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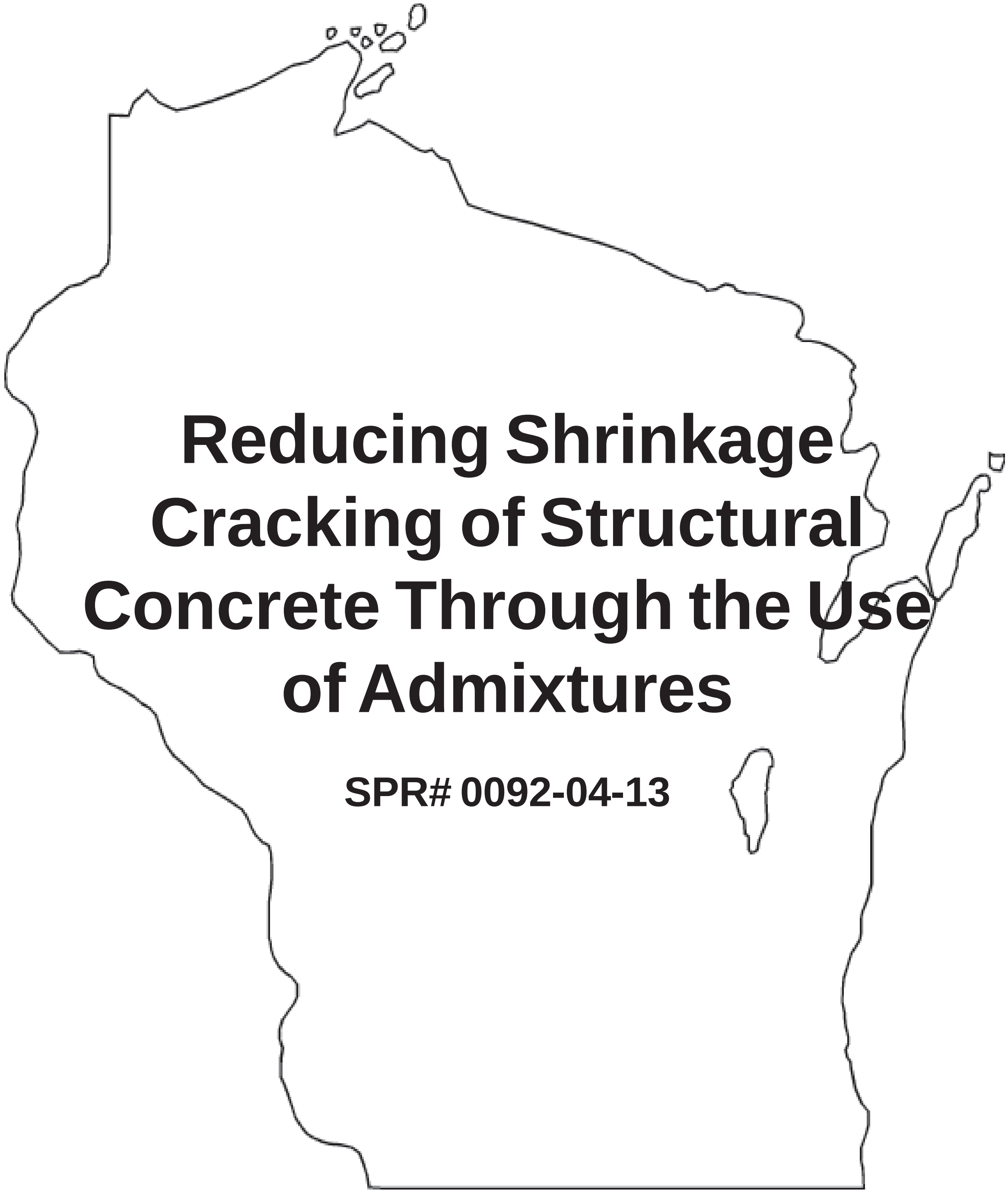

Reducing Shrinkage Cracking of Structural Concrete Through the Use of Admixtures

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Tarun R. Naik, Yoon-moon Chun, Rudolph N. Kraus
Department of Civil Engineering and Mechanics
University of Wisconsin-Milwaukee

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REDUCING SHRINKAGE CRACKING OF STRUCTURAL CONCRETE THROUGH THE USE OF ADMIXTURES

Final Report

by

Tarun R. Naik, Yoon-moon Chun, and Rudolph N. Kraus

UWM Center for By-Products Utilization
Department of Civil Engineering and Mechanics
University of Wisconsin-Milwaukee

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Acronyms and Abbreviations

ACI	American Concrete Institute
ASTM	American Society for Testing and Materials
CBU	Center for By-Products Utilization at the University of Wisconsin-Milwaukee
UWM	University of Wisconsin-Milwaukee
WHRP	Wisconsin Highway Research Program
WisDOT	Wisconsin Department of Transportation
A1	Aggregate 1 (crushed quartzite stone)
A2	Aggregate 2 (semi-crushed river gravel)
A3	Aggregate 3 (crushed dolomitic limestone)
AEA	Air-Entraining Admixture
Cm	Cementitious Materials (cement and fly ash in this research)
FA	Fly Ash
fl. oz.	fluid ounce
MRWRA	Mid-Range Water-Reducing Admixture
S1	Shrinkage-reducing admixture 1 (Eucon SRA from Euclid)
S2	Shrinkage-reducing admixture 2 (Eclipse Plus from Grace)
S3	Shrinkage-reducing admixture 3 (Tetraguard AS20 from Degussa [Master Builders])
SRA	Shrinkage-Reducing Admixture
SSD	Saturated Surface-Dry
WRA	Water-Reducing Admixture

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Department of Civil Engineering and Mechanics
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16. Abstract
Shrinkage-reducing admixtures (SRAs) from three manufacturers (SRA-1, Eucon SRA from Euclid; SRA-2, Eclipse Plus from Grace; and SRA-3, Tetraguard AS20 from Degussa) were evaluated in WisDOT Grade A no-ash, Grade A-FA Class C fly ash, and selected high-cementitious concrete mixtures. The three SRAs showed similar performance in reducing the drying shrinkage and autogenous shrinkage of concrete. SRAs eliminated much of the initial drying shrinkage of concrete. They reduced the 4-day drying shrinkage for Grade A and A-FA concrete mixtures by up to 67 to 83%. The 28-day drying shrinkage was reduced by up to 48 to 66%. To minimize the drying shrinkage of concrete, use of the following amounts of SRA is recommended: (1) 25 fl. oz./100 lb of cement (1.6 L/100 kg of cement), or 1.1 gal./yd^3 (5.5 L/m^3), for Grade A concrete; and (2) 40 fl. oz./100 lb of cementitious materials (2.6 L/100 kg of cementitious materials), or 1.75 gal./yd^3 (8.7 L/m^3), for Grade A-FA concrete. In most cases, SRA-1 and SRA-3 worked like water-reducing admixtures and often increased the strength and the resistance to chloride-ion penetration. SRA-2 sometimes decreased the strength and did not considerably affect the chloride-ion penetrability. All three SRAs did not influence the changes in air content and slump of fresh concrete mixtures during the first hour.

Use of crushed dolomitic limestone led to the lowest early-period drying shrinkage, followed by semi-crushed river gravel, and crushed quartzite stone. Later on however, the drying shrinkage became similar, river gravel often leading to the highest late-period drying shrinkage. Use of 30% more cement and fly ash resulted in either similar or higher autogenous shrinkage, and either similar or lower drying shrinkage.

17. Key Words
Air content, autogenous shrinkage, chloride-ion penetration, concrete, drying shrinkage, shrinkage-reducing admixtures, strength.

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Executive Summary

PROJECT SUMMARY, BACKGROUND, AND PROCESS

At the time of publication of this report, cracking of bridge concrete decks due to drying shrinkage and autogenous shrinkage continues to be a concern of Wisconsin Department of Transportation (WisDOT). Cracking leads to higher life-cycle costs. The use of high-range water-reducing admixtures and steel fibers has had limited success in the reduction of overall deck cracking. As an alternative, concrete deck cracking can be reduced possibly by using shrinkage-reducing admixtures (SRAs).

The main objective of this research, within the scope of the project funded by Wisconsin Highway Research Program (WHRP), was to evaluate and compare the effectiveness of three different brands of shrinkage-reducing admixtures (SRA-1, SRA-2, and SRA-3) for reducing autogenous shrinkage and drying shrinkage of concrete made with and without fly ash. In addition, the effects of the SRAs on concrete air content, slump, initial setting time, compressive strength, splitting-tensile strength, chloride-ion penetrability, and changes in air content and slump during the first hour after concrete production were investigated.

Concrete mixtures were made based on mixture proportions of WisDOT Grade A, Grade A-FA, and a high-cementitious concrete mixture. Grade A concrete contained no supplementary cementitious materials (fly ash or ground granulated blast furnace slag). In Grade A-FA and the high-cementitious concrete, Class C fly ash was used to replace 35% of cement. The high-cementitious concrete contained 30% more cement and fly ash than Grade A-FA concrete.

The coarse aggregate used in this research conformed to the gradation requirements of WisDOT Size No. 1 (AASHTO No. 67) (0.75" maximum size). A majority of WisDOT paving concrete contains a blend of WisDOT No. 1 and No. 2 (1.5" maximum size) coarse aggregates. However, the shrinkage-reducing effects of SRAs are the results of their functioning in the cementitious paste.

Effects of three types of coarse aggregate were also evaluated using Grade A-FA mixture proportions: Aggregate 1, crushed quartzite stone; Aggregate 2, semi-crushed river gravel; and Aggregate 3, crushed dolomitic limestone.

Fresh concrete mixtures had an air content of 6 ± 1.5% and slump of 1 to 4 inches. Sealed beam specimens were used to evaluate the autogenous shrinkage of concrete up to the age of 56 days following JSCE procedure. ASTM standard test method (C 157) was used to evaluate the drying shrinkage of concrete. The drying shrinkage test results were collected for air-storage period of up to 112 days (subsequent to 28 days of moist curing) for all of the concrete mixtures.

In this research project, several sources of shrinkage-reducing admixtures (SRAs) were identified. The following three were selected and evaluated:

(1) SRA-1: Eucon SRA from Euclid Chemical Company;

(2) SRA-2: Eclipse Plus from Grace Construction Products; and
(3) SRA-3: Tetraguard AS20 from Degussa (formerly Master Builders).

Each SRA was used with a mid-range water-reducing admixture (MRWRA) and air-entraining admixture (AEA) supplied by the same manufacturer as the SRA. SRA was added last into a concrete mixer after all the other ingredients were intermixed.

FINDINGS AND CONCLUSIONS

Based on the test results obtained from this experimental program and the interpretation of the results, the following summary of results and recommendations are given by the research team:

1. **Drying shrinkage and SRA dosage rates:** SRA-1, SRA-2, and SRA-3 showed similar performance in reducing the drying shrinkage of concrete. Drying shrinkage normally includes the effect of autogenous shrinkage.

   (a) To minimize the drying shrinkage of concrete, the following amounts of SRA are recommended:

      (i) Up to 25 fl. oz./100 lb of cement (1.6 L/100 kg of cement), or 1.1 gal./yd^3 (5.5 L/m^3), for Grade A no-ash concrete; and

      (ii) Up to 40 fl. oz./100 lb of cementitious materials (2.6 L/100 kg of cementitious materials), or 1.75 gal./yd^3 (8.7 L/m^3), for Grade A-FA fly ash concrete.

   In November 2005, the market prices of SRAs ranged between $15 to 20 per gallon ($4.00 to 5.25 per liter). Taking the minimum price of $15/gal. ($4.00/L), the cost of SRA translates to about $16/$yd^3$ ($22/$m^3$) for Grade A no-ash concrete and $26/$yd^3$ ($35/$m^3$) for Grade A-FA fly ash concrete containing the maximum effective dosages of SRA.

   (b) The drying shrinkage reduced in an approximately direct proportion to the amount of SRA used. When SRA is used in excess of the above recommended dosage rates, drying shrinkage may not reduce any further.

   (c) SRA was most effective in reducing the drying shrinkage of concrete during early periods (up to about four days) of exposure to dry air when the rate of drying shrinkage is otherwise the highest. In effect, SRAs eliminated much of the initial high drying shrinkage of concrete.

   (d) By using SRAs in Grade A and A-FA concrete mixtures, the 4-day drying shrinkage was reduced by up to 67 to 83%, and the 28-day drying shrinkage reduced by up to 48 to 66%.

(e) Compared with Grade A no-ash concrete, Grade A-FA fly ash concrete generally showed a slightly higher drying shrinkage when using the same SRA dosage and required more SRA to achieve similar drying shrinkage.

2. **Autogenous shrinkage:** Overall, SRA-1, SRA-2, and SRA-3 showed similar performance in reducing the autogenous shrinkage of concrete. As for the effect of fly ash on autogenous shrinkage, compared with Grade A no-ash concrete mixtures, Grade A-FA fly ash concrete mixtures (with and without SRA) usually exhibited a lower autogenous shrinkage at early ages and then a higher autogenous shrinkage starting from 14 to 56 days.

3. **MRWRA demand:** Many times, SRA-1 and SRA-3 had an effect similar to water-reducing admixtures and significantly reduced the required amounts of mid-range water-reducing admixtures (MRWRAs). SRA-2 generally did not have a noticeable water-reducing effect.

4. **AEA demand:** Each SRA had a different effect on the AEA demand.
   (a) SRA-1 reduced the AEA-1 demand significantly, bringing it close to zero.
   (b) When SRA-2 was used with AEA-2 and MRWRA-2, the AEA-2 demand increased sharply and the air content and strength of concrete generally decreased. Use of SRA-2 with some other AEA and MRWRA might help to solve this problem.
   (c) When SRA-3 was used at its maximum dosage, it increased the AEA-3 demand.

5. **Changes in air content and slump:** Fresh concrete mixtures had an initial air content of 6 ± 1.5%. SRAs did not significantly affect the changes in air content and slump of fresh concrete mixtures during the first hour after the concrete was mixed. The changes in air content and slump during the first hour were about the same regardless of whether SRAs were used or not. Thus, there was no adverse effect of the SRAs on the initial air content, air-content stability, and slump retention of fresh concrete.

6. Compressive strength:
   (a) Usually, SRA-1 and SRA-3 either did not affect or increased the compressive strength.
   (b) Concrete mixtures made with chemical admixtures from Source 2 showed a relatively low compressive strength. An increase in SRA-2 dosage either did not affect or lowered the compressive strength. This could be due to the significant increase in AEA-2 demand with increasing SRA-2 dosage.

7. Splitting-tensile strength:
   (a) SRA-1 and SRA-3 generally did not affect the splitting-tensile strength.
   (b) SRA-2 either did not affect or lowered the splitting-tensile strength.

8. Chloride-ion penetrability:
   (a) SRA-1 and SRA-3 either did not affect or improved the resistance of concrete to chloride-ion penetration (less chloride-ion penetration into concrete).
   (b) SRA-2 did not considerably affect the chloride-ion penetrability.
   (c) Concrete mixtures containing chemical admixtures from Source 1 showed the highest resistance to chloride-ion penetration (the least penetration). The concrete mixtures

containing chemical admixtures from Source 2 generally showed the lowest resistance to chloride-ion penetration at 182 days (the highest penetration), most likely due to the relatively lower strength of these concrete mixtures.

9. **Effect of the type of coarse aggregate:**
   (a) Drying shrinkage:
      (i) Use of Aggregate 3 (crushed dolomitic limestone) often led to the lowest early-period (at 7 days) drying shrinkage, followed by Aggregate 2 (semi-crushed river gravel), and Aggregate 1 (crushed quartzite stone).
      (ii) However, the late-period (at 56 days) drying shrinkage of the concrete made with Aggregate 2 or 3 became either approximately the same as or higher than that of the concrete made with Aggregate 1. Often, use of Aggregate 2 resulted in the highest late-period drying shrinkage.

   (b) Autogenous shrinkage: Use of Aggregate 3 resulted in the lowest autogenous shrinkage, followed by Aggregate 2, and Aggregate 1 (the highest autogenous shrinkage), especially at early ages.
   (c) Compressive strength: Use of Aggregate 3 led to the highest compressive strength of concrete, followed by Aggregate 1, and Aggregate 2 (the lowest compressive strength).
   (d) Chloride-ion penetrability: The type of coarse aggregate did not noticeably affect the 182-day chloride-ion penetrability into concrete.
   (e) Thus, use of dolomitic limestone seems to be helpful in reducing early autogenous shrinkage and drying shrinkage compared with using river gravel or quartzite stone.

10. **Effect of higher cementitious materials:** Compared to Grade A-FA fly ash concrete, the high-cementitious concrete with a higher cementitious materials content (leading to lower W/Cm) generally exhibited either similar or higher autogenous shrinkage, either similar or lower drying shrinkage, higher compressive strength, and higher resistance to chloride-ion penetration.

A relatively simple way to quantify the effectiveness of SRA for reducing drying shrinkage as well as autogenous shrinkage is the drying shrinkage test. For this purpose, drying shrinkage results between the control (no SRA) and SRA-containing concrete mixtures can be compared. This does not directly measure the benefits of using SRA in actual pavements such as reduced cracking, reduced curling, longer joint spacing, improved smoothness, and lower maintenance costs.

Use of SRA can bring about the following benefits to concrete bridge decks and other types of concrete pavements:

1. Reduced autogenous shrinkage cracking.
2. Reduced drying shrinkage cracking.
3. Less corrosion of steel reinforcing bars and steel beams, and less spalling of concrete by reducing penetration of moisture and chloride ions through micro- and macro-cracks.
4. Reduced curling.
5. Longer joint spacing.

6. Less deterioration from cracking, soaking, and spalling along joints.
7. A smoother ride.
8. Fewer repairs, traffic congestions, accidents, and detouring.
9. Lower life-cycle costs.

SRA may greatly increase the effectiveness of concrete pavement repairs. So far, fresh (unshrunk) concrete has been placed to repair sections of existing aged (shrunk) concrete pavements. This often caused cracking in the repair and/or in the original concrete pavements. By using SRA, fresh concrete is made somewhat similar to preshrunk fabric/pavement and thus more compatible with existing concrete pavements. In addition, use of SRA will significantly reduce the autogenous shrinkage of typically high-cementitious repair concrete materials.

The material cost of SRA is rather high. By using SRA, however, the life and performance of bridge concrete decks and concrete pavements can be improved. Also, use of certain brands of SRA (SRA-1 and SRA-3) either reduces or eliminates the cost of using water-reducing admixtures and/or air-entraining admixtures.

The results obtained in this research should be useful in Wisconsin to villages, cities, counties, state departments, and other states as well as federal units of government.

RECOMMENDATIONS FOR FURTHER ACTION

The manufacturers of the three SRAs advise varying degrees of caution in using their SRAs in concrete subjected to freezing and thawing and/or deicing salts:

1. Euclid Chemical on SRA-1: "The de-icing salts resistance according to the ASTM C-672 Standard may not be achieved."
2. Grace Construction Products on SRA-2: "Testing should be done on your own mixes to determine your own [freezing and thawing resistance] results."
3. Degussa on SRA-3: "All projects requiring … [SRA-3] in concrete applications exposed to freezing and thawing environments must be pre-approved and require field trials prior to use."

It is known that salt-scaling test results are sensitive to the condition of finished surface of concrete specimens. Freezing and thawing tests and salt-scaling tests were not part of this research conducted for the WHRP. Without conducting an independent evaluation of freezing and thawing resistance and salt-scaling resistance of concrete, it is difficult to say if these properties will be actually influenced by the use of SRAs. As an example of the importance of an independent evaluation: before this research was conducted, it was reported that SRAs reduce compressive strength of concrete; but it turned out that two out of the three brands of SRAs evaluated can actually increase the strength of concrete.

Based on the results of this research, SRA-1 appears to be the best product, followed by SRA-3, and lastly SRA-2 (due to its high AEA-2 demand and relatively lowered concrete strength).

It is recommended that an additional study be conducted to evaluate SRA-1 and SRA-3 further for their effects on the freezing and thawing resistance and salt-scaling resistance of concrete. This may involve six concrete mixtures: Grade A control (no SRA), SRA-1, and SRA-3 mixtures; and Grade A-FA control (no SRA), SRA-1, and SRA-3 mixtures. The distinction, if any, between the control and SRA-treated concrete mixtures may show up in several weeks after start of testing.

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Chapter 1. Introduction

1.1 General

Concrete is one of the most durable construction materials. However, cracking adversely affects its durability, functionality, and appearance. A major cause of cracking is related to shrinkage-induced strains, creating stresses when concrete is restrained. The shrinkage of concrete is often attributed to drying of the concrete over a long period of time, and recent observations have also focused on early age autogenous shrinkage problems. Cracked concrete typically needs to be repaired to prevent further deterioration due to freezing and thawing, and corrosion of steel reinforcement resulting from infiltration of water with or without chloride ions from de-icing salts. The cracking leads to additional costs for repair to prevent premature deterioration of the concrete and the corrosion of reinforcement steel. Cracking can significantly reduce the service life of concrete bridge decks, pavements, and other concrete structures.

Use of shrinkage-reducing admixtures is advocated as one of the most effective ways of reducing shrinkage cracking. The reduction in capillary tension by organic agents of shrinkage-reducing admixtures decreases the concrete volume changes due to internal self-desiccation or air drying of concrete [Ribeiro et al. 2003]. "The molecules of the shrinkage-reducing admixture reduce capillary tension in concrete pores; however, these molecules may be absorbed during the hydration of cementitious materials thereby reducing the effectiveness of the shrinkage-reducing admixture over time." In one case [Bentz et al. 2002], it was reported that the use of shrinkage-reducing admixtures could increase setting time and reduce compressive strength of concrete, and affect air-void system in concrete.

Control of cracking may also be done by providing appropriate reinforcement. The reinforcement, however, does not reduce shrinkage but helps to keep cracks from widening. The use of expansive cements, coal-combustion products containing calcium sulfite or sulfate (a.k.a. clean-coal ash), and fibers is one way of counteracting shrinkage. Usually, expansive cements and clean-coal ash produce expansion by formation of ettringite. When the expansion is restrained by reinforcement, a compressive prestress is induced in concrete, compensating shrinkage.

1.2 Objectives

The objective of this research was to investigate the effectiveness of shrinkage-reducing admixtures for reducing autogenous shrinkage and drying shrinkage by performing laboratory tests on concrete mixtures made with and without fly ash. The research was also conducted to study the effects of shrinkage-reducing admixtures on other properties of concrete including slump, air content, compressive strength, splitting-tensile strength, and chloride-ion penetrability.

1.3 Scope of Work

In this research, three sources (manufacturers) of chemical admixtures were selected. For each source, concrete mixtures were made using mid-range water-reducing admixture (MRWRA), air-entraining admixture (AEA), and shrinkage-reducing admixture (SRA). For each source, three dosage rates of SRA were used: (1) zero (reference); (2) the average recommended dosage rate (average of the minimum and maximum dosage rates); and (3) the maximum recommended dosage rate. The reference (base) concrete mixtures were: (1) WisDOT Grade A (no fly ash); (2)

WisDOT Grade A-FA (fly ash); and (3) CBU High-Cm A-FA-A (30% higher cementitious materials than WisDOT Grade A-FA). These mixtures were made with crushed quartzite stone.

Using WisDOT Grade A-FA mixture proportions, additional concrete mixtures were made with two more types of coarse aggregates (semi-crushed river gravel and crushed dolomitic limestone).

The properties of concrete tested include changes in slump and air content during the first hour, initial setting time, autogenous shrinkage, compressive strength, splitting-tensile strength, drying shrinkage, and chloride-ion penetrability.

1.4 Research Plan Used

Background

- WisDOT has specified High-Performance Concrete in bridge decks.
- Cracking continues to be observed – Leads to higher life-cycle costs
  - Attributed to Shrinkage Cracking
  - Autogenous Cracking
- WisDOT attempted to control cracking
  - High-Range Water-Reducing Admixture (also called superplasticizer)
  - Steel Fibers
- Admixtures that may help to reduce shrinkage
  - Control of Autogenous and Drying Shrinkage
    - Chemical Admixtures
    - Mineral Admixtures
    - Fibers

Project Objectives

(1) Identify potential shrinkage-reducing admixtures.
(2) Document capability of each admixture for reducing autogenous and drying shrinkage.
(3) Determine the effect of shrinkage-reducing admixture on air-entrained concrete.
(4) Evaluate the effects of different aggregate types in concrete containing shrinkage-reducing admixtures.
(5) Submit a final report to WHRP that contains all test results and evaluation of the shrinkage-reducing admixture performance.
(6) Develop recommendations for use of each admixture including the dosage rate.

Project Progress

Task 1: Literature Review

An extensive review of literature applicable to the use of shrinkage-reducing admixtures and other emerging materials for concrete was conducted as a part of this project. A significant amount of literature exists regarding the use of shrinkage-reducing materials for autogenous and drying shrinkage.

Independent studies have not been reported that have specifically established the recommended dosage rates for shrinkage-reducing admixtures from various suppliers.

- Shrinkage Reducing Admixtures.
  - Euclid - Eucon SRA

- Grace Construction Products - Eclipse Plus
- Degussa (Master Builders) - Tetraguard AS20
- Compatible water-reducing admixture (mid-range WRA) and air-entraining admixture procured from each company.

❖ Wisconsin Department of Transportation's specifications Section 501 and Quality Management Program (QMP) Concrete Structures Specifications.
- Grade Series A concrete mixtures applicable to the project
- Section 501 specifies that a ¾-inch aggregate may be used for Series A concrete mixtures
- One-inch maximum sized aggregate is specified per QMP 502
- Maximum W/Cm: 0.45

Table 1-1. Grade A to A-IS Concrete Mixtures from Section 501.3.2.2 of WisDOT Specifications

Concrete grade	Cement, lb/yd^3	Class C fly ash, lb/yd^3	Slag, lb/yd^3	Total aggregate, lb/yd^3	Fine aggregate, % of total agg. (% when crushed coarse agg. is used)	Design water, gals/yd^3 (lbs/yd^3)	Max. Water, gals/yd^3 (lbs/yd^3)	W/Cm at design water
A	565	0	0	3120	30-40 (30-45)	27 (225)	32 (267)	0.40
A2	530	0	0	3190	30-40 (30-45)	25 (209)	30 (250)	0.39
A3	517	0	0	3210	30-40 (30-45)	25 (209)	30 (250)	0.40
A-FA	395	170	0	3080	30-40 (30-45)	27 (225)	32 (267)	0.40
A-S	395	0	170	3100	30-40 (30-45)	27 (225)	32 (267)	0.40
A-S2	285	0	285	3090	30-40 (30-45)	27 (225)	32 (267)	0.39
A-T	395	Total 170		3090	30-40 (30-45)	27 (225)	32 (267)	0.40
A-IP	565	0	0	3100	30-40 (30-45)	27 (225)	32 (267)	0.40
A-IS	565	0	0	3090	30-40 (30-45)	27 (225)	32 (267)	0.40

Notes:
Slump: 1 to 4 inches. Air content: 6 ± 1.5%.
Aggregate quantities are based on oven dried weight and specific gravity of 2.65.
All concrete grades shall contain a water-reducing admixture.
All concrete grades are to be air entrained.
Grade A, A-FA, A-S, A-T, A-IS, and A-IP: For concrete pavements, concrete in structures, and incidental construction.
Grade A-FA, A-S, A-T, A-IS, and A-IP: For concrete for structures if used in decks, curbs, railings, parapets, medians and sidewalks.
Grade A2 and A-S2: For concrete pavement, curb, gutter, curb & gutter, barrier, or sidewalk if placing by a slip-formed process.
Grade A3: For concrete pavement and incidental construction on low-volume state trunk highways and other roads under municipal or local jurisdiction in areas that have a proven performance record.

