Development of High Performance Lightweight Concrete Mixes for Prestressed Bridge Girders

by

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Dedication

To Kelly, Mom, Dad, and Sam

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Abstract

Development of High Performance Lightweight Concrete Mixes for Prestressed Bridge Girders

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High performance lightweight concrete allows new options in the use of prestressed bridge girders. Three iterations of concrete mix designs were performed to develop two concrete mixes for use, one with $f_c^{'} = 6000$ psi at 28 days and the other with $f_c^{'} = 8000$ psi at 28 days. Compressive strength, modulus of elasticity, tensile strength, and flexural strength tests were carried out on each of the mixes.

Two mixes were chosen which satisfied the specifications. Creep and shrinkage tests were carried out on both. Also, two 40-foot pretensioned bridge girders were fabricated from the 6000 psi mix and three 40-foot pretensioned

bridge girders were fabricated from the 8000 psi mix. The 6000 psi mix performed well in both strength and workability tests, allowing it to be specified as a 7000 psi mix. The 8000 psi mix performed marginally, not reaching strength and being difficult to work. It can be specified as a 7500 psi mix.

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Chapter 1: Introduction

1.1 Basics of Lightweight Concrete

Concrete plays a large role in each of our everyday lives. As the most popular material for bridge structures in Texas, it is seen everywhere in the state. Its combination of superior mechanical properties and inexpensive price (compared to other materials such as composites) make it a popular material.

Concrete in its most basic form is comprised of four components: cement, fine aggregate, coarse aggregate, and water. The cement, fine aggregate, and water combine to form the mortar which binds the coarse aggregate into a material which takes the shape of the form into which it is poured, hardening into a very strong solid for a beam or column element in a bridge structure [1].

For these main ingredients, there are some typical choices. For the cement, a hydraulic gray cement generally is used. Sand is usually the fine aggregate. The coarse aggregate generally is a river gravel or crushed limestone depending on the local geology and supply of rock for the concrete. Also, chemical admixtures can be added to change the fresh and hardened concrete properties to the engineer's liking.

Numerous variations and modifications can be made to these simple ingredients. Admixtures such as silica fume and fly ash can be added in replacement of cement to provide differing mechanical and chemical properties.

Also, lightweight aggregates such as expanded clays and shales can be used in place of the coarse aggregate.

This thesis is a portion of the Center for Transportation Research (CTR) Project 0-1852 sponsored by the Texas Department of Transportation (TxDOT) that focuses on possible applications for high performance lightweight concrete in bridge girders. Lightweight concrete receives its name because its hardened weight is 80% or less of the weight of normal weight concrete [2]. Two different types of lightweight concrete exist: all-lightweight concrete and sand-lightweight concrete. They differ in the type of fine aggregate used. All-lightweight concrete uses a lightweight fine aggregate while sand-lightweight uses natural sand as the fine aggregate.

The majority of the weight savings in lightweight concrete comes from the coarse aggregate. Lightweight concrete uses aggregate that must be manufactured or modified in some way. Most lightweight aggregates are expanded clays or shales. The clay and shale are mined from the ground and then placed in a kiln. While in the kiln, the clay or shale expands due to the heat. This creates a hard, porous aggregate which weighs 40-50% less than typical coarse aggregate [1].

This project focuses on the use of high strength lightweight concrete in pretensioned concrete highway bridge girders. Sand-lightweight concrete was chosen for the concrete due to its ability to reach higher strengths than the all-lightweight aggregate [2].

1.2 History of Use of Lightweight Concrete

Lightweight concrete has been widely used over the last fifty years. One of its first uses was during World War I, when the United States built experimental ships out of the material since availability of metal was limited at that time [3]. Also, the San Francisco-Oakland Bay Bridge used lightweight concrete in its deck in 1936 [4].

During the 1950s, lightweight concrete grew in popularity [5]. During this time, many of the original attempts at building structures out of this material were made. From these attempts, much was learned about the mechanical properties of lightweight concrete. Furthermore, lightweight concrete proved its usefulness to structural designers and engineers as a reliable material which could be used in special situations [1].

The popularity of lightweight concrete grew throughout the 1960s with many highway departments choosing to try lightweight concrete in various applications, such as decks and prestressed girders [6]. Its use was temporarily set back in the energy crisis in the 1970s and 1980s due to the increase in cost of expanding the aggregate.

At the present time, lightweight concrete has again become a popular structural material. Many engineers have started to use it as it has proved to be an economical choice for many jobs where member dead weight is the largest component of the load to be resisted. Building slabs have become a popular application for lightweight concrete use.

In prestressed construction, production of double tee members for parking garages often uses lightweight concrete. The reduced weight of lightweight concrete allows shipment of two members on a truck, reducing costs to the provider [7].

At the moment, use of lightweight concrete is generally restricted to applications where a large mass of concrete is needed but where structural demands in flexure and shear are fairly low. Use of lightweight concrete in other applications has been minimal.

1.3 Potential Use of Lightweight Concrete in Prestressed Bridge Girders

Within the last few years, high performance concrete has grown in popularity in the materials world. Due to improvements in concrete technology made possible by advanced admixtures, substantially more strength and durability characteristics are being demanded of concrete. This high performance concrete, which generally includes high strength concrete, has been utilized in many different applications [8].

Recently, a project was undertaken at The University of Texas at Austin where very high strength normal weight concrete mixes ranging from 6000 psi to 15000 psi were developed for prestressed concrete bridge girders [9]. The bridge girders were actually produced in regional casting yards and placed into service in a couple of bridges in Texas [10]. I-shaped girders were produced for a bridge in

San Angelo while U-shaped girders ware produced for an overpass in Houston. The performance of these bridges has been excellent. The use of higher strength concrete has allowed the use of fewer girders in each span, increasing the economy of these projects.

These successes led to the question of whether high strength, high performance lightweight concrete could be used for prestressed girders in Texas. The success of the high performance normal weight concrete girders indicated that use of high performance lightweight concrete might be feasible.

Experience with lightweight concrete bridge girders has been minimal. Quite a few bridges have been constructed using lightweight concrete. However, usage has generally been restricted to the deck. A couple of bridges have been constructed of all lightweight concrete but these generally were of lower strength concrete and did not focus on high strength, high performance lightweight concrete.

There are numerous reasons that justify a serious look at high strength, high performance lightweight concrete for bridge girders. First is the obvious reduction in weight. A 20% reduction in weight allows a smaller section to be used since dead weight demand has been significantly reduced. If a smaller section is not chosen, a longer span can be used [1]. Lightweight concrete girders are well suited for use in applications where spans must be long due to restrictions on the placement of supports. The second advantage is the higher strength. Higher strength concrete also allows a smaller section to be used. However, since sections are standardized according to the American Association of State

Highway Transportation Officials (AASHTO) geometries, a higher compressive strength concrete will allow girders to be used at a larger spacing per span, reducing the number of girders. Use of fewer girders usually means a reduction in cost, resulting in a lower cost project. However, it must be noted that the higher compressive strength of the girders is created with the use of more cement per cubic yard. Therefore, the girders will cost more per linear foot than the average normal weight concrete girder with the same strength. This increase in cost needs to be balanced with the decrease in cost due to the use of fewer girders at longer spans and spacings to determine what is the most efficient.

As is obvious, prestressed girders made of high strength, high performance concrete hold a lot of possible advantages over normal weight concrete. However, their feasibility must still be proven.

1.4 OBJECTIVES

The main objective of this portion of Project 0-1852 was to determine whether high strength high performance lightweight concrete mix designs could be developed with $f_c^{'}$ = 6000 psi and $f_c^{'}$ = 8000 psi for use in prestressed concrete girders. Also, the equilibrium unit weight needed to be not more than 122 pounds per cubic foot (pcf). The equilibrium unit weight is the weight of the concrete at ambient conditions after the concrete has been allowed to shed water [2]. To determine this, a variety of tasks were undertaken:

a) Literature discussing high strength lightweight concrete was located and evaluated. Of most interest was literature that investigated the use of lightweight concrete in precast bridges using an expanded clay or shale aggregate. It was hoped that this literature would give a general idea of possible mix designs along with possible expectations for the lightweight concrete and its performance. Also, hopefully, this literature would show the approximate difficulty of developing high strength concrete mixes.

b) Previous use of lightweight concrete in Texas was studied. Since this project was sponsored by the Texas Department of Transportation (TxDOT), it was natural to see whether TxDOT had used lightweight concrete and how well the concrete had performed in the state. This research would give a good idea of the characteristics of Texas lightweight concrete.

c) Two mix designs were to be developed for use in prestressed bridge girders. These mixes were to have the following characteristics:

Both mixes should use 1/2 to 3/4 inch maximum size commercially available aggregate within the state of Texas. Also, both mixes should have a equilibrium unit weight not more than 122 pound per cubic foot (pcf).

One mix should have a 28 or 56 day compressive strength of 6000 psi and the other should have a 28 or 56 day compressive strength of 8000 psi. Both should achieve 3500 psi in 24 to 48 hours to permit early release in pretensioning applications. Also, the tensile behavior of both mixes should be obtained along with the creep and shrinkage behavior. These tests would give the full documentation of the important design properties of the concrete mix.

d) The concrete should be workable enough for reasonable placement in pretensioned girder forms.

1.5 SCOPE

The research undertaken during this portion of Project 0-1852 was concerned with developing and refining of two concrete mixes for use in prestressed concrete girders. To accomplish this, a total of 35 concrete mixes were created and fabricated in the laboratory of the Construction Materials Research Group at The University of Texas at Austin.

Tests were performed on specimens of these mixes to determine the compressive strength, modulus of elasticity, and tensile strength. The unit weight was also measured. These tests gave a good understanding of the behavior of these lightweight concretes.

Then, when the most promising concrete mixes were determined, creep and shrinkage specimens were created and tested to ascertain the creep and shrinkage behavior of the two concrete mixes used for fabrication of precast prestressed concrete beams which were tested at Ferguson Structural Engineering Laboratory at The University of Texas at Austin.

1.6 ORGANIZATION OF THIS REPORT

This report is divided into six chapters.

The first chapter gives a general background of lightweight concrete as well as the reasons for performing this study. Furthermore, the objectives of the study are defined as well as the scope.

The second chapter provides a review of the pertinent literature regarding high strength high performance lightweight concrete. Also, reports dealing with the use of lightweight concrete in bridges are summarized.

The third chapter documents the iteratative process used to arrive at the final two mixes specified for lightweight concrete with $f_c^{'}$ = 6000 psi and $f_c^{'}$ = 8000 psi strengths. The procedures used as well as the results from each portion of the study are given and discussed. Also, the thought process of how the two concrete mixes were chosen is given.

The fourth chapter documents the behavior of the 6000 psi mix. All pertinent mechanical properties are given and discussed along with the mix design.

The fifth chapter documents the behavior of the 8000 psi mix. Similar to Chapter 4, this chapter gives the pertinent mechanical properties along with the mix design.

The sixth and final chapter summarizes the research and gives the specifications for the two final mixes. The conclusions are presented here along with possible implementation guidelines. Furthermore, recommended topics for possible future research are presented.

Chapter 2: Literature Review

To gain perspective on the use of lightweight concrete around the world, available literature from The University of Texas at Austin library as well as from a Texas Industries, Incorporated (TxI) collection of items was reviewed. This literature provided an overview of previous work done on lightweight concrete as well as its uses in prestressed bridge girders.

2.1 GENERAL RESEARCH ON HIGH STRENGTH LIGHTWEIGHT CONCRETE

Lightweight concrete has been used for various applications in many states. However, much recent research has focused on high performance concrete, which includes high strength concrete. This research has progressed as normal weight concrete has also been pushed to achieve new standards of strength and workability. Also, new developments in petroleum platform construction have further shaped the development and understanding of these concrete mixtures. Following is a discussion of papers on the development of high strength lightweight concrete as well as the mechanical properties and workability aspects. The focus will be on mixes developed using expanded clays as the coarse aggregate.

2.1.1 Martinez Morales (1982) [2]

This study, performed at Cornell University, was one of the first studies that looked at the mechanical properties of lightweight concrete in depth. They tested three different types of lightweight concrete, low strength with $f_c^{'}$ < 4000 psi, moderate strength with 4000 psi < $f_c^{'}$ < 6000 psi, and high strength with $f_c^{'}$ > 6000 psi. Due to the focus of this report, only results from the high strength concrete mixes will be presented.

The concrete developed in their study utilized Type I cement and also used all lightweight aggregate, which differed somewhat from the conditions seen in the current study. The amount of cement was 10 sacks per yard (945 pounds), similar to the final total cementitious material for the 8000 psi concrete developed later in the current project.

The following tests were performed on the concrete mixes: compressive strength, modulus of elasticity, modulus of rupture, and splitting tensile strength.

For compressive strength, their concrete averaged approximately 8000 psi. The high strength lightweight concrete also exhibited a faster strength gain than did the other varieties of concrete. 3500 psi was achieved at one day of age. The modulus of elasticity ranged from 2,500,000 to 3,000,0000 psi for all the cylinders tested.

Modulus of rupture values averaged around 800 psi for moist cured condition and 430 psi for dry cured conditions. This showed the importance of keeping specimens wet before testing, along with the importance of moist curing on tensile strength. Splitting tensile results averaged 560 psi for wet cured and 365 psi for dry cured specimens.

Also, the authors proposed various curve fit expressions for static modulus of elasticity, modulus of rupture, and splitting tensile strength to complement accepted AASHTO equations [12]. Following are the Martinez expressions along with the companion AASHTO expression:

For modulus of elasticity,

Martinez $E_c = (40000\sqrt{f_c^{'}} + 1000000)(w_c / 145)^{1.5}$ **Equation 2.1**

AASHTO $E_c = 33 w_c^{1.5} \sqrt{f_c^{'}}$ **Equation 2.2**

(The AASHTO equation is AASHTO Equation 8.7.1 [12].)

For modulus of rupture,

Martinez $f_r = 6.5\sqrt{f_c^{'}}$ **Equation 2.3**

AASHTO $f_r = 6.3\sqrt{f_c^{'}}$ **Equation 2.4**

(The AASHTO equation is from AASHTO 8.15.2.1.1 [12].)

For splitting tensile strength,

Martinez $f_{sp}^{'} = 5\sqrt{f_c^{'}}$ **Equation 2.5**

AASHTO $f_{sp}^{'} = 5\sqrt{f_c^{'}}$ **Equation 2.6**

(The AASHTO equation is arrived at indirectly from AASHTO 8.15.5.2.4 [12].)

2.1.2 Shideler (1957) [5]

Shideler presented one of the first comprehensive studies on lightweight concrete. He tested both normal strength and high strength concrete. The high strength concrete had $f_c^{'} > 7000$ psi. He tested for compressive strength, modulus of elasticity, creep, drying shrinkage, bond, and flexural strength. Eight lightweight aggregates were used in the testing.

Shideler found he could produce concrete with $f_c^{'} > 8000$ psi using an expanded clay. He was able to exceed 3500 psi at 2 days using this aggregate. Also, he found the modulus of elasticity to be between 2,000,000 psi and 3,000,000 psi for high strength concrete using expanded clay depending on whether the concrete was wet or dry.

Modulus of rupture was 600 psi at 28 days for the expanded clay aggregate. He also found that creep of the various lightweight concrete was greater than creep for comparable normal weight concrete.

Overall, Shideler found that performance of the lightweight concrete was good and structural grade concrete could be produced with each of the aggregates he tested.

2.1.3 Zhang and Gjørv (1993) [13]

Lightweight aggregate has been often in Norway due to its use in offshore oil platforms. Zhang and Gjørv have studied some of this lightweight concrete.

They developed nine lightweight concrete mixes for use. They utilized silica fume as the pozzolanic admixture. The worst performing concrete still achieved a compressive strength of 8310 psi at 28 days. All mixes were 6000 psi by 3 days.

Zhang and Gjørv hypothesized that the lightweight aggregate strength control maximum strength of the mix. The cement content, silica fume, and sand have lesser effects.

2.1.4 Burg, Cichanski, and Hoff (1998) [14]

Since lightweight concrete has often been used in offshore oil platforms, some high strength lightweight mixes have been developed. Burg, et al were able to develop one using just cement and fly ash as the cementitious material.

The mix contained 700 lbs of cement and 200 lbs of fly ash per cubic yard of concrete. The fine aggregate was natural sand. The mix achieved a strength of 8500 psi at 90 days. At three days, the concrete had an approximate strength of 6800 psi. Although it is not noted explicitly in the paper, the concrete apparently achieved a strength above 3500 psi at one day of age.

As for other properties, the concrete had a modulus of elasticity of 4,000,000-4,500,000 psi at 90 days. The authors evaluated both Equations 2.1 and 2.2 with the data and verified that Equation 2.1 was the better fit for the modulus of elasticity data.

The splitting strength was between 250 and 500 psi for dry curing and 500-700 psi for moist curing, which exceeded Equation 2.4.

Also, the permeability of the concrete was rated as moderate. When the authors compared the value to one from normal weight concrete, the permeability was nearly the same. From this data, the authors concluded that this particular mix was suitable for the arctic environment for which they were designing the mix.

2.1.5 Nilsen and Aïtcen (1992) [15]

Nilsen and Aïtcen looked at the properties of high strength concrete containing various types of aggregates. In this current report, the results for concrete with lightweight aggregate will be the focus.

The lightweight concrete was made with an expanded shale for the coarse aggregate and natural sand for the fine aggregate. Silica fume was used as an admixture to help produce the strength that was needed. Also, Type III Portland cement was used. The two mixes performed produced concrete with compressive strengths of 13100 and 10700 psi, respectively at 28 days of age. Also, both concretes attained 8500 psi and 7000 psi at one day of age, well more than the 3500 psi needed for the current project.

They found that the AASHTO code Equation 8.7.1 [12] (Equation 2.2 in this report) for lightweight concrete modulus of elasticity underestimated the modulus of elasticity, a finding that agrees with previous research by Martinez.

As for drying shrinkage, lightweight concrete performed similarly to normal weight concrete. No advantage could be seen to either one of the two concretes.

2.1.6 Zhang and Gjørv (1991) [16]

Zhang and Gjørv also produced another paper dealing with the properties of high strength lightweight concrete.

This paper dealt with many of the same mixes that were discussed in Section 2.1.2. However, this paper had a different focus than the earlier one.

The conclusions of interest were:

a) The ratio of tensile strength to compressive strength in lightweight concrete is less than the same ratio in normal weight concrete.

b) The strength of the lightweight aggregate is the primary factor controlling the strength of high strength lightweight concrete.

2.1.7 Mircea, Ioani, Filip, and Pepenar (1994) [17]

Along with the mechanical properties of strength, modulus of elasticity, and tensile strength, the durability of lightweight concrete must be understood.

The authors tested 260 reinforced and prestressed beams under different aggressive environments for durability. The beams were made of both lightweight and normal weight concrete and were precracked.

The beams were then placed in various environments and allowed to sit for ten years. After ten years, the beams were analyzed and loaded to failure to see if they maintained their strength.

The conclusions were that the lightweight concrete performed as well as the normal weight concrete. The density of the lightweight concrete decreased 2.2% while the normal weight companion tests decreased 2.0%. Also, both mixes of concrete increased in modulus of elasticity with the lightweight gaining 12% while the normal weight gained 25%. For the strength, the lightweight concrete increased 17-25% while the normal weight gained 7-15%. Overall, the results were similar with neither concrete performing poorly.

Also, higher cement contents generally proved to reduce the size of the cracking inside the beams. Since high cement contents generally portend higher strength concrete, this means that the higher strength beams were able to resist crack growth better.

2.1.7 Reichard (1967) [18]

Reichard published one of the first studies on creep and shrinkage of lightweight aggregate concrete. His work is still the basis for the lightweight concrete creep and shrinkage recommendation by ACI Committee 213 [33].

Reichard found that shrinkage of lightweight aggregate concrete ranged from 0.02% to 0.08% of the total length at 90 days. The average was approximately 0.05%. At 2 years, the shrinkage ranged from 0.04% to 0.09% with an average approximately 0.07%. Lightweight concrete generally plateaued around 150 days of age. Very little drying shrinkage would occur after this time period.

Reichard also tested creep and shrinkage together. For this behavior, he found that it ranged from 0.06% to 0.14% of the total length at 90 days. At 2 years, the creep ranged from 0.09% to 0.22%. The average at 2 years was approximately 0.16% of the total length.

Reichard also showed that creep plus shrinkage increased as cement content was increased. It was approximately linear, with the creep plus shrinkage equaling 0.28% of the total length at 1 year for cement contents of 700 pounds per cubic yard, a similar amount to that expected in the current project.

2.2 Performance of Lightweight Concrete in Prestressed Members

Lightweight concrete has been used in bridges around the world. Different parts of the bridge structure have been fabricated with lightweight concrete. Results have been mixed.

2.2.1 Lightweight Aggregate Bridge Construction and Performance in Europe

European countries and especially Norway have built many bridges with lightweight concrete. They have had success with the material. Following are some examples.

2.2.1.1 Mays and Barnes (1991) [19]

Mays and Barnes looked at the performance of many lightweight concrete structures in the United Kingdom. Of most interest is their discussion of lightweight concrete bridge structures in place.

Overall, the structures were all in good shape. They showed some wear and tear, but when compared to adjacent normal weight concrete structures built at about the same time, the lightweight concrete structures actually outperformed the normal weight structures. Also, measured chloride levels in the lightweight concrete were lower at larger depths than in normal weight concrete structures. The performance was satisfactory for all the bridge structures.

2.2.1.2 Laamanen (1993) [20]

In his report, Laamanen discusses the Sundbru bridge in Eidsvoll, Norway which used high strength lightweight concrete. The bridge, built in 1991-1992, utilized natural sand and lightweight aggregate Leca, an expanded clay.

Overall performance of the concrete in the bridge was excellent. The compressive strength of the concrete averaged to 9700 psi at 28 days, achieved with the use of silica fume as an admixture. The modulus of elasticity was 3,080,000 at psi at 28 days. The weight of the concrete averaged between 115 pounds per cubic foot (pcf) and 118 pcf for the equilibrium unit weight.

Measured chloride and freeze-thaw resistance indicated that the concrete performed as well as comparable normal weight concrete. Overall, the performance of this bridge was a success.

2.2.1.3 Melby, Jordet, and Hansvold (1993) [21]

In 1988, Norway introduced a new standard for design of concrete structures with higher limits for concrete strength. This new standard encouraged designers to use higher strength concrete in their structures.

Since high strength lightweight concrete had become a viable option due to the introduction of water-reducing admixtures and silica fumes, designers chose it for two bridges in Norway, Sandhornøya and Støvset.

Both bridges were long-span cantilever bridges. Sandhornøya had a midspan of 505 ft and was the first bridge in Norway where lightweight concrete was used in the superstructure.

The concrete performed satisfactorily. The strength was adequate (no exact values given) while the modulus of elasticity was 3,260,000 psi at 28 days, larger than usual for lightweight concrete. After five years, the concrete was inspected for its performance. The structural state of the bridge was good with some cracking. It was theorized by the authors that the cracking was caused by the inferior curing conditions faced by the bridge. Specifically, the bridge was cured in low temperatures in the middle of the winter. Also, the concrete proved to be very resistant to chloride penetration.

Overall, the lightweight concrete proved to be economical for use in long-span bridges. The author concluded that as long as steps are taken to monitor the bridge since durability of lightweight concrete is not fully understood, then lightweight concrete makes a good choice for a bridge material.

2.2.1.4 Sandvik (1993) [22]

Sandvik provided an overview of bridges built in Norway with lightweight concrete since 1987. Eight bridges had been constructed using high strength lightweight aggregate concrete. All are found in marine environment. Some of the bridges included in his study are also found in the previous papers of fellow Norwegians.

Overall, Sandvik found the use of high strength lightweight concrete to be minimal due to the unfamiliarity of designers with the material. However, in those bridges where it was used, the performance has been comparable to that of the normal weight concrete with no major problems reported with any of the bridges.

2.2.2 Lightweight Concrete Bridge Performance in United States

Lightweight concrete has been widely used in bridges in the United States since the 1960s. Most experiences have been good as lightweight concrete has performed similarly to normal weight concrete.

