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Use of Admixtures for Concrete

John J. Schemmel

Final Report

2004

USE OF ADMIXTURES FOR CONCRETE
TRC-9803

FINAL REPORT

Prepared by

John J. Schemmel, PhD, PE
University of Arkansas
South Dakota State University

Prepared for

Arkansas Highway and Transportation Department
Mack-Blackwell National Rural Transportation Study Center
in cooperation with
U.S. Department of Transportation
Federal Highway Administration

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In addressing the issue of drying shrinkage cracking, admixture suppliers have introduced a new line of products known as Shrinkage Reducing Admixtures (SRA). These admixtures are designed to reduce drying shrinkage and any associated cracking. Early reports from one manufacture indicate that drying shrinkage can be reduced up to 80% at 28 days and up to 50% after one year.

This document reports on findings from a study of one SRA. An air-entrained structural concrete, intended for use in bridge decks, was used in this study. Straight cement and cement with 20 percent (by weight) fly ash along with a SRA admixture dosage ranging from 1 to 2% by weight of cement were examined.

While the admixture proved very effective in reducing shrinkage and its associated cracking, the freezing and thawing durability of the concrete was greatly reduced. This behavior prompted the admixture supplier to cease the sale of the SRA for applications subject to freezing and thawing action.

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This document reports on findings from a study of one SRA. An air-entrained structural concrete, intended for use in bridge decks, was used in this study. Straight cement and cement with 20 percent (by weight) fly ash along with a SRA admixture dosage ranging from 1 to 2% by weight of cement were examined.

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Executive Summary

s report documents a laboratory investigation of a shrinkage reducing admixture (SRA). Small scale field trials were included in this work following completion of the main body of research. The primary objectives of the study were to 1) evaluate the effectiveness of the SRA on reducing shrinkage and 2) assess the impact of the SRA on the engineering properties of both fresh and hardened concrete. This research focused on concretes used in the construction of decks for highway bridges. Engineering properties of principal interest included workability, compressive strength, compressive strength development, resistance to freezing and thawing, and shrinkage potential.

The parameters for the concrete mixtures and SRA dosages were as follows. The baseline concrete was a structural air-entrained mixture commonly used by the Arkansas State Highway and Transportation Department. One variation of this mixture used 20 percent, replacement by weight, fly ash. Dosages of the SRA ranged from 1 to 2 percent by weight of the cement. Tests were conducted to determine properties of both the fresh and hardened concrete. These included slump, air content, density, temperature, loss of slump, compressive strength and its development, freeze-thaw durability, air void system characteristics, and shrinkage potential.

The following general comments can be made based on the results of this work.

- The SRA material investigated did reduce the magnitude of shrinkage in unrestrained prism specimens.
- The SRA had little impact on most of the properties of the fresh concrete.
- For some combinations of cement, fly ash, and SRA dosage, the 28-day compressive strength of the resulting concrete was greater than that for the baseline mixture.
- The freezing and thawing durability of concretes containing an SRA is greatly reduced. The loss of durability was less dramatic with mixtures that contained fly ash.
- Petrographic analysis of hardened concrete specimens indicated that the air content of the hardened concrete was noticeably less than that recorded from tests on the fresh concrete.
- Further research is needed to determine if the "third generation" of the SRA has resolved the de-training effects.

The remainder of this report presents details regarding the research undertaken. This includes a review of current information on SRA's, a discussion of the tests and test methodologies used, results from laboratory testing, findings from a limited field study, as well as conclusions and recommendations based on this work.

1

troduction

Advancements in admixture technology have contributed greatly to the development and evolution of high performance concretes. Achieving levels of performance previous unattainable has, in many cases, become common place. Examples include mixtures with high rates of strength development, high ultimate strengths, improved workability, and greatly enhanced durability. The net result is structures which are expected to last longer and perform better than those constructed in the past.

This evolution of concrete continues with the introduction of a new chemical admixture, specifically a Shrinkage Reducing Admixture (SRA). While this admixture has only recently become commercially available, it was actually formulated several years ago (1). In simple terms, SRA's reduce shrinkage by reducing the surface tension forces acting on water found in the pores of the cement paste. Reducing the local forces in the pores lessens the overall "inward" force on the paste and in turn reduces the shrinkage of the cement paste and thus the concrete mixture. The creation of local surface tension forces is caused by the evaporation of water from the concrete. Left unchecked, this evaporation can lead to drying shrinkage and possibly drying shrinkage cracking.

Cracking, of any kind, often contributes to the premature deterioration of a structural element. Such deterioration typically adds to maintenance costs and eventually can be cause for the complete replacement of a structural element. Hence, there has been an increasing effort to identify the causes, and find ways to minimize the extent, of cracking (2,3,4). Attempts have been made to achieve a reduction in shrinkage by making changes to the water/cement ratio, water content, aggregate characteristics, and curing conditions, for example. However, these approaches have had mixed results. Further, there has been no independent analysis of the impact and effects that a rinkage reducing admixture might have on drying shrinkage or any related cracking. This report presents the dings from a comprehensive, independent, investigation of one brand of SRA.

1.1 Scope of Work

The primary objectives of this research were to 1) evaluate the effectiveness of a SRA on reducing shrinkage and 2) assess the impact of the SRA on other engineering properties of fresh and hardened concrete. The baseline (reference) mixture for this research was a structural air-entrained, Class S(AE), concrete which satisfied the Arkansas State Highway and Transportation Department (AHTD) specifications for bridge decks.

The SRA used in this study, specifically Eclipse® from WR Grace, was evaluated at three different dosage rates; 1.0%, 1.5%, and 2.0% by weight of cementitious material. These dosage rates were recommended by the manufacturer. In addition to a straight cement mixture, a mixture with 20 percent fly ash was included in this research. An air-entraining admixture, also provided by WR Grace, was used as needed to achieve the desired air content in the fresh concrete. The testing program for this projected evaluated the basic fresh concrete properties, slump loss, compressive strength, freezing and thawing durability, unrestrained shrinkage, and restrained shrinkage characteristics of the mixture combinations considered. Details regarding mixture proportions, batching procedures, and test methodologies are provided elsewhere in this report.

oblem Statement

It is not at all uncommon for a highway bridge deck to develop cracks, to some extent, at a relatively early age. In fact, the results of a survey by Krauss and Rogalla (5) suggest that early age transverse deck cracks exist in more than 100,000 bridges in the United States. Furthermore, this survey showed that thirty-one states reported that they perceived bridge deck cracking to be a problem in their state. Arkansas is not immune to the problem of premature cracking in bridge decks.

Over the past several years, the Arkansas State Highway and Transportation Department (AHTD) has been encountering problems with the unexpected early age cracking of highway bridge decks. In fact, a number of bridge decks developed visible cracks within 28 days after placement of the concrete. Since 1992, the AHTD has investigated several possible causes of this cracking. Some of the suspected causes included the presence of fly ash and broadly grouped environmental conditions. Unfortunately, the AHTD was unable to conclusively identify a factor, or factors, as the primary cause of the early cracking of the deck concrete.

From its research, the AHTD was able to identify a potential contributor to the premature cracking in bridge decks. This factor is drying shrinkage. The loss of water to evaporation causes a concrete mixture to shrink. This volume change is restrained in a bridge deck due to the presence of the structural reinforcement. The net effect of these two conditions is the cracking of the concrete. While it is believed that this mechanism produces the cracks, again it is not entirely clear what influences the degree to which the concrete shrinks, and thus the degree to which it cracks.

ew chemical admixture, known as a Shrinkage Reducing Admixture, may be one possible means to reduce ıng shrinkage and its related cracking. While the use of such an admixture does not necessarily address the root cause of shrinkage in concrete, it does present an option to minimizing crack. However, since SRA's are a new product, there is little information in the technical literature regarding the effect of this admixture on the properties and performance of bridge deck concrete.

The primary objectives of this research were to 1) evaluate the effectiveness of a SRA on reducing shrinkage and 2) assess the impact of the SRA on other engineering properties of fresh and hardened concrete. The baseline (reference) mixture for this research was a structural air-entrained, Class S(AE), concrete. The SRA used in this study was evaluated at dosage rates of 1.0%, 1.5%, and 2.0% by weight of cementitious material. The testing program for this projected evaluated the basic fresh concrete properties, slump loss, compressive strength, freezing and thawing durability, unrestrained shrinkage, and restrained shrinkage characteristics of the mixture combinations considered. Details regarding mixture proportions, batching procedures, test methodologies and the like are provided elsewhere in this report.

3

terature Review

3.1 Shrinkage Reducing Admixtures

The basic principle of a Shrinkage Reducing Admixture is to reduce the surface tension generated by pore water between the hydration solids in hardened cement paste. It is believed that if the surface tension of the water is reduced then the stress developed due to evaporation of the pore water will also be reduced. Thus, a reduction in shrinkage, and ultimately a reduction in shrinkage cracking, will take place (4). SRA's are able to decreases the surface tension of the water because their viscosity is greater than that of water (6). This principal is based on "The Capillary Tension Theory". This theory has had a significant influence on the development of SRA's. The theory was presented in a paper by Powers in 1969, and is the leading theory for explaining the mechanism of drying shrinkage in concrete (7). The theory states that when water evaporates from the capillary pores of hardened concrete, the surface tension of the pore water produces a stress on the adjacent solids. See Figure 3.1. The concrete responds to this stress by shrinking.

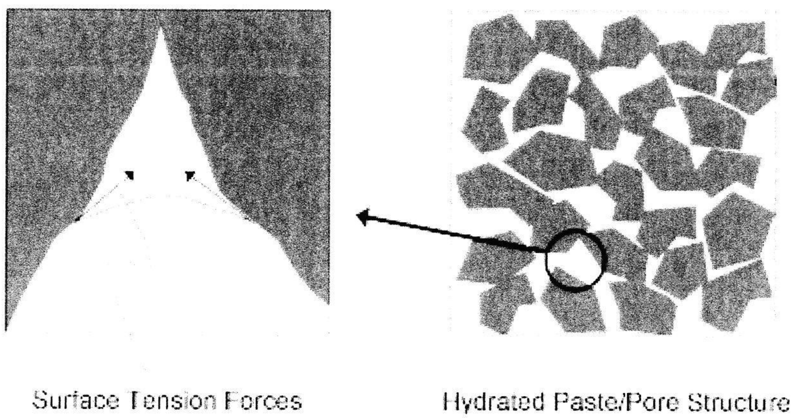

Figure 3.1: Evaporation of Pore Water

The first written report on the use of an SRA's was in 1983 by Ogawa and Tomita (5). In a partnered effort between, Nihon Cement Co., Ltd., Sanyo Chemical Industries, and Master Builders Technologies an SRA was developed under the name Tetraguard AS20. In 1985, a U.S. patent was granted for the SRA(8). Master Builders performed a product feasibility study on SRA's and concluded that the product was too expensive for the U.S. market. In 1996, Berke of W.R. Grace was granted a patent for an SRA. This SRA was developed through a joint effort between ARCO Chemical Company and W.R. Grace. Research to evaluate the effectiveness of this product was conducted at the National Science Foundation Center for Advanced Cement-Based Materials (ACBM), headquartered at Northwestern University. The research was directed by Surendra Shah.

W. R. Grace has marketed their SRA product under the name Eclipse™. Once Eclipse™ was on the market, Master Builders began to market their product under the name Tetraguard. These are currently the only two commercially available SRA's.

3.2 Shoya and Sugita

oya and Sugita conducted a study of four organic surfactant shrinkage reducing admixtures (1). The nulations for these admixtures where 1) Lower Alcohol Alkylen Oxide Adducts, 2) Lower Alcohol Alkylen Oxide Adducts, 3) Polypropylene Glycol, and 4) Glycol Ether Derivative. Tests were conducted on mixtures using the four admixtures in an effort to quantify the effect the SRA's on shrinkage, it's associated cracking, compressive strength, and the modulus of elasticity. Testing variables included the SRA formulation, the SRA dosage rate, the type of test specimen, the means for introducing the admixture, and the relative humidity maintained during testing.

Shrinkage tests were conducted on small, 1 x 1 x 16 cm, prisms of hardened cement paste. The cement paste mixture had a water/cement ratio of 0.30. Three dosage rates, 0%, 2% and 6% by weight of cement, were considered. Length change measurements began after 28 days and continued for 60 days. Weight loss was also monitored.

Cracking was evaluated using a restrained concrete specimen as depicted in the reference. The concrete used in these tests had a water/cement ratio of 0.55. The dosage rates for the SRA included 0, 3.75, and 7.5 kg/m3. An air-entraining water-reducer and a high-range water-reducer were also used in the mixture. An expansive cement was used with a topically applied SRA. Testing began 7 days after curing. Length change was measured using contact and Whittmore strain gauges. Crack width was measured with a crack gauge and contact strain gauge.

Testing showed that all four SRA's reduced shrinkage. Shrinkage reduction ranged from 40 to 60% relative to the control. The lower alcohol alkylene oxide adducts and glycol ether derivative formulations were most effective. Shrinkage reduction was most pronounced when the relative humidity was between 20 and 45%. Shrinkage tended to increase with lower relative humidity.

ts further showed that the lower alcohol alkylene oxide adducts and polypropylene glycol formulations caused a slight reduction in compressive strength and modulus of elasticity at 7 days of age. Some improvement occurred by 28 days. The strength and modulus values for the glycol ether derivative mixture were found higher than the control. It was determined that these higher values were due to the fact that the SRA dissipated the air content in the concrete. Time to cracking was found proportional to the dosage rate of the SRA.

