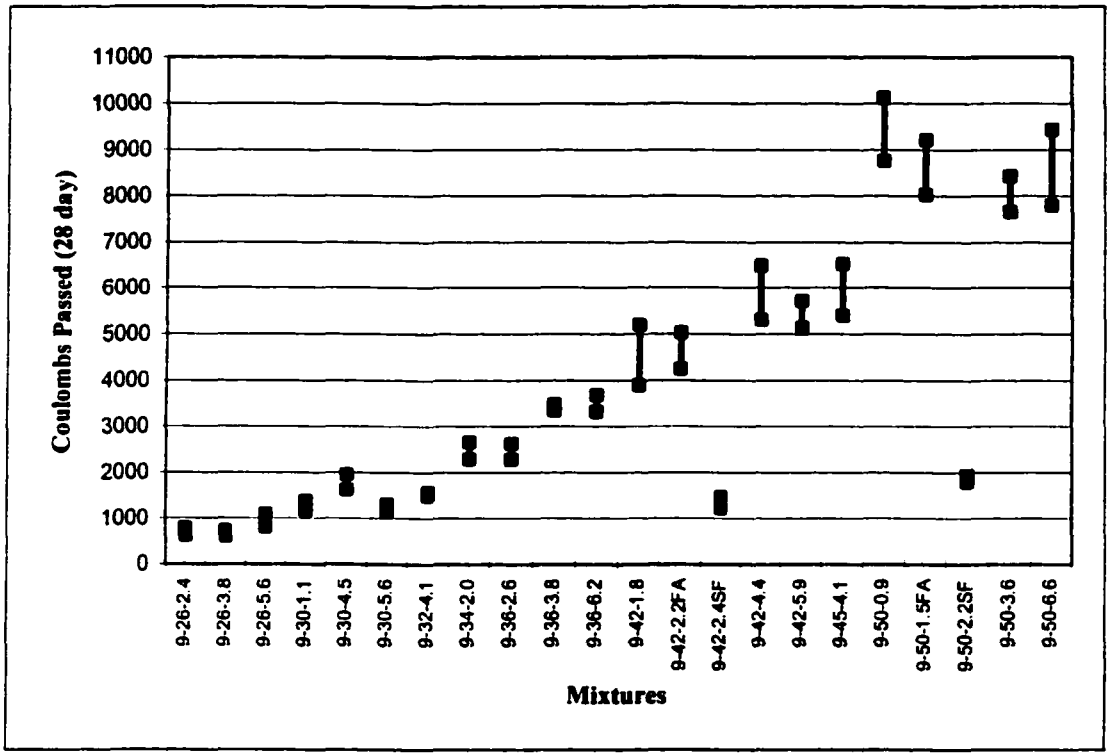


Figure D.1 90 Percent Confidence Intervals for 28 Day RCIP.

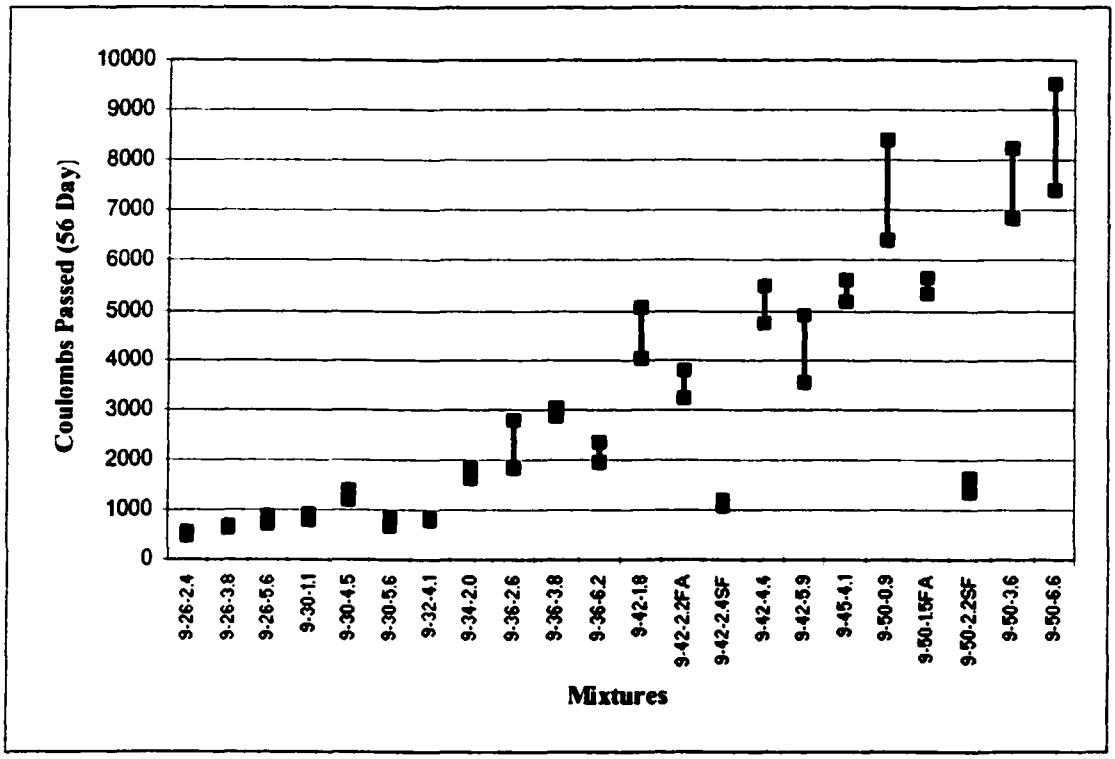


Figure D.2 90 Percent Confidence Intervals for 56 Day RCIP.

Table D.1 Individual Tests and Statistical Data for 28 Day RCIP.

| Mixture Designation | Number of Coulombs Passed Specimens | | | | Average (coulombs) | Std. Dev. (coulombs) | 90 Percent Confidence Intervals | | Coefficient of Variation (%) |
|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | | | Lower Limit | Upper Limit | |
| 9-26-2.4 | 573 | 657 | 846 | 765 | 710 | 104 | 625 | 796 | 14.61 |
| 9-26-3.8 | 558 | 738 | 645 | 742 | 671 | 76 | 608 | 733 | 11.30 |
| 9-26-5.6 | 1249 | 813 | 908 | 855 | 956 | 172 | 815 | 1098 | 18.02 |
| 9-30-1.1 | 1437 | 1274 | 1070 | 1298 | 1270 | 131 | 1162 | 1378 | 10.32 |
| 9-30-4.5 | 1743 | 2049 | 1854 | 1508 | 1789 | 196 | 1628 | 1949 | 10.93 |
| 9-30-5.6 | 1083 | 1320 | 1326 | 1159 | 1222 | 105 | 1136 | 1308 | 8.55 |
| 9-32-4.1 | 1515 | 1612 | 1524 | 1483 | 1534 | 48 | 1494 | 1573 | 3.12 |
| 9-34-2.0 | 2623 | 2146 | 2383 | 2733 | 2471 | 226 | 2285 | 2657 | 9.16 |
| 9-36-2.6 | 2290 | 2812 | 2340 | 2371 | 2453 | 209 | 2281 | 2625 | 8.52 |
| 9-36-3.8 | 3353 | 3327 | 3452 | 3533 | 3416 | 82 | 3349 | 3484 | 2.40 |
| 9-36-6.2 | 3282 | 3560 | 3837 | 3324 | 3501 | 221 | 3319 | 3683 | 6.32 |
| 9-42-1.8 | 3484 | 4912 | 4187 | 5602 | 4546 | 791 | 3895 | 5197 | 17.41 |
| 9-42-2.2FA | 4588 | 4309 | 5435 | 4223 | 4639 | 479 | 4245 | 5033 | 10.33 |
| 9-42-2.4SF | 1238 | 1506 | 1149 | 1478 | 1343 | 153 | 1217 | 1468 | 11.38 |
| 9-42-4.4 | 5496 | 5565 | 7150 | 5409 | 5905 | 721 | 5312 | 6498 | 12.21 |
| 9-42-5.9 | 5278 | 5102 | 6029 | 5313 | 5431 | 355 | 5139 | 5722 | 6.53 |
| 9-45-4.1 | 6621 | 5169 | 5409 | 6679 | 5970 | 686 | 5405 | 6534 | 11.49 |
| 9-50-0.9 | 9411 | 10760 | 9134 | 8493 | 9450 | 827 | 8770 | 10129 | 8.75 |
| 9-50-1.5FA | 9160 | 9471 | 7724 | 8138 | 8623 | 716 | 8034 | 9212 | 8.30 |
| 9-50-2.2SF | 1964 | 1936 | 1791 | 1780 | 1868 | 83 | 1800 | 1936 | 4.44 |
| 9-50-3.6 | 7358 | 8599 | 7912 | 8357 | 8057 | 473 | 7668 | 8445 | 5.87 |
| 9-50-6.6 | 7318 | 9867 | 8066 | 9239 | 8623 | 993 | 7806 | 9439 | 11.51 |

Table D.2 Individual Tests and Statistical Data for 56 Day RCIP Tests.

| Mixture Designation | Number of Coulombs Passed Specimens | | | | Average (coulombs) | Std. Dev. (coulombs) | 90 Percent Confidence Intervals | | Coefficient of Variation (%) |
|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | | | Lower Limit | Upper Limit | |
| 9-26-2.4 | 456 | 497 | 543 | 584 | 520 | 48 | 480 | 560 | 9.25 |
| 9-26-3.8 | 698 | 623 | 683 | 637 | 660 | 31 | 635 | 686 | 4.71 |
| 9-26-5.6 | 904 | 722 | 713 | 855 | 799 | 83 | 730 | 867 | 10.38 |
| 9-30-1.1 | 746 | 963 | 895 | 793 | 849 | 85 | 779 | 919 | 10.00 |
| 9-30-4.5 | 1088 | 1299 | 1358 | 1377 | 1281 | 115 | 1186 | 1375 | 8.97 |
| 9-30-5.6 | 804 | 816 | 784 | 621 | 756 | 79 | 691 | 821 | 10.44 |
| 9-32-4.1 | 822 | 863 | 803 | 755 | 811 | 39 | 779 | 843 | 4.79 |
| 9-34-2.0 | 1553 | 1883 | 1759 | 1759 | 1739 | 118 | 1641 | 1836 | 6.81 |
| 9-36-2.6 | 2023 | 3327 | 1828 | 2097 | 2319 | 590 | 1833 | 2804 | 25.46 |
| 9-36-3.8 | 2808 | 2951 | 3112 | 2923 | 2949 | 109 | 2859 | 3038 | 3.68 |
| 9-36-6.2 | 1771 | 2343 | 2178 | 2372 | 2166 | 240 | 1969 | 2363 | 11.07 |
| 9-42-1.8 | 5339 | 3640 | 4343 | 4880 | 4551 | 633 | 4030 | 5071 | 13.91 |
| 9-42-2.2FA | 3236 | 3175 | 3613 | 4033 | 3514 | 343 | 3232 | 3797 | 9.77 |
| 9-42-2.4SF | 1206 | 1164 | 1152 | 1013 | 1134 | 73 | 1074 | 1193 | 6.40 |
| 9-42-4.4 | 5190 | 4433 | 5727 | 5088 | 5110 | 460 | 4731 | 5488 | 9.00 |
| 9-42-5.9 | 5623 | 3759 | 3881 | 3602 | 4216 | 818 | 3543 | 4889 | 19.41 |
| 9-45-4.1 | 5508 | 5673 | 5057 | | 5413 | 260 | 5199 | 5627 | 4.81 |
| 9-50-0.9 | 6467 | 9144 | 6619 | | 7410 | 1228 | 6400 | 8420 | 16.57 |
| 9-50-1.5FA | 5322 | 5830 | 5376 | 5434 | 5491 | 200 | 5326 | 5655 | 3.64 |
| 9-50-2.2SF | 1269 | 1542 | 1642 | | 1484 | 158 | 1355 | 1614 | 10.62 |
| 9-50-3.6 | 7298 | 8690 | 6328 | 7879 | 7549 | 861 | 6841 | 8257 | 11.40 |
| 9-50-6.6 | 6623 | 10193 | 8299 | 8751 | 8467 | 1274 | 7419 | 9514 | 15.04 |

# APPENDIX E

Appendix E contains the individual tests results for Chapter 6.


| | |
|---|---|
| Calculated Prestress Losses (AASHTO and PCI) | pp. 245 - 268 |
| Strain Measurements for each Girder | pp. 269 - 307 |
| Hardened Concrete Properties | pp. 308 - 317 |
| Calculations for Losses Due to Temperature Change | pp. 318 - 319 |
| Calculations for Modified Kcir | pp. 320 - 324 |

The following pages contain the prestress loss calculations (AASHTO and PCI) for Girder/Beam 1.

## BEAM 1

### Section Properties

Sb = 899.63 $in^3$

Area = 163.25 $in^2$

y = 13.75 in.

cgs = 6.4 in.

e = 7.35

### Strand Properties

fse = 185 ksi

Area = 0.217 $in^2$

Fse = 401.45 kips

Total number of strands = 10

### Concrete Properties

fci = 8.696 ksi

fc = 10 ksi

Total Air Content = 2%

Unit Weight = 151.1 $lb/ft^3$

| Number of Strands (1) | Distance from bottom fiber (2) | 1*2 |
|---|---|---|
| 3 | 2 | 6 |
| 3 | 4 | 12 |
| 1 | 6 | 6 |
| 1 | 8 | 8 |
| 1 | 10 | 10 |
| 1 | 22 | 22 |

**fbot=-Fse(1/A+e/Sb)**

Fse = 401.45

1/A = 0.006125574

e/sb = 0.008170025

fbot = -5.738968511 ksi

| fbot/fci = -0.659954981 | -66.00 % |
|---|---|

**AASHTO Losses**

**ELASTIC SHORTENING**

Modulus of Elasticity

| | |
|---|---|
| concrete = | 5600 ksi (1 day) |
| strand = | 28500 ksi |
| n = | 5.09 |

Strands

| | |
|---|---|
| total # = | 10 |
| total area = | 2.17 $in^2$ |
| $f_{pu}$ = | 270 ksi |
| tension after stressing = | 204.25 ksi |

elongation of the strands (in)

| | |
|---|---|
| 1 | 8.750 |
| 2 | 8.750 |
| 3 | 8.750 |
| 4 | 8.250 |
| 5 | 8.500 |
| 6 | 8.500 |
| 7 | 8.625 |
| 8 | 8.500 |
| 9 | 8.625 |
| 10 | 8.750 |
| average elongation = | 8.600 in. |
| length of strand = | 100 ft |

$f_{cgp} = F/A + Fe^2/I - M_G e/I$

| | | |
|---|---|---|
| F (Ppi) = | 443.22 kips | |
| $M_G$ = | 0 at ends | |
| $M_G$ = | 148.00 k - in | at center |
| w = | 171.30 lb/ft | |
| $f_{cgp}$ = | 4.65 ksi | at ends |
| $f_{cgp}$ = | 4.56 ksi | at center |

$\Delta f_{pES} = (E_p/E_{ci})f_{cgp}$ section 5.9.5.2.3a

| | | |
|---|---|---|
| $\Delta f_{pES}$ = | 23.67 ksi | at ends |
| $\Delta f_{pES}$ = | 23.22 ksi | at center |

**CREEP**

$\Delta f_{pCR} = 12.0 f_{cgp} - 7.0 \Delta f_{cdp}$

| | | |
|---|---|---|
| $\Delta f_{cdp}$ = | 0 ksi | |
| $f_{cgp}$ = | 4.65 ksi | at ends |
| $f_{cgp}$ = | 4.56 ksi | at center |

| | | |
|---|---|---|
| $\Delta f_{pCR}$ = | 55.81 ksi | at ends |
| $\Delta f_{pCR}$ = | 54.75 ksi | at center |

**SHRINKAGE**

$\Delta f_{pSR} = (17.0 - 0.150\ H)$

H = 65 %

| | |
|---|---|
| $\Delta f_{pSR}$ = | 7.25 |

**RELAXATION**

$\Delta f_{pR2} = (20 - 0.4\Delta f_{pES} - 0.2(\Delta f_{pSR} + \Delta f_{pCR}))*0.30$

| | | |
|---|---|---|
| $\Delta f_{pES}$ = | 23.67 ksi | at ends |
| $\Delta f_{pES}$ = | 23.22 ksi | at center |
| $\Delta f_{pSR}$ = | 7.25 | |
| $\Delta f_{pCR}$ = | 55.81 ksi | at ends |
| $\Delta f_{pCR}$ = | 54.75 ksi | at center |

| | | |
|---|---|---|
| $\Delta f_{pR2}$ = | -0.62368 ksi | at ends |
| $\Delta f_{pR2}$ = | -0.50665 ksi | at center |

$\Delta f_{pR1} = (\log(24.0t)/40.0)(f_{pi}/f_{py} - 0.55)f_{pi}$

| | |
|---|---|
| t = | 1 day |
| $f_{pi}$ = | 204.25 ksi |
| $f_{py}$ = | 270 ksi |

| | |
|---|---|
| $\Delta f_{pR1}$ = | 1.46 ksi |

**TOTAL LOSSES**

$\Delta f_{pT} = \Delta f_{pES} + \Delta f_{pSR} + \Delta f_{pCR} + \Delta f_{pR1} + \Delta f_{pR2}$

| | |
|---|---|
| $\Delta f_{pT}$ = | 87.56 at ends |
| $\Delta f_{pT}$ = | 86.17 at center |

**PCI Losses**

**ELASTIC SHORTENING**

Modulus of Elasticity

concrete = 5600 ksi (1 day)
concrete = 6000 ksi (28 days)
strand = 28500 ksi
$n_{one\ day}$ = 5.09
$n_{28\ days}$ = 4.75

Strands

total # = 10
total area = 2.17 $in^2$
tension after stressing = 204.25 ksi
elongation of the strands (in)

| | |
|---|---|
| 1 | 8.750 |
| 2 | 8.750 |
| 3 | 8.750 |
| 4 | 8.250 |
| 5 | 8.500 |
| 6 | 8.500 |
| 7 | 8.625 |
| 8 | 8.500 |
| 9 | 8.625 |
| 10 | 8.750 |

average = 8.600 in.
length of strand = 100 ft.

Ppi = 443.22 kips
Kcir = 0.895

$f_{cir} = K_{cir}(P_{pi}(1/A_g + e^2/I_g)) - f_g$

e = 7.35 in.
$A_g$ = 163.25 $in^2$
$I_g$ = 12370 $in^4$
$f_g$ = 0 ksi at ends
$f_g$ = 0.088 ksi at center
$f_{cir}$ = 4.16 ksi at ends
$f_{cir}$ = 4.07 ksi at center

$ES = K_{es}nf_{cir}$

$K_{es}$ = 1.0

**ES = 21.18 ksi at ends**

**CREEP**

$CR = K_{cr}n(f_{cir} - f_{cds})$

$K_{cr}$ = 2.0 for p/s members
$f_{cir}$ = 4.16 ksi at ends
$f_{cir}$ = 4.07 ksi at center

$f_{cds}$ = 0 ksi

CR = 39.54 ksi at ends
CR = 38.71 ksi at center

**SHRINKAGE**

$SH = 8.2*10^{-6}K_{sh}E_s(1 - 0.06V/S)(100 - RH)$

RH = 65 %
Volume = 47016 $in^3$
Surface Area = 28224 $in^2$
V/A = 1.67
$K_{sh}$ = 1
$E_s$ = 28500 ksi

SH = 7.36 ksi

$f_g = M_G e/I$

w = 171.30 lb/ft
$M_G$ = 148.00 k - in

| ES = 20.74 ksi at center |
|---|

**RELAXATION**

$RE = ( K_{re} - J(SH + CR + ES))C$

$K_{re}$ = 5

J = 0.040

SH = 7.36 ksi

CR = 39.54 ksi at ends

CR = 38.71 ksi at center

ES = 21.18 ksi at ends

ES = 20.74 ksi at center

C = 1.05

$f_{pi}$ = 204.25 ksi

$f_{pu}$ = 270 ksi

$f_{pi}/f_{pu}$ = 0.76

| RE = 2.39 ksi at ends |
|---|
| RE = 2.44 ksi at center |

**Total Losses**

ES = 21.18 ksi at ends

ES = 20.74 ksi at center

CR = 39.54 ksi at ends

CR = 38.71 ksi at center

SH = 7.36 ksi

RE = 2.39 ksi at ends

RE = 2.44 ksi at center

| **Total Losses at Ends = 70.48 ksi** |
|---|
| **Total Losses at Center = 69.25 ksi** |

The following pages contain the prestress loss calculations (AASHTO and PCI) for Girder/Beam 2.