2.2.2.1 Hanson [23]

Hanson wrote an early paper discussing the use of lightweight concrete for prestressed concrete construction. He focused on the expanded shale aggregate which was available in the Rocky Mountain area.

The main advantages of lightweight concrete, Hanson concluded, were the ability to produce smaller sections due to the decrease in weight of the concrete. Also, another advantage was the decreased transportation cost, as a lower weight will allow more units to be placed on a truck for transfer.

However, substantial attention was focused on the strength of the concrete. Due to the desire of precast manufacturers to release their forms in one day, a concrete mix must be developed which has sufficient strength at one day to allow for release. Also, Hanson suggests that a lightweight concrete mix must also have an adequate modulus of elasticity, as this will help reduce camber of the unit, a significant problem with lightweight concrete prestressed members.

2.2.2.2 Jennings and Brewer, Florida Department of Transportation (FDOT,1964) [6]

One of the first documented experiences with lightweight concrete in the United States is from FDOT. FDOT faced a problem in that it wanted to replace a steel truss bridge which spanned 120 feet. They wanted to continue to use the bridge but replace the structure with prestressed concrete. The 120 foot span was considered to be too long for typical normal weight concrete prestressed girder construction. Therefore, it was decided to try lightweight concrete for the substructure, superstructure, and deck.

In the bridge, the girders were American Association of State Highway Transportation Officials (AASHTO) Type IV girders. Six girders supported each span of a 28 foot wide deck.

The lightweight aggregate used was Solite, an expanded clay. The specification for the lightweight concrete was that it had to have an equilibrium unit weight less than 120 pcf. The concrete performed well above minimum standards. The prestressed girder concrete tested at 6500 psi at 28 days. Although release strengths are not mentioned, it is noted that the concrete checked out well above the minimum design strengths. The deck concrete tested at 4000 psi at 7 and 5000 psi at 28 days.

The biggest problem encountered during the construction of this bridge was the variation in moisture condition of the coarse aggregate. Florida officials chose to handle this problem by sprinkling the stockpiled aggregate for 24 hours prior to production of the concrete.

2.2.2.3 Murillo, Thomas, and Smith (1994) [24]

Another advantage of lightweight concrete for segmental bridges is in the seismic area. Lightweight concrete can alleviate two problems faced by normal weight segmental concrete bridges; the lateral forces induced by ground motions which shake the foundations of elevated superstructures and the out-of-phase oscillations of the superstructure.

Their paper discussed the choice of lightweight concrete for a 1.2 mile long bridge located in California between the cities of Benicia and Martinez. The bridge has been designed to withstand a 7.3 magnitude earthquake on the Richter scale.

The lightweight concrete box girder bridge turned out to be the most economical bridge of the four surveyed, costing $8 to $42 million less than the others. The concrete chosen had natural sand as the fine aggregate and an expanded shale as the coarse aggregate. The spans were 528 feet in the center and 335 feet on the ends.

Increasing the prestress placed into the girders, thereby increasing the camber, combatted the reduced modulus of elasticity of the lightweight concrete. Also, the box girders are prestressed longitudinally, transversely, and vertically. This three-dimensional prestressing provided for a relatively crack-free structure.

Overall, performance of the bridge was expected to be more than adequate, providing increased seismic resistance for a smaller cost.

2.2.2.4 Vaysburd (1996) [4]

In his article in Concrete International, Vaysburd looked at durability of lightweight concrete structures. By comparing the mechanical properties of lightweight concrete to normal weight concrete, he found that lightweight concrete actually should perform better than normal weight concrete in resisting crack formation.

Vaysburd found that the lower modulus of elasticity, higher drying shrinkage, and and higher creep values of lightweight concrete compared to normal weight concrete gave lightweight concrete the ability to sustain greater tensile strains. Because of this, the lightweight concrete actually would have more crack resistance. Also, tests have shown that lightweight concrete has lower permeability values than comparable normal weight concrete.

Furthermore, lightweight concrete generally has more cement per cubic yard than normal weight concrete. Therefore, this delays the carbonation and steel depassivation (the start of corrosion) by having more calcium hydroxide available.

To back these findings, Vaysburd looked at two bridges which used lightweight concrete in their decks in the United States. The first example, the William Preston Lane, Jr. Memorial Bridge in Maryland was constructed in 1952 with an expanded shale deck. An inspection in 1975 showed that the lightweight concrete had outperformed the normal weight concrete in the bridge. Therefore, the remaining normal weight decks were replaced with lightweight concrete. Also, The San Francisco-Oakland Bay Bridge was constructed in 1936 with an expanded shale deck while the lower deck of the bridge was reconstructed with an expanded shale deck in the early 1960s. The lightweight decks showed some chloride contamination in the top inch of the exposed surfaces. However, the chloride levels at the steel layer had not reached a worrisome level. On the other hand, the parts of the bridge using normal weight concrete were in need of replacement due to spalling.

2.2.3 Lightweight Concrete Bridge Performance in Texas

From internal information provided by the Texas Department of Transportation (TxDOT), use of lightweight concrete in Texas bridges has been fairly minimal. Most, if not all, of the experience with lightweight concrete has been limited to use in decks.

Typical of the use of lightweight concrete is its use in the Rainbow Bridge over the Neches River. The width of the deck needed to be expanded to meet specifications. However, engineers did not want to increase the dead load on the structure. Therefore, lightweight concrete was chosen since it allowed engineers to obtain the width of the deck they wanted without increasing dead load.

Overall, performance of lightweight concrete has been comparable to that of normalweight concrete. Most of the elements constructed of lightweight concrete are rated at 6 or 7 on the BRINSAP scale, meaning satisfactory performance with some signs of wear.

Perhaps the worst performance came in the Pierce Elevated in Houston. Lightweight concrete was used in the deck and had terrible performance. There were large problems with spalling and cracking of the deck. However, it has been speculated that these problems with performance grew out of bad construction practices. Investigations showed that the concrete was constructed without the minimum cover needed for pretection of the steel bars from corrosion. Therefore, the bars corroded and spalled, cracking the concrete.

Otherwise, overall performance of lightweight concrete in Texas has been good. Whenever suitable construction practices have been followed, lightweight concrete has proved to be an appropriate choice of material.

Chapter 3: Mix Designs

3.1 First Iteration

In order to produce concrete with the proper specifications for the project, many different mix designs had to be created and tested. The initial mix designs were chosen to provide a wide variety of materials and amounts. It was planned that later mix designs would focus on refining specific promising mixes.

Also, these initial iterations provided a chance to practice using the lightweight aggregate. Lightweight aggregate requires different preparation procedures than typical aggregates such as crushed limestone and river gravel due to the high moisture amounts that lightweight aggregates absorb.

Therefore, these initial mix designs served two purposes. First, they gave the approximate mix proportions for use in the project and second, they helped the project staff learn the appropriate methods for mixing lightweight concrete.

3.1.1 Decisions on Materials to Use

Concrete is comprised of four distinct components: cementitious materials (includes cement and/or pozzolonic admixtures), coarse aggregate, fine aggregate, and water. However, in these basic categories, a multitude of options exist from which the materials can be chosen.

However, a couple of general rules guided the process. First, the materials had to be widely available inside the state of Texas. Precast operators, the people who eventually would utilize the mix designs, must be able to obtain the aggregates in a timely manner. Second, the mix designs needed to be as simple as possible. Therefore, exotic admixtures or materials that are not familiar to precasters should not be used. These mixes also needed to be easily reproducible.

3.1.1.1 Type of Cement

Since this lightweight concrete was being used in a precast environment, high early-strength values were necessary so that the strands could be released in approximately 24 hours. The precast plant where the beams for this project were fabricated requires that concrete be at least 3500 psi before release of strands. Because of these early high strength requirements, Type III cement was chosen. Type III cement is the typical cement used in precast plants due to its high strength gain at early ages.

Many cement manufacturers exist around Central Texas. However, only one company makes Type III cement and packages it in small enough quantities for laboratory use. Therefore, the Alamo Cement plant north of San Antonio provided the cement for the laboratory mix designs in this project. The brand name of the cement was Alamo Red Bag. Alamo provides much of the cement for the precast plants around Central Texas.

3.1.1.2 Type of Fine Aggregate

Since the concrete was required to have an equilibrium unit weight no more than122 pcf, this allowed the use of sand as the fine aggregate of choice. It was felt that a fine aggregate made up of lightweight materials would not provide the performance needed to reach the high strength specifications. Since a sand-lightweight concrete easily fell within the weight specifications, sand became the lightweight fine aggregate of choice.

The sand used in the early stages of the project was Colorado River sand from Capital Aggregates. Midway through the project, a new shipment of sand was obtained. Due to a sand shortage in the Austin area, a new supplier was located, suggested by Capital Aggregates. The sand from the new supplier was also Colorado River sand, similar to the earlier type.

3.1.1.3 Type of Coarse Aggregate

Once again, availability of aggregates constrained the choices for lightweight aggregates. In the state of Texas at the present time, apparently only one company produces lightweight aggregate, Texas Industries, Inc. (TxI). They produce two separate lightweight aggregates, Clodine and Streetman. Clodine is an expanded clay while Streetman is an expanded shale. Discussions with CoreSlab Industries, a precast manufacturer of double-tee members for parking garages, showed that they used Streetman for use in manufacture of double-tee members. However, use of Clodine is also widespread in manufacture of lightweight concrete and slabs.

From these two choices, Clodine was available to us from a local ready-mix concrete plant, Rainbow Industries. They were willing to provide small amounts of aggregate at any time when needed. The aggregate had a maximum size of 3/4 inch and was well-graded. Therefore, Clodine was used as the initial lightweight aggregate.

3.1.1.4 Type of Fly Ash

A Class C fly ash was used in all the mixes that utilized fly ash. Fly ash was used due to the excellent permeability characteristics of concrete incorporating fly ash. The fly ash was also obtained from Rainbow Industries as they again were willing to contribute fly ash to the project.

Class C fly ash was chosen due to its widespread availability in Texas. Also, its ability to aid in the formation of late-age strength was desirable since Type III cement generally slows in its late-age strength production compared to Type I cement.

3.1.1.5 Type of Admixtures

A major concern was the workability of the concrete. Since these specific mixes of concrete needed to be used in a precast environment, this concrete needed to have a large slump.

Generally, large slumps are achieved in concrete through the use of more water in the mix. However, more water in a mix reduces the strength. Therefore, admixtures were chosen to produce the necessary slump to cast these beams.

The admixtures needed to serve two purposes. Due to the large amount of cement expected in these initial mixes, these mixes have a higher temperature than normal mixes. With an increased temperature, the concrete would experience rapid slump loss. Therefore, a retardant would be needed to slow down the set times. Since the laboratory had access to Daratard-17 by Grace, this was the retardant chosen.

The second purpose was to produce the slump needed for these mix designs. Again, due to the large amount of cement, small slumps were expected. Therefore, a superplasticizer was needed to increase the slump to the target of 7 to 9 inches. ADVA Superflow was the choice. Again, this can be attributed to its ready availability.

Both these admixtures are widely available throughout Texas from Grace. Many precast plants around Austin use Grace admixtures.

3.1.2 Initial Variables

After the initial decisions about which materials would be used, proportions had to be decided. To do this, existing literature was reviewed to provide some ideas about possible proportions for high strength mixes. Also, local precasters were contacted to determine any possible high strength lightweight mixes that they used. A local precaster used a blended coarse aggregate with crushed limestone and lightweight aggregate [6]. However, use of this was ruled out because the mix was too heavy.

Furthermore, most literature indicated that silica fume was a key admixture in creating high strength concrete. However, it had been decided not to use silica fume due to its high cost and low availability compared to fly ash.

Therefore, most of the first mixes were based on prior experiences. Consultation with Dr. Ramon Carrasquillo provided the mixes developed for the first part of the project.

The mix designs for all the mixes are presented in Appendix A of this paper.

3.1.2.1 Water/Cement Ratio

Although water/cement ratio does not play as large a role in strength in lightweight concrete as it does in normal weight concrete, it still is a significant quantity. Due to its widespread use in the field of concrete design and its familiarity to most people in the field, it is a convenient measure for controlling concrete strength since it usually gives a rough idea of the resultant compressive strength of the concrete.

For these initial mixes, prior experience and previous literature provided a guide to initial values of the water/cement ratio. From these, values in the range of 0.30 to 0.35 were chosen. Obviously, workability is a prime issue. Therefore, the water/cement ratios needed to be as large as possible to maximize workability and minimize use of superplasticizer. Table 3.1 presents the water/cement ratios used in the first portion of this project.

Table 3.1 Water/Cement Ratios and Cementitious Material Amounts for First Iteration

Mix Number	Water/Cement Ratio	Pounds Cementitious Material/Cubic Yard
1	0.35	600
2	0.35	600
3	0.35	600
4	0.35	600
5	0.35	600
6	0.35	600
7	0.35	600
8	0.35	600
H-1	0.32	800
H-2	0.32	800
H-3	0.32	800
H-4	0.32	800

3.1.2.2 Amount of Fly Ash

Using fly ash was not a foregone conclusion in these mixes. Prior documentation [37] has shown that fly ash reduces early-age strength of concrete significantly. Since one of the main emphases of these concrete mixes was to obtain high early-age strength, fly ash could have created a problem.

Therefore, these initial mixes were made both with fly ash and without fly ash. The proportion was chosen to be 25% replacement with fly ash by weight of cement.

3.1.2.3 Coarse Aggregate Factor

Another goal of these early mixes was to ascertain the amount of coarse aggregate that is needed to produce a workable mix and the required proportion between the sand and lightweight aggregate. In normal weight high strength concrete made with crushed limestone or river gravel, the concrete gains a significant portion of its strength from the aggregate. However, in lightweight concrete, the aggregate does not contribute significantly to the strength. Although very weak aggregate could detract from the strength, increasing the amount of lightweight aggregate in the matrix does not effectively increase the strength or the stiffness.

Due to this reason, workability became the main concern when proportioning the coarse aggregate. The proper proportion between coarse and fine aggregate had to be found in order to give the proper finishing characteristics and adequate slump. Also, since sand serves as a binder in concrete, there had to be an ample amount to hold the concrete together.

For these initial mixes, two separate proportions were chosen for the coarse aggregate and the sand. It was hoped that these two proportions would provide the extreme range on the possible behavior. In other words, one mix would have about the maximum amount of sand (making it “sandy”) that could be used before the concrete would become too sticky while the other would have the maximum amount of lightweight aggregate (making the mix “rocky” or “coarse”).

3.1.3 Procedures

For production of the concrete, ASTM procedures were followed. This was done in order to have the best possible comparison between previously published data and the data in this project.

3.1.3.1 Preparation of the Aggregate

The aggregate presented the most difficulties during the mixing of the concrete. Most users of lightweight aggregate wet down the aggregate for at least 24 hours prior to placement in concrete mixer. In most precast and ready-mix concrete plants, aggregate is placed in a stockpile and then a sprinkler wets the pile for at least 24 hours. The aggregate then will be somewhere between the saturated surface dry (SSD) state and the saturated state.

Production of concrete at the laboratory presented a large problem. First, no facilities were available to allow use of a sprinkler that would reach the stockpile of aggregate. The closest practical procedure would have been to submerge the aggregate until loading it into the mixer. However, this was not desired since the aggregate would then be too wet before placement in the mixer. Also, most literature on the subject of lightweight aggregate concrete has had the aggregate added while in a moist condition [2,16].

Because of these problems, it was decided to submerge the aggregate in tubs of water for 24 hours prior to mixing of the concrete. If possible, the aggregate would begin soaking in the tubs 72 hours prior to concrete mixing. Figure 3.1 shows the aggregate soaking in the tub.

Figure 3.1 Aggregate Soaking in Tub Before Drying

Approximately an hour before mixing, the aggregate was removed from the tubs and then placed on a concrete deck outside. The water not soaked up by the aggregate or clinging to the surface drained away from the aggregate with the help of the sun and wind. The aggregate was then added to the mixer.

3.1.3.2 Production of Concrete

Concrete was produced in accordance with ASTM Procedure C685 [25].

First, a moisture content of the sand was taken so that the water could be adjusted to account for the absorption capacity of the sand. Second, the amounts of cement, fly ash, sand, and water were weighed out. The scale had an accuracy of 0.1 pound, more than ample when dealing with the size of proportions in this project.

Third, the aggregate was weighed out. No moisture contents were taken since the ASTM test for moisture content in normal weight aggregate is considered an extremely unreliable test for lightweight aggregate. The aggregate was assumed to be close to SSD state. Fourth, the mixer was buttered with 10% of the cement weight and sand weight to reduce the losses in the mixer. Fifth, the components were placed in the mixer. Figure 3.2 shows the mixer used in this project.

Figure 3.2 Concrete Mixer

The lightweight aggregate was added first followed by the sand. The mixer was then turned for a short time to produce a good mixture of the two components. After these two, the cement and then the fly ash was added. Again, the mixer was turned a number of turns and allowed to mix all the components well.

Now, the water was added. As the mixer was rotating, half the weight of the water was added. The mixer was allowed to spin until the water was accepted by the cement and fly ash. After there was no visible free water (and the aggregate and mortar was starting to clump), the rest of the water was added slowly as the mixer was spinning. This was done to aid complete mixing of the concrete.

After the water was completely added, the mixer was spun for three minutes. The concrete was then allowed to rest for three minutes. Then, the concrete was spun for another two minutes. At the end of the two minutes, a slump test on the concrete was taken.

After the slump test was taken, superplasticizer was added in 2 fluid ounce increments until concrete with the slump desired was produced.

The concrete was then emptied into a wheelbarrow. Specimens were then prepared in accordance with ASTM standards depending on need.

3.1.4 Initial Results

To accurately document the behavior of the test specimens, the test regimen in Table 3.2 was developed.

Table 3.2 Test Regimen for Concrete Specimens

Days	Compressive Strength	Modulus of Elasticity	Modulus of Rupture	Splitting Tensile Strength
1	X	X	X	X
3	X			
7	X			
28	X	X	X	X

This test regimen allowed for full investigation of the mix designs. Since these mixes were intended for pretensioned concrete, the focus was on high early-age strength, namely 1 day strength. The three-day and seven-day strength tests allowed for further refinement of the concrete strength curve. Finally, the 28 day test finished the test regimen. Since most concrete data are based on 28 day strengths, this seemed to be the most logical place to finish the testing.

3.1.4.1 Compressive Strengths

All compressive strength tests followed ASTM Test Procedure C39 [26]. The cylinders were moist-cured until the time of the test. The apparatus used in the test is shown in Figure 3.3.

Figure 3.3 Apparatus for Compressive Test

3.1.4.1.1 6000 psi Mixes

A graph of the age vs. strength curves for concrete mixes in the first iteration is presented in Figure 3.4. As can be seen, these strengths were highly variable.

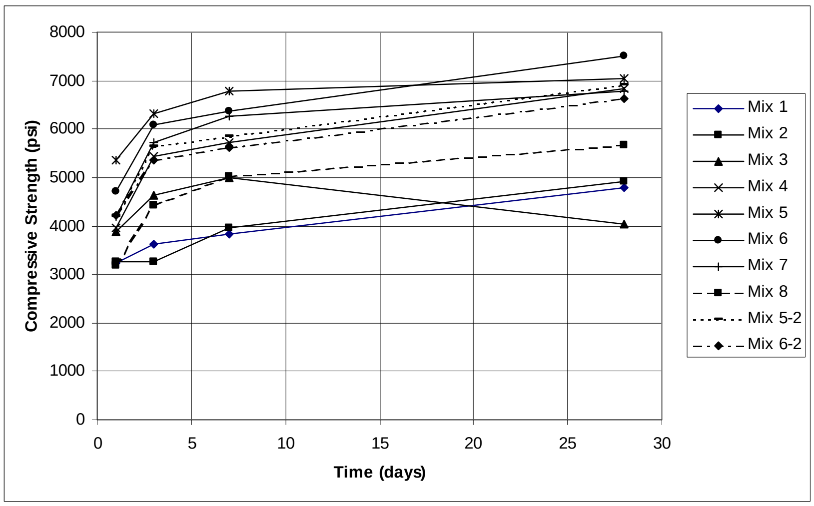

Figure 3.4 Compressive Strengths of Initial 6000 psi Mixes

However, it is doubtful that this means that there was great variability in the concrete.

The first conclusion taken from these results is that the handling of the concrete was not very good. Because this was the first time the project staff made concrete in a laboratory, many mistakes were made during the placement and testing of the concrete. Mix 3 in Figure 3.4 probably did not really lose strength as it matured from 7 to 28 days. Therefore, some type of error existed in the placement or the testing of the concrete.

Because of these problems, Mixes 1-3 hold no significance. Coincidentally, they are the three weakest mixes. They were the first three mixes produced. They really should be considered learning mixes.

The other mixes were better controlled and gave good results.

Most interestingly, all of the concrete except for Mix 8 reached the desired 6000 psi at 28 days. These results show that 6000 psi lightweight concrete can be reached easily.

Also, the 1 day compressive strengths indicated satisfactory strength. As previously mentioned, the concrete needed to be at least 3500 psi at one day to allow the precast plant to release the prestress. As can be seen in Figure 3.4, most of the significant mixes reached this goal in one day.

However, these same mixes needed repeatability to be considered candidates for use in the beams. Therefore, two mixes were chosen to be repeated.

Figure 3.5 shows the results of two mixes which were repeated in comparison with their original results.

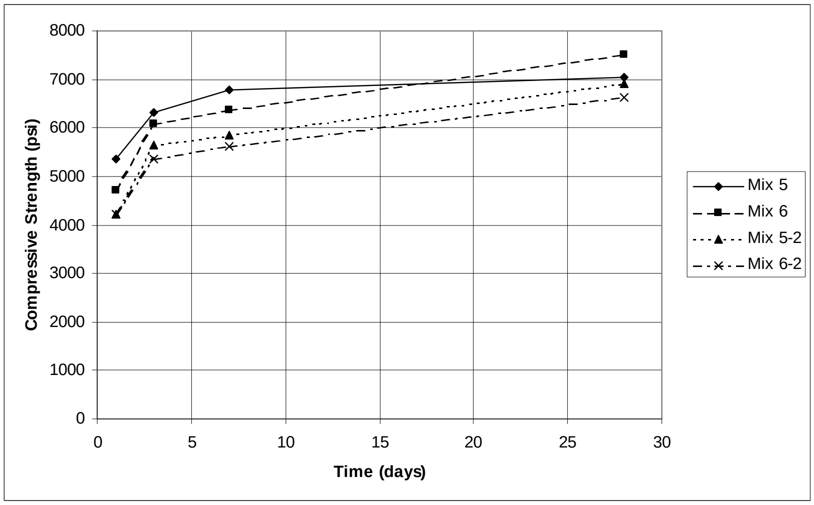

Figure 3.5 Compressive Strength of Repeated Mixes in Initial Series

Obviously, Figure 3.5 raises problems. Neither of the repeated mixes reached the strength of the original ones. Also, the curve for Mix 5-2 did not match the slope of Mix 5. The slopes were nearly equal for Mixes 6 and 6-2. However, the differences in the strengths of the concrete mixes are problematic.

There are a couple of possible explanations for this lack of repeatability. First and most likely, a difference in the moisture condition of the aggregate could have played a role in the strength. Due to the inexact nature of determining when the aggregate is in the SSD condition, the aggregate would often be added in varying surface conditions despite the best efforts of the staff. This affects the yield of the concrete. If the aggregate has different amounts of water absorbed but the same weight is placed in two mixes, a different volume of aggregate is placed in the two mixes, causing a different yield. This problem resurfaced later in the mixing process.

Second, the temperature and the ambient conditions could have caused a difference in the strength. On the warmer days when Mixes 5 and 6 were produced, the ambient air temperatures promote the reaction of the cement and the water, perhaps creating more strength.

3.1.4.1.2 8000 psi Mixes

The 8000 psi mixes had many disappointing results. They did not reach the strengths necessary to be considered a success. Figure 3.6 shows the compressive strengths of the concrete that were expected to be 8000 psi.