3.3 Fujiwara, Tomita, and Shimoyama

Fujiwara, et. al, conducted tests using two different SRA's. Both of the SRA's were a lower alcohol alkylene oxide adducts but each had different viscosities and molecular weights (9). The two SRA's will be designated "A" and "B" for this discussion. Product A has a lower viscosity than B, while B's molecular weight is about twice that of A. An air-entraining agent was used along with product A, and an air-entraining and water reducing agent was used with product B.

The main focus of this work was to determine the effects of SRAs on the frost resistance of concrete. Both SRAs were evaluated under freezing and thawing conditions for air contents ranging between 2.0% and 8.0%. The air-void system was also examined. This series of testing is referred to as Test Series I. The next series of tests, identified as Test Series II, examined other factors influencing durability such as the degree of saturation, viscosity of capillary water, and compressive strength. This series of tests considered product B only, and no other admixtures were used. Lastly, an eight year in place durability study was performed. This series was identified as Test Series III. Each series of tests included different dosages of the SRAs.

Freezing and thawing test were conducted using 1 x 1 x 4 cm prisms and followed ASTM C 666 Procedure A. The prisms were allowed to cure in water for 28 days before testing. Freeze-thaw testing indicated that product A erformed well when the air content was above 5.0%. However, product B did not perform well, even when the air tent was above 5.0%. Petrographic analysis was performed on some of the test specimens. It was found that even when the mixtures had an adequate spacing factors, 0.1-0.3 mm, mixtures which used product B still performed poorly.

The degree of saturation test was conducted by altering the method of curing. All of the specimens were cured for 14 days in water. After 14 days, half of the specimens were then cured at 20 °C and a relative humidity of 60 percent, and the other specimens continued to cure in water for an additional 7 days. The specimens that were cured at 20 °C had a degree of saturation less than the critical saturation, indicating that pressure in the capillary water should not be generated during the first freeze-thaw cycles. It was found that concretes which had a degree of saturation of 1.0 deteriorated very rapidly.

It was concluded that one possible explanation for the early deterioration was due to the SRA's having a higher viscosity than water. The higher viscosity of the SRA would actually produce a greater capillary pressure especially below 0 °C, and thus causing a durability problem.

Compressive strength testing showed that this strength decreased slightly with an increase in dosage of product B. In this test series, product B was used without other admixtures. Product B had some air-entraining ability which increased the air content on the order of 1.7 percentage points.

In Test Series III, in-place concrete underwent approximately 90 cycles of freezing and thawing per year for eight years. The concrete has shown no signs of deterioration. It is believed that this is due to the fact that the moisture condition and freezing rate is much lower than that of the specimens subjected to the ASTM freezing and thawing (9).

3.4 Shah, Marikunte, Yang, and Aldea

ah, et. al, performed research on an SRA having a propylene glycol derivative formulation (10). Dosage rates of and 2.0% by weight of cement were investigated. When an SRA was used, an equal amount of water was removed from the mixture. The scope of testing included restrained shrinkage, free shrinkage, weight loss, compressive strength, and fracture toughness. Mixtures proportions were 1 part cement: 2 parts sand: and 2 parts coarse aggregate. A water to cement ratio of 0.5 was used.

Restrained shrinkage was evaluated using a ring type specimen. The inner steel restraining ring had a diameter of 254 mm and a wall thickness of 25.5 mm. The concrete specimen had a height of 140 mm and an outside diameter of 375 mm. The free shrinkage specimens were 400 mm in length and 100 mm^2 in cross section. Fracture toughness specimens had dimensions of 225 mm x 25 mm x 50 mm. Compressive strength specimens were 75 mm x 150 mm. All test specimens were removed from their molds after 24 hours and cured at 30 °C and a relative humidity of 40 percent.

Free shrinkage was performed according to ASTM C157. Weight loss measurements were also performed on the free shrinkage specimens. A microscope was used to measure crack width of the restrained shrinkage specimens. Compression testing was performed to record not only peak stress but also to record post peak values. Fracture testing was performed according to International Union of Testing and Research Laboratories for Materials and Structures (RILEM) specifications.

Slump values ranged between 228 to 242 mm. The SRA did not have any influence on the slump. Compressive strength was very similar at 7 days, but specimens that contained SRA actually had about a 10 percent strength gain over the control specimens at 28 days.

sults from fracture testing found that plain, and SRA, concrete had very similar modulus of elasticity values. Concrete containing 1.0% SRA always had a higher value of critical crack tip opening displacement than plain concrete. Concrete containing 2.0% SRA had very similar critical crack tip opening displacements at 7 days but the values were lower at 28 days. These values are important to how resistant a concrete is to cracking. If the values of critical crack tip opening displacements are higher and the values from modulus of elasticity are lower, then the concrete will be more ductile and will not crack as soon.

Free shrinkage at 50 days was reduced by 32% and 45% for SRA dosages of 1.0% and 2.0%, respectively. Also a reduction in weight loss of 12% and 25% was observed for concrete containing 1.0% and 2.0% SRA, respectively.

The results from restrained cracking test found that plain concrete cracked between 10 and 14 days. Concrete containing 1.0% SRA cracked between 10 and 15 days, but only two of three specimens containing 2.0% SRA cracked, and this was at 48 days of a 50 day test (10).

3.5 Berke, Dallaire, Hicks, and Kerkar

Berke, et al, has conducted extensive laboratory and field research on SRA products (11). The SRA in the Berke report is a glycol ether blend. One objective of this study was to determine the impact of curing on length change for SRA and non-SRA concrete mixtures. The study also evaluated a large-scale field trial containing SRA concrete mixtures. Additionally, the authors proposed and tested the theory that the SRA dosage should be ecified as a percent by mass of water. The dosage of SRA is typically specified as a percent by mass of cement. authors felt that a constant dosage rate by weight of water would produce results that are more predictable. The idea was that the SRA works to reduce the surface tension of the water and does not impact the cement. The scope of testing included fresh properties, compressive strength, unrestrained length change, and corrosion and chloride analysis. The testing and mixing procedures followed ACI and ASTM guidelines.

Concrete was mixed according to ASTM C192. One minute after all water reducing admixtures were introduced, the SRA was added. When the SRA was added, an equal volume of water was removed from the concrete mixture. A minimum of two 102 mm x 203 mm compressive strength specimens were cast for each age to be tested. Generally, compressive strengths were tested at 1, 7, 14, and 28 days.

The curing study evaluated concrete mixtures with water to cement ratios ranging from 0.35 to 0.5. The cement content was kept constant while the water content was varied. The design air content was 6.0%. The SRA was evaluated at dosage rates of 0, 1, and 2.0% by mass of cement.

Except for the curing process, the free shrinkage prisms were tested according to ASTM C157. ASTM C157 calls for a 28 day wet cure. The authors elected to cure the specimens as much as 14 days in the molds to reflect actual field conditions. After curing in the molds for the specified time, the specimens were stripped and standard wet curing was continued until the specimens reached an age of 28 days. After 28 days, the specimens were then placed in a controlled environment at 22.8 °C and a relative humidity of 50 percent. Measurements of free shrinkage were taken out to 180 days after the specimens were molded.

It was found that the reduction in shrinkage increased with lower water to cement ratio mixtures. This was explained by the fact that the cement was kept constant and the water content was lowered. Thus, the concentration of SRA, relative to the water content, was higher with low water to cement ratios. This led to the next series of testing.

The next study evaluated a constant SRA percent by mass of mixture water. Water to cement ratios ranged from 0.31 to 0.53. The design air content was 2.0%. Dosage rates of 0 and 5.0% of SRA by mass of water were used. It was determined that dosing the SRA by percent mass of water is appropriate over a wider range of mixture designs. This is because the SRA is acting the water and is not related to the cement content. Long-term shrinkage reduction was on the order of 40%.

Test results indicated that the SRA reduced both field and laboratory shrinkage. It was found that drying shrinkage was significantly reduced with an increase in wet curing time. The effectiveness of the SRA tended to increase with an increase in the dosage relative to water content. The authors felt the best method for characterizing the performance of the SRA is by expressing dosage as a percent SRA by mass of water, since the SRA is acting on the water. The SRA was also found to be non-corrosive (11).

3.6 Summary

The previous research efforts indicate that when using an SRA there tends to be no significant change in slump. Research does show that some loss of air content in the fresh concrete may take place. Depending on the SRA, compressive strength may be increased or decreased on the order of 10 to 15%. Most SRA's reported on will reduce free shrinkage about 40 to 50%. The time to cracking in restrained shrinkage testing was improved when an SRA was used, especially at dosage rate of 2.0% by weight of cement. Shrinkage reduction of unrestrained length change specimens and time to cracking of restrained specimens have both been shown to be proportional to the dosage rate of SRA. Freezing and thawing testing has produced mixed results. Some SRA's performed well under freezing and thawing test, while others performed rather poorly. It has been determined that the curing process had a significant impact on this durability. If the specimens were allowed to air cure for several days before freeze and thaw testing began, the durability was improved. Field concrete containing SRA has shown no signs of deterioration under normal freezing and thawing conditions.

4

search Approach

As noted earlier, this research examined the impact of a commercially available shrinkage reducing admixture on the properties of a structural air-entrained concrete. An extensive experimental test program was devised in order to conduct this examination. Although the research was conducted in a laboratory environment, every effort was made to mimic actual field production practices. For example, the concretes tested were adapted from AHTD approved mixtures, constituent materials were obtained locally, and aggregates were kept outdoors. Further, local ready-mix concrete producers were consulted for advice relative to batching and mixing procedures.

For this research, over 130 batches of concrete were produced. Of this total, approximately 50 batches were produced in an effort to refine the proportions of the various mixtures. The remaining 80 plus batches were used to prepare specimens for the formal testing program. Testing included determining the fresh properties, slump loss, compressive strength, unrestrained length change, restrained shrinkage, and freeze-thaw durability. A few tests to evaluate the loss of entrained air were also conducted. The following sections detail the materials used, mixture proportions, production process, and testing procedures.

4.1 Proportioning Criteria

The mixtures used for this research were proportioned based on AHTD Standard Specifications for Class S(AE), or Structural Air-Entrained, concrete. The AHTD specifications specifically call for (12),

- a minimum cement content of 611 lb./yd^3 (362 kg/m^3)(6.5 Bags/cu.yd)
- a maximum water to cement ratio of 0.44
- The water to cement ratio and minimum cement content correspond to a water content of 270 lb./yd^3 (159 kg/m3)
- use of Type I Portland cement
- Fly ash, Class C or F, may be used as a partial replacement for cement. Replacement may not exceed 20% by weight of cement
- the coarse aggregate to consist of crushed stone, or gravel, with 100% passing the 1-1/4 in. (32 mm) sieve
- a minimum compressive strength of 4000 psi (28.0 MPa)
- slump in the range of 1 to 4 in. (25 to 100 mm)
- an air content in the range of 4 to 8%

4.2 Mixture Proportions

o control mixtures were established for this research. The first mixture, which is designated throughout this rt by the symbol "Cntl", used cement only in the binder. The second control mixture, designated "Cntl-FA", used fly ash as a partial replacement for the cement. Fly ash was used at the maximum amount permitted, or 20% by weight of cement. The proportions for the two control mixtures were derived from mixtures that had previously been approved by the AHTD. The target values for slump and air content were set at 3 in (76 mm), and 6.0%, respectively. These values were selected because they were thought to be typical of that found in field construction. The proportions for the mixtures obtained from the AHTD were adjusted for the characteristics of locally available materials. They were further refined through laboratory testing to obtain proper yield and meet the target values for slump, air content, and compressive strength. Table 4-1 gives the final proportions for the two control mixtures.

The addition of the shrinkage reducing admixture to the control mixtures resulted in one minor alternation to the basic proportions. For each gallon of SRA used in a cubic yard of concrete a gallon of water was removed from the batch. This was done according to the recommendation of the admixture producer (13). Three dosage rates for the SRA were considered in this research, 1.0%, 1.5%, and 2.0% by weight of cementious materials. These are manufacturer recommended dosage rates. Refer to Appendix A for example calculations for converting the SRA dosage rates to lbs, gal, oz, and mL per cubic yard. Mixtures that contain the SRA are designated by adding the symbol "-SR" to those identifiers defined earlier. The batch quantities for the SRA mixtures are the same as their controls, except for the water content. For example, with the 1.5% SRA mixture the water content became 335 lb (152 kg.) rather than 348 lb. (158 kg) for the control. For the cement and fly ash mixture the water content became 300 lb. (136kg) as opposed to 315 lb. (143kg) for the control. Although the SRA contains no water, the admixture will contribute to the overall porosity of the concrete in the same fashion that an equal volume of water would (13).

Table 4-1: Proportions for Control Mixtures

	Weight (kg/m^3)	
Material	Control (Cntl)	Control w/ Fly Ash (Cntl-FA)
Water	158	143
Cement	364	291
Fly Ash	0	73.0
Coarse Aggregate	1,101	1,101
Fine Aggregate	729	661
Air-entrainment (ml)	217	271

1 kg/m3 = 1.68 lb./yd^3
1 ml = 0.0338 oz

4.2 Materials

As much as possible, the materials used in this study were obtained locally. Ash Grove Type I cement, purchased at cal hardware store, was used. Although obtained as bagged cement, this is the same material provided to local ready-mix producers in bulk. Fly Ash Products in Pine Bluff, AR supplied a Class C fly ash. The coarse aggregate was crushed limestone obtained from McClinton-Anchor's quarry in West Fork, AR. The fine aggregate, provided by Arkohla Sand and Gravel, was Arkansas River sand. Daravair 1000TM and EclipseTM, both WR Grace Company products, were used for the air-entrainer and shrinkage reducing admixture, respectively. W.R. Grace's Darex 2TM air-entrainer, Lonestar bulk cement, and Blue Circle bulk cement were also used in the research.