**BEAM 2**

**Section Properties**

Sb = 899.63 $in^3$

Area = 163.25 $in^2$

y = 13.75 in.

cgs = 6 in.

e = 7.75

**Strand Properties**

fse = 185 ksi

Area = 0.217 $in^2$

Fse = 361.305 kips

Total number of strands = 9

**Concrete Properties**

fci = 6.127 ksi

fc = 10 ksi

Total Air Content = 6%

Unit Weight = 146.9 $lb/ft^3$

| Number of Strands (1) | Distance from bottom fiber (2) | 1*2 |
|---|---|---|
| 3 | 2 | 6 |
| 3 | 4 | 12 |
| 1 | 6 | 6 |
| 1 | 8 | 8 |
| 0 | 10 | 0 |
| 1 | 22 | 22 |

**fbot = -Fse(1/A+e/Sb)**

Fse = 361.305

1/A = 0.006125574

e/sb = 0.008614653

fbot = -5.325717703 ksi

| **fbot/fci = -0.869221104** | **-86.92 %** |
|---|---|

**AASHTO Losses**

**ELASTIC SHORTENING**

Modulus of Elasticity

| | |
|---|---|
| concrete = | 4700 ksi (1 day) |
| strand = | 28500 ksi |
| n = | 6.06 |

Strands

| | |
|---|---|
| total # = | 9 |
| total area = | 1.953 $in^2$ |
| $f_{pu}$ = | 270 ksi |
| tension after stressing = | 202.20 ksi |

elongation of the strands (in)

| | |
|---|---|
| 1 | 8.250 |
| 2 | 8.500 |
| 3 | 8.500 |
| 4 | 8.625 |
| 5 | 8.625 |
| 6 | 8.750 |
| 7 | 8.500 |
| 8 | 8.500 |
| 9 | |
| 10 | 8.375 |
| average elongation = | 8.514 in. |
| length of strand = | 100 ft |

$f_{cgp} = F/A + Fe^2/I - M_G e/I$

| | | |
|---|---|---|
| F (Ppi) = | 394.91 kips | |
| $M_G$ = | 0 at ends | |
| $M_G$ = | 143.89 k - in | at center |
| w = | 166.54 lb/ft | |
| $f_{cgp}$ = | 4.34 ksi | at ends |
| $f_{cgp}$ = | 4.25 ksi | at center |

$\Delta f_{pES} = (E_p/E_{ci})f_{cgp}$ section 5.9.5.2.3a

| | | |
|---|---|---|
| $\Delta f_{pES}$ = | 26.30 ksi | at ends |
| $\Delta f_{pES}$ = | 25.75 ksi | at center |

**CREEP**

$\Delta f_{pCR} = 12.0 f_{cgp} - 7.0 \Delta f_{cdp}$

$\Delta f_{cdp}$ = 0 ksi

| | | |
|---|---|---|
| $f_{cgp}$ = | 4.34 ksi | at ends |
| $f_{cgp}$ = | 4.25 ksi | at center |

| | | |
|---|---|---|
| $\Delta f_{pCR}$ = | 52.04 ksi | at ends |
| $\Delta f_{pCR}$ = | 50.96 ksi | at center |

**SHRINKAGE**

$\Delta f_{pSR} = (17.0 - 0.150\ H)$

H = 65 %

| | |
|---|---|
| $\Delta f_{pSR}$ = | 7.25 |

**RELAXATION**

$\Delta f_{pR2} = (20 - 0.4\Delta f_{pES} - 0.2(\Delta f_{pSR} + \Delta f_{pCR}))*0.30$

| | | |
|---|---|---|
| $\Delta f_{pES}$ = | 26.30 ksi | at ends |
| $\Delta f_{pES}$ = | 25.75 ksi | at center |
| $\Delta f_{pSR}$ = | 7.25 | |
| $\Delta f_{pCR}$ = | 52.04 ksi | at ends |
| $\Delta f_{pCR}$ = | 50.96 ksi | at center |

| | | |
|---|---|---|
| $\Delta f_{pR2}$ = | -0.71276 ksi | at ends |
| $\Delta f_{pR2}$ = | -0.58226 ksi | at center |

$\Delta f_{pR1} = (\log(24.0t)/40.0)(f_{pj}/f_{py} - 0.55)f_{pj}$

| | |
|---|---|
| t = | 1 day |
| $f_{pj}$ = | 202.20 ksi |
| $f_{py}$ = | 270 ksi |

| | |
|---|---|
| $\Delta f_{pR1}$ = | 1.39 ksi |

**TOTAL LOSSES**

$\Delta f_{pT} = \Delta f_{pES} + \Delta f_{pSR} + \Delta f_{pCR} + \Delta f_{pR1} + \Delta f_{pR2}$

| | |
|---|---|
| $\Delta f_{pT}$ = | 86.26 at ends |
| $\Delta f_{pT}$ = | 84.76 at center |

**PCI Losses**

**ELASTIC SHORTENING**

Modulus of Elasticity

concrete = 4700 ksi (1 day)
concrete = 5500 ksi (28days)
strand = 28500 ksi
$n_{one\ day}$ = 6.06
$n_{28\ days}$ = 5.18

Strands

total # = 9
total area = 1.953 $in^2$
tension after stressing = 202.20 ksi
elongation of the strands (in)

| | |
|---|---|
| 1 | 8.250 |
| 2 | 8.500 |
| 3 | 8.500 |
| 4 | 8.625 |
| 5 | 8.625 |
| 6 | 8.750 |
| 7 | 8.500 |
| 8 | 8.500 |
| 9 | |
| 10 | 8.375 |
| average = | 8.514 in. |
| length of strand = | 100 ft. |

Ppi = 394.91 kips
Kcir = 0.886

$f_{cir} = K_{cir}(P_{pi}(1/A_g + e^2/I_g)) - f_g$

e = 7.75 in.
$A_g$ = 163.25 $in^2$
$I_g$ = 12370 $in^4$
$f_g$ = 0 ksi at ends
$f_g$ = 0.090 ksi at center
$f_{cir}$ = 3.84 ksi at ends
$f_{cir}$ = 3.75 ksi at center

$ES = K_{es}nf_{cir}$

$K_{es}$ = 1.0

| | | |
|---|---|---|
| **ES =** | **23.30 ksi** | at ends |
| **ES =** | **22.75 ksi** | at center |

**CREEP**

$CR = K_{cr}n(f_{cir} - f_{cds})$

$K_{cr}$ = 2.0 for p/s members
$f_{cir}$ = 3.84 ksi at ends
$f_{cir}$ = 3.75 ksi at center

$f_{cds}$ = 0 ksi

| | | |
|---|---|---|
| CR = | 39.82 ksi | at ends |
| CR = | 38.88 ksi | at center |

**SHRINKAGE**

$SH = 8.2*10^{-6}K_{sh}E_s(1 - 0.06V/S)(100 - RH)$

RH = 65 %
Volume = 47016 $in^3$
Surface Area = 28224 $in^2$
V/A = 1.67
$K_{sh}$ = 1
$E_s$ = 28500 ksi

| | |
|---|---|
| SH = | 7.36 ksi |

$f_g = M_G e/I$

w = 166.54 lb/ft
$M_G$ = 143.89 k - in

**RELAXATION**

$RE = ( K_{re} - J(SH + CR + ES))C$

$K_{re}$ = 5

J = 0.040

SH = 7.36 ksi

CR = 39.82 ksi at ends

CR = 38.88 ksi at center

ES = 23.30 ksi at ends

ES = 22.75 ksi at center

C = 1.00

$f_{pi}$ = 202.20 ksi

$f_{pu}$ = 270 ksi

$f_{pi}/f_{pu}$ = 0.75

| |
|---|
| RE = 2.18 ksi at ends |
| RE = 2.24 ksi at center |

**Total Losses**

ES = 23.30 ksi at ends

ES = 22.75 ksi at center

CR = 39.82 ksi at ends

CR = 38.88 ksi at center

SH = 7.36 ksi

RE = 2.18 ksi at ends

RE = 2.24 ksi at center

| |
|---|
| **Total Losses at Ends = 72.66 ksi** |
| **Total Losses at Center = 71.24 ksi** |

The following pages contain the prestress loss calculations (AASHTO and PCI) for Girder/Beam 3.

## BEAM 3

**Section Properties**

Sb = 899.63 $in^3$

Area = 163.25 $in^2$

y = 13.75 in.

cgs = 7 in.

e = 6.75

**Strand Properties**

fse = 185 ksi

Area = 0.217 $in^2$

Fse = 321.16 kips

Total number of strands = 8

**Concrete Properties**

fci = 6.127 ksi

fc = 10 ksi

Total Air Content = 6%

Unit Weight = 146.9 $lb/ft^3$

| Number of Strands (1) | Distance from bottom fiber (2) | 1*2 |
|---|---|---|
| 3 | 2 | 6 |
| 1 | 4 | 4 |
| 1 | 6 | 6 |
| 1 | 8 | 8 |
| 1 | 10 | 10 |
| 1 | 22 | 22 |

**fbot = -Fse(1/A+e/Sb)**

Fse = 321.16

1/A = 0.006125574

e/sb = 0.007503085

fbot = -4.376980084 ksi

| **fbot/fci = -0.714375728** | **-71.44 %** |
|---|---|

**AASHTO Losses**

**ELASTIC SHORTENING**

Modulus of Elasticity

| | |
|---|---|
| concrete = | 4700 ksi (1 day) |
| strand = | 28500 ksi |
| n = | 6.06 |

Strands

| | |
|---|---|
| total # = | 8 |
| total area = | 1.736 $in^2$ |
| $f_{pu}$ = | 270 ksi |
| tension after stressing = | 200.76 ksi |

elongation of the strands (in)

| | |
|---|---|
| 1 | 8.250 |
| 2 | 8.500 |
| 3 | 8.500 |
| 4 | |
| 5 | 8.625 |
| 6 | |
| 7 | 8.500 |
| 8 | 8.500 |
| 9 | 8.375 |
| 10 | 8.375 |
| average elongation = | 8.453 in. |
| length of strand = | 100 ft |

$f_{cgp} = F/A + Fe^2/I - M_G e/I$

| | | |
|---|---|---|
| F (Ppi) = | 348.52 kips | |
| $M_G$ = | 0 at ends | |
| $M_G$ = | 143.89 k - in | at center |
| w = | 166.5377 lb/ft | |
| $f_{cgp}$ = | 3.42 ksi | at ends |
| $f_{cgp}$ = | 3.34 ksi | at center |

$\Delta f_{pES} = (E_p/E_{ci})f_{cgp}$ section 5.9.5.2.3a

| | | |
|---|---|---|
| $\Delta f_{pES}$ = | 20.73 ksi | at ends |
| $\Delta f_{pES}$ = | 20.25 ksi | at center |

**CREEP**

$\Delta f_{pCR} = 12.0 f_{cgp} - 7.0 \Delta f_{cdp}$

$\Delta f_{cdp}$ = 0 ksi

| | | |
|---|---|---|
| $f_{cgp}$ = | 3.42 ksi | at ends |
| $f_{cgp}$ = | 3.34 ksi | at center |

| | | |
|---|---|---|
| $\Delta f_{pCR}$ = | 41.02 ksi | at ends |
| $\Delta f_{pCR}$ = | 40.08 ksi | at center |

**SHRINKAGE**

$\Delta f_{pSR} = (17.0 - 0.150\ H)$

H = 65 %

| | |
|---|---|
| $\Delta f_{pSR}$ = | 7.25 |

**RELAXATION**

$\Delta f_{pR2} = (20 - 0.4\Delta f_{pES} - 0.2(\Delta f_{pSR} + \Delta f_{pCR}))*0.30$

| | | |
|---|---|---|
| $\Delta f_{pES}$ = | 20.73 ksi | at ends |
| $\Delta f_{pES}$ = | 20.25 ksi | at center |
| $\Delta f_{pSR}$ = | 7.25 | |
| $\Delta f_{pCR}$ = | 41.02 ksi | at ends |
| $\Delta f_{pCR}$ = | 40.08 ksi | at center |

| | | |
|---|---|---|
| $\Delta f_{pR2}$ = | 0.62 ksi | at ends |
| $\Delta f_{pR2}$ = | 0.73 ksi | at center |

$\Delta f_{pR1} = (\log(24.0t)/40.0)(f_{pj}/f_{py} - 0.55)f_{pj}$

| | |
|---|---|
| t = | 1 day |
| $f_{pj}$ = | 200.76 ksi |
| $f_{py}$ = | 270 ksi |

| | |
|---|---|
| $\Delta f_{pR1}$ = | 1.34 ksi |

**TOTAL LOSSES**

$\Delta f_{pT} = \Delta f_{pES} + \Delta f_{pSR} + \Delta f_{pCR} + \Delta f_{pR1} + \Delta f_{pR2}$

| | |
|---|---|
| $\Delta f_{pT}$ = | 70.96 at ends |
| $\Delta f_{pT}$ = | 69.66 at center |

**PCI Losses**

**ELASTIC SHORTENING**

Modulus of Elasticity

concrete = 4700 ksi (1 day)
concrete = 5500 ksi (28 days)
strand = 28500 ksi
$n_{one\ day}$ = 6.06
$n_{28\ days}$ = 5.18

Strands

total # = 8
total area = 1.736 $in^2$
tension after stressing = 200.76 ksi
elongation of the strands (in)

| | |
|---|---|
| 1 | 8.250 |
| 2 | 8.500 |
| 3 | 8.500 |
| 4 | |
| 5 | 8.625 |
| 6 | |
| 7 | 8.500 |
| 8 | 8.500 |
| 9 | 8.375 |
| 10 | 8.375 |

average = 8.453 in.
length of strand = 100 ft.

Ppi = 348.52 kips
Kcir = 0.91

$f_{cir} = K_{cir}(P_{pi}(1/A_g + e^2/I_g)) - f_g$

e = 6.75 in.
$A_g$ = 163.25 $in^2$
$I_g$ = 12370 $in^4$
$f_g$ = 0 ksi at ends
$f_g$ = 0.079 ksi at center
$f_{cir}$ = 3.11 ksi at ends
$f_{cir}$ = 3.03 ksi at center

$ES = K_{es}nf_{cir}$

$K_{es}$ = 1.0

| | |
|---|---|
| **ES = 18.86 ksi** | at ends |
| **ES = 18.39 ksi** | at center |

**CREEP**

$CR = K_{cr}n(f_{cir} - f_{cds})$

$K_{cr}$ = 2.0 for p/s members
$f_{cir}$ = 3.11 ksi at ends
$f_{cir}$ = 3.03 ksi at center

$f_{cds}$ = 0 ksi

| | | |
|---|---|---|
| CR = | 32.24 ksi | at ends |
| CR = | 31.43 ksi | at center |

**SHRINKAGE**

$SH = 8.2*10^{-6}K_{sh}E_s(1 - 0.06V/S)(100 - RH)$

RH = 65 %
Volume = 47016 $in^3$
Surface Area = 28224 $in^2$
V/A = 1.67
$K_{sh}$ = 1
$E_s$ = 28500 ksi

| | |
|---|---|
| SH = | 7.36 ksi |

$f_g = M_G e/I$

w = 166.54 lb/ft
$M_G$ = 143.89 k - in

**RELAXATION**

$RE = ( K_{re} - J(SH + CR + ES))C$

$K_{re}$ = 5

J = 0.040

SH = 7.36 ksi

CR = 32.24 ksi at ends

CR = 31.43 ksi at center

ES = 18.86 ksi at ends

ES = 18.39 ksi at center

C = 0.95

$f_{pi}$ = 200.76 ksi

$f_{pu}$ = 270 ksi

$f_{pi}/f_{pu}$ = 0.74

| |
|---|
| RE = 2.53 ksi at ends |
| RE = 2.58 ksi at center |

**Total Losses**

ES = 18.86 ksi at ends

ES = 18.39 ksi at center

CR = 32.24 ksi at ends

CR = 31.43 ksi at center

SH = 7.36 ksi

RE = 2.53 ksi at ends

RE = 2.58 ksi at center

| |
|---|
| **Total Losses at Ends = 61.00 ksi** |
| **Total Losses at Center = 59.75 ksi** |

The following pages contain the prestress loss calculations (AASHTO and PCI) for Girder/Beam 4.

## BEAM 4

**Section Properties**

Sb = 899.63 $in^3$

Area = 163.25 $in^2$

y = 13.75 in.

cgs = 5.75 in.

e = 8

**Strand Properties**

fse = 185 ksi

Area = 0.217 $in^2$

Fse = 321.16 kips

Total number of strands = 8

**Concrete Properties**

fci = 8.696 ksi

fc = 10 ksi

Total Air Content = 2%

Unit Weight = 151.1 $lb/ft^3$

| Number of Strands (1) | Distance from bottom fiber (2) | 1*2 |
|---|---|---|
| 3 | 2 | 6 |
| 3 | 4 | 12 |
| 1 | 6 | 6 |
| 0 | 8 | 0 |
| 0 | 10 | 0 |
| 1 | 22 | 22 |

**fbot = -Fse(1/A+e/Sb)**

Fse = 321.16

1/A = 0.006125574

e/sb = 0.008892545

fbot = -4.823219093 ksi

| **fbot/fci = -0.55464801** | **-55.46 %** |
|---|---|

**AASHTO Losses**

**ELASTIC SHORTENING**

Modulus of Elasticity

| | |
|---|---|
| concrete = | 5600 ksi (1 day) |
| strand = | 28500 ksi |
| n = | 5.09 |

Strands

| | |
|---|---|
| total # = | 8 |
| total area = | 1.736 $in^2$ |
| $f_{pu}$ = | 270 ksi |
| tension after stressing = | 204.47 ksi |

elongation of the strands (in)

| | |
|---|---|
| 1 | 8.750 |
| 2 | 8.750 |
| 3 | 8.750 |
| 4 | 8.250 |
| 5 | 8.500 |
| 6 | 8.500 |
| 7 | 8.625 |
| 8 | |
| 9 | |
| 10 | 8.750 |
| average elongation = | 8.609 in. |
| length of strand = | 100 ft |

$f_{cgp} = F/A + Fe^2/I - M_G e/I$

| | | |
|---|---|---|
| F (Ppi) = | 354.96 kips | |
| $M_G$ = | 0 at ends | |
| $M_G$ = | 148.00 k - in | at center |
| w = | 171.30 lb/ft | |
| $f_{cgp}$ = | 4.01 ksi | at ends |
| $f_{cgp}$ = | 3.92 ksi | at center |

$\Delta f_{pES} = (E_p/E_{ci})f_{cgp}$ section 5.9.5.2.3a

| | | |
|---|---|---|
| $\Delta f_{pES}$ = | 20.41 ksi | at ends |
| $\Delta f_{pES}$ = | 19.93 ksi | at center |

**CREEP**

$\Delta f_{pCR} = 12.0 f_{cgp} - 7.0 \Delta f_{cdp}$

$\Delta f_{cdp}$ = 0 ksi

| | | |
|---|---|---|
| $f_{cgp}$ = | 4.01 ksi | at ends |
| $f_{cgp}$ = | 3.92 ksi | at center |

| | | |
|---|---|---|
| $\Delta f_{pCR}$ = | 48.13 ksi | at ends |
| $\Delta f_{pCR}$ = | 46.98 ksi | at center |

**SHRINKAGE**

$\Delta f_{pSR} = (17.0 - 0.150\ H)$

H = 65 %

| | |
|---|---|
| $\Delta f_{pSR}$ = | 7.25 |

**RELAXATION**

$\Delta f_{pR2} = (20 - 0.4\Delta f_{pES} - 0.2(\Delta f_{pSR} + \Delta f_{pCR}))*0.30$

| | | |
|---|---|---|
| $\Delta f_{pES}$ = | 20.41 ksi | at ends |
| $\Delta f_{pES}$ = | 19.93 ksi | at center |
| $\Delta f_{pSR}$ = | 7.25 | |
| $\Delta f_{pCR}$ = | 48.13 ksi | at ends |
| $\Delta f_{pCR}$ = | 46.98 ksi | at center |

| | | |
|---|---|---|
| $\Delta f_{pR2}$ = | 0.23 ksi | at ends |
| $\Delta f_{pR2}$ = | 0.36 ksi | at center |

$\Delta f_{pR1} = (\log(24.0t)/40.0)(f_{pj}/f_{py} - 0.55)f_{pj}$

| | |
|---|---|
| t = | 1 day |
| $f_{pj}$ = | 204.4727 ksi |
| $f_{py}$ = | 270 ksi |

| | |
|---|---|
| $\Delta f_{pR1}$ = | 1.46 ksi |

**TOTAL LOSSES**

$\Delta f_{pT} = \Delta f_{pES} + \Delta f_{pSR} + \Delta f_{pCR} + \Delta f_{pR1} + \Delta f_{pR2}$

| | |
|---|---|
| $\Delta f_{pT}$ = | 77.48 at ends |
| $\Delta f_{pT}$ = | 75.97 at center |

**PCI Losses**

**ELASTIC SHORTENING**

Modulus of Elasticity

concrete = 5600 ksi (I day)
concrete = 6000 ksi (28 days)
strand = 28500 ksi
$n_{one\ day}$ = 5.09
$n_{28\ days}$ = 4.75

Strands

total # = 8
total area = 1.736 $in^2$
tension after stressing = 204.47 ksi
elongation of the strands (in)

| | |
|---|---|
| 1 | 8.750 |
| 2 | 8.750 |
| 3 | 8.750 |
| 4 | 8.250 |
| 5 | 8.500 |
| 6 | 8.500 |
| 7 | 8.625 |
| 8 | |
| 9 | |
| 10 | 8.750 |

average = 8.609 in.
length of strand = 100 ft.