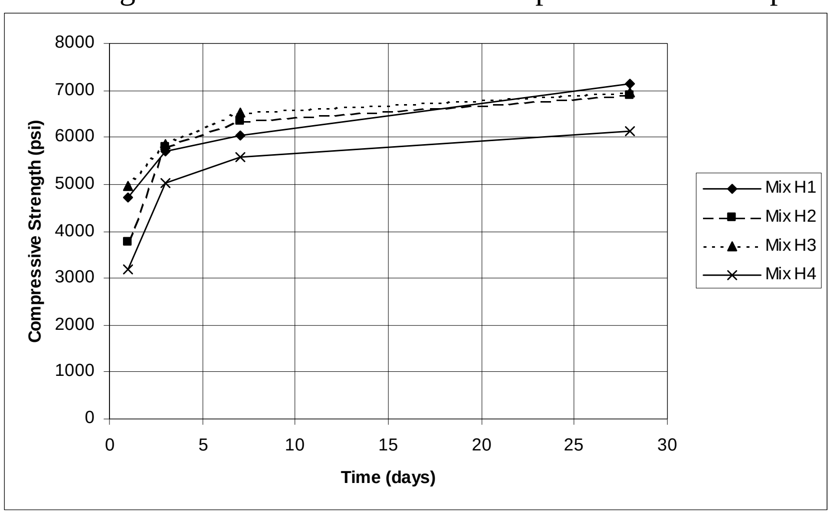

Figure 3.6 Compressive Strengths of 8000 psi Concrete Mixes

The 8000 psi concrete mixes did not reach the required strengths for acceptance. All the mixes were at least 1000 psi short of the target. Since all of the concrete mixes used exactly the same amount of cement in the mix, the results were pretty consistent, as would be expected. Obviously, it was not enough cement to produce the required strength.

The fly ash did not play much of a role in strength formation. Mixes H2 and H4 both had fly ash replacement at 25% of the weight of cement. Due to inconsistency of Mix H4 compared to the other concrete mixes, this probably is insignificant. Therefore, looking at Mix H2 compared to Mix H1, fly ash barely reduces the compressive strength.

The aggregate also does not play a large role in strength formation. Mixes H3 and H4 had much more coarse aggregate than did Mixes H1 and H2. The strength did not suffer at either end of the spectrum. Obviously, workability is going to play the largest role in determining the appropriate mix proportions.

3.1.4.2 Modulus of Elasticity

Another significant property was the elastic modulus. The modulus was determined using ASTM Test Procedure C469 [27]. The test setup is shown in Figure 3.7.

Figure 3.7 Test Setup for Modulus of Elasticity

The modulus was tested at 1 and 28 days. One day was chosen since this was when the concrete would be stressed due to pretensioning while the 28 day test would provide the elastic modulus used for service conditions.

Since bridge girders generally remain in the elastic range, this test holds a great deal of importance when calculating deflections and loss of prestress. Also, lightweight concrete generally has a reduced elastic modulus when compared to normal weight concrete. It was important to know the reduction in elastic modulus.

Figure 3.8 presents the modulus of elasticity results for the first batch of mixes.

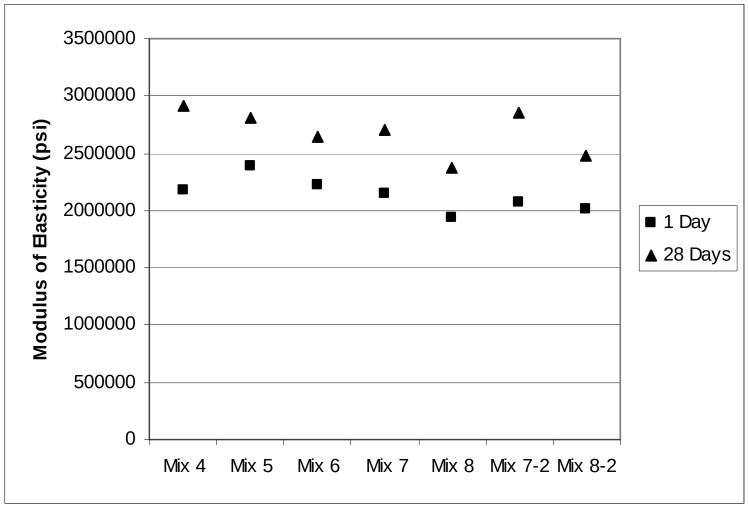

Figure 3.8 Modulus of Elasticity for 6000 psi Mixes in First Iteration

As can be seen from Figure 3.8 the modulus of elasticity generally was from 2,000,000 to 2,500,000 psi for 1 day age while the 28 day modulus of elasticity was from 2,500,000 to 3,000,000 psi, values which agreed with previous research.

The same results can be seen for the 8000 psi concrete in Figure 3.9.

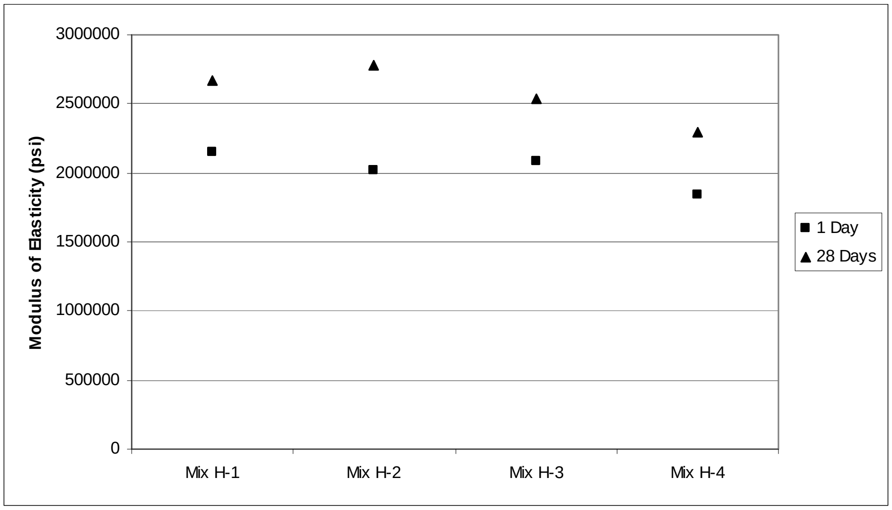

Figure 3.9 Modulus of Elasticity of 8000 psi Initial Concrete Mixes

These results were similar to the results for the 6000 psi concrete mixes. The moduli fell in the same ranges for both 1 day and 28 day tests. These results were predicted by Martinez [2] who showed that elastic modulus in lightweight concrete does not increase proportionally to strength gain in high strength concrete.

3.1.4.3 Flexural and Tensile Properties

To complete the battery of tests carried out on the first sequence of concrete mixes, two different tensile tests were performed. Beams were fabricated to allow performance of the Modulus of Rupture (MOR) test (ASTM test C78) [28] while cylinders were reserved for the split cylinder test (ASTM test C496) [29]. Both tests are very commonly used to measure tensile properties of concrete. Figure 3.10 and 3.11 show the test setup for both tests.

Figure 3.10 Test Setup for Splitting Tensile Test

Figure 3.11 Machine Used for Modulus of Rupture Tests

Since lightweight concrete was being used, much lower tensile values were expected. Since both concrete mixes being developed were for use in prestressed construction, tensile properties are very important in the determination of the allowable amount of prestress. Allowable amounts of prestress are controlled by AASHTO 9.15.2 [12]. Tensile strength of the concrete generally controls when the top fiber of the concrete at beam end goes into tension due to the eccentricity of prestress. Obviously, the tensile strength is very important.

The results for both MOR test and splitting tensile tests are presented in Figure 3.12.

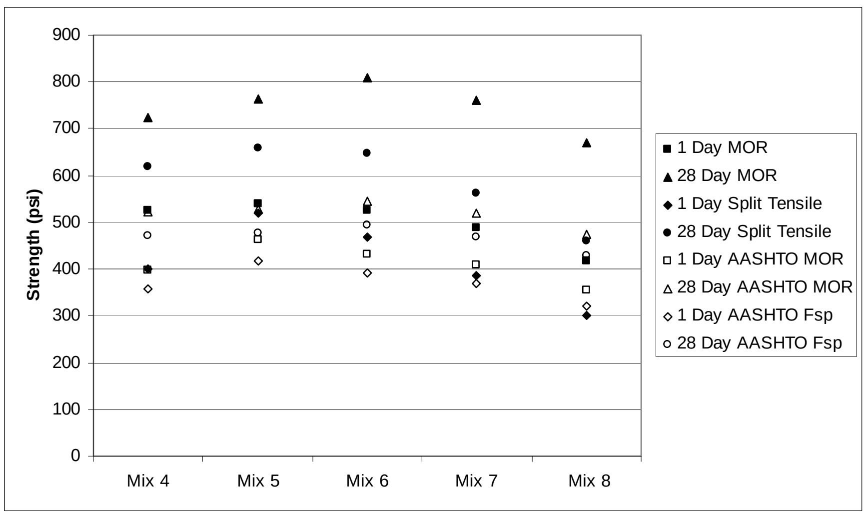

Figure 3.12 Tensile and Flexural Tests for Initial 6000 psi Mixes

Both the MOR test and splitting tensile tests gained from 200 to 250 psi from one day to 28 days. Also, Mix 6 achieved the highest strength for 28 day MOR while Mix 5 had the highest splitting tensile strength at 28 days. Generally, as a rule of thumb, higher compressive strength meant higher tensile strengths. This rule is followed here as Mixes 5 and 6 had the highest compressive strengths.

Another interesting results can be seen when the results are compared to the AASHTO equations for MOR and splitting tensile strength. AASHTO 8.7.2 [12] allows the use of $6.3\sqrt{f_c^{'}}$ (Equation 2.4) as an expression for MOR for sand-lightweight concrete. Figure 3.12 shows the comparison to the allowed AASHTO values for flexural strength. All five mixes outperformed the AASHTO values at both 1 day and 28 days.

The 8000 psi mixes showed similar results. Figure 3.13 gives the tensile and flexural properties for the four mixes tested in this initial series.

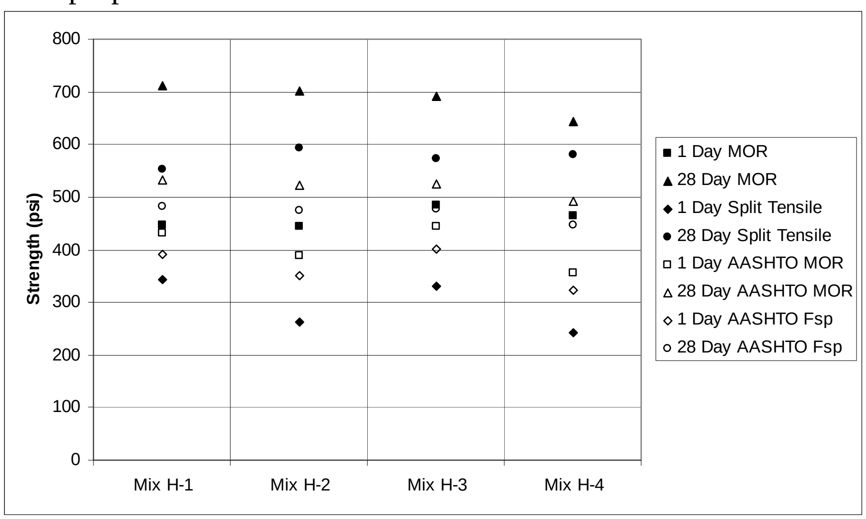

Figure 3.13 Tensile Properties for Initial 8000 psi Mixes

The results for the 8000 psi mixes were very similar to the results from the 6000 psi mixes. However, the results from the 8000 psi mixes did not reach as high a tensile strength as the 6000 psi mixes did. Also, the one day splitting tensile strengths were extremely low, lower than all of the results for the 6000 psi mixes. However, the modulus of rupture values met expectations, as did the 28 day splitting tensile tests. All values were satisfactory for the 28 day strengths. They also outperformed the AASHTO values for the modulus of rupture.

These results from the initial mixes of the concrete indicated that the tensile strength of the concrete should not be a main concern in the further iterations of the concrete mix design.

3.2 Second Iteration

Once the initial iteration was complete, the approximate proportions for the 6000 psi mix were known. However, the approximate mix proportions for the 8000 psi still needed to be found. Therefore, the main goal was to refine the 6000 psi mix while increasing the cement content for the 8000 psi mix to reach the needed strength.

Five mixes were developed for test during this iteration. Although five mixes does not seem like a large number, these mixes were done three times apiece due to the addition of a new variable to the test program.

3.2.1 Modification of Variables

During this iteration, a new variable, coarse aggregate type, was added while the older variables were refined.

3.2.1.1 Water/Cement Ratio

From the results of the first iteration of mixes, it was recognized that the mixes were not reaching the 8000 psi requirement at 28 days. Since the water/cement ratio was 0.32 for those mixes, the mixes in this portion of the project concentrated on lowering the water/cement ratio to achieve higher strengths. Table 3.3 presents the water/cement ratios used in this portion of the project.

Table 3.3 Water/Cement Ratios for Second Iteration

Mix Number	Water/ Cement Ratio	Pounds Cementitious Material/Cubic Yard
1	0.28	800
2	0.26	850
3	0.26	900
4	0.28	800
5	0.28	800

When compared to the values in Table 3.1 from the first iteration, it can be seen that these water/cement ratios have dropped significantly.

These lower water/cement ratios pose definite workability problems. The lowering of the water/cement ratios means that the use of superplasticizers and admixtures had to increase to counter the loss in workability.

3.2.1.2 Coarse Aggregate Factors

From the mixes of the first iteration, very little valid information about the best coarse aggregate fraction was received. Due to the handling of the coarse aggregate, there was very little uniformity in the moisture conditions of the aggregate. The results did not provide any indication as to the appropriate amount of coarse aggregate.

Therefore, for these five mixes, the amount of coarse aggregate and the proportion between the fine and the coarse was varied throughout the sequence of tests. Since these mixes would be closer to the actual proportions, it was hoped that the results from this sequence of tests would provide a good idea as to proportions needed.

Table 3.4 shows the coarse aggregate factors for these five mixes.

Table 3.4 Water/Cement Ratios and Coarse Aggregate/Fine Aggregate Proportions for Secondary Five Mixes

Mix Number	Water/Cement Ratio	Coarse Aggregate/ Fine Aggregate
1	0.28	1.1
2	0.26	1.25
3	0.26	1.1
4	0.28	1.25
5	0.28	1.15

Three separate coarse aggregate factors were chosen for these five mixes. The mixes had two different water/cement ratios. Each water/cement ratio had at least two different coarse aggregate factors that were tested along with it.

3.2.1.3 Types of Aggregate

One of the stated objectives of this project was to test at least three lightweight aggregates that are available for use in the Texas area. However, at the moment, there are apparently only two aggregates that are widely available in

Texas. These are Clodine and Streetman, both manufactured by Texas Industries (TxI).

In order to satisfy the requirement, a third aggregate needed to be obtained. With the help of TxI, a third aggregate was imported from Colorado. Three shipments of aggregates were delivered to Ferguson Structural Engineering Laboratory and stockpiled outside. The three aggregates used were Clodine, Streetman, and Western.

Clodine is an expanded clay from the TxI plant south of Houston, Texas. It comes in a variety of maximum aggregate sizes ranging from 3/8 inch to 3/4 inch. Figure 3.14 shows the appearance and maximum size of the aggregate.

Figure 3.14 Apperance and Maximum Size of Clodine Aggregate

The Clodine had a maximum size of 3/4 inch and was well-graded. Figure 3.15 presents the grading curve for this aggregate.

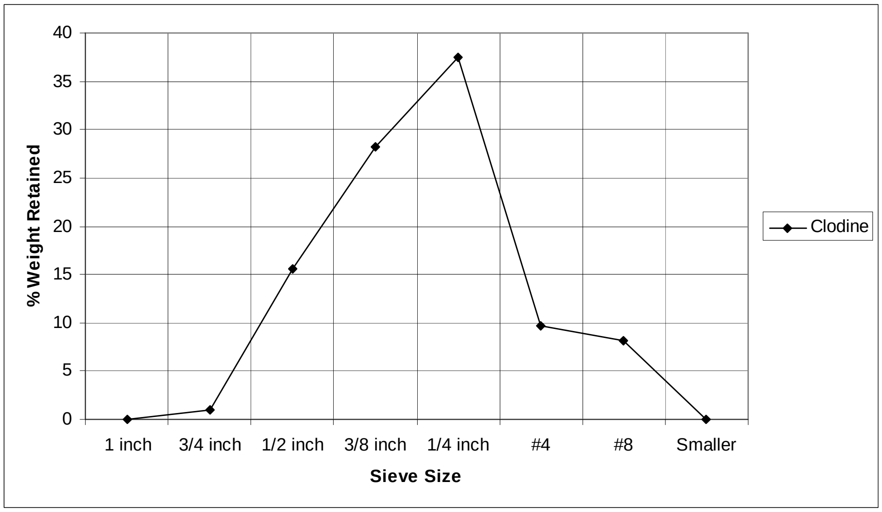

Figure 3.15 Grading Curve for Clodine Aggregate

This aggregate was well-graded with a decent distribution around the 1/4 inch sieve.

Next, Streetman is an expanded shale produced south of Dallas at a TxI plant. Streetman is often used in precast plants as an aggregate for double-tee members for parking garage structures. It comes in a smaller size than does Clodine and the Western aggregate. This smaller size allows it to fit in congested areas. Figure 3.16 shows the appearance and maximum size of the Streetman aggregate.

Figure 3.16 Appearance and Maximum Size of Streetman Aggregate

Figure 3.17 shows the grading curve. The maximum size is 3/8 inch, substantially smaller than the other two aggregates.

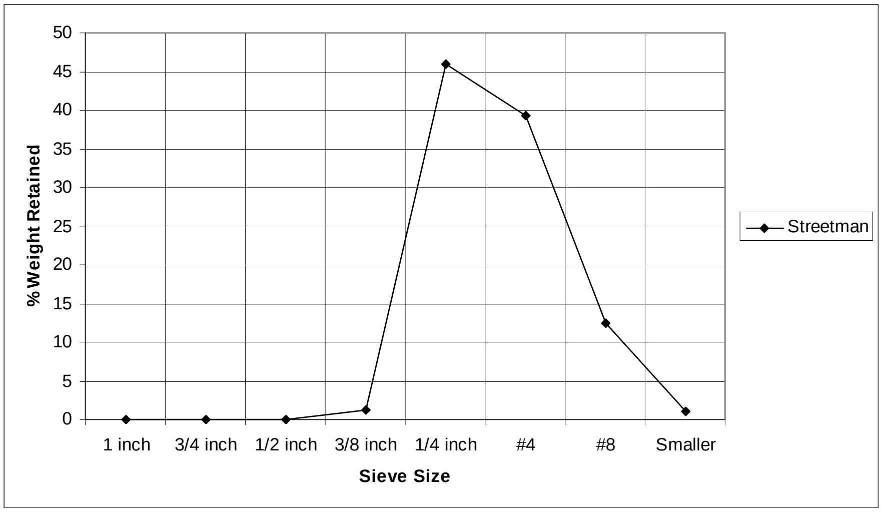

Figure 3.17 Grading Curve for Streetman Aggregate

Third, Western aggregate is an aggregate produced by a TxI subsidiary in Colorado. It also is an expanded clay like the Clodine. However, the shipment received was poorly graded, posing a problem as some grading is needed to produce a well consolidated mixture of concrete. Figure 3.18 shows the appearance and maximum size of the Western aggregate.

Figure 3.18 Appearance and Maximum Size of Western Aggregate

Figure 3.19 shows the grading curve for the Western aggregate.

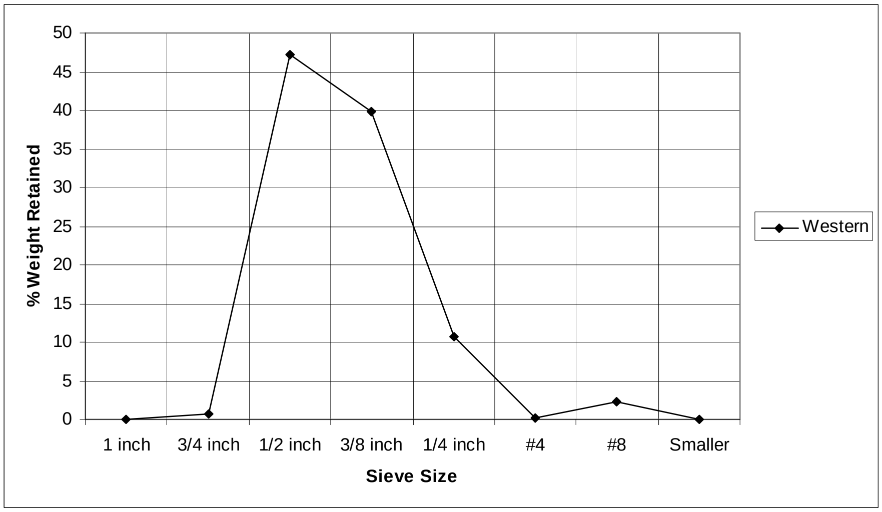

Figure 3.19 Grading Curve for Western Aggregate

The distribution of the Western aggregate was not very good. Almost all the aggregate was caught on the 1/2 inch and 3/8 inch sieves.

3.2.2 Procedures

The same ASTM procedures were followed in the making of the concrete for this portion of the test program. However, there was one major change in the way the concrete was produced.

During the first iteration series of concrete production, the coarse aggregate was allowed to dry in the sun on a concrete deck. This left the aggregate exposed to both wind and sun, the two major environmental drying agents. This caused the aggregate to often be in widely varying moisture states when it was added.

Therefore, with the help of Don Reeves from TxI, a new system was developed in which the aggregate was dried to a consistent moisture state.

First, the aggregate was soaked in tubs for at least 24 hours. Then, the aggregate was placed in rectangular wooden beds with a screen bottom. The aggregate was also covered with black plastic sheeting to protect against wind and rain. Aggregate is shown drying in Figure 3.20. The aggregate was allowed to dry for an hour.

Figure 3.20 Drying of Aggregate on Screened Bed

During this hour, the other concrete materials were batched. After the hour was up, a dry rodded unit weight (DRUW) was taken. The DRUW was checked against previous DRUWs taken during the test program. If the aggregate was within 2% of the previous DRUWs, it was allowed to proceed. If the aggregate was too wet, the aggregate was allowed to dry for fifteen minutes and the DRUW was checked after this period of time. The aggregate never became too dry with this practice. Since DRUW is based on a constant volume, the coarse aggregate was at a consistent moisture state and was allowed to proceed.

3.2.3 Results

The results were much more meaningful for this set of mixes due to the increased care shown in preparing the coarse aggregate and in mixing the concrete. The results overall were consistent and provided a good basis for further development of concrete.

3.2.3.1 Workability Issues

Since all three aggregate were expected to achieve approximately the same compressive strength, workability played a large role in differentiating the three aggregates. Workability was judged by how much superplasticizer was required to achieve the same slump as well as how well the concrete flowed after 30-45 minutes in the wheelbarrow.

Although quick placement is expected for mixes at the precast plant, the ability to remain reasonably workable for a 30 minute period played a large role in determining the best mix. The concrete needed to be placed in the forms, flow easily around the strands, and fill in the spaces without honeycombing. An overly stiff mix would not be able to do this.

To look at one aspect of workability, Table 3.5 presents the amount of superplasticizer added for every 100 pounds of cement.

Table 3.5 Average Superplasticizer Dosage Rates for Mixes with Three Aggregates

Aggregate	**Dosage Rate (fl. oz./100 cwt.)**
Western	4.70
Clodine	4.63
Streetman	5.06

Since all these mixes were dosed until they had the same amount of slump, approximately 9 inches, this table gives the average dosage rate needed to force the concrete mix to that point.

Table 3.5 shows that the mixes made with the Western and Clodine aggregates needed approximately the same dosage rate to reach the target slump while the Streetman needed about 6% more superplasticizer. The mixes with Western and Clodine aggregates were initially more workable before the addition of superplasticizer which brought all the mixes to the same point of workability.

Since Streetman had a smaller maximum size than did the Western and Clodine aggregates, an equal weight of Streetman would have more surface area than a comparable weight of Western or Clodine. Therefore, the Streetman aggregate is able to absorb more mixing water in the mix, which causes the lower initial slump.