Task 2: Admixture Performance for Autogenous and Drying Shrinkage – Average SRA Dosages

❖ Shrinkage Reducing Admixtures and Compatible WRA and AEA
- Euclid - SRA-1, WRA-1, AEA-1
- Grace Construction Products - SRA-2, WRA-2, AEA-2
- Degussa (Master Builders) - SRA-3, WRA-3, AEA-3

❖ Reference Mixtures (Six Reference Mixtures)
- Grade A (three reference mixtures containing AEA and WRA from each admixture company)

    - Crushed quartzite stone for coarse aggregate
        - ¾-inch maximum size aggregate
    - Air Entrained - 4.5% to 7.5%
- Grade A-FA (three Reference mixtures containing AEA and WRA from each admixture company)
    - Class C Fly Ash
    - Crushed quartzite stone for coarse aggregate
        - ¾-inch maximum size aggregate
    - Air Entrained - 4.5% to 7.5%

- Mixtures Containing Shrinkage Reducing Admixtures (six mixtures total)
    - Each SRA used at the average dosage rate (average of the minimum and maximum dosage rates) recommended by its manufacturer
        - Grade A mixtures containing SRA
            - Three sources of SRA
        - Grade A-FA mixtures containing SRA
            - Three sources of SRA

- Mixtures Containing Higher Cementitious Materials Content (six mixtures total)
    - Reference mixtures without SRA (three mixtures – one for each source of admixture)
        - Cementitous Materials Content Increased by 30% Compared with A-FA Mixtures
            - Cement content increased to 514 (lb/yd^3)
            - ASTM C 618 Class C Fly Ash Content 221 (lb/yd^3)
            - Water plus AEA
    - Mixtures containing average dosages of SRAs (three mixtures – one for each source of admixture)
        - Cementitous Materials Content Increased by 30% Compared with A-FA Mixtures
            - Cement content increased to 514 (lb/yd^3)
            - ASTM C 618 Class C Fly Ash Content 221 (lb/yd^3)
            - Water plus AEA

- Testing of Concrete Mixtures (nine Reference + nine SRA mixtures)
    - Compressive Strength (4 × 8-inch cylinders) (ASTM C 39)
        - Test Ages: 1-day, 3, 7, 14, 28, 91, and 182 days
    - Splitting-Tensile Strength (4 × 8-inch cylinders) (ASTM C 496)
        - Test Ages: 1-day, 3, 7, 14, 28, 91, and 182 days
    - Autogenous Shrinkage – testing per method presented at JCI International Conference 1998
        - Testing begins at initial setting of concrete – determined per ASTM C 403
        - Sealed specimen testing in molds up to 24 hours
        - Demolded, sealed, and then tested at 3, 7, 14, 28, and 56 days
    - Drying Shrinkage (ASTM C 157) (testing terminated at project completion)
    - Electrical Indication of Chloride-Ion Penetrability into Concrete (ASTM C 1202)
        - Test Ages: 28, 56, and 182 days

Table 1-2. Mixture Details – Task 2

Mixture designation*	Laboratory mixture designation	Cement (lb/yd^3)	Class C fly ash (lb/yd^3)	Total aggregate (lb/yd^3)	Fine aggregate (% of total agg.)	Design water (lbs/yd^3)	SRA	WRA	AEA
S1-00	A-1	565	0	3120	45	225	…	WRA-1	AEA-1
S2-00	A-2	565	0	3120	45	225	…	WRA-2	AEA-2
S3-00	A-3	565	0	3120	45	225	…	WRA-3	AEA-3
S1-00-FA	A-FA-1	395	170	3080	45	225	…	WRA-1	AEA-1
S2-00-FA	A-FA-2	395	170	3080	45	225	…	WRA-2	AEA-2
S3-00-FA	A-FA-3	395	170	3080	45	225	…	WRA-3	AEA-3
S1-24	A-S1	565	0	3120	45	225	SRA-1	WRA-1	AEA-1
S2-28	A-S2	565	0	3120	45	225	SRA-2	WRA-2	AEA-2
S3-27	A-S3	565	0	3120	45	225	SRA-3	WRA-3	AEA-3
S1-24-FA	A-FA-S1	395	170	3080	45	225	SRA-1	WRA-1	AEA-1
S2-28-FA	A-FA-S2	395	170	3080	45	225	SRA-2	WRA-2	AEA-2
S3-27-FA	A-FA-S3	395	170	3080	45	225	SRA-3	WRA-3	AEA-3
S1-00-FA-H	A-FA-1A	514	221	2900	45	292	…	WRA-1	AEA-1
S2-00-FA-H	A-FA-2A	514	221	2900	45	292	…	WRA-2	AEA-2
S3-00-FA-H	A-FA-3A	514	221	2900	45	292	…	WRA-3	AEA-3
S1-24-FA-H	A-FA-S1A	514	221	2900	45	292	SRA-1	WRA-1	AEA-1
S2-30-FA-H	A-FA-S2A	514	221	2900	45	292	SRA-2	WRA-2	AEA-2
S3-27-FA-H	A-FA-S3A	514	221	2900	45	292	SRA-3	WRA-3	AEA-3

Coarse aggregate: A1, crushed quartzite stone.
* The number following S1-, S2-, or S3- indicates the approximate dosage rate of SRA in fl. oz./100 lb of cementitious materials. See Section 1.5 for more details.

Task 2A: Admixture Performance for Autogenous and Drying Shrinkage – Maximum SRA Dosages

- Testing of Concrete Mixtures with Higher SRA Dosage (six mixtures)
  - Dosages of SRA increased to the maximum dosage rates recommended by manufacturers
  - Six mixtures selected for evaluation from Task 2
    - Three mixtures without fly ash (modified mixture series A with SRA)
    - Three mixtures with fly ash (modified mixture series A-FA with SRA)
  - Compressive Strength
  - Splitting-Tensile Strength
  - Autogenous Shrinkage
  - Drying Shrinkage
  - Chloride-Ion Penetrability

Table 1-3. Mixture Details – Task 2A

Mixture designation	Laboratory mixture designation	Cement (lb/yd^3)	Class C fly ash (lb/yd^3)	Total aggregate (lb/yd^3)	Fine aggregate (% of total agg.)	Design water (lbs/yd^3)	SRA	WRA	AEA
S1-32	A-S1S	565	0	3120	45	225	SRA-1*	WRA-1	AEA-1
S2-45	A-S2S	565	0	3120	45	225	SRA-2*	WRA-2	AEA-2
S3-38	A-S3S	565	0	3120	45	225	SRA-3*	WRA-3	AEA-3
S1-32-FA	A-FA-S1S	395	170	3080	45	225	SRA-1*	WRA-1	AEA-1
S2-45-FA	A-FA-S2S	395	170	3080	45	225	SRA-2*	WRA-2	AEA-2
S3-38-FA	A-FA-S3S	395	170	3080	45	225	SRA-3*	WRA-3	AEA-3

Coarse aggregate: A1, crushed quartzite stone.
* Dosage rate of each SRA increased to the maximum dosage rate recommended by its manufacturer.

Task 3: Laboratory Evaluation of the Effect of Type of Coarse Aggregate on Shrinkage – A2 Semi-Crushed River Gravel

- Six Mixtures Selected
  - Grade A-FA Series Mixtures from Task 2
    - Semi-crushed river gravel for coarse aggregate
      - ¾-inch maximum size aggregate
    - ASTM C 618 Class C Fly Ash
    - Air Entrained - 4.5% to 7.5%

- Testing of Concrete Mixtures (six mixtures)
  - Compressive Strength
  - Autogenous Shrinkage
  - Drying Shrinkage
  - Chloride-Ion Penetrability

- Comparison of Shrinkage Results to Task 2
  - Modify dosage rate recommendation as applicable

Table 1-4. Mixture Details – Task 3

Mixture designation	Laboratory mixture designation	Cement (lb/yd^3)	Class C fly ash (lb/yd^3)	Total aggregate (lb/yd^3)	Fine aggregate (% of total agg.)	Design water (lbs/yd^3)	SRA	WRA	AEA
S1-00-FA-A2	A-FA-1-A2	395	170	3080	40	225	…	WRA-1	AEA-1
S2-00-FA-A2	A-FA-2-A2	395	170	3080	40	225	…	WRA-2	AEA-2
S3-00-FA-A2	A-FA-3-A2	395	170	3080	40	225	…	WRA-3	AEA-3
S1-24-FA-A2	A-FA-S1-A2	395	170	3080	40	225	SRA-1	WRA-1	AEA-1
S2-28-FA-A2	A-FA-S2-A2	395	170	3080	40	225	SRA-2	WRA-2	AEA-2
S3-27-FA-A2	A-FA-S3-A2	395	170	3080	40	225	SRA-3	WRA-3	AEA-3

Coarse aggregate: A2, semi-crushed river gravel.
The same dosage rate of SRA, WRA, and AEA will be applied as determined in Task 2.

Task 3A: Laboratory Evaluation of the Effect of Type of Coarse Aggregate on Shrinkage – A3 Crushed Dolomitic Limestone

- Repeat Task 3 using crushed dolomitic limestone as coarse aggregate

Table 1-5. Mixture Details – Task 3A

Mixture designation	Laboratory mixture designation	Cement (lb/yd^3)	Class C fly ash (lb/yd^3)	Total aggregate (lb/yd^3)	Fine aggregate (% of total agg.)	Design water (lbs/yd^3)	SRA	WRA	AEA
S1-00-FA-A3	A-FA-1-A3	395	170	3080	45	225	…	WRA-1	AEA-1
S2-00-FA-A3	A-FA-2-A3	395	170	3080	45	225	…	WRA-2	AEA-2
S3-00-FA-A3	A-FA-3-A3	395	170	3080	45	225	…	WRA-3	AEA-3
S1-24-FA-A3	A-FA-S1-A3	395	170	3080	45	225	SRA-1	WRA-1	AEA-1
S2-28-FA-A3	A-FA-S2-A3	395	170	3080	45	225	SRA-2	WRA-2	AEA-2
S3-27-FA-A3	A-FA-S3-A3	395	170	3080	45	225	SRA-3	WRA-3	AEA-3

Coarse aggregate: A3, crushed dolomitic limestone.
The same dosage rate of SRA, WRA, and AEA will be applied as determined in Task 2.

Task 4: Laboratory Evaluation of the SRA Effect on Air-Entrained Concrete

- Effect of SRA on Air Entrainment (twelve mixtures total)
  - Reference mixtures without SRA
    - Three mixtures without fly ash
    - Three mixtures with fly ash
  - Mixtures with SRA, each SRA used at its average dosage rate
    - Three mixtures without fly ash
    - Three mixtures with fly ash

- Testing of Effect of SRA on Air content
  - Testing of air content at 10-minute intervals – up to one hour
  - ASTM C 231 Type B meter

Table 1-6. Mixture Details – Task 4

Mixture designation	Laboratory mixture designation	Cement (lb/yd^3)	Class C fly ash (lb/yd^3)	Total aggregate (lb/yd^3)	Fine aggregate (% of total agg.)	Design water (lbs/yd^3)	SRA	WRA	AEA
S1-00-air	A-1-air	565	0	3120	45	225	…	WRA-1	AEA-1
S2-00-air	A-2-air	565	0	3120	45	225	…	WRA-2	AEA-2
S3-00-air	A-3-air	565	0	3120	45	225	…	WRA-3	AEA-3
S1-00-FA-air	A-FA-1-air	395	170	3080	45	225	…	WRA-1	AEA-1
S2-00-FA-air	A-FA-2-air	395	170	3080	45	225	…	WRA-2	AEA-2
S3-00-FA-air	A-FA-3-air	395	170	3080	45	225	…	WRA-3	AEA-3
S1-24-air	A-S1-air	565	0	3120	45	225	SRA-1	WRA-1	AEA-1
S2-28-air	A-S2-air	565	0	3120	45	225	SRA-2	WRA-2	AEA-2
S3-27-air	A-S3-air	565	0	3120	45	225	SRA-3	WRA-3	AEA-3
S1-24-FA-air	A-FA-S1-air	395	170	3080	45	225	SRA-1	WRA-1	AEA-1
S2-28-FA-air	A-FA-S2-air	395	170	3080	45	225	SRA-2	WRA-2	AEA-2
S3-27-FA-air	A-FA-S3-air	395	170	3080	45	225	SRA-3	WRA-3	AEA-3

Coarse aggregate: A1, crushed quartzite stone.
The same dosage rate of SRA, WRA, and AEA will be used as determined in Task 2.

Task 5: Evaluation of Test Results
Test results were evaluated for each of the concrete mixtures tested for Tasks 2, 3, and 4. The effectiveness of the shrinkage-reducing materials for reduction of autogenous and drying shrinkage was noted. To determine the effectiveness of the chemical admixtures and other materials, shrinkage test results were compared to results obtained from a reference concrete mixture without shrinkage-reducing admixture.

Task 6: Recommendations for Use of SRA
Recommendations were made that included information on the manufacturers of the shrinkage-reducing admixtures and other materials, recommended dosage rates for reducing autogenous and drying shrinkage, effects of the admixtures on air-entrained concrete, effects of aggregate type, etc.

Task 7: Reports
Quarterly Reports and Final Report.

The test results for the concrete mixtures made in Tasks 2 and 2A are also available elsewhere [Sutaria 2005].

1.5 Mixture Designation

The designation of a concrete mixture was based on the source of chemicals, dosage rate of SRA, whether fly ash was used, whether higher amounts of cementitious materials were used, type of coarse aggregate, and whether the mixture was for monitoring changes in air content and slump. The mixtures were designated using the following coding system:

S*x*-*yy*(-FA)(-H)(-Az)(-air)

where,
x: Chemical admixtures source number;
yy: Nominal SRA dosage rate (fl. oz./100 lb of cementitious materials);
FA: Fly ash used to replace 35% of cement;
H: Higher amounts of cementitious materials content (about 735 vs. 565 lb/yd^3);
z: Coarse aggregate type number, if other than aggregate Type 1 was used; and
air: Air content change during the first 1 hour evaluated.

Refer to Table 3-11 for manufacturers' recommended dosage rates of SRAs.

Examples of mixture designations:

S1-00

This mixture was made with: (1) chemical admixtures from Source 1 (Euclid); (2) zero SRA-1; (3) zero fly ash; (4) about 565 pounds of cement; and (4) coarse aggregate Type 1 (crushed quartzite stone).

S2-30-FA-H

This mixture was made with: (1) chemical admixtures from Source 2 (Grace); (2) 30 fl. oz. of SRA-2 per 100 pounds of cementitious materials; (3) fly ash; (4) about 735 pounds of cementitious materials; and (5) coarse aggregate Type 1 (crushed quartzite stone).

S3-27-FA-A2

This mixture was made with: (1) chemical admixtures from Source 3 (Degussa); (2) 27 fl. oz. of SRA-3 per 100 pounds of cementitious materials; (3) fly ash; (4) about 565 pounds of cementitious materials; and (5) coarse aggregate Type 2 (semi-crushed river gravel).

Chapter 2. Literature Review

2.1 Introduction

Shrinkage cracking is a major cause of concern for concrete structures. In addition to weakening the structure, these shrinkage cracks have the potential to allow infiltration of moisture and chloride ions that accelerate the corrosion of steel reinforcement and reduce the durability of concrete [Gilbert 2001]. The four main types of shrinkage associated with concrete are plastic shrinkage, autogenous shrinkage, carbonation shrinkage, and drying shrinkage.

Plastic shrinkage is associated with moisture loss from freshly poured concrete into the surrounding environment. Autogenous shrinkage is the early shrinkage of concrete caused by loss of water from capillary pores due to the hydration of cementitious materials, without loss of water into the surrounding environment. This type of shrinkage tends to increase at a lower water to cementitious materials ratio (W/Cm) and at a higher cement content of a concrete mixture. Carbonation shrinkage is caused by the chemical reactions of various cement hydration products with carbon dioxide present in the air. This type of shrinkage is usually limited to the surface of the concrete. Drying shrinkage can be defined as the volumetric change due to the drying of hardened concrete. This type of shrinkage is caused by the diffusion of water from hardened concrete into the surrounding environment [Mokarem 2002]. In the following sections more details about the mechanisms of autogenous shrinkage and drying shrinkage are described.

2.2 Autogenous Shrinkage

Autogenous shrinkage is the volume change of the cement paste due to self-desiccation and chemical shrinkage after initial setting has occurred. Autogenous shrinkage is a microscopic volume change occurring after the initial setting in situations where the supply of water from outside of concrete is not enough. As the hydration of cementitious materials progresses, very fine pores are produced within the hardened cement paste due to the formation of calcium silicate hydrate (CSH) gel. As the hydration further progresses, capillary pore water and then gel water is consumed and menisci are produced in these pores due to a lack of water supply from outside. As a result of negative pressure in the pores, hardened paste shows shrinkage [JCI 1998].

Autogenous shrinkage is the early shrinkage of concrete caused by the loss of water from capillary pores due to the hydration of cementitious materials, without the loss of water into the surrounding environment. This phenomenon is known as self-desiccation of concrete. Self-desiccation occurs in all concrete irrespectively of the W/Cm ratio [Aïtcin 2003]. However, its effects are very different in normal concrete and high-performance concrete. Generally concrete with a low W/Cm may be defined as high-performance concrete [Aïtcin 2003]. In high-performance concrete, significantly more cementitious materials and less mixing water are used compared with normal concrete. In normal concrete with W/Cm above about 0.45, there is substantially more water than required for hydration of cementitious material particles. This excess amount of water is contained in well-connected capillaries. Menisci created by the process of self-desiccation occur in large capillaries. But, stresses generated in large capillaries are very low, resulting in lower autogenous shrinkage. On the other hand, in case of high-performance concrete, pore network is essentially composed of fine capillaries due to low W/Cm and high amounts of cementitious hydration products. When self-desiccation starts to take place, very high tensile stresses are generated in these fine pores, resulting in higher autogenous shrinkage [Aïtcin 2003].

Bentz and associates [Bentz et al. 2002] explained autogenous shrinkage of high-performance concrete as follows: In high-performance concrete a dense microstructure can form within a few days, preventing the introduction of external curing water. The reaction products that are formed during the hydration of cement occupy less space than the corresponding reactants. Cement paste hydrating under sealed condition self-desiccate and creates empty pores within the hydration paste structure. If external water is not available to fill these empty pores, then large tensile stresses are generated in the pores, resulting in considerable amount of shrinkage.

A study [Holt 2002] reported on very early age autogenous shrinkage. It explains the phenomenon of chemical shrinkage as follows: the primary suspect for early age (< 1 day) autogenous shrinkage is chemical shrinkage, which is an internal volume reduction, while autogenous shrinkage is an external volume reduction. "The basic reactions of cement clinker are well understood and generally defined by four reactions of C_3S, C_2S, C_3A, and C_4AF. Each of these requires water for reaction, is exothermic, and results in a decreased volume of the reaction products" [Holt 2002]. At later ages, the contribution of chemical shrinkage to autogenous shrinkage will slow as the concrete gains strength and resists stresses due to chemical shrinkage. Still the autogenous shrinkage will continue as the cement hydration reaction lowers the internal relative humidity, which is known as self-desiccation [Holt 2001].

2.3 Drying Shrinkage

Both autogenous shrinkage and drying shrinkage occur due to decrease in humidity in the hardened cementitious paste. Drying shrinkage is different from autogenous shrinkage with regard to the mechanism of a decrease in humidity. Drying shrinkage is caused by the diffusion of water from concrete into the outer surrounding environment [JCI 1998].

Drying shrinkage refers to the reduction in concrete volume resulting from the loss of capillary water by evaporation. This shrinkage causes an increase in tensile stress of restrained concrete, which leads the concrete to cracking, internal warping, and external deflection, even if the concrete is not subjected to any kind of external loading.

According Mehta and Monteiro [1993] the change in volume of drying concrete is not equal to the volume of water removed. The reason is that the loss of water from large capillaries (> 50 nm) may be considered as free water, and its removal does not cause a volume change. Loss of water held by capillary tension in small capillaries (5 to 50 nm) may cause shrinkage of concrete. It is also possible that shrinkage is related to the removal of interlayer water, which is also known as zeolite water. This water is associated with CSH structure. "It has been suggested that a monomolecular water layer between the layer of CSH is strongly held by hydrogen bonding. The interlayer water is lost only on strong drying (i.e., below 11 percent relative humidity). The CSH structure shrinks considerably when the interlayer water is lost" [Mehta and Monteiro 1993].

The drying shrinkage of hydrated cement paste begins at the surface of the concrete. Depending on the relative humidity of the ambient air and the size of capillaries in the cement paste structure, drying shrinkage progresses more or less rapidly through concrete. The drying in ordinary concrete is, therefore, rapid because the capillary network is well connected and contains large capillaries. In the case of high-performance concrete, drying shrinkage is slow because the capillaries are very fine and soon get disconnected by hydration products [Aïtcin 2003].

2.4 Factors Affecting Shrinkage of Concrete

The magnitude of shrinkage deformations depends on concrete mixture proportions and material properties, method of curing, ambient temperature and humidity conditions, and geometry of the concrete element [Mehta and Monteiro 1993, Neville 1995].

Cement properties and cement content in concrete influence concrete shrinkage. As the fineness of cement increases, so does the hydration rate of cement, leading to an increase in the autogenous shrinkage of concrete. Bentz and associates [Bentz et al. 2001] studied the influence of cement particle-size distribution on early age autogenous strain and stress in concrete. The experimental results indicate that a small autogenous expansion as opposed to shrinkage may be produced through the use of coarser cements. Therefore early age cracking could possibly be avoided. Although coarser particles of cement are relatively beneficial in minimizing early age cracking, they may be detrimental to long-term strength [Bentz et al. 2001]. Autogenous shrinkage of concrete is also influenced by the mineral composition of cement. Increased fineness and increased content of C_3A and C_4AF contributes to the increase in early shrinkage of concrete [Aïtcin 2003]. Mehta and Monteiro [1993] state that the variation in fineness and composition of portland cement affect the rate of hydration, but not the volume and characteristics of hydration products. Therefore, normal changes in fineness and composition of cement have negligible effect on drying shrinkage of concrete [Mehta and Monteiro 1993]. Higher cement content with lower W/Cm in concrete results in higher autogenous shrinkage due to self-desiccation and chemical shrinkage, but may reduce drying shrinkage due to dense microstructure and poor pore connectivity.

Modulus of elasticity is the most important property of aggregate that directly influences drying shrinkage of concrete. Troxell and associates [Troxell et al. 1958] reported that the drying shrinkage of concrete increased 2.5 times when an aggregate with high elastic modulus was substituted by an aggregate with low elastic modulus. Large aggregates permit the use of a leaner concrete mixture, and resulting in lower shrinkage. Increase in the aggregates content also reduces the shrinkage of concrete [Neville 1995]. The pore structure of aggregate particles may have a strong effect on autogenous shrinkage. Aggregate particles may contain water in coarse pores, which provides the “internal curing” for hydrating cement paste hence reducing autogenous shrinkage. Lura and associates [Lura et al. 2001] reported that the addition of light-weight aggregates (LWA) in the concrete mixture reduces the self-desiccation of cement paste. In their study LWA concrete with aggregate having a degree of saturation 50 % and 100 % exhibited autogenous swelling, up to an age of 90 days. On the other hand, normal weight aggregate concrete mixture exhibited shrinkage of up to 470 micronstrain at the same age. LWA concrete showed low drying shrinkage at the initial age, but at later ages the rate of shrinkage was higher compared with normal weight aggregate concrete due to lower modulus of elasticity of LWA offering less resistance to the shrinkage of the cement paste. Matsushita and Tsuruta [Matsushita and Tsuruta 1998] reported effects of the type of coarse aggregate on autogenous shrinkage of concrete. The coarse aggregate studied included Andesite, Crystalline Schist, and Amphibolite. It was concluded that if the volume of coarse aggregate was maintained constant, the type of coarse aggregate negligibly affected the autogenous shrinkage of high-strength concrete.

The particle size distribution, morphology, and surface characteristics of fly ash used as a mineral admixture has a considerable influence on the water requirement, workability, and rate of strength development of concrete [Mehta and Monteiro 1993]. Class C fly ash is more chemically active than the low-calcium Class F fly ash. Yuan and Cook [1983] reported that the replacement of cement by Class C fly ash had little influence on drying shrinkage of concrete. In a recent investigation on self-consolidating concrete [Naik et al. 2005], replacement of 30% and 50% of cement with Class C fly ash increased drying shrinkage. Tangtermsirikul [1998] studied effect of chemical composition, particle size, and replacement percentages of fly ash on the autogenous shrinkage of cement paste. Fly ash with higher SO_3 content exhibited lower autogenous shrinkage. As for the effect of particle size of fly ash, paste containing fly ash with a smaller average size than cement exhibited higher autogenous shrinkage compared with plain cement paste. Although replacement level of fly ash is not as influential as the particle size of fly ash, a higher replacement level of cement with fly ash helped to reduce the autogenous shrinkage.

A high temperature and a low relative humidity of the ambient environment accelerate the diffusion of the adsorbed water and capillary water into the atmosphere, and consequently, increases the drying shrinkage of concrete. An increase in the atmospheric humidity slows down the rate of moisture flow from the interior to the outer surface of concrete. At 100% relative humidity, it is assumed that the drying shrinkage of concrete is zero [Mehta and Monteiro 1993].

The size and shape of a concrete element have a considerable effect on the rate and total amount of shrinkage. The size and shape are often considered together as the volume-to-surface area ratio. A high volume-to-surface ratio usually results in lower shrinkage magnitudes [Neville 1995].

2.5 Shrinkage-Reducing Admixtures (SRAs)

Shrinkage-reducing admixtures (SRAs) have been used for several years to reduce the autogenous shrinkage and drying shrinkage of concrete. References on shrinkage-reducing admixtures in technical literature trace their origin to Japan during in the 1980s. SRA composition varies depending on the manufacturer, but it generally consists of a surface-active organic polymer solution. SRAs are designed with the specific aim of reducing the surface tension of the pore solution. As a result, SRA reduces capillary stresses within the pore structure that are responsible for the shrinkage in concrete that is subjected to air-drying or internal self-desiccation [Roncero et al. 2003].

Ribeiro and associates [Ribeiro et al. 2003] have reported effectiveness of shrinkage-reducing admixtures on different concrete mixtures using two SRA products at different dosage rates. All the mixtures were prepared with 25% replacement of cement by fly ash. Their study showed a maximum reduction in drying shrinkage of about 30% with the use of SRA. They attributed the reduction in shrinkage to the reduction of capillary tension in concrete pores with the use of SRAs. The reduction in shrinkage was related to admixture dosage. The maximum reduction in drying shrinkage was obtained with the maximum dosage of SRA. It was also observed that there was a reduction in compressive strength due to incorporation of SRAs. The reduction in compressive strength was more pronounced at early ages.

Roncero and associates [Roncero et al. 2003] evaluated the influence of SRA on the microstructure and long-term behavior of concrete. In their study, concrete mixtures were prepared at 0.4 W/C and with 0% (reference), 1%, and 2% of SRA by mass of cement. After two years of drying at 50% relative humidity, the drying shrinkage strain reduced by about 26%

and 51% for the concrete mixtures with 1% and 2% of SRA, respectively, compared to the reference mixture. On the other hand, in sealed condition, a slight expansion was observed for both the 1% and 2% SRA concrete mixtures. The reference concrete mixture showed autogenous shrinkage, especially during the first three weeks. A reduction in compressive strength was also observed with incorporation of SRA.

Berke and associates [Berke et al. 2003] have studied the performance of concrete containing a brand of glycol-ether based SRA. The aim of the study was to produce concrete with good quality air-void systems needed for freezing and thawing resistance, while reducing shrinkage with the SRA. The results showed that good air-void systems were obtainable with that particular glycol-ether based SRA. However, this was not always the case, especially when the air-entraining admixture (AEA) and mixture proportions were not properly selected to maintain the quality of the air-void system when using the SRA.

Chapter 3. Materials

3.1 Portland Cement

ASTM Type I portland cement was used in this research. The chemical composition and physical properties of the cement are presented in Table 3-1 and Table 3-2, respectively, along with the requirements of ASTM Standard Specification for Portland Cement (C 150). The cement met the chemical and physical requirements of ASTM C 150.

Table 3-1. Chemical Composition of Portland Cement

Item	Test result (% by mass)	Standard requirement of ASTM C 150 for Type I cement
Silicon dioxide, SiO_2	20.2	…
Aluminum oxide, Al_2O_3	4.5	…
Ferric oxide, Fe_2O_3	2.6	…
Calcium oxide, CaO	64.2	…
Magnesium oxide, MgO	2.5	6.0 maximum
Sulfur trioxide, SO_3	2.4	3.0 maximum, when $C_3A \leq 8\%$ 3.5 maximum, when $C_3A > 8\%$
Loss on ignition	1.4	3.0 maximum
Insoluble residue	0.4	0.75 maximum
Free lime	1.5	…
Tricalcium silicate, C_3S	67	…
Tricalcium aluminate, C_3A	8	…
Total alkali as sodium oxide	0.53	…

Table 3-2. Physical Properties of Portland Cement

ASTM	Item	Test result	Standard requirement of ASTM C 150 for Type I cement
C 185	Air content of mortar (volume %)	6	12 maximum
C 204	Fineness (specific surface) by Blaine air-permeability apparatus (m^2/kg)	364	280 minimum
C 151	Autoclave expansion (%)	0.07	0.80 maximum
C 109	Compressive strength of Cement Mortars (psi):		
	1 day	2080	…
	3 days	3590	1740 minimum
	7 days	4400	2760 minimum
	28 days	5620	…
C 191	Initial time of setting by Vicat needle (minutes)	105	Between 45 to 375
C 188	Density (g/cm^3)	3.15	…

3.2 Fly Ash

ASTM Class C fly ash was obtained from the We Energies' Pleasant Prairie Power Plant (P4) for this research. The chemical composition and physical properties of the fly ash are shown in Table 3-3 and Table 3-4, respectively, along with the requirements of ASTM Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete (C 618).