Ppi = 354.96 kips
Kcir = 0.91

$f_{cir} = K_{cir}(P_{pi}(1/A_g + e^2/I_g)) - f_g$

e = 8 in.
$A_g$ = 163.25 $in^2$
$I_g$ = 12370 $in^4$
$f_g$ = 0 ksi at ends
$f_g$ = 0.096 ksi at center
$f_{cir}$ = 3.65 ksi at ends
$f_{cir}$ = 3.55 ksi at center

$ES = K_{es}nf_{cir}$

$K_{es}$ = 1.0

| | | |
|---|---|---|
| **ES =** | **18.58 ksi** | at ends |
| **ES =** | **18.09 ksi** | at center |

**CREEP**

$CR = K_{cr}n(f_{cir} - f_{cds})$

$K_{cr}$ = 2.0 for p/s members
$f_{cir}$ = 3.65 ksi at ends
$f_{cir}$ = 3.55 ksi at center

$f_{cds}$ = 0 ksi

| | | |
|---|---|---|
| CR = | 34.67 ksi | at ends |
| CR = | 33.76 ksi | at center |

**SHRINKAGE**

$SH = 8.2*10^{-6}K_{sh}E_s(1 - 0.06V/S)(100 - RH)$

RH = 65 %
Volume = 47016 $in^3$
Surface Area = 28224 $in^2$
V/A = 1.67
$K_{sh}$ = 1
$E_s$ = 28500 ksi

| | |
|---|---|
| SH = | 7.36 ksi |

$f_g = M_G e/I$

w = 171.30 lb/ft
$M_G$ = 148.00 k - in

**RELAXATION**

$RE = ( K_{re} - J(SH + CR + ES))C$

| | |
|---|---|
| $K_{re}$ = | 5 |
| J = | 0.040 |
| SH = | 7.36 ksi |
| CR = | 34.67 ksi at ends |
| CR = | 33.76 ksi at center |
| ES = | 18.58 ksi at ends |
| ES = | 18.09 ksi at center |
| C = | 1.05 |
| $f_{pi}$ = | 204.47 ksi |
| $f_{pu}$ = | 270 ksi |
| $f_{pi}/f_{pu}$ = | 0.76 |

| | |
|---|---|
| RE = | 2.70 ksi at ends |
| RE = | 2.76 ksi at center |

**Total Losses**

| | | |
|---|---|---|
| ES = | 18.58 ksi | at ends |
| ES = | 18.09 ksi | at center |
| CR = | 34.67 ksi | at ends |
| CR = | 33.76 ksi | at center |
| SH = | 7.36 ksi | |
| RE = | 2.70 ksi | at ends |
| RE = | 2.76 ksi | at center |

| | |
|---|---|
| **Total Losses at Ends =** | **63.32 ksi** |
| **Total Losses at Center =** | **61.98 ksi** |

The following pages contain the strain measurements for Girder/Beam 1.

**Beam 1**

| | | Before Cutting 12/20/00 East | | Before Cutting 12/20/00 West | | After Cutting 12/20/00 East | | After Cutting 12/20/00 West | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| North | | | | | | | | | | | Strain | Microstrain | Losses (ksi) |
| Top | 60 - 68 | 770 | 766 | 814 | 816 | 768 | 768 | 812 | 811 | 1.75 | 1.42E-05 | 14 | 0.40 |
| | 68 - 76 | 655 | 658 | 186 | 190 | 591 | 592 | 109 | 111 | 71.50 | 0.000579 | 579 | 16.51 |
| Bottom | 60 - 68 | 783 | 778 | 787 | 787 | 661 | 662 | 664 | 663 | 121.25 | 0.000982 | 982 | 27.99 |
| | 68 - 76 | 1160 | 1157 | 829 | 827 | 1035 | 1034 | 699 | 698 | 126.75 | 0.001027 | 1027 | 29.26 |
| Top | 144 - 152 | 830 | 826 | 778 | 771 | 819 | 819 | 773 | 774 | 5.00 | 4.05E-05 | 41 | 1.15 |
| | 152 - 160 | 772 | 768 | 836 | 833 | 760 | 760 | 824 | 823 | 10.50 | 8.51E-05 | 85 | 2.42 |
| Bottom | 144 - 152 | 826 | 825 | 803 | 803 | 705 | 705 | 690 | 688 | 117.25 | 0.00095 | 950 | 27.07 |
| | 152 - 160 | 751 | 747 | 50 | 35 | 629 | 629 | | | 120.00 | 0.000972 | 972 | 27.70 |
| South | | | | | | | | | | | | | 0.00 |
| Top | 60 - 68 | 972 | 970 | 770 | 771 | 964 | 965 | 763 | 762 | 7.25 | 5.87E-05 | 59 | 1.67 |
| | 68 - 76 | 843 | 849 | 788 | 788 | 795 | 794 | 731 | 731 | 54.25 | 0.000439 | 439 | 12.52 |
| Bottom | 60 - 68 | 792 | 799 | 1495 | 1501 | 681 | 681 | 1397 | 1394 | 108.50 | 0.000879 | 879 | 25.05 |
| | 68 - 76 | 1018 | 1015 | 757 | 752 | 899 | 898 | 636 | 638 | 117.75 | 0.000954 | 954 | 27.18 |

Distance for DEMEC to extreme fiber = 19
c.g.s without top strand = 4.67

| **North End** | | **At C.G.S.** | | **Average** |
|---|---|---|---|---|
| | Slope | Strain | Stress (ksi) | |
| Distance = 60 - 68 | 50.94 | 998.94 | 28.47 | 28.98 |
| Distance = 68 - 76 | 23.55 | 1034.45 | 29.48 | |

| **Center** | | **At C.G.S.** | | |
|---|---|---|---|---|
| | Slope | Strain | Stress (ksi) | |
| Distance = 144 - 152 | 47.85 | 965.52 | 27.52 | 27.83 |
| Distance = 152 - 160 | 47.85 | 987.79 | 28.15 | |

| **South End** | | **At C.G.S.** | | |
|---|---|---|---|---|
| | Slope | Strain | Stress (ksi) | |
| Distance = 60 - 68 | 43.16 | 893.09 | 25.45 | 26.45 |
| Distance = 68 - 76 | 27.07 | 962.71 | 27.44 | |

5-Jan-01

| | | East | | West | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| North | | | | | | | Strain | Microstrain | Losses (ksi) |
| Top | 60 - 68 | 760 | 760 | 796 | 795 | 13.75 | 0.000111 | 111 | 3.17 |
| | 68 - 76 | 577 | 577 | 135 | 137 | 65.75 | 0.000533 | 533 | 15.18 |
| Bottom | 60 - 68 | 609 | 609 | 614 | 614 | 172.25 | 0.001395 | 1395 | 39.76 |
| | 68 - 76 | 985 | 984 | 651 | 652 | 175.25 | 0.00142 | 1420 | 40.46 |
| Top | 144 - 152 | 805 | 806 | 756 | 756 | 20.50 | 0.000166 | 166 | 4.73 |
| | 152 - 160 | 747 | 747 | 805 | 806 | 26.00 | 0.000211 | 211 | 6.00 |
| Bottom | 144 - 152 | 651 | 653 | 640 | 640 | 168.25 | 0.001363 | 1363 | 38.84 |
| | 152 - 160 | 577 | 576 | | | 172.50 | 0.001397 | 1397 | 39.82 |
| South | | | | | | | | | |
| Top | 60 - 68 | 954 | 953 | 746 | 746 | 21.00 | 0.00017 | 170 | 4.85 |
| | 68 - 76 | 778 | 779 | 713 | 712 | 71.50 | 0.000579 | 579 | 16.51 |
| Bottom | 60 - 68 | 630 | 629 | 1342 | 1342 | 161.00 | 0.001304 | 1304 | 37.17 |
| | 68 - 76 | 844 | 845 | 588 | 588 | 169.25 | 0.001371 | 1371 | 39.07 |

Distance for DEMEC to extreme fiber = 19
c.g.s without top strand = 4.67

| **North End** | | **At C.G.S.** | | **Average** |
|---|---|---|---|---|
| | Slope | Strain | Stress (ksi) | |
| Distance = 60 - 68 | 67.57 | 1417.52 | 40.40 | 40.65 |
| Distance = 68 - 76 | 46.68 | 1434.93 | 40.90 | |

| **Center** | | **At C.G.S.** | | |
|---|---|---|---|---|
| | Slope | Strain | Stress (ksi) | |
| Distance = 144 - 152 | 62.99 | 1383.61 | 39.43 | 39.92 |
| Distance = 152 - 160 | 62.99 | 1418.04 | 40.41 | |

| **South End** | | **At C.G.S.** | | |
|---|---|---|---|---|
| | Slope | Strain | Stress (ksi) | |
| Distance = 60 - 68 | 59.68 | 1323.80 | 37.73 | 38.60 |
| Distance = 68 - 76 | 41.67 | 1384.68 | 39.46 | |

18-Jan-01

| | | East | | West | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| North | | | | | | | Strain | Microstrain | Losses (ksi) |
| Top | 60 - 68 | 764 | 763 | 806 | 804 | 7.25 | 5.87E-05 | 59 | 1.67 |
| | 68 - 76 | 583 | 584 | 110 | 115 | 74.25 | 0.000601 | 601 | 17.14 |
| Bottom | 60 - 68 | 605 | 605 | 611 | 612 | 175.50 | 0.001422 | 1422 | 40.51 |
| | 68 - 76 | 981 | 981 | 650 | 650 | 177.75 | 0.00144 | 1440 | 41.03 |
| Top | 144 - 152 | 816 | 817 | 765 | 766 | 10.25 | 8.3E-05 | 83 | 2.37 |
| | 152 - 160 | 754 | 754 | 814 | 813 | 18.50 | 0.00015 | 150 | 4.27 |
| Bottom | 144 - 152 | 650 | 652 | 641 | 642 | 168.00 | 0.001361 | 1361 | 38.78 |
| | 152 - 160 | 575 | 574 | | | 174.50 | 0.001413 | 1413 | 40.28 |
| South | | | | | | | | | |
| Top | 60 - 68 | 968 | 968 | 760 | 759 | 7.00 | 5.67E-05 | 57 | 1.62 |
| | 68 - 76 | 791 | 791 | 725 | 726 | 58.75 | 0.000476 | 476 | 13.56 |
| Bottom | 60 - 68 | 627 | 627 | 1334 | 1335 | 166.00 | 0.001345 | 1345 | 38.32 |
| | 68 - 76 | 846 | 846 | 589 | 589 | 168.00 | 0.001361 | 1361 | 38.78 |

Distance for DEMEC to extreme fiber = 19
c.g.s without top strand = 4.67

| **North End** | | **At C.G.S.** | | **Average** |
|---|---|---|---|---|
| | Slope | Strain | Stress (ksi) | |
| Distance = 60 - 68 | 71.73 | 1445.22 | 41.19 | 41.32 |
| Distance = 68 - 76 | 44.12 | 1454.34 | 41.45 | |

| **Center** | | **At C.G.S.** | | |
|---|---|---|---|---|
| | Slope | Strain | Stress (ksi) | |
| Distance = 144 - 152 | 67.25 | 1382.99 | 39.42 | 40.17 |
| Distance = 152 - 160 | 67.25 | 1435.64 | 40.92 | |

| **South End** | | **At C.G.S.** | | |
|---|---|---|---|---|
| | Slope | Strain | Stress (ksi) | |
| Distance = 60 - 68 | 67.78 | 1366.97 | 38.96 | 39.09 |
| Distance = 68 - 76 | 46.58 | 1376.17 | 39.22 | |

2-Feb-01

| | | East | | West | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| North | | | | | | | Strain | Microstrain | Losses (ksi) |
| Top | 60 - 68 | 752 | 752 | 793 | 792 | 19.25 | 0.000156 | 156 | 4.44 |
| | 68 - 76 | 571 | 570 | 63 | 70 | 103.75 | 0.00084 | 840 | 23.95 |
| Bottom | 60 - 68 | 578 | 579 | 584 | 585 | 202.25 | 0.001638 | 1638 | 46.69 |
| | 68 - 76 | 955 | 955 | 625 | 626 | 203.00 | 0.001644 | 1644 | 46.86 |
| Top | 144 - 152 | 804 | 805 | 752 | 752 | 23.00 | 0.000186 | 186 | 5.31 |
| | 152 - 160 | 740 | 740 | 798 | 799 | 33.00 | 0.000267 | 267 | 7.62 |
| Bottom | 144 - 152 | 624 | 624 | 615 | 617 | 194.25 | 0.001573 | 1573 | 44.84 |
| | 152 - 160 | 550 | 550 | | | 199.00 | 0.001612 | 1612 | 45.94 |
| South | | | | | | | | | |
| Top | 60 - 68 | 950 | 948 | 742 | 743 | 25.00 | 0.000203 | 203 | 5.77 |
| | 68 - 76 | 778 | 779 | 715 | 715 | 70.25 | 0.000569 | 569 | 16.22 |
| Bottom | 60 - 68 | 604 | 603 | 1311 | 1311 | 189.50 | 0.001535 | 1535 | 43.75 |
| | 68 - 76 | 821 | 822 | 565 | 566 | 192.00 | 0.001555 | 1555 | 44.32 |

Distance for DEMEC to extreme fiber = 19
c.g.s without top strand = 4.67

| **North End** | | **At C.G.S.** | | **Average** |
|---|---|---|---|---|
| | Slope | Strain | Stress (ksi) | |
| Distance = 60 - 68 | 78.02 | 1663.97 | 47.42 | 47.34 |
| Distance = 68 - 76 | 42.31 | 1658.26 | 47.26 | |

| **Center** | | **At C.G.S.** | | |
|---|---|---|---|---|
| | Slope | Strain | Stress (ksi) | |
| Distance = 144 - 152 | 73.01 | 1597.52 | 45.53 | 46.08 |
| Distance = 152 - 160 | 73.01 | 1635.99 | 46.63 | |

| **South End** | | **At C.G.S.** | | |
|---|---|---|---|---|
| | Slope | Strain | Stress (ksi) | |
| Distance = 60 - 68 | 70.13 | 1558.09 | 44.41 | 44.61 |
| Distance = 68 - 76 | 51.90 | 1572.33 | 44.81 | |

19-Feb-01

| | | East | | West | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| North | | | | | | | Strain | Microstrain | Losses (ksi) |
| Top | 60 - 68 | 768 | 768 | 805 | 805 | 5.00 | 4.05E-05 | 41 | 1.15 |
| | 68 - 76 | 582 | 582 | 136 | 140 | 62.25 | 0.000504 | 504 | 14.37 |
| Bottom | 60 - 68 | 588 | 588 | 591 | 592 | 194.00 | 0.001571 | 1571 | 44.78 |
| | 68 - 76 | 961 | 961 | 629 | 629 | 198.25 | 0.001606 | 1606 | 45.77 |
| Top | 144 - 152 | 814 | 815 | 762 | 762 | 13.00 | 0.000105 | 105 | 3.00 |
| | 152 - 160 | 752 | 752 | 811 | 810 | 21.00 | 0.00017 | 170 | 4.85 |
| Bottom | 144 - 152 | 632 | 638 | 625 | 628 | 183.50 | 0.001486 | 1486 | 42.36 |
| | 152 - 160 | 557 | 555 | | | 193.00 | 0.001563 | 1563 | 44.55 |
| South | | | | | | | | | |
| Top | 60 - 68 | 931 | 935 | 755 | 758 | 26.00 | 0.000211 | 211 | 6.00 |
| | 68 - 76 | 783 | 783 | 720 | 721 | 65.25 | 0.000529 | 529 | 15.06 |
| Bottom | 60 - 68 | 609 | 610 | 1319 | 1320 | 182.25 | 0.001476 | 1476 | 42.07 |
| | 68 - 76 | 825 | 825 | 570 | 568 | 188.50 | 0.001527 | 1527 | 43.52 |

Distance for DEMEC to extreme fiber = 19
c.g.s without top strand = 4.67

| **North End** | | **At C.G.S.** | | **Average** |
|---|---|---|---|---|
| | Slope | Strain | Stress (ksi) | |
| Distance = 60 - 68 | 80.57 | 1597.99 | 45.54 | 45.93 |
| Distance = 68 - 76 | 57.98 | 1624.96 | 46.31 | |

| **Center** | | **At C.G.S.** | | |
|---|---|---|---|---|
| | Slope | Strain | Stress (ksi) | |
| Distance = 144 - 152 | 72.69 | 1510.34 | 43.04 | 44.14 |
| Distance = 152 - 160 | 72.69 | 1587.29 | 45.24 | |

| **South End** | | **At C.G.S.** | | |
|---|---|---|---|---|
| | Slope | Strain | Stress (ksi) | |
| Distance = 60 - 68 | 66.61 | 1498.21 | 42.70 | 43.35 |
| Distance = 68 - 76 | 52.54 | 1544.19 | 44.01 | |

14-Mar-01

| | | East | | West | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| North | | | | | | | Strain | Microstrain | Losses (ksi) |
| Top | 60 - 68 | 765 | 765 | 800 | 794 | 10.50 | 8.51E-05 | 85 | 2.42 |
| | 68 - 76 | 575 | 576 | | | 81.00 | 0.000656 | 656 | 18.70 |
| Bottom | 60 - 68 | 576 | 576 | 583 | 583 | 204.25 | 0.001654 | 1654 | 47.15 |
| | 68 - 76 | 954 | 954 | 620 | 621 | 206.00 | 0.001669 | 1669 | 47.56 |
| Top | 144 - 152 | 810 | 810 | 760 | 760 | 16.25 | 0.000132 | 132 | 3.75 |
| | 152 - 160 | 750 | 750 | 809 | 807 | 23.25 | 0.000188 | 188 | 5.37 |
| Bottom | 144 - 152 | 626 | 626 | 615 | 618 | 193.00 | 0.001563 | 1563 | 44.55 |
| | 152 - 160 | 550 | 550 | | | 199.00 | 0.001612 | 1612 | 45.94 |
| South | | | | | | | | | |
| Top | 60 - 68 | | | 759 | 760 | 11.00 | 8.91E-05 | 89 | 2.54 |
| | 68 - 76 | 784 | 783 | 720 | 720 | 65.25 | 0.000529 | 529 | 15.06 |
| Bottom | 60 - 68 | 605 | 605 | 1312 | 1312 | 188.25 | 0.001525 | 1525 | 43.46 |
| | 68 - 76 | 820 | 820 | 566 | 565 | 192.75 | 0.001561 | 1561 | 44.50 |

Distance for DEMEC to extreme fiber = 19

c.g.s without top strand = 4.67

| **North End** | | **At C.G.S.** | | **Average** |
|---|---|---|---|---|
| | Slope | Strain | Stress (ksi) | |
| Distance = 60 - 68 | 82.60 | 1681.68 | 47.93 | 47.99 |
| Distance = 68 - 76 | 53.29 | 1686.19 | 48.06 | |

| **Center** | | **At C.G.S.** | | |
|---|---|---|---|---|
| | Slope | Strain | Stress (ksi) | |
| Distance = 144 - 152 | 75.35 | 1588.17 | 45.26 | 45.96 |
| Distance = 152 - 160 | 75.35 | 1636.77 | 46.65 | |

| **South End** | | **At C.G.S.** | | |
|---|---|---|---|---|
| | Slope | Strain | Stress (ksi) | |
| Distance = 60 - 68 | 75.56 | 1549.76 | 44.17 | 44.59 |
| Distance = 68 - 76 | 54.36 | 1579.21 | 45.01 | |

19-Apr-01

| | | East | | West | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| North | | | | | | | Strain | Microstrain | Losses (ksi) |
| Top | 60 - 68 | 767 | 768 | 803 | 800 | 7.00 | 0.0000567 | 57 | 1.62 |
| | 68 - 76 | 580 | 581 | 125 | 125 | 69.50 | 0.00056295 | 563 | 16.04 |
| Bottom | 60 - 68 | 571 | 571 | 576 | 576 | 210.25 | 0.00170303 | 1703 | 48.54 |
| | 68 - 76 | 948 | 945 | 612 | 611 | 214.25 | 0.00173543 | 1735 | 49.46 |
| Top | 144 - 152 | 815 | 813 | 760 | 759 | 14.50 | 0.00011745 | 117 | 3.35 |
| | 152 - 160 | 751 | 750 | 810 | 809 | 22.25 | 0.00018023 | 180 | 5.14 |
| Bottom | 144 - 152 | 623 | 621 | 611 | 611 | 197.75 | 0.00160178 | 1602 | 45.65 |
| | 152 - 160 | 543 | | | | 208.00 | 0.0016848 | 1685 | 48.02 |
| South | | | | | | | | | |
| Top | 60 - 68 | | | 761 | 762 | 9.00 | 0.0000729 | 73 | 2.08 |
| | 68 - 76 | 791 | 791 | 726 | 725 | 58.75 | 0.00047588 | 476 | 13.56 |
| Bottom | 60 - 68 | 596 | 597 | 1302 | 1302 | 197.50 | 0.00159975 | 1600 | 45.59 |
| | 68 - 76 | 815 | 815 | 562 | 561 | 197.25 | 0.00159773 | 1598 | 45.54 |