Also, another interesting observation was the fact that all three mixes had increased cohesiveness after thirty minutes. This observation is anecdotal as no test was performed to verify this. However, both project staff members noted the difficulty in placing concrete with all three aggregate after thirty minutes had expired. After these thirty minutes, the concrete became gradually more difficult to place.

3.2.3.2 Yield Issues

Often, during the first iteration series of mixing concrete, the amount of concrete produced did not agree with the theoretical amount. Obviously, a problem existed with the yield of the concrete mixes.

From discussions with Don Reeves from TxI, it was realized that lightweight concrete has more variability with yield than does normal weight concrete.

Overyielding and underyielding are both major problems. Basically, if either one occurs, the concrete produced is not one that was designed. Therefore, during this sequence of mixing, a test for fresh unit weight of the concrete was added, determining whether or not the concrete had overyielded or underyielded.

Table 3.6 presents the results of the tests for yielding. Expected yield for all mixes done in the series was 3.5 cubic feet.

Table 3.6 Average Yields for Identical Mixes Produced with Three Aggregates

Aggregate	Yield from Expected (%)	Average	Std. Deviation
Western	-3.31	3.40	0.12
Clodine	-4.74	3.33	0.05
Streetman	-1.93	3.47	0.10

These results showed one of the main problems that exists with lightweight concrete, the inability to tightly control the volume of the concrete output. This wide variation comes about due to the difficulty of controlling the state of water in the aggregates. In normal weight concrete, the coarse aggregate absorbs little water, causing the calculated yield to closely agree with results of volumetric measurements. In lightweight concrete, the aggregate can soak up or give off a large amount of water which causes more problems and discrepancies in the volumetric yield prediction process.

The underyielding was caused by the variability in the volume of lightweight aggregate placed in the mix. Since the lightweight aggregate was batched by weight computed at SSD and since the aggregate was usually wetter than SSD, the volume of the aggregate actually placed in the mix was actually less than what was needed to produce the right amount of concrete.

3.2.3.3 Mechanical Properties

3.2.3.3.1 Compressive Strength

Due to better control of the aggregate in this sequence of mixes, the results are much more meaningful and provide a more accurate portayal of the strength expected when actually using these mixes.

Figure 3.21 presents the strength curves for the mixes with 0.28 water/cement ratio. Data on all the mix designs performed are given in Appendix B. They were expected to reach a compressive strength of around 6000 psi at 28 days. The major variation among the mixes was the amount of coarse aggregate used.

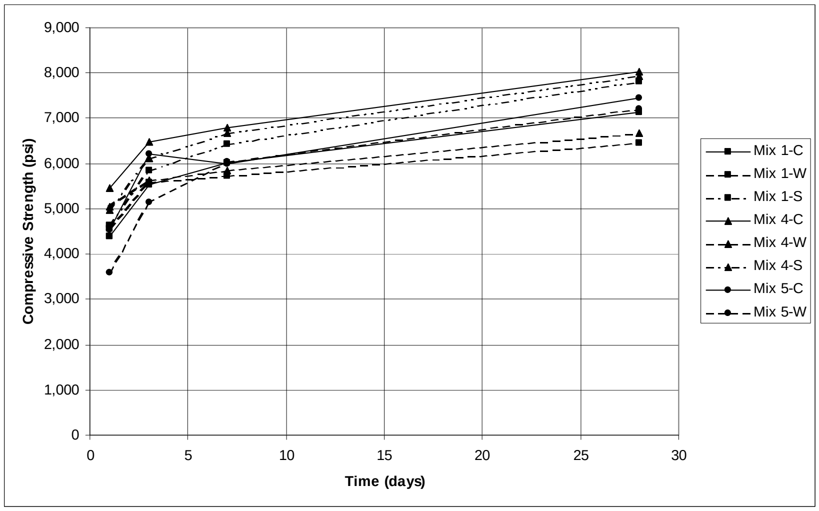

Figure 3.21 Age-Strength Curves for 0.28 Water/Cement Ratio Mixes from Second Iteration Mix Designs

Several important results are shown in Figure 3.22. First, the mixes produced with Western aggregates had much lower strengths at all ages than did the mixes produced with the other two aggregates. Also, the Western aggregate mixes did not gain as much strength from 7 to 28 days as did the other two aggregates.

Second, Mix 4 seemed to perform the best of all the mixes. Both 4-C and 4-S produced the highest two strengths at all dates when strength was measured. Another notable fact was the strength that was eventually achieved. These two mixes almost reached 8000 psi at 28 days and were over 5000 psi at one day. They both easily satisfied the strength requirement for the 6000 psi mix.

The greater strength in the 6000 psi mix seems to be related to the amount of coarse aggregate. In Mix 4, the coarse aggregate/fine aggregate proportion was the highest. If this trend holds up, there perhaps could be problems since a high amount of lightweight aggregate could pose workability problems..

Figure 3.22 shows the results from the 0.26 water/cement ratio mixes.

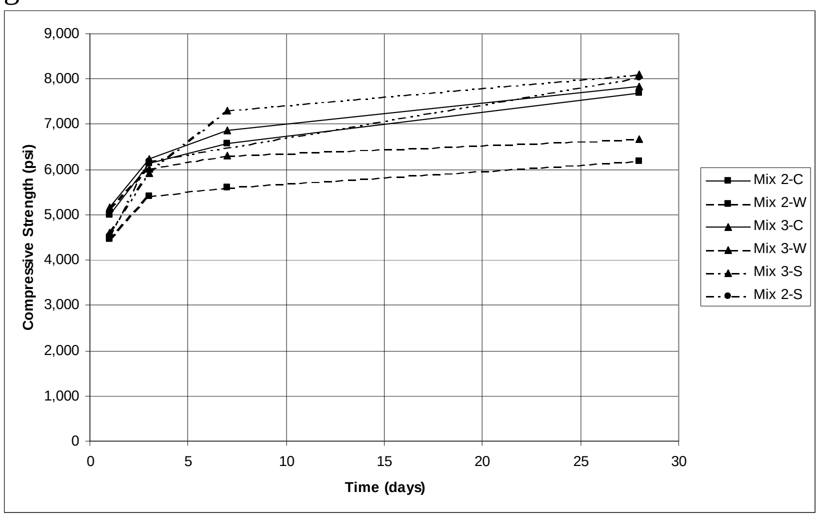

Figure 3.22 Age-Strength Curves for 0.26 Water/Cement Ratio Mixes from Second Iteration Mix Designs

Some of the observations from the 0.28 water/cement ratio mixes hold true for these mixes. The mixes made with Western aggregates underperformed again. They were significantly lower than the mixes made with Clodine and Streetman.

The strength development by the mixes with Clodine and Streetman were extremely similar to Mix 1,4, and 5 from this iteration. The maximum strength varied from 7500 to 8000 psi while the 1 day strength varied were from 4500 to 5000 psi. These all satisfy the 6000 psi specifications quite easily.

From these results, it could be seen that the 6000 psi concrete will be easy to produce. The 8000 psi concrete seemed to be a tougher goal to reach. Many of the mixes hover right around the 8000 psi mark. However, they were produced under laboratory conditions, which cannot be expected at a prestressed plant.

3.2.3.3.1 Flexural and Tensile Properties

Once again, there were no specifications for flexural and tensile performance for the mixes. However, they still were of a great interest due to the use of tensile properties in the design of prestressing force placed into girders.

Figure 3.23 presents the MOR results for this sequence of tests.

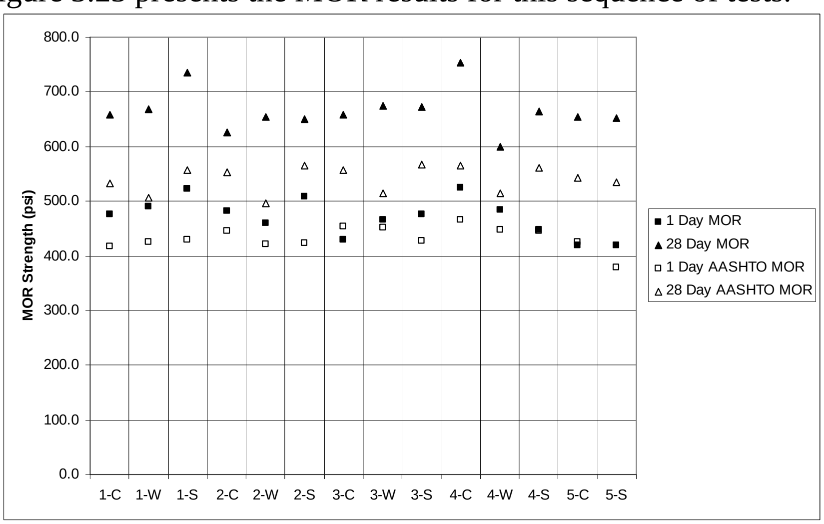

Figure 3.23 MOR Results for Mixes from Second Iteration of Mix Designs

There really is not much of a pattern in these results. The mixes all performed relatively equally, especially when the inaccuracy of the test is considered.

All of these mixes had MOR values from 425 to 500 psi at 1 day and 650 to 700 psi at 28 days. Although no pattern could be discerned, the consistency is heartening since it indicated reasonable flexural strength can be expected from these mixes.

Also, the mixes outperformed the AASHTO equation for MOR at both 1 day and 28 days, showing that the mixes behaved well in flexure and that the AASHTO equation is conservative.

Figure 3.24 presents the splitting tensile results from these mixes.

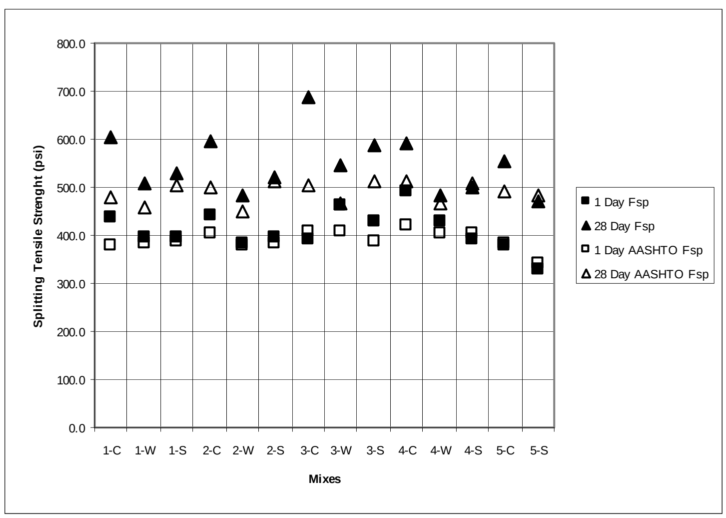

Figure 3.24 Splitting Tensile Results from Mixes Produced in Second Iteration of Mix Designs

Again, as in the MOR tests, no strong patterns developed. There was no correlation between MOR and tensile strength. However, one small pattern did emerge during these tests. The concrete made with Clodine aggregate generally produced better results than the concrete made with the other two aggregates. In all five mixes, the concrete made with Clodine produced the strongest concrete in the splitting tensile test.

In modulus of rupture and compressive strength, the Streetman aggregate matched the Clodine aggregate in performance. Split tensile strength is the first indication that the Clodine aggregate performed better than the Streetman aggregate in any of the mechanical properties measured. Along with the results from the workability measures, the Clodine aggregate emerged from this sequence of tests as the favored aggregate for use in the concrete for prestressed applications.

3.2.3.3.3 Unit Weight Results

For the first iteration of concrete mixes produced, this measure was not taken. However, after recognition of the problems with yield as well as the fact that the specifications called for concrete to be of equilibrium weight not more than 122 pounds per cubic foot (pcf), the weight of the concrete was taken at four different times, fresh, 7 days, 28 days, and equilibrium.

Figure 3.25 presents the results.

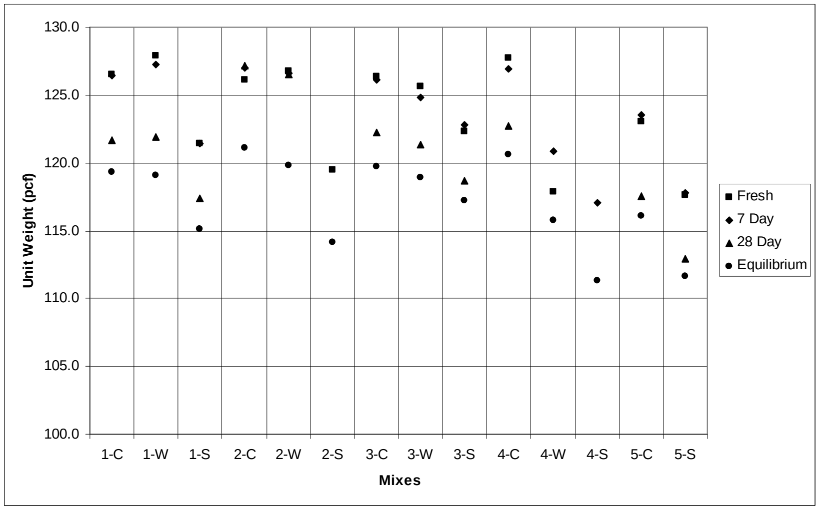

Figure 3.25 Weights of the Mixes in Second Iteration of Mix Designs

Several interesting observations can be made from this set of data. First and most importantly, all of the mixes satisfied the requirements about weight. They all had equilibrium weights less than 122 pcf.

Also, the amount of weight these mixes lost from when they were fresh to their equilibrium weights was considerable. This possibly can be attributed to the amount of excess water which was placed in these mixes due to the moisture state of the aggregate. Since this water was not needed to hydrate the cement, it bled out.

This drying loss provided some relief to the researchers. Despite the high initial weights, the 122 pcf qualification was still satisfied. Due to the high fresh unit weights of all the mixes, they all underyielded. However, the mixes can be adjusted for shedding enough water to reach the appropriate barrier.

3.3 Third Iteration

After completion of the first two iterations, the 6000 psi mix design was close to finalization while the 8000 psi mix design still had not been obtained. The first two iterations had narrowed down some decisions such as the aggregate that would be used for the project. Also, it provided excellent experience in producing concrete to ASTM standards. Therefore, on this third iteration, it was expected that the final mix design would be designed and produced.

3.3.1 Modification of Variables

Perhaps the biggest decision that was made after the second iteration involved choice of aggregate. The results overwhelmingly suggested that Clodine provided the best mix of strength and workability for the project. Due to its larger size than Streetman, the Clodine required less superplasticizer to be workable. However, its larger size did not take away its ability to gain strength where it was extremely competitive with the Streetman aggregate in producing the strength that was needed.

Also, the second iteration gave good indications about the amount of cement that would be needed to reach the 8000 psi barrier. The 6000 psi barrier had easily been reached, but 8000 psi still needed to be achieved. It was obvious from the concrete results that more cement would be needed and therefore, a lower water/cement ratio.

3.3.1.1 Amount of Cement and Water/Cement Ratio

From the previous two iterations, it was apparent that the water/cement ratio had been narrowed down to between 0.25 and 0.30 for both 6000 psi and 8000 psi mixes. Also, the 6000 psi barrier had easily been reached, leaving the remaining decisions how to find a workable mix for use in the precast environment.

However, the 8000 psi target was still posing problems. Although some of the mixes from the second iteration had exceeded 8000 psi, they had not exceeded it by enough to say with confidence that the mixes were 8000 psi mixes. Therefore, some additional strength was still needed.

Due to the inadequate strength, the next order of business was to increase the amount of cement in the mixes from the previous maximum of 800 pounds of cement per cubic yard. Therefore, this sequence of mixes looked to increase the amount of cement to reach the 8000 psi barrier.

Table 3.7 presents the amount of cement in the final sequence of mixes.

Table 3.7 Amount of Cementitious Material per Cubic Yard for Final Iteration Mixes

Mix Number	Lbs. Cementitious Material/Cubic Yard	Water/Cement Ratio
Mix F-1	550	0.36
Mix F-2	600	0.35
Mix F-3	600	0.35
Mix F-4	600	0.35
Mix F-5	657	0.33
Mix F-6	800	0.28
Mix F-7	978	0.25

Mix F-8	978	0.25
Mix F-9	978	0.25

As can be seen from the table, Mixes F-1 through F-5 were focused on narrowing down the 6000 psi mix. The weights of cement in the mix designs were similar to the amount seen in the mixes in the first and second iterations shown in Tables 3.1 and 3.4. Mix F-1 was concerned with seeing if less cement could be used, thereby making the concrete more economical. Mixes F-2 through F-4 were refinements of earlier mixes. Mix F-5 was done in response to underyielding problems.

Mixes F-6 through F-9 were done in response to the 8000 psi strength problems. Mixes F-7 through F-9 were based upon a mix done for an earlier high strength normal weight concrete project for TxDOT done by John Myers [11]. The volume of normal weight aggregate was replaced by an equal volume of lightweight aggregate.

3.3.1.2 Chemical Admixtures

For this sequence of the project, the same chemical admixtures were used. Again, Daratard-17 and ADVA Superflow were the two chemical admixtures of choice. However, it was expected that larger amounts of superplasticizer and retardant would reflect the large amount of cement being used in Mixes F-7 through F-9.

The same goal of 7-9 inches of slump was still the guide for the amount of superplasticizer.

3.3.2 Procedures

The same procedures as those used in the second iteration were followed for these nine mixes. Again, a rodded unit weight of the aggregate was taken to ensure that the aggregates were in a consistent moisture state when poured. There was a little more consistency for this portion of the project since Clodine was used as the aggregate for all of the mixes. Because of these reasons, the variability inherent to the aggregate was reduced to a manageable level.

Also, the aggregate was dried the same way, by placing it on a screen and allowing it to dry with the aid of gravity. The other materials were all batched in the same way.

The big difference came in the type of cylinders used. Previously, 4 inch X 8 inch cylinders had been used for all of the tests using cylinders throughout the project. They minimized the concrete usage as well as made the placement easier. However, along with the 4 inch X 8 inch cylinders, 6 inch X 12 inch cylinders were also cast. They would provide an important check for the tests since the larger cylinders generally produce more conservative results.

3.3.3 Properties

3.3.3.1 Workability

The mixes designed for 6000 psi did not pose any problems for workability. They performed similarly to the mixes made with Clodine from the second iteration, requiring approximately the same amount of chemical admixture for the desired workability. Also, they remained workable for the same period of time, about thirty minutes.

On the other hand, the mixes with 978 pounds of cement per cubic yard were another matter. As expected, they required more superplasticizer due to the increased amount of cement. However, this did not mean that they also needed an increased dosage rate. Table 3.8 shows the dosage rate for each of the mixes in this sequence.

Table 3.8 Dosage Rates of Superplasticizer for Third Iteration

Mix Number	Dosage Rate (fl. oz.)/100 lbs. Cement
Mix F-1	13.1
Mix F-2	5.4
Mix F-3	5.4
Mix F-4	7.2
Mix F-5	4.9
Mix F-6	5.4
Mix F-7	5.5
Mix F-8	5.5
Mix F-9	5.5

As can be seen, the dosage rate overall stayed pretty constant for these mixes. Except for a few aberrations (Mix F-1 and Mix F-4) which can be blamed on experimental error, the dosage rate generally ran about 5.5 fluid ounces per 100 pounds of cement.

However, the use of retardant changed for the mixes with higher amounts of cement. On the first mix tried, Mix F-7, the concrete set very quickly. The concrete also appeared extremely sticky and was difficult to scoop out and place in cylinders after a short time. Again, although precast plants generally place their concrete very quickly, this could pose a problem since more than 15 minutes of dependable workable time is needed.

To combat this problem, retardant dosage was increased. Beforehand, a negligible amount of retardant was added to the mix. However, after encountering this problem in Mix F-7, the retarder dosage was increased for Mix F-8 from 1.1 fluid ounces per 100 pounds cement to 2.75 fluid ounces per 100 pounds cement. In Mix F-8, this seemed to adequately restrain the reaction of the cement with the water enough to place all the concrete. Retardant would then become an integral part of the chemical admixture mix.

3.3.3.2 Mechanical Properties

3.3.3.2.1 Compressive Strength

For these results, the data from the 6 inch X 12 inch cylinders will be presented as these data are more reliable and accepted.

Figure 3.26 presents the compressive strengths from the mixes designed for 6000 psi.

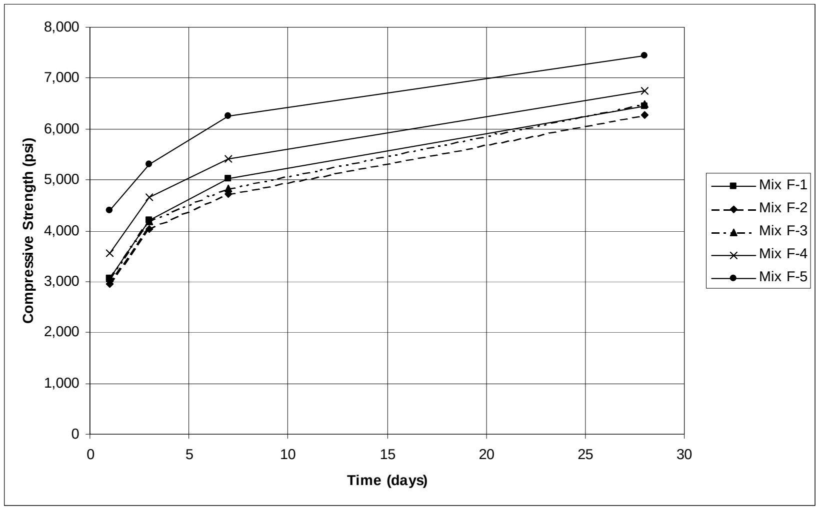

Figure 3.26 Age-Strength Curves for 6000 psi Mixes in Third Iteration

Although the results were down somewhat from the second iteration, a couple of mixes still were performing well above specifications. Mixes F-4 and F-5 would both be satisfactory for use as the 6000 psi mix in the field. However, due to its increased 1 day strength, Mix F-5 is recommended since it provides an adequate cushion to the precast yard for release. On any of the other mixes, other conditions such as the environment or a mistake in batching could disturb strength gain enough so that the strands could not be released. However, Mix F-5 has enough of a cushion to withstand these problems and still let the strands be released.

Of more interest was how the 8000 psi mixes behaved. The hope was that the increased cement content would provide the bump that was needed to reach the 8000 psi barrier.

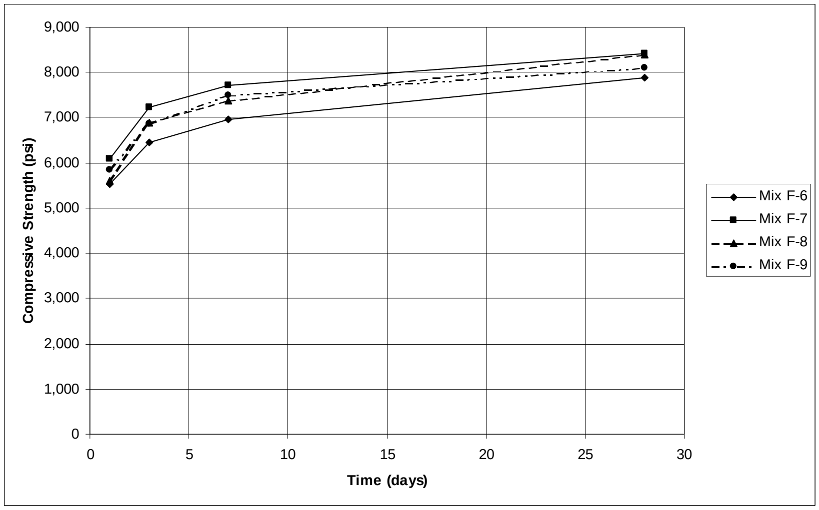

Figure 3.27 Age-Strength Curves for 8000 psi Mixes for Third Iteration

From Figure 3.27, it is seen that three concrete mixes finally reached the strengths needed for 8000 psi. Mix F-6, a repeat of a mix in the second iteration, almost reached 8000 psi just like the mixes that had 800 pounds of cemetitious materials. Mixes F-7 and F-8, which were exactly the same, except that different amounts of retardant were used to control the workability, performed nearly the same. Mix F-8 lagged a bit due to the extra retardant but eventually caught up at 28 days. Both mixes were well above the 8000 psi level. Mix F-9 had an increased amount of coarse aggregate but proved to be a little too low in strength.