Table 3-3. Chemical Composition of Fly Ash

Item	Test result (% by mass)	Requirement of ASTM C 618 for Class C fly ash
Silicon dioxide, SiO_2	36.2	…
Aluminum oxide, Al_2O_3	19.0	…
Ferric oxide, Fe_2O_3	5.6	…
$SiO_2 + Al_2O_3 + Fe_2O_3$	60.8	50 minimum
Calcium oxide, CaO	23.4	…
Magnesium oxide, MgO	3.7	…
Sulfur trioxide, SO_3	2.1	5.0 maximum
Sodium oxide, Na_2O	1.0	…
Potassium oxide, K_2O	1.0	…

Table 3-4. Physical Properties of Fly Ash

Item	Test result	Requirement of ASTM C 618 for Class C fly ash
Strength activity index (% of Control) 7 days 28 days	 98 99	75 minimum, at either 7 or 28 days
Water requirement (% of Control)	91	105 maximum
Autoclave expansion (%)	0.05	Between -0.80 to +0.80
Density (g/cm^3)	2.53	…

3.3 Fine Aggregate (Sand)

Natural sand was used as fine aggregate in this research. The properties of fine aggregate are shown in Table 3-5. Sieve analysis results are presented in Table 3-6 along with the grading requirements of ASTM Standard Specification for Concrete Aggregates (C 33). The sand met the requirements of ASTM C 33.

Table 3-5. Properties of Fine Aggregate (Sand)

ASTM	Item	Test result
C 128	Bulk specific gravity on oven-dry basis Bulk specific gravity on SSD* basis Apparent specific gravity SSD* Absorption (%)	2.62 2.66 2.72 1.37
C 29	Bulk density (lb/ft^3) Void content (%)	112 33

* Saturated surface-dry

Table 3-6. Gradation of Fine Aggregate (Sand)

	Fineness modulus	Amounts finer than each sieve (% by mass)						
		3/8-in., 9.5 mm	No. 4, 4.75 mm	No. 8, 2.36 mm	No. 16, 1.18 mm	No. 30, 600 µm	No. 50, 300 µm	No. 100, 150 µm
Test Result	2.7	100	99	87	71	50	18	4
Requirement of ASTM C 33	2.3~3.1	100	95 - 100	80 - 100	50 - 85	25 - 60	5 - 30	0 - 10

3.4 Coarse Aggregates

Three types of coarse aggregate were used in this research: A1, crushed quartzite stone; A2, semi-crushed river gravel (from Chippewa River in Eau Claire, WI); and A3, crushed dolomitic limestone (from Sussex, WI). The physical properties and the gradation of the coarse aggregates are shown in Table 3-7 and Table 3-8, respectively, along with the requirements of ASTM C 33. The coarse aggregates met the requirements of ASTM C 33. All of the three types of coarse aggregate had a nominal maximum size of 3/4 inches and met the grading requirements for WisDOT Size No. 1 (AASHTO No. 67).

Table 3-7. Properties of Coarse Aggregates

ASTM	Item	A1 result	A2 result	A3 result	Requirements of ASTM C 33
C 117	Materials finer than 75µm by washing (%)	0.5	0.6	0.9	1.0 maximum
C 127	Bulk specific gravity on oven-dry basis	2.65	2.60	2.89	…
	Bulk specific gravity on SSD* basis	2.66	2.64	2.94	…
	Apparent specific gravity	2.68	2.70	3.05	…
	SSD* Absorption (%)	0.42	1.3	1.4	…
C 29	Bulk density (lb/ft^3)	97	108	…	…
	Void content (%)	42	33	…	…

* Saturated surface-dry

Table 3-8. Gradation of Coarse Aggregates

	Amounts finer than each sieve (% by mass)					
	1-in., 25.0 mm	3/4-in., 19.0 mm	1/2-in., 12.5 mm	3/8-in., 9.5 mm	No. 4, 4.75 mm	No. 8, 2.36 mm
A1 Result	100	95	55	31	3	2
A2 Result	100	92	62	43	5	2
A3 Result	100	92	47	20	8	5
Requirement of ASTM C 33 for Size No. 67	100	90 - 100	…	20 - 55	0 - 10	0 - 5

3.5 Chemical Admixtures

In total, three shrinkage-reducing admixtures were identified and evaluated in this project.

The properties of the mid-range water-reducing admixtures (MRWRAs), air-entraining admixtures (AEAs), and shrinkage-reducing admixtures (SRAs) used for this research are listed in Table 3-9 to Table 3-11, including their designations, brand names (trade names), chemical names, water content, specific gravity, and manufactures' recommended dosage rates. Admixtures with designation "1" were supplied by Euclid Chemical Company; "2" by Grace Construction; and "3" by Degussa (Master Builders).

Table 3-9. Properties of Mid-Range Water-Reducing Admixtures

Admixture designation	Brand names	Chemical names or ingredients	Water content (%)	Specific gravity	Recommended dosage rate
MRWRA-1	Eucon MR	Calcium nitrate tetrahydrate Calcium lignosulphonate Sodium thiocyanate Sodium glucoheptonate	60	1.29	4 - 14 fl. oz./100 lb of "cement"
MRWRA-2	Darcem 65	Aqueous solution of lignosulfonate Melamine polymer Amine	60	1.14	3 - 9 fl. oz./100 lb of "cement"
MRWRA-3	Polyheed 997	Sulphonate salt solution	60	1.27	3 - 15 fl. oz./100 lb of "cementitious material"

Table 3-10. Properties of Air-Entraining Admixtures

Admixture designation	Brand names	Chemical names or ingredients	Water content (%)	Specific gravity	Recommended dosage rate (fl. oz./100 lb of "cement")
AEA-1	AEA-92	Sodium olefin sulfonate Water	93	1.01	0.5 - 1
AEA-2	Darex II AEA	Alkaline solution of fatty acid salts Water	90	1.04	0.5 - 5
AEA-3	Micro Air	Alpha olefin sulfonate Potassium hydroxide Water	90	1.01	0.125 - 1.5

Table 3-11. Properties of Shrinkage-Reducing Admixtures

Admixture designation	Brand names	Chemical names or ingredients	Water content (%)	Specific gravity	Recommended dosage rate	Recommended dosage rate when converted for WisDOT Concrete Grades A and A-FA (fl. oz./100 lb of cementitious materials)
SRA-1	Eucon SRA	Diethylene glycol monobutyl ether	0	0.95	1 - 2% by mass of “cementitious"	16.2 - 32.3
SRA-2	Eclipse Plus	Aliphatic propylene glycol ethers	0	0.96	0.5 - 2.0 gal/yd^3	11.3 - 45.3
SRA-3	Tetraguard AS20	Polyoxyalkylene alkyl ether	0	0.99	1.0 - 2.5% by mass of cementitious materials	15.3 - 38.4

Chapter 4. Specimen Preparation and Test Methods

4.1 Mixing and Specimen Preparation

Test specimens of concrete were made and cured according to the ASTM Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory (C 192).

The concrete mixers used in this research were electrical power-driven, revolving drum, tilting mixers.

Concrete mixing and specimen preparation were executed as follows:

Before starting the rotation of the mixer, the coarse aggregate and some of the mixing water were added in the mixing drum. The mixer was then started and was stopped after it turned a few revolutions. Next, fine aggregate (sand) was added, and the mixer was started again and was stopped again after it turned a few more revolutions. Finally, the cement, the rest of the water, and MRWRA were added.

After this, the mixer was started and it turned for three minutes; during this time, AEA and then SRA were added. This was followed by a 3-minute rest, and a final 2-minute mixing. When necessary, water, MRWRA, and/or AEA were incrementally added during the mixing process to modify the concrete mixture to obtain the desired slump (1 to 4 inches) and air content (4.5 to 7.5%). Most of the Grade A and Grade A-FA mixtures were produced to achieve the design W/Cm of 0.40. The CBU high-Cm A-FA-A mixtures had a lower W/Cm (0.30 to 0.36).

The properties of freshly mixed concrete were determined, and test specimens were cast for the evaluation of time of initial setting, autogenous shrinkage, strength, drying shrinkage, and chloride-ion penetrability of concrete.

The specimens for time of setting and autogenous shrinkage were kept in sealed condition.

To prevent evaporation of water from the unhardened concrete specimens for strength, drying shrinkage, and chloride-ion penetrability, the cast specimens were covered with either lids or plastic sheets. The specimens were removed from the molds 24 ± 8 hours after casting. The demolded specimens were moist cured at 73 ± 3°F, either in a moist room at a relative humidity of not less than 95% or in lime-saturated water.

4.2 Test Methods

The tests performed on fresh concrete are shown in Table 4-1. The test methods, specimens, and ages for other properties are shown in Table 4-2.

Table 4-1. Test Methods for Fresh Concrete Properties

Property	Test Method
Slump	ASTM C 143
Density	ASTM C 138
Air content by the pressure method	ASTM C 231
Concrete temperature	ASTM C 1064

Table 4-2. Test Methods for Other Properties of Concrete

Property	Test method	Specimen	Number tested each time	Test ages
Time of initial setting	ASTM C 403	6" diameter × 5" high sieved mortar	2	Until time of initial setting
Autogenous shrinkage	UWM-CBU*	4" × 4" × 13 ¾" beam	3	Time of initial setting and between 15 to 18 hours (≈ 0.7 days); and 1, 3, 7, 14, 28, and 56 days.
Compressive strength	ASTM C 39	4" diameter × 8" high cylinder	3	1, 3, 7, 14, 28, 91, and 182 days
Splitting-tensile strength	ASTM C 496	4" diameter × 8" high cylinder	3	1, 3, 7, 14, 28, 91, and 182 days
Drying shrinkage	ASTM C 157	3" × 3" × 11 ¼" beam	3	1 and 28 days during water storage. Subsequently after 4, 7, 14, 28, 56, 112 days during air storage at a relative humidity of 50 ± 4%.
Electrical indication of chloride-ion penetrability	ASTM C 1202	2" thick slice saw-cut from the top of the 4" diameter × 8" high cylinder	3	28, 56, and 182 days

* A detailed and working improvement built upon a test procedure originally drafted by the Japan Concrete Institute (JCI) [JCI 1998]. For more details, see Appendix A – Setup and Test Methods for Autogenous .

4.3 Pictures of Specimens and Testing

Pictures of test apparatus, specimens, and testing are presented in Fig. 4-1 through Fig. 4-20.

Fig. 4-1. Slump test of fresh concrete

Fig. 4-2. Testing for air content of fresh concrete

Fig. 4-3. Wet-sieving of concrete through a 4.75-mm sieve for obtaining a sample for initial setting time test of concrete

Fig. 4-4. Testing for initial setting time of concrete by penetration resistance

Fig. 4-5. Autogenous shrinkage beam mold

Fig. 4-6. Casting of a concrete beam for autogenous shrinkage test

Fig. 4-7. Sealed autogenous shrinkage beam immediately after casting

Fig. 4-8. Sealed autogenous shrinkage beam with its aluminum bushings removed, and consolidated again by gently tapping the sides and ends with a rubber mallet

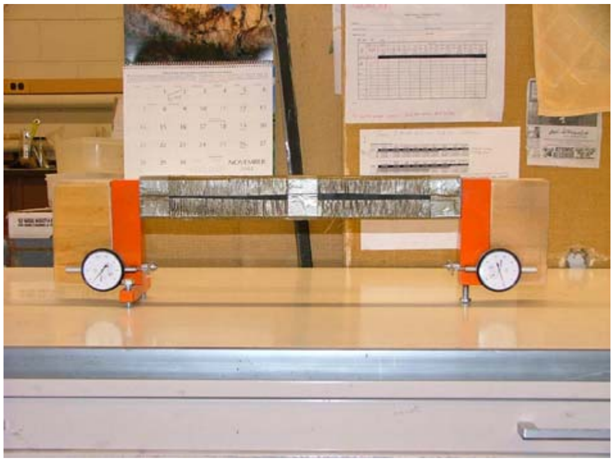


Fig. 4-9. Comparator for autogenous shrinkage test

Fig. 4-10. Autogenous shrinkage test setup while beams are in molds

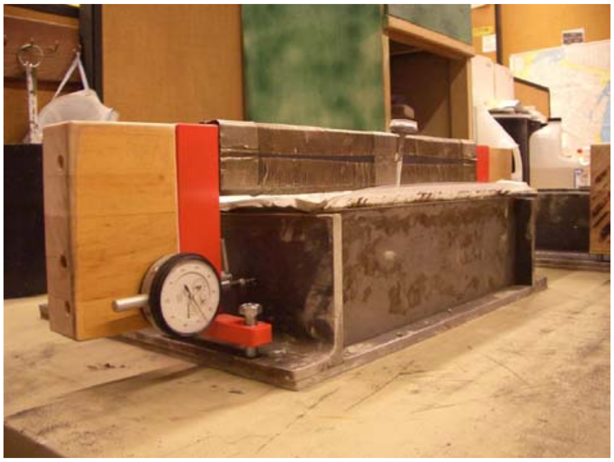


Fig. 4-11. Autogenous shrinkage test setup

Fig. 4-12. Storage of autogenous shrinkage beams, sealed with aluminum adhesive tape, following removal from molds

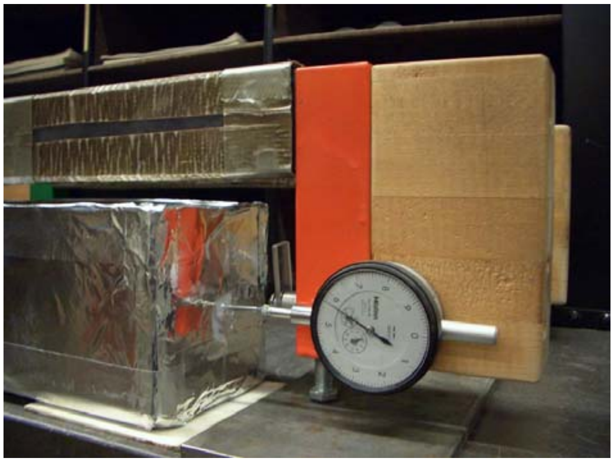


Fig. 4-13. Autogenous shrinkage test setup after beams are sealed with aluminum adhesive tape

Fig. 4-14. Drying shrinkage beam mold with plastic liners

Fig. 4-15. Drying shrinkage test setup

Fig. 4-16. Air storage of drying shrinkage beam specimens, following 28 days of moist curing in lime-saturated water

Fig. 4-17. Compressive strength test of concrete

Fig. 4-18. Splitting tension strength test of concrete

Fig. 4-19. Setup for electrical indication of chloride-ion penetrability test

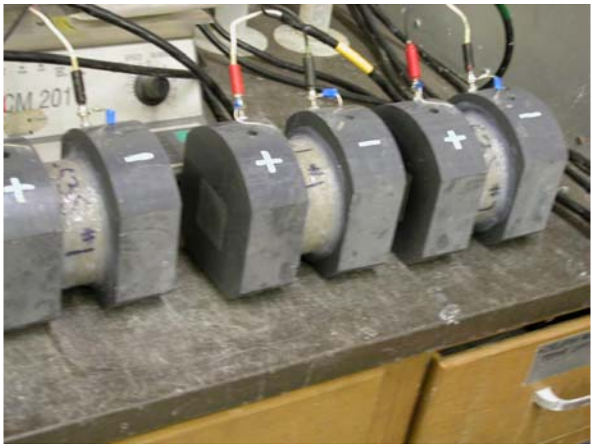


Fig. 4-20. Specimens in contact with 3% NaCl (–) and 0.3 N NaOH (+) solutions and subject to 60 V DC

Chapter 5. Concrete Mixtures Containing Chemical Admixtures from Source 1

5.1 Mixture Proportions and Time of Initial Setting (Chemical 1)

Table 5-1 shows the mixture proportions and fresh properties of WisDOT Grade A, Grade A-FA, and CBU high-Cm A-FA-A concrete mixtures made with chemical admixture from Source 1 (Euclid) and coarse aggregate A1 (crushed quartizite stone). The table also includes Grade A-FA mixtures made with coarse aggregates A2 (semi-crushed river gravel) and A3 (crushed dolomitic limestone).

Table 5-1. Mixture Proportions and Fresh Properties of Concrete (Chemical 1)

Mixture designation*	S1-00	S1-24	S1-32	S1-00-FA	S1-24-FA	S1-32-FA	S1-00-FA-H	S1-24-FA-H	S1-00-FA-A2	S1-24-FA-A2	S1-00-FA-A3	S1-24-FA-A3
Laboratory mixture designation	A-1	A-S1	A-S1S	A-FA-1	A-FA-S1	A-FA-S1S	A-FA-1A	A-FA-S1A	A-FA-1-A2	A-FA-S1-A2	A-FA-1-A3	A-FA-S1-A3
Cement (lb/yd^3)	541	550	551	394	392	384	509	514	386	394	393	394
Class C Fly Ash (lb/yd^3)	0	0	0	170	169	165	219	221	166	170	169	170
Water (lb/yd^3)	237	215	216	226	210	223	238	224	221	203	226	221
Fine aggregate, SSD (lb/yd^3)	1360	1380	1390	1400	1400	1360	1310	1320	1220	1250	1400	1400
Coarse aggregate, ≤ 3/4 in., SSD (lb/yd^3)	1650	1680	1680	1700	1690	1650	1580	1600	1830	1870	1710	1710
MRWRA-1 (fl. oz./yd^3)	70.7	21.3	21.5	22.0	21.8	21.4	29.1	29.2	12.7	5.2	23.6	6.0
AEA-1 (fl. oz./yd^3)	3.2	0.8	0.6	4.0	0.5	1.4	5.8	1.3	4.1	0.5	8.0	0.5
SRA-1 (fl. oz./yd^3)	0	133	178	0	136	177	0	177	0	137	0	136
W/Cm	0.44	0.39	0.39	0.40	0.37	0.41	0.33	0.30	0.40	0.36	0.40	0.39
Slump (in.)	2.25	2	2	2	2	1.5	2	2	3	3.5	2.4	2.5
Air content (%)	7.2	7.5	6.7	6.0	6.4	7.5	5.7	6.0	6.0	6.4	7.5	6.8
Air temperature (°F)	69	69	69	69	69	69	69	68	70	69	68	68
Concrete temperature (°F)	70	70	70	70	70	70	70	70	69	71	66	68
Density (lb/ft^3)	141	142	143	144	143	141	143	144	142	144	144	145

* The number following S1- indicates the approximate dosage rate of SRA-1 in fl. oz./100 lb of cementitious materials. See Section 1.5 for more details.

Fig. 5-1 and Fig. 5-2 show the influence of SRA-1 on MRWRA-1 demand and W/Cm of concrete, and Fig. 5-3 and Fig. 5-4 show the influence of SRA-1 on AEA-1 demand and air content of concrete.

SRA-1 had a water-reducing effect. Concrete mixtures containing SRA-1 required only minimal amounts of MRWRA-1 and AEA-1. Incorporation of SRA-1 in Grade A mixtures led to significantly reduced required dosage rates of MRWRA-1 and a lower W/Cm (Fig. 5-1). When SRA-1 was used in Grade A-FA mixtures made with coarse aggregates A2 and A3, the required amounts of MRWRA-1 again decreased considerably (Fig. 5-2). Use of SRA-1 in any grade of concrete mixtures led to a sharp reduction in the required dosages of AEA-1 (Fig. 5-3, Fig. 5-4).

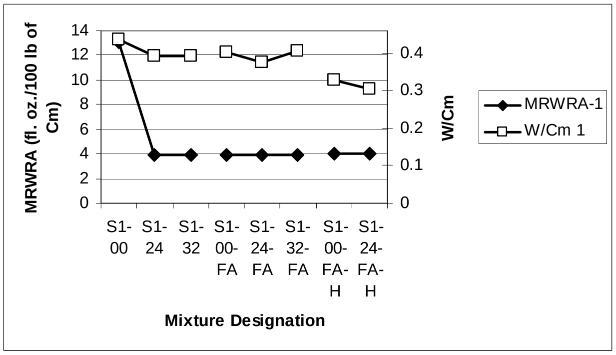


Fig. 5-1. MRWRA demand and W/Cm of concrete as influenced by SRA (Chemical 1, Aggregate 1)

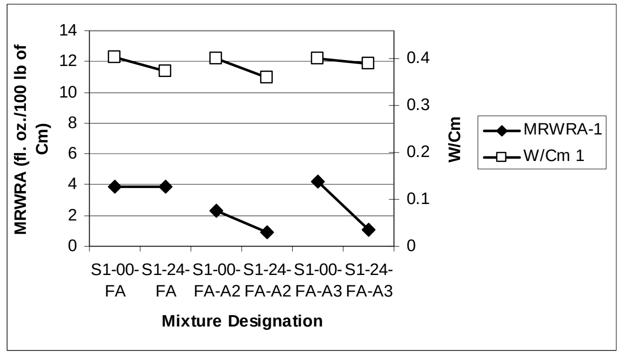


Fig. 5-2. MRWRA demand and W/Cm of concrete as influenced by SRA (Chemical 1; Aggregates 1, 2, 3)

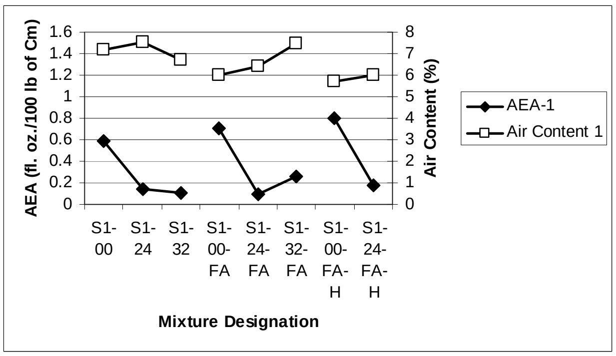


Fig. 5-3. AEA demand and air content of concrete as influenced by SRA (Chemical 1, Aggregate 1)

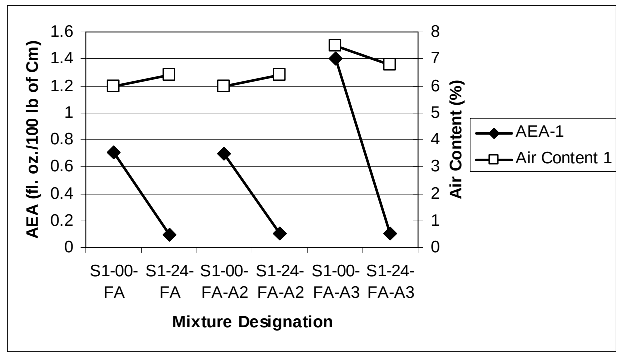


Fig. 5-4. AEA demand and air content of concrete as influenced by SRA (Chemical 1; Aggregates 1, 2, 3)

Time of initial setting of concrete was determined for starting the measurements for autogenous shrinkage. The use of SRA-1 did not considerably change the time of initial setting of concrete (Table 5-2). The time of setting was either reduced by up to 1.25 hours or increased by up to 1.75 hours upon using SRA-1.

Time of initial setting of concrete increased for Grade A-FA fly ash concrete mixtures by 3 to 5 hours compared to corresponding Grade A no-ash concrete mixtures. Use of high amounts of cementitious materials decreased the setting time by about an hour compared to corresponding Grade A-FA fly ash concrete mixtures. The influence of coarse aggregate type on the initial setting time was not significant.

Table 5-2. Time of Initial Setting of Concrete (Chemical 1)

Mixture designation	S1-00	S1-24	S1-32	S1-00-FA	S1-24-FA	S1-32-FA	S1-00-FA-H	S1-24-FA-H	S1-00-FA-A2	S1-24-FA-A2	S1-00-FA-A3	S1-24-FA-A3
Time of initial setting (hours)	6.25	5.5	6	9	10.5	10	8	9.75	8.75	7.75	10	8.75
Difference from no-SRA concrete (hours)	0	-0.75	-0.25	0	1.5	1	0	1.75	0	-1	0	-1.25

5.2 Autogenous Shrinkage (Chemical 1)

The test results for autogenous shrinkage of concrete mixtures containing chemical admixtures from Source 1 are presented in Table 5-3, and Fig. 5-5 through Fig. 5-14.

The autogenous shrinkage of the Grade A concrete S1-00 steadily increased and reached 222 microstrain at 56 days (Table 5-3, Fig. 5-5). As the amount of SRA-1 increased up to 32 fl. oz./100 lb of cement, the autogenous shrinkage decreased proportionally (Fig. 5-6). The relative reduction was more pronounced at 3 days than at 56 days, as evidenced by the nearly parallel data lines for autogenous shrinkage between 3 days and 56 days in Fig. 5-6.

Table 5-3. Autogenous Shrinkage of Concrete (Chemical 1)

Age (days)	Autogenous shrinkage* (microstrain)											
	S1-00	S1-24	S1-32	S1-00-FA	S1-24-FA	S1-32-FA	S1-00-FA-H	S1-24-FA-H	S1-00-FA-A2	S1-24-FA-A2	S1-00-FA-A3	S1-24-FA-A3
0.7	17	-14	6	3	-6	-3	-6	…	-22	0	-24	-7
1	26	23	9	26	0	3	32	6	-10	4	-9	1
3	93	51	42	102	35	32	88	32	5	23	-5	-5
7	117	77	59	134	44	33	141	53	52	55	26	8
14	151	115	100	173	56	64	225	99	76	70	65	37
28	181	145	117	260	114	123	312	160	123	91	117	63
56	222	170	158	365	204	222	405	259	164	149	182	91

* 0 at time of initial setting. -: Expansion. +: Shrinkage.