Distance for DEMEC to extreme fiber = 19
c.g.s without top strand = 4.67

| **North End** | | **At C.G.S.** | | **Average** |
|---|---|---|---|---|
| | Slope | Strain | Stress (ksi) | |
| Distance = 60 - 68 | 86.65 | 1731.62 | 49.35 | 49.70 |
| Distance = 68 - 76 | 61.71 | 1755.79 | 50.04 | |

| **Center** | | **At C.G.S.** | | |
|---|---|---|---|---|
| | Slope | Strain | Stress (ksi) | |
| Distance = 144 - 152 | 78.12 | 1627.56 | 46.39 | 47.57 |
| Distance = 152 - 160 | 78.12 | 1710.58 | 48.75 | |

| **South End** | | **At C.G.S.** | | |
|---|---|---|---|---|
| | Slope | Strain | Stress (ksi) | |
| Distance = 60 - 68 | 80.36 | 1626.27 | 46.35 | 46.22 |
| Distance = 68 - 76 | 59.04 | 1617.21 | 46.09 | |

25-Jun-01 180 days

| | | East | | West | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| North | | | | | | | Strain | Microstrain | Losses (ksi) |
| Top | 60 - 68 | 760 | 760 | 790 | 792 | 16.00 | 0.00013 | 130 | 3.69 |
| | 68 - 76 | 572 | 570 | 135 | 135 | 69.25 | 0.000561 | 561 | 15.99 |
| Bottom | 60 - 68 | 550 | 552 | 558 | 559 | 229.00 | 0.001855 | 1855 | 52.86 |
| | 68 - 76 | 930 | 928 | 595 | 594 | 231.50 | 0.001875 | 1875 | 53.44 |
| Top | 144 - 152 | 808 | 810 | 753 | 752 | 20.50 | 0.000166 | 166 | 4.73 |
| | 152 - 160 | 745 | 742 | 798 | 798 | 31.50 | 0.000255 | 255 | 7.27 |
| Bottom | 144 - 152 | | | 591 | 591 | 212.00 | 0.001717 | 1717 | 48.94 |
| | 152 - 160 | | | | | #DIV/0! | #DIV/0! | #DIV/0! | #DIV/0! |
| South | | | | | | | | | |
| Top | 60 - 68 | | | 760 | 755 | 13.00 | 0.000105 | 105 | 3.00 |
| | 68 - 76 | 785 | 785 | 716 | 715 | 66.75 | 0.000541 | 541 | 15.41 |
| Bottom | 60 - 68 | 580 | 578 | 1286 | 1285 | 214.50 | 0.001737 | 1737 | 49.52 |
| | 68 - 76 | 795 | 795 | 537 | 538 | 219.25 | 0.001776 | 1776 | 50.61 |

Distance for DEMEC to extreme fiber = 19

c.g.s without top strand = 4.67

| **North End** | | **At C.G.S.** | | **Average** |
|---|---|---|---|---|
| | Slope | Strain | Stress (ksi) | |
| Distance = 60 - 68 | 90.81 | 1884.87 | 53.72 | 53.91 |
| Distance = 68 - 76 | 69.17 | 1897.98 | 54.09 | |

| **Center** | | **At C.G.S.** | | |
|---|---|---|---|---|
| | Slope | Strain | Stress (ksi) | |
| Distance = 144 - 152 | 81.64 | 1744.14 | 49.71 | 49.71 |
| Distance = 152 - 160 | 81.64 | #DIV/0! | #DIV/0! | |

| **South End** | | **At C.G.S.** | | |
|---|---|---|---|---|
| | Slope | Strain | Stress (ksi) | |
| Distance = 60 - 68 | 85.90 | 1765.80 | 50.33 | 50.78 |
| Distance = 68 - 76 | 65.01 | 1797.38 | 51.23 | |

21-Dec-01 360 days

| | | East | | West | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| North | | | | | | | Strain | Microstrain | Losses (ksi) |
| Top | 60 - 68 | 756 | 756 | 783 | 783 | 22.00 | 0.000178 | 178 | 5.08 |
| | 68 - 76 | 579 | 579 | | | -156.75 | -0.00127 | -1270 | -36.19 |
| Bottom | 60 - 68 | | | 542 | 545 | 243.50 | 0.001972 | 1972 | 56.21 |
| | 68 - 76 | | | 578 | 578 | 250.00 | 0.002025 | 2025 | 57.71 |
| Top | 144 - 152 | 798 | 795 | 742 | 744 | 31.50 | 0.000255 | 255 | 7.27 |
| | 152 - 160 | 738 | 739 | 799 | 799 | 33.50 | 0.000271 | 271 | 7.73 |
| Bottom | 144 - 152 | | | 576 | 575 | 227.50 | 0.001843 | 1843 | 52.52 |
| | 152 - 160 | | | | | #DIV/0! | #DIV/0! | #DIV/0! | #DIV/0! |
| South | | | | | | | | | |
| Top | 60 - 68 | | | 748 | 749 | 22.00 | 0.000178 | 178 | 5.08 |
| | 68 - 76 | 790 | 789 | 716 | 715 | 64.50 | 0.000522 | 522 | 14.89 |
| Bottom | 60 - 68 | 563 | 563 | 1263 | 1263 | 233.75 | 0.001893 | 1893 | 53.96 |
| | 68 - 76 | 777 | 778 | 523 | 522 | 235.50 | 0.001908 | 1908 | 54.37 |

Distance for DEMEC to extreme fiber = 19
c.g.s without top strand = 4.67

| **North End** | | **At C.G.S.** | | **Average** |
|---|---|---|---|---|
| | Slope | Strain | Stress (ksi) | |
| Distance = 60 - 68 | 94.43 | 2003.51 | 57.10 | 58.22 |
| Distance = 68 - 76 | 173.40 | 2082.22 | 59.34 | |

| **Center** | | **At C.G.S.** | | |
|---|---|---|---|---|
| | Slope | Strain | Stress (ksi) | |
| Distance = 144 - 152 | 83.56 | 1870.32 | 53.30 | 53.30 |
| Distance = 152 - 160 | 83.56 | #DIV/0! | #DIV/0! | |

| **South End** | | **At C.G.S.** | | |
|---|---|---|---|---|
| | Slope | Strain | Stress (ksi) | |
| Distance = 60 - 68 | 90.27 | 1923.16 | 54.81 | 54.93 |
| Distance = 68 - 76 | 72.90 | 1931.61 | 55.05 | |

The following pages contain the strain measurements for Girder 2/Beam 2.

| | | Before Cutting 12/22/00 East | | Before Cutting 12/22/00 West | | After Cutting 12/22/00 East | | After Cutting 12/22/00 West | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| North | | | | | | | | | | Difference | Strain | Microstrain | Losses (ksi) |
| Top | 60 - 68 | 689 | 689 | 822 | 824 | 684 | 684 | 821 | 821 | 3.50 | 2.835E-05 | 28 | 0.81 |
| | 68 - 76 | 669 | 668 | 762 | 761 | 663 | 662 | 759 | 759 | 4.25 | 3.443E-05 | 34 | 0.98 |
| Bottom | 60 - 68 | 733 | 733 | 800 | 801 | 594 | 594 | 665 | 664 | 137.50 | 0.0011138 | 1114 | 31.74 |
| | 68 - 76 | 742 | 742 | 803 | 803 | 600 | 601 | 661 | 661 | 141.75 | 0.0011482 | 1148 | 32.72 |
| Top | 144 - 152 | 957 | 959 | 835 | 835 | 952 | 953 | 826 | 827 | 7.00 | 0.0000567 | 57 | 1.62 |
| | 152 - 160 | 598 | 598 | 768 | 767 | 592 | 591 | 758 | 758 | 8.00 | 0.0000648 | 65 | 1.85 |
| Bottom | 144 - 152 | 239 | 237 | 809 | 810 | 98 | 95 | 672 | 673 | 139.25 | 0.0011279 | 1128 | 32.15 |
| | 152 - 160 | 1298 | 1299 | 774 | 775 | 1163 | 1164 | 632 | 636 | 137.75 | 0.0011158 | 1116 | 31.80 |
| South | | | | | | | | | | | | | 0.00 |
| Top | 60 - 68 | 824 | 824 | 795 | 795 | 821 | 820 | 792 | 791 | 3.50 | 2.835E-05 | 28 | 0.81 |
| | 68 - 76 | 791 | 791 | 813 | 813 | 787 | 786 | 810 | 810 | 3.75 | 3.038E-05 | 30 | 0.87 |
| Bottom | 60 - 68 | 1082 | 1084 | 773 | 772 | 951 | 952 | 644 | 645 | 129.75 | 0.001051 | 1051 | 29.95 |
| | 68 - 76 | 1072 | 1072 | 679 | 680 | 940 | 939 | 550 | 549 | 131.25 | 0.0010631 | 1063 | 30.30 |

Distance for DEMEC to extreme fiber = 19

c.g.s without top strand = 4

| North End | Slope | At C.G.S. Strain | Stress (ksi) | Average |
|---|---|---|---|---|
| Distance = 60 - 68 | 57.13 | 1170.88 | 33.37 | 33.88 |
| Distance = 68 - 76 | 58.62 | 1206.79 | 34.39 | |

| Center | Slope | At C.G.S. Strain | Stress (ksi) | |
|---|---|---|---|---|
| Distance = 144 - 152 | 56.38 | 1184.31 | 33.75 | 33.58 |
| Distance = 152 - 160 | 56.38 | 1172.16 | 33.41 | |

| South End | Slope | At C.G.S. Strain | Stress (ksi) | |
|---|---|---|---|---|
| Distance = 60 - 68 | 53.82 | 1104.80 | 31.49 | 31.67 |
| Distance = 68 - 76 | 54.36 | 1117.48 | 31.85 | |

5-Jan-01

| | | East | | West | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| North | | | | | | Difference | Strain | Microstrain | Losses (ksi) |
| Top | 60 - 68 | 678 | 678 | 813 | 813 | 10.50 | 0.00008505 | 85 | 2.42 |
| | 68 - 76 | 654 | 654 | 742 | 743 | 16.75 | 0.000135675 | 136 | 3.87 |
| Bottom | 60 - 68 | 522 | 522 | 588 | 589 | 211.50 | 0.00171315 | 1713 | 48.82 |
| | 68 - 76 | 526 | 525 | 583 | 583 | 218.25 | 0.001767825 | 1768 | 50.38 |
| Top | 144 - 152 | 948 | 948 | 819 | 820 | 12.75 | 0.000103275 | 103 | 2.94 |
| | 152 - 160 | 585 | 585 | 755 | 757 | 12.25 | 0.000099225 | 99 | 2.83 |
| Bottom | 144 - 152 | 21 | 20 | 595 | 596 | 215.75 | 0.001747575 | 1748 | 49.81 |
| | 152 - 160 | 1091 | 1091 | 556 | 557 | 212.75 | 0.001723275 | 1723 | 49.11 |
| South | | | | | | | | | |
| Top | 60 - 68 | 817 | 816 | 781 | 783 | 10.25 | 0.000083025 | 83 | 2.37 |
| | 68 - 76 | 780 | 780 | 804 | 802 | 10.50 | 0.00008505 | 85 | 2.42 |
| Bottom | 60 - 68 | 875 | 875 | 566 | 567 | 207.00 | 0.0016767 | 1677 | 47.79 |
| | 68 - 76 | 866 | 867 | 468 | 468 | 208.50 | 0.00168885 | 1689 | 48.13 |

Distance for DEMEC to extreme fiber = 19

c.g.s without top strand = 4

| **North End** | Slope | At C.G.S. Strain | Stress (ksi) | Average |
|---|---|---|---|---|
| Distance = 60 - 68 | 85.69 | 1798.84 | 51.27 | 52.05 |
| Distance = 68 - 76 | 85.90 | 1853.73 | 52.83 | |

| **Center** | Slope | At C.G.S. Strain | Stress (ksi) | |
|---|---|---|---|---|
| Distance = 144 - 152 | 86.54 | 1834.12 | 52.27 | 51.93 |
| Distance = 152 - 160 | 86.54 | 1809.82 | 51.58 | |

| **South End** | Slope | At C.G.S. Strain | Stress (ksi) | |
|---|---|---|---|---|
| Distance = 60 - 68 | 83.88 | 1760.58 | 50.18 | 50.36 |
| Distance = 68 - 76 | 84.41 | 1773.26 | 50.54 | |

18-Jan-01

| | | East | | West | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| North | | | | | | Difference | Strain | Microstrain | Losses (ksi) |
| Top | 60 - 68 | 673 | 675 | 812 | 813 | 12.75 | 0.000103275 | 103 | 2.94 |
| | 68 - 76 | 651 | 651 | 740 | 740 | 19.50 | 0.00015795 | 158 | 4.50 |
| Bottom | 60 - 68 | 510 | 510 | 575 | 574 | 224.50 | 0.00181845 | 1818 | 51.83 |
| | 68 - 76 | 513 | 513 | 572 | 573 | 229.75 | 0.001860975 | 1861 | 53.04 |
| Top | 144 - 152 | 939 | 941 | 820 | 821 | 16.25 | 0.000131625 | 132 | 3.75 |
| | 152 - 160 | 582 | 582 | 763 | 764 | 10.00 | 0.000081 | 81 | 2.31 |
| Bottom | 144 - 152 | 3 | 3 | 585 | 584 | 230.00 | 0.001863 | 1863 | 53.10 |
| | 152 - 160 | 1075 | 1077 | 544 | 543 | 226.75 | 0.001836675 | 1837 | 52.35 |
| South | | | | | | | | | |
| Top | 60 - 68 | 813 | 815 | 778 | 777 | 13.75 | 0.000111375 | 111 | 3.17 |
| | 68 - 76 | 779 | 780 | 809 | 809 | 7.75 | 0.000062775 | 63 | 1.79 |
| Bottom | 60 - 68 | 863 | 863 | 562 | 561 | 215.50 | 0.00174555 | 1746 | 49.75 |
| | 68 - 76 | 855 | 854 | 458 | 460 | 219.00 | 0.0017739 | 1774 | 50.56 |

Distance for DEMEC to extreme fiber = 19

c.g.s without top strand = 4

| **North End** | | **At C.G.S.** | | **Average** |
|---|---|---|---|---|
| | Slope | Strain | Stress (ksi) | |
| Distance = 60 - 68 | 90.27 | 1908.72 | 54.40 | 55.00 |
| Distance = 68 - 76 | 89.63 | 1950.61 | 55.59 | |

| **Center** | | **At C.G.S.** | | |
|---|---|---|---|---|
| | Slope | Strain | Stress (ksi) | |
| Distance = 144 - 152 | 91.13 | 1954.13 | 55.69 | 55.32 |
| Distance = 152 - 160 | 91.13 | 1927.80 | 54.94 | |

| **South End** | | **At C.G.S.** | | |
|---|---|---|---|---|
| | Slope | Strain | Stress (ksi) | |
| Distance = 60 - 68 | 86.01 | 1831.56 | 52.20 | 52.66 |
| Distance = 68 - 76 | 90.06 | 1863.96 | 53.12 | |

5-Feb-01

| | | East | | West | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| North | | | | | | Difference | Strain | Microstrain | Losses (ksi) |
| Top | 60 - 68 | 652 | 652 | 793 | 793 | 33.50 | 0.00027135 | 271 | 7.73 |
| | 68 - 76 | 633 | 633 | 720 | 721 | 38.25 | 0.000309825 | 310 | 8.83 |
| Bottom | 60 - 68 | 475 | 475 | 546 | 546 | 256.25 | 0.002075625 | 2076 | 59.16 |
| | 68 - 76 | 475 | 476 | 539 | 540 | 265.00 | 0.0021465 | 2147 | 61.18 |
| Top | 144 - 152 | 920 | 921 | 800 | 799 | 36.50 | 0.00029565 | 296 | 8.43 |
| | 152 - 160 | 562 | 562 | 738 | 737 | 33.00 | 0.0002673 | 267 | 7.62 |
| Bottom | 144 - 152 | | | 552 | 552 | 257.50 | 0.00208575 | 2086 | 59.44 |
| | 152 - 160 | 1042 | 1043 | 510 | 510 | 260.25 | 0.002108025 | 2108 | 60.08 |
| South | | | | | | | | | |
| Top | 60 - 68 | 793 | 792 | 755 | 755 | 35.75 | 0.000289575 | 290 | 8.25 |
| | 68 - 76 | 763 | 763 | 792 | 792 | 24.50 | 0.00019845 | 198 | 5.66 |
| Bottom | 60 - 68 | 828 | 830 | 528 | 527 | 249.50 | 0.00202095 | 2021 | 57.60 |
| | 68 - 76 | 822 | 822 | 427 | 426 | 251.50 | 0.00203715 | 2037 | 58.06 |

Distance for DEMEC to extreme fiber = 19

c.g.s without top strand = 4

| **North End** | Slope | At C.G.S. Strain | Stress (ksi) | Average |
|---|---|---|---|---|
| Distance = 60 - 68 | 94.96 | 2170.59 | 61.86 | 62.90 |
| Distance = 68 - 76 | 96.67 | 2243.17 | 63.93 | |

| **Center** | Slope | At C.G.S. Strain | Stress (ksi) | |
|---|---|---|---|---|
| Distance = 144 - 152 | 94.22 | 2179.97 | 62.13 | 62.45 |
| Distance = 152 - 160 | 94.22 | 2202.24 | 62.76 | |

| **South End** | Slope | At C.G.S. Strain | Stress (ksi) | |
|---|---|---|---|---|
| Distance = 60 - 68 | 91.13 | 2112.08 | 60.19 | 60.51 |
| Distance = 68 - 76 | 96.77 | 2133.92 | 60.82 | |

19-Feb-01

| | | East | | West | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| North | | | | | | Difference | Strain | Microstrain | Losses (ksi) |
| Top | 60 - 68 | 676 | 677 | 812 | 811 | 12.00 | 0.0000972 | 97 | 2.77 |
| | 68 - 76 | 648 | 648 | 731 | 731 | 25.50 | 0.00020655 | 207 | 5.89 |
| Bottom | 60 - 68 | 489 | 488 | 549 | 549 | 248.00 | 0.0020088 | 2009 | 57.25 |
| | 68 - 76 | 521 | | 550 | 551 | 242.00 | 0.0019602 | 1960 | 55.87 |
| Top | 144 - 152 | 943 | 944 | 822 | 821 | 14.00 | 0.0001134 | 113 | 3.23 |
| | 152 - 160 | 584 | 583 | 757 | 760 | 11.75 | 0.000095175 | 95 | 2.71 |
| Bottom | 144 - 152 | | | 562 | 564 | 246.50 | 0.00199665 | 1997 | 56.90 |
| | 152 - 160 | 1052 | 1053 | 519 | 518 | 251.00 | 0.0020331 | 2033 | 57.94 |
| South | | | | | | | | | |
| Top | 60 - 68 | 816 | 815 | 778 | 782 | 11.75 | 0.000095175 | 95 | 2.71 |
| | 68 - 76 | 782 | 782 | 802 | 803 | 9.75 | 0.000078975 | 79 | 2.25 |
| Bottom | 60 - 68 | 840 | 841 | 528 | 530 | 243.00 | 0.0019683 | 1968 | 56.10 |
| | 68 - 76 | 834 | 831 | 434 | 431 | 243.25 | 0.001970325 | 1970 | 56.15 |

Distance for DEMEC to extreme fiber = 19

c.g.s without top strand = 4

| **North End** | | **At C.G.S.** | | **Average** |
|---|---|---|---|---|
| | Slope | Strain | Stress (ksi) | |
| Distance = 60 - 68 | 100.61 | 2109.41 | 60.12 | 59.31 |
| Distance = 68 - 76 | 92.30 | 2052.50 | 58.50 | |

| **Center** | | **At C.G.S.** | | |
|---|---|---|---|---|
| | Slope | Strain | Stress (ksi) | |
| Distance = 144 - 152 | 99.12 | 2095.77 | 59.73 | 60.25 |
| Distance = 152 - 160 | 99.12 | 2132.22 | 60.77 | |

| **South End** | | **At C.G.S.** | | |
|---|---|---|---|---|
| | Slope | Strain | Stress (ksi) | |
| Distance = 60 - 68 | 98.59 | 2066.89 | 58.91 | 58.95 |
| Distance = 68 - 76 | 99.54 | 2069.87 | 58.99 | |