4.3 Mixture Procedures

A fairly routine procedure was used to produce a batch of concrete for testing. Guidance was received from W.R. Grace regarding the addition and mixing of the SRA. Batch size varied according to the amount of concrete required for a specific test series. For example, batches on the order of 3.0 ft^3 (0.084 m^3) were produced when shrinkage beams and ring specimens were molded.

Generally, the aggregates used for mixing were kept outdoors. A wheelbarrow of coarse and fine aggregate was obtained from the storage bins and then moved into the lab. Next, the aggregates were thoroughly mixed in their wheelbarrows in an effort to achieve a uniform moisture content. The aggregates were then covered with plastic to prevent moisture loss. The aggregate moisture content was determined just prior to batching a mix. A small sample of material, about 1,500 grams, was obtained and placed in a 9-inch by 9-inch (229 mm by 229 mm) microwavable dish. The weight of the empty dish was previously obtained and recorded. The samples were then weighed and placed in a microwave oven for intervals of no more than 10 minutes. After 10 minutes, the specimens e removed from the microwave and stirred with a metal spoon. A small brush was used to clean the spoon to ensure that no material was lost. The aggregates were then returned to the microwave for 10 minute intervals, stirred between each interval, until the aggregates were dry. It was found that, under normal conditions, 25 minutes of drying was sufficient to completely dry the aggregate. The dry weight was then recorded. At this point, the moisture content was computed using Equation 1.

$$Moisture\ Content(\%) = \frac{\text{Wet wt.} - \text{Dry wt.}}{\text{Dry wt.} - \text{Empty Pan wt.}} * 100 \qquad \text{Equation 1}$$

The moisture content values for the aggregates were used to adjust the batch quantities. It was found that accurate moisture contents were critical to obtaining consistent fresh concrete properties.

During the summer months, when outside temperatures became very high, >90° F (>32° C), the aggregates were moved indoors for several days prior to mixing to allow them to cool. It was discovered that during the summer the high temperature of the aggregates lead to a high concrete temperature. This in turn appeared to cause a decrease in the air content of the concrete. This problem will be discussed more later.

Mixing was accomplished with a 6.0 ft^3 (0.17 m^3) rotating-drum mixer. The mixer rotates at about 1 revolution every 2.25 to 2.5 seconds. In preparation for mixing, the drum was "buttered" with water. This was accomplished by putting the drum in a mixing position and adding about 5 gallons of water. With the water in the drum, the mixer was then turned on and tilted toward a discharge position. This insured that all surfaces in the mixer were ted. The water was then discharged from the drum and allowed to drip several minutes to produce something like a saturated surface dry condition for the inside surface of the mixing drum. Then, half of the coarse and fine aggregates were added to the mixer. A solution of half the water and all of the air-entrainer followed. Next, half of the cementitious materials were added. Subsequently, the remaining water, coarse aggregate, fine aggregate, and cementitious materials were added, in that order, and mixed for 5 minutes, or about 120 revolutions of the mixer. When called for, the SRA was added at this point. To add the SRA, the mixing drum was tilted to an agitation angle, and the SRA was poured from a beaker. The SRA was allowed to drip from the beaker for about 15 seconds. e mixing drum was then tilted down to a mixing angle. All ingredients were then mixed for an additional 2 minutes, or 50 revolutions of the drum. Finally, the mixture was discharged from the drum and test specimens were prepared.

Subsection 802.08 of the AHTD Standard Specifications (12) states that concrete shall be mixed "Not less than 70 nor more than 100 revolutions of the drum or blades at the rate of rotation specified by the manufacturer as the mixing speed". W.R. Grace suggested that the concrete, less the SRA, be mixed 70 to 80 revolutions. The SRA should then be added and mixed for an additional 30 to 50 revolutions. This would violate current AHTD specifications. The procedure used in this research was to mix all ingredients, less the SRA, for 120 revolutions followed by 50 revolutions with the SRA. Thus, with this mixing process a total of 170 revolutions occurred at mixing speed. Although this is out of the specified limits, it was deemed acceptable since there is no other agitation of the concrete such as the agitation speed of the drum or hauling of the concrete.

4.4 Testing Procedures

A rigorous experimental testing program was conducted in order to evaluate the impact of the SRA on the engineering properties and performance characteristics of a structural concrete. Tests were conducted on both the fresh and hardened concrete. Fresh concrete tests included slump, slump loss, air content by the pressure method, unit weight, temperature, and a few test on air loss. Hardened concrete tests include compressive strength, unrestrained shrinkage, restrained shrinkage, and freezing and thawing durability. For the most part, tests were conducted according to their appropriate ASTM standard. One exception was the restrained shrinkage test, for which there is no ASTM standard. Here, a procedure based on that described in NCHRP Report 380 (5) was used. ographic analyses were conducted, by two outside organizations, on the control specimens from the freeze-thaw testing.

4.4.1 Fresh Properties

Fresh concrete properties; slump, air content, temperature, and density, were determined for every batch of concrete produced for the test program. All of these tests were performed by American Concrete Institute (ACI) certified Concrete Field Testing Technicians.

4.4.2 Slump Loss

The loss of slump with time was investigated to determine if the SRA has any retarding side effects. Once the normal mixing procedure was completed the concrete was discharged into a wheelbarrow and tests were run to determine initial fresh properties. Three 4 x 8 in. (102 x 204 mm) cylinders were also cast to verify compressive strength. One cylinder was tested at 7 days and the remaining two tested at 28 days. The time at which the last ingredient was added to the mixer was recorded as "time zero". After all initial tests were completed, the remaining concrete was returned to the mixer along with the concrete used for the slump test. The time when the concrete was reintroduced to the mixer was recorded. Slump was then measured at 15 minute intervals from the time the concrete was reintroduced to the mixer. A quantity of concrete sufficient to conduct two slump tests was discharged from the mixer. The slump was measured by two technicians. While a slump test was being conducted, the angle of the mixing drum was altered in order to mimic the agitation action of a ready-mixed concrete truck. Once the test was completed the concrete was returned to the drum and the material was recombined at mixing speed for ut 2 minutes. The mixer was again placed in agitation mode until it was time for the next test, or roughly 13 minutes. This process was continued until the measured slump was about one inch. A total of 20 batches were produced with the Cntl., Cntl.-FA, Cntl.-1.5%SR, and Cntl.-FA-1.5%SR each replicated three times. Two replications were produced for the Cntl-SR(1.0%), Cntl-SR(2.0%), Cntl-FA-SR(1.0%), and Cntl-FA-SR(2.0%) mixtures.

4.4.3 Air Loss

Three batches of the Cntl and Cntl-SR(1.5%) mixtures were produced to study the change in air content over time. After discharge from the mixer, the standard fresh property tests were performed and three 4 x 8 in. (102 x 204 mm) compression test cylinders were molded. Subsequently, air content tests were conducted every 3 to 5 minutes until all the concrete had been used. Throughout this test, every effort was made to minimize any disturbance of the remaining portion of the batch. Two technicians conducted a total of seven air content tests on a batch of concrete. Batch size for this test was 2.5 ft^3.

4.4.4 Compressive Strength

Compressive strength was determined using 4 x 8 in. (102 x 204 mm) cylinders. Cylinders were cast using single use plastic molds. Standard curing, as defined in ASTM C31(14), was followed and achieved by using a water tank and heater. Specimens were tested, using 0.5 in (12 mm) thick unbonded neoprene end caps with a durometer reading of 65 ± 5, in a Forney 400 K compression test machine.

Nine cylinders were molded for each batch of concrete produced. Three cylinders were tested at 7, 28, and 56 days of age. Thus, the batch size for this series was 2.0 ft^3 (0.056 m^3).

Three replicate batches were produced for each of the Cntl, Cntl-FA, Cntl-SR(1.5%), and Cntl-FA-SR(1.5%) mixtures. Two replications were produced for the Cntl-SR(1.0%), Cntl-SR(2.0%), Cntl-FA-SR(1.0%), and Cntl-FA-SR(2.0%) mixtures.

4.4.5 Freeze and Thawing

Testing was performed in accordance with ASTM C 666, Procedure A. Six 3 x 3 x 16 in. (76 x 76 x 406 mm) freeze-thaw specimens and three 4 x 8 in. (102 x 204 mm) compression cylinders were cast, and the fresh properties measured, from a 2.0 ft^3 (0.056 m^3) batch of concrete. Five of the freeze-thaw specimens were placed in the test chamber while the sixth was used as a control. After 14 days of curing in a water tank at 73° F (23° C), the test specimens were weighed, tested for their initial fundamental transverse frequency, and then placed in the test chamber. The control specimen was tested for initial fundamental transverse frequency and placed in a water bath located inside a refrigerator. The water temperature was held at 40° F (4.4° C). One compression cylinder was tested at 7 days with the remaining two tested at 28 days.

A beam located in the center of the freeze/thaw chamber had two temperature probes placed in its ends along with two thermocouples. One of the probes controlled the temperature recording device. The other probe regulated when the chamber would switch from a freeze cycle to a thawing cycle. The thermocouples were used to verify that the temperature recorders were correctly calibrated. The temperature range during testing was 0°±3° F to 40°±3° F (–17.8°±1.7° C to 4.4°±1.7° C). The freeze/thaw chamber would typically complete 6 to 7 cycles per day. At intervals not exceeding 36 freezing and thawing cycles, and when in the thawed condition, the specimens were removed from the test chamber. At the same time the control was removed from its environment. First, a specimen was patted dry with a cotton towel to produce a saturated surface dry condition. The specimen was then weighed, and the weight was recorded. The specimen was then tested for its' fundamental transverse frequency.

Fundamental transverse frequency was determined, according to ASTM C 215, with an impact resonance device. The specimen was positioned on rubber pad supports, located 8.83 in (224 mm) on center. These are attached to a rigid base as shown in Figure 4.1. The pad supports were cut from 0.5 in (12 mm) thick neoprene pads that had been used for unbonded caps in compressive strength testing. A small piezometric accelerometer, weighing 0.133 oz., is held tightly against the specimen at one end. The accelerometer has an operating range of 10 to 10,000 Hz, a self-resonant frequency of 100 kHz, and a voltage sensitivity in excess of 10mV/g. Amplitude deviation was within a 3 percent range. The specimen was struck at mid-height near its' mid-length with a ball peen hammer. The hammer weight was approximately 1.3 lbs (590 g).

accelerometer was connected to a power unit, which supplied a digitized output signal to a personal computer. A software program, developed at North Carolina State University, which utilizes Lab Windows Version 2.0, was used to control and perform the data analysis. The program was written so that acquisition of the output from the accelerometer would be self-initiating. The sampling rate was 50kHz with 2,048 sample points collected. The program transformed the data to time-base values, and conducted a fast Fourier transform (FFT) on the first 1024 data points. The program examined the FFT output and selected the frequency with the largest amplitude as the fundamental or resonant frequency.

The output from the accelerometer is then processed by a data acquisition system with the fundamental transverse frequency being determined automatically. The frequencies were then recorded. The operator then input the frequencies into a spreadsheet to determine the dynamic modulus of elasticity of the specimen per equations in ASTM C 215. Refer to Equation 2 below, along with its explanation of the variables.

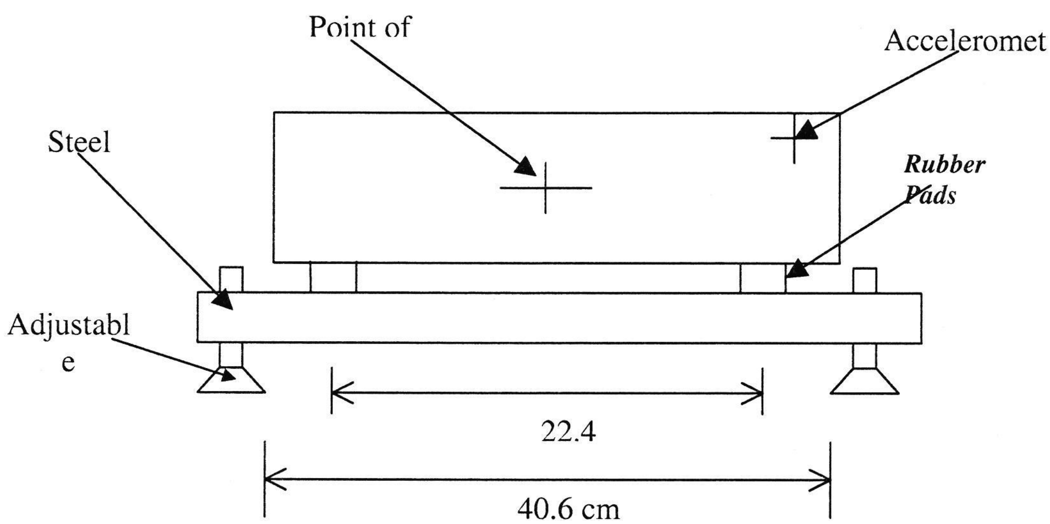

Figure 4.1: Freeze/Thaw Testing Setup

$$\text{Dynamic } E = CWn^2 \qquad \text{Equation 2}$$

n = fundamental transverse frequency, Hz

W = weight of specimen, lb.

C = 0.00245 $[(L^3T)/(bh^3)]$ = 0.015276

L = length of specimen, in.