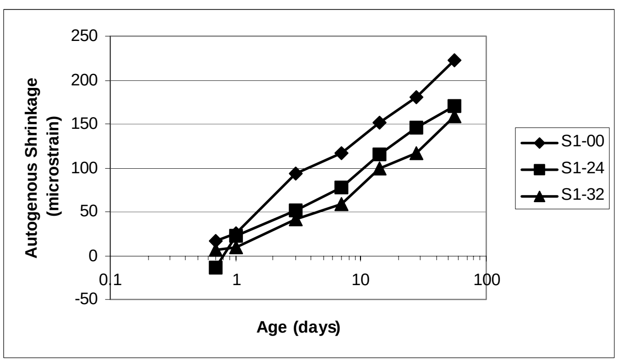


Fig. 5-5. Autogenous shrinkage of Grade A no-ash concrete vs. age (Chemical 1, Aggregate 1)

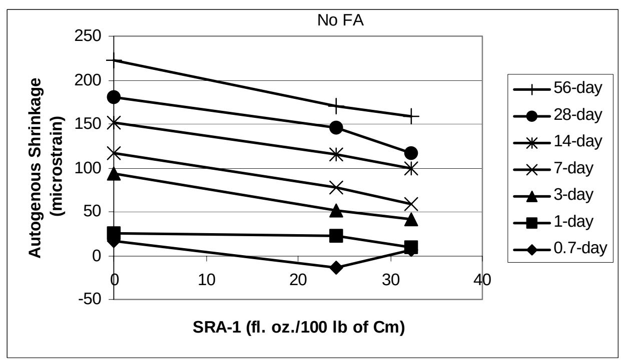


Fig. 5-6. Autogenous shrinkage of Grade A no-ash concrete vs. SRA dosage rate (Chemical 1, Aggregate 1)

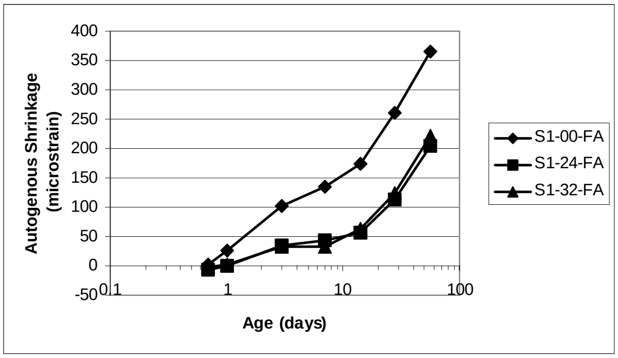


Fig. 5-7. Autogenous shrinkage of Grade A-FA fly ash concrete vs. age (Chemical 1, Aggregate 1)

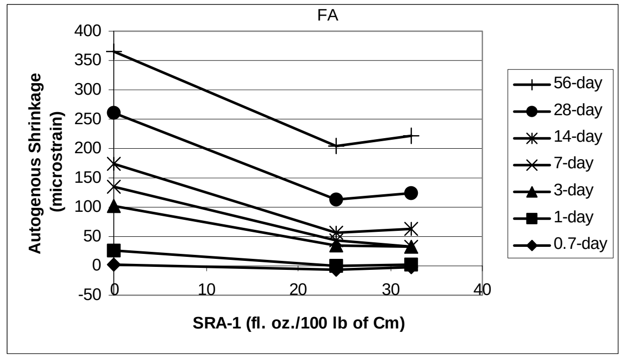


Fig. 5-8. Autogenous shrinkage of Grade A-FA fly ash concrete vs. SRA dosage rate (Chemical 1, Aggregate 1)

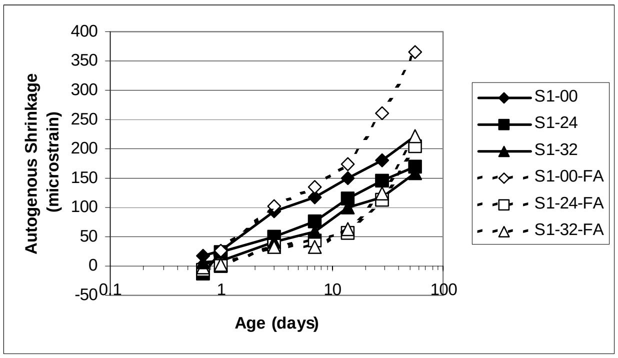


Fig. 5-9. Autogenous shrinkage of Grade A no-ash concrete and Grade A-FA fly ash concrete vs. age (Chemical 1, Aggregate 1)

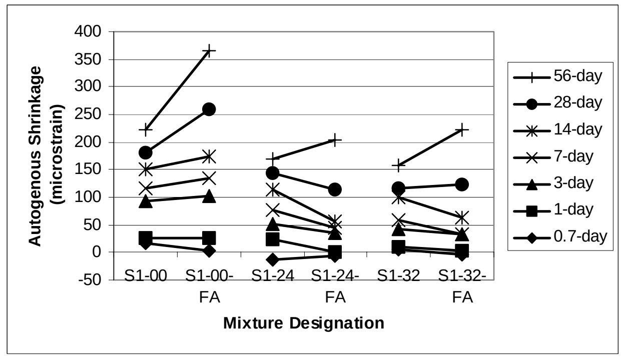


Fig. 5-10. Autogenous shrinkage of no-SRA concrete and SRA concrete vs. fly ash content (Chemical 1, Aggregate 1)

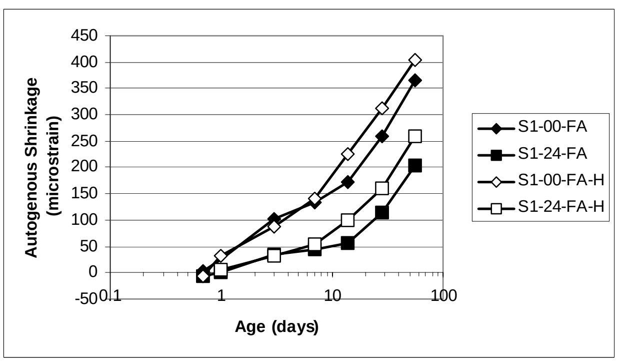


Fig. 5-11. Autogenous shrinkage of Grade A-FA fly ash concrete and high-Cm concrete vs. age (Chemical 1, Aggregate 1)

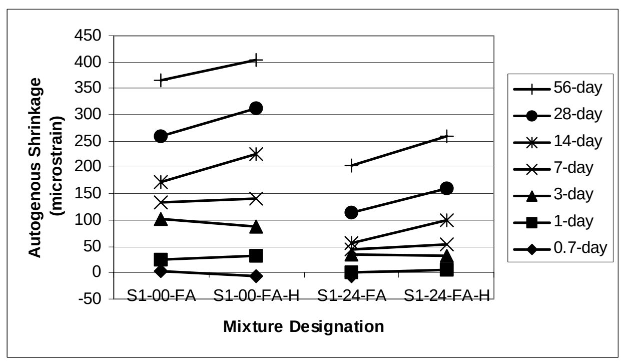


Fig. 5-12. Autogenous shrinkage of concrete vs. cementitious materials content (Chemical 1, Aggregate 1)

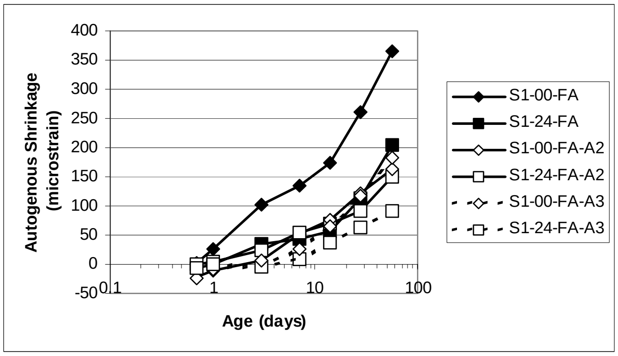


Fig. 5-13. Autogenous shrinkage of Grade A-FA fly ash concrete made with A1, A2, A3 vs. age (Chemical 1; Aggregates 1, 2, 3)

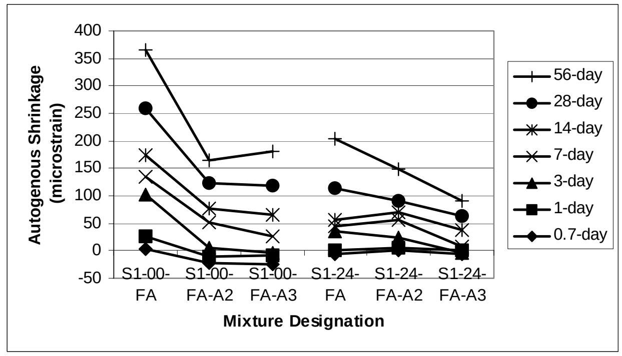


Fig. 5-14. Autogenous shrinkage of Grade A-FA fly ash concrete vs. aggregate type (Chemical 1; Aggregates 1, 2, 3)

The Grade A-FA concrete S1-00-FA showed a relatively steep increase in autogenous shrinkage after 14 days (Fig. 5-7). The addition of SRA-1 to Grade A-FA concrete considerably reduced the autogenous shrinkage of concrete, especially at relatively early ages of up to 14 days, after which the autogenous shrinkage increased rather suddenly (Fig. 5-7, Fig. 5-8).

When compared to the Grade A no-ash concrete mixtures, the Grade A-FA fly ash concrete mixtures showed either a similar (S1-00-FA) or lower (S1-24-FA, S1-32-FA) autogenous shrinkage at ages of up to about 14 to 28 days (Fig. 5-9 and Fig. 5-10). But afterward, the Grade A-FA fly ash concrete mixtures began to show a higher autogenous shrinkage than the Grade A no-ash concrete mixtures. The late hydration reaction of fly ash may have increased the chemical shrinkage, and therefore autogenous shrinkage, of the Grade A-FA fly ash concrete mixtures at later ages.

Compared with Grade A-FA concrete mixtures, the concrete mixtures having a higher cementitious materials content showed a similar autogenous shrinkage at early ages of up to 7 days and a somewhat higher autogenous shrinkage afterward (Fig. 5-11, Fig. 5-12).

As for the influence of the type of coarse aggregate, the concrete mixtures made with Aggregates 2 and 3 showed a significantly lower autogenous shrinkage than the ones made with Aggregate 1 (Fig. 5-13, Fig. 5-14). SRA-1 was not effective in reducing the autogenous shrinkage of the Grade A-FA fly ash concrete made with Aggregate 2. But still, the autogenous shrinkage of concrete mixtures containing Aggregate 2 was either similar or lower than that of the SRA-1 treated concrete mixtures containing Aggregate 1. SRA-1 was highly effective when used with Aggregate 3, resulting in the lowest autogenous shrinkage of the concrete mixture S1-24-FA-A3 among all of the Grade A-FA concrete mixtures made with chemical admixtures from Source 1.

5.3 Drying Shrinkage (Chemical 1)

The test results for drying shrinkage of concrete (subsequent to 28 days of moist curing) are shown in Table 5-4, Table 5-5, and Fig. 5-15 through Fig. 5-24. The test results for expansion of concrete during moist curing from 1 to 28 days are shown in Appendix B.

The relative reduction in drying shrinkage was greater at early ages (Table 5-5).

The Grade A no-ash concrete mixtures containing SRA-1 showed a much lower drying shrinkage than the Grade A reference (no SRA) concrete mixture (Fig. 5-15, Fig. 5-16). The reduction was proportional to the dosage rate of SRA-1, for up to at least 32 fl. oz./100 lb cement.

Table 5-4. Drying Shrinkage of Concrete Subsequent to 28 Days of Moist Curing (Chemical 1)

Air-storage period subsequent to 28 days of moist curing (days)	Drying shrinkage (microstrain)											
	S1-00	S1-24	S1-32	S1-00-FA	S1-24-FA	S1-32-FA	S1-00-FA-H	S1-24-FA-H	S1-00-FA-A2	S1-24-FA-A2	S1-00-FA-A3	S1-24-FA-A3
4	149	60	34	237	113	65	197	20	…	85	160	23
7	235	120	65	307	153	92	293	77	263	155	273	40
14	352	163	120	407	206	190	347	157	380	205	390	167
28	422	203	154	470	290	212	433	247	443	300	443	293
56	464	263	214	520	336	275	433	307	503	405	483	357
112	539	317	234	520	373	302	537	307	547	450	517	380
Average	360	188	137	410	245	189	373	186	427	267	378	210

Table 5-5. Relative Reduction in Drying Shrinkage of Concrete (Chemical 1)

Air-storage period subsequent to 28 days of moist curing (days)	Relative reduction in drying shrinkage (%)											
	S1-00	S1-24	S1-32	S1-00-FA	S1-24-FA	S1-32-FA	S1-00-FA-H	S1-24-FA-H	S1-00-FA-A2	S1-24-FA-A2	S1-00-FA-A3	S1-24-FA-A3
4	0	60	77	0	52	73	0	90	0	…	0	85
7	0	49	72	0	50	70	0	74	0	41	0	85
14	0	54	66	0	49	53	0	55	0	46	0	57
28	0	52	64	0	38	55	0	43	0	32	0	34
56	0	43	54	0	35	47	0	29	0	20	0	26
112	0	41	57	0	28	42	0	43	0	18	0	26
Average	0	48	62	0	40	54	0	50	0	38	0	44

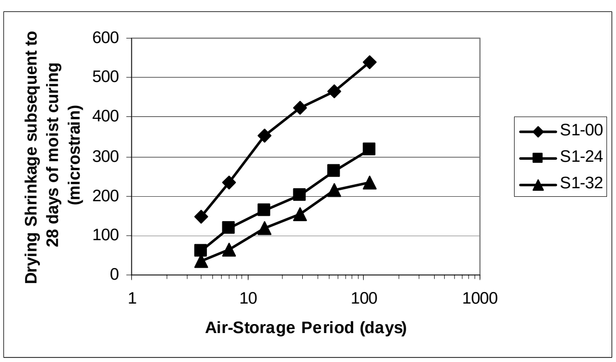


Fig. 5-15. Drying shrinkage of Grade A no-ash concrete vs. air-storage period (Chemical 1, Aggregate 1)

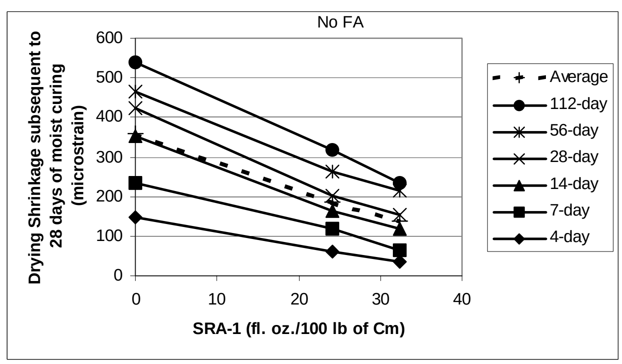
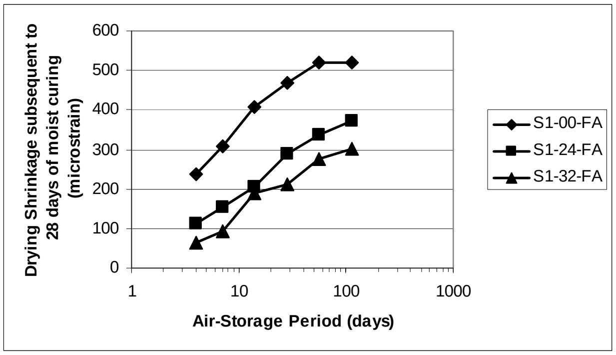


Fig. 5-16. Drying shrinkage of Grade A no-ash concrete vs. SRA dosage rate (Chemical 1, Aggregate 1)



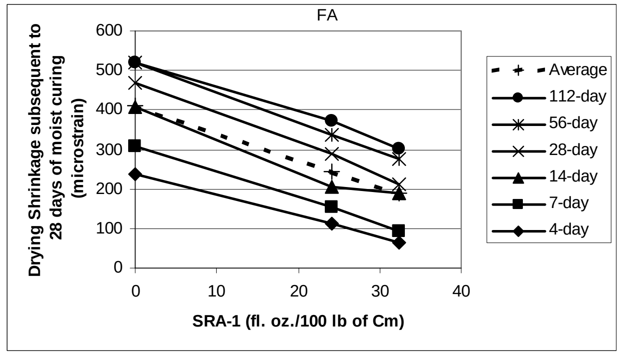
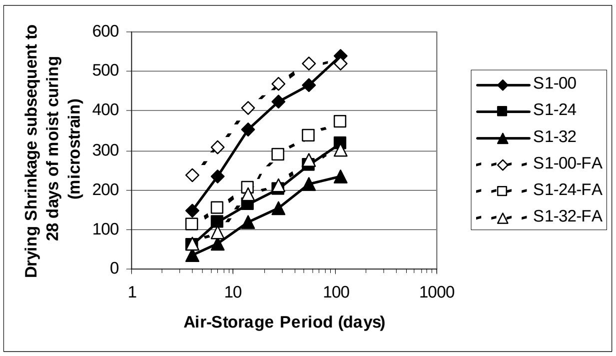


Fig. 5-17. Drying shrinkage of Grade A-FA fly ash concrete vs. air-storage period (Chemical 1, Aggregate 1)

Fig. 5-18. Drying shrinkage of Grade A-FA fly ash concrete vs. SRA dosage rate (Chemical 1, Aggregate 1)



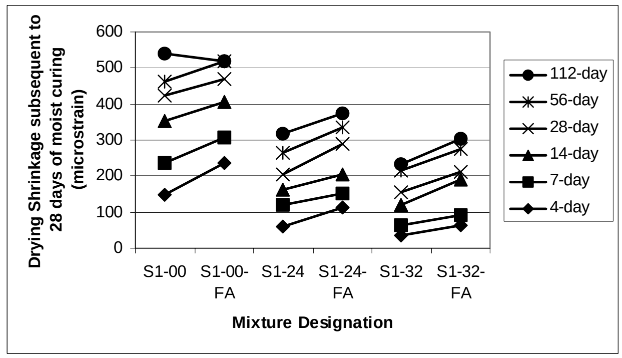
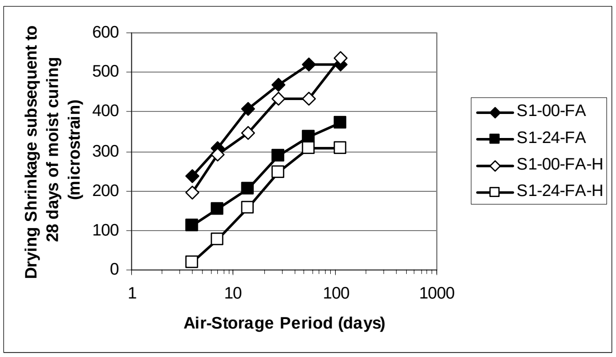


Fig. 5-19. Drying shrinkage of Grade A no-ash concrete and Grade A-FA fly ash concrete vs. air-storage period (Chemical 1, Aggregate 1)

Fig. 5-20. Drying shrinkage of no-SRA concrete and SRA concrete vs. fly ash content (Chemical 1, Aggregate 1)



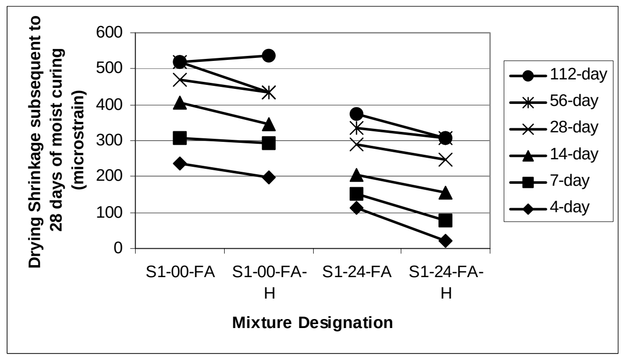


Fig. 5-21. Drying shrinkage of Grade A-FA fly ash concrete and high-Cm concrete vs. air-storage period (Chemical 1, Aggregate 1)

Fig. 5-22. Drying shrinkage of concrete vs. cementitious materials content (Chemical 1, Aggregate 1)

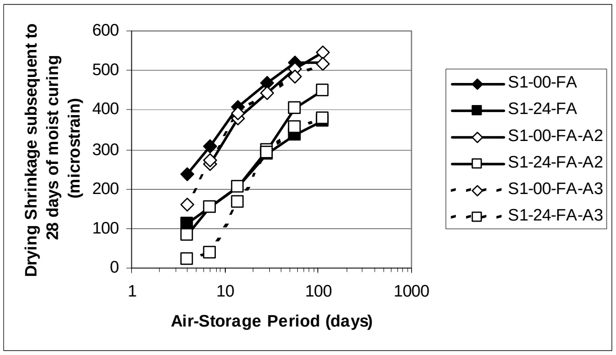


Fig. 5-23. Drying shrinkage of Grade A-FA fly ash concrete made with A1, A2, A3 vs. age (Chemical 1; Aggregates 1, 2, 3)

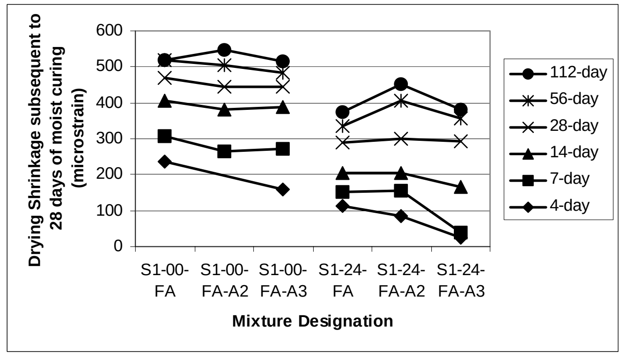


Fig. 5-24. Drying shrinkage of Grade A-FA fly ash concrete vs. aggregate type (Chemical 1; Aggregates 1, 2, 3)

SRA-1 was also quite effective in reducing the drying shrinkage of Grade A-FA fly ash concrete mixtures (Fig. 5-17, Fig. 5-18). The data lines are nearly parallel between the air-storage periods of 4 days and 112 days, which means the relative reduction in drying shrinkage was greater at early ages (Fig. 5-18, Table 5-5).

The Grade A-FA fly ash concrete mixtures showed a somewhat higher drying shrinkage than their Grade A no-ash counterparts (Fig. 5-19, Fig. 5-20). However, this can be overcome with the use of more SRA-1 in Grade A-FA fly ash concrete mixtures. For example, the drying shrinkage of the concrete S1-32-FA is similar to that of the concrete S1-24.

The high-Cm concrete showed a somewhat lower drying shrinkage compared with Grade A-FA concrete (Fig. 5-21, Fig. 5-22). This may be due to a dense microstructure and a higher modulus of elasticity of the high-Cm concrete. SRA-1 was effective in reducing the drying shrinkage of the high-Cm concrete.

Fig. 5-23 and Fig. 5-24 show the influence of the type of coarse aggregate on drying shrinkage. At the air-storage period of 4 days, the concrete mixtures made with Aggregate 3 showed a lower drying shrinkage than the ones made with Aggregates 1 and 2. At air-storage period of 14 days and afterward, the drying shrinkage of concrete mixtures became similar regardless of the type of coarse aggregate, use of Aggregate 2 resulting in somewhat higher drying shrinkage at late air-storage periods. As a whole, the effect of the type of coarse aggregate on drying shrinkage appears to be relatively small.

5.4 Compressive Strength (Chemical 1)

The test results for compressive strength of concrete are shown in Table 5-6, and Fig. 5-25 through Fig. 5-29.

The concrete mixtures containing SRA-1 generally showed somewhat higher compressive strength than their reference (no SRA) concrete mixtures. The SRA-1 concrete mixtures usually had a lower W/Cm compared with the reference concrete mixtures (Table 5-1). SRA-1 itself does not seem to have affected the compressive strength of concrete considerably. At 1 day only, some SRA-1 concrete mixtures (S1-24, S1-24-FA, S1-24-FA-H) showed a little lower compressive strength than their reference concrete mixtures (Table 5-6). The remaining SRA-1 concrete mixtures showed higher compressive strength than their reference concrete mixtures at all test ages. SRA-1 improved the workability of concrete mixtures; therefore, the use of SRA-1 reduced the MRWRA-1 demand and sometimes even the W/Cm of the mixtures, resulting in higher compressive strength of concrete.

Table 5-6. Compressive Strength of Concrete (Chemical 1)

Age (days)	Compressive strength (psi)											
	S1-00	S1-24	S1-32	S1-00-FA	S1-24-FA	S1-32-FA	S1-00-FA-H	S1-24-FA-H	S1-00-FA-A2	S1-24-FA-A2	S1-00-FA-A3	S1-24-FA-A3
1	2360	2180	2560	1310	1140	1700	2080	1665	830	1040	810	1090
3	3940	4380	4630	3220	3740	3920	4440	4510	2720	3190	2840	3570
7	4970	5120	5020	4510	4960	5190	5300	5820	3720	4380	4130	4990
14	4880	5400	5790	5220	5820	5590	6170	6710	4470	5110	5190	6150
28	5610	5830	6060	5720	6760	6670	7020	7360	4830	5730	5500	7010
91	6500	6500	7040	7120	7995	7930	8010	8360	6140	6790	6020	8270
182	7020	7440	8055	7380	8215	8310	8690	9585	6430	7100	6140	8740

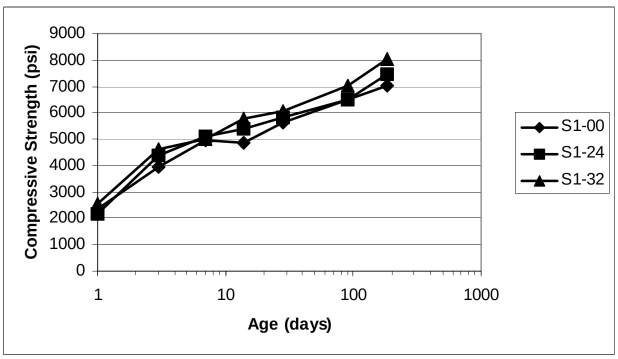


Fig. 5-25. Compressive strength of Grade A no-ash concrete vs. age (Chemical 1, Aggregate 1)

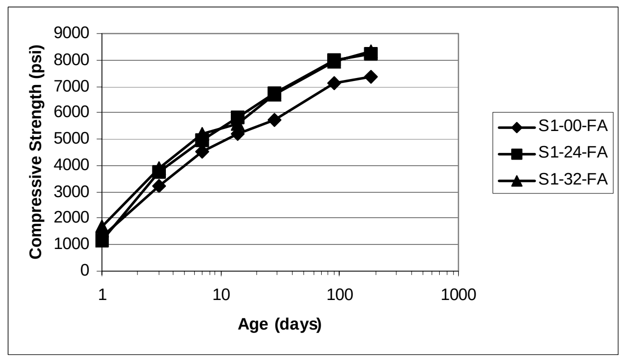


Fig. 5-26. Compressive strength of Grade A-FA fly ash concrete vs. age (Chemical 1, Aggregate 1)

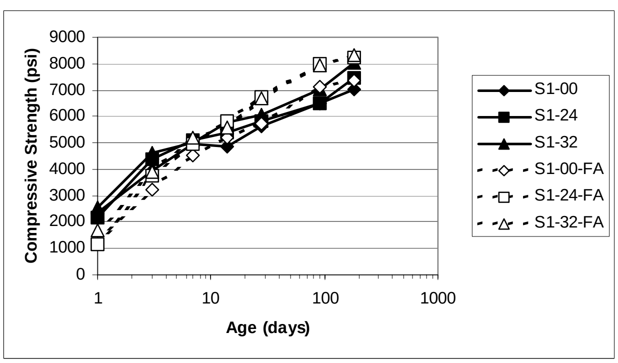


Fig. 5-27. Compressive strength of Grade A no-ash concrete and Grade A-FA fly ash concrete vs. age (Chemical 1, Aggregate 1)

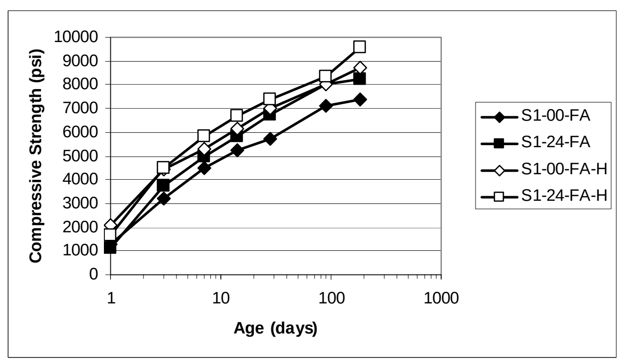


Fig. 5-28. Compressive strength of Grade A-FA fly ash concrete and high-Cm concrete vs. age (Chemical 1, Aggregate 1)

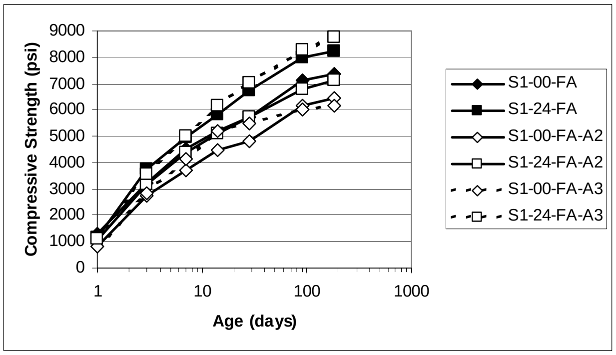


Fig. 5-29. Compressive strength of Grade A-FA fly ash concrete made with A1, A2, A3 vs. age (Chemical 1; Aggregates 1, 2, 3)

Compared with Grade A no-ash concrete mixtures, Grade A-FA fly ash concrete mixtures showed a lower compressive strength at 1 and 3 days, and a higher compressive strength at 14, 28, and 91 days (Fig. 5-27). The 182-day strength of Grade A-FA fly ash concrete mixtures was 3 to 10% higher than that of Grade A no-ash concrete mixtures.

The high-Cm concrete mixtures showed average about 900 psi higher compressive strength than corresponding Grade A-FA fly ash concrete mixtures (Fig. 5-28). Compared with corresponding Grade A no-ash concrete mixtures, the high-Cm concrete mixtures showed higher compressive strength at all test ages, except at 1 day (Table 5-6).

The concrete mixtures made with Aggregates 1 and 3 (both crushed stone) showed generally higher compressive strength than the concrete mixtures made with Aggregate 2 (semi-crushed river gravel) (Fig. 5-29).

5.5 Splitting-Tensile Strength (Chemical 1)

The test results for splitting-tensile strength of concrete are shown in Table 5-7, and Fig. 5-30 through Fig. 5-34.