14-Mar-01

| | | East | | West | | Difference | Strain | Microstrain | Losses (ksi) |
|---|---|---|---|---|---|---|---|---|---|
| North | | | | | | | | | |
| Top | 60 - 68 | 662 | 663 | 804 | 804 | 22.75 | 0.000184275 | 184 | 5.25 |
| | 68 - 76 | 632 | 632 | 707 | 706 | 45.75 | 0.000370575 | 371 | 10.56 |
| Bottom | 60 - 68 | 468 | 470 | 534 | 535 | 265.00 | 0.0021465 | 2147 | 61.18 |
| | 68 - 76 | | | 536 | 536 | 267.00 | 0.0021627 | 2163 | 61.64 |
| Top | 144 - 152 | 929 | 928 | 810 | 810 | 27.25 | 0.000220725 | 221 | 6.29 |
| | 152 - 160 | 568 | 567 | 748 | 749 | 24.75 | 0.000200475 | 200 | 5.71 |
| Bottom | 144 - 152 | | | 548 | 545 | 263.00 | 0.0021303 | 2130 | 60.71 |
| | 152 - 160 | 1030 | 1029 | 506 | 505 | 269.00 | 0.0021789 | 2179 | 62.10 |
| South | | | | | | | | | |
| Top | 60 - 68 | 802 | 800 | 766 | 766 | 26.00 | 0.0002106 | 211 | 6.00 |
| | 68 - 76 | 772 | 772 | 799 | 795 | 17.50 | 0.00014175 | 142 | 4.04 |
| Bottom | 60 - 68 | 825 | 824 | 523 | 522 | 254.25 | 0.002059425 | 2059 | 58.69 |
| | 68 - 76 | 819 | 819 | 420 | 421 | 256.00 | 0.0020736 | 2074 | 59.10 |

Distance for DEMEC to extreme fiber = 19
c.g.s without top strand = 4

| **North End** | Slope | At C.G.S. Strain | Stress (ksi) | Average |
|---|---|---|---|---|
| Distance = 60 - 68 | 103.28 | 2249.78 | 64.12 | 64.22 |
| Distance = 68 - 76 | 94.32 | 2257.02 | 64.33 | |

| **Center** | Slope | At C.G.S. Strain | Stress (ksi) | |
|---|---|---|---|---|
| Distance = 144 - 152 | 100.50 | 2230.80 | 63.58 | 64.27 |
| Distance = 152 - 160 | 100.50 | 2279.40 | 64.96 | |

| **South End** | Slope | At C.G.S. Strain | Stress (ksi) | |
|---|---|---|---|---|
| Distance = 60 - 68 | 97.31 | 2156.73 | 61.47 | 61.73 |
| Distance = 68 - 76 | 101.68 | 2175.28 | 62.00 | |

19-Apr-01

| | | East | | West | | Difference | Strain | Microstrain | Losses (ksi) |
|---|---|---|---|---|---|---|---|---|---|
| North | | | | | | | | | |
| Top | 60 - 68 | 666 | 665 | 813 | 813 | 16.75 | 0.000136 | 136 | 3.87 |
| | 68 - 76 | 640 | 639 | 720 | 715 | 36.50 | 0.000296 | 296 | 8.43 |
| Bottom | 60 - 68 | 461 | 462 | 529 | 528 | 271.75 | 0.002201 | 2201 | 62.73 |
| | 68 - 76 | | | 532 | 532 | 271.00 | 0.002195 | 2195 | 62.56 |
| Top | 144 - 152 | 937 | 937 | 816 | 815 | 20.25 | 0.000164 | 164 | 4.67 |
| | 152 - 160 | 577 | 575 | 756 | 756 | 16.75 | 0.000136 | 136 | 3.87 |
| Bottom | 144 - 152 | | | 540 | 539 | 270.00 | 0.002187 | 2187 | 62.33 |
| | 152 - 160 | 1021 | 1022 | 501 | 502 | 275.00 | 0.002228 | 2228 | 63.48 |
| South | | | | | | | | | 0.00 |
| Top | 60 - 68 | 809 | 808 | 768 | 767 | 21.50 | 0.000174 | 174 | 4.96 |
| | 68 - 76 | 777 | 777 | 804 | 805 | 11.25 | 9.11E-05 | 91 | 2.60 |
| Bottom | 60 - 68 | 817 | 817 | 519 | 519 | 259.75 | 0.002104 | 2104 | 59.96 |
| | 68 - 76 | 813 | 813 | 415 | 415 | 261.75 | 0.00212 | 2120 | 60.42 |

Distance for DEMEC to extreme fiber = 19

c.g.s without top strand = 4

| **North End** | | **At C.G.S.** | | **Average** |
|---|---|---|---|---|
| | Slope | Strain | Stress (ksi) | |
| Distance = 60 - 68 | 108.71 | 2309.89 | 65.83 | 65.62 |
| Distance = 68 - 76 | 99.97 | 2295.07 | 65.41 | |

| **Center** | | **At C.G.S.** | | |
|---|---|---|---|---|
| | Slope | Strain | Stress (ksi) | |
| Distance = 144 - 152 | 106.47 | 2293.47 | 65.36 | 65.94 |
| Distance = 152 - 160 | 106.47 | 2333.97 | 66.52 | |

| **South End** | | **At C.G.S.** | | |
|---|---|---|---|---|
| | Slope | Strain | Stress (ksi) | |
| Distance = 60 - 68 | 101.57 | 2205.54 | 62.86 | 63.16 |
| Distance = 68 - 76 | 106.79 | 2226.97 | 63.47 | |

| | | 25-Jun-01 | | | 180 | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | East | | West | | | | | |
| North | | | | | | Difference | Strain | Microstrain | Losses (ksi) |
| Top | 60 - 68 | | | 790 | 796 | 30.00 | 0.000243 | 243 | 6.93 |
| | 68 - 76 | 630 | 630 | 709 | 710 | 45.25 | 0.000367 | 367 | 10.45 |
| Bottom | 60 - 68 | 445 | 445 | 510 | 508 | 289.75 | 0.002347 | 2347 | 66.89 |
| | 68 - 76 | | | 510 | 510 | 293.00 | 0.002373 | 2373 | 67.64 |
| Top | 144 - 152 | | | 810 | 811 | 24.50 | 0.000198 | 198 | 5.66 |
| | 152 - 160 | 565 | 565 | 745 | 744 | 28.00 | 0.000227 | 227 | 6.46 |
| Bottom | 144 - 152 | | | 518 | 516 | 292.50 | 0.002369 | 2369 | 67.52 |
| | 152 - 160 | 1000 | 1000 | 475 | 475 | 299.00 | 0.002422 | 2422 | 69.02 |
| South | | | | | | | | | 0.00 |
| Top | 60 - 68 | 802 | 802 | 761 | 763 | 27.50 | 0.000223 | 223 | 6.35 |
| | 68 - 76 | 771 | 775 | 803 | 803 | 14.00 | 0.000113 | 113 | 3.23 |
| Bottom | 60 - 68 | 800 | 800 | 500 | 500 | 277.75 | 0.00225 | 2250 | 64.12 |
| | 68 - 76 | 790 | 790 | 400 | 395 | 282.00 | 0.002284 | 2284 | 65.10 |

Distance for DEMEC to extreme fiber = 19

c.g.s without top strand = 4

| **North End** | | **At C.G.S.** | | **Average** |
|---|---|---|---|---|
| | Slope | Strain | Stress (ksi) | |
| Distance = 60 - 68 | 110.74 | 2457.71 | 70.04 | 70.35 |
| Distance = 68 - 76 | 105.62 | 2478.92 | 70.65 | |
| **Center** | | **At C.G.S.** | | |
| | Slope | Strain | Stress (ksi) | |
| Distance = 144 - 152 | 114.25 | 2483.50 | 70.78 | 71.53 |
| Distance = 152 - 160 | 114.25 | 2536.15 | 72.28 | |
| **South End** | | **At C.G.S.** | | |
| | Slope | Strain | Stress (ksi) | |
| Distance = 60 - 68 | 106.69 | 2356.46 | 67.16 | 67.76 |
| Distance = 68 - 76 | 114.25 | 2398.45 | 68.36 | |

| | | 21-Dec-01 | | | 360 | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | East | | West | | | | | |
| North | | | | | | Difference | Strain | Microstrain | Losses (ksi) |
| Top | 60 - 68 | | | 798 | 799 | 24.50 | 0.000198 | 198 | 5.66 |
| | 68 - 76 | 620 | 620 | 712 | 714 | 48.50 | 0.000393 | 393 | 11.20 |
| Bottom | 60 - 68 | 435 | 434 | 492 | 491 | 303.75 | 0.00246 | 2460 | 70.12 |
| | 68 - 76 | | | 502 | 503 | 300.50 | 0.002434 | 2434 | 69.37 |
| Top | 144 - 152 | | | 803 | 802 | 32.50 | 0.000263 | 263 | 7.50 |
| | 152 - 160 | 551 | 551 | 737 | 737 | 38.75 | 0.000314 | 314 | 8.95 |
| Bottom | 144 - 152 | | | 508 | 507 | 302.00 | 0.002446 | 2446 | 69.72 |
| | 152 - 160 | 987 | 987 | 464 | 464 | 311.00 | 0.002519 | 2519 | 71.79 |
| South | | | | | | | | | 0.00 |
| Top | 60 - 68 | 790 | 790 | | | 34.00 | 0.000275 | 275 | 7.85 |
| | 68 - 76 | 766 | 765 | | | 25.50 | 0.000207 | 207 | 5.89 |
| Bottom | 60 - 68 | 785 | 785 | 483 | 483 | 293.75 | 0.002379 | 2379 | 67.81 |
| | 68 - 76 | 781 | 782 | 384 | 384 | 293.00 | 0.002373 | 2373 | 67.64 |

Distance for DEMEC to extreme fiber = 19
c.g.s without top strand = 4

| **North End** | | **At C.G.S.** | | **Average** |
|---|---|---|---|---|
| | Slope | Strain | Stress (ksi) | |
| Distance = 60 - 68 | 119.05 | 2579.42 | 73.51 | 72.97 |
| Distance = 68 - 76 | 107.43 | 2541.48 | 72.43 | |

| **Center** | | **At C.G.S.** | | |
|---|---|---|---|---|
| | Slope | Strain | Stress (ksi) | |
| Distance = 144 - 152 | 114.89 | 2561.09 | 72.99 | 74.03 |
| Distance = 152 - 160 | 114.89 | 2633.99 | 75.07 | |

| **South End** | | **At C.G.S.** | | |
|---|---|---|---|---|
| | Slope | Strain | Stress (ksi) | |
| Distance = 60 - 68 | 110.74 | 2490.11 | 70.97 | 70.93 |
| Distance = 68 - 76 | 114.04 | 2487.34 | 70.89 | |

The following pages contain the strain measurements for Girder/Beam 3.

| | | Before Cutting 12/22/00 East | | Before Cutting 12/22/00 West | | After Cutting 12/22/00 East | | After Cutting 12/22/00 West | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| North | | | | | | | | | | Difference | Strain | Microstrain | Losses (ksi) |
| Top | 60 - 68 | 724 | 723 | 815 | 815 | 714 | 713 | 806 | 804 | 10.00 | 0.000081 | 81 | 2.31 |
| | 68 - 76 | 746 | 746 | 881 | 881 | 737 | 736 | 872 | 872 | 9.25 | 7.49E-05 | 75 | 2.14 |
| Bottom | 60 - 68 | 779 | 777 | 871 | 871 | 671 | 671 | 766 | 765 | 106.25 | 0.000861 | 861 | 24.53 |
| | 68 - 76 | 770 | 771 | 791 | 792 | 676 | 676 | 692 | 689 | 97.75 | 0.000792 | 792 | 22.57 |
| Top | 144 - 152 | 794 | 793 | 644 | 644 | 781 | 779 | 630 | 631 | 13.50 | 0.000109 | 109 | 3.12 |
| | 152 - 160 | 804 | 803 | 975 | 972 | 793 | 790 | 961 | 962 | 12.00 | 9.72E-05 | 97 | 2.77 |
| Bottom | 144 - 152 | 777 | 776 | 915 | 915 | 676 | 675 | 812 | 812 | 102.00 | 0.000826 | 826 | 23.55 |
| | 152 - 160 | 843 | 842 | 787 | 785 | 745 | 745 | 684 | 684 | 99.75 | 0.000808 | 808 | 23.03 |
| South | | | | | | | | | | | | | |
| Top | 60 - 68 | 768 | 768 | 747 | 745 | 756 | 757 | 736 | 735 | 11.00 | 8.91E-05 | 89 | 2.54 |
| | 68 - 76 | 732 | 731 | 767 | 767 | 723 | 723 | 756 | 757 | 9.50 | 7.7E-05 | 77 | 2.19 |
| Bottom | 60 - 68 | 614 | 614 | 774 | 774 | 513 | 512 | 623 | 674 | 113.50 | 0.000919 | 919 | 26.20 |
| | 68 - 76 | 782 | 781 | 953 | 954 | 682 | 683 | 847 | 846 | 103.00 | 0.000834 | 834 | 23.78 |

Distance for DEMEC to extreme fiber = 19
c.g.s without top strand = 4.86

| **North End** | | **At C.G.S.** | | **Average** |
|---|---|---|---|---|
| | Slope | Strain | Stress (ksi) | |
| Distance = 60 - 68 | 41.03 | 866.37 | 24.69 | 23.70 |
| Distance = 68 - 76 | 37.73 | 797.06 | 22.72 | |

| **Center** | | **At C.G.S.** | | |
|---|---|---|---|---|
| | Slope | Strain | Stress (ksi) | |
| Distance = 144 - 152 | 37.73 | 831.48 | 23.70 | 23.44 |
| Distance = 152 - 160 | 37.41 | 813.21 | 23.18 | |

| **South End** | | **At C.G.S.** | | |
|---|---|---|---|---|
| | Slope | Strain | Stress (ksi) | |
| Distance = 60 - 68 | 43.70 | 925.47 | 26.38 | 25.16 |
| Distance = 68 - 76 | 39.86 | 839.88 | 23.94 | |

18-Jan-01

| | | East | | West | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| North | | | | | | Difference | Strain | Microstrain | Losses (ksi) |
| Top | 60 - 68 | 708 | 707 | 798 | 798 | 16.50 | 0.00013365 | 134 | 3.81 |
| | 68 - 76 | 725 | 723 | 861 | 861 | 21.00 | 0.0001701 | 170 | 4.85 |
| Bottom | 60 - 68 | 597 | 595 | 683 | 682 | 185.25 | 0.001500525 | 1501 | 42.76 |
| | 68 - 76 | 595 | 593 | 609 | 609 | 179.50 | 0.00145395 | 1454 | 41.44 |
| Top | 144 - 152 | 766 | 766 | 618 | 618 | 26.75 | 0.000216675 | 217 | 6.18 |
| | 152 - 160 | 777 | 776 | 948 | 949 | 26.00 | 0.0002106 | 211 | 6.00 |
| Bottom | 144 - 152 | 601 | 604 | 737 | 737 | 176.00 | 0.0014256 | 1426 | 40.63 |
| | 152 - 160 | 663 | 664 | 605 | 605 | 180.00 | 0.001458 | 1458 | 41.55 |
| South | | | | | | | | | |
| Top | 60 - 68 | 746 | 747 | 719 | 720 | 24.00 | 0.0001944 | 194 | 5.54 |
| | 68 - 76 | 717 | 718 | 751 | 751 | 15.00 | 0.0001215 | 122 | 3.46 |
| Bottom | 60 - 68 | 429 | 429 | 595 | 596 | 181.75 | 0.001472175 | 1472 | 41.96 |
| | 68 - 76 | 604 | 605 | 768 | 768 | 181.25 | 0.001468125 | 1468 | 41.84 |

Distance for DEMEC to extreme fiber = 19
c.g.s without top strand = 4.86

| **North End** | | **At C.G.S.** | | **Average** |
|---|---|---|---|---|
| | Slope | Strain | Stress (ksi) | |
| Distance = 60 - 68 | 71.94 | 1510.60 | 43.05 | 42.38 |
| Distance = 68 - 76 | 67.57 | 1463.41 | 41.71 | |

| **Center** | | **At C.G.S.** | | |
|---|---|---|---|---|
| | Slope | Strain | Stress (ksi) | |
| Distance = 144 - 152 | 63.63 | 1434.51 | 40.88 | 41.35 |
| Distance = 152 - 160 | 65.65 | 1467.19 | 41.81 | |

| **South End** | | **At C.G.S.** | | |
|---|---|---|---|---|
| | Slope | Strain | Stress (ksi) | |
| Distance = 60 - 68 | 67.25 | 1481.59 | 42.23 | 42.17 |
| Distance = 68 - 76 | 70.88 | 1478.05 | 42.12 | |

5-Feb-01

| | | East | | West | | Difference | Strain | Microstrain | Losses (ksi) |
|---|---|---|---|---|---|---|---|---|---|
| North | | | | | | | | | |
| Top | 60 - 68 | 687 | 686 | 776 | 775 | 38.25 | 0.000309825 | 310 | 8.83 |
| | 68 - 76 | 704 | 704 | 842 | 841 | 40.75 | 0.000330075 | 330 | 9.41 |
| Bottom | 60 - 68 | 567 | 568 | 651 | 653 | 214.75 | 0.001739475 | 1739 | 49.58 |
| | 68 - 76 | 568 | 564 | 579 | 578 | 208.75 | 0.001690875 | 1691 | 48.19 |
| Top | 144 - 152 | 745 | 744 | 595 | 594 | 49.25 | 0.000398925 | 399 | 11.37 |
| | 152 - 160 | 755 | 755 | 923 | 923 | 49.50 | 0.00040095 | 401 | 11.43 |
| Bottom | 144 - 152 | 571 | 571 | 704 | 704 | 208.25 | 0.001686825 | 1687 | 48.07 |
| | 152 - 160 | 635 | 633 | 574 | 574 | 210.25 | 0.001703025 | 1703 | 48.54 |
| South | | | | | | | | | |
| Top | 60 - 68 | 727 | 729 | 697 | 696 | 44.75 | 0.000362475 | 362 | 10.33 |
| | 68 - 76 | 694 | 694 | 731 | 730 | 37.00 | 0.0002997 | 300 | 8.54 |
| Bottom | 60 - 68 | 401 | 401 | 565 | 565 | 211.00 | 0.0017091 | 1709 | 48.71 |
| | 68 - 76 | 577 | 577 | 735 | 735 | 211.50 | 0.00171315 | 1713 | 48.82 |

Distance for DEMEC to extreme fiber = 19

c.g.s without top strand = 4.86

| **North End** | Slope | At C.G.S. Strain | Stress (ksi) | Average |
|---|---|---|---|---|
| Distance = 60 - 68 | 75.24 | 1750.01 | 49.88 | 49.18 |
| Distance = 68 - 76 | 71.62 | 1700.90 | 48.48 | |

| **Center** | Slope | At C.G.S. Strain | Stress (ksi) | |
|---|---|---|---|---|
| Distance = 144 - 152 | 67.78 | 1696.31 | 48.34 | 48.58 |
| Distance = 152 - 160 | 68.53 | 1712.62 | 48.81 | |

| **South End** | Slope | At C.G.S. Strain | Stress (ksi) | |
|---|---|---|---|---|
| Distance = 60 - 68 | 70.88 | 1719.02 | 48.99 | 49.06 |
| Distance = 68 - 76 | 74.39 | 1723.56 | 49.12 | |

19-Feb-01

| | | East | | West | | Difference | Strain | Microstrain | Losses (ksi) |
|---|---|---|---|---|---|---|---|---|---|
| North | | | | | | | | | |
| Top | 60 - 68 | 705 | 706 | 795 | 795 | 19.00 | 0.0001539 | 154 | 4.39 |
| | 68 - 76 | 726 | 724 | 860 | 861 | 20.75 | 0.000168075 | 168 | 4.79 |
| Bottom | 60 - 68 | 579 | 583 | 662 | 662 | 203.00 | 0.0016443 | 1644 | 46.86 |
| | 68 - 76 | 594 | 596 | 585 | 589 | 190.00 | 0.001539 | 1539 | 43.86 |
| Top | 144 - 152 | 762 | 761 | 614 | 614 | 31.00 | 0.0002511 | 251 | 7.16 |
| | 152 - 160 | 775 | 775 | 943 | 943 | 29.50 | 0.00023895 | 239 | 6.81 |
| Bottom | 144 - 152 | 588 | 589 | 719 | 719 | 192.00 | 0.0015552 | 1555 | 44.32 |
| | 152 - 160 | 640 | 639 | 581 | 581 | 204.00 | 0.0016524 | 1652 | 47.09 |
| South | | | | | | | | | |
| Top | 60 - 68 | 745 | 745 | 711 | 710 | 29.25 | 0.000236925 | 237 | 6.75 |
| | 68 - 76 | 715 | 715 | 744 | 744 | 19.75 | 0.000159975 | 160 | 4.56 |
| Bottom | 60 - 68 | 410 | 410 | 573 | 572 | 202.75 | 0.001642275 | 1642 | 46.80 |
| | 68 - 76 | 587 | 586 | 742 | 744 | 202.75 | 0.001642275 | 1642 | 46.80 |