= dimensions of cross section of prism, in., t being in the direction in which it is driven.

– a correction factor which depends on the ratio of the radius of gyration to the length of the specimen which is obtained from the ASTM standards.

For This research: L= 16 in (406 mm), t = 3 in (76 mm), b = 3 in (76 mm), T = 1.233

Each specimen was struck a minimum of three times, more if necessary, to ensure replication of the frequency and dynamic modulus values. Specimens were then returned to the chamber and positioned in a new location to minimize any effects from localized irregularities in heating or freezing. Testing continued for 300 cycles or until the relative dynamic modulus, or durability factor, fell below 60%, which ever occurred first.

Due to the time necessary to complete a freeze-thaw test, only one replication was conducted for the Cntl, Cntl/SR 2.0%, Cntl-FA, and Cntl-FA-SR(1.5%) mixtures. Three replications of the Cntl-SR(1.5%) mixture were completed.

Due to the results from the freeze-thaw, and on the recommendation of the SRA manufacturer, this test program was expanded to consider: 1) variations in the mixing process, 2) another air-entraining admixture formulation, and 3) other brands of cement. It was felt that this additional testing would provide a more thorough picture of the impact that an SRA might have on freeze-thaw durability and help to determine the cause of some freeze-thaw failures.

4.4.6 Scaling

A purely visual evaluation was used to determine the severity of scaling of four sets of specimens that had undergone 300 cycles of freezing and thawing. A rating system, similar to that found in ASTM C672, was used and is shown in 2. Accessing scaling was done in conjunction with representatives from W.R. Grace. Although there are no written reports of scaling problems associated with SRA's, the representatives from W.R. Grace seemed particularly interested in the scaling damage of the freeze/thaw beams. The examination of surface scaling was initiated by the W.R. Grace representatives.

Table 4-2: Rating for Scaling Severity

Rating Used	Condition of Surface	ASTM C 672
0-1	No scaling	0
2-3	Very slight scaling (3.2 mm (1/8 in) depth, max, no coarse aggregate. visible)	1
4-5	Slight to moderate scaling	2
6-7	Moderate scaling (some coarse aggregate visible)	3
8-9	Moderate to severe scaling	4
10	Severe scaling (coarse aggregate visible over entire surface.)	5

4.4.7 Petrographic Analysis

nce freeze and thaw durability testing was completed for a series, the control beams were cut into four equal tions as seen in Figure 4.2. The sections were then sent to both W.R. Grace and the AHTD for petrographic analysis. The AHTD received sections 2 & 3, while W.R. Grace received sections 1 & 4. This approach would allow for verification of the test results.

Petrographic analysis was performed and the values of air content, void frequency, specific surface, spacing factor, and paste-air ratio were reported as according to ASTM C457.

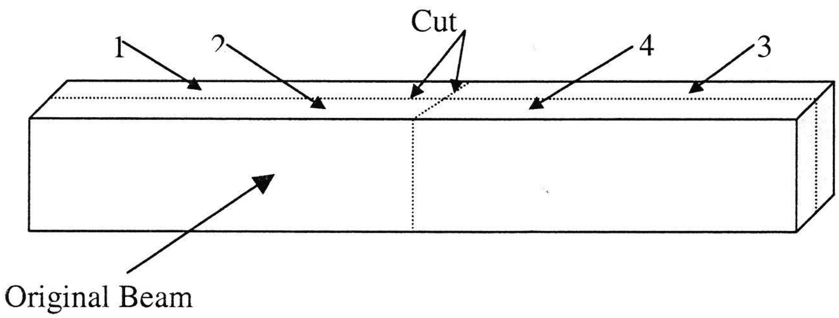

Figure 4.2: Freeze Thaw Specimen

4.4.8 Unrestrained Shrinkage Test (Shrinkage Beams)

estrained shrinkage beams were molded and tested, for the most part, according to ASTM C 490 and C 157. ı ne beams were 4 x 4 x 11.25 in. (102 x 102 x 286 mm) in size and had a gage length, or distance between the inside faces of the gage studs, of 10 in. (254 mm). The beams were cast in two layers. Each layer was rodded approximately 1 time per square inch of top surface area and the mold tapped with a rubber mallet approximately 15 times. It was important to ensure that enough material was properly placed around the gage studs, with as few air voids as possible, to create a good bond. The beams were then struck off with a magnesium concrete float. After casting, the beams were covered with a plastic sheet and stored in the laboratory at ambient temperature for 24 hours. After 24 hours the beams were removed from their molds and transported from the Engineering Research Center to an environmental chamber located at Bell Engineering Center. The beams were then allowed to acclimate, for about 1 hour, to the chamber's temperature of 73° F (23° C) and relative humidity of 50%. A comparator, which was stored in the environmental chamber, was used to measure any changes in specimen length. Readings for the beams were taken at 1, 3, 7, 14, 21, 28, 42, and 56 days. Thereafter, readings were taken approximately one or two times a month and are continuing indefinitely.

Three shrinkage beams and three 4 x 8 in. (102 x 204 mm) compression cylinders were molded, from a batch of concrete. The typical batch size was 3.0 ft^3 (0.085 m^3) when restrained shrinkage specimens were also molded and 1.5 ft^3 (0.042 m^3) when only unrestrained shrinkage specimens were molded. The cylinders were cast to verify compressive strength, with one cylinder being tested at 7 days and the remaining two tested at 28 days.

4.4.9 Restrained Shrinkage Test (Shrinkage Rings)

ıtrained shrinkage was evaluated by a test that is based on a procedure described in NCHRP Report 380 (5). ..wever, the equipment and procedures used in this research vary slightly from that employed in the NCHRP study. The mold for the rings is shown in Figure 4.3. To conduct this test, a 70 mm (2.75 in.) thick concrete ring was cast around an inner circular form. A section of 305 mm (12 in.) heavy wall PVC gravity sewer pipe, PSM SDR26 and meeting ASTM D3034, was used as the interior form in this research.

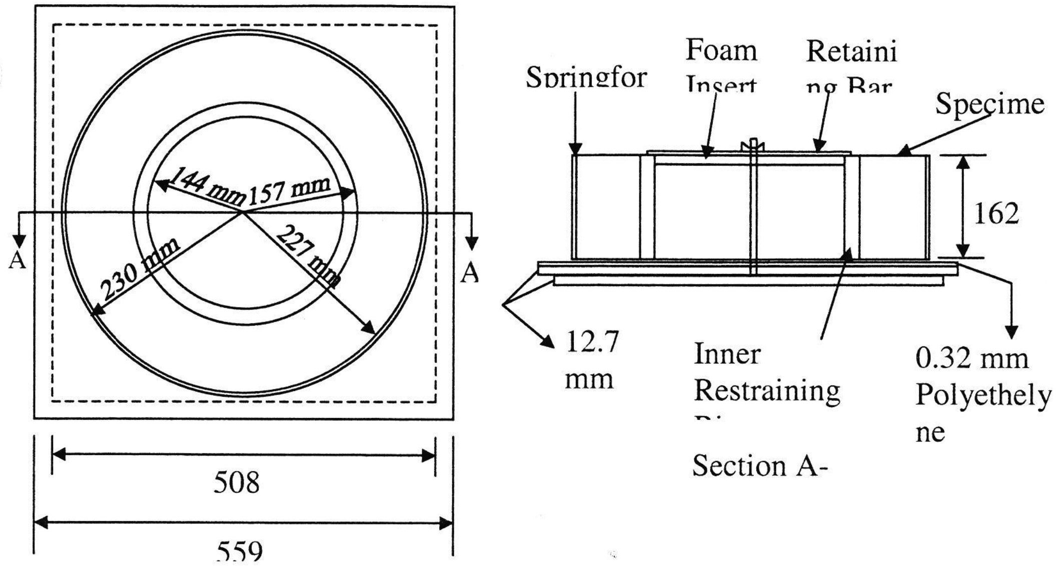

Figure 4.3 Shrinkage Ring Setup

This pipe has an outside diameter of 318 mm (12.5 in.) and a wall thickness of 12.5 mm (0.5 in.). This material was chosen over the more commonly used steel form for a number of reasons, two of which are discussed here. First, PVC has a linear stress-strain relationship. It was felt that this characteristic would be of value in the data lysis process. Second, PVC has a relatively small modulus of elasticity which means that it will provide less restraint as compared to a steel form. Consequently, the concrete specimen would be less likely to crack. In turn, this means that a test can run for a longer period of time, thus providing the benefit of more information on the early age performance of a concrete mixture. A reusable fiberglass "spring" column form, having a wall thickness of 6.4 mm (0.25 in.), was used for the outer form. The height of a test specimen was 162 mm (6.5 in.). The ring specimen was cast on a flat wooden base that was covered by a 3.2 mm (0.125 in.) thick polyethylene sheet.

Two foil type 1/4 bridge strain gages with a 1.2 in. (30.5 mm) gage length are attached to the inside face of the interior form. The gages are positioned 180° from each other. The strain gages are used to indirectly monitor shrinkage. As the concrete shrinks it compresses the interior PVC form and generates strain in the form. This strain is an indicator of the amount of shrinkage taking place in the concrete. Higher strain suggests greater shrinkage. An automated data acquisition system was devised to record the strain in the PVC forms. The system actually records a voltage that later can be converted to microstrain. At this time, the conversion factor has not been determined. Therefore, results will be presented in terms of volts. Voltage readings are automatically taken every 60 minutes.

If the strain in the concrete exceeds its' tensile capacity the concrete cracks and the test is terminated. If the concrete does not crack, termination is based on the number of days the test has been running. Specimens are typically monitored for between 30 and 50 days.

Shrinkage rings were cast from the same batch of concrete as the unrestrained beams. Therefore, three replications of the Cntl and Cntl-SR(1.5%) and 1 replication of the Cntl-FA and Cntl-FA-SR(1.5%) mixtures have been luced. Three rings were molded from each batch of concrete. Therefore, a batch size of 3.0 ft^3 (0.085 m^3) is necessary to mold the requisite beam, ring, and cylinder specimens. Curing and storage of the rings follows the same procedure used for the beams. First, the rings are covered with a plastic sheet and stored in the laboratory for 24 hours. They are then moved to the environmental chamber where they are exposed to a temperature of 73° F (23° C) and a relative humidity of 50% for the duration of the test. The outer form, retaining bar, and foam insert are all removed from the specimen. The specimen is then broken free from the base. This is to minimize the restraint due to friction between the concrete and base. The strain gages that are located on the inner ring are then visually checked for any damage. The strain gauges are then connected to the computer for monitoring. Three cimens from each of two different mixtures are tested at one time.

5

ta Analysis and Results

Presented herein is a summary of the results gathered from the extensive laboratory testing program conducted for this research. Unless otherwise noted, the data presented in the tables and figures represents average values computed using all of the data collected for a specific test.

5.1 Fresh Properties

Average fresh property results for all batches of the Cntl., Cntl./SR-1.5%, Cntl./FA, and Cntl./FA/SR-1.5% mixtures can be found in Table 5-1. Overall, it can be seen from Table 5-1 that the addition of the SRA produced a slight increase, in the initial slump, a decrease in the average air content, and little change in the density of a mixture. The average 28-day compressive strength decreased slightly with the Cntl mixtures but noticeably increased with the Cntl/FA mixture when the SRA was present.

Table 5-1. Average Fresh Property

Mixture	Slump (in.)	Air Content (%)	Unit Weight (pcf)	28 day Strength (psi)
Cntl.	3.00	6.1	145	6416
Cntl./SR-1.5%	3.50	5.7	146	6366
Cntl./FA	3.50	6.8	144	5869
Cntl./FA/SR-1.5%	3.70	5.4	146	6942

Slump values are round to the nearest 0.25 inch

Table 5-2. Range of Fresh Property

Mixture	Slump Range (in.)	Air Content Range (%)
Cntl.	2.25 to 4.00	5.2 to 7.8
Cntl./SR-1.5%	2.50 to 4.50	4.1 to 7.2
Cntl./FA	2.75 to 4.00	5.5 to 9.0
Cntl./FA/SR-1.5%	2.25 to 4.50	4.0 to 7.8

Slump values are round to the nearest 0.25 inch

Table 5-2 lists the range in measured slump for the base mixtures. Given that the aggregates were stockpiled outdoors and that batching and mixing was comparable to a ready-mix operation, the slump ranges are no greater than that which might be expected from natural variability. For the base mixtures listed in Table 5-2, the measured ıps fell within a range of 3.50 ± 1.00 in., and for all mixtures tested in this research the range was 3.50 ± 1.50 This suggests that there was good control over the mixing process. Several batches had measured slumps from 4.00 to 4.50 in., but only one batch had a value greater than 4.50 in., and it was 4.75 in. The maximum slump allowed by AHTD specifications is 4.00 inches. Even though some slump values fell outside this limit, it is felt that all slumps were consistent with normal construction practices. The SRA mixtures did tend to have a slightly larger range of slump. This is most likely due to the SRA dissipating some of the entrained air, which may have caused the slump to be more variable.

content of the fresh concrete was generally reduced with the addition of the SRA. On average, the difference in fresh air content between the Cntl. and Cntl./SR-1.5% mixtures was 0.4 percentage points. This difference was 1.4 percentage points for the fly ash mixtures. Moreover, the SRA mixtures tended to have more variability in air content when compared to the control mixtures. The effect the SRA had on air content made determining the proper dosage of AEA very difficult.