Table 5-7. Splitting-Tensile Strength of Concrete (Chemical 1)

Age (days)	Splitting-tensile strength (psi)								
	S1-00	S1-24	S1-32	S1-00-FA	S1-24-FA	S1-32-FA	S1-00-FA-H	S1-24-FA-H	S1-00-FA-A2*
1	360	280	370	210	170	250	260	250	120
3	480	520	510	430	450	350	500	510	350
7	540	530	520	470	550	530	550	580	460
14	550	520	550	460	580	530	480	610	500
28	540	600	570	540	650	610	630	710	520
91	650	630	640	740	665	705	700	710	610
182	670	710	670	670	740	790	720	710	700

* Extra test results.

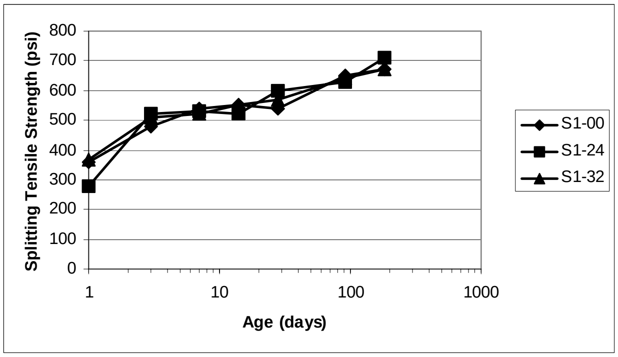


Fig. 5-30. Splitting strength of Grade A no-ash concrete vs. age (Chemical 1, Aggregate 1)

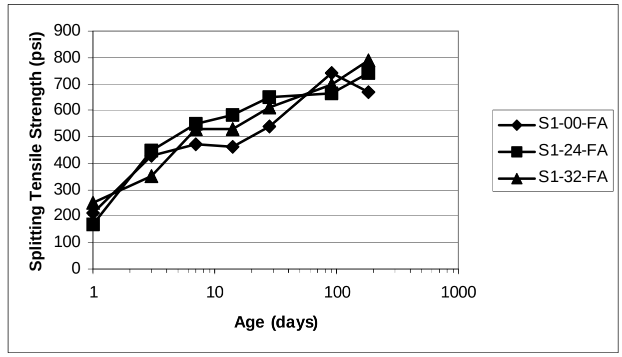


Fig. 5-31. Splitting strength of Grade A-FA fly ash concrete vs. age (Chemical 1, Aggregate 1)

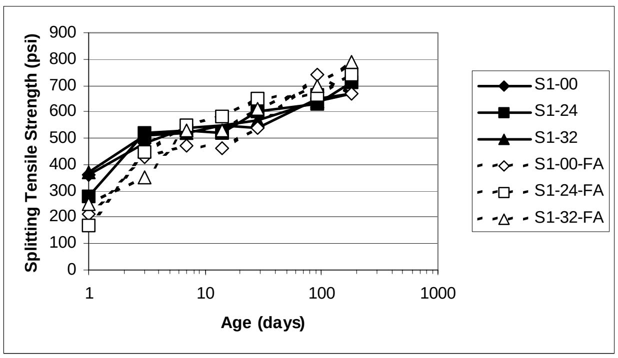


Fig. 5-32. Splitting-tensile strength of Grade A no-ash concrete and Grade A-FA fly ash concrete vs. age (Chemical 1, Aggregate 1)

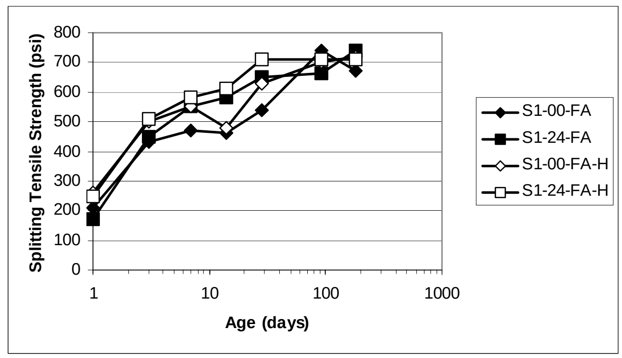


Fig. 5-33. Splitting-tensile strength of Grade A-FA fly ash concrete and high-Cm concrete vs. age (Chemical 1, Aggregate 1)

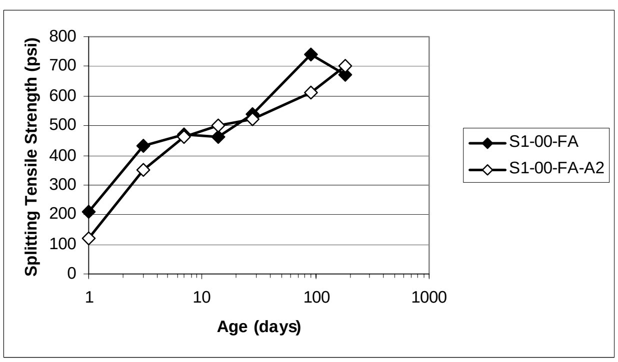


Fig. 5-34. Splitting-tensile strength of Grade A-FA fly ash concrete made with A1, A2 vs. age (Chemical 1; Aggregates 1, 2)

SRA-1 either did not noticeably affect or slightly increased the splitting-tensile strength of concrete.

Compared to Grade A no-ash concrete mixtures, Grade A-FA fly ash concrete mixtures showed a lower splitting-tensile strength at early ages of 1 and 3 days, and either a similar or slightly higher splitting-tensile strength at 7 days and afterward (Fig. 5-32). The high-Cm concrete mixtures showed a little higher splitting-tensile strength than Grade A-FA fly ash concrete mixtures (Fig. 5-33). The Grade A-FA fly ash concrete mixture made with Aggregate 1 showed somewhat higher splitting-tensile strength than the Grade A-FA fly ash concrete mixture made with Aggregate 2 (Fig. 5-34).

5.6 Chloride-Ion Penetrability (Chemical 1)

The test results for electrical indication of chloride-ion penetrability into concrete are shown in Table 5-8, and Fig. 5-35 through Fig. 5-44.

Table 5-8. Chloride-Ion Penetrability into Concrete (Chemical 1)

Age (days)	Chloride-ion penetrability (Coulomb)											
	S1-00	S1-24	S1-32	S1-00-FA	S1-24-FA	S1-32-FA	S1-00-FA-H	S1-24-FA-H	S1-00-FA-A2	S1-24-FA-A2	S1-00-FA-A3	S1-24-FA-A3
28	2820	2180	1970	1970	1940	1480	1910	1560	2810	2390	3410	3940
56	2090	1810	1630	1020	1220	960	1070	960	1600	1540	1570	1750
182	1580	1470	1150	480	550	570	430	380	720	720	800	850

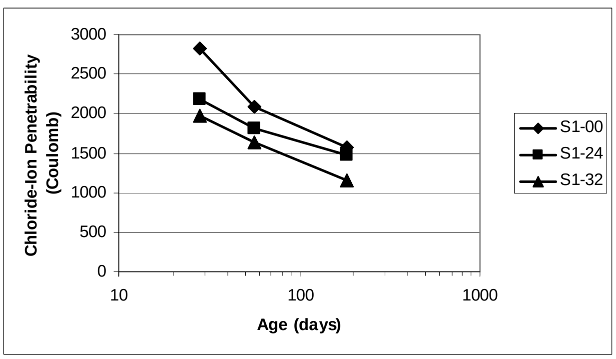


Fig. 5-35. Chloride-ion penetrability into Grade A no-ash concrete vs. age (Chemical 1, Aggregate 1)

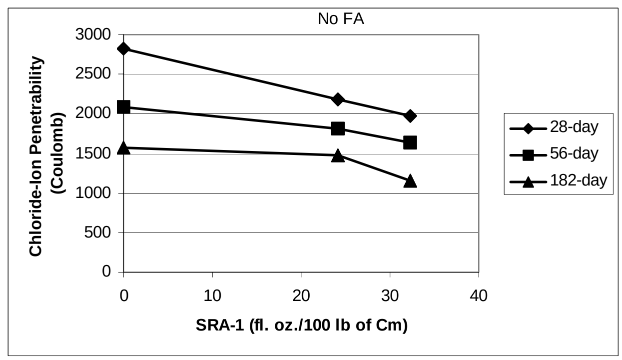


Fig. 5-36. Chloride-ion penetrability into Grade A no-ash concrete vs. SRA dosage rate (Chemical 1, Aggregate 1)

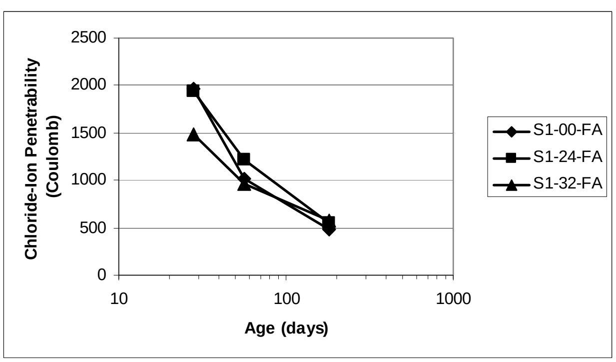


Fig. 5-37. Chloride-ion penetrability into Grade A-FA fly ash concrete vs. age (Chemical 1, Aggregate 1)

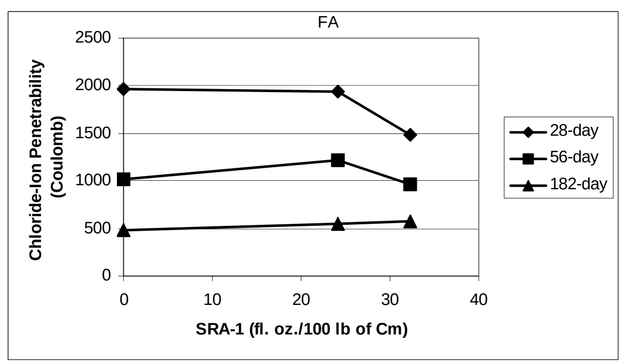


Fig. 5-38. Chloride-ion penetrability into Grade A-FA fly ash concrete vs. SRA dosage rate (Chemical 1, Aggregate 1)

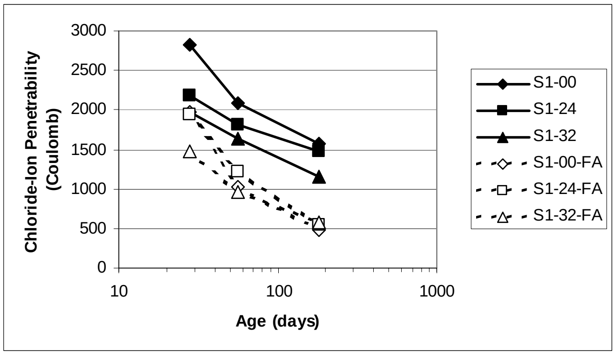


Fig. 5-39. Chloride-ion penetrability into Grade A no-ash concrete and Grade A-FA fly ash concrete vs. age (Chemical 1, Aggregate 1)

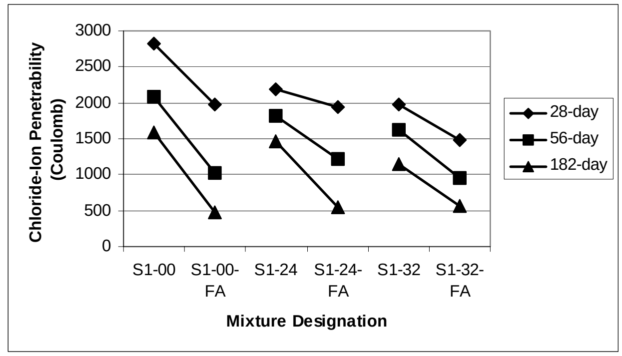


Fig. 5-40. Chloride-ion penetrability into no-SRA concrete and SRA concrete vs. fly ash content (Chemical 1, Aggregate 1)

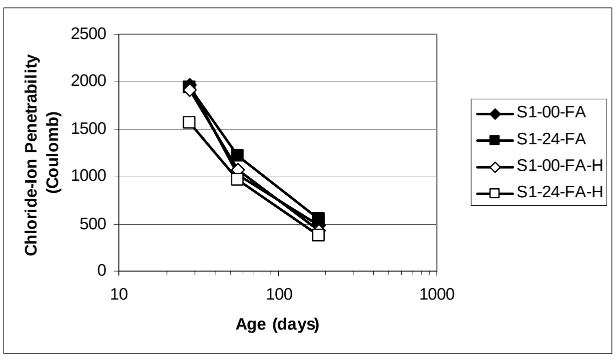


Fig. 5-41. Chloride-ion penetrability into Grade A-FA fly ash concrete and high-Cm concrete vs. age (Chemical 1, Aggregate 1)

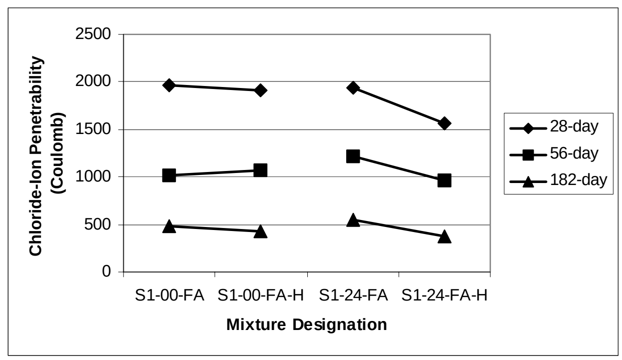


Fig. 5-42. Chloride-ion penetrability into concrete vs. cementitious materials content (Chemical 1, Aggregate 1)

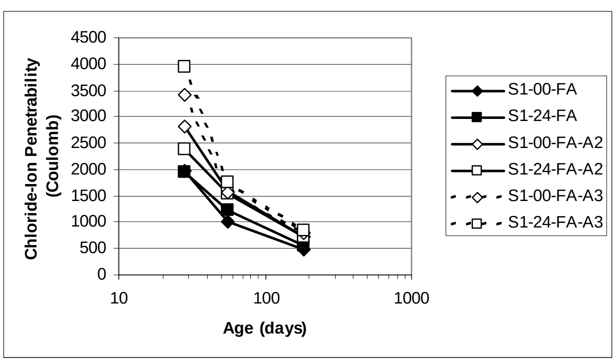


Fig. 5-43. Chloride-ion penetrability into Grade A-FA fly ash concrete made with A1, A2, A3 vs. age (Chemical 1; Aggregates 1, 2, 3)

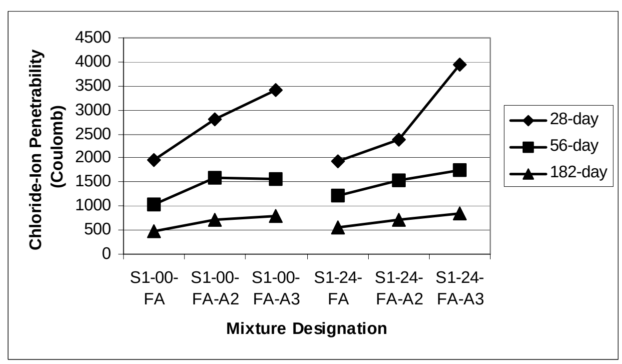


Fig. 5-44. Chloride-ion penetrability into Grade A-FA fly ash concrete vs. aggregate type (Chemical 1; Aggregates 1, 2, 3)

As the age increased, the chloride-ion penetrability decreased due to improvement in microstructure of cementitious paste in concrete. Use of SRA-1 was somewhat helpful in reducing the chloride-ion penetrability into Grade A no-ash concrete (a higher resistance to penetration) (Fig. 5-35, Fig. 5-36). Grade A-FA fly ash concrete mixtures showed much higher resistance to chloride-ion penetration (a lower penetrability into concrete) than their Grade A no-ash counterparts (Fig. 5-39, Fig. 5-40). Use of more cementitious materials did not noticeably improve the resistance of concrete to chloride-ion penetration (Fig. 5-41, Fig. 5-42). Use of SRA-1 in high-Cm concrete mixtures did not noticeably affect their resistance to chloride-ion penetration.

As for the effect of the type of aggregate, Aggregate 1 was the best, leading to the lowest penetrability (the highest resistance to penetration) (Fig. 5-43, Fig. 5-44). Aggregate 2 was the second best, and the concrete mixtures made with Aggregate 3 allowed the highest penetrability of chloride ions into concrete (the lowest resistance to penetration). The compressive strength of concrete mixtures containing Aggregate 2 was lower than that of the concrete mixtures made with Aggregate 1 or 3 (Table 5-6, Fig. 5-29). So, there was no correlation between the compressive strength and the chloride-ion penetration resistance of concrete in this case. Use of SRA-1 itself did not significantly increase or decrease the chloride-ion penetrability into Grade A-FA fly ash concrete (Fig. 5-43).

5.7 Air Content and Slump Losses (Chemical 1)

The SRA-1 concrete mixtures S1-24 and S1-24-FA were repeated in the laboratory, and the changes in their air content and slump during the first hour were measured and compared against those of the reference (no SRA) concrete mixtures S1-00 and S1-00-FA that were also repeated. The mixture proportions of the concrete mixtures are shown in Table 5-9, including the initial air content and slump of fresh concrete. Use of SRA-1 reduced the MRWRA-1 and AEA-1 demands.

Table 5-9. Mixture Proportions of Concrete for Air Content (Chemical 1)

Mixture designation*	S1-00-air	S1-24-air	S1-00-FA-air	S1-24-FA-air
Laboratory mixture designation	A-1-air	A-S1-air	A-FA-1-air	A-FA-S1-air
Cement (lb/yd^3)	558	547	395	393
Class C Fly Ash (lb/yd^3)	0	0	170	169
Water (lb/yd^3)	231	218	231	225
Fine aggregate, SSD (lb/yd^3)	1410	1380	1400	1400
Coarse aggregate, ≤ 3/4 in., SSD (lb/yd^3)	1700	1670	1700	1690
W/Cm	0.41	0.40	0.41	0.40
MRWRA-1 (fl. oz./yd^3)	98.7	21.3	22.2	16.9
AEA-1 (fl. oz./yd^3)	3.2	0.7	3.9	0.5
SRA-1 (fl. oz./yd^3)	0	132	0	135
Slump (in.)	2	3.25	3.5	3.25
Air content (%)	6.0	7.8	5.6	5.3
Air temperature (°F)	68	67	68	68
Concrete temperature (°F)	69	69	71	0
Density (lb/ft^3)	144	141	144	144

* The number following S1- indicates the approximate dosage rate of SRA-1 in fl. oz./100 lb of cementitious materials. See Section 1.5 for more details.

The losses of the air content and slump of fresh concrete mixtures are shown in Table 5-10, and Fig. 5-45 and Fig. 5-46. The air content was stable, decreasing by only about 1% in one hour. Use of SRA-1 did not affect the loss of air content. The slump decreased by 1 to 2 inches in one hour. But all four mixtures retained a final slump of 1 inch or higher. The loss of slump was not significantly affected by SRA-1 use.

Table 5-10. Changes in Air Content and Slump of Fresh Concrete (Chemical 1)

Time (minutes)	Air content (%)				Slump (in.)			
	S1-00-air	S1-24-air	S1-00-FA-air	S1-24-FA-air	S1-00-air	S1-24-air	S1-00-FA-air	S1-24-FA-air
0	6.0	7.8	5.6	5.3	2.00	3.25	3.50	3.25
10	5.5	7.7	5.3	5.5	1.38	2.75	3.00	3.25
20	5.3	8.0	4.9	5.4	1.13	2.38	2.88	2.75
30	5.3	7.5	4.9	5.2	1.13	2.13	3.00	2.25
40	5.3	7.4	4.8	4.8	1.13	2.00	2.50	2.00
50	5.4	7.2	4.7	4.6	1.00	1.63	2.50	2.00
60	5.3	6.5	4.7	4.3	1.00	1.50	2.50	1.25

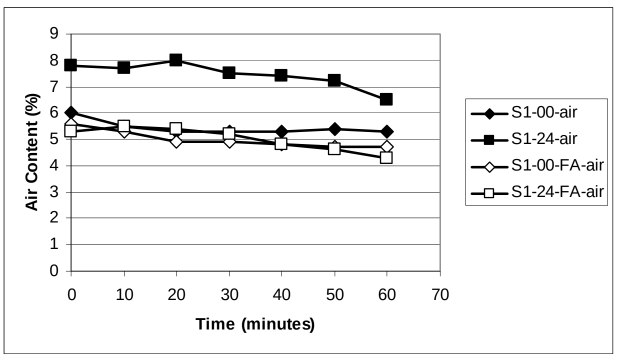


Fig. 5-45. Change in air content of fresh concrete (Chemical 1)

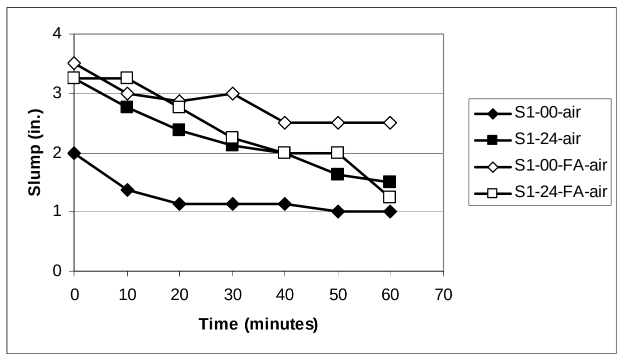


Fig. 5-46. Change in slump of fresh concrete (Chemical 1)

Chapter 6. Concrete Mixtures Containing Chemical Admixtures from Source 2

6.1 Mixture Proportions and Time of Initial Setting (Chemical 2)

Table 6-1 shows the mixture proportions and fresh properties of concrete mixtures containing chemical admixtures from Source 2 (Grace).

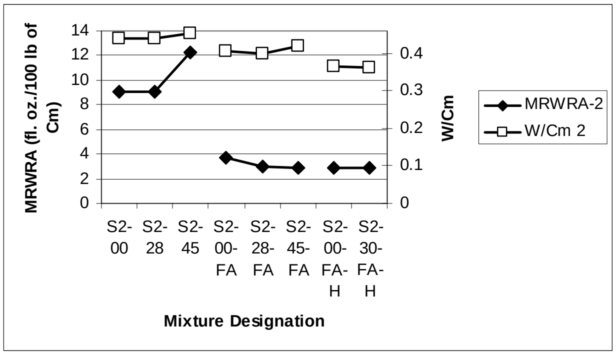
Table 6-1. Mixture Proportions and Fresh Properties of Concrete (Chemical 2)

Mixture designation*	S2-00	S2-28	S2-45	S2-00-FA	S2-28-FA	S2-45-FA	S2-00-FA-H	S2-30-FA-H	S2-00-FA-A2	S2-28-FA-A2	S2-00-FA-A3	S2-28-FA-A3
Laboratory mixture designation	A-2	A-S2	A-S2S	A-FA-2	A-FA-S2	A-FA-S2S	A-FA-2A	A-FA-S2A	A-FA-2-A2	A-FA-S2-A2	A-FA-2-A3	A-FA-S2-A3
Cement (lb/yd^3)	544	552	549	382	387	394	505	500	390	395	397	401
Class C Fly Ash (lb/yd^3)	0	0	0	164	167	170	217	215	168	170	171	173
Water (lb/yd^3)	239	243	248	221	221	237	263	258	215	232	230	235
Fine aggregate, SSD (lb/yd^3)	1370	1390	1380	1360	1380	1400	1300	1290	1230	1250	1420	1430
Coarse aggregate, ≤ 3/4 in., SSD (lb/yd^3)	1660	1680	1670	1640	1670	1700	1570	1560	1850	1870	1730	1740
MRWRA-2 (fl. oz./yd^3)	49.3	49.8	67.2	20.3	16.4	16.3	21.0	20.8	12.6	13.0	31.7	12.4
AEA-2 (fl. oz./yd^3)	6	110	177	22	110	177	41	144	20	84	22	97
SRA-2 (fl. oz./yd^3)	0	154	249	0	154	255	0	218	0	160	0	163
W/Cm	0.44	0.44	0.45	0.40	0.40	0.42	0.36	0.36	0.39	0.41	0.40	0.41
Slump (in.)	4.5	2.25	2	4.5	2.75	3	2.75	3.5	3	2.25	2.75	2.25
Air content (%)	6.5	5.4	4.6	7.4	5.9	4.6	5.7	4.8	7.0	4.6	6.4	4.8
Air temperature (°F)	69	68	69	68	69	69	69	69	67	70	68	68
Concrete temperature (°F)	70	70	70	69	70	70	70	70	70	71	67	68
Density (lb/ft^3)	141	144	143	140	142	145	143	142	143	145	146	148

* The number following S2- indicates the approximate dosage rate of SRA-2 in fl. oz./100 lb of cementitious materials. See Section 1.5 for more details.

Fig. 6-1 and Fig. 6-2 show the influence of SRA-2 on MRWRA-2 demand and W/Cm of concrete mixtures. In general, SRA-2 did not have a considerable effect on MRWRA-2 demand. Use of fly ash reduced the MRWRA-2 demand (Fig. 6-1).

Fig. 6-3 and Fig. 6-4 show the influence of SRA-2 on AEA-2 demand and air content of concrete. Use of SRA-2 significantly increased the AEA-2 demand and lowered the air content of concrete mixtures.



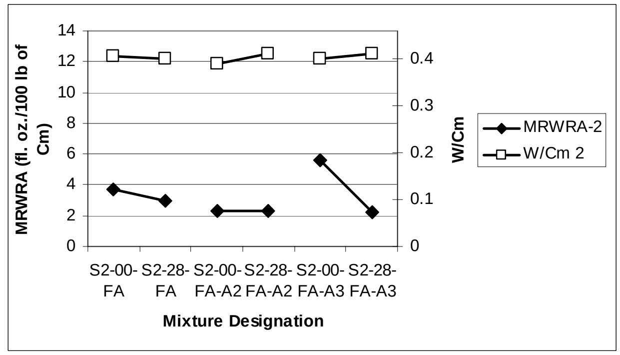
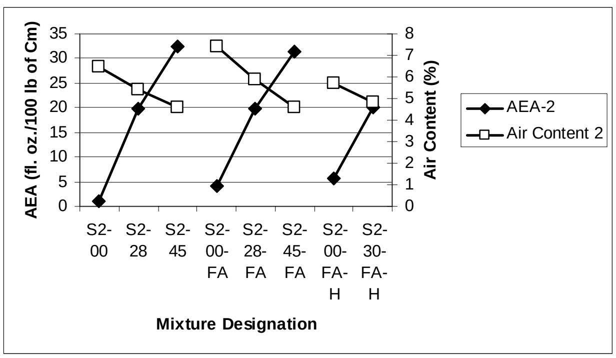


Fig. 6-1. MRWRA demand and W/Cm of concrete as influenced by SRA (Chemical 2, Aggregate 1)

Fig. 6-2. MRWRA demand and W/Cm of concrete as influenced by SRA (Chemical 2; Aggregates 1, 2, 3)



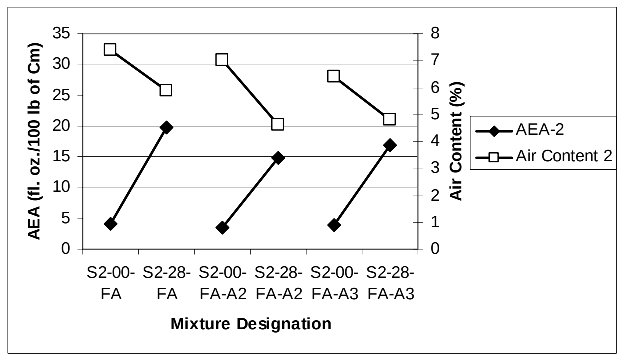


Fig. 6-3. AEA demand and air content of concrete as influenced by SRA (Chemical 2, Aggregate 1)

Fig. 6-4. AEA demand and air content of concrete as influenced by SRA (Chemical 2; Aggregates 1, 2, 3)

Time of initial setting of concrete was determined for starting the measurements for autogenous shrinkage. In general, SRA-2 increased the time of initial setting of concrete (Table 6-2). In most cases, this retarding effect was not significant (0.75 to 2 hours). But, the initial setting time of some SRA-2 concrete mixtures were 4 to 4.75 hours longer compared with their reference (no SRA) concrete mixtures. According to Mehta and Monteiro [1993], an overdose of air-entraining admixtures can make the cement particles hydrophobic and delay cement hydration.