Distance for DEMEC to extreme fiber = 19
c.g.s without top strand = 4.86

| **North End** | Slope | At C.G.S. Strain | Stress (ksi) | Average |
|---|---|---|---|---|
| Distance = 60 - 68 | 78.44 | 1655.28 | 47.18 | 45.66 |
| Distance = 68 - 76 | 72.15 | 1549.10 | 44.15 | |

| **Center** | Slope | At C.G.S. Strain | Stress (ksi) | |
|---|---|---|---|---|
| Distance = 144 - 152 | 68.64 | 1564.81 | 44.60 | 45.99 |
| Distance = 152 - 160 | 74.39 | 1662.81 | 47.39 | |

| **South End** | Slope | At C.G.S. Strain | Stress (ksi) | |
|---|---|---|---|---|
| Distance = 60 - 68 | 73.97 | 1652.63 | 47.10 | 47.11 |
| Distance = 68 - 76 | 78.02 | 1653.20 | 47.12 | |

14-Mar-01

| | | East | | West | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| North | | | | | | Difference | Strain | Microstrain | Losses (ksi) |
| Top | 60 - 68 | 695 | 694 | 784 | 781 | 30.75 | 0.000249 | 249 | 7.10 |
| | 68 - 76 | 710 | 710 | 854 | 854 | 31.50 | 0.000255 | 255 | 7.27 |
| Bottom | 60 - 68 | 565 | 566 | 650 | 649 | 217.00 | 0.001758 | 1758 | 50.09 |
| | 68 - 76 | 575 | 574 | 573 | 572 | 207.50 | 0.001681 | 1681 | 47.90 |
| Top | 144 - 152 | 746 | 747 | 604 | 604 | 43.50 | 0.000352 | 352 | 10.04 |
| | 152 - 160 | 830 | 834 | 935 | 935 | 5.00 | 4.05E-05 | 41 | 1.15 |
| Bottom | 144 - 152 | 572 | 571 | 708 | 708 | 206.00 | 0.001669 | 1669 | 47.56 |
| | 152 - 160 | 635 | 635 | 570 | 569 | 212.00 | 0.001717 | 1717 | 48.94 |
| South | | | | | | | | | |
| Top | 60 - 68 | 737 | 739 | 703 | 705 | 36.00 | 0.000292 | 292 | 8.31 |
| | 68 - 76 | 709 | 707 | 739 | 737 | 26.25 | 0.000213 | 213 | 6.06 |
| Bottom | 60 - 68 | 395 | 394 | 562 | 561 | 216.00 | 0.00175 | 1750 | 49.86 |
| | 68 - 76 | 576 | 574 | 736 | 735 | 212.25 | 0.001719 | 1719 | 49.00 |

Distance for DEMEC to extreme fiber = 19
c.g.s without top strand = 4.86

| **North End** | | **At C.G.S.** | | **Average** |
|---|---|---|---|---|
| | Slope | Strain | Stress (ksi) | |
| Distance = 60 - 68 | 79.40 | 1768.82 | 50.41 | 49.31 |
| Distance = 68 - 76 | 75.03 | 1691.25 | 48.20 | |

| **Center** | | **At C.G.S.** | | |
|---|---|---|---|---|
| | Slope | Strain | Stress (ksi) | |
| Distance = 144 - 152 | 69.28 | 1678.30 | 47.83 | 48.56 |
| Distance = 152 - 160 | 88.25 | 1729.55 | 49.29 | |

| **South End** | | **At C.G.S.** | | |
|---|---|---|---|---|
| | Slope | Strain | Stress (ksi) | |
| Distance = 60 - 68 | 76.74 | 1760.34 | 50.17 | 49.74 |
| Distance = 68 - 76 | 79.29 | 1730.33 | 49.31 | |

19-Apr-01

| | | East | | West | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| North | | | | | | Difference | Strain | Microstrain | Losses (ksi) |
| Top | 60 - 68 | 705 | 705 | 791 | 789 | 21.75 | 0.000176 | 176 | 5.02 |
| | 68 - 76 | 711 | 715 | 860 | 860 | 27.00 | 0.000219 | 219 | 6.23 |
| Bottom | 60 - 68 | 560 | 560 | 645 | 645 | 222.00 | 0.001798 | 1798 | 51.25 |
| | 68 - 76 | 575 | 576 | 565 | 566 | 210.50 | 0.001705 | 1705 | 48.59 |
| Top | 144 - 152 | 750 | 752 | 609 | 608 | 39.00 | 0.000316 | 316 | 9.00 |
| | 152 - 160 | 771 | 772 | 941 | 941 | 32.25 | 0.000261 | 261 | 7.44 |
| Bottom | 144 - 152 | 561 | 564 | 701 | 700 | 214.25 | 0.001735 | 1735 | 49.46 |
| | 152 - 160 | 622 | 624 | 563 | 564 | 221.00 | 0.00179 | 1790 | 51.02 |
| South | | | | | | | | | |
| Top | 60 - 68 | 745 | 743 | 703 | 703 | 33.50 | 0.000271 | 271 | 7.73 |
| | 68 - 76 | 710 | 710 | 740 | 740 | 24.25 | 0.000196 | 196 | 5.60 |
| Bottom | 60 - 68 | 394 | 395 | 555 | 557 | 218.75 | 0.001772 | 1772 | 50.50 |
| | 68 - 76 | 570 | 570 | 728 | 729 | 218.25 | 0.001768 | 1768 | 50.38 |

Distance for DEMEC to extreme fiber = 19

c.g.s without top strand = 4.86

| **North End** | | **At C.G.S.** | | **Average** |
|---|---|---|---|---|
| | Slope | Strain | Stress (ksi) | |
| Distance = 60 - 68 | 85.37 | 1810.15 | 51.59 | 50.25 |
| Distance = 68 - 76 | 78.23 | 1716.00 | 48.91 | |

| **Center** | | **At C.G.S.** | | |
|---|---|---|---|---|
| | Slope | Strain | Stress (ksi) | |
| Distance = 144 - 152 | 74.71 | 1745.88 | 49.76 | 50.55 |
| Distance = 152 - 160 | 80.47 | 1801.37 | 51.34 | |

| **South End** | | **At C.G.S.** | | |
|---|---|---|---|---|
| | Slope | Strain | Stress (ksi) | |
| Distance = 60 - 68 | 78.98 | 1782.93 | 50.81 | 50.76 |
| Distance = 68 - 76 | 82.71 | 1779.40 | 50.71 | |

25-Jun-01 180

| | | East | | West | | Difference | Strain | Microstrain | Losses (ksi) |
|---|---|---|---|---|---|---|---|---|---|
| North | | | | | | | | | |
| Top | 60 - 68 | 685 | 685 | 772 | 770 | 41.25 | 0.000334 | 334 | 9.52 |
| | 68 - 76 | 705 | 705 | 840 | 839 | 41.25 | 0.000334 | 334 | 9.52 |
| Bottom | 60 - 68 | 539 | 533 | 627 | 624 | 243.75 | 0.001974 | 1974 | 56.27 |
| | 68 - 76 | | | 545 | 545 | 246.50 | 0.001997 | 1997 | 56.90 |
| Top | 144 - 152 | 745 | 745 | 597 | 598 | 47.50 | 0.000385 | 385 | 10.97 |
| | 152 - 160 | 762 | 762 | 925 | 925 | 45.00 | 0.000365 | 365 | 10.39 |
| Bottom | 144 - 152 | 545 | 545 | 676 | 676 | 235.25 | 0.001906 | 1906 | 54.31 |
| | 152 - 160 | 610 | 607 | 543 | 540 | 239.25 | 0.001938 | 1938 | 55.23 |
| South | | | | | | | | | |
| Top | 60 - 68 | 731 | 731 | 700 | 700 | 41.50 | 0.000336 | 336 | 9.58 |
| | 68 - 76 | 701 | 699 | | | 31.50 | 0.000255 | 255 | 7.27 |
| Bottom | 60 - 68 | 375 | 375 | 533 | 533 | 240.00 | 0.001944 | 1944 | 55.40 |
| | 68 - 76 | 552 | 550 | 705 | 705 | 239.50 | 0.00194 | 1940 | 55.29 |

Distance for DEMEC to extreme fiber = 19
c.g.s without top strand = 4.86

| **North End** | | **At C.G.S.** | | **Average** |
|---|---|---|---|---|
| | Slope | Strain | Stress (ksi) | |
| Distance = 60 - 68 | 86.33 | 1986.46 | 56.61 | 56.93 |
| Distance = 68 - 76 | 87.50 | 2008.90 | 57.25 | |

| **Center** | | **At C.G.S.** | | |
|---|---|---|---|---|
| | Slope | Strain | Stress (ksi) | |
| Distance = 144 - 152 | 80.04 | 1916.73 | 54.63 | 55.09 |
| Distance = 152 - 160 | 82.81 | 1949.52 | 55.56 | |

| **South End** | | **At C.G.S.** | | |
|---|---|---|---|---|
| | Slope | Strain | Stress (ksi) | |
| Distance = 60 - 68 | 84.62 | 1955.85 | 55.74 | 55.69 |
| Distance = 68 - 76 | 88.67 | 1952.36 | 55.64 | |

| | | 21-Dec-01 | | | 360 | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | East | | West | | | | | |
| North | | | | | | Difference | Strain | Microstrain | Losses (ksi) |
| Top | 60 - 68 | 686 | 682 | 774 | 774 | 40.25 | 0.000326 | 326 | 9.29 |
| | 68 - 76 | 700 | 699 | 846 | 846 | 40.75 | 0.00033 | 330 | 9.41 |
| Bottom | 60 - 68 | 527 | 527 | 614 | | 253.00 | 0.002049 | 2049 | 58.41 |
| | 68 - 76 | | | 532 | | 259.00 | 0.002098 | 2098 | 59.79 |
| Top | 144 - 152 | 740 | 738 | 597 | 597 | 50.75 | 0.000411 | 411 | 11.72 |
| | 152 - 160 | 758 | 758 | 929 | 929 | 45.00 | 0.000365 | 365 | 10.39 |
| Bottom | 144 - 152 | 535 | 539 | 663 | 662 | 246.00 | 0.001993 | 1993 | 56.79 |
| | 152 - 160 | | | 529 | 528 | 257.50 | 0.002086 | 2086 | 59.44 |
| South | | | | | | | | | |
| Top | 60 - 68 | 738 | 737 | 694 | 692 | 41.75 | 0.000338 | 338 | 9.64 |
| | 68 - 76 | 698 | 700 | | | 32.50 | 0.000263 | 263 | 7.50 |
| Bottom | 60 - 68 | 355 | 358 | 521 | 521 | 255.25 | 0.002068 | 2068 | 58.92 |
| | 68 - 76 | 537 | 535 | 694 | 694 | 252.50 | 0.002045 | 2045 | 58.29 |

Distance for DEMEC to extreme fiber = 19

c.g.s without top strand = 4.86

| **North End** | | **At C.G.S.** | | **Average** |
|---|---|---|---|---|
| | Slope | Strain | Stress (ksi) | |
| Distance = 60 - 68 | 90.70 | 2062.00 | 58.77 | 59.46 |
| Distance = 68 - 76 | 93.04 | 2110.93 | 60.16 | |

| **Center** | | **At C.G.S.** | | |
|---|---|---|---|---|
| | Slope | Strain | Stress (ksi) | |
| Distance = 144 - 152 | 83.24 | 2004.25 | 57.12 | 58.46 |
| Distance = 152 - 160 | 90.59 | 2098.43 | 59.81 | |

| **South End** | | **At C.G.S.** | | |
|---|---|---|---|---|
| | Slope | Strain | Stress (ksi) | |
| Distance = 60 - 68 | 91.02 | 2080.27 | 59.29 | 58.98 |
| Distance = 68 - 76 | 93.79 | 2058.38 | 58.66 | |

The following pages contain the strain measurements for Girder/Beam 4.

| | | Before Cutting 12/20/00 | | | | After Cutting 12/20/00 | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | East | | West | | East | | West | | | | | |
| North | | | | | | | | | | Difference | Strain | Microstrain | Losses (ksi) |
| Top | 60 - 68 | 828 | 826 | 693 | 691 | 776 | 778 | 633 | 634 | 54.25 | 0.00043943 | 439 | 12.52 |
| | 68 - 76 | 813 | 809 | 876 | 872 | 807 | 809 | 874 | 875 | 1.25 | 1.0125E-05 | 10 | 0.29 |
| Bottom | 60 - 68 | 889 | 887 | 789 | 788 | 780 | 779 | 688 | 688 | 104.50 | 0.00084645 | 846 | 24.12 |
| | 68 - 76 | 841 | 838 | 786 | 786 | 735 | 734 | 685 | 687 | 102.50 | 0.00083025 | 830 | 23.66 |
| Top | 144 - 152 | 732 | 732 | 783 | 782 | 729 | 728 | 779 | 779 | 3.50 | 0.00002835 | 28 | 0.81 |
| | 152 - 160 | 530 | 529 | 596 | 593 | 532 | 532 | 591 | 590 | 0.75 | 6.075E-06 | 6 | 0.17 |
| Bottom | 144 - 152 | 787 | 784 | 786 | 784 | 683 | 682 | 688 | 688 | 100.00 | 0.00081 | 810 | 23.09 |
| | 152 - 160 | 790 | 789 | 778 | 783 | 689 | 687 | 681 | 684 | 99.75 | 0.00080798 | 808 | 23.03 |
| South | | | | | | | | | | | | | |
| Top | 60 - 68 | 765 | 765 | 790 | 788 | 762 | 763 | 784 | 787 | 3.00 | 0.0000243 | 24 | 0.69 |
| | 68 - 76 | 807 | 809 | 788 | 785 | 792 | 794 | 766 | 765 | 18.00 | 0.0001458 | 146 | 4.16 |
| Bottom | 60 - 68 | 943 | 944 | 787 | 786 | 835 | 835 | 688 | 688 | 103.50 | 0.00083835 | 838 | 23.89 |
| | 68 - 76 | 794 | 795 | 790 | 790 | 687 | 688 | 687 | 688 | 104.75 | 0.00084848 | 848 | 24.18 |
| | | | | | | | | | | | | | |
| | | | | | | Distance for DEMEC to extreme fiber = | | | | 19 | | | |
| | | | | | | c.g.s without top strand = | | | | 3.48 | | | |
| | | | | | | | | | | | | | |
| | | | | | | | | **North End** | | **At C.G.S.** | | | **Average** |
| | | | | | | | | | | Slope | Strain | Stress (ksi) | |
| | | | | | | | | Distance = 60 - 68 | | 21.42 | 879.01 | 25.05 | 25.29 |
| | | | | | | | | Distance = 68 - 76 | | 43.16 | 895.86 | 25.53 | |
| | | | | | | | | | | | | | |
| | | | | | | | | **Center** | | **At C.G.S.** | | | |
| | | | | | | | | | | Slope | Strain | Stress (ksi) | |
| | | | | | | | | Distance = 144 - 152 | | 41.14 | 872.53 | 24.87 | 24.86 |
| | | | | | | | | Distance = 152 - 160 | | 42.21 | 872.13 | 24.86 | |
| | | | | | | | | | | | | | |
| | | | | | | | | **South End** | | **At C.G.S.** | | | |
| | | | | | | | | | | Slope | Strain | Stress (ksi) | |
| | | | | | | | | Distance = 60 - 68 | | 42.84 | 903.47 | 25.75 | 25.77 |
| | | | | | | | | Distance = 68 - 76 | | 36.98 | 904.69 | 25.78 | |

| | | 05-Jan-01 | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | East | | West | | | | | |
| North | | | | | | Difference | Strain | Microstrain | Losses (ksi) |
| Top | 60 - 68 | 763 | 763 | 615 | 615 | 70.50 | 0.00057105 | 571 | 16.27 |
| | 68 - 76 | 804 | 803 | 867 | 866 | 7.50 | 0.00006075 | 61 | 1.73 |
| Bottom | 60 - 68 | 736 | 738 | 640 | 639 | 150.00 | 0.001215 | 1215 | 34.63 |
| | 68 - 76 | 694 | 694 | 636 | 638 | 147.25 | 0.001192725 | 1193 | 33.99 |
| Top | 144 - 152 | 722 | 721 | 772 | 771 | 10.75 | 0.000087075 | 87 | 2.48 |
| | 152 - 160 | 524 | 524 | 577 | 577 | 11.50 | 0.00009315 | 93 | 2.65 |
| Bottom | 144 - 152 | 638 | 638 | 638 | 638 | 147.25 | 0.001192725 | 1193 | 33.99 |
| | 152 - 160 | 644 | 643 | 651 | 640 | 140.50 | 0.00113805 | 1138 | 32.43 |
| South | | | | | | | | | |
| Top | 60 - 68 | 755 | 750 | 774 | 774 | 13.75 | 0.000111375 | 111 | 3.17 |
| | 68 - 76 | 788 | 787 | 760 | 757 | 24.25 | 0.000196425 | 196 | 5.60 |
| Bottom | 60 - 68 | 797 | 797 | 638 | 639 | 147.25 | 0.001192725 | 1193 | 33.99 |
| | 68 - 76 | 645 | 647 | 635 | 637 | 151.25 | 0.001225125 | 1225 | 34.92 |
| | | | | | | | | | |
| | | | | | | | | | |
| | | | | | | | | | |
| | | Distance for DEMEC to extreme fiber = | | | | 19 | | | |
| | | | c.g.s without top strand = | | | 3.48 | | | |
| | | | | | | | | | |
| | | | | **North End** | | **At C.G.S.** | | | **Average** |
| | | | | | | Slope | Strain | Stress (ksi) | |
| | | | | Distance = 60 - 68 | | 33.89 | 1266.52 | 36.10 | 36.33 |
| | | | | Distance = 68 - 76 | | 59.58 | 1283.28 | 36.57 | |
| | | | | | | | | | |
| | | | | **Center** | | **At C.G.S.** | | | |
| | | | | | | Slope | Strain | Stress (ksi) | |
| | | | | Distance = 144 - 152 | | 58.19 | 1281.18 | 36.51 | 35.67 |
| | | | | Distance = 152 - 160 | | 54.99 | 1221.64 | 34.82 | |
| | | | | | | | | | |
| | | | | **South End** | | **At C.G.S.** | | | |
| | | | | | | Slope | Strain | Stress (ksi) | |
| | | | | Distance = 60 - 68 | | 56.91 | 1279.23 | 36.46 | 36.86 |
| | | | | Distance = 68 - 76 | | 54.14 | 1307.42 | 37.26 | |

| | | 18-Jan-01 | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | East | | West | | | | | |
| North | | | | | | Difference | Strain | Microstrain | Losses (ksi) |
| Top | 60 - 68 | 769 | 770 | 630 | 631 | 59.50 | 0.000482 | 482 | 13.74 |
| | 68 - 76 | 805 | 806 | 874 | 872 | 3.25 | 2.63E-05 | 26 | 0.75 |
| Bottom | 60 - 68 | 735 | 734 | 638 | 637 | 152.25 | 0.001233 | 1233 | 35.15 |
| | 68 - 76 | 689 | 689 | 634 | 635 | 151.00 | 0.001223 | 1223 | 34.86 |
| Top | 144 - 152 | 727 | 726 | 776 | 776 | 6.00 | 4.86E-05 | 49 | 1.39 |
| | 152 - 160 | 529 | 529 | 586 | 587 | 4.25 | 3.44E-05 | 34 | 0.98 |
| Bottom | 144 - 152 | 633 | 633 | 639 | 640 | 149.00 | 0.001207 | 1207 | 34.40 |
| | 152 - 160 | 639 | 641 | 636 | 634 | 147.50 | 0.001195 | 1195 | 34.05 |
| South | | | | | | | | | |
| Top | 60 - 68 | 758 | 758 | 786 | 786 | 5.00 | 4.05E-05 | 41 | 1.15 |
| | 68 - 76 | 790 | 790 | 762 | 763 | 21.00 | 0.00017 | 170 | 4.85 |
| Bottom | 60 - 68 | 789 | 787 | 640 | 640 | 151.00 | 0.001223 | 1223 | 34.86 |
| | 68 - 76 | 648 | 647 | 637 | 637 | 150.00 | 0.001215 | 1215 | 34.63 |
| | | | | | | | | | |
| | | | | | | | | | |
| | | | | | | | | | |
| | | Distance for DEMEC to extreme fiber = | | | | 19 | | | |
| | | | c.g.s without top strand = | | | 3.48 | | | |
| | | | | | | | | | |
| | | | | North End | | At C.G.S. | | | Average |
| | | | | | | Slope | Strain | Stress (ksi) | |
| | | | | Distance = 60 - 68 | | 39.54 | 1293.33 | 36.86 | 37.22 |
| | | | | Distance = 68 - 76 | | 62.99 | 1318.84 | 37.59 | |
| | | | | | | | | | |
| | | | | Center | | At C.G.S. | | | |
| | | | | | | Slope | Strain | Stress (ksi) | |
| | | | | Distance = 144 - 152 | | 60.96 | 1299.56 | 37.04 | 36.87 |
| | | | | Distance = 152 - 160 | | 61.07 | 1287.58 | 36.70 | |
| | | | | | | | | | |
| | | | | South End | | At C.G.S. | | | |
| | | | | | | Slope | Strain | Stress (ksi) | |
| | | | | Distance = 60 - 68 | | 62.24 | 1317.71 | 37.55 | 37.28 |
| | | | | Distance = 68 - 76 | | 54.99 | 1298.59 | 37.01 | |