Three air contents were greater than the 8.0% maximum limit set by AHTD, but all three were less than or equal to 9.0%. Interestingly all three batches had compressive strengths greater than the minimum 4,000 psi required by the AHTD. One batch containing bulk Blue Circle cement had a measured air content that fell below the 4.0% minimum, at 3.8%.

Also, it was observed that high ambient temperatures, on the order of 90° F, tended to magnify the loss of entrained air in the SRA mixtures. This may partially explain the greater variability in air content with the fly ash mixtures. Testing of fly ash mixtures started in the winter months and extended well into the summer. The change in ambient temperatures over this period greatly affected the AEA dosage, which in turn affected the air content.

It was much easier to achieve a specified fresh concrete air content with Darex 2™ than with Daravair 1000™. Regardless of the AEA dosage used, it was not possible to achieve an air content of 6.0% or more when Daravair 1000™ was used with the Cntl/FA/SR-2.0% mixture. A 6.0% air content was achieved in the Cntl/FA/SR-2.0 mixture when Darex 2™ was used at a dosage rate of 3.5 oz/cwt. While this is on the high end of typical dosage rates, it is far less than the 20 oz/cwt required when Daravair 1000™ was used.

5.2 Slump Loss

The loss of slump with time, presented by a trend line for each mixture, is depicted in Figure 5.1. Relative slump is calculated by dividing a slump measurement by the initial slump. Thus, all curves commence at a relative slump of 1.0. A linear trend line was then fit to the data by a feature in Microsoft's Excel spreadsheet software.

Figure 5.1 indicates that the rate at which slump is lost is slowed somewhat by the addition of the SRA. This slight retarding effect is also reported by W.R. Grace (13). In addition, the fly ash mixtures tended to lose slump faster than the non-fly ash mixtures. Subsection 802.08 of the AHTD Standard Specifications states that concrete shall be delivered and discharged from the truck into the forms within 90 minutes after introduction of the mixing water to the cement. During slump loss testing, most batches of concrete had a slump of 1 inch, which is the AHTD minimally accepted value, at 90 minutes. Thus, the SRA mixtures would have sufficient slump at 90 minutes to allow their use.

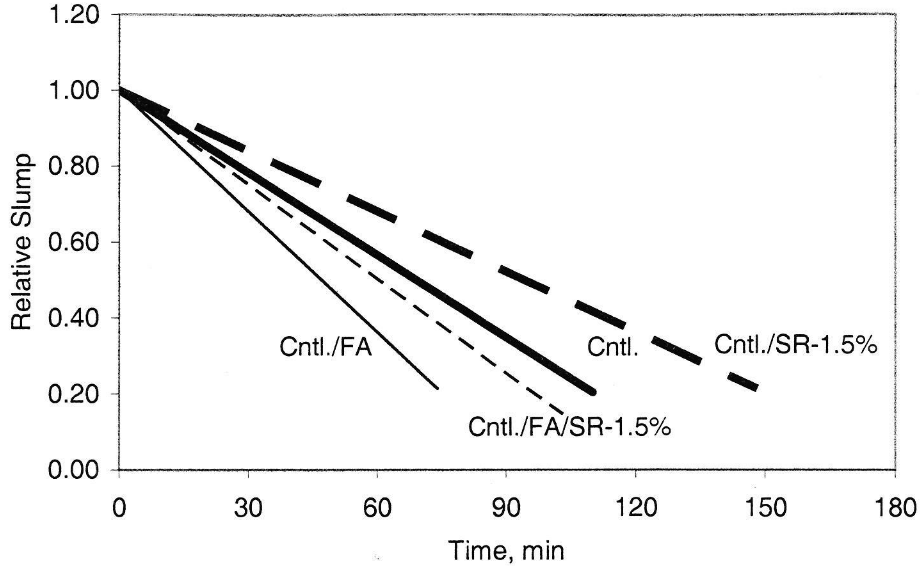

Figure 5.1 Relative Slump Loss

5.3 Air Loss

An evaluation of the loss of entrained air over time was performed as a consequence of findings from the freeze-thaw and petrographic tests. Figure 5.2 presents data from the air loss tests conducted on the Cntl and Cntl/SR-1.5% mixtures. Linear trend lines, generated by Excel, are superimposed over the test data. This data indicates that there is a more pronounced loss of entrained air for an SRA mixture as compared to a non-SRA mixture. Approximately 25 minutes after mixing, the reduction in air content is on the order of 15% for the SRA mixture while it is only about 5% for the non-SRA mix. The loss of entrained air in SRA mixtures has also been reported by others (XX). Since SRA's work to reduce the surface tension of water, it is postulated that the SRA may also reduce the stability of the entrained air bubbles.

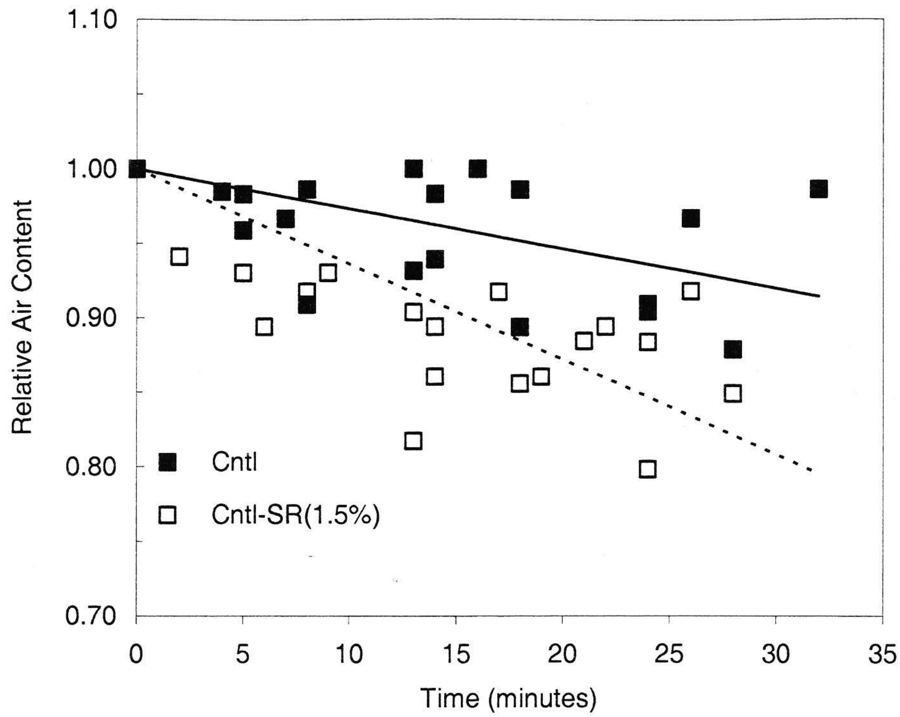

Figure 5.2 Relative Air Loss

believed that the loss of entrained air was a contributing factor to the poor freeze-thaw durability exhibited by some SRA mixtures. Thus, it is imperative that users of an SRA be made aware of the potential for the air content to noticeably decrease before the concrete hardens. Higher dosages of an air-entrainer, alternate AEA formulations, and strategies to reduce the temperature of the fresh concrete may provide the means to overcome this problem.

5.4 Compressive Strength

The addition of the SRA has a moderate, and mixed, effect on compressive strength. Figures 5.3 and 5.4 depict the compressive strength development of the Cntl. and Cntl./FA mixtures, respectively. Analysis of the compressive strength data was complicated by the variations in air content among the batches produced for testing. To account for this variation, compressive strengths were increased, or decreased, at a rate of 5% for each 1% difference between the measured air content and a baseline value of 6.0%. A 6.0% baseline was selected, as it is the mid-point of the AHTD specified range. Figures 5.5 and 5.6 are plots of the compressive strength values adjusted for the measured air content. Adjusting the compressive strength for differing air contents, had little effect on the relationship among the various Cntl. of Cntl./FA mixtures. It did, however, help confirm that the SRA mixtures developed higher compressive strengths.

The SRA mixtures have a slightly higher adjusted compressive strength when compared to their controls. The increase is greatest with the 1.0% SRA addition rate. At 28 days, the Cntl/SR-1.0% and the Cntl/FA/SR-1.0% mixtures had compressive strengths about 15% greater then their respective controls, Cntl and Cntl/FA. The compressive strengths for the other SRA dosages were only slightly greater than their controls at 28 days. Shah (9) also reported a 10% greater strength gain at 28 days for concrete containing SRA when compared to a control crete.

The AHTD specification for compressive strength (for S(AE) concrete) is a minimum 28-day strength of 4,000 psi. Considering each mixture and all batches tested, the average compressive strength was above 5,500psi at 28 days, which is above the specified minimum. Only one batch of Cntl./SR-1.5% had an average compressive strength below the minimum of 4,000psi, having a value of 3,700 psi.

ngth development of the SRA mixtures appears to be consistent with conventional concrete. For the Cntl series, 80 to 85% of the 28-day strength was developed by 7 days. For the Cntl/FA series, the 7-day strength is about 75 to 80% of that at 28 days.

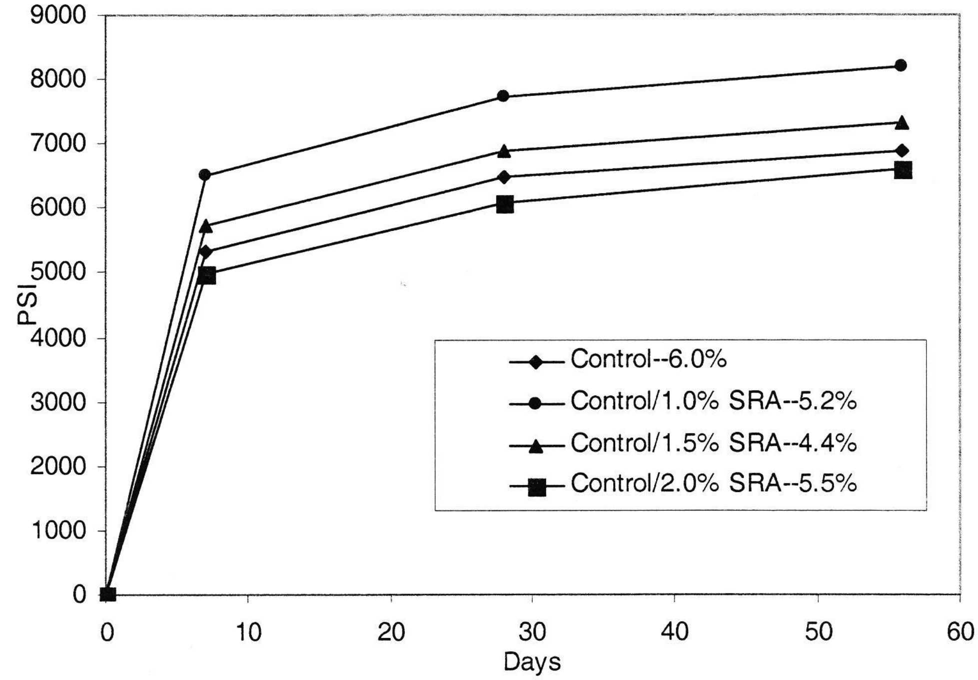

Figure 5.3 Compressive Strength Data for the Cntl. Mixtures

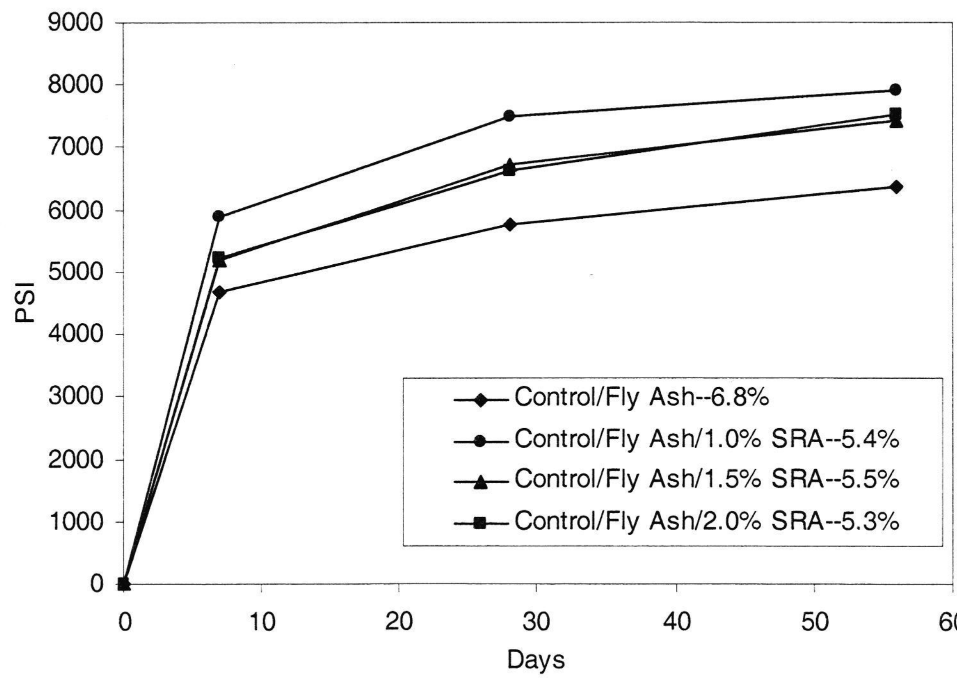

Figure 5.4 Compressive Strength Data for the Cntl./FA Mixtures

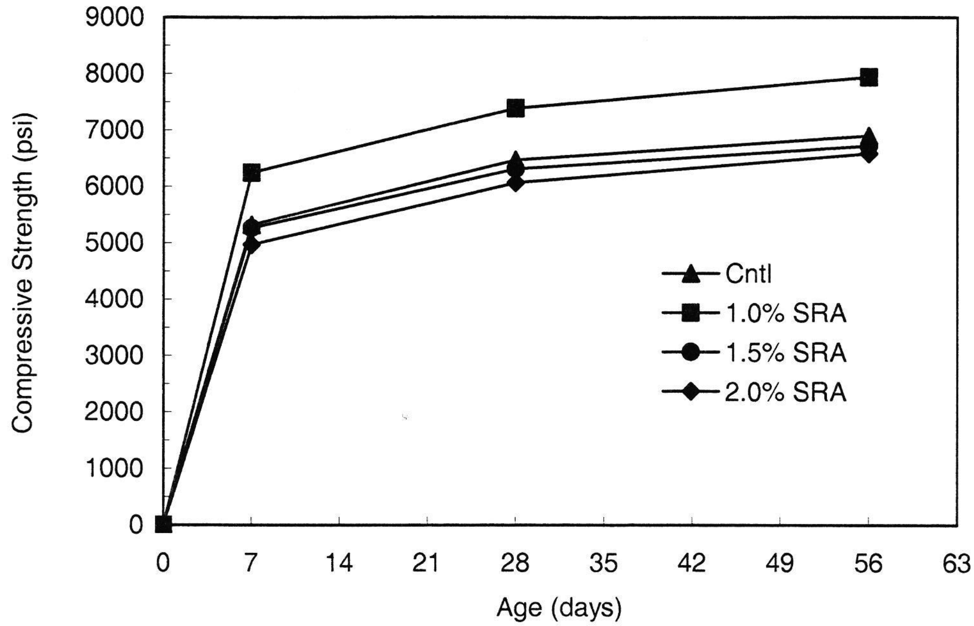

Figure5.5 Compressive Strength Data for the Cntl. Mixtures, Adjusted to 6.0% Air Content