Table 6-2. Time of Initial Setting of Concrete (Chemical 2)

Mixture designation	S2-00	S2-28	S2-45	S2-00-FA	S2-28-FA	S2-45-FA	S2-00-FA-H	S2-30-FA-H	S2-00-FA-A2	S2-28-FA-A2	S2-00-FA-A3	S2-28-FA-A3
Time of initial setting (hours)	6.25	7	11	12.5	14	14	9	13	8.25	10.25	11.25	11.17
Difference from no-SRA concrete (hours)	0	0.75	4.75	0	1.5	1.5	0	4	0	2	0	-0.08

Use of fly ash lengthened the time of initial setting by about 3 to 7 hours. Use of higher amounts of cementitious materials reduced the setting time by about 1 to 3.5 hours. When chemical admixtures from Source 2 were used, the A-FA fly ash concrete mixtures made with Aggregates 2 and 3 showed a somewhat shorter time of initial setting compared with the corresponding A-FA concrete mixtures made with Aggregate 1.

6.2 Autogenous Shrinkage (Chemical 2)

Table 6-3 and Fig. 6-5 to Fig. 6-14 show the autogenous shrinkage of concrete containing chemical admixtures from Source 2.

Table 6-3. Autogenous Shrinkage of Concrete (Chemical 2)

Age (days)	Autogenous shrinkage* (microstrain)											
	S2-00	S2-28	S2-45	S2-00-FA	S2-28-FA	S2-45-FA	S2-00-FA-H	S2-30-FA-H	S2-00-FA-A2	S2-28-FA-A2	S2-00-FA-A3	S2-28-FA-A3
0.7	6	2	-6	14	-3	6	12	-9	-17	-24	-9	-13
1	12	19	-13	15	2	9	44	-1	-7	-13	-3	-12
3	85	78	64	70	29	58	94	44	15	13	9	-8
7	137	128	120	96	71	99	147	64	69	50	47	4
14	184	154	152	140	82	108	196	73	100	59	100	29
28	213	160	175	213	117	128	281	141	138	85	165	61
56	274	166	190	251	170	183	365	196	211	106	248	105

* 0 at time of initial setting. -: Expansion. +: Shrinkage.

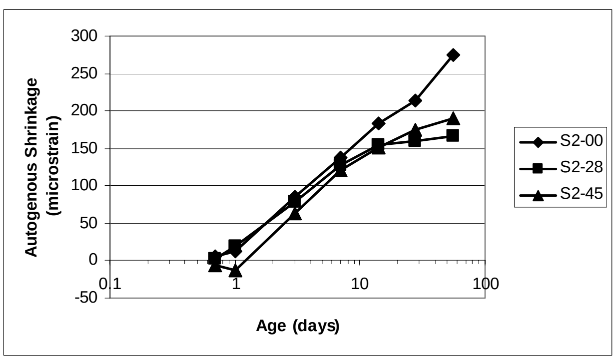


Fig. 6-5. Autogenous shrinkage of Grade A no-ash concrete vs. age (Chemical 2, Aggregate 1)

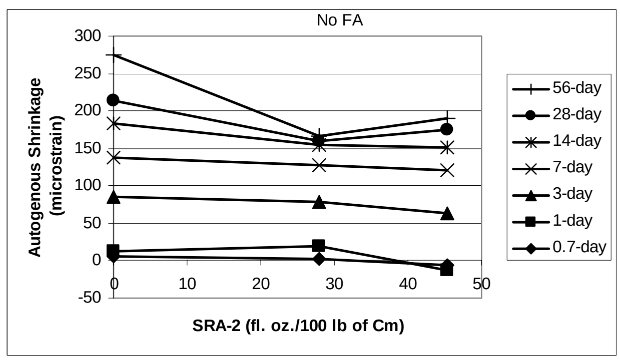


Fig. 6-6. Autogenous shrinkage of Grade A no-ash concrete vs. SRA dosage rate (Chemical 2, Aggregate 1)

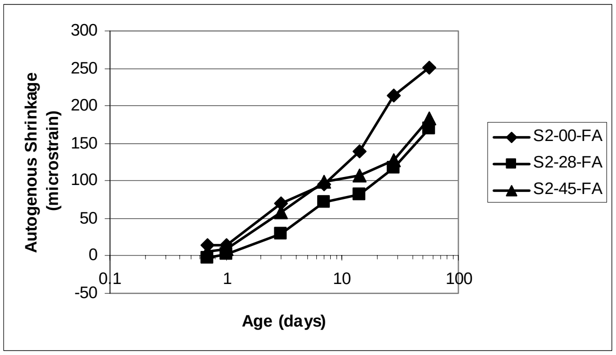


Fig. 6-7. Autogenous shrinkage of Grade A-FA fly ash concrete vs. age (Chemical 2, Aggregate 1)

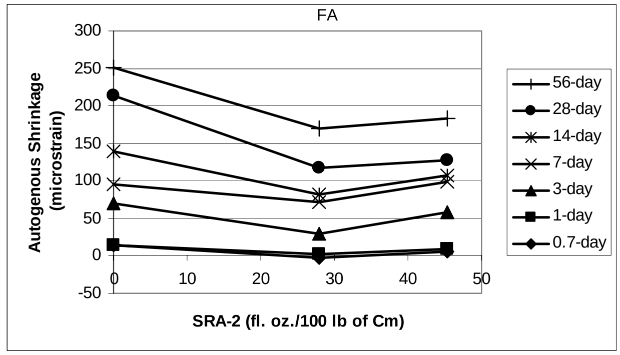


Fig. 6-8. Autogenous shrinkage of Grade A-FA fly ash concrete vs. SRA dosage rate (Chemical 2, Aggregate 1)

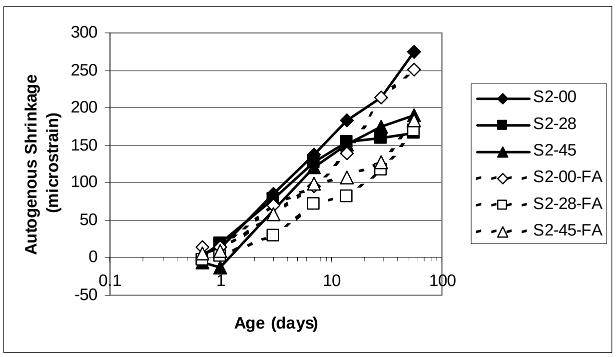


Fig. 6-9. Autogenous shrinkage of Grade A no-ash concrete and Grade A-FA fly ash concrete vs. age (Chemical 2, Aggregate 1)

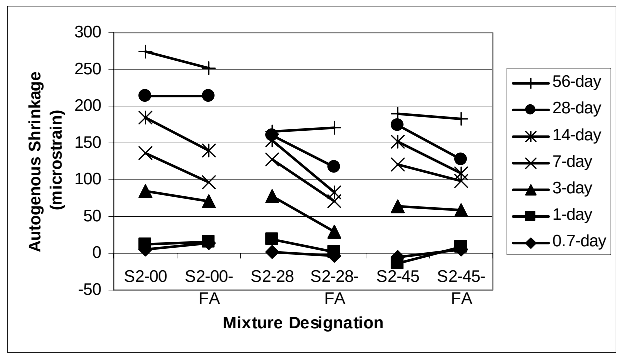


Fig. 6-10. Autogenous shrinkage of no-SRA concrete and SRA concrete vs. fly ash content (Chemical 2, Aggregate 1)

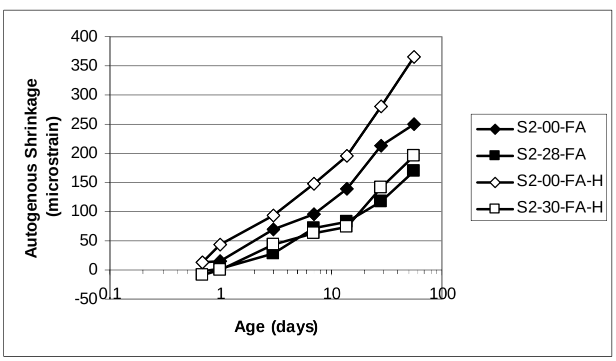


Fig. 6-11. Autogenous shrinkage of Grade A-FA fly ash concrete and high-Cm concrete vs. age (Chemical 2, Aggregate 1)

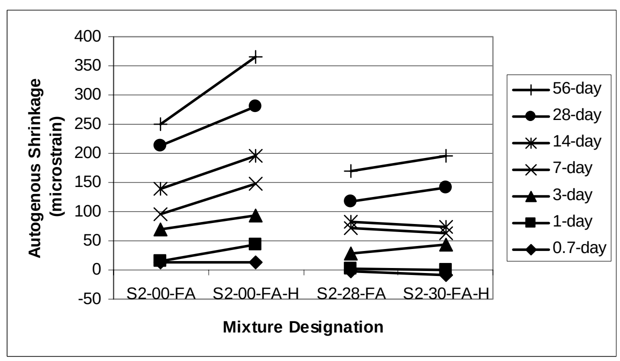


Fig. 6-12. Autogenous shrinkage of concrete vs. cementitious materials content (Chemical 2, Aggregate 1)

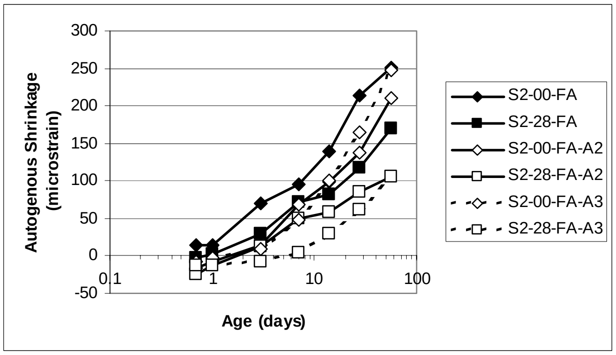


Fig. 6-13. Autogenous shrinkage of Grade A-FA fly ash concrete made with A1, A2, A3 vs. age (Chemical 2; Aggregates 1, 2, 3)

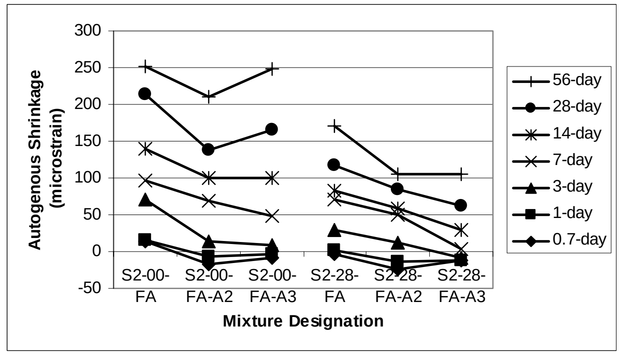


Fig. 6-14. Autogenous shrinkage of Grade A-FA fly ash concrete vs. aggregate type (Chemical 2; Aggregates 1, 2, 3)

The autogenous shrinkage of the reference (no SRA) Grade A no-ash concrete mixture S2-00 continued to increase (Fig. 6-5, Fig. 6-6). In comparison, the autogenous shrinkage of the Grade A no-ash concrete mixtures containing SRA-2 began to be curbed after 7 days and became considerably separated from that of the reference mixture S2-00 at 56 days.

Compared with the reference (no SRA) Grade A-FA fly ash concrete mixture, the Grade A-FA fly ash concrete mixtures containing SRA-2 showed either a similar or lower autogenous shrinkage for up to 7 days and a lower autogenous shrinkage afterward (Fig. 6-7, Fig. 6-8).

When compared with the Grade A no-ash concrete mixtures, the Grade A-FA fly ash concrete mixtures generally showed a lower autogenous shrinkage at 3, 7, 14, and 28 days (Fig. 6-9, Fig. 6-10). But the autogenous shrinkage of the Grade A-FA fly ash concrete mixtures became similar to that of the Grade A no-ash concrete mixtures at 56 days.

When higher amounts of cementitious materials were used without SRA-2, autogenous shrinkage of concrete increased considerably (Fig. 6-12, Fig. 6-13). When higher amounts of cementitious materials were used with SRA-2, the autogenous shrinkage of the concrete mixture S2-30-FA-H was only slightly higher than that of S2-28-FA.

SRA-2 was effective in reducing the autogenous shrinkage of concrete mixtures made with Aggregates 1, 2, and 3 (Fig. 6-13, Fig. 6-14). The concrete mixtures made with Aggregates 2 and 3 generally showed a lower autogenous shrinkage than those made with Aggregate 1. The mixtures made with Aggregate 3 showed the lowest autogenous shrinkage at early ages, but their autogenous shrinkage tended to increase and exceed that of the concrete mixtures made with Aggregate 2 at later ages.

6.3 Drying Shrinkage (Chemical 2)

The test results for drying shrinkage of concrete (subsequent to 28 days of moist curing) are shown in Table 6-4, Table 6-5, and Fig. 6-15 through Fig. 6-24. The test results for expansion of concrete during moist curing from 1 to 28 days are shown in Appendix B.

The Grade A no-ash concrete mixtures containing SRA-2 showed a much lower drying shrinkage than the reference (no SRA) Grade A no-ash concrete mixture S20-00 (Fig. 6-15, Fig. 6-16), especially at early ages. Beyond a SRA-2 dosage rate of at most 28 fl. oz. per 100 pounds of cement, a further reduction in drying shrinkage was not achieved.

SRA-2 was also quite effective in reducing the drying shrinkage of Grade A-FA fly ash concrete mixtures (Fig. 6-17, Fig. 6-18), especially at early ages. The reduction was nearly proportional to the SRA-2 dosage rate of up to 45 fl. oz./100 pounds of cementitious materials. The data lines were roughly parallel between the air-storage periods of 4 days and 112 days.

Table 6-4. Drying Shrinkage of Concrete Subsequent to 28 Days of Moist Curing (Chemical 2)

Air-storage period subsequent to 28 days of moist curing (days)	Drying shrinkage (microstrain)											
	S2-00	S2-28	S2-45	S2-00-FA	S2-28-FA	S2-45-FA	S2-00-FA-H	S2-30-FA-H	S2-00-FA-A2	S2-28-FA-A2	S2-00-FA-A3	S2-28-FA-A3
4	245	55	80	253	63	44	200	164	213	77	160	63
7	282	132	125	361	147	75	266	192	337	150	317	127
14	378	158	170	418	222	124	366	260	440	233	413	237
28	458	215	240	478	290	164	486	364	540	333	510	327
56	465	258	285	528	350	287	503	402	637	443	587	393
112	515	328	350	558	390	337	503	449	647	483	587	427
Average	391	191	208	433	244	172	387	305	469	287	429	262

Table 6-5. Relative Reduction in Drying Shrinkage of Concrete (Chemical 2)

Air-storage period subsequent to 28 days of moist curing (days)	Relative reduction in drying shrinkage (%)											
	S2-00	S2-28	S2-45	S2-00-FA	S2-28-FA	S2-45-FA	S2-00-FA-H	S2-30-FA-H	S2-00-FA-A2	S2-28-FA-A2	S2-00-FA-A3	S2-28-FA-A3
4	0	78	67	0	75	83	0	18	0	64	0	60
7	0	53	56	0	59	79	0	28	0	55	0	60
14	0	58	55	0	47	70	0	29	0	47	0	43
28	0	53	48	0	39	66	0	25	0	38	0	36
56	0	45	39	0	34	46	0	20	0	30	0	33
112	0	36	32	0	30	40	0	11	0	25	0	27
Average	0	51	47	0	44	60	0	21	0	39	0	39

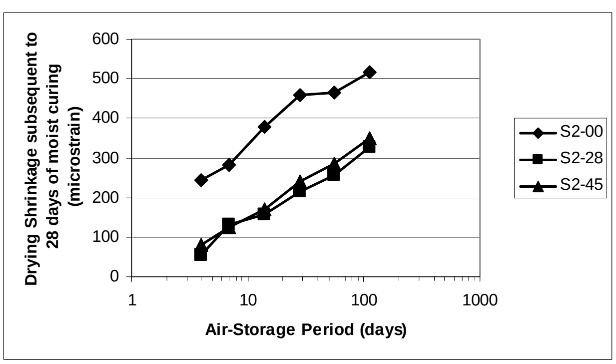


Fig. 6-15. Drying shrinkage of Grade A no-ash concrete vs. air-storage period (Chemical 2, Aggregate 1)

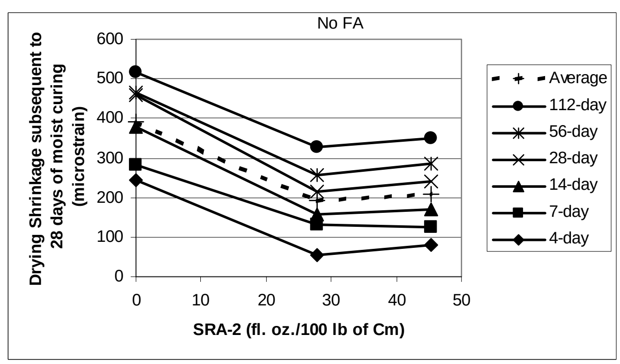


Fig. 6-16. Drying shrinkage of Grade A no-ash concrete vs. SRA dosage rate (Chemical 2, Aggregate 1)

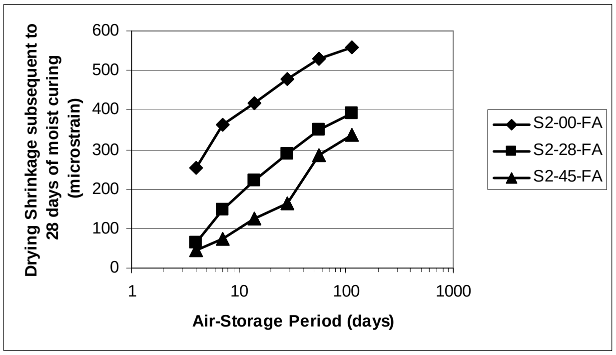


Fig. 6-17. Drying shrinkage of Grade A-FA fly ash concrete vs. air-storage period (Chemical 2, Aggregate 1)

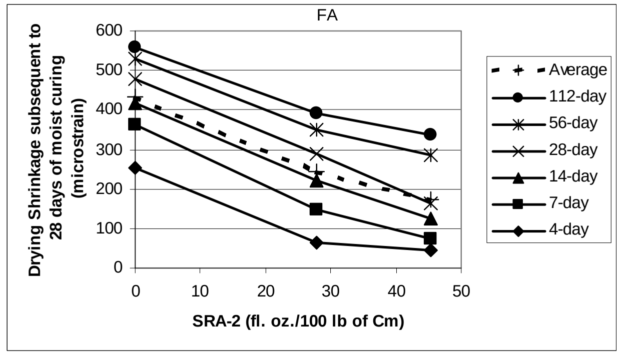


Fig. 6-18. Drying shrinkage of Grade A-FA fly ash concrete vs. SRA dosage rate (Chemical 2, Aggregate 1)

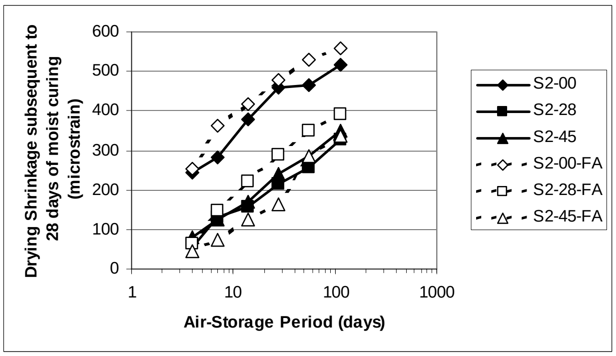


Fig. 6-19. Drying shrinkage of Grade A no-ash concrete and Grade A-FA fly ash concrete vs. air-storage period (Chemical 2, Aggregate 1)

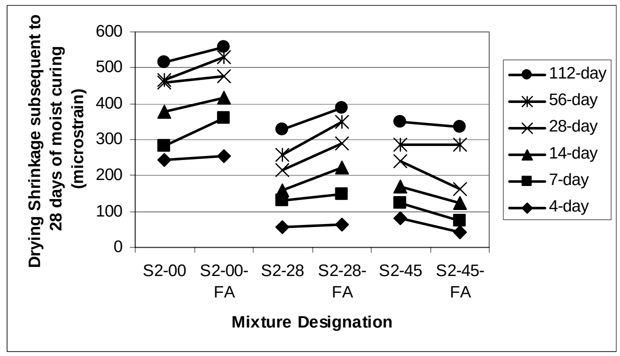


Fig. 6-20. Drying shrinkage of no-SRA concrete and SRA concrete vs. fly ash content (Chemical 2, Aggregate 1)

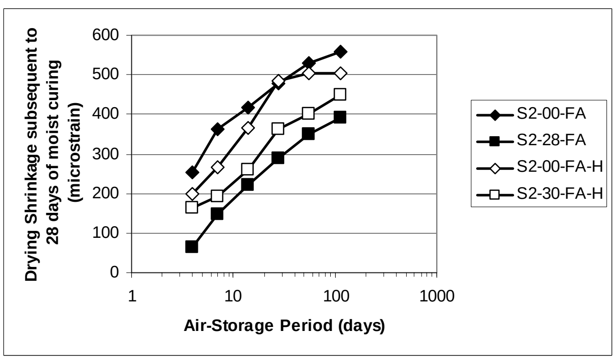


Fig. 6-21. Drying shrinkage of Grade A-FA fly ash concrete and high-Cm concrete vs. air-storage period (Chemical 2, Aggregate 1)

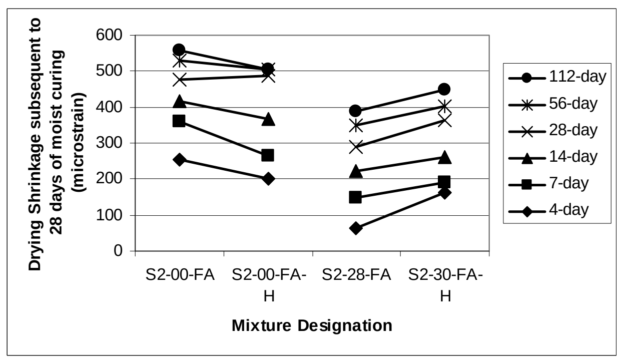


Fig. 6-22. Drying shrinkage of concrete vs. cementitious materials content (Chemical 2, Aggregate 1)

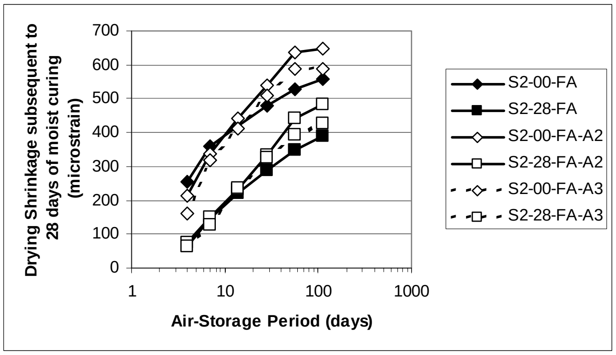


Fig. 6-23. Drying shrinkage of Grade A-FA fly ash concrete made with A1, A2, A3 vs. age (Chemical 2; Aggregates 1, 2, 3)

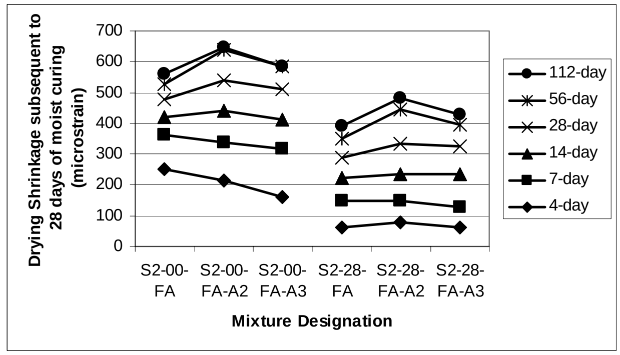


Fig. 6-24. Drying shrinkage of Grade A-FA fly ash concrete vs. aggregate type (Chemical 2; Aggregates 1, 2, 3)

For a SRA-2 dosage rate of up to 28 fl. oz./100 lb of cementitious materials, the Grade A-FA fly ash concrete mixtures showed a somewhat higher drying shrinkage than their Grade A no-ash counterparts (Fig. 6-19, Fig. 6-20). On the other hand, the concrete mixture S2-45-FA showed either a lower or similar drying shrinkage compared with the concrete mixture S2-45.

The reference (no SRA) high-Cm concrete mixture showed a lower drying shrinkage compared with the reference (no SRA) Grade A-FA fly ash concrete mixture (Fig. 6-21, Fig. 6-22). But the high-Cm concrete containing SRA-2 showed a higher drying shrinkage than the Grade A-FA concrete containing SRA-2. In reducing the drying shrinkage, SRA-2 was not as effective in high-Cm concrete mixtures as it was in Grade A-FA fly ash concrete mixtures.

Fig. 6-23 and Fig. 6-24 show the influence of the type of coarse aggregate on drying shrinkage. SRA-2 was effective in reducing the drying shrinkage of concrete mixtures made with Aggregates 1, 2, and 3. At early periods of air storage, the drying shrinkage of concrete mixtures made with Aggregates 2 and 3 was either similar or somewhat lower compared with that of the concrete mixtures made with Aggregate 1. However, at air-storage periods of 7 days and afterward, the concrete mixtures made with Aggregate 1 showed either similar or lower drying shrinkage compared with the concrete mixtures made with Aggregates 2 and 3.

6.4 Compressive Strength (Chemical 2)

The test results for compressive strength of concrete are shown in Table 6-6, and Fig. 6-25 through Fig. 6-29.

Table 6-6. Compressive Strength of Concrete (Chemical 2)

Age (days)	Compressive strength (psi)											
	S2-00	S2-28	S2-45	S2-00-FA	S2-28-FA	S2-45-FA	S2-00-FA-H	S2-30-FA-H	S2-00-FA-A2	S2-28-FA-A2	S2-00-FA-A3	S2-28-FA-A3
1	1830	1260	850	730	750	530	1430	860	660	670	790	540
3	2980	2230	2280	1960	2470	2090	3200	2530	2160	1810	2990	2620
7	3810	2600	2900	3010	3250	2800	4030	3300	3150	3110	4260	3860
14	4070	3150	3260	3300	3740	3500	4490	3580	3600	3410	5040	4520
28	4310	3700	3610	4530	4610	4050	5520	5020	4290	3760	6210	5300
91	5580	4270	4120	5510	5990	5470	7200	6800	5040	4390	6810	5920
182	5190	4780	4815	6155	6120	6210	7340	6680	5300	4930	7740	7190

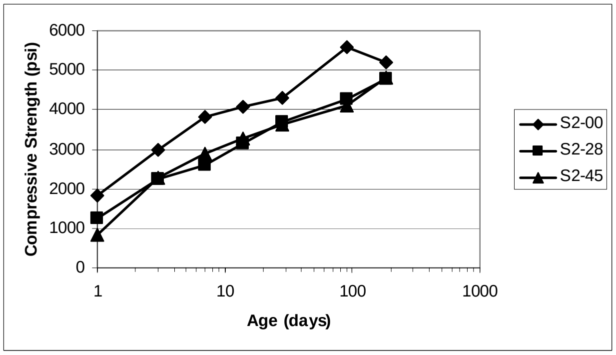


Fig. 6-25. Compressive strength of Grade A no-ash concrete vs. age (Chemical 2, Aggregate 1)

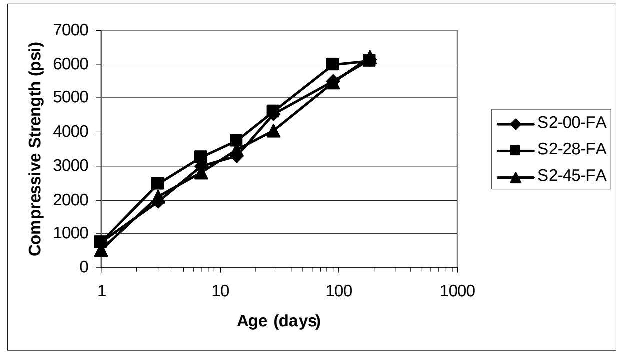


Fig. 6-26. Compressive strength of Grade A-FA fly ash concrete vs. age (Chemical 2, Aggregate 1)

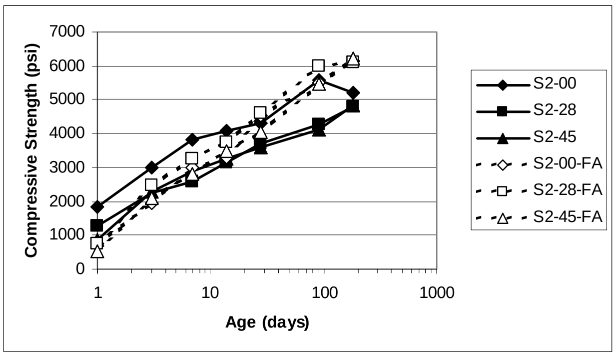


Fig. 6-27. Compressive strength of Grade A no-ash concrete and Grade A-FA fly ash concrete vs. age (Chemical 2, Aggregate 1)

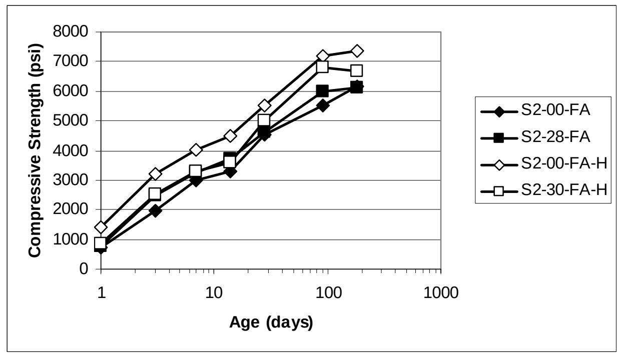


Fig. 6-28. Compressive strength of Grade A-FA fly ash concrete and high-Cm concrete vs. age (Chemical 2, Aggregate 1)

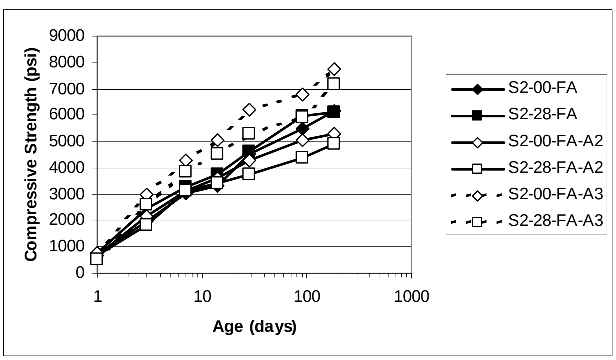


Fig. 6-29. Compressive strength of Grade A-FA fly ash concrete made with A1, A2, A3 vs. age (Chemical 2; Aggregates 1, 2, 3)

The concrete mixtures containing SRA-2 showed generally lower compressive strength than their reference (no SRA) concrete mixtures. SRA-2 lowered the compressive strength of concrete when used in Grade A no-ash concrete mixtures (Fig. 6-25), the high-Cm mixtures (Fig. 6-28), and Grade A-FA fly ash concrete mixtures made with Aggregates 2 and 3 (Fig. 6-29). As the only exception, SRA-2 either did not noticeably affect or slightly increased the compressive strength when used in Grade A-FA fly ash concrete mixtures made with Aggregate 1 (Fig. 6-26).