Therefore, Mix F-8 was chosen as the 8000 psi mix for use in the precast yard for the production of the beams.

3.3.3.2.2 Tensile Properties

The MOR tests were not done for these specific mixes. The data from the first two iterations gave a good idea of the values for lightweight concrete. Therefore, the splitting tensile test was the only one performed on these specimens. This test was still important since it played a role in the design of the tensile reinforcement of the beam.

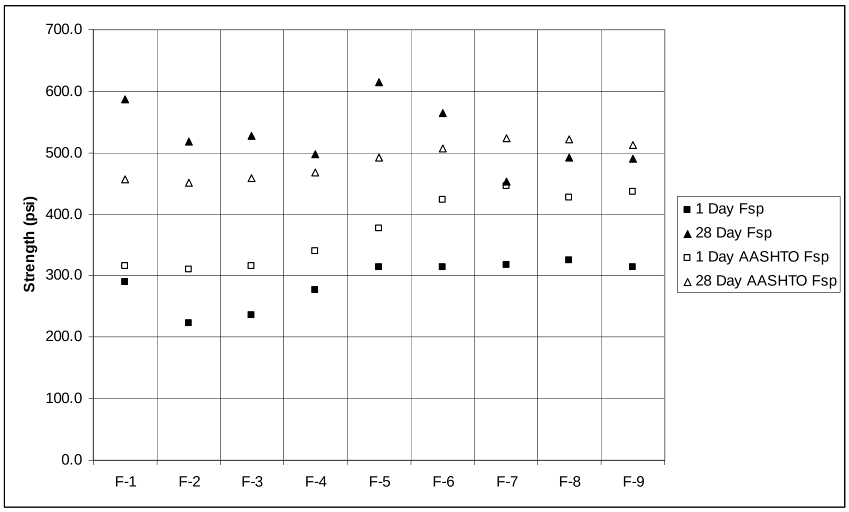

Figure 3.28 Splitting Tensile Strengths of Mixes in Third Iteration

The results from these tests were different from what was expected which maybe can be attributed to the use of 6 inch X 12 inch cylinders. Also, a refinement in the testing procedure of slowing down the loading rate to ASTM standards also played a large role.

The splitting tensile strengths were lower than expected from the second iteration. The 1 day strengths with the 6 inch X 12 inch cylinders were usually around 300 psi although the second iteration with 4 inch X 8 inch cylinders generally produced strengths around 400 psi. Also, the 28 day strengths came out to be around 500 psi which was a little lower than the usual 550-600 psi of the second iteration.

These results can be attributed to the change in cylinders size and to the slowing of the loading rate used in this round of tests. The concrete felt the full effect of the load this time and was properly allowed to react, producing the lower results.

Also, the concrete was allowed to dry too much before the test. Martinez [2] showed that splitting tensile strengths of dry cylinders are only 50-60% those of wet cylinders. These cylinders had dried for 45 minutes prior to testing, affecting the strength.

3.3.3.2.3 Unit Weight Results

Again, the unit weights of the concrete mixes were taken at various times to make sure they followed specifications of being not more than 122 pounds per cubic foot (pcf) at equilibrium weight. Figure 3.29 presents these results.

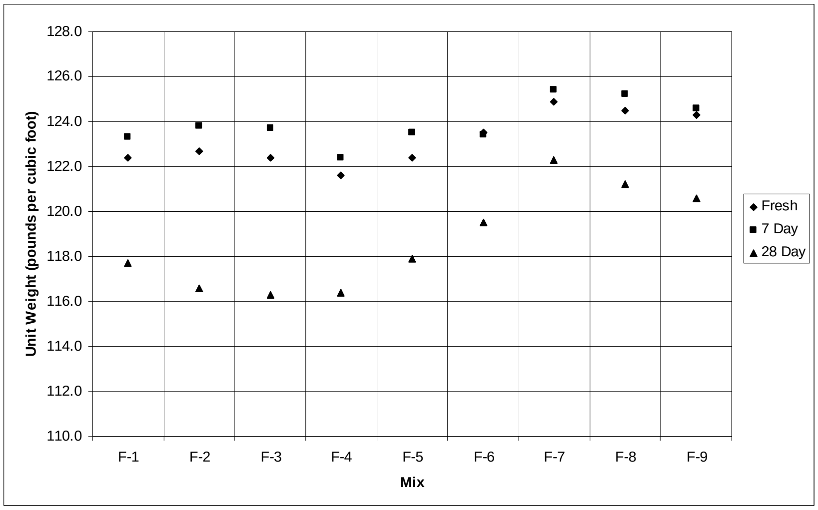

Figure 3.29 Unit Weights of Mixes from Third Iteration

Although equilibrium weight was not measured, the unit weights shown in Figure 3.15 prove that the concrete satisfies the requirement since all the 28 day weights meet the 122 pcf requirement. From prior experience in the first two iterations, it is known that the concrete loses weight from 28 day weight to equilibrium. Therefore, these mixes performed well.

From Figure 3.29, it is shown that all the unit weights meet the 122 pcf barrier except F-7 which falls closely enough since it will still lose weight until equilibrium. The mixes using more cement such as F-7 through F-9 had larger unit weights due to the reduction of lightweight aggregate volume. However, they still met the specification, making them available for use.

Chapter 4: 6000 psi Mix

4.1 MIX PROPORTIONS

Mix F-5 was chosen for the 6000 psi mix. It combined dependable 1 day strength with acceptable workability properties. Performance during mix trials indicated this mix could be repeated with high confidence.

Table 4.1 presents the theoretical mix proportions for the 6000 psi mix for one yard of concrete.

Table 4.1 Mix Proportions per Cubic Yard of 6000 psi Mix

Component	Proportion
Cement	504 lb
Fly Ash	168 lb
Lightweight Aggregate	1264 lb
Sand	1149 lb
Water	222 lb
Daratard-17	12 oz
ADVA Superflow	34 oz

Mix F-5 was scaled up from Mix F-3 due to yielding problems. Since the mix underyielded in previous tests, the mix proportions were increased by the percentage this mix tended to underyield.

The mix is a 7.15 sack mix when including the fly ash in the cementitious materials. The fly ash comprises 25% of the cementitious material by weight. The water/cement ratio is 0.33.

This mix assumes that the lightweight aggregate will be added in the saturated surface dry condition after submersion or sprinkling for at least 24 hours. The proportions of the chemical admixtures are adjustable to optimize their use. The amounts reported here provide a guideline for approximate amounts to be used. However, more superplasticizer could be used depending on weather conditions.

4.2 PROPERTIES

4.2.1 Workability

Among the biggest concerns at the initiation of this project was achieving adequate workability. Due to the high cement contents, some difficulty was expected.

However, in lab mixing, this mix performed admirably in workability measures. The mix provided enough time for placement in forms at a prestressed plant as long as mechanical vibration was available, a standard practice at precast plants.

4.2.1.1 Slump

Due to the demands of placement, this concrete needed to flow. Since prestressed plants use mechanized carts with hoppers and chutes (sidewinders) for placement, high slump concrete was needed to aid in removal from the sidewinder into the forms. A sidewinder is shown in Figure 4.1.

Figure 4.1 Sidewinder at Heldenfels Precast Plant

The sidewinders do not have any way to mix the concrete or vibrate it. This caused the need for concrete that could easily slide out of the sidewinder into the forms.

Slump for this concrete was specified between 7 and 9 inches. A concrete with this amount of slump is extremely thick. This slump was achieved through the addition of the appropriate amount of superplasticizer. Before the superplasticizer is added to the mixer, this concrete mix has approximately 1/2 to 1 inch of slump.

In the trial mixing period, the 6000 psi mix had 6 fluid ounces of ADVA Superflow added to achieve 6.5 inches of slump. This amount was appropriate for five cubic feet of concrete. Factored for a cubic yard of concrete would give 34 fluid ounces of superplasticizer. This is the amount used in the final mix.

However, this amount is not definitive. Due to the inherent variability of concrete, some change in amount of superplasticizer should be expected

4.2.1.2 Finishability

The other aspect of workability lies in the finishability of the concrete. This is a measure of how well the concrete responds to placement into edges and corners and how well the concrete takes a smooth surface.

For the application in pretensioned girders, the concrete did not need to finish smoothly. Actually, a rough surface is preferable since that surface promotes good bond between the deck and girder, allowing good transfer of the horizontal shear between the deck and girder.

No good, objective measure exists for finishability. Relying on first-hand observation is the only way to have any idea as to how well the concrete finishes.

During the trial mixes in the laboratory, finishing the concrete to a smooth surface was difficult. Even with extreme caution and care, some aggregate was still visible in the top portion of concrete surfaces after finishing of the concrete. The aggregate was completely covered by paste and only protruded above the surface by approximately 1/16 inch, a minor amount. This finish was acceptable due to the rough surface desired for good bond.

The concrete could be pushed and shaped into position by a trowel. Also, fine troweling of the surface did finish the surface to the rough surface described above.

4.2.1.3 Consistency

Another important characteristic of the concrete was its consistency. This property is closely related to slump and finishability, yet encompasses some different aspects.

After completion of rotation in the laboratory mixer, the concrete remained with a slump of 7 to 9 inches for fifteen minutes. There was no segregation of the paste from the aggregate and the aggregate remained properly coated for the whole time.

After thirty minutes minutes, the concrete started to bind. The concrete was cohesive and difficult to scoop from the wheelbarrow. The concrete could still be vibrated into place. However, the difficulty in handling had increased.

Mixing with a shovel after this time alleviated the problem somewhat. The concrete remained in this state for a substantial period of time, approximately thirty minutes. Since prestressed plants place their concrete extremely fast, this provided an acceptable window of time for the concrete.

4.2.2 Mechanical Properties

Along with the workability properties, the mechanical properties of the concrete played a large role in its acceptance for usage. Mix F-5 satisfied the specifications placed upon it at the beginning of the project.

4.2.2.1 Compressive Strength

Obviously, the most important aspect to be satisfied was the ultimate compressive strength of the mix. At the same time, the mix also needed to have an adequate strength at one day for release in the precast plants. Figure 4.2 presents the age-strength relationship for the 6000 psi mix.

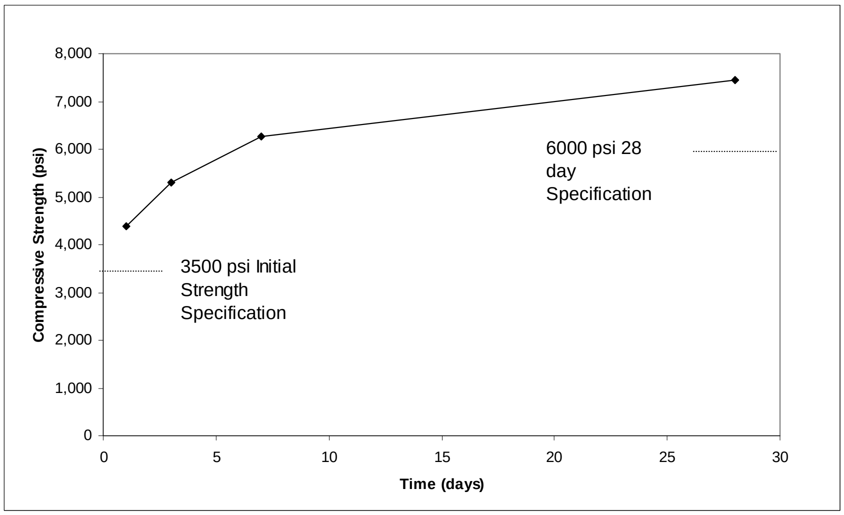

Figure 4.2 Age-Strength Compressive Strength Relationship for 6000 psi Mix

As can be seen from Figure 4.2, this mix easily satisfied the first requirement, namely that the mix had to achieve at least 6000 psi at 28 days. In fact, it performed much better than that, reaching 7400 psi.

The mix reached a high 28 day compressive strength due to the need to satisfy the companion requirement for the initial 1 day strength. Since the 1 day strength needed to be at least 3500 psi for initial release of the strands, any mix that was chosen had to provide a decent margin in case the concrete underperformed.

There were other interesting aspects to the performance of this mix. The concrete continued to gain substantially in strength after seven days, a somewhat surprising result considering the use of Type III cement. In fact, the strength gain is quite gradual and consistent, indicating that this concrete probably gained more strength past 28 days.

This gain in strength can be attributed to the use of fly ash. The use of fly ash contributes to the long term strength gain of the concrete since it is similar to cement in its chemistry but reacts at a much slower rate. The fly ash also helps increase the ultimate strength of the concrete at later ages. This is invaluable due to the use of the Type III cement. The fly ash helps counteract the tendency of Type III cement to stop gaining strength after seven days.

4.2.2.2 Modulus of Elasticity

Modulus of elasticity plays a large role in determining the deflections of the member. Overall, lightweight concrete has values of modulus of elasticity less than those of normal weight concrete. However, of more interest is comparing the values to other tests done on lightweight concrete. In Figure 4.3, the data from the 6000 psi mix is compared to data from four other papers. All involved lightweight concrete and focused mainly on high strength concrete.

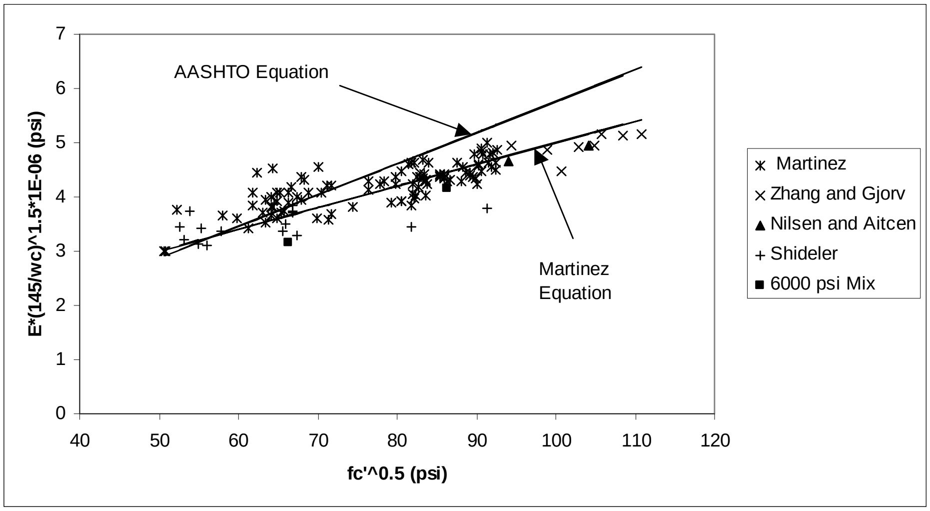

Figure 4.3 Comparison of Moduli of Elasticity days for 6000 psi Mix

Figure 4.3 shows how well the concrete designed for this project compared to other concrete in other projects. Before discussion of the 6000 psi concrete, one item must be noted. This graph substantiates the assertion of Martinez [2] that the AASHTO equation does not predict the modulus of elasticity well for high strength lightweight concrete. It also shows that the equation developed by Martinez for lightweight concrete does a better job of predicting modulus of elasticity.

For the 6000 psi concrete, it performed well within the scatter band of the Martinez [2], Shideler [5], and Zhang and Gjørv [16] data which were similar in strength and composition to the concrete developed in this project. Of the two data points for the 6000 psi concrete, the more important data point, that for the concrete at 28 days, lay close to Equation 2.1.

From this data, it can be seen that the 6000 psi concrete performed well in the modulus of elasticity test and was similar to other concrete produced in other tests.

4.2.2.3 Tensile Strength

Since this mix was F-5, the tensile strength was determined with the use of 6 X 12 inch splitting tensile cylinders. In Figure 4.4, the splitting tensile strength of the 6000 psi mix is compared to data from Martinez [2] and Zhang [16]. Both Martinez and Zhang used all-lightweight concrete which have lower values of splitting tensile strength. Therefore, both AASHTO equations for all-lightweight and sand-lightweight concrete are included in the graph to give a full understanding of the behavior.

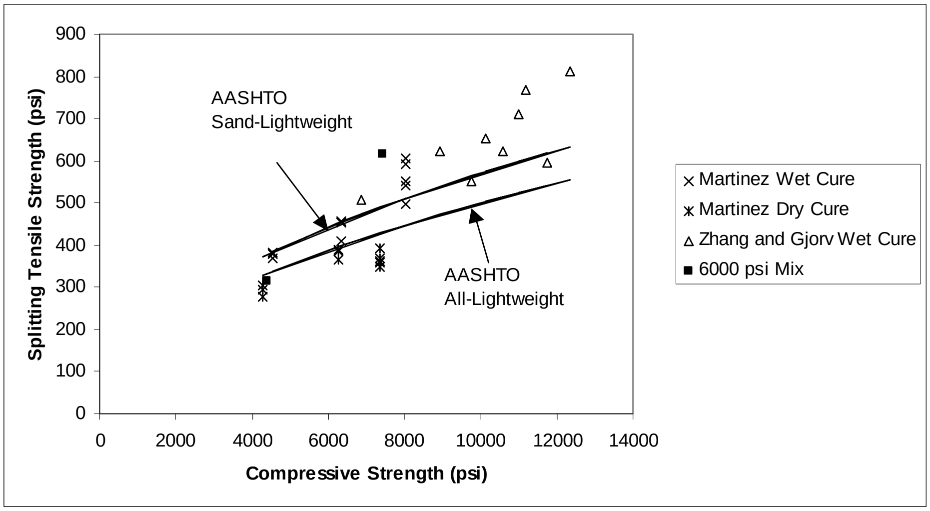

Figure 4.4 Comparison of Splitting Tensile Values for 6000 psi Concrete

Both the 1 day and 28 day values are included in this chart. The 28 day value is of more interest. The 6000 psi concrete performed well. The splitting tensile strength was well over the AASHTO predicted equation at 28 days, which was expected since the AASHTO equation is conservative for splitting tensile strength.

From this result, it is decided that the 6000 psi concrete mix has adequate tensile strength.

4.2.3 Creep and Shrinkage

4.2.3.1 Creep

One of the biggest concerns with lightweight concrete is its creep under sustained load. Since this lightweight concrete will be placed under sustained load from the prestress placed into the beam, this is a very important value. The creep of the 6000 psi mix was tested according to ASTM C512-87 [30]. Figure 4.5 shows loaded creep specimens.

Figure 4.5 Creep Cylinders

The strains were measured with a DEMEC device. Metal disks are placed approximately 8 inches apart. Then, a gauge is used to measure changes in this distance. For these cylinders, three different measurements were taken on opposite sides of the cylinder and averaged to find the creep.

In this thesis, the results from the cylinders whose initial loading was at 2 days and 7 days are presented. The cylinders were loaded to 40% of their ultimate strength at that age as per ASTM C512-87 [30]. These cylinders are of more interest due to the fact that most prestressing is introduced into the concrete at early ages, 1 or 2 days.

Also, this thesis reports the creep plus shrinkage data for these concrete mixes. No room was available with the appropriate ASTM conditions for measuring creep only. Therefore, the specimens had to be placed in ambient air conditions. They were protected from the elements, but not from changes in temperature and humidity. Therefore, these data include drying shrinkage. The creep and shrinkage behavior could not be separated since two different size specimens were used for each test. Due to the size effect of concrete, the results are incompatible and cannot be mixed.

At the time of this report, the project had not finished measuring the creep behavior of the concrete. Appendix C contains the current creep data as well as the plots for the cylinders analyzed in this report.

Figure 4.6 presents the early age creep data from the 6000 psi concrete mix.

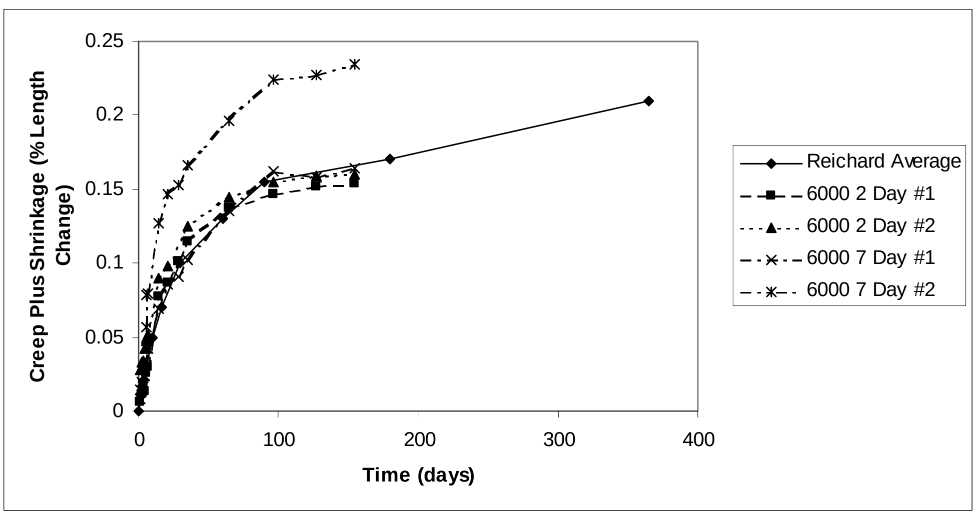

Figure 4.6 Early Age Creep Plus Shrinkage of Cylinders

From Figure 4.6, the creep plus shrinkage is very consistent with the Reichard [18] average of lightweight concrete creep plus shrinkage behavior.

Three of the four cylinders analyzed fall nearly on top of the Reichard average. The 6000 7 day #2 cylinder is considered an outlier and is not considered when making judgments about the behavior of this mix.

Figure 4.6 shows that creep of the 6000 psi mix is common and should not be a factor that causes concern.

Another measure of creep is the creep coefficient.

The creep coefficient is defined as the following [31]:

$$C_u = \frac{\varepsilon_{cu}}{\varepsilon_{ci}} \qquad \textbf{Equation 5.1}$$

where ε_{ci} is the initial elastic strain and ε_{cu} is the additional strain resulting from creep.

Table 4.2 presents the other measures of creep.

Table 4.2 Five Month Creep plus Shrinkage Performance of 6000 psi Mix

Age at Loading	Initial Elastic Strain (microstrain)	Creep Coefficient
2 days	702.5	3.19
2 days	516.4	4.09
7 days	827.1	2.96
7 days	1084.5	3.16

Table 4.2 shows a different story.

Here, 6000 psi 2 day cylinder #2 is the outlier, different from when the data was compared to data from Reichard [18]. However, it must be noted that for this cylinder there was a great deal of strain from immediately after loading to 2 hours later, suggesting that there was a misreading of the immediate elastic strain (Appendix C). Therefore, this cylinder cannot be considered a true picture of the creep plus shrinkage.

Table 4.2 suggests that the creep coefficient after five months is approximately 3.1. This number falls on the high end of the normal weight scale which generally ranges from 1.6 to 3.2 [31]. However, as seen when compared to data from Reichard [18], the creep plus shrinkage of this concrete was normal.

4.2.3.2 Shrinkage

Shrinkage is another problem seen in lightweight aggregate concrete. Figure 4.7 shows the shrinkage of both dry and wet cured concrete over a four month period.