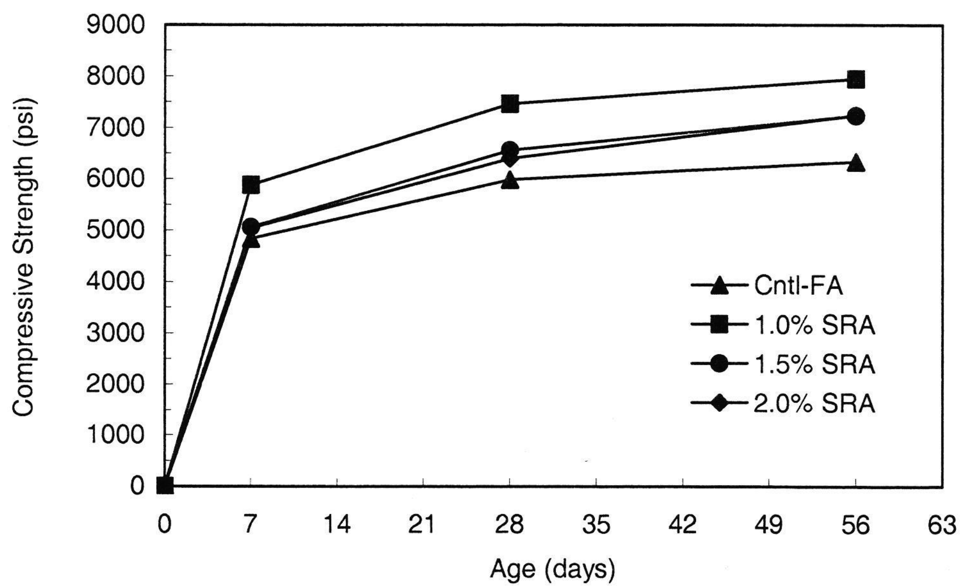

Figure 5.6 Compressive Strength Data for the Cntl./FA Mixtures, Adjusted to 6.0% Air Content

5.5 Freeze and Thawing

Data for freeze/thaw testing is given in Table 5-3. Typically, three or four different mixtures were tested in the freeze/thaw chamber at any one time. A group of mixtures is referred to below as a "Test Series". The different [illegible]tures were batched on the same day, which allowed them to be tested for their dynamic modulus at the same [illegible].

Table 5-3 Freeze/Thaw Test Data

Mix Type	DF	Air (%)	f'c (psi)	Specimen Series	Test Series	Notes
Cntl.	92	7.2	5908	5003-5008	1	
Cntl./SR-1.5%	17	6.0	6788	5012-5017	1	
Cntl./FA	90	6.0	6877	5021-5026	1	
Cntl./SR-1.5%	32	5.5	7236	5030-5035	2	
Cntl./SR-2.0%	26	6.1	6646	5039-5044	2	
Cntl./FA/SR-1.5%	86	5.5	7971	5048-5053	2	
Cntl./SR-1.5%	94	7.0	5721	5057-5062	3	Bulk Ashgrove
Cntl./SR-1.5%	5	3.8	5431	5066-5071	3	Bulk Blue Circle
Cntl./SR-1.5%	52	6.3	4448	5075-5080	3	Bulk Lonestar

Table 5-3 Freeze/Thaw Test Data (continued)

Mix Type	DF	Air (%)	f'c (psi)	Specimen Series	Test Series	Notes
Cntl./SR-1.5%	89	6.3	6169	5092-5096	4	Mix SRA for 5 min.
Cntl./SR-1.5%	93	7.3	5511	5100-5104	4	AEA: Darex 2™
Cntl./SR-1.5%	89	7.3	4496	5134-5138	4	Bulk Blue Circle
Cntl./SR-1.5%	91	6.8	5606	5145-5149	4	
Cntl./SR-2.0%	96	7.7	4176	5173-5177	5	AEA: Darex 2™
Cntl./FA/SR-2.0%	95	6.0	5836	5187-5190	5	AEA: Darex 2™
Cntl./SR-2.0%	90	6.4	5065	5195-5198	5	
Cntl./FA/SR-2.0%	89	5.3	6412	5205-5209	5	

5.5.1 Test Series 1

In this series, specimens from three mixes; Cntl., Cntl./SR-1.5%, and Cntl./FA, were tested. Five test specimens and one control beam were molded from each batch. Both non-SRA mixtures performed well with durability factors of 90 or above. However, the Cntl./SR-1.5% mix performed very poorly. Its durability factor was only 17. This was a surprise, since at that point in the research the literature review had not uncovered any reports of problems with the freeze/thaw durability of an SRA mixture. A subsequent literature search turned up two papers (8, 15) which described a similar problem with freeze/thaw durability.

5.5.2 Test Series 2

Based on the results of Series 1, it was decided that additional batches of SRA concrete should be tested to further investigate any potential freeze-thaw durability problems. Thus, this series included Cntl./SR-1.5%, Cntl./FA/SR-1.5%, and Cntl./SR-2.0% mixtures. Durability factors for these mixtures were 32, 86, and 26 respectively. From these results, it appeared that the SRA was causing a catastrophic durability problem. It was also noted that the fly ash mixture performed fairly well.

From these results, it was postulated that the freeze-thaw problem might be due to a cement-admixture incompatibility. This was hypothesized because the fly ash mixture performed better in freeze/thaw testing than the straight cement mixture. Also, none of the mixtures had unusually low or high air contents. In order to test this theory, three brands of bulk cement were obtained for testing. Bulk cement was used to insure that the cement would not be a mixture of several different suppliers, which can be the case with bagged cement. Testing of different cements became the focus of Test Series 3.

5.5.3 Test Series 3

st Series 3 consisted of three Cntl./SR-1.5% mixtures containing three different brands of bulk cement. They luded AshGrove, Blue Circle, and LoneStar. Using different brands of cements presented some extra problems. The air entraining dosage varied for each of the cement brands. The proper AEA dosage rate was determined through many trial batches with AshGrove cement. While it would be naive to expect the same dosage of AEA to perform in the same manner for all three brands of cement, this assumption had to be made due to time constraints.

The results from Test Series 3 did not seem to indicate that there is a problem with a specific brand of cement. Rather, the results suggest a more global problem. The mixture containing the AshGrove cement had a durability factor of 94, while the Blue Circle and the LoneStar mixtures had durability factors of 5 and 52, respectively. The low durability factor of the Blue Circle mixture could be explained by a low air content of 3.8%. The LoneStar durability of 52 was not fully understood until a petrographic analysis was completed, and this will be discussed later. At this point, W.R. Grace was notified about the durability problem with the SRA. W. R. Grace (16) made several recommendations concerning mixing procedure and fresh air content that lead to Test Series 4.

5.5.4 Test Series 4

W. R. Grace recommended four additional batches of concrete be produced. These included 1) a Cntl./SR-1.5% mixture, mixing the SRA for 5 minutes rather than the normal 2 minutes, 2) a Cntl./SR-1.5% mixture, adding sufficient AEA to obtain a fresh concrete air content of 7.0% and mix the SRA for 5 minutes, 3) a Cntl./SR-1.5% mixture, using Darex 2™ AEA rather than the Daravair 1000™ to achieve air content of 7.0% and mix SRA for 5 minutes, and 4) retest the mixture containing bulk Blue Circle cement since its air content was so low.

All mixtures passed freeze/thaw testing with durability's of 89 or greater. It is felt that the higher fresh air contents e a factor in these results being achieved. The air contents for the four respective mixtures were 6.3, 6.8, 7.3, and 7.3%. In Series 1 through 3, only one batch of SRA concrete had an air content greater than 6.3%, and it was 7.0%. Further, the only two batches of SRA concrete that passed freeze/thaw testing in Test Series 1 through 3 was the batch having 7.0% air and a fly ash mixture that had a very high compressive strength.

It was not difficult to achieve 7.0% air content with Darex 2™, but this was not so with Daravair 1000™. Mixing the SRA for 5 minutes rather than two minutes appeared to have no impact on freeze/thaw performance.

5.5.5 Test Series 5

Since it was much easier to achieve a target air content with Darex 2™, it was decided that this AEA should be tested further. Also, since this research started, W.R. Grace began to suggest that the optimal dosage of Eclipse™ is 2.0% by weight of cement. This, and the fact that very few 2.0% SRA mixtures had been tested, lead to Test series 5. Test series 5 included 4 mixes, Cntl./SR-2.0% and Cntl./FA/SR-2.0% using Daravair 1000™ and the same mixes using Darex 2™. The target air content was 7.0% but not less than 6.0%.

It was impossible to achieve a fresh air content greater than 6.0% using Daravair 1000™ for the Cntl./FA/SR-2.0% mixture. An air content of only 5.3 was achieved at very high dosage rates of AEA, as much as 20 oz/cwt. The air contents of the other mixtures were 6.0, 6.4, and 7.7%. All of the mixtures passed with durability factors of 89 or better. The mixtures containing the Darex 2™ had durability factors about 5 points greater than the mixtures containing Daravair 1000™.

R. Grace indicated (16) that Darex 2™ works better than Daravair 1000™ when used with Eclipse™. The drawback to Darex 2™ is that the air void system is not as good. The air bubbles are larger and more widely spaced.

It should also be noted that none of the fly ash mixtures failed freeze/thaw testing even when air contents were relatively low, on the order of 5.3%. This is probably due to high compressive strengths of these mixtures, ecially when the air contents were low.

It was concluded from the freeze/thaw testing that if the fresh air content is above 6.5% that this would generally produce a durable mixture. It was also concluded that the type (formulation) of AEA greatly affects the dosage rate and ease of obtaining a specified air content.

5.6 Scaling

Table 5-4 shows the rating system used to determine the severity of scaling, which is a modified rating scale adopted from ASTM C 672. Table 5-5 presents the findings from an assessment of scaling along with other performance data.

Four sets of freeze/thaw beams, which had completed the required 300 cycles of freezing/thawing, were selected to be assessed for scaling. It was decided that the Cntl and Cntl./SR-1.5% batches, which had similar fresh and hardened properties, would be assessed for scaling. This same process of selection was used to identify the Cntl/FA and the Cntl/FA/SR-1.5% batches for scaling assessment.

Table 5-4 Rating for Scaling Severity

Rating Used	Condition of Surface	ASTM C 672
0-1	No scaling	0
2-3	Very slight scaling (3.2 mm (1/8 in) depth, max, no coarse aggregate. visible)	1
4-5	Slight to moderate scaling	2
6-7	Moderate scaling (some coarse aggregate visible)	3
8-9	Moderate to severe scaling	4
10	Severe scaling (coarse aggregate visible over entire surface.)	5

Table 5-5 Scaling Results

Mix Type	Scaling Factor	DF	Air (%)	f'c (psi)	Specimen Series	Test Series
Cntl.	3	92	7.2	5908	5003-5008	1
Cntl./SR-1.5%*	5	94	7.0	5721	5057-5062	3
Cntl./FA	2	90	6.0	6877	5021-5026	1
Cntl./FA/SR-1.5%	6	86	5.5	7971	5048-5053	2

*Bulk Ashgrove Cement

It was determined that the prisms containing the SRA experienced a higher level of scaling than did the control specimens. In general, this trend was observed for all freeze/thaw batches containing the SRA. Other researchers e also noted a higher degree of scaling in concrete containing an SRA (XX).

5.7 Petrographic Analysis

Petrographic analysis was performed on some of the freeze/thaw control specimens in an effort to determine the causes of poor durability with some mixtures. A general summary of the results of this analysis is presented in Table 5-6. Plots of spacing factor versus durability factors are presented in Figures 5.6 and 5.7. Specimens will be rred to by their "Specimen Series" number which can be found in Table 5-6.