The generally lower compressive strength of the concrete mixtures containing SRA-2 is possibly due to the use of very high dosages of AEA-2. The W/Cm and density of concrete mixtures alone do not give a satisfactory answer as to the cause of the reduction in compressive strength. Compared with the reference (no SRA) concrete mixtures, the concrete mixtures containing SRA-2 generally had a higher W/Cm, a lower air content, and a higher density.

Compared with Grade A no-ash concrete mixtures, Grade A-FA fly ash concrete mixtures showed a lower compressive strength at early ages, and a higher compressive strength at later ages (Fig. 6-27).

The high-Cm concrete mixtures showed a higher compressive strength than corresponding Grade A-FA fly ash concrete mixtures (Fig. 6-28). Compared with corresponding Grade A no-ash concrete mixtures, the high-Cm concrete mixtures showed a higher compressive strength at all test ages, except at 1 day (Table 6-6).

The concrete mixtures made with Aggregates 1 and 3 (both crushed stone) generally showed a higher compressive strength than the concrete mixtures made with Aggregate 2 (semi-crushed river gravel) (Fig. 6-29). The mixtures made with Aggregate 3 showed the highest compressive strength, and the mixtures made with Aggregate 1 showed the second highest compressive strength.

6.5 Splitting-Tensile Strength (Chemical 2)

The test results for splitting-tensile strength of concrete containing chemical admixtures from Source 2 are shown in Table 6-7, and Fig. 6-30 through Fig. 6-33.

The splitting-tensile strength was similar in trends to the corresponding compressive strength (Section 6.4).

SRA-2 decreased the splitting-tensile strength of Grade A no-ash concrete (Fig. 6-30) and high-Cm concrete (Fig. 6-33) considerably. The Grade A-FA fly ash concrete mixtures containing SRA-2 showed about the same splitting-tensile strength as the reference (no SRA) Grade A-FA fly ash concrete mixture (Fig. 6-31).

Compared to Grade A no-ash concrete mixtures, Grade A-FA fly ash concrete mixtures showed a lower splitting-tensile strength at early ages and a higher splitting-tensile strength at later ages (Fig. 6-32). The reference (no SRA) high-Cm concrete S2-00-FA-H showed a higher splitting-tensile strength than the reference (no SRA) Grade A-FA fly ash concrete S2-00-FA (Fig. 6-33). The splitting-tensile strength of the SRA-2 high-Cm concrete S2-30-FA-H was similar to that of the SRA-2 Grade A-FA concrete S2-28-FA.

Table 6-7. Splitting-Tensile Strength of Concrete (Chemical 2)

Age (days)	Splitting-tensile strength (psi)							
	S2-00	S2-28	S2-45	S2-00-FA	S2-28-FA	S2-45-FA	S2-00-FA-H	S2-30-FA-H
1	250	190	150	120	120	100	210	130
3	370	320	310	310	300	280	410	300
7	400	330	360	380	410	410	490	420
14	490	410	390	450	430	380	530	440
28	560	460	450	510	520	450	610	550
91	610	490	490	590	630	620	680	610
182	610	500	…	625	650	710	680	750

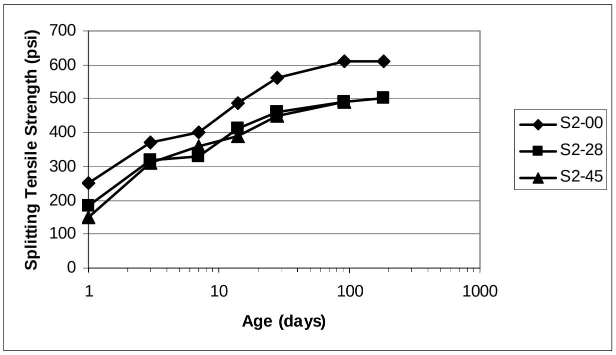


Fig. 6-30. Splitting strength of Grade A no-ash concrete vs. age (Chemical 2, Aggregate 1)

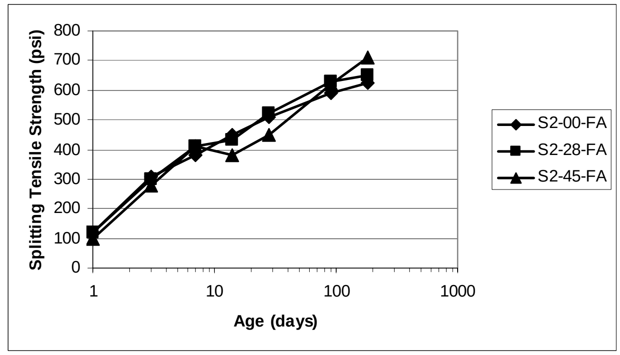


Fig. 6-31. Splitting strength of Grade A-FA fly ash concrete vs. age (Chemical 2, Aggregate 1)

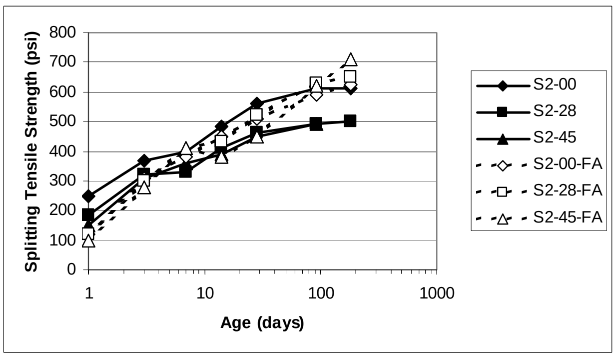


Fig. 6-32. Splitting-tensile strength of Grade A no-ash concrete and Grade A-FA fly ash concrete vs. age (Chemical 2, Aggregate 1)

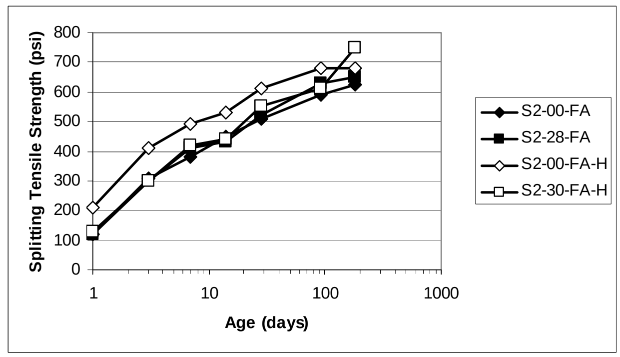


Fig. 6-33. Splitting-tensile strength of Grade A-FA fly ash concrete and high-Cm concrete vs. age (Chemical 2, Aggregate 1)

6.6 Chloride-Ion Penetrability (Chemical 2)

The test results for electrical indication of chloride-ion penetrability into concrete are shown in Table 6-8, and Fig. 6-34 through Fig. 6-43.

As the age increased, the chloride-ion penetrability decreased due to improvement in microstructure of cementitious paste in concrete.

Table 6-8. Chloride-Ion Penetrability into Concrete (Chemical 2)

Age (days)	Chloride-ion penetrability (Coulomb)											
	S2-00	S2-28	S2-45	S2-00-FA	S2-28-FA	S2-45-FA	S2-00-FA-H	S2-30-FA-H	S2-00-FA-A2	S2-28-FA-A2	S2-00-FA-A3	S2-28-FA-A3
28	5280	4490	3310	4740	2530	3140	2840	3430	3920	3300	3080	4140
56	3210	3690	2750	1880	1290	1780	1310	1800	2100	1910	1960	2450
182	2230	2560	2300	1000	630	850	490	710	960	1070	990	870

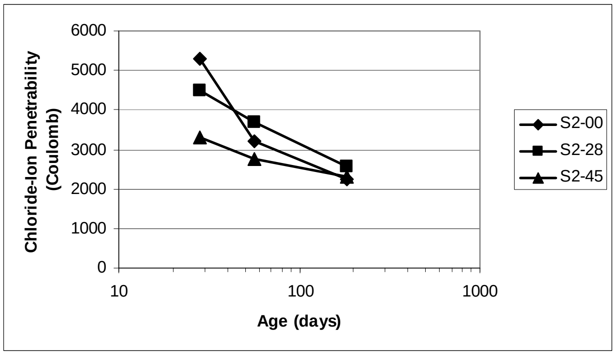


Fig. 6-34. Chloride-ion penetrability into Grade A no-ash concrete vs. age (Chemical 2, Aggregate 1)

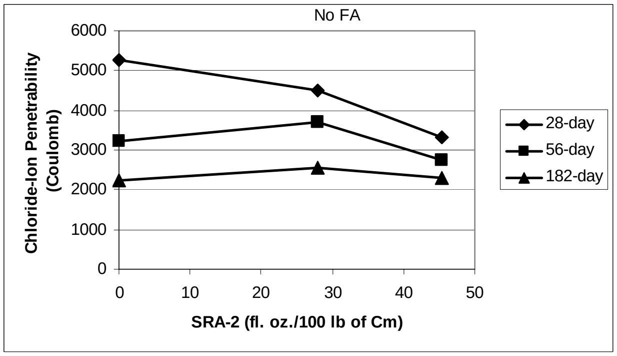


Fig. 6-35. Chloride-ion penetrability into Grade A no-ash concrete vs. SRA dosage rate (Chemical 2, Aggregate 1)

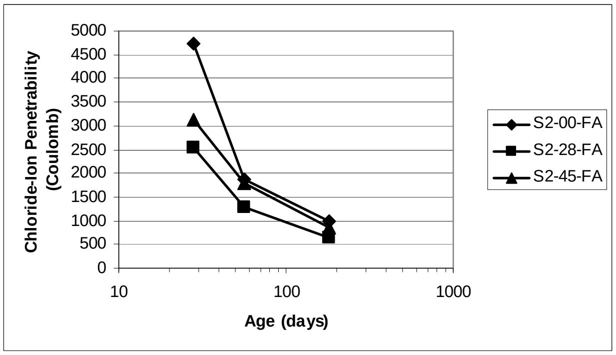


Fig. 6-36. Chloride-ion penetrability into Grade A-FA fly ash concrete vs. age (Chemical 2, Aggregate 1)

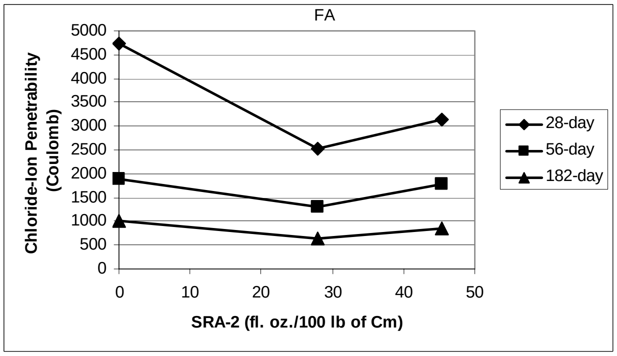


Fig. 6-37. Chloride-ion penetrability into Grade A-FA fly ash concrete vs. SRA dosage rate (Chemical 2, Aggregate 1)

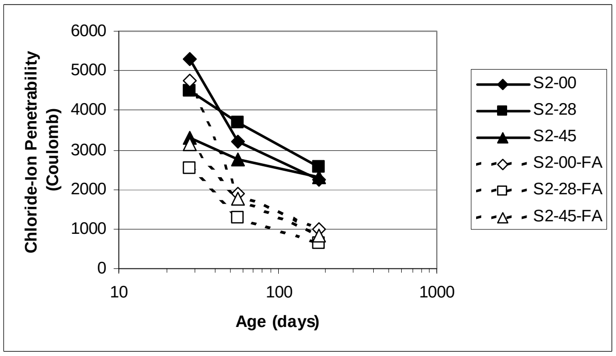


Fig. 6-38. Chloride-ion penetrability into Grade A no-ash concrete and Grade A-FA fly ash concrete vs. age (Chemical 2, Aggregate 1)

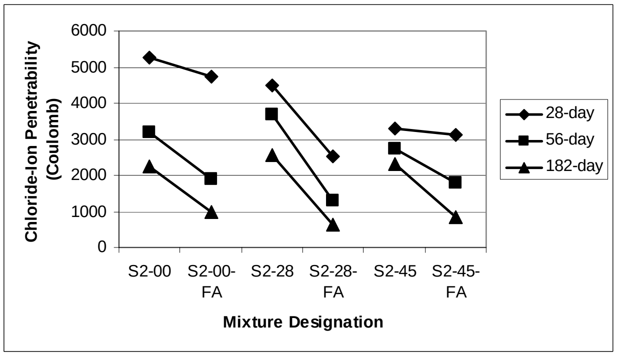
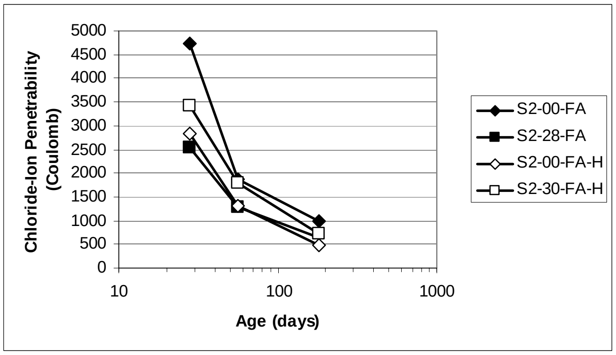


Fig. 6-39. Chloride-ion penetrability into no-SRA concrete and SRA concrete vs. fly ash content (Chemical 2, Aggregate 1)



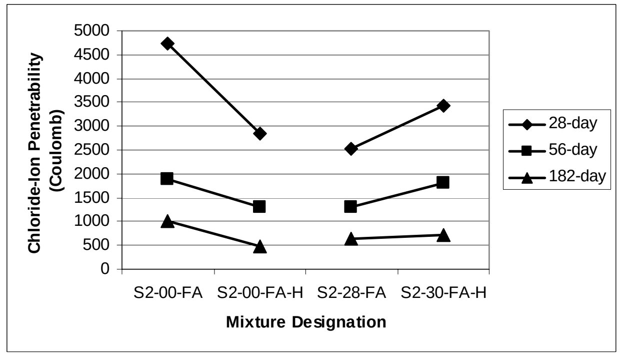
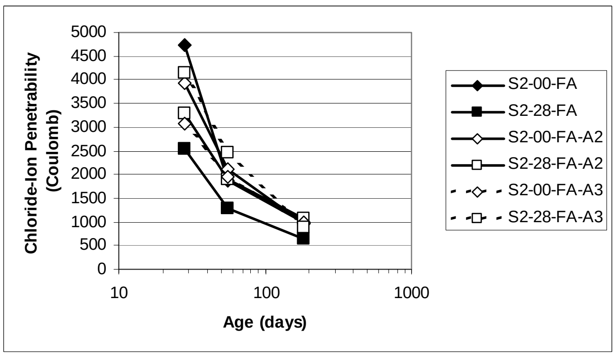


Fig. 6-40. Chloride-ion penetrability into Grade A-FA fly ash concrete and high-Cm concrete vs. age (Chemical 2, Aggregate 1)

Fig. 6-41. Chloride-ion penetrability into concrete vs. cementitious materials content (Chemical 2, Aggregate 1)



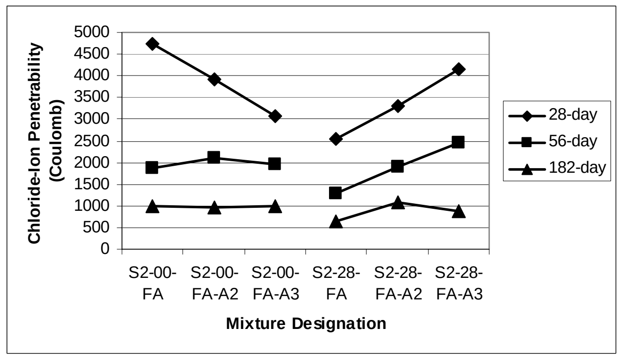


Fig. 6-42. Chloride-ion penetrability into Grade A-FA fly ash concrete made with A1, A2, A3 vs. age (Chemical 2; Aggregates 1, 2, 3)

Fig. 6-43. Chloride-ion penetrability into Grade A-FA fly ash concrete vs. aggregate type (Chemical 2; Aggregates 1, 2, 3)

Use of SRA-2 was helpful in reducing the 28-day chloride-ion penetrability into Grade A no-ash concrete (Fig. 6-34, Fig. 6-35) and Grade A-FA fly ash concrete mixtures made with Aggregates 1 and 2 (Fig. 6-36, Fig. 6-37, Fig. 6-42, Fig. 6-43). On the other hand, SRA-2 somewhat increased the chloride-ion penetrability into the high-Cm concrete and Grade A-FA fly ash concrete made with Aggregate 3 (a lower resistance to penetration).

The chloride-ion penetrability into Grade A-FA fly ash concrete mixtures was much lower (higher resistance to penetration) than that into Grade A no-ash concrete mixtures (Fig. 6-38, Fig. 6-39). Overall, the use of higher amounts of cementitious materials did not significantly affect the chloride-ion penetrability into concrete (Fig. 6-40, Fig. 6-41).

When used without SRA-2, use of Aggregate 3 led to the lowest 28-day chloride-ion penetrability (the highest resistance to penetration) (Fig. 6-43); the 56-day and 182-day chloride-ion penetrability was similar regardless of aggregate type. When used with SRA-2, Aggregate 1 led to the lowest early-age chloride-ion penetrability (the highest resistance to penetration), followed by Aggregate 2, and Aggregate 3.

6.7 Air Content and Slump Losses (Chemical 2)

The SRA concrete mixtures S2-28 and S2-28-FA were repeated in the laboratory, and the changes in their air content and slump during the first hour were measured and compared against those of the reference (no SRA) concrete mixtures S2-00 and S2-00-FA that were also repeated.

The mixture proportions of the concrete mixtures are shown in Table 6-9, including the initial air content and slump of fresh concrete. Use of SRA-2 reduced the MRWRA-2 demand and increased the AEA-2 demand.

Table 6-9. Mixture Proportions of Concrete for Air Content (Chemical 2)

Mixture designation*	S2-00-air	S2-28-air	S2-00-FA-air	S2-28-FA-air
Laboratory mixture designation	A-2-air	A-S2-air	A-FA-2-air	A-FA-S2-air
Cement (lb/yd^3)	552	549	387	392
Class C Fly Ash (lb/yd^3)	0	0	167	169
Water (lb/yd^3)	228	236	231	235
Fine aggregate, SSD (lb/yd^3)	1390	1375	1381	1394
Coarse aggregate, ≤ 3/4 in., SSD (lb/yd^3)	1682	1673	1666	1687
W/Cm	0.41	0.43	0.42	0.42
MRWRA-2 (fl. oz./yd^3)	146	98	48	19
AEA-2 (fl. oz./yd^3)	7	109	24	111
SRA-2 (fl. oz./yd^3)	0	155	0	159
Slump (in.)	2.25	2.5	2	2.5
Air content (%)	7.0	6.1	6.9	5.6
Air temperature (°F)	68	67	68	68
Concrete temperature (°F)	71	0	0	0
Density (lb/ft^3)	143	142	142	144

* The number following S2- indicates the approximate dosage rate of SRA-2 in fl. oz./100 lb of cementitious materials. See Section 1.5 for more details.

The changes in air content and slump of fresh concrete mixtures are shown in Table 6-10, and Fig. 6-44 and Fig. 6-45.

Table 6-10. Changes in Air Content and Slump of Fresh Concrete (Chemical 2)

Time (minutes)	Air content (%)				Slump (in.)			
	S2-00-air	S2-28-air	S2-00-FA-air	S2-28-FA-air	S2-00-air	S2-28-air	S2-00-FA-air	S2-28-FA-air
0	7.0	6.1	6.9	5.6	2.25	2.50	2.00	2.50
10	5.9	5.3	6.5	5.5	1.13	1.75	1.50	2.25
20	4.5	4.6	6.4	5.5	0.88	1.25	1.38	1.50
30	4.0	4.3	6.2	5.6	0.88	1.25	1.13	1.50
40	3.9	4.0	6.0	5.5	0.75	1.00	1.00	1.25
50	3.8	4.3	5.8	5.7	0.75	0.75	0.63	1.50
60	3.9	3.9	5.7	5.9	0.75	0.75	0.75	1.50

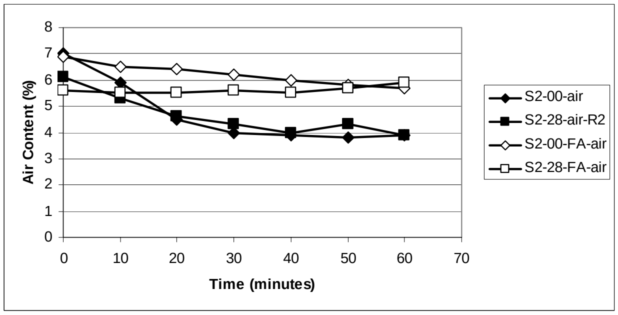


Fig. 6-44. Change in air content of fresh concrete (Chemical 2)

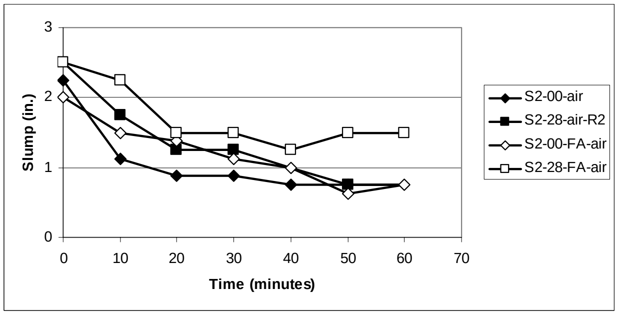


Fig. 6-45. Change in slump of fresh concrete (Chemical 2)

The air content of Grade A no-ash concrete mixtures decreased considerably during the first 30 minutes and then stabilized at about 4%. The air content of Grade A-FA fly ash concrete mixtures was very stable, meaning that fly ash helped to minimize the loss of air content. The air content of the concrete mixture S2-28-FA-air was practically constant during the first hour. Use of SRA-2 did not affect the loss of air content considerably.

The slump of concrete mixtures decreased by 1 to 1.75 inches in one hour. But all four mixtures retained a final slump of 0.75 inches or higher. Fly ash was helpful in retaining slump. The concrete mixtures containing SRA-2 retained slump better than corresponding no-SRA concrete mixtures.

Chapter 7. Concrete Mixtures Containing Chemical Admixtures from Source 3

7.1 Mixture Proportions and Time of Initial Setting (Chemical 3)

Table 7-1 shows the mixture proportions and fresh properties of concrete mixtures containing chemical admixtures from Source 3 (Degussa, formerly Master Builders).

Table 7-1. Mixture Proportions and Fresh Properties of Concrete (Chemical 3)

Mixture designation*	S3-00	S3-27	S3-38	S3-00-FA	S3-27-FA	S3-38-FA	S3-00-FA-H	S3-27-FA-H	S3-00-FA-A2	S3-27-FA-A2	S3-00-FA-A3	S3-27-FA-A3
Laboratory mixture designation	A-3	A-S3	A-S3S	A-FA-3	A-FA-S3	A-FA-S3S	A-FA-3A	A-FA-S3A	A-FA-3-A2	A-FA-S3-A2	A-FA-3-A3	A-FA-S3-A3
Cement (lb/yd^3)	550	556	549	392	387	385	498	510	392	393	403	401
Class C Fly Ash (lb/yd^3)	0	0	0	169	167	166	214	219	169	169	174	173
Water (lb/yd^3)	226	222	222	226	200	206	243	217	210	220	231	222
Fine aggregate, SSD (lb/yd^3)	1380	1400	1380	1390	1380	1370	1280	1310	1240	1250	1440	1430
Coarse aggregate, ≤ 3/4 in., SSD (lb/yd^3)	1680	1690	1680	1690	1670	1660	1550	1590	1860	1850	1750	1750
MRWRA-3 (fl. oz./yd^3)	81.6	16.5	42.8	41.7	16.6	16.0	21.3	21.8	24.3	0.7	35.7	4.3
AEA-3 (fl. oz./yd^3)	1.6	2.5	10.2	2.9	3.6	7.8	15.2	13.5	5.5	1.1	2.3	1.6
SRA-3 (fl. oz./yd^3)	0	152	208	0	149	209	0	196	0	153	0	156
W/Cm	0.41	0.40	0.41	0.40	0.36	0.37	0.34	0.30	0.37	0.39	0.40	0.39
Slump (in.)	3	2.5	2	3.25	2.75	2.75	3	2.25	2.75	3.75	2.25	2.25
Air content (%)	6.2	5.8	6.2	5.7	7.2	6.0	7.2	6.3	6.0	5.8	5.5	5.5
Air temperature (°F)	69	69	69	69	69	69	69	69	68	68	67	68
Concrete temperature (°F)	69	70	70	70	70	70	70	70	68	70	67	66
Density (lb/ft^3)	142	144	142	143	141	141	140	143	143	144	148	148

* The number following S3- indicates the approximate dosage rate of SRA-3 in fl. oz./100 lb of cementitious materials. See Section 1.5 for more details.

Fig. 7-1 and Fig. 7-2 show the influence of SRA-3 on MRWRA-3 demand and W/Cm of concrete. Overall, use of SRA-3 reduced either the MRWRA-3 demand, or W/Cm, or both of concrete mixtures, meaning that SRA-3 had a water-reducing effect. Use of fly ash reduced the MRWRA-3 demand (Fig. 7-1).

Fig. 7-3 and Fig. 7-4 show the influence of SRA-3 on AEA-3 demand and air content of concrete. When SRA-3 was used at its average dosage rate, the AEA-3 demand remained more or less the same as the reference (no SRA) concrete mixtures. When SRA-3 was used at its maximum dosage rate, the AEA-3 demand increased (Fig. 7-3). The AEA-3 dosage rate itself was very small (about 2 fl. oz. or less per 100 lb of cementitious materials) regardless of the SRA-3 dosage.