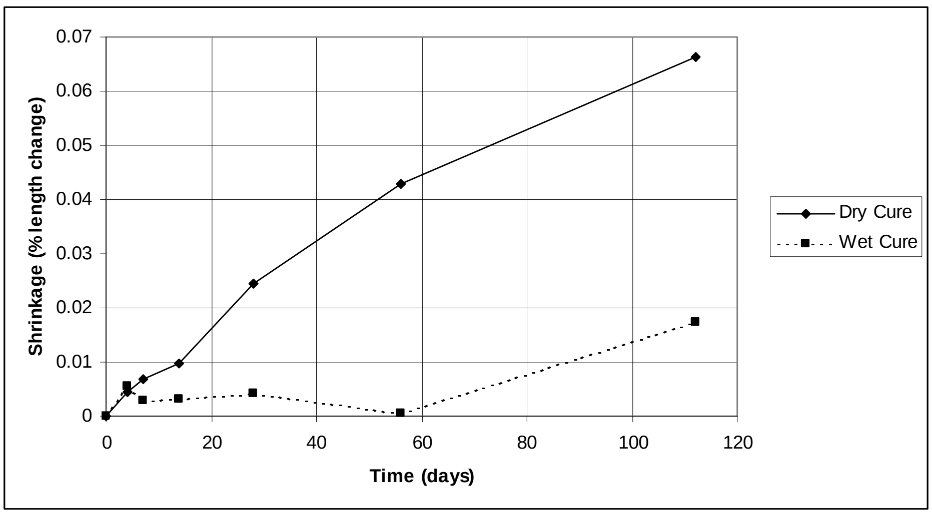

Figure 4.7 Shrinkage of 6000 psi Mix

When compared to Reichard [18], these shrinkage values were average for lightweight concrete. Reichard tested 24 different lightweight aggregates in concrete for creep and shrinkage. He found that lightweight aggregate concrete that was dry cured at a constant temperature and humidity had shrinkages from

0.02% to 0.08% at 90 days. From the 6000 psi data, the shrinkage at 90 days in constant temperature and humidity was approximately 0.055%. Also, Reichard showed that lightweight concrete shrinkage generally plateaued at approximately 150 days, a data point that has not been reached yet.

Therefore, the shrinkage of the 6000 psi mix was average. The results agreed with data from Reichard [18], the data upon which ACI Committee 213 [33] bases its creep and shrinkage recommendations.

4.3 JOBSITE PERFORMANCE

One of the most important aspects of this project was to determine how well the concrete performed when mixed and placed at the precast plant. The actual use of the concrete would gauge the performance of the concrete and help determine the ability of precast plants to handle the use of lightweight concrete for prestressing.

At the jobsite, the aggregate was sprinkled for 48 hours prior to initial use. For the 6000 psi mix, two different trials were run. On the first day, two different 20 foot beams designed to represent the highest level of reinforcement congestion likely to be encountered in beams in practice were produced. One used this 6000 psi concrete mix. The other used a companion 8000 psi mix. This allowed determination of the approximate behavior of the concrete before placement in full length specimens.

After that, two 40 foot beams were produced using the 6000 psi mix. On the same day, a normalweight 40 foot beam was also cast.

4.3.1 Workability

At the plant, the slump of the concrete was again controlled through the use of superplasticizer to achieve the desired slump. For the 20 foot beam, one three cubic yard batch of concrete was used to produce the concrete. For this batch, a dosage rate of 5.96 oz./100 pounds of cementitious material (cement plus fly ash) was used. This dosage rate was a little larger than predicted from laboratory calculations, but this was expected. The concrete produced a slump of 6.5 inches, a little lower than desired. However, the concrete performed extremely well during placement in the highly congested beams as it required little vibration to be placed. Overall, the concrete for this beam performed well and verified the concrete mix design process of the first part of this project.

After observing the initial trial 20 foot beam, it was felt that the mix was ready for placement into the two 40-ft beams that would actually be load tested later in the project. To produce these beams, two three-yard batches of concrete would be mixed. The proportions were expected to be the same as for the 20 foot beam.

The first batch again used 150 ounces of superplasticizer, a dosage rate of 5.96 oz./100 pounds of cement. The slump for this batch when it left the batch plant was 9 inches. However, after transport, this concrete had lost 1 inch of slump and was down to 8 inches.

The slump of the first batch is shown in Figure 4.8.

Figure 4.8 Slump of First Batch of 6000 psi Concrete

This concrete proved to be slightly thin (not cohesive). To correct this problem, the next batch of concrete was given 120 ounces of superplasticizer. This dosage solved the problem as the concrete retained its slump of 7 inches on the way to the prestressed bed. Figure 4.9 shows the slump of the second batch.

Figure 4.9 Slump of Second Batch of 6000 psi Concrete

As was expected, the beams produced from the 6000 psi mix concrete exhibited an excellent finish. No problems were seen with honeycombing or voids in the concrete. The finish was comparable to other normal weight girders produced at the Heldenfels precast plant. Figure 4.10 shows the finish of the 6000 psi beams.

Figure 4.10 Finish of Girder Made with 6000 psi Mix Concrete

Overall, the workability of the concrete proved to be fine. The workers reported no problems with placement as the concrete finished well in the bed. Also, the workers did not have to do a great deal of work to get the concrete placed into the forms as the concrete was easily placed. This particular mix proved to be excellent for prestressed applications.

4.3.2 Compressive Strength

Obviously, determination of the mechanical properties of this concrete plays the greatest role in determining the performance. Of these properties, the compressive strength was the most important. Figure 4.11 shows the age-strength curve for the concrete used in the 6000 psi beams.

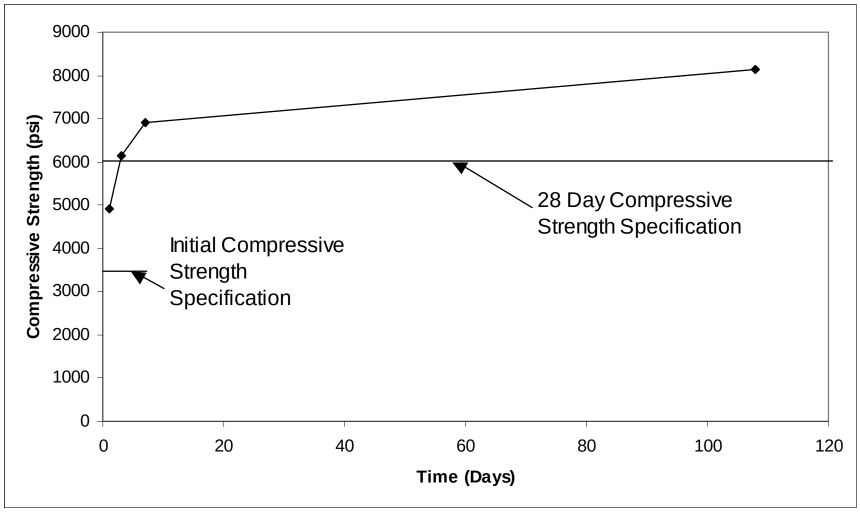

Figure 4.11 Age-Strength Curve of 6000 psi Mix

Interesting results arose out of the performance of the 6000 psi beam. First off, the strengths were approximately 10 to 15% higher than the laboratory results, a surprising result since field results generally are less than laboratory results.

The 1 day strength was more than adequate for the prestressed yard as a compressive strength of 4950 psi was seen at release. The concrete continued to gain strength up to 8100 psi the day the first beam test took place.

This increased strength was a pleasant surprise. However, it did lead to the question of why there was so much extra strength. There was more cement in the mix, yet the proportions such as water-cement ratio stayed the same otherwise, so this would seem not to be the reason. Also, the compressive strength of this mix was much greater than the concrete used for the 20 ft beam which was produced at the same plant a couple of days earlier. Although a full age-strength curve was not obtained, the 1 day and 3 day strengths of that beam were measured as 3520 psi and 4629 psi, respectively. Since this mix was just used as a check, this data were used to proceed with the fabrication of the 40 foot beams.

As for reasons for the high strength, none can be proven or even hypothesized. A staff member watched the batching of the concrete and saw that the proportions added were identical to the proportions ordered. Therefore, no additional cement was placed in the mix. The aggregate was in a moisture state between SSD and saturated, which was typical for mixing of the project.

The data presented at the beginning of this chapter should be taken as the mechanical properties of this mix. The compressive strength of the concrete at the precast plant was an aberration, one that was positive.

4.3.3 Tensile Strength

Due to the time constraints of the project, a 1 day splitting tensile and modulus of rupture tests were all that were taken. Figures 4.12 and 4.13 show their comparison to data already produced.

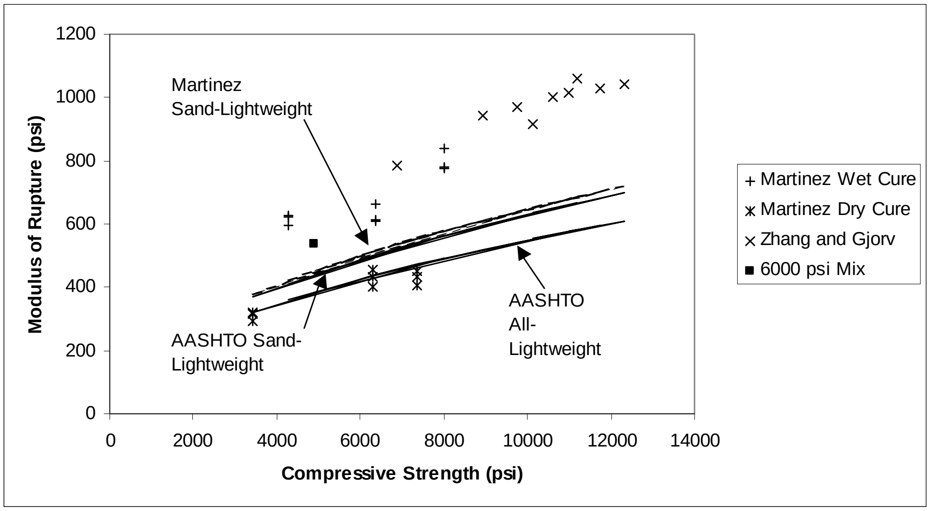

Figure 4.12 Comparison of MOR Data for 6000 psi Mix

From Figure 4.12, the 1 day 6000 psi MOR point exceeded both the AASHTO [12] and Martinez [2] recommendations. Although a 28 day data point was not taken, previous experience in the project assured the staff that the MOR at 28 days would be adequate since the concrete would still grow in strength.

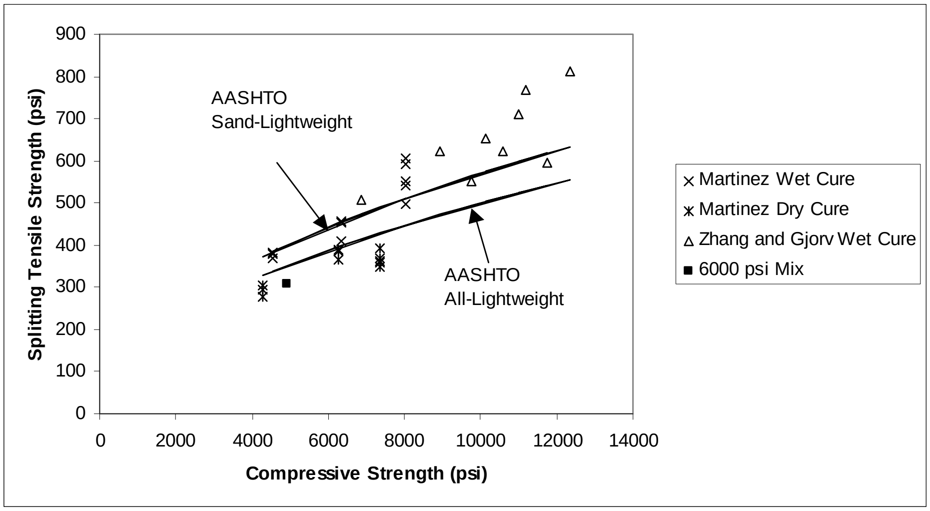

Figure 4.13 Comparison of Splitting Tensile Data for 6000 psi Mix

Just as in the last iteration, the splitting tensile data at 1 day did not meet the code equation. Although this occurred, the staff did not decide to do a 28 day test since the last iteration showed that the strength gain would be enough that the splitting tensile strength would exceed the AASHTO [16] equation at 28 days.

Chapter 5: 8000 psi Mix

5.1 Mix Proportions

As a companion to the 6000 psi mix, another high strength concrete mix was developed. A higher strength was desired to provide more options for applications for long span girders.

The 8000 psi mix was developed using a previously designed normal weight mix from Myers [11] as a starting point. A high strength normal weight concrete mix was designed by him for a Houston bridge overpass. To change this mix to a lightweight concrete mix, the coarse aggregate was replaced by an equal volume of lightweight aggregate.

Table 5.1 shows the mix proportions.

Table 5.1 Mix Proportions per Cubic Yard for 8000 psi Mix

Component	Proportion
Cement	671 lb
Fly Ash	316 lb
Lightweight Aggregate	1123 lb
Sand	1029 lb
Water	247 lb
Daratard-17	12 oz
ADVA Superflow	54 oz

Discussion in the previous chapter focused on the 6000 psi mix. Many of the things discussed there are the same for this mix of concrete. However, there are a couple of differences that should be noted.

First, this mix is a 10.5 sack (987 pounds) cement mix of concrete. This is an extremely large amount of cementitious material. The amount of cement in this mix of concrete is not easily controlled. Some problems associated with high cement contents are shrinkage cracks and high curing temperatures which can cause the concrete not to reach the target strength.

Also, the larger amount of cement meant that the aggregate amounts had to be reduced. Therefore, this mix was richer and less rocky than the 6000 psi mix. This also caused an increased amount of superplasticizer to be used in this mix.

5.2 PROPERTIES

5.2.1 Workability

Due to the large amount of cementitious material in this mix, workability was the major concern in the prestressing yard. The high cement content dictated the use of a large amount of superplasticizer to produce the requisite flowing concrete that was needed for placement. Also, the elevated temperature of the concrete might reduce a great deal of the slump in the concrete.

Because of these problems, the dosage of superplasticizer was an important aspect of this mix. The correct balance had to be obtained between an amount that provided for enough flowability and yet did not cause segregation of the concrete.

5.2.1.1 Slump

As in the 6000 psi mix, 7 to 9 inches of slump was the desired target. This was achieved by adding superplasticizer after an initial slump had been taken.

Two trial mixes were performed in the laboratory test phase to verify the performance of the mix. Both times, 10 fluid ounces of superplasticizer were added to achieve the appropriate amount of slump in 5 cubic foot trial batches. This comes to a dosage rate of 5.47 fluid ounces/100 pounds of cementitious material.

During the laboratory trial period, the second mix had 9.5 inches of slump, two inches greater than the initial mix. This was a result of an increased retardant dosage, a different admixture from the superplasticizer. The dosage increased from 5 oz/cubic yard to 12 oz/ cubic yard of concrete. Since the retardant also served as a water reducer, the slump increased.

One other aspect of slump noticed during the trial period was the loss of slump by the concrete. After the concrete was emptied out of the mixer, the concrete remained workable for approximately twenty minutes. After that time, the concrete grew increasingly difficult to work. When the final test beams and cylinders were being placed, approximately 30 minutes after removal from the mixer, the concrete only had about 3 to 4 inches of slump.

This loss of slump was a concern. However, no modifications were made. Due to the speed at which concrete is usually placed at a prestressing plant, the concrete was deemed be satisfactory.

5.2.1.2 Finishability

Again, finishability was not a major concern. Since this concrete would be going into beams, a rough finish was desired to promote bond between the slab and the beam. This bond also transfers horizontal shear between the two components of construction. The concrete contained too much coarse aggregate to achieve a flat surface on the top of the concrete. Acknowledging that, the concrete performed adequately. The concrete was able to be placed into the forms and finished with a minimum of voids. This was the most important aspect.

5.2.2 Mechanical Properties

Obviously, mechanical properties again play the largest role in the acceptance of the concrete for use at a prestressing yard. The basic governing requirement was 8000 psi at 28 days. In order to reach this 8000 psi, the concrete will more than satisfy the desired 3500 psi 1 day strength.

5.2.2.1 Compressive Strength

The results of the laboratory trials were very encouraging for use of this concrete. Figure 5.1 shows the age-strength relationship of the 8000 psi concrete mix.

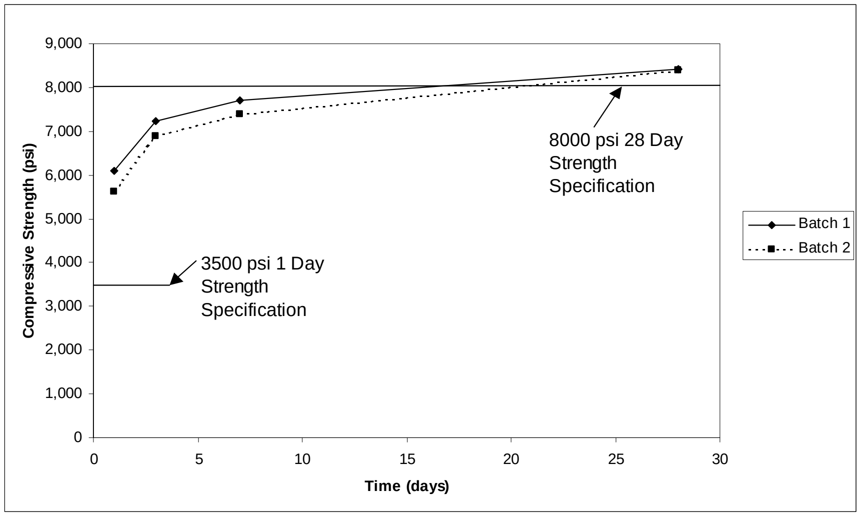

__Figure 5.1 Age-Strength Relationship of 8000 psi Mix__

As can be seen, the 8000 psi mix performed satisfactorily. Both batches achieved strengths in the mid 8000 psi range at 28 days. Also, the initial strength was far more than adequate with a strength of at least 5500 psi at one day.

The strength curves are typical of concrete and show that the concrete was continuing to gain strength at later ages. Also, there was some significant early age difference between the first batch of concrete and the second batch. This caused some concern. However, when the concrete reached later ages, the strengths were remarkably similar. This alleviated any fears that this particular mix of concrete performed differently during two separate tests.

5.2.2.3 Modulus of Elasticity

As discussed in Chapter 4, modulus of elasticity is an important property for this lightweight concrete. The 8000 psi concrete was expected to have somewhat larger values of modulus of elasticity than the 6000 psi concrete. However, Figure 5.2 shows the 6000 and 8000 psi mixes normalized on the same graph.

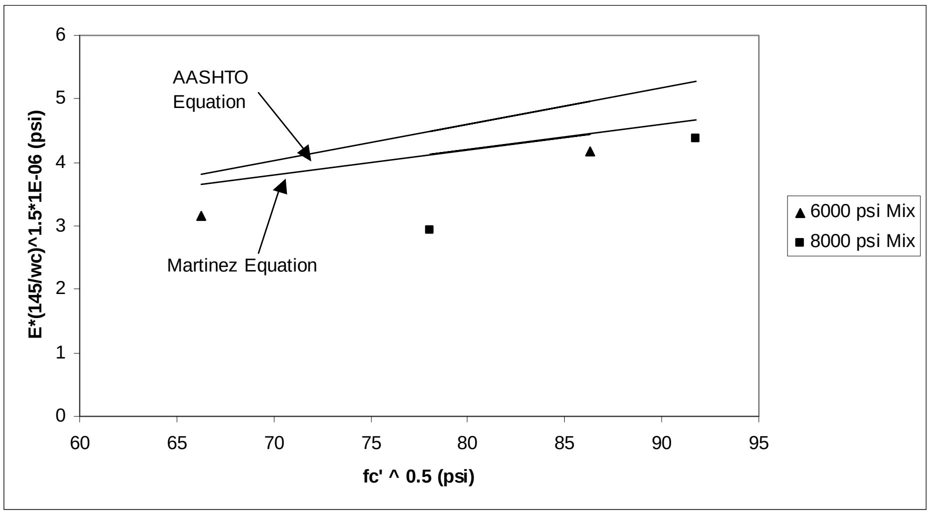

Figure 5.2 Relation of Moduli of Elasticity Values to Code Values

Figure 5.2 shows that the two mixes produced in this project varied similarly to the predictive equations for modulus of elasticity. Except for the 1 day 8000 psi value, which was low, all the concrete values were very similar.

This figure also shows how the Martinez and AASHTO equations overestimated the modulus of elasticity values for both mixes. However, there is always a great deal of scatter in these values. Figure 5.3 shows the 8000 psi data among other data.

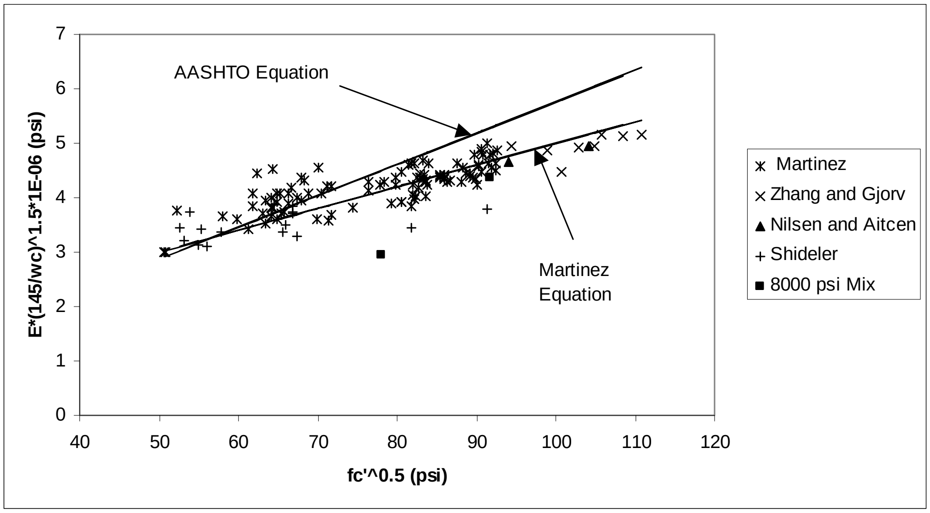

Figure 5.3 Comparison of Modulus of Elasticity for 8000 psi Concrete

As can be seen, the two equations based on strength were not able to predict the measured modulus, which came in lower than both of them.

The low value of the modulus does not indicate that the modulus of elasticity underperformed for this concrete. It has been well noted in other literature that the ACI equation overestimated the modulus of elasticity for high strength lightweight concrete [2,16]. The Martinez [2] prediction was within 7%, which is fairly close when considering the inherent variability in modulus of elasticity measurements. Also, the 28 day value fell well within the scatter band produced by all the data, indicating that the 8000 psi mix has consistent performance with other high strength lightweight concrete.

Overall, the performance of the 8000 psi concrete in the laboratory E_c test is fine. Kolozs [34] goes into greater detail into the losses and deflections of the beams, which are the areas that are affected the most by the modulus of elasticity.

5.2.2.3 Split Cylinder Tensile Strength

The split cylinder tensile strengths of the concrete again did not play a major role in the selection of the appropriate concrete mix. However, due to the use of tensile properties in prestressed design, the properties were measured to verify that the 8000 psi mix had adequate performance in this aspect.

In terms of tensile strength, the 8000 psi mix actually performed relatively poorly. When compared to the 6000 psi mix, the values for the 8000 psi mix were much less. Splitting tensile strength of 6 X 12 inch cylinders was 318 psi at one day and 452 psi at 28 days. This was about 50 psi below those of the 6000 psi mix. This reflected earlier split tensile results.

Figure 5.4 gives a comparison of split tensile values to values from other studies.

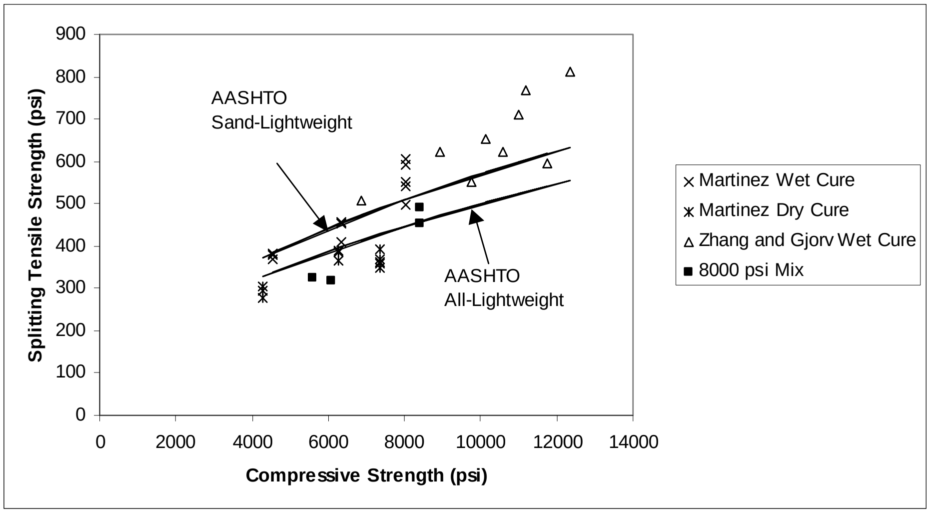

Figure 5.4 Comparison of 8000 psi Mix Split Tensile Values to Other Studies

Figure 5.4 shows that the values for the 8000 psi concrete were very low when compared to values from other studies. All four values fell beneath the equation given by AASHTO [12] for sand-lightweight concrete. The 28 day strengths, of more interest since these are the strengths usually given as the split tensile strengths of the concrete mix, are closer to the equation but still do not reach it.