Table 5-6 Petrographic Analysis

Mix Type	DF	Fresh Air (%)	Hardened Air (%)	f'c (psi)	Spacing Factor (in.)	Specimen Series
Cntl.	92	7.2	6.4	5908	0.0041	5003-5008
Cntl./SR-1.5%	17	6.0	3.8	6788	0.0089	5012-5017
Cntl./SR-1.5%	32	5.5	4.5	7236	0.0106	5030-5035
Cntl./SR-1.5%	94	7.0	5.2	5721	0.0067	5057-5062
Cntl./SR-1.5%	5	3.8	3.9	5431	0.0135	5066-5071
Cntl./SR-1.5%	52	6.3	5.7	4448	0.0076	5075-5080
Cntl./SR-1.5%	89	6.3		6169		5092-5096
Cntl./SR-1.5%	93	7.3	4.8	5511	0.0051	5100-5104
Cntl./SR-1.5%	89	7.3	5.8	4496	0.0060	5134-5138
Cntl./SR-1.5%	91	6.8	5.0	5606	0.0059	5145-5149

Table 5-6 Petrographic Analysis

Mix Type	DF	Fresh Air (%)	Hardened Air (%)	f'c (psi)	Spacing Factor (in.)	Specimen Series
Cntl./SR-2.0%	26	6.1	4.2	6646	0.0099	5039-5044
Cntl./SR-2.0%	96	7.7		4176		5173-5177
Cntl./SR-2.0%	90	6.4		5065		5195-5198
Cntl./FA	90	6.0	4.3	6877	0.0046	5021-5026
Cntl./FA/SR-1.5%	86	5.5	3.5	7971	0.0099	5048-5053
Cntl./FA/SR-2.0%	95	6.0		5836		5187-5190
Cntl./FA/SR-2.0%	89	5.3		6412		5205-5209

The Cntl. and Cntl./FA specimens performed very well under freeze/thaw testing. This can be explained by the fact that both the Cntl. and Cntl./FA mixtures had spacing factor less than 0.008 inches, generally regarded as the upper limit for acceptable freeze/thaw behavior. It was concluded that the poor durability factors of specimens 5012-5017 (Cntl./SR-1.5%), 5030-5035 (Cntl./SR-1.5%), and 5039-5044 (Cntl./SR-2.0%) could be explained by their spacing factors being greater than 0.008 in. Even though these mixes had acceptable fresh air contents, their hardened air contents were only 3.8, 4.5, and 4.2, which are very low relative to freeze/thaw durability. Specimens 5048-5053 (Cntl./FA/SR-1.5%) had a spacing factor greater than 0.008 inches, but also had a very high compressive strength, 7,970 psi. It is felt that this high strength contributed to the mixture's durability factor of 86.

ecimens 5021-5026, the Cntl./FA mixture, had a low hardened air content of 4.3, but the spacing factor was only 0.0046 in., well below the 0.008 in. upper limit. It is believed that the adequacy of the spacing factor resulted in a durability factor of 90. Specimens 5039-5044, a Cntl./SR-2.0% mixture, had very similar fresh and hardened air contents, but the spacing factor was twice that of specimens 5021-5026. The larger spacing factor lead to poor freeze/thaw durability with a durability factor of only 26.

Through the petrographic analysis, it was determined that the hardened air content of the SRA mixtures was 1.5 to 2.0 percentage points less than the measured fresh air content. It was also found that in SRA mixtures there was an unusually high proportion of large air voids. In Figure 5.8, it can be seen that spacing factors of the SRA mixtures that failed were all above the acceptable limit of 0.008 in.

It can be seen from Figure 5.7, that most durable concretes had a minimum hardened air of 4.8%. Recall that SRA concretes were found to lose approximately 1.5 to 2.0 percentage points of air between fresh and hardened states. Thus, the minimum air content of the plastic concrete should be approximately 6.5% for SRA mixtures. During freeze/thaw testing, it was also observed that a minimum fresh air content of approximately 6.5% was necessary for durable concrete. With SRA concrete mixtures requiring higher air contents, this may mean that the cementious material content may need to be adjusted for a loss in strength.

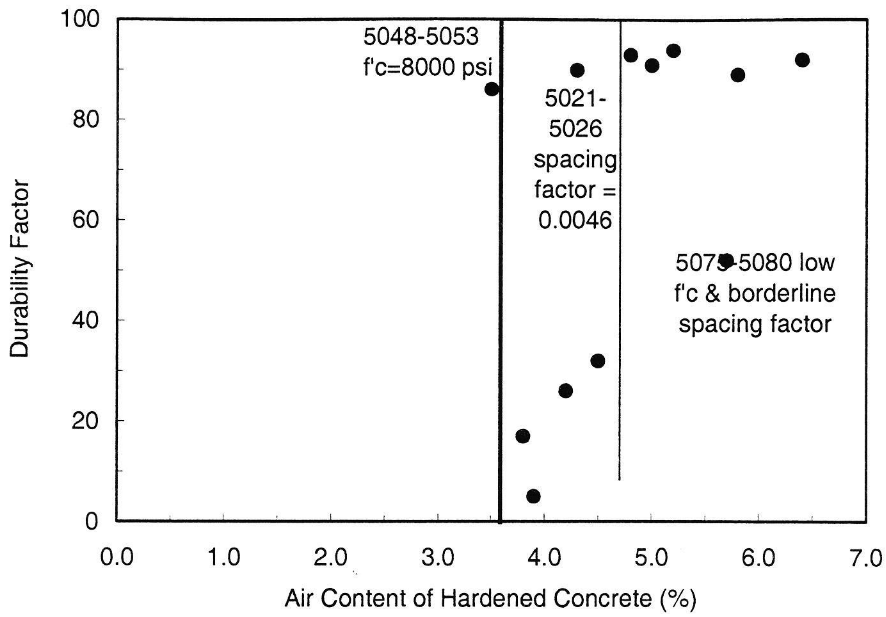

Figure 5.7 Hardened Air Content vs Durability Factor

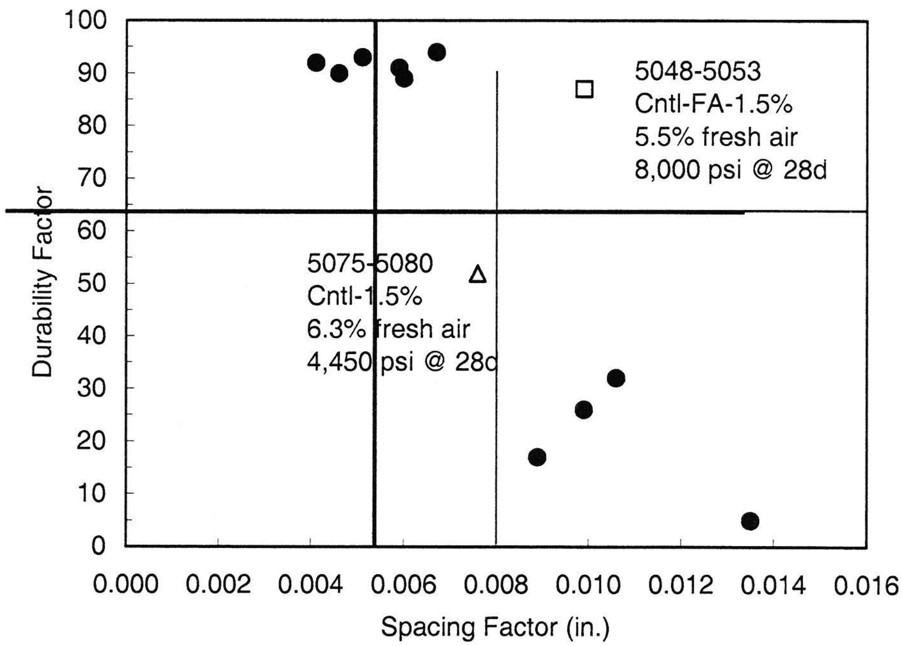

Figure 5.8 Spacing Factor vs Durability Factor

Specimens containing Darex 2™ as the AEA faired well under freeze/thaw testing. The minimum durability factor of the three mixtures containing Darex 2™ was 93. These mixtures included Cntl./SR-1.5% (5100-5104), Cntl./SR-2.0% (5173-5177), and Cntl./FA/SR-2.0% (5187-5190). The fresh air contents were 7.3, 7.7, and 6.0%, respectively. The Cntl./SR-1.5% mixture is the only sample that has undergone petrographic analysis. This sample had a difference of 2.6 percentage points between the fresh and hardened air contents. Further petrographic analyses should be performed to determine the loss of air using Darex 2™ before any conclusions can be drawn regarding its performance.

8 Unrestrained Shrinkage Test (Shrinkage Prisms)

Table 5-7 lists the average 28 day percent length change and corresponding percent reduction in shrinkage, relative to the control mixtures. Values for the Cntl., Cntl./FA, Cntl./SR-1.5%, and Cntl./FA/SR-1.5% represent the average of three sets of beams, while the other mixtures are the average of two set of beams. A set of beams consists of three specimens. Tables 5-8 and 5-9 summarize the reduction of shrinkage at various ages for the Cntl./SR-1.5% and Cntl./FA/SR-1.5% mixtures when compared to their control mixtures.

Table 5-7 Percent Length Change

Mix	Avg. 28d % ΔL	% < Cntl.
Cntl.	0.0325	0
Cntl./SR-1.0%	0.0206	37
Cntl./SR-1.5%	0.0151	53
Cntl./SR-2.0%	0.0171	47

Cntl./FA	0.0255	0
Cntl./FA/SR-1.0%	0.0172	33
Cntl./FA/SR-1.5%	0.0154	40
Cntl.FA/SR-2.0%	0.0132	48

Table 5-8 Percent Reduction in Length Change vs the Control Mixture

Cntl./SR-1.5%				
Batch 1				
Days	7	28	56	250
%Reduction	62	60	55	49

Batch 2				
Days	7	28	56	222
%Reduction	55	48	42	36

Batch 3				
Days	7	28	59	164
%Reduction	60	53	39	27

Table 5-9 Percent Reduction in Length Change vs the Control/FA Mixture

Batch 1			
Days	7	28	122
%Reduction	48	44	31

Batch 2			
Days	6	28	93
%Reduction	25	25	18

Batch 3			
Days	7	29	56
%Reduction	83	45	44

In general, Table 5-7 indicates that the reduction in shrinkage is proportional to the dosage of the SRA. It can be seen that the Cntl. mixtures had shrinkage reductions of 37, 53, and 47% at SRA dosages of 1.0, 1.5, and 2.0%, respectively. The Cntl./FA mixtures had reductions of 33, 40, and 48% at SRA dosages of 1.0, 1.5, and 2.0%, respectively.

The Cntl./SR-1.5% mixture experienced approximately a 60% reduction in shrinkage at 7 days compared to the Cntl. mixture as can be seen in Table 5-8. At 28 days of age, the Cntl./SR-1.5% mixture had an average reduction in shrinkage of about 55%. The Cntl./FA/SR-1.5% mixture experienced, on average, 50% and 40% reductions in length change at 7 and 28 days, respectively, when compared to the Cntl./FA mixture.

Figure 5.9 represents the percent length change over time for the Cntl. and Cntl./SR-1.5% mixtures, while Figure 5.10 represent the same information for the Cntl./FA and Cntl./FA/SR-1.5% mixtures. While Table 5-7 represents the percent length change at only one instant in time, Figures 5.9 and 5.10 represent the percent length change over as many as 250 days. It can be seen that the greatest reduction in shrinkage takes place prior to about 90 days. This when the concrete has a lower compressive strength and is most vulnerable to cracking. After about 90 days, the shrinkage tends to level off and the individual curves become fairly parallel. This indicates that mixtures containing the SRA produce a long-term reduction in shrinkage.

The overall reduction in shrinkage for the Cntl./SR-1.5% mixture leveled off around 40%. The reduction in shrinkage generally ranged between 40 and 60% over time. The overall reduction in shrinkage for the ntl./FA/SR-1.5% can be estimated as 30% at 90 days. It should be noted that all specimens for the Cntl./FA/SR- % had not been tested at 90 days. The reduction in shrinkage for the Cntl./FA mixtures ranged between 20 and o0% over time. This range is greater than that for the Cntl. mixtures. More shrinkage specimens should be evaluated in order to get a clearer picture of the shrinkage reduction of the fly ash mixtures. All of the values mentioned above are very consistent with values of shrinkage reduction reported by other researchers (XX).

The Cntl./FA mixture had approximately 20% less shrinkage than the Cntl. mixture. At 28 days and an SRA dosage of 1.0%, both the Cntl./SR-1.0% and the Cntl./FA/SR-1.0% had an approximate reduction in shrinkage of 35%. At a 2.0% dosage rate, the reduction was on the order of 45%. The 1.5% SRA dosage rate did not have as consistent results. With additional testing, the behavior would be clarified. Although the reduction in shrinkage for each dosage rate of SRA was very similar between the Cntl./SR and the Cntl./FA/SR mixtures, the fly ash mixtures had less total shrinkage. This is because the Cntl./FA mixture had 20% less shrinkage than the Cntl. mixture.