| | | 02-Feb-01 | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | East | | West | | | | | |
| North | | | | | | Difference | Strain | Microstrain | Losses (ksi) |
| Top | 60 - 68 | 760 | 759 | 619 | 618 | 70.50 | 0.000571 | 571 | 16.27 |
| | 68 - 76 | 800 | 799 | 867 | 867 | 9.25 | 7.49E-05 | 75 | 2.14 |
| Bottom | 60 - 68 | 714 | 714 | 615 | 615 | 173.75 | 0.001407 | 1407 | 40.11 |
| | 68 - 76 | 669 | 668 | 612 | 612 | 172.50 | 0.001397 | 1397 | 39.82 |
| Top | 144 - 152 | 720 | 720 | 767 | 770 | 13.00 | 0.000105 | 105 | 3.00 |
| | 152 - 160 | 520 | 520 | 575 | 575 | 14.50 | 0.000117 | 117 | 3.35 |
| Bottom | 144 - 152 | 612 | 611 | 614 | 614 | 172.50 | 0.001397 | 1397 | 39.82 |
| | 152 - 160 | 617 | 615 | 610 | 613 | 171.25 | 0.001387 | 1387 | 39.53 |
| South | | | | | | | | | |
| Top | 60 - 68 | 748 | 749 | 775 | 773 | 15.75 | 0.000128 | 128 | 3.64 |
| | 68 - 76 | 780 | 784 | 756 | 756 | 28.25 | 0.000229 | 229 | 6.52 |
| Bottom | 60 - 68 | 766 | 767 | 618 | 616 | 173.25 | 0.001403 | 1403 | 39.99 |
| | 68 - 76 | 624 | 622 | 610 | 610 | 175.75 | 0.001424 | 1424 | 40.57 |
| | | | | | | | | | |
| | | | | | | | | | |
| | | | | | | | | | |
| | | Distance for DEMEC to extreme fiber = | | | | 19 | | | |
| | | | c.g.s without top strand = | | | 3.48 | | | |
| | | | | | | | | | |
| | | | | North End | | At C.G.S. | | | Average |
| | | | | | | Slope | Strain | Stress (ksi) | |
| | | | | Distance = 60 - 68 | | 44.02 | 1474.28 | 42.02 | 42.43 |
| | | | | Distance = 68 - 76 | | 69.60 | 1503.04 | 42.84 | |
| | | | | | | | | | |
| | | | | Center | | At C.G.S. | | | |
| | | | | | | Slope | Strain | Stress (ksi) | |
| | | | | Distance = 144 - 152 | | 68.00 | 1500.61 | 42.77 | 42.60 |
| | | | | Distance = 152 - 160 | | 66.83 | 1488.70 | 42.43 | |
| | | | | | | | | | |
| | | | | South End | | At C.G.S. | | | |
| | | | | | | Slope | Strain | Stress (ksi) | |
| | | | | Distance = 60 - 68 | | 67.14 | 1505.39 | 42.90 | 43.10 |
| | | | | Distance = 68 - 76 | | 62.88 | 1519.16 | 43.30 | |

| | | 19-Feb-01 | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | East | | West | | | | | |
| North | | | | | | Difference | Strain | Microstrain | Losses (ksi) |
| Top | 60 - 68 | 782 | 781 | 630 | 634 | 52.75 | 0.000427 | 427 | 12.18 |
| | 68 - 76 | 815 | 813 | 885 | 885 | -7.00 | -5.67E-05 | -57 | -1.62 |
| Bottom | 60 - 68 | 724 | 723 | 631 | 631 | 161.00 | 0.001304 | 1304 | 37.17 |
| | 68 - 76 | 680 | 680 | 623 | 623 | 161.25 | 0.001306 | 1306 | 37.22 |
| Top | 144 - 152 | 732 | 734 | 782 | 785 | -1.00 | -8.1E-06 | -8 | -0.23 |
| | 152 - 160 | 537 | 538 | 587 | 587 | -0.25 | -2.03E-06 | -2 | -0.06 |
| Bottom | 144 - 152 | 617 | 617 | 629 | 625 | 163.25 | 0.001322 | 1322 | 37.69 |
| | 152 - 160 | 623 | 625 | 621 | 618 | 163.25 | 0.001322 | 1322 | 37.69 |
| South | | | | | | | | | |
| Top | 60 - 68 | 762 | 762 | 788 | 790 | 1.50 | 1.22E-05 | 12 | 0.35 |
| | 68 - 76 | 786 | 785 | 771 | 771 | 19.00 | 0.000154 | 154 | 4.39 |
| Bottom | 60 - 68 | 775 | 774 | 627 | 627 | 164.25 | 0.00133 | 1330 | 37.92 |
| | 68 - 76 | 631 | 629 | 618 | 615 | 169.00 | 0.001369 | 1369 | 39.01 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Distance for DEMEC to extreme fiber = | | | | 19 | | | |
| | | | c.g.s without top strand = | | | 3.48 | | | |
| | | | | | | | | | |
| | | | | **North End** | | **At C.G.S.** | | | **Average** |
| | | | | | | Slope | Strain | Stress (ksi) | |
| | | | | Distance = 60 - 68 | | 46.15 | 1374.25 | 39.17 | 39.75 |
| | | | | Distance = 68 - 76 | | 71.73 | 1415.15 | 40.33 | |
| | | | | | | | | | |
| | | | | **Center** | | **At C.G.S.** | | | |
| | | | | | | Slope | Strain | Stress (ksi) | |
| | | | | Distance = 144 - 152 | | 70.02 | 1428.76 | 40.72 | 40.71 |
| | | | | Distance = 152 - 160 | | 69.70 | 1428.27 | 40.71 | |
| | | | | | | | | | |
| | | | | **South End** | | **At C.G.S.** | | | |
| | | | | | | Slope | Strain | Stress (ksi) | |
| | | | | Distance = 60 - 68 | | 69.38 | 1435.89 | 40.92 | 41.35 |
| | | | | Distance = 68 - 76 | | 63.95 | 1466.10 | 41.78 | |

| | | 14-Mar-01 | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | East | | West | | | | | |
| North | | | | | | Difference | Strain | Microstrain | Losses (ksi) |
| Top | 60 - 68 | 771 | 769 | 627 | 627 | 61.00 | 0.000494 | 494 | 14.08 |
| | 68 - 76 | 801 | 802 | 869 | 868 | 7.50 | 6.08E-05 | 61 | 1.73 |
| Bottom | 60 - 68 | 710 | 710 | 620 | 621 | 173.00 | 0.001401 | 1401 | 39.94 |
| | 68 - 76 | 665 | 665 | 615 | 615 | 172.75 | 0.001399 | 1399 | 39.88 |
| Top | 144 - 152 | 724 | 724 | 774 | 775 | 8.00 | 6.48E-05 | 65 | 1.85 |
| | 152 - 160 | 525 | 525 | 583 | 582 | 8.25 | 6.68E-05 | 67 | 1.90 |
| Bottom | 144 - 152 | 605 | 605 | 611 | 611 | 177.25 | 0.001436 | 1436 | 40.92 |
| | 152 - 160 | 615 | 615 | 607 | 604 | 174.75 | 0.001415 | 1415 | 40.34 |
| South | | | | | | | | | |
| Top | 60 - 68 | 756 | 758 | 781 | 781 | 8.00 | 6.48E-05 | 65 | 1.85 |
| | 68 - 76 | 784 | 782 | 760 | 760 | 25.75 | 0.000209 | 209 | 5.94 |
| Bottom | 60 - 68 | 763 | 761 | 617 | 616 | 175.75 | 0.001424 | 1424 | 40.57 |
| | 68 - 76 | 616 | 617 | 615 | 610 | 177.75 | 0.00144 | 1440 | 41.03 |
| | | | | | | | | | |
| | | Distance for DEMEC to extreme fiber = | | | | 19 | | | |
| | | | c.g.s without top strand = | | | 3.48 | | | |
| | | | | | | | | | |
| | | | | **North End** | | **At C.G.S.** | | | **Average** |
| | | | | | | Slope | Strain | Stress (ksi) | |
| | | | | Distance = 60 - 68 | | 47.75 | 1473.88 | 42.01 | 42.47 |
| | | | | Distance = 68 - 76 | | 70.45 | 1506.36 | 42.93 | |
| | | | | | | | | | |
| | | | | **Center** | | **At C.G.S.** | | | |
| | | | | | | Slope | Strain | Stress (ksi) | |
| | | | | Distance = 144 - 152 | | 72.15 | 1545.40 | 44.04 | 43.73 |
| | | | | Distance = 152 - 160 | | 70.98 | 1523.37 | 43.42 | |
| | | | | | | | | | |
| | | | | **South End** | | **At C.G.S.** | | | |
| | | | | | | Slope | Strain | Stress (ksi) | |
| | | | | Distance = 60 - 68 | | 71.51 | 1532.28 | 43.67 | 43.76 |
| | | | | Distance = 68 - 76 | | 64.80 | 1538.27 | 43.84 | |

| | | 19-Apr-01 | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | East | | West | | | | | |
| North | | | | | | Difference | Strain | Microstrain | Losses (ksi) |
| Top | 60 - 68 | 782 | 782 | 635 | 638 | 50.25 | 0.000407025 | 407 | 11.60 |
| | 68 - 76 | 812 | 813 | 883 | 885 | -5.75 | -0.000046575 | -47 | -1.33 |
| Bottom | 60 - 68 | 706 | 705 | 610 | 609 | 180.75 | 0.001464075 | 1464 | 41.73 |
| | 68 - 76 | 662 | 662 | 607 | 609 | 177.75 | 0.001439775 | 1440 | 41.03 |
| Top | 144 - 152 | 725 | 725 | 779 | 780 | 5.00 | 0.0000405 | 41 | 1.15 |
| | 152 - 160 | 539 | 538 | 588 | 586 | -0.75 | -0.000006075 | -6 | -0.17 |
| Bottom | 144 - 152 | 601 | 603 | 606 | 605 | 181.50 | 0.00147015 | 1470 | 41.90 |
| | 152 - 160 | 614 | 615 | 590 | 595 | 181.50 | 0.00147015 | 1470 | 41.90 |
| South | | | | | | | | | |
| Top | 60 - 68 | 759 | 759 | 789 | 790 | 2.75 | 0.000022275 | 22 | 0.63 |
| | 68 - 76 | 798 | 795 | 766 | 767 | 15.75 | 0.000127575 | 128 | 3.64 |
| Bottom | 60 - 68 | 758 | 756 | 610 | 610 | 181.50 | 0.00147015 | 1470 | 41.90 |
| | 68 - 76 | 615 | 614 | 613 | | 179.00 | 0.0014499 | 1450 | 41.32 |
| | | | | | | | | | |
| | | Distance for DEMEC to extreme fiber = | | | | 19 | | | |
| | | | c.g.s without top strand = | | | 3.48 | | | |
| | | | | | | | | | |
| | | | | **North End** | | **At C.G.S.** | | | **Average** |
| | | | | | | Slope | Strain | Stress (ksi) | |
| | | | | Distance = 60 - 68 | | 55.63 | 1548.64 | 44.14 | 44.28 |
| | | | | Distance = 68 - 76 | | 78.23 | 1558.68 | 44.42 | |
| | | | | | | | | | |
| | | | | **Center** | | **At C.G.S.** | | | |
| | | | | | | Slope | Strain | Stress (ksi) | |
| | | | | Distance = 144 - 152 | | 75.24 | 1584.52 | 45.16 | 45.21 |
| | | | | Distance = 152 - 160 | | 77.70 | 1588.25 | 45.27 | |
| | | | | | | | | | |
| | | | | **South End** | | **At C.G.S.** | | | |
| | | | | | | Slope | Strain | Stress (ksi) | |
| | | | | Distance = 60 - 68 | | 76.20 | 1585.98 | 45.20 | 44.77 |
| | | | | Distance = 68 - 76 | | 69.60 | 1555.69 | 44.34 | |

| | | 25-Jun-01 | | | | 180 days | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | East | | West | | | | | |
| North | | | | | | Difference | Strain | Microstrain | Losses (ksi) |
| Top | 60 - 68 | 778 | 775 | 620 | 625 | 60.00 | 0.000486 | 486 | 13.85 |
| | 68 - 76 | 795 | 792 | 865 | 864 | 13.50 | 0.00010935 | 109 | 3.12 |
| Bottom | 60 - 68 | 688 | 688 | 595 | 595 | 196.75 | 0.00159368 | 1594 | 45.42 |
| | 68 - 76 | 645 | 645 | 589 | 590 | 195.50 | 0.00158355 | 1584 | 45.13 |
| Top | 144 - 152 | 700 | 698 | 768 | 770 | 23.25 | 0.00018833 | 188 | 5.37 |
| | 152 - 160 | 553 | 550 | 576 | 580 | -2.75 | -2.228E-05 | -22 | -0.63 |
| Bottom | 144 - 152 | 584 | 585 | 588 | 588 | 199.00 | 0.0016119 | 1612 | 45.94 |
| | 152 - 160 | 590 | 585 | 588 | 585 | 198.00 | 0.0016038 | 1604 | 45.71 |
| South | | | | | | | | | |
| Top | 60 - 68 | 753 | 755 | 792 | 790 | 4.50 | 0.00003645 | 36 | 1.04 |
| | 68 - 76 | | | 759 | 760 | 27.00 | 0.0002187 | 219 | 6.23 |
| Bottom | 60 - 68 | 740 | 740 | 595 | 595 | 197.50 | 0.00159975 | 1600 | 45.59 |
| | 68 - 76 | 601 | 600 | | | 194.00 | 0.0015714 | 1571 | 44.78 |
| | | | | | | | | | |
| | | Distance for DEMEC to extreme fiber = | | | | 19 | | | |
| | | | c.g.s without top strand = | | | 3.48 | | | |
| | | | | | | | | | |
| | | | | **North End** | | **At C.G.S.** | | | **Average** |
| | | | | | | Slope | Strain | Stress (ksi) | |
| | | | | Distance = 60 - 68 | | 58.30 | 1682.29 | 47.95 | 48.22 |
| | | | | Distance = 68 - 76 | | 77.59 | 1701.49 | 48.49 | |
| | | | | | | | | | |
| | | | | **Center** | | **At C.G.S.** | | | |
| | | | | | | Slope | Strain | Stress (ksi) | |
| | | | | Distance = 144 - 152 | | 74.93 | 1725.79 | 49.18 | 49.30 |
| | | | | Distance = 152 - 160 | | 85.58 | 1733.89 | 49.42 | |
| | | | | | | | | | |
| | | | | **South End** | | **At C.G.S.** | | | |
| | | | | | | Slope | Strain | Stress (ksi) | |
| | | | | Distance = 60 - 68 | | 82.28 | 1724.81 | 49.16 | 48.51 |
| | | | | Distance = 68 - 76 | | 71.19 | 1679.62 | 47.87 | |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | 21-Dec-01 | | | | 360 | | | |
| | | East | | West | | | | | |
| North | | | | | | Difference | Strain | Microstrain | Losses (ksi) |
| Top | 60 - 68 | 781 | 778 | 621 | 620 | 59.50 | 0.000482 | 482 | 13.74 |
| | 68 - 76 | 779 | 779 | 853 | 852 | 26.75 | 0.000217 | 217 | 6.18 |
| Bottom | 60 - 68 | 679 | 678 | 581 | 583 | 208.00 | 0.001685 | 1685 | 48.02 |
| | 68 - 76 | 634 | 634 | 580 | 579 | 206.00 | 0.001669 | 1669 | 47.56 |
| Top | 144 - 152 | 679 | 675 | 769 | 770 | 34.00 | 0.000275 | 275 | 7.85 |
| | 152 - 160 | 518 | 521 | 580 | 578 | 12.75 | 0.000103 | 103 | 2.94 |
| Bottom | 144 - 152 | 575 | 574 | 577 | 579 | 209.00 | 0.001693 | 1693 | 48.25 |
| | 152 - 160 | 581 | 580 | 570 | 569 | 210.00 | 0.001701 | 1701 | 48.48 |
| South | | | | | | | | | |
| Top | 60 - 68 | 747 | 746 | 763 | 765 | 21.75 | 0.000176 | 176 | 5.02 |
| | 68 - 76 | | | 773 | 772 | 14.00 | 0.000113 | 113 | 3.23 |
| Bottom | 60 - 68 | 729 | 729 | 580 | 579 | 210.75 | 0.001707 | 1707 | 48.65 |
| | 68 - 76 | 591 | 588 | | | 205.00 | 0.001661 | 1661 | 47.32 |
| | | | | | | | | | |
| | | Distance for DEMEC to extreme fiber = | | | | 19 | | | |
| | | | c.g.s without top strand = | | | 3.48 | | | |
| | | | | | | | | | |
| | | | | North End | | At C.G.S. | | | Average |
| | | | | | | Slope | Strain | Stress (ksi) | |
| | | | | Distance = 60 - 68 | | 63.31 | 1781.03 | 50.76 | 50.81 |
| | | | | Distance = 68 - 76 | | 76.42 | 1784.75 | 50.87 | |
| | | | | | | | | | |
| | | | | Center | | At C.G.S. | | | |
| | | | | | | Slope | Strain | Stress (ksi) | |
| | | | | Distance = 144 - 152 | | 74.61 | 1806.30 | 51.48 | 51.80 |
| | | | | Distance = 152 - 160 | | 84.09 | 1828.82 | 52.12 | |
| | | | | | | | | | |
| | | | | South End | | At C.G.S. | | | |
| | | | | | | Slope | Strain | Stress (ksi) | |
| | | | | Distance = 60 - 68 | | 80.57 | 1829.55 | 52.14 | 51.50 |
| | | | | Distance = 68 - 76 | | 81.43 | 1784.27 | 50.85 | |

Hardened Concrete Properties for the Girders/Beams.