A possible reason to explain this discrepancy is the moisture state of the specimens when tested. The split cylinder test is very dependent on the moisture state of the specimen. Martinez [2] tested both wet and dry cured cylinders and found that the dry-cured cylinders had values 23% lower than those of corresponding moist-cured concretes.

These concrete specimens tested had been allowed to dry for approximately an hour before testing. The outer surfaces where cracks would initiate dry before testing. Although the specimens had been kept in the moist room prior to testing, they were dry when testing began. This could have caused the low values for the split cylinder test.

Considering that the 28 day values were 13% and 6% lower than the AASHTO [12] sand-lightweight concrete values, keeping the cylinders wet until testing might have caused the tested values to exceed the equation.

5.2.2 Creep and Shrinkage

5.2.3.1 Creep

The creep of the 8000 psi concrete mix was tested the same way as for the 6000 psi concrete mix. Details of the tests are given in Chapter 4.

Also, creep plus shrinkage again was factored into these tests since there was no control of humidity and temperature in the room where the creep tests were occurring. Therefore, the data are compared to data from Reichard [18], who compiled data on lightweight concrete behavior in creep and shrinkage.

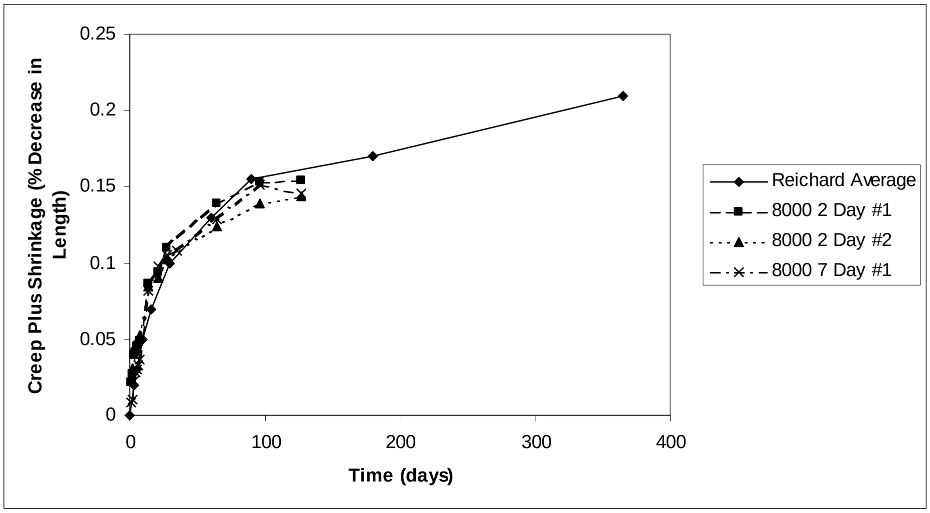

Figure 5.5 Creep Plus Shrinkage Behavior of 8000 psi Concrete Mix

Figure 5.5 shows that the 8000 psi concrete mix nearly falls on top of the Reichard [18] average for lightweight concrete in creep plus shrinkage. Obviously, the behavior of the 8000 psi concrete is very common and average for lightweight concrete. This shows that creep plus shrinkage of this concrete can be predicted.

Table 5.2 shows the creep plus shrinkage data in a different way. It utilizes Equation 4.1 and describes creep with creep coefficients.

Table 5.2 Four Month Creep Plus Shrinkage Behavior of 8000 psi Concrete

Age at Loading	Initial Elastic Strain (microstrain)	Creep Coefficient
2 days	725.4	3.13
2 days	764.6	2.88
7 days	750.6	2.95

Table 5.2 shows that the 8000 psi concrete mix behaves similarly to the 6000 psi concrete mix. Again, the creep coefficient averaged around 3, slightly

less than the 6000 psi concrete mix. This can be attributed to the fact that this data were the four month data, not the five month data like the 6000 psi mix. Once the five month data are added, the creep coefficient likely will be the same for both mixes.

Overall, the creep plus shrinkage behavior can be predicted using data from Reichard [18], which are the data in ACI Committee 213 [33] report. This result is good since it shows that the behavior of the 8000 psi mix is ordinary and not difficult to understand.

5.2.3.2 Shrinkage

Shrinkage also can affect long-term deformations of lightweight aggregate concrete. Figure 5.6 gives the shrinkage results for the 8000 psi concrete.

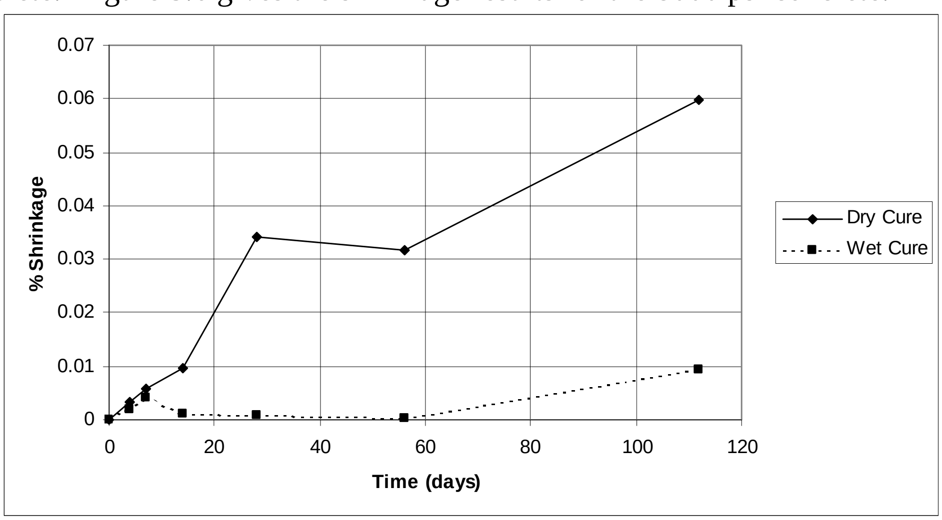

Figure 5.6 Shrinkage Results for 8000 psi Mix

Again, when compared to data from Reichard [18], the 8000 psi concrete proved to be average in its amount of shrinkage. Reichard showed that lightweight concrete decreased from 0.02% to 0.08% at 90 days due to drying shrinkage for dry cured specimens. From Figure 5.6, the 8000 psi concrete has decreased approximately 0.05% at 90 days, placing it firmly in the middle of data from Reichard.

Also, Reichard [18] showed that lightweight concrete plateaus at approximately 150 days of age for drying shrinkage. Although this data point has not been reached yet, it is expected to occur in this concrete.

5.3 JOBSITE PERFORMANCE

The performance of the 8000 psi mix did not measure up to the performance of the 6000 psi mix. Jobsite performance results were mixed.

5.3.1 Workability

More concern was always present when dealing with the 8000 psi mix. due to the high cement content and increased amount of superplasticizer used.

To produce the three 40 foot concrete beams to be made of 8000 psi concrete, three batches of concrete were mixed. Each batch of concrete was three cubic yards in size. Again, 7-9 inches of slump was the target for this concrete.

Each of the three batches of concrete had a different amount of superplasticizer. The results of workability tests are summarized in Table 5.3.

Table 5.3 Summary of Workability Results for 8000 psi Mix in Field

Batch	Superplasticizer Added	Dosage Rate	Slump at Batch Plant	Slump at Forms
1	215 oz	7.7 oz/100 wt	6.5 inches	3 inches
2	235 oz	8.4 oz/100 wt	8.5 inches	7 inches
3	265 oz	9.5 oz/100 wt	11 inches	8 inches

Figures 5.7 through 5.9 show the slumps of the concrete out in the field.

Figure 5.7 Slump for First Batch of 8000 psi Concrete

Figure 5.8 Slump for Second Batch of 8000 psi Concrete

Figure 5.9 Slump for Third Batch of 8000 psi Concrete

As can be seen, there was more need for adjusting superplasticizer for the 8000 psi mix. For each batch of concrete, the amount of superplasticizer was increased. The concrete was being sent out of the batch plant at adequate slumps. However, the concrete was losing slump during the short trip in the sidewinder.

Most interesting of all was the last batch of concrete. The concrete was sent from the batch plant at 11 inches of slump, essentially flowing concrete. It behaved like water. By the time it had reached the line where the beams were being cast, it was down to a slump that was desirable.

The workers at the prestressed plant found the first two batches to be difficult to work and place into the appropriate forms when compared to the concrete mixes they used everyday at the precast plant. Unlike the 6000 psi concrete, a great deal of work had to be done to get the concrete into the forms.

A couple of reasons might have contributed to the problems with the loss of slump. First was the method of transportation used by Heldenfels. The sidewinders did not have any way to mix the concrete during the trip. Therefore, the concrete sat unagitated in the sidewinder for 2-3 minutes until it reached the forms. Also, the concrete was vibrated by the trip since the sidewinder bounced along the road which compacted the concrete. Instead of vibration, the concrete needed stirring to mix the contents instead of vibrating them.

The other reason probably explains the slump loss better. Since the mix is a 10.5 sack mix using Type III cement, the mix reaches extremely high temperature when compared to moderate strength concrete. The high temperature of the concrete probably consumed some of the slump and caused problems with the workability. The day was already extremely hot with temperature around 95 degrees Fahrenheit. Although no temperature measurement was taken, the concrete was estimated at 110 degrees. This is a sign that the concrete was running too hot and could lead to trouble.

Soroka and Ravina [35] documented this phenomenon. They showed that slump loss in concrete is accelerated by temperatures over 86°F. Although no temperature was taken of the concrete, the ambient air temperature that day was approximately 95°F, hot enough to aid this process.

Also, Punkki, et al. [36] showed that high strength concrete utilizing a large amount of superplasticizer had problems with loss of workability. They showed that besides slump, which decreased, high strength concrete showed a loss in plastic viscosity greater than the loss in normal strength concrete. This very likely is the explanation for the cohesiveness shown by the concrete.

However, these problems with workability did not cause any problems with the finish of the concrete. The prestressed bridge girders compared adequately to girders made with normal weight concrete. There were no voids or honeycombing which might be expected with a cohesive mix such as the 8000 psi concrete mix.

Figure 5.10 Finish of Girder with 8000 psi Concrete Mix

Overall, the workability performance was disappointing. Although the workers were able to place the concrete into forms, the concrete did not behave like the laboratory concrete.

5.3.2 Compressive Strength

After the extraordinary performance of the 6000 psi mix, it was hoped that the 8000 psi mix would perform equally as well to give a well defined split between their compressive strengths.

However, problems with workability indicated that the 8000 psi concrete fabricated at Heldenfels would not perform similarly to the 8000 psi concrete fabricated in the laboratory.

Figure 5.11 gives the age-strength data for this mix.

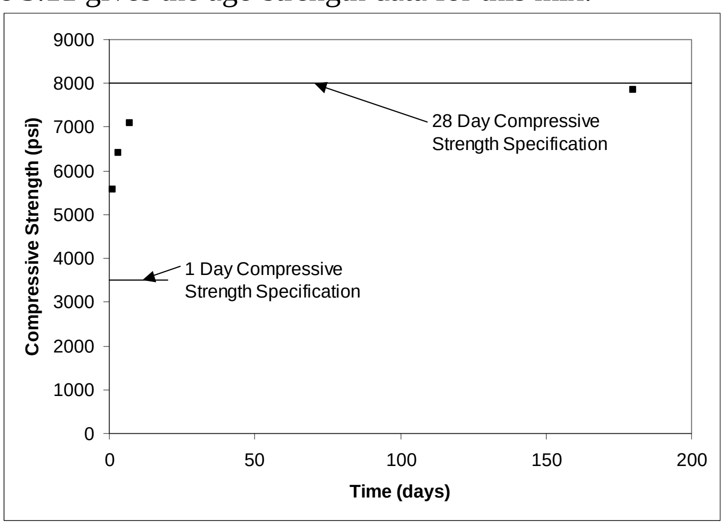

Figure 5.11 Age-Strength Curve for 8000 psi Concrete Used in Beams

In Figure 5.11, a line is not drawn between the points since that would not approximate the strength gain. A 28 day compressive strength was not taken due to a lack of cylinders. After the 7 day tests had been completed, the staff realized that enough cylinders did not exist to allow 28 day compressive tests and also compressive and modulus of elasticity tests for the beam development length tests that would come later in the project. Therefore, a 180 day compressive strength test was done since a beam test took place at this date.

As can be seen from Figure 5.11, the 28 day strength was not adequate. Therefore, this mix did not meet that specifications. It is believed that this occurred for the same reasons that workability was not adequate. With the slump loss often occurs loss in strength.

5.3.3 Flexural and Split Cylinder Tensile Strength

The 8000 psi concrete field mix also was tested at 1 day for flexural and split cylinder tensile strength. Figure 5.12 and 5.13 present this data and compare it to values from other studies.

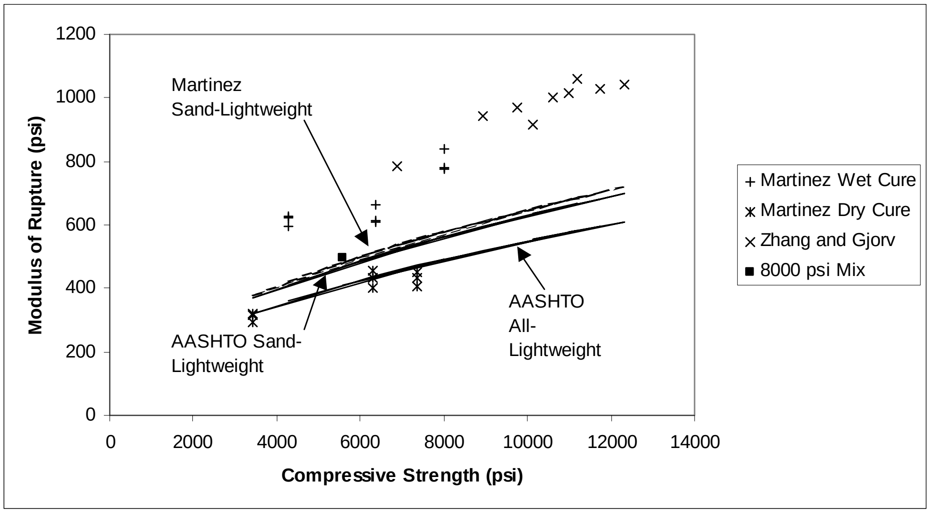

Figure 5.12 Flexural Strength of 8000 psi Mix Compared to Other Values

As is seen in Figure 5.12, the 1 day flexural strength of the 8000 psi field mix was adequate. The value exceeded both the AASHTO [12] and Martinez [2] equations for flexural strength of sand-lightweight concrete.

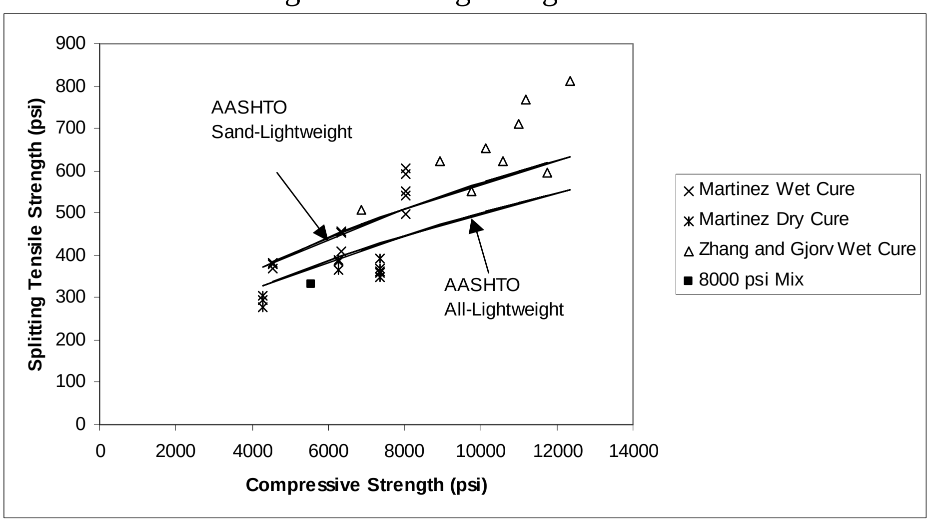

Figure 5.13 Splitting Tensile Strength of 8000 psi Mix Compared to Other Values

As is seen from Figure 5.13, the value of the 1 day strength fell beneath the AASHTO [12] value for sand-lightweight concrete. This result was similar to the earlier values received for the split cylinder test for this same mix of concrete in the laboratory. Therefore, the likely reason for the low strength was the same, the drying out of the concrete before testing.

Overall, the performance of this concrete mix was disappointing. The 28 day strength specification was not met while the workability in the field was problematic.

Chapter 6: Conclusions

6.1 Summary

This portion of the project was carried out to determine the feasibility of utilization of high strength lightweight concrete in pretensioned bridge girders. For these bridge girders, two distinct concrete mixes were developed. One was intended to have a 28 day strength of 6000 psi while the other was intended to have a 28 day strength of 8000 psi. Both also were intended to have a strength of at least 3500 psi at one day of age for release of prestress in precast plants.

To obtain these two mixes, an ambitious laboratory mixing and testing program was implemented. Thirty-five mixes were designed and fabricated. For each of the mixes, mechanical behavior was determined to adequately describe the concrete mix. Tests were performed to give compressive strength, modulus of elasticity, modulus of rupture, and splitting tensile strength. These four tests provide the moist important data for utilization in girder design.

Furthermore, the slump of the concrete and finishability was noted for help in choosing the appropriate concrete. From these mixes, two laboratory concrete mixes were chosen that combined the best mechanical performance with adequate workability performance.

Using the 6000 psi mix, one 20 foot long and two 40 foot long beams were cast. Using the 8000 psi mix, one 20 foot long beam and three 40 foot long beams were fabricated. The beams were then brought to Ferguson Structural Engineering Laboratory for performance testing.

6.2 Conclusions

6.2.1 6000 psi Mix

The 6000 psi mix was controlled by the 1 day strength requirement for the concrete. In order to achieve 3500 psi at 1 day with Type III cement and 25% replacement of fly ash, a certain minimum amount of cement was needed.

1. The 1 day strength of the concrete was approximately 4000 psi.
2. The 28 day strength of the concrete averaged 7200 psi in the laboratory.
3. The 28 day strength of the concrete in the field was 7800 psi.
4. Approximately 5.5 fluid ounces of superplasticizer were required for every 100 pounds of cementitious material to produce the needed 7-9 inches of slump.
5. The fresh unit weight of the concrete was 127 pounds per cubic foot (pcf) which later decreased to 118 pcf at equilibrium conditions.
6. The concrete continued to gain some strength after 28 days.
7. The concrete finished adequately in the precast plant.
8. This concrete mix provides about 30 minutes of working time under room temperature and average humidity conditions.
9. The concrete placed well at the precast plant. The workers could tell no difference between this mix and normal weight prestressed concrete girder mixes used at Heldenfels.
10. Creep and shrinkage of the 6000 psi was high when compared to normal weight concrete. However, the results were reasonable when compared to other lightweight concrete.

The 6000 psi concrete produced excellent results. The concrete met all the mechanical strength requirements while also providing the needed workability.

6.2.2 8000 psi Mix

The 8000 psi mix was controlled by the 28 day strength of the concrete. To reach this goal, a large amount of cement was required. The following are conclusions about the development of the 8000 psi mix.

1. The 1 day strength was 5500 psi, easily surpassing the 1 day strength requirement.
2. The 28 day strength of this mix of concrete was 8600 psi.
3. The 28 day estimate of strength of this mix in the field was 7900 psi.
4. Further laboratory mixing should have done to understand fully the compressive strength.
5. This concrete required a superplasticizer dosage of 7 fluid ounces per 100 pounds of cement.
6. The fresh unit weight of the concrete was 129 pcf, dropping to 122 pcf at equilibrium conditions.
7. The concrete was somewhat difficult to work in the laboratory; however, it was not unmanageable.
8. At room temperature and humidity conditions, this concrete only gives about 20 minutes of time where the concrete is workable.
9. At Heldenfels precast plant, the concrete required more work to place than the comparable concrete of the 6000 psi concrete. The workers said that

the 8000 psi mix required a lot of work to be placed properly in the girder forms.

10. Creep and shrinkage of the 8000 psi mix was good. Again, it was high compared to normal weight concrete. However, the performance was good compared to lightweight aggregate concrete.

Overall, the performance of the 8000 psi concrete was somewhat disappointing. The field performance did not agree with the laboratory performance. The performance in the field was problematic and not adequate. It would be acceptable for a nominal 7500 psi mix

6.3 IMPLEMENTATION

From the results of this study, the following recommendations can be made.

1. The 6000 psi mix is recommended for use in precast plants for high strength lightweight concrete. Using this amount of cement, 7000 psi is the expected minimum 28 day strength. 7500 psi is more typical of the long-term strength expected from this mix. This provides excellent margins for plant use. The mix is presented in Table 6.1.

Table 6.1 Recommended Mix Proportions for 6000 psi Mix

Component	Proportion
Cement	504 lb
Fly Ash	168 lb
Lightweight Aggregate	1264 lb
Sand	1149 lb
Water	222 lb
Daratard-17	12 oz
ADVA Superflow	34 oz

2. The 8000 psi mix should rerated as a 7500 psi mix only. The field performance of the 8000 psi mix was marginal. Table 6.2 shows the 8000 psi mix (rerated as a 7500 psi mix).

Table 6.2 Recommended Mix Proportions for 7500 psi Mix

Component	Proportion
Cement	671 lb
Fly Ash	316 lb
Lightweight Aggregate	1123 lb
Sand	1029 lb
Water	247 lb
Daratard-17	12 oz
ADVA Superflow	54 oz

3. The 6000 psi mix is more workable, making it easier to use for precast plants. Precast plants should be able to use the 6000 psi mix design with a minimum of training in lightweight concrete.
4. The 8000 psi mix is more risky with respect to workability. It may cause problems for precast plants who choose to use it, particularly in hot weather. Its high slump loss and loss in workability combine to make it a more difficult mix to use. Its use is suggested for precast plants whose personnel have wide experience with high strength concrete containing a

large amount of cement per cubic yard. This mix can be used with minimal problems. It just requires workers with experience to control it.

6.4 Recommendations for Future Study

The following are recommended for future study.

1. Further lab mixing of the recommended 6000 psi and 8000 psi mixes to gain an average age-strength curve with standard deviations.
2. Exploration of the use of silica fume in lightweight concrete. Silica fume has been proven to produce lightweight concrete with strengths in excess of 10,000 psi [16].
3. Testing of different types of sand with different gradations to understand the interaction of sand with this lightweight aggregate.
4. Further laboratory testing of lightweight aggregate concrete to understand overyielding and underyielding.