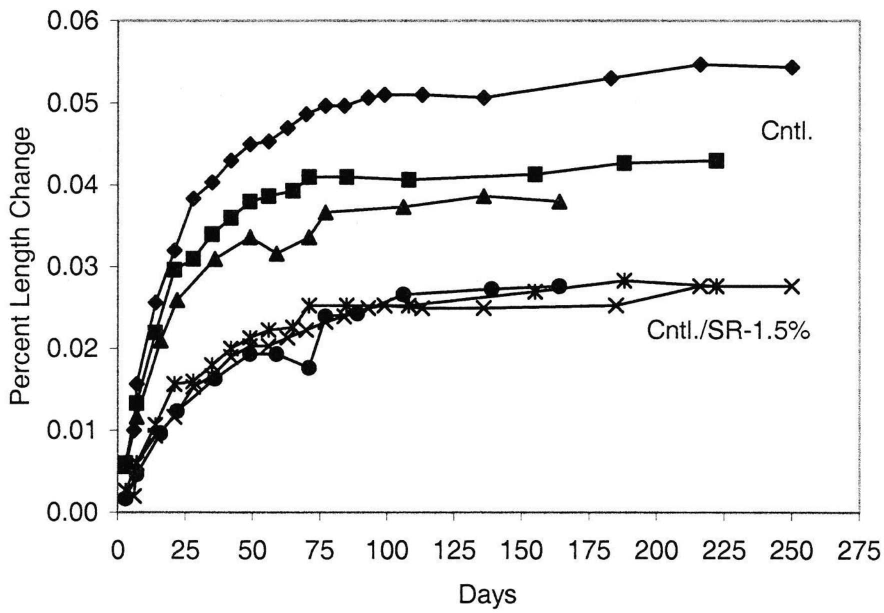

Figure 5.9 Control Percent Length Change vs Days

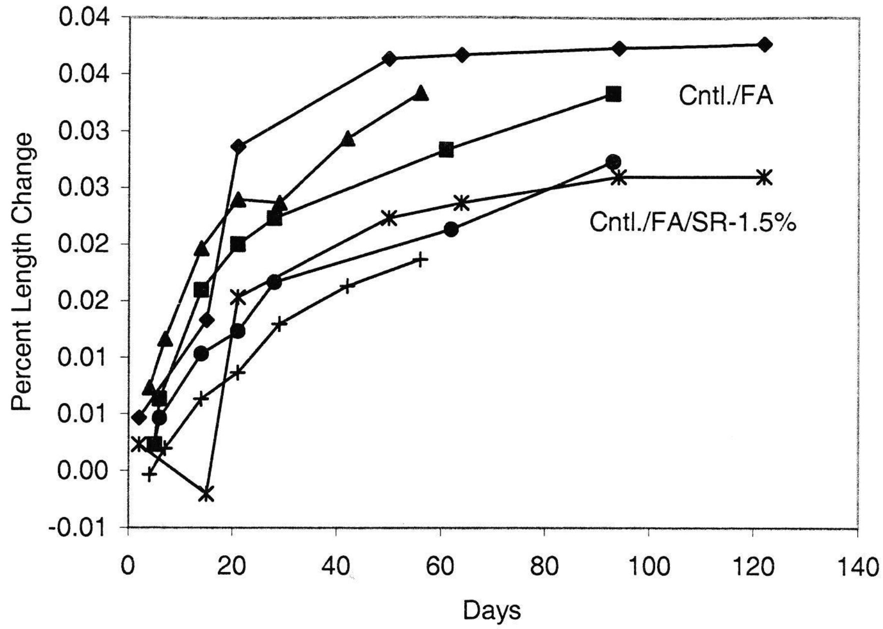

Figure 5.10 Control/Fly Ash Percent Length Change vs Days

5.9 Restrained Shrinkage Test (Shrinkage Rings)

phs of the data from the restrained shrinkage tests are shown in Figures 5.11 and 5.12. Figure 5.11 represents e average of three specimens for each of three batches of concrete. In Figure 5.12, the data for plastic rings represents the average of 2 specimens for each of two batches, and the data for the steel rings represents one specimen for each of 2 batches. It should be noted that the voltage readings recorded by the data acquisition system have not been calibrated to produce a numerical value for the actual amount of shrinkage that takes place.

The SRA consistently reduced shrinkage in the restrained shrinkage test. The separation of the plotted data tends to widen until the readings were ceased at approximately 40 days. This same type of shrinkage reduction behavior was observed in the unrestrained shrinkage test. The unrestrained shrinkage test indicated that an increase in shrinkage reduction took place until about 90 days, at which time the shrinkage measurements leveled off.

An inner plastic restraining ring was used with the Cntl and Cntl/SR-1.5% mixtures. When testing Cntl/FA and Cntl/FA/SR-1.5% mixtures, two plastic and one steel ring was used for each batch. This was done in order to compare the effects of the plastic ring with the steel ring. A steel ring has been the accepted practice for this test by other researchers. When compared to the steel rings, plastic rings resulted in a greater difference in the voltage measurements of the Cntl./FA and the Cntl./FA/SR-1.5% mixtures. At high voltage readings, the steel and plastic rings performed in a similar manner. As the test progressed and the concrete shrinkage becomes greater, the steel ring does not show the same degree of change in voltage readings as the plastic rings. This behavior can be seen in

Figure 5.12

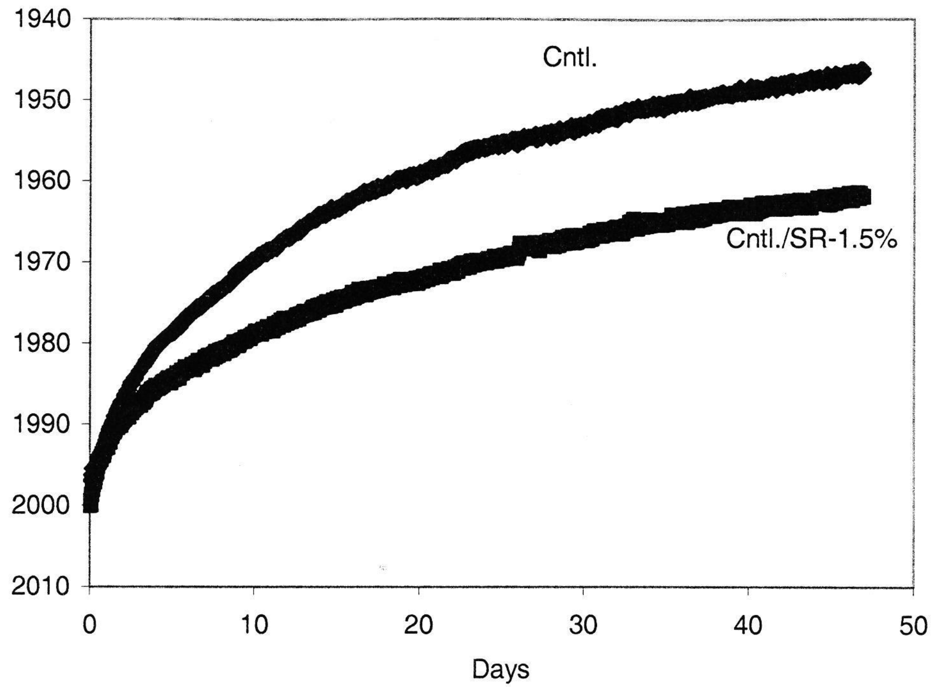

Figure 5.11 Average Restrained Shrinkage for Cntl. Mixtures

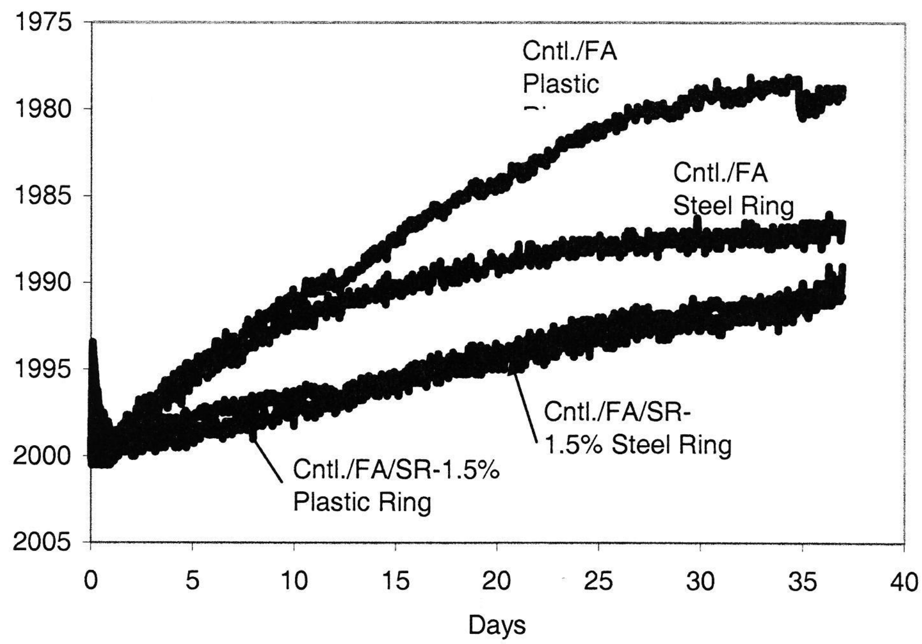

Figure 5.12 Average Restrained Shrinkage for Cntl./FA Mixtures

›nclusions and Recommendations

This research investigated a commercially available SRA, Eclipse™. The admixture was added at dosage rates of 1.0, 1.5, and 2.0% by weight of cement to AHTD Class S (AE) concrete mixtures. Two control mixtures were used. One contained straight portland cement, and the other mixture contained 20% fly ash by weight of cement. The conclusions and recommendations that follow apply to these mixtures. The use of an SRA in other mixtures should be evaluated through trial batching.

Conclusions

- The SRA had minimal effect on initial slump and workability.
- The SRA had a slight retarding effect on the loss of slump.
- When using an SRA, it was difficult to achieve a desired air content, and some cases nearly impossible. It was also found that high ambient temperatures seemed to magnify this problem.
- The type of AEA used had a significant impact on the development of an air void system and thus on the measured air content.
- It was found that concrete containing SRA tended to lose approximately 15% more of its entrained air in the first 25 minutes after mixing as compared to its control mixture. It is believed that this loss of air contributed to the poor durability of some concrete batches.
- SRA concrete mixtures had slightly higher compressive strengths than the control mixtures. This was most pronounced at a 1.0% SRA dosage rate. This resulted in about a 15% increase in strength at 28-days.
- With SRA concrete mixtures, a fresh air content less than 6.5% would likely lead to a freeze/thaw durability problem. Air contents greater than 6.5% would likely produce durable concrete, to a point. An upper limit on air content, for durability, was not evident from this research
- Mixtures containing fly ash tended to perform better in a freeze/thaw environment than did the straight cement counterparts.
- A simple visual evaluation of scaling concluded that scaling was worse in all concrete containing SRA.
- Petrographic analysis determined that the fresh air content of SRA concrete was higher when compared to the hardened concrete values. This difference could be as much as 2.0 percentage points. Also, concrete containing the SRA tended to have a greater number of larger air-voids which were widely spaced. It was determined that a hardened concrete air content of 5.0% should produce durable concrete. This would result in a fresh air content on the order of 6.5%.
- For both the Cntl./SR-1.5% and Cntl./FA/SR-1.5% mixtures, unrestrained shrinkage was reduced on the order of 40 -50% at 28-days, and long-term shrinkage reduction was on the order of 30-40%. Reduction of shrinkage was generally proportional to the dosage of SRA.

- Restrained shrinkage was consistently reduced when the SRA was used. The inner plastic restraining ring also produced a greater difference in voltage readings when compared to the steel ring. This is thought to provide more data and a better picture of the shrinkage when compared to a steel ring.

Recommendations

It is evident that the SRA tested reduces drying shrinkage. Further, this particular SRA could be used at the present time in structures which have minimal exposure to a freeze/thaw environment, but where crack control is important. If the concrete is going to be exposed to freezing and thawing conditions, then this admixture should not be used until all durability issues can be resolved, or explained.

If an air content is specified, trial batches should be conducted to determine the influence of the SRA on the AEA dosage. Otherwise, manufacturer recommended dosage rates and batching procedures should be followed.

Large-scale field trials should be conducted to evaluate the performance of the SRA in actual practice. Fresh properties, compressive strength, workability, shrinkage reduction, freeze/thaw testing, and long-term durability should all be investigated.

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Appendix A
Example Calculations and Equations

Example 1: Calculation of SRA Dosage

1 gal. SRA = 7.9 lbs.
l. = 128 oz.
oz. = 29.6 mL

To find the dosage of 1.0% SRA by weight of cement per cubic yard of concrete.

$$\frac{1.0\% SRA}{100\%}\left(\frac{611 lbs\ Cement}{yd^3}\right)=\frac{6.11 lbs\ SRA}{yd^3}$$

$$\frac{6.11 lbs\ SRA}{yd^3}\left(\frac{1 gal\ SRA}{7.9 lbs\ SRA}\right)=\frac{0.773 gal\ SRA}{yd^3}$$

$$\frac{0.773 gal\ SRA}{yd^3}\left(\frac{128 oz}{1 gal}\right)=\frac{98.94 oz\ SRA}{yd^3}$$

$$\frac{98.94 oz\ SRA}{yd^3}\left(\frac{29.6 mL}{1 oz}\right)=\frac{2929 mL\ SRA}{yd^3}$$

Example 2. Calculation of Durability Factor of Freeze/Thaw Specimens

is procedure is outlined in ASTM C666. This example is taken for Specimen 5003

Given: Frequency @ 0 cycles = 1753
Frequency @ 304 cycles = 1629

$$DF = \{[(1629)^2 / (1753)^2] * 100\} * (304/300) = 88$$