Table E.1. Compressive Strength for Girders 1 and 4.

| Compressive Strength for Girders 1 and 4 (2.3 % Air) | | | | | |
|---|---|---|---|---|---|
| Age (days) | Specimens | | | | Average (psi) |
| | 1 | 2 | 3 | 4 | |
| 1 | 8438 | 8915 | 8278 | 9154 | 8696 |
| 14 | 10026 | 10417 | 10137 | | 10193 |
| 28 | 11668 | 10854 | 11163 | 10538 | 11056 |
| 56 | 12419 | 12438 | 12460 | | 12439 |
| 180 | 13948 | 14719 | 15040 | 14128 | 14459 |
| 360 | 16270 | 15492 | 15392 | 15301 | 15614 |

Table E.2. Compressive Strength for Girders 2 and 3.

| Compressive Strength for Girders 2 and 3 (6.2 % Air) | | | | | |
|---|---|---|---|---|---|
| Age (days) | Specimens | | | | Average (psi) |
| | 1 | 2 | 3 | 4 | |
| 1 | 6048 | 6207 | 6485 | 6048 | 6197 |
| 14 | 6791 | 7168 | 7306 | 7161 | 7107 |
| 28 | 7797 | 8507 | 8650 | 8608 | 8391 |
| 56 | 9480 | 9293 | 8816 | 9272 | 9215 |
| 180 | 10845 | 11007 | 10250 | 10908 | 10753 |
| 360 | 11297 | 11287 | 12134 | 11128 | 11462 |

**Shrinkage for Girders 1 and 4.**

| One - Day | | |
|---|---|---|
| Reference Bar | Prism Length | Difference |
| 0.0793 | 0.0512 | 0.0281 |
| 0.0793 | 0.1049 | -0.0256 |
| 0.0793 | 0.1095 | -0.0302 |

| 14 Day | | | | |
|---|---|---|---|---|
| Measurement | Difference | Change in Length | Strain | Micro-Strain |
| 0.0471 | 0.0322 | -0.0041 | -0.00041 | -410 |
| 0.1001 | -0.0208 | -0.0048 | -0.00048 | -480 |
| 0.1055 | -0.0262 | -0.004 | -0.0004 | -400 |

| 28 day | | | | |
|---|---|---|---|---|
| Measurement | Difference | Change in Length | Strain | Micro-Strain |
| 0.0451 | 0.0342 | -0.0061 | -0.00061 | -610 |
| 0.0992 | -0.0199 | -0.0057 | -0.00057 | -570 |
| 0.1035 | -0.0242 | -0.006 | -0.0006 | -600 |

| 43 day | | | | |
|---|---|---|---|---|
| Measurement | Difference | Change in Length | Strain | Micro-Strain |
| 0.0447 | 0.0346 | -0.0065 | -0.00065 | -650 |
| 0.0986 | -0.0193 | -0.0063 | -0.00063 | -630 |
| 0.1035 | -0.0242 | -0.006 | -0.0006 | -600 |

| 60 day | | | | |
|---|---|---|---|---|
| Measurement | Difference | Change in Length | Strain | Micro-Strain |
| 0.0447 | 0.0346 | -0.0065 | -0.00065 | -650 |
| 0.0988 | -0.0195 | -0.0061 | -0.00061 | -610 |
| 0.1032 | -0.0239 | -0.0063 | -0.00063 | -630 |

| 84 day | | | | |
|---|---|---|---|---|
| Measurement | Difference | Change in Length | Strain | Micro-Strain |
| 0.0446 | 0.0347 | -0.0066 | -0.00066 | -660 |
| 0.0988 | -0.0195 | -0.0061 | -0.00061 | -610 |
| 0.103 | -0.0237 | -0.0065 | -0.00065 | -650 |

| 120 day | | | | |
|---|---|---|---|---|
| Measurement | Difference | Change in Length | Strain | Micro-Strain |
| 0.0444 | 0.0349 | -0.0068 | -0.00068 | -680 |
| 0.0987 | -0.0194 | -0.0062 | -0.00062 | -620 |
| 0.1026 | -0.0233 | -0.0069 | -0.00069 | -690 |

| 180 day | | | | |
|---|---|---|---|---|
| Measurement | Difference | Change in Length | Strain | Micro-Strain |
| 0.0443 | 0.035 | -0.0069 | -0.00069 | -690 |
| 0.0984 | -0.0191 | -0.0065 | -0.00065 | -650 |
| 0.1025 | -0.0232 | -0.007 | -0.0007 | -700 |

| 360 day | | | | |
|---|---|---|---|---|
| Measurement | Difference | Change in Length | Strain | Micro-Strain |
| 0.0442 | 0.0351 | -0.007 | -0.0007 | -700 |
| 0.0986 | -0.0193 | -0.0063 | -0.00063 | -630 |
| 0.1023 | -0.023 | -0.0072 | -0.00072 | -720 |

**Shrinkage for Girders 2 and 3.**

| One - Day | | |
|---|---|---|
| Reference Bar | Prism Length | Difference |
| 0.0893 | 0.1102 | -0.0209 |
| 0.0893 | 0.0545 | 0.0348 |
| 0.0893 | 0.1053 | -0.016 |

| 14 Day | | | | |
|---|---|---|---|---|
| Measurement | Difference | Change in Length | Strain | Micro-Strain |
| 0.1057 | -0.0164 | -0.0045 | -0.00045 | -450 |
| 0.0492 | 0.0401 | -0.0053 | -0.00053 | -530 |
| 0.1017 | -0.0124 | -0.0036 | -0.00036 | -360 |

| 28 day | | | | |
|---|---|---|---|---|
| Measurement | Difference | Change in Length | Strain | Micro-Strain |
| 0.1037 | -0.0144 | -0.0065 | -0.00065 | -650 |
| 0.0477 | 0.0416 | -0.0068 | -0.00068 | -680 |
| 0.1002 | -0.0109 | -0.0051 | -0.00051 | -510 |

| 43 day | | | | |
|---|---|---|---|---|
| Measurement | Difference | Change in Length | Strain | Micro-Strain |
| 0.1033 | -0.014 | -0.0069 | -0.00069 | -690 |
| 0.0475 | 0.0418 | -0.007 | -0.0007 | -700 |
| 0.0997 | -0.0104 | -0.0056 | -0.00056 | -560 |

| 60 day | | | | |
|---|---|---|---|---|
| Measurement | Difference | Change in Length | Strain | Micro-Strain |
| 0.1031 | -0.0138 | -0.0071 | -0.00071 | -710 |
| 0.047 | 0.0423 | -0.0075 | -0.00075 | -750 |
| 0.0995 | -0.0102 | -0.0058 | -0.00058 | -580 |

| 84 day | | | | |
|---|---|---|---|---|
| Measurement | Difference | Change in Length | Strain | Micro-Strain |
| 0.103 | -0.0137 | -0.0072 | -0.00072 | -720 |
| 0.0471 | 0.0422 | -0.0074 | -0.00074 | -740 |
| 0.0996 | -0.0103 | -0.0057 | -0.00057 | -570 |

| 120 day | | | | |
|---|---|---|---|---|
| Measurement | Difference | Change in Length | Strain | Micro-Strain |
| 0.1028 | -0.0135 | -0.0074 | -0.00074 | -740 |
| 0.0469 | 0.0424 | -0.0076 | -0.00076 | -760 |
| 0.0995 | -0.0102 | -0.0058 | -0.00058 | -580 |

| 180 day | | | | |
|---|---|---|---|---|
| Measurement | Difference | Change in Length | Strain | Micro-Strain |
| 0.1026 | -0.0133 | -0.0076 | -0.00076 | -760 |
| 0.0466 | 0.0427 | -0.0079 | -0.00079 | -790 |
| 0.0991 | -0.0098 | -0.0062 | -0.00062 | -620 |

| 360 day | | | | |
|---|---|---|---|---|
| Measurement | Difference | Change in Length | Strain | Micro-Strain |
| 0.1026 | -0.0133 | -0.0076 | -0.00076 | -760 |
| 0.0463 | 0.043 | -0.0082 | -0.00082 | -820 |
| 0.0988 | -0.0095 | -0.0065 | -0.00065 | -650 |

**Modulus of Elasticity for Girders 1 and 4.**

Age 14 days

| Specimen | 40% fc (lbs) | 40% fc (psi) | Load (lbs) @ 0.00005 | Stress (psi) @ 0.00005 | Strain @ 40% fc | | Change in Stress | Change in Strain | MOE (ksi) | Average MOE (ksi) |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 50224 | 4000 | 4620 | 368 | 0.000677 | 0.00005 | 3632 | 0.000627 | 5793 | |
| 1 | 50224 | 4000 | 4830 | 384 | 0.000678 | 0.00005 | 3616 | 0.000628 | 5757 | |
| 2 | 50224 | 4000 | 4365 | 347 | 0.000691 | 0.00005 | 3653 | 0.000641 | 5698 | **5768** |
| 2 | 50224 | 4000 | 4605 | 366 | 0.000689 | 0.00005 | 3634 | 0.000639 | 5686 | |
| 3 | 50224 | 4000 | 4560 | 363 | 0.000675 | 0.00005 | 3637 | 0.000625 | 5819 | |
| 3 | 50224 | 4000 | 4425 | 352 | 0.000673 | 0.00005 | 3648 | 0.000623 | 5855 | |

Age 28 days

| Specimen | 40% fc (lbs) | 40% fc (psi) | Load (lbs) @ 0.00005 | Stress (psi) @ 0.00005 | Strain @ 40% fc | | Change in Stress | Change in Strain | MOE (ksi) | Average MOE (ksi) |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 58650 | 4671 | 4365 | 347 | 0.000757 | 0.00005 | 4324 | 0.000707 | 6116 | |
| 1 | 58650 | 4671 | 4395 | 350 | 0.000747 | 0.00005 | 4321 | 0.000697 | 6200 | |
| 2 | 58650 | 4671 | 4920 | 392 | 0.000766 | 0.00005 | 4280 | 0.000716 | 5977 | **6054** |
| 2 | 58650 | 4671 | 4560 | 363 | 0.000763 | 0.00005 | 4308 | 0.000713 | 6042 | |
| 3 | 58650 | 4671 | 3825 | 304 | 0.000782 | 0.00005 | 4367 | 0.000732 | 5965 | |
| 3 | 58650 | 4671 | 4125 | 328 | 0.000771 | 0.00005 | 4343 | 0.000721 | 6023 | |

Age 56 days

| Specimen | 40% fc (lbs) | 40% fc (psi) | Load (lbs) @ 0.00005 | Stress (psi) @ 0.00005 | Strain @ 40% fc | | Change in Stress | Change in Strain | MOE (ksi) | Average MOE (ksi) |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 62425 | 4972 | 5000 | 398 | 0.000777 | 0.00005 | 4574 | 0.000727 | 6291 | |
| 1 | 62425 | 4972 | 5020 | 399 | 0.000774 | 0.00005 | 4572 | 0.000724 | 6315 | |
| 2 | 62425 | 4972 | 4460 | 355 | 0.000798 | 0.00005 | 4617 | 0.000748 | 6172 | **6331** |
| 2 | 62425 | 4972 | 4420 | 352 | 0.000795 | 0.00005 | 4620 | 0.000745 | 6201 | |
| 3 | 62425 | 4972 | 4720 | 376 | 0.000759 | 0.00005 | 4596 | 0.000709 | 6483 | |
| 3 | 62425 | 4972 | 4920 | 392 | 0.000752 | 0.00005 | 4580 | 0.000702 | 6524 | |

Age 180 days

| Specimen | 40% fc (lbs) | 40% fc (psi) | Load (lbs) @ 0.00005 | Stress (psi) @ 0.00005 | Strain @ 40% fc | | Change in Stress | Change in Strain | MOE (ksi) | Average MOE (ksi) |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 70052 | 5579 | 4920 | 392 | 0.000819 | 0.00005 | 5188 | 0.000769 | 6746 | |
| 1 | 70052 | 5579 | 4980 | 396 | 0.000815 | 0.00005 | 5183 | 0.000765 | 6775 | |
| 2 | 70052 | 5579 | 4760 | 379 | 0.000810 | 0.00005 | 5200 | 0.000760 | 6843 | **6773** |
| 2 | 70052 | 5579 | 4780 | 380 | 0.000798 | 0.00005 | 5199 | 0.000748 | 6950 | |
| 3 | 70052 | 5579 | 4860 | 387 | 0.000831 | 0.00005 | 5192 | 0.000781 | 6648 | |
| 3 | 70052 | 5579 | 5080 | 404 | 0.000825 | 0.00005 | 5175 | 0.000775 | 6677 | |

Age 360 days

| Specimen | 40% fc (lbs) | 40% fc (psi) | Load (lbs) @ 0.00005 | Stress (psi) @ 0.00005 | Strain @ 40% fc | | Change in Stress | Change in Strain | MOE (ksi) | Average MOE (ksi) |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 79760 | 6352 | 4980 | 396 | 0.0009 | 0.00005 | 5956 | 0.00085 | 7007 | |
| 1 | 79760 | 6352 | 4440 | 353 | 0.000905 | 0.00005 | 5999 | 0.000855 | 7016 | |
| 2 | 79760 | 6352 | 4940 | 393 | 0.001006 | 0.00005 | 5959 | 0.000956 | 6233 | **6913** |
| 2 | 79760 | 6352 | 4880 | 388 | 0.000892 | 0.00005 | 5964 | 0.000842 | 7083 | |
| 3 | 79760 | 6352 | 4440 | 353 | 0.000899 | 0.00005 | 5999 | 0.000849 | 7066 | |
| 3 | 79760 | 6352 | 5060 | 403 | 0.000891 | 0.00005 | 5950 | 0.000841 | 7075 | |

**Modulus of Elasticity for Girders 2 and 3.**

Age 14 days

| Specimen | 40% fc (lbs) | 40% fc (psi) | Load (lbs) @ 0.00005 | Stress (psi) @ 0.00005 | Strain @ 40% fc | | Change in Stress | Change in Strain | MOE (ksi) | Average MOE (ksi) |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 35600 | 2835 | 3990 | 318 | 0.000547 | 0.00005 | 2518 | 0.000497 | 5066 | |
| 1 | 35600 | 2835 | 3840 | 306 | 0.000547 | 0.00005 | 2530 | 0.000497 | 5090 | |
| 2 | 35600 | 2835 | 3330 | 265 | 0.000583 | 0.00005 | 2570 | 0.000533 | 4822 | **4959** |
| 2 | 35600 | 2835 | 3765 | 300 | 0.000574 | 0.00005 | 2536 | 0.000524 | 4839 | |
| 3 | 35600 | 2835 | 3960 | 315 | 0.000542 | 0.00005 | 2520 | 0.000492 | 5122 | |
| 3 | 35600 | 2835 | 3945 | 314 | 0.000574 | 0.00005 | 2521 | 0.000524 | 4812 | |

Age 28 days

| Specimen | 40% fc (lbs) | 40% fc (psi) | Load (lbs) @ 0.00005 | Stress (psi) @ 0.00005 | Strain @ 40% fc | | Change in Stress | Change in Strain | MOE (ksi) | Average MOE (ksi) |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 42172 | 3359 | 3960 | 315 | 0.000613 | 0.00005 | 3044 | 0.000563 | 5406 | |
| 1 | 42172 | 3359 | 4020 | 320 | 0.000604 | 0.00005 | 3039 | 0.000554 | 5485 | |
| 2 | 42172 | 3359 | 4080 | 325 | 0.000585 | 0.00005 | 3034 | 0.000535 | 5671 | **5490** |
| 2 | 42172 | 3359 | 4110 | 327 | 0.000585 | 0.00005 | 3032 | 0.000535 | 5667 | |
| 3 | 42172 | 3359 | 4125 | 328 | 0.000620 | 0.00005 | 3030 | 0.00057 | 5317 | |
| 3 | 42172 | 3359 | 4035 | 321 | 0.000613 | 0.00005 | 3038 | 0.000563 | 5395 | |

Age 56 days

| Specimen | 40% fc (lbs) | 40% fc (psi) | Load (lbs) @ 0.00005 | Stress (psi) @ 0.00005 | Strain @ 40% fc | | Change in Stress | Change in Strain | MOE (ksi) | Average MOE (ksi) |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 46961 | 3740 | 4040 | 322 | 0.000684 | 0.00005 | 3419 | 0.000634 | 5392 | |
| 1 | 46961 | 3740 | 3780 | 301 | 0.000687 | 0.00005 | 3439 | 0.000637 | 5399 | |
| 2 | 46961 | 3740 | 3720 | 296 | 0.000704 | 0.00005 | 3444 | 0.000654 | 5266 | **5375** |
| 2 | 46961 | 3740 | 3900 | 310 | 0.000697 | 0.00005 | 3430 | 0.000647 | 5301 | |
| 3 | 46961 | 3740 | 3940 | 314 | 0.000681 | 0.00005 | 3427 | 0.000631 | 5430 | |
| 3 | 46961 | 3740 | 3980 | 317 | 0.000677 | 0.00005 | 3423 | 0.000627 | 5460 | |

Age 180 days

| Specimen | 40% fc (lbs) | 40% fc (psi) | Load (lbs) @ 0.00005 | Stress (psi) @ 0.00005 | Strain @ 40% fc | | Change in Stress | Change in Strain | MOE (ksi) | Average MOE (ksi) |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 54874 | 4370 | 3500 | 279 | 0.000773 | 0.00005 | 4092 | 0.000723 | 5659 | |
| 1 | 54874 | 4370 | 3840 | 306 | 0.000759 | 0.00005 | 4065 | 0.000709 | 5733 | |
| 2 | 54874 | 4370 | 4080 | 325 | 0.000781 | 0.00005 | 4046 | 0.000731 | 5534 | 5534 |
| 2 | 54874 | 4370 | 4220 | 336 | 0.000769 | 0.00005 | 4035 | 0.000719 | 5611 | |
| 3 | 54874 | 4370 | 3740 | 298 | 0.000819 | 0.00005 | 4073 | 0.000769 | 5296 | |
| 3 | 54874 | 4370 | 4040 | 322 | 0.000804 | 0.00005 | 4049 | 0.000754 | 5370 | |

Age 360 days

| Specimen | 40% fc (lbs) | 40% fc (psi) | Load (lbs) @ 0.00005 | Stress (psi) @ 0.00005 | Strain @ 40% fc | | Change in Stress | Change in Strain | MOE (ksi) | Average MOE (ksi) |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 56712 | 4517 | 4280 | 341 | 0.000743 | 0.00005 | 4176 | 0.000693 | 6026 | |
| 1 | 56712 | 4517 | 4380 | 349 | 0.000738 | 0.00005 | 4168 | 0.000688 | 6058 | |
| 2 | 56712 | 4517 | 3620 | 288 | 0.000756 | 0.00005 | 4229 | 0.000706 | 5990 | 5992 |
| 2 | 56712 | 4517 | 3740 | 298 | 0.000748 | 0.00005 | 4219 | 0.000698 | 6045 | |
| 3 | 56712 | 4517 | 3660 | 291 | 0.000765 | 0.00005 | 4225 | 0.000715 | 5910 | |
| 3 | 56712 | 4517 | 4060 | 323 | 0.000758 | 0.00005 | 4194 | 0.000708 | 5923 | |

**Calculations for Prestress Losses due to Temperature Change.**

Thermal expansion for concrete and strand $= 6 \times 10^{-6}$ in./in./ degree F

Modulus of Elasticity of the strand = 28,500 ksi

Assume a 20 F change in temperature:

Loss = ($6 \times 10^{-6}$ in./in./ degree F)(28,500 ksi)(20 F)
Loss = 3.42 ksi

Assume a 30 F change in temperature:

Loss = ($6 \times 10^{-6}$ in./in./ degree F)(28,500 ksi)(30 F)
Loss = 5.13 ksi

**Calculations for Modified Kcir for Elastic Shortening Losses.**

**For Girder 1:**

Assume Kcir = 0.90

Calculate ES Losses

$f_{cir} = K_{cir}(P_{pi}(1/A_g + e^2/I_g)) - f_g$

$ES = K_{es}nf_{cir}$

ES = 21.30 ksi

Calculate Kcir by

Kcir = (202.5 – 21.30)/202.5

Kcir = 0.89

Try Kcir = 0.89

Calculate ES Losses

$f_{cir} = K_{cir}(P_{pi}(1/A_g + e^2/I_g)) - f_g$

$ES = K_{es}nf_{cir}$

ES = 21.06 ksi

Calculate Kcir by

Kcir = (202.5 – 21.06)/202.5

Kcir = 0.896

Try Kcir = 0.895

Calculate ES Losses

$f_{cir} = K_{cir}(P_{pi}(1/A_g + e^2/I_g)) - f_g$

$ES = K_{es}nf_{cir}$

ES = 21.18 ksi

Calculate Kcir by

Kcir = (202.5 – 21.18)/202.5

Kcir = 0.895

0.895 = 0.895 Okay

**Use Kcir = 0.895**

**For Girder 2:**

Assume Kcir = 0.90

Calculate ES Losses

$f_{cir} = K_{cir}(P_{pi}(1/A_g + e^2/I_g)) - f_g$

$ES = K_{es}nf_{cir}$

ES = 23.67 ksi

Calculate Kcir by

Kcir = (202.5 – 23.67)/202.5

Kcir = 0.88

Try Kcir = 0.88

Calculate ES Losses

$f_{cir} = K_{cir}(P_{pi}(1/A_g + e^2/I_g)) - f_g$

$ES = K_{es}nf_{cir}$

ES = 23.14 ksi

Calculate Kcir by

Kcir = (202.5 – 23.14)/202.5

Kcir = 0.886

Try Kcir = 0.886

Calculate ES Losses

$f_{cir} = K_{cir}(P_{pi}(1/A_g + e^2/I_g)) - f_g$

$ES = K_{es}nf_{cir}$

ES = 23.30 ksi

Calculate Kcir by

Kcir = (202.5 – 23.30)/202.5

Kcir = 0.885

0.886 = 0.885 Okay

**Use Kcir = 0.886**

**For Girder 3:**

Assume Kcir = 0.90

Calculate ES Losses

$f_{cir} = K_{cir}(P_{pi}(1/A_g + e^2/I_g)) - f_g$

$ES = K_{es}nf_{cir}$

ES = 18.66 ksi

Calculate Kcir by

Kcir = (202.5 – 18.66)/202.5

Kcir = 0.91

Try Kcir = 0.91

Calculate ES Losses

$f_{cir} = K_{cir}(P_{pi}(1/A_g + e^2/I_g)) - f_g$

$ES = K_{es}nf_{cir}$

ES = 18.86 ksi

Calculate Kcir by

Kcir = (202.5 – 18.86)/202.5

Kcir = 0.91

0.91 = 0.91 Okay

**Use Kcir = 0.91**

**For Girder 4:**

Assume Kcir = 0.90

Calculate ES Losses

$f_{cir} = K_{cir}(P_{pi}(1/A_g + e^2/I_g)) - f_g$

$ES = K_{es}nf_{cir}$

ES = 18.37 ksi

Calculate Kcir by

Kcir = (202.5 – 18.37)/202.5

Kcir = 0.91

Try Kcir = 0.91

Calculate ES Losses

$f_{cir} = K_{cir}(P_{pi}(1/A_g + e^2/I_g)) - f_g$

$ES = K_{es}nf_{cir}$

ES = 18.58 ksi

Calculate Kcir by

Kcir = (202.5 – 18.58)/202.5

Kcir = 0.91

0.91 = 0.91 Okay

**Use Kcir = 0.91**