Appendix A: Mix Designs

	Cement	Fly Ash	Lightweight Aggregate	Sand	Water
Mix #1	600	0	1155	1387	210
Mix #2	450	150	1155	1371	210
Mix #3	600	0	1260	1207	210
Mix #4	450	150	1260	1181	210
Mix #5	600	0	1155	1122	210
Mix #6	600	0	1271	1013	210
Mix #7	600	0	1328	1090	210
Mix #8	600	0	1155	1122	210
Mix #H-1	800	0	1155	1100	256
Mix #H-2	600	200	1155	1065	256
Mix #H-3	800	0	1260	920	256
Mix #H-4	600	200	1260	885	256

	Daratard	ADVA Superflow	Daravair
Mix #1	6 oz.	30 oz.	0 oz.
Mix #2	6 oz.	30 oz.	0 oz.
Mix #3	6 oz.	30 oz.	0 oz.
Mix #4	6 oz.	30 oz.	0 oz.
Mix #5	6 oz.	30 oz.	1 oz.
Mix #6	6 oz.	30 oz.	0.5 oz.
Mix #7	6 oz.	30 oz.	0 oz.
Mix #8	6 oz.	30 oz.	0.5 oz.
Mix #H-1	8 oz.	40 oz.	0 oz.
Mix #H-2	8 oz.	40 oz.	0 oz.
Mix #H-3	8 oz.	40 oz.	0 oz.
Mix #H-4	8 oz.	40 oz.	0 oz.

Table A.1 Mix Designs in First Iteration

(All quantities are pounds per cubic yard unless otherwise noted)

	Cement	Fly Ash	Lightweight Aggregate	Sand	Water
Mix #1-C	600	200	1161	1098	224
Mix #1-S	600	200	1173	1067	200
Mix #1-W	600	200	1161	1055	224
Mix #2-C	637.5	212.5	1205	983	221
Mix #2-S	637.5	212.5	1205	964	221
Mix #2-W	637.5	212.5	1205	964	221
Mix #3-C	675	225	1103	1003	234
Mix #3-S	675	225	1103	1003	234
Mix #3-W	675	225	1103	1003	234
Mix #4-C	600	200	1231	985	224
Mix #4-S	600	200	1231	985	224
Mix #4-W	600	200	1231	985	224
Mix #5-C	600	200	1184	1031	224
Mix #5-S	600	200	1184	1031	224

	Daratard	ADVA Superflow	Daravair
Mix #1-C	4 oz.	27 oz.	0 oz.
Mix #1-S	4 oz.	39 oz.	0 oz.
Mix #1-W	4 oz.	31 oz.	0 oz.
Mix #2-C	4 oz.	31 oz.	0 oz.
Mix #2-S	4 oz.	39 oz.	0 oz.
Mix #2-W	4 oz.	31 oz.	0 oz.
Mix #3-C	4 oz.	42 oz.	0 oz.
Mix #3-S	4 oz.	39 oz.	0 oz.
Mix #3-W	4 oz.	42 oz.	0 oz.
Mix #4-C	4 oz.	54 oz.	0 oz.
Mix #4-S	4 oz.	46 oz.	0 oz.
Mix #4-W	4 oz.	46 oz.	0 oz.
Mix #5-C	4 oz.	31 oz.	0 oz.
Mix #5-S	4 oz.	39 oz.	0 oz.

Table A.2 Mix Designs for Second Iteration

(All quantities are in pounds per cubic yard unless otherwise noted)

	Cement	Fly Ash	Lightweight Aggregate	Sand	Water
Mix #F-1	412.5	137.5	1333	1159	198
Mix #F-2	450	150	1244	1186	210
Mix #F-3	450	150	1300	1130	210
Mix #F-4	450	150	1300	1130	210
Mix #F-5	494	165	1239	1126	217
Mix #F-6	600	200	1231	985	224
Mix #F-7	671	316	1123	1029	247
Mix #F-8	671	316	1123	1029	247
Mix #F-9	671	316	1153	978	247

	Daratard	ADVA Superflow	Daravair
Mix #F-1	0 oz.	72 oz.	0 oz.
Mix #F-2	0 oz.	33 oz.	0 oz.
Mix #F-3	4 oz.	33 oz.	0 oz.
Mix #F-4	5 oz.	43 oz.	0 oz.
Mix #F-5	12 oz.	34 oz.	0 oz.
Mix #F-6	5 oz.	43 oz.	0 oz.
Mix #F-7	12 oz.	54 oz.	0 oz.
Mix #F-8	27 oz.	54 oz.	0 oz.
Mix #F-9	16 oz.	54 oz.	0 oz.

Table A.3 Mix Designs for Third Iteration

(All proportions are pounds per cubic yard unless otherwise noted)

Appendix B: Test Results for Mixes

	6000 psi Mixes							
Mix Number	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Compressive Strength (psi)								
1 Day	3227	3273	3890	3954	5364	4714	4197	3193
3 Day	3636	3265	4642	5442	6318	6085	5730	4424
7 Day	3827	3959	5007	5713	6793	6363	6277	5033
28 Day	4794	4921	4042	6841	7039	7498	6789	5667
Modulus of Elasticity (ksi)								
1 Day	3174	1815	2111	2177	2389	2224	2147	1938
28 Day	3591	3506	3460	2918	2816	2648	2701	2377
Modulus of Rupture (psi)								
1 Day	n/a	503	508	525	540	525	488	418
28 Day	746	724	765	725	765	810	761	670
Splitting Strength (psi)								
1 Day	511	383	466	399	519	468	386	300
28 Day	678	582	639	620	659	647	561	459
Weights (lb/ft^3)								
7 Day	129.9	129.3	128.5	128.8	125.2	126.9	124.3	117.9
28 Day	125.6	123.0	123.8	123.8	121.4	122.3	117.6	111.6
Equilibrium	122.0	120.0	120.3	119.6	118.1	118.3	115.6	109.6

Table B.1 Results for Mix Designs in First Iteration

	Repeats		8000 psi Mixes				Hybrid
Mix Number	**5-2**	**6-2**	**H1**	**H2**	**H3**	**H4**	**9**
Compressive Strength (psi)							
1 Day	4220	4218	4710	3785	4961	3201	4469
3 Day	5635	5360	5697	5795	5842	5018	5871
7 Day	5860	5624	6044	6339	6521	5589	6346
28 Day	6910	6637	7130	6905	6973	6126	6851
Modulus of Elasticity (ksi)							
1 Day	2074	2014	2156	2023	2084	1840	1984
28 Day	2857	2473	2670	2784	2539	2297	2600
Modulus of Rupture (psi)							
1 Day	n/a	n/a	448	445	485	464	n/a
28 Day	n/a	n/a	713	703	693	643	n/a
Splitting Strength (psi)							
1 Day	436	369	343	263	329	244	439
28 Day	606	567	553	594	574	581	562
Weights (lb/ft^3)							
7 Day	123.8	122.3	124.2	125.4	123.3	123.4	123.6
28 Day	118.9	116.9	119.7	120.3	119.1	n/a	118.8
Equilibrium	117.6	117.7	117.4	116.4	118.1	116.0	117.8

Table B.1 (cont.) Results for Mix Designs in First Iteration

Mix Number	1-C	1-W	1-S	2-C	2-W	2-S
Compressive Strength (psi)						
1 Day	4395	4549	4643	4985	4463	4527
3 Day	5532	5574	5845	6133	5420	6182
7 Day	6008	5730	6432	6579	5609	N/A
28 Day	7125	6441	7812	7685	6185	8023
Modulus of Elasticity (ksi)						
1 Day	2217	1980	2297	2253	2068	2742
28 Day	2755	2828	2297	2845	2757	2742
Modulus of Rupture (psi)						
1 Day	475	490	523	483	460	508
28 Day	658	668	735	625	655	650
Splitting Strength (psi)						
1 Day	437	394	397	440	382	398
28 Day	606	507	531	595	482	520
Weights (lb/ft^3)						
Fresh	126.5	127.9	121.4	126.1	126.8	119.5
7 Day	126.5	127.3	121.4	127.0	126.6	
28 Day	121.7	122.0	117.4	127.2	126.5	
Equilbrium	119.3	119.1	115.1	121.1	119.8	114.2

Table B.2 Results for Mix Designs in Second Iteration

Mix Number	3-C	3-W	3-S	4-C	4-W	4-S	5-C	5-S
Compressive Strength (psi)								
1 Day	5164	5141	4599	5448	5054	4980	4544	3600
3 Day	6234	6015	5908	6479	5633	6119	6217	5151
7 Day	6874	6312	7305	6799	5857	6681	6001	6051
28 Day	7839	6677	8103	8037	6660	7935	7441	7216
Modulus of Elasticity (ksi)								
1 Day	2212	2383	2273	2250	2354	2242	2075	1125
28 Day	2791	3186	2814	2797	2989	2773	2637	2199
Modulus of Rupture (psi)								
1 Day	430	465	475	525	484	448	420	420
28 Day	658	675	673	753	599	665	655	653
Splitting Strength (psi)								
1 Day	392	461	431	491	429	392	380	328
28 Day	689	544	587	590	483	499	555	472
Weights (lb/ft^3)								
Fresh	126.4	125.6	122.3	127.8	117.9		123.1	117.6
7 Day	126.1	124.8	122.8	126.9	120.8	117.1	123.5	117.8
28 Day	122.2	121.4	118.7	122.7			117.5	112.9
Equilbrium	119.7	118.9	117.2	120.6	115.8	111.3	116.1	111.7

Table B.2 (cont.) Results for Mix Designs in Second Iteration

Mix Number	F-1	F1 4x8	F-2	F2 4x8	F-3	F3 4x8	F-4	F4 4x8
Compressive Strength (psi)								
1 Day	3060	2952	2946	2717	3061	2733	3554	3265
3 Day	4202	4503	4031	3974	4188	4252	4647	4401
7 Day	5029	N/A	4728	4706	4827	4947	5423	5130
28 Day	6443	6571	6272	6156	6492	6177	6760	6629
Modulus of Elasticity (ksi)								
1 Day	1980	N/A	1996	N/A	2140	1903	2099	1891
28 Day	3017	2853	3095	3109	2907	2840	2904	3029
Splitting Strength (psi)								
1 Day	290	259	222	272	236	253	277	291
28 Day	587	N/A	518	561	527	548	498	518
Weights (lb/ft^3)								
Fresh	122.4		122.7		122.4		121.6	
7 Day	123.3		123.8		123.7		122.4	
28 Day	117.7		116.6		116.3		116.4	

Table B.3 Results for Mix Designs in Third Iteration

Mix Number	F-5	F5 4x8	F-6	F6 4x8	F-7	F7 4x8	F-8	F8 4x8	F-9	F9 4x8
Compressive Strength (psi)										
1 Day	4393	3899	5525	5019	6092	5609	5610	5236	5856	5216
3 Day	5297	5038	6454	6139	7225	6853	6885	6703	6871	6534
7 Day	6261	6038	6953	6663	7715	7717	7379	7724	7502	7569
28 Day	7449	7184	7892	7973	8420	8632	8391	8626	8100	8432
Modulus of Elasticity (ksi)										
1 Day	2315	N/A	2321	2226	2273	2306	2520	N/A	2498	2514
28 Day	3053	2169	3147	3324	3385	3611	3390	3722	3396	3285
Splitting Strength (psi)										
1 Day	313	328	313	373	318	377	326	409	313	394
28 Day	614	593	564	568	452	575	491	581	491	604
Weights (lb/ft^3)										
Fresh	122.4		123.5		124.9		124.5		124.3	
7 Day	123.5		123.4		125.4		125.2		124.6	
28 Day	117.9		119.5		122.3		121.2		120.6	

Table B.3 (cont.) Results for Mix Designs in Third Iteration

Appendix C: Creep Data Sheets

	Top	Middle	Bottom	Average
1 Day	92.67	88.75	101.50	94.31
2 Days	94.50	98.25	109.50	100.75
3 Days	95.33	100.50	116.75	104.19
4 Days	109.00	107.00	95.00	103.67
5 Days	115.17	113.25	128.25	118.89
6 Days	121.00	118.25	130.00	123.08
7 Days	120.50	120.25	132.00	124.25
14 Days	166.50	183.75	195.75	182.00
21 Days	175.67	196.00	208.00	193.22
28 Days	188.50	216.50	228.25	211.08
35 Days	204.83	232.25	246.50	227.86
65 Days	233.83	259.00	276.00	256.28
96 Days	241.83	274.00	286.75	267.53
127 Days	249.33	278.75	292.75	273.61
155 Days	251.67	282.50	294.75	276.31

	Strain	Creep Strain	Creep Coefficient	% Length Change
1 Day	7.64E-04	6.14E-05	1.09	0.0061
2 Days	8.16E-04	1.14E-04	1.16	0.0114
3 Days	8.44E-04	1.42E-04	1.20	0.0142
4 Days	8.40E-04	1.37E-04	1.20	0.0137
5 Days	9.63E-04	2.61E-04	1.37	0.0261
6 Days	9.97E-04	2.95E-04	1.42	0.0295
7 Days	1.01E-03	3.04E-04	1.43	0.0304
14 Days	1.47E-03	7.72E-04	2.10	0.0772
21 Days	1.57E-03	8.63E-04	2.23	0.0863
28 Days	1.71E-03	1.01E-03	2.43	0.1007
35 Days	1.85E-03	1.14E-03	2.63	0.1143
65 Days	2.08E-03	1.37E-03	2.96	0.1373
96 Days	2.17E-03	1.46E-03	3.08	0.1465
127 Days	2.22E-03	1.51E-03	3.16	0.1514
155 Days	2.24E-03	1.54E-03	3.19	0.1536

Table C.1 Creep Plus Shrinkage Data for 6000 psi Cylinder #1 Loaded at 2 Days

	Top	Middle	Average
1 Day	89.83	107.00	98.42
2 Day	96.83	111.33	104.08
3 Day	102.50	109.33	105.92
4 Day	112.33	120.50	116.42
5 Day	117.67	127.33	122.50
6 Day	120.67	129.00	124.83
7 Day	123.67	131.33	127.50
14 Day	171.33	178.50	174.92
21 Day	182.00	188.33	185.17
35 Day	217.83	217.83	217.83
66 Day	244.50	240.33	242.42
97 Day	255.33	254.17	254.75
127 Day	260.83	258.50	259.67
155 Day	262.83	258.83	260.83

	Strain	Creep Strain	Creep Coefficent	% Length Change
1 Day	7.97E-04	2.81E-04	1.54	0.0281
2 Day	8.43E-04	3.27E-04	1.63	0.0327
3 Day	8.58E-04	3.42E-04	1.66	0.0342
4 Day	9.43E-04	4.27E-04	1.83	0.0427
5 Day	9.92E-04	4.76E-04	1.92	0.0476
6 Day	1.01E-03	4.95E-04	1.96	0.0495
7 Day	1.03E-03	5.16E-04	2.00	0.0516
14 Day	1.42E-03	9.00E-04	2.74	0.0900
21 Day	1.50E-03	9.83E-04	2.90	0.0983
35 Day	1.76E-03	1.25E-03	3.42	0.1248
66 Day	1.96E-03	1.45E-03	3.80	0.1447
97 Day	2.06E-03	1.55E-03	4.00	0.1547
127 Day	2.10E-03	1.59E-03	4.07	0.1587
155 Day	2.11E-03	1.60E-03	4.09	0.1596

Table C.2 Creep Plus Shrinkage Data for 6000 psi Cylinder #2 Loaded at 2 Days

	Top	Middle	Bottom	Average
1 Day	102.83	126.67	129.83	119.78
2 Day	110.83	135.33	132.33	126.17
3 Day	118.50	141.17	134.50	131.39
4 Day	127.50	149.67	139.50	138.89
5 Day	129.00	157.00	134.33	140.11
6 Day	141.00	166.00	154.67	153.89
7 Day	141.50	168.83	152.67	154.33
14 Day	171.33	199.67	190.83	187.28
21 Day	191.83	220.33	211.33	207.83
28 Day	197.83	228.83	214.50	213.72
35 Day	209.83	244.33	230.33	228.17
65 Day	249.83	282.83	276.33	269.67
96 Day	281.50	313.17	311.33	302.00
127 Day	285.33	310.83	296.67	297.61
155 Day	293.17	320.67	301.50	305.11

	Strain	Creep Strain	Creep Coefficient	% Length Change
1 Day	9.70E-04	1.43E-04	1.17	0.0143
2 Day	1.02E-03	1.95E-04	1.24	0.0195
3 Day	1.06E-03	2.37E-04	1.29	0.0237
4 Day	1.13E-03	2.98E-04	1.36	0.0298
5 Day	1.13E-03	3.08E-04	1.37	0.0308
6 Day	1.25E-03	4.19E-04	1.51	0.0419
7 Day	1.25E-03	4.23E-04	1.51	0.0423
14 Day	1.52E-03	6.90E-04	1.83	0.0690
21 Day	1.68E-03	8.56E-04	2.04	0.0856
28 Day	1.73E-03	9.04E-04	2.09	0.0904
35 Day	1.85E-03	1.02E-03	2.23	0.1021
65 Day	2.18E-03	1.36E-03	2.64	0.1357
96 Day	2.45E-03	1.62E-03	2.96	0.1619
127 Day	2.41E-03	1.58E-03	2.91	0.1584
155 Day	2.47E-03	1.64E-03	2.99	0.1644

Table C.3 Creep Plus Shrinkage Data for 6000 psi Cylinder #1 Loaded at 7 Days

	Top	Middle	Bottom	Average
1 Day	158.00	144.50	131.67	144.72
2 Day	159.67	150.67	140.00	150.11
3 Day	165.00	159.50	144.83	156.44
4 Day	174.67	170.50	143.50	162.89
5 Day	177.83	173.67	260.00	203.83
6 Day	226.50	187.50	277.50	230.50
7 Day	229.25	185.00	280.50	231.58
14 Day	302.00	218.67	353.00	291.22
21 Day	328.25	239.33	375.75	314.44
28 Day	333.25	248.33	387.50	323.03
35 Day	355.50	260.17	401.00	338.89
65 Day	394.00	297.00	437.50	376.17
96 Day	430.25	329.83	472.00	410.69
127 Day	435.50	332.50	474.25	414.08
155 Day	444.50	343.33	481.75	423.19

	Strain	Creep Strain	Creep Coefficient	% Length Change
1 Day	1.17E-03	8.77E-05	1.08	0.0088
2 Day	1.22E-03	1.31E-04	1.12	0.0131
3 Day	1.27E-03	1.83E-04	1.17	0.0183
4 Day	1.32E-03	2.35E-04	1.22	0.0235
5 Day	1.65E-03	5.67E-04	1.52	0.0567
6 Day	1.87E-03	7.83E-04	1.72	0.0783
7 Day	1.88E-03	7.91E-04	1.73	0.0791
14 Day	2.36E-03	1.27E-03	2.18	0.1274
21 Day	2.55E-03	1.46E-03	2.35	0.1463
28 Day	2.62E-03	1.53E-03	2.41	0.1532
35 Day	2.75E-03	1.66E-03	2.53	0.1661
65 Day	3.05E-03	1.96E-03	2.81	0.1962
96 Day	3.33E-03	2.24E-03	3.07	0.2242
127 Day	3.35E-03	2.27E-03	3.09	0.2270
155 Day	3.43E-03	2.34E-03	3.16	0.2343

Table C.4 Creep Plus Shrinkage Data for 6000 psi Cylinder #2 Loaded at 7 Days

	Top	Middle	Bottom	Average
1 Day	123.00	120.17	105.50	116.22
2 Day	129.50	129.83	110.50	123.28
3 Day	144.17	147.33	124.33	138.61
4 Day	146.83	148.83	127.00	140.89
5 Day	151.00	154.00	132.00	145.67
6 Day	154.33	151.67	133.33	146.44
7 Day	158.67	154.17	138.17	150.33
14 Day	207.33	204.17	179.00	196.83
21 Day	215.00	211.50	189.33	205.28
28 Day	234.33	232.33	208.00	224.89
65 Day	268.83	271.17	242.50	260.83
96 Day	286.83	289.17	259.33	278.44
127 Day	287.00	290.17	263.00	280.06

	Strain	Creep Strain	Creep Coefficient	% Length Change
1 Day	9.41E-04	2.16E-04	1.30	0.0216
2 Day	9.99E-04	2.73E-04	1.38	0.0273
3 Day	1.12E-03	3.97E-04	1.55	0.0397
4 Day	1.14E-03	4.16E-04	1.57	0.0416
5 Day	1.18E-03	4.55E-04	1.63	0.0455
6 Day	1.19E-03	4.61E-04	1.64	0.0461
7 Day	1.22E-03	4.92E-04	1.68	0.0492
14 Day	1.59E-03	8.69E-04	2.20	0.0869
21 Day	1.66E-03	9.37E-04	2.29	0.0937
28 Day	1.82E-03	1.10E-03	2.51	0.1096
65 Day	2.11E-03	1.39E-03	2.91	0.1387
96 Day	2.26E-03	1.53E-03	3.11	0.1530
127 Day	2.27E-03	1.54E-03	3.13	0.1543

Table C.5 Creep Plus Shrinkage Data for 8000 psi Cylinder #1 Loaded at 2 Days

	Top	Middle	Bottom	Average
1 Day	129.50	108.83	134.50	124.28
2 Day	141.33	118.00	138.33	132.56
3 Day	156.67	130.17	146.17	144.33
4 Day	161.33	135.33	149.17	148.61
5 Day	165.50	140.17	154.17	153.28
6 Day	167.83	142.17	155.33	155.11
7 Day	174.67	146.50	158.17	159.78
14 Day	214.50	183.83	196.67	198.33
21 Day	221.83	192.00	201.83	205.22
28 Day	234.67	204.67	222.00	220.44
65 Day	261.83	232.83	248.50	247.72
96 Day	278.17	252.17	266.67	265.67
127 Day	285.17	257.17	272.00	271.44

	Strain	Creep Strain	Creep Coefficient	% Length Change
1 Day	1.01E-03	2.42E-04	1.32	0.0242
2 Day	1.07E-03	3.09E-04	1.40	0.0309
3 Day	1.17E-03	4.05E-04	1.53	0.0405
4 Day	1.20E-03	4.39E-04	1.57	0.0439
5 Day	1.24E-03	4.77E-04	1.62	0.0477
6 Day	1.26E-03	4.92E-04	1.64	0.0492
7 Day	1.29E-03	5.30E-04	1.69	0.0530
14 Day	1.61E-03	8.42E-04	2.10	0.0842
21 Day	1.66E-03	8.98E-04	2.17	0.0898
28 Day	1.79E-03	1.02E-03	2.34	0.1021
65 Day	2.01E-03	1.24E-03	2.62	0.1242
96 Day	2.15E-03	1.39E-03	2.81	0.1387
127 Day	2.20E-03	1.43E-03	2.88	0.1434

Table C.6 Creep Plus Shrinkage Data for 8000 psi Cylinder #2 Loaded at 2 Days

	Top	Middle	Bottom	Average
1 Day	113.75	105.00	89.50	102.75
2 Day	113.75	107.00	94.75	105.17
3 Day	132.75	122.00	108.00	120.92
4 Day	150.25	130.50	100.00	126.92
5 Day	146.25	131.50	111.00	129.58
6 Day	151.00	131.00	118.50	133.50
7 Day	154.75	136.50	122.00	137.75
14 Day	213.50	191.75	175.50	193.58
21 Day	233.00	212.00	196.50	213.83
28 Day	242.00	216.00	209.00	222.33
35 Day	242.50	222.25	212.00	225.58
65 Day	271.50	247.25	236.25	251.67
96 Day	299.50	275.75	261.75	279.00
127 Day	293.25	269.25	256.25	272.92

	Strain	Creep Strain	Creep Coefficient	% Length Change
1 Day	8.32E-04	8.17E-05	1.11	0.0082
2 Day	8.52E-04	1.01E-04	1.13	0.0101
3 Day	9.79E-04	2.29E-04	1.30	0.0229
4 Day	1.03E-03	2.77E-04	1.37	0.0277
5 Day	1.05E-03	2.99E-04	1.40	0.0299
6 Day	1.08E-03	3.31E-04	1.44	0.0331
7 Day	1.12E-03	3.65E-04	1.49	0.0365
14 Day	1.57E-03	8.17E-04	2.09	0.0817
21 Day	1.73E-03	9.81E-04	2.31	0.0981
28 Day	1.80E-03	1.05E-03	2.40	0.1050
35 Day	1.83E-03	1.08E-03	2.43	0.1077
65 Day	2.04E-03	1.29E-03	2.72	0.1288
96 Day	2.26E-03	1.51E-03	3.01	0.1509
127 Day	2.21E-03	1.46E-03	2.95	0.1460

Table C.7 Creep Plus Shrinkage Data for 8000 psi Cylinder #1 Loaded at 7 Days

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