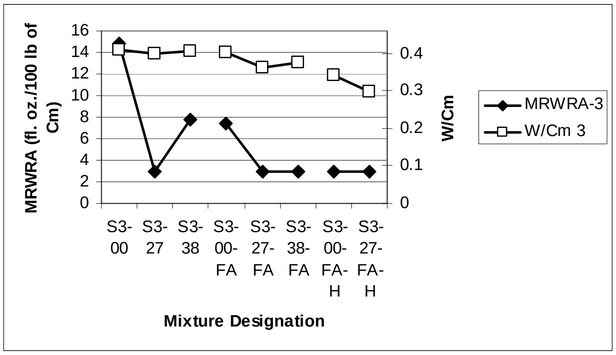


Fig. 7-1. MRWRA demand and W/Cm of concrete as influenced by SRA (Chemical 3, Aggregate 1)

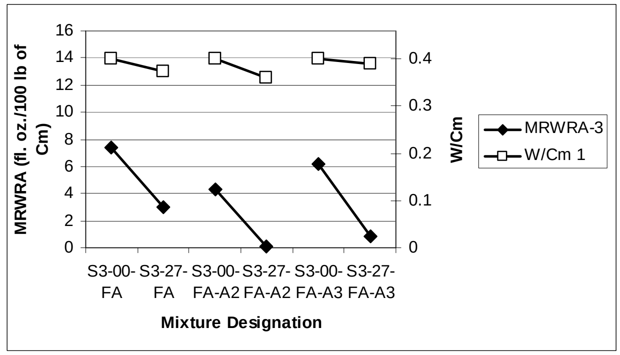


Fig. 7-2. MRWRA demand and W/Cm of concrete as influenced by SRA (Chemical 3; Aggregates 1, 2, 3)

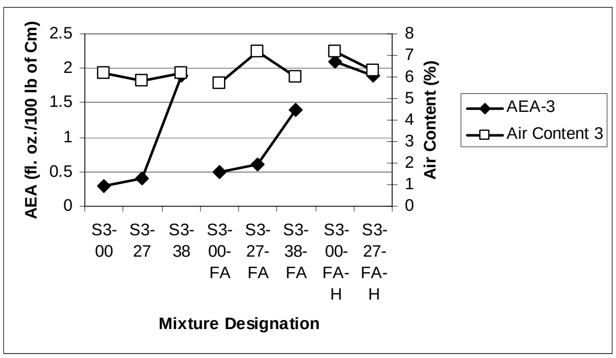


Fig. 7-3. AEA demand and air content of concrete as influenced by SRA (Chemical 3, Aggregate 1)

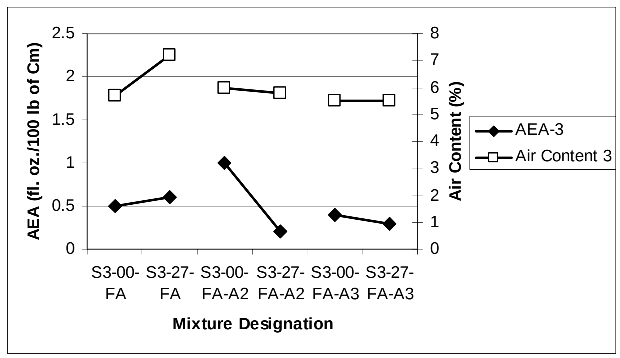


Fig. 7-4. AEA demand and air content of concrete as influenced by SRA (Chemical 3; Aggregates 1, 2, 3)

Time of initial setting of concrete was determined for starting the measurements for autogenous shrinkage. The time of initial setting of the reference (no SRA) Grade A-FA fly ash concrete was exceptionally long (15 hours) (Table 6-2). The rest of the concrete mixtures made with chemical admixtures from Source 3 showed a initial setting time of 7 to 10.75 hours. In general, the effect of SRA-3 on the time of initial setting of concrete was relatively small (-2 to +2.5 hours).

Table 7-2. Time of Initial Setting of Concrete (Chemical 3)

Mixture designation	S3-00	S3-27	S3-38	S3-00-FA	S3-27-FA	S3-38-FA	S3-00-FA-H	S3-27-FA-H	S3-00-FA-A2	S3-27-FA-A2	S3-00-FA-A3	S3-27-FA-A3
Time of initial setting (hours)	7	8.25	8.5	15	8.5	8	7.75	10.25	9.33	8.75	10.75	8.75
Difference from no-SRA concrete (hours)	0	1.25	1.5	0	-6.5	-7	0	2.5	0	-0.58	0	-2

7.2 Autogenous Shrinkage (Chemical 3)

Table 7-3 and Fig. 7-5 to Fig. 7-14 show the autogenous shrinkage of concrete containing chemical admixtures from Source 3.

Table 7-3. Autogenous Shrinkage of Concrete (Chemical 3)

Age (days)	Autogenous shrinkage* (microstrain)											
	S3-00	S3-27	S3-38	S3-00-FA	S3-27-FA	S3-38-FA	S3-00-FA-H	S3-27-FA-H	S3-00-FA-A2	S3-27-FA-A2	S3-00-FA-A3	S3-27-FA-A3
0.7	2	2	-3	9	3	0	-3	-1	-11	-4	-16	-10
1	17	20	9	12	17	-3	-1	20	9	1	-8	-10
3	94	26	65	48	35	12	44	35	38	3	14	-15
7	137	74	105	88	61	41	122	88	80	24	47	-9
14	152	103	135	155	108	73	207	138	110	50	93	13
28	190	140	178	275	175	137	298	228	173	82	175	55
56	214	187	216	351	225	215	370	295	257	144	252	137

* 0 at time of initial setting. -: Expansion. +: Shrinkage.

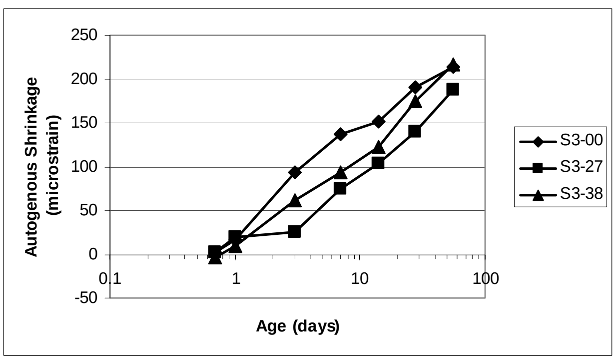


Fig. 7-5. Autogenous shrinkage of Grade A no-ash concrete vs. age (Chemical 3, Aggregate 1)

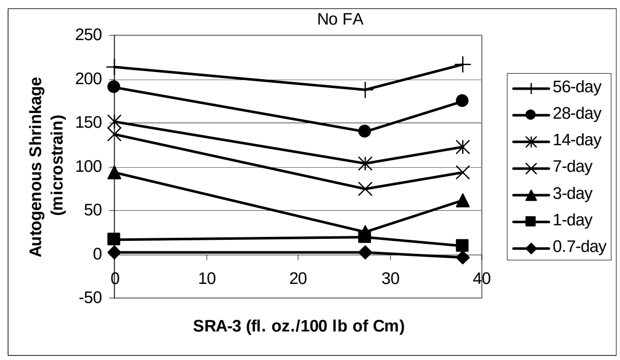


Fig. 7-6. Autogenous shrinkage of Grade A no-ash concrete vs. SRA dosage rate (Chemical 3, Aggregate 1)

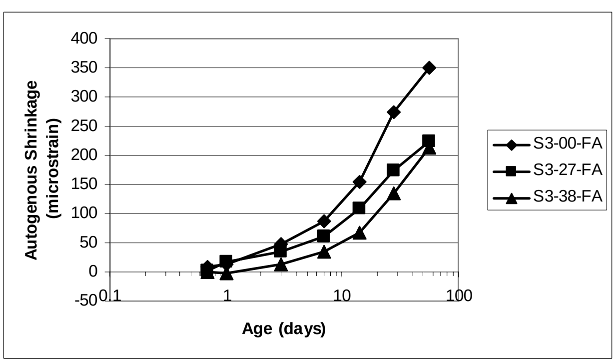


Fig. 7-7. Autogenous shrinkage of Grade A-FA fly ash concrete vs. age (Chemical 3, Aggregate 1)

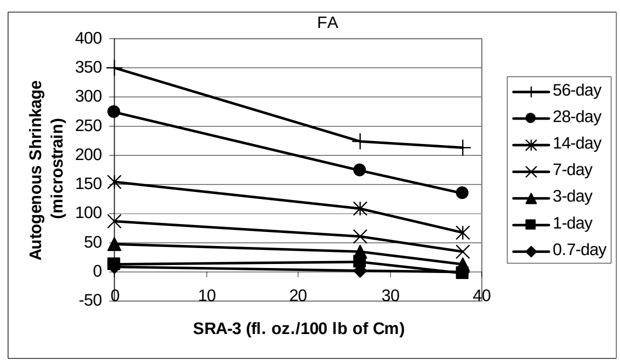
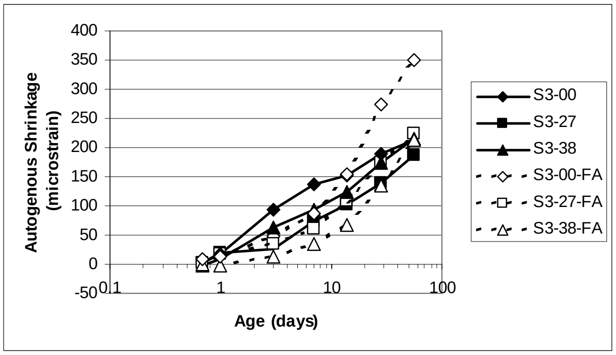


Fig. 7-8. Autogenous shrinkage of Grade A-FA fly ash concrete vs. SRA dosage rate (Chemical 3, Aggregate 1)



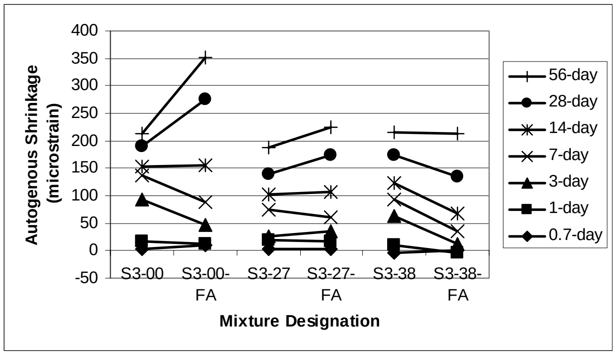
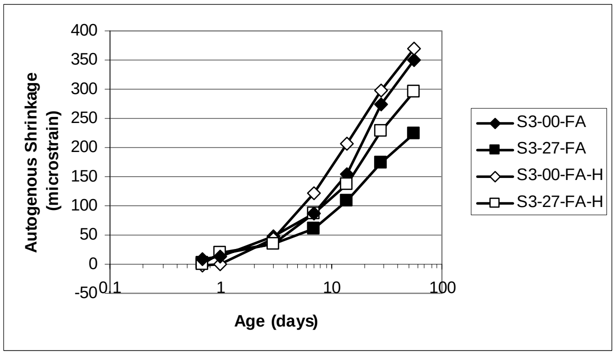


Fig. 7-9. Autogenous shrinkage of Grade A no-ash concrete and Grade A-FA fly ash concrete vs. age (Chemical 3, Aggregate 1)

Fig. 7-10. Autogenous shrinkage of no-SRA concrete and SRA concrete vs. fly ash content (Chemical 3, Aggregate 1)



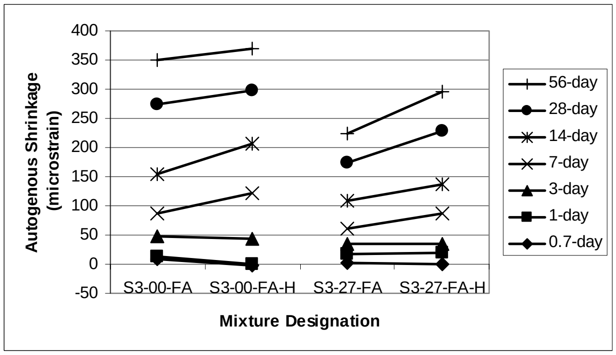
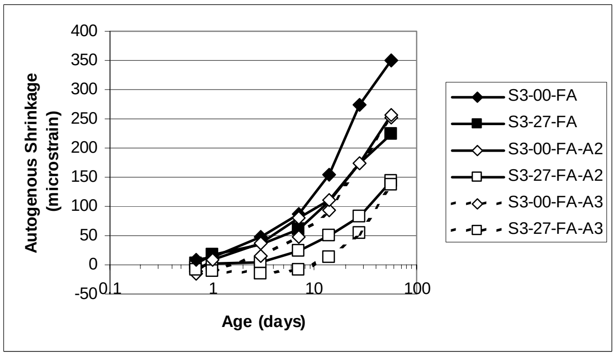


Fig. 7-11. Autogenous shrinkage of Grade A-FA fly ash concrete and high-Cm concrete vs. age (Chemical 3, Aggregate 1)

Fig. 7-12. Autogenous shrinkage of concrete vs. cementitious materials content (Chemical 3, Aggregate 1)



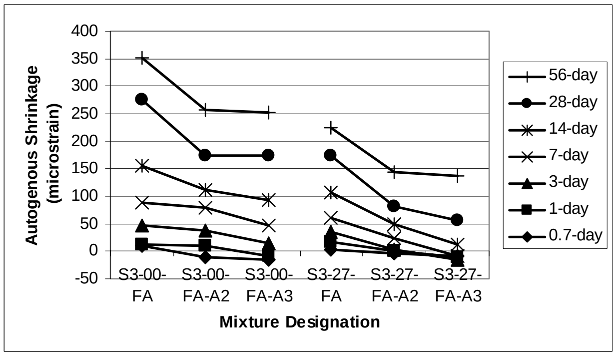


Fig. 7-13. Autogenous shrinkage of Grade A-FA fly ash concrete made with A1, A2, A3 vs. age (Chemical 3; Aggregates 1, 2, 3)

Fig. 7-14. Autogenous shrinkage of Grade A-FA fly ash concrete vs. aggregate type (Chemical 3; Aggregates 1, 2, 3)

Use of SRA-3 was somewhat helpful in reducing the autogenous shrinkage of Grade A no-ash concrete mixtures at ages of up to about 28 days (Fig. 7-5, Fig. 7-6). SRA-3 was effective in reducing the autogenous shrinkage of Grade A-FA fly ash concrete mixtures, especially at later ages of 28 and 56 days (Fig. 7-7, Fig. 7-8).

In comparison with Grade A no-ash concrete mixtures, Grade A-FA fly ash concrete mixtures generally showed a lower autogenous shrinkage at ages of up to 14 days but either a similar or higher autogenous shrinkage at 28 and 56 days (Fig. 7-9, Fig. 7-10).

SRA-3 somewhat reduced the autogenous shrinkage of high-Cm concrete mixtures (Fig. 7-11, Fig. 7-12). The high-Cm concrete mixtures showed a higher autogenous shrinkage compared with Grade A-FA fly ash concrete mixtures.

SRA-3 was effective in reducing the autogenous shrinkage of concrete mixtures made with Aggregates 1, 2, and 3 (Fig. 7-13, Fig. 7-14). The concrete mixtures made with Aggregates 2 and 3 showed a lower autogenous shrinkage than those made with Aggregate 1. The mixtures made with Aggregate 3 showed the lowest autogenous shrinkage at early ages of up to about 14 days.

7.3 Drying Shrinkage (Chemical 3)

The test results for drying shrinkage of concrete (subsequent to 28 days of moist curing) are shown in Table 7-4, Table 7-5, and Fig. 7-15 through Fig. 7-24. The test results for expansion of concrete during moist curing from 1 to 28 days are shown in Appendix B.

Table 7-4. Drying Shrinkage of Concrete Subsequent to 28 Days of Moist Curing (Chemical 3)

Air-storage period subsequent to 28 days of moist curing (days)	Drying shrinkage (microstrain)											
	S3-00	S3-27	S3-38	S3-00-FA	S3-27-FA	S3-38-FA	S3-00-FA-H	S3-27-FA-H	S3-00-FA-A2	S3-27-FA-A2	S3-00-FA-A3	S3-27-FA-A3
4	229	35	66	330	131	67	229	101	235	70	197	43
7	312	73	86	375	175	107	305	196	345	120	320	60
14	420	125	176	442	255	200	394	215	445	180	417	150
28	477	175	250	500	341	260	469	301	500	273	450	263
56	560	262	310	519	343	337	487	315	570	403	517	313
112	564	287	336	545	395	355	554	335	610	450	560	333
Average	427	160	204	452	273	221	406	244	451	249	410	194

Table 7-5. Relative Reduction in Drying Shrinkage of Concrete (Chemical 3)

Air-storage period subsequent to 28 days of moist curing (days)	Relative reduction in drying shrinkage (%)											
	S3-00	S3-27	S3-38	S3-00-FA	S3-27-FA	S3-38-FA	S3-00-FA-H	S3-27-FA-H	S3-00-FA-A2	S3-27-FA-A2	S3-00-FA-A3	S3-27-FA-A3
4	0	85	71	0	60	80	0	56	0	70	0	78
7	0	77	72	0	53	71	0	36	0	65	0	81
14	0	70	58	0	42	55	0	45	0	60	0	64
28	0	63	48	0	32	48	0	36	0	45	0	41
56	0	53	45	0	34	35	0	35	0	29	0	39
112	0	49	40	0	28	35	0	40	0	26	0	40
Average	0	63	52	0	40	51	0	40	0	45	0	53

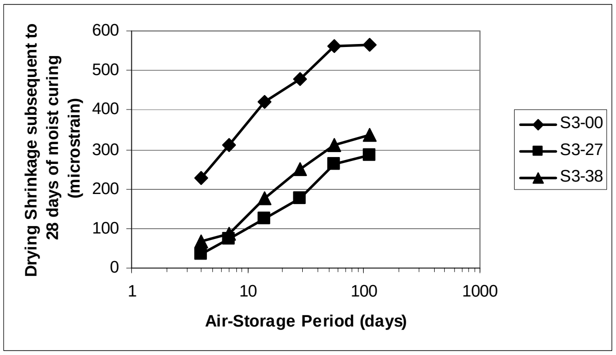


Fig. 7-15. Drying shrinkage of Grade A no-ash concrete vs. air-storage period (Chemical 3, Aggregate 1)

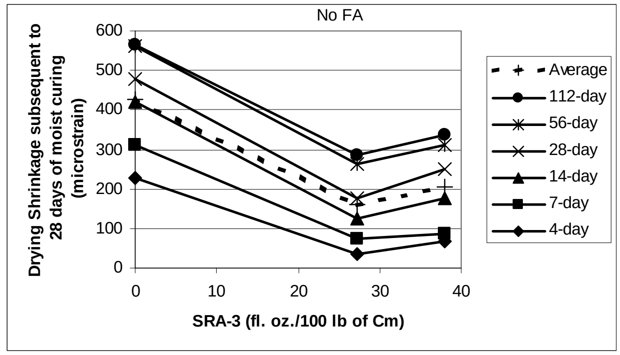


Fig. 7-16. Drying shrinkage of Grade A no-ash concrete vs. SRA dosage rate (Chemical 3, Aggregate 1)

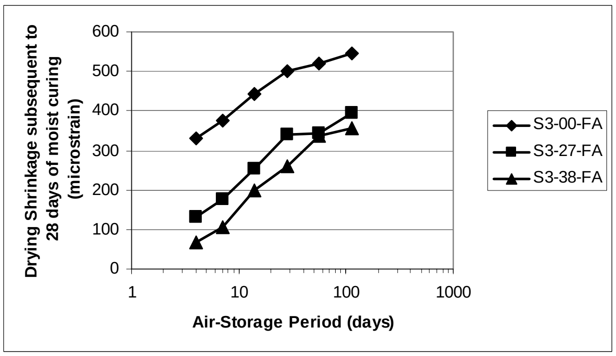


Fig. 7-17. Drying shrinkage of Grade A-FA fly ash concrete vs. air-storage period (Chemical 3, Aggregate 1)

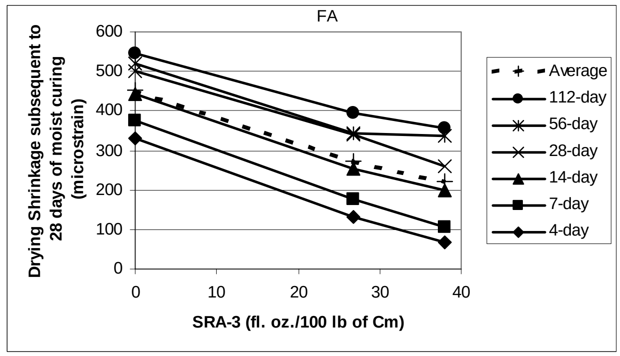


Fig. 7-18. Drying shrinkage of Grade A-FA fly ash concrete vs. SRA dosage rate (Chemical 3, Aggregate 1)

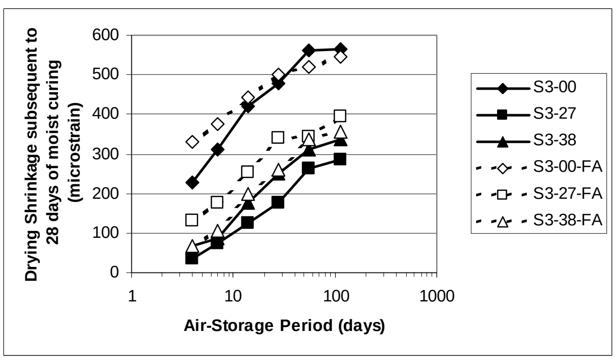


Fig. 7-19. Drying shrinkage of Grade A no-ash concrete and Grade A-FA fly ash concrete vs. air-storage period (Chemical 3, Aggregate 1)

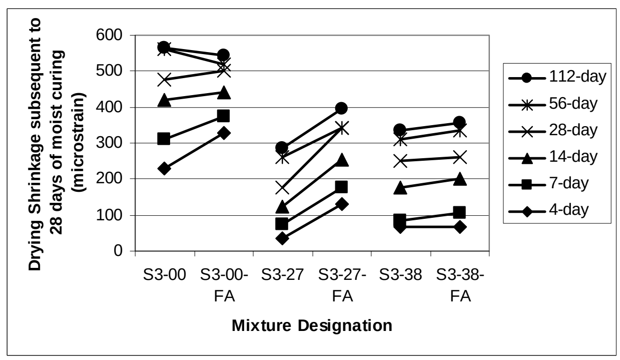


Fig. 7-20. Drying shrinkage of no-SRA concrete and SRA concrete vs. fly ash content (Chemical 3, Aggregate 1)

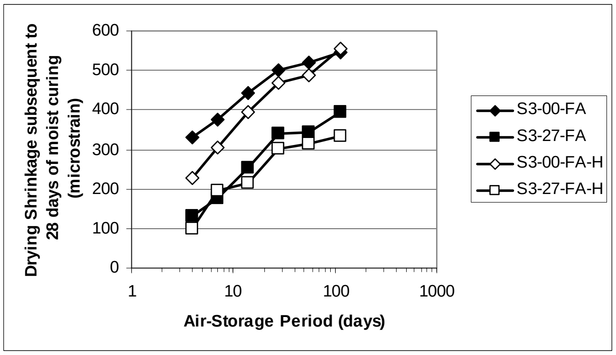


Fig. 7-21. Drying shrinkage of Grade A-FA fly ash concrete and high-Cm concrete vs. air-storage period (Chemical 3, Aggregate 1)

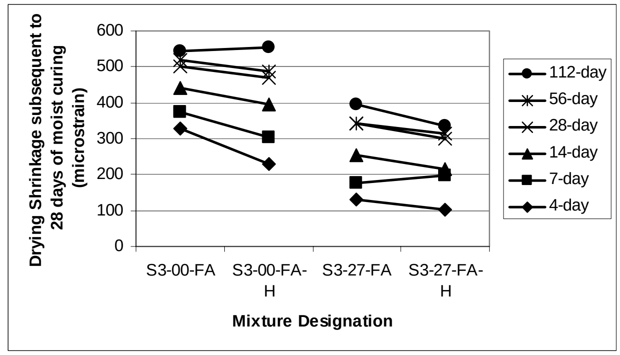


Fig. 7-22. Drying shrinkage of concrete vs. cementitious materials content (Chemical 3, Aggregate 1)

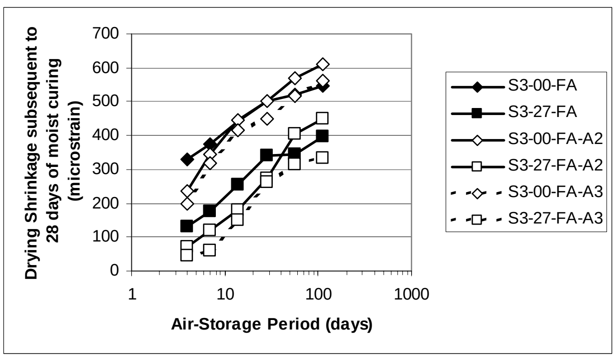


Fig. 7-23. Drying shrinkage of Grade A-FA fly ash concrete made with A1, A2, A3 vs. age (Chemical 3; Aggregates 1, 2, 3)

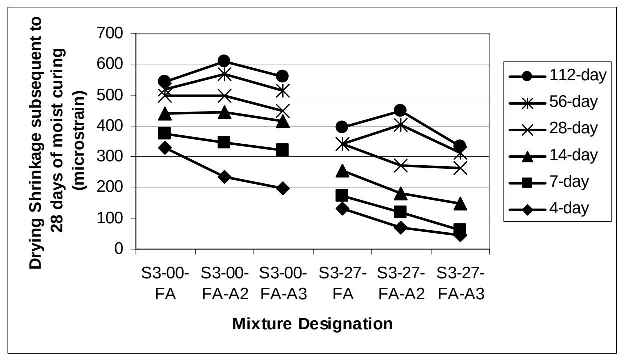


Fig. 7-24. Drying shrinkage of Grade A-FA fly ash concrete vs. aggregate type (Chemical 3; Aggregates 1, 2, 3)

Grade A no-ash concrete mixtures containing SRA-3 showed a much lower drying shrinkage than the reference (no SRA) concrete mixture S3-00 (Fig. 7-15, Fig. 7-16), especially at early ages. Beyond a SRA-3 dosage rate of 27 fl. oz. or less per 100 pounds of cement, a further reduction in drying shrinkage was not achieved. Rather, the drying shrinkage increased slightly when the SRA-3 dosage rate increased from 27 to 38 fl. oz. per 100 pounds of cement.

SRA-3 was also quite effective in reducing the drying shrinkage of Grade A-FA fly ash concrete mixtures (Fig. 7-17, Fig. 7-18), especially at early ages. The reduction was almost proportional to the SRA-3 dosage rate of up to at least 38 fl. oz. per 100 pounds of cementitious materials. The data lines were nearly parallel between the air-storage periods of 4 days and 112 days.

Overall, for a SRA-3 dosage rate of up to 27 fl. oz./100 lb of cementitious materials, Grade A-FA fly ash concrete mixtures showed a somewhat higher drying shrinkage than their Grade A no-ash counterparts (Fig. 7-19, Fig. 7-20). But when the SRA-3 dosage rate increased to 38 fl. oz./100 lb of cementitious materials, the drying shrinkage of the concrete S3-38-FA was about the same as that of the concrete S3-38.

SRA-3 was effective in reducing the drying shrinkage of high-Cm concrete. The high-Cm concrete mixtures showed either a similar or slightly lower drying shrinkage compared with Grade A-FA fly ash concrete mixtures (Fig. 7-21, Fig. 7-22).

Fig. 7-23 and Fig. 7-24 show the influence of the type of coarse aggregate on drying shrinkage of concrete. SRA-3 was effective in reducing the drying shrinkage of concrete made with Aggregates 1, 2, and 3. Overall, at early periods of air storage, use of Aggregate 3 led to the lowest drying shrinkage, followed by Aggregate 2. But at later air-storage periods, drying shrinkage became similar regardless of the type of coarse aggregate, use of Aggregate 2 resulting in the highest drying shrinkage.

7.4 Compressive Strength (Chemical 3)

The test results for compressive strength of concrete are shown in Table 7-6, and Fig. 7-25 through Fig. 7-29.

SRA-3 did not affect the compressive strength of Grade A no-ash concrete mixtures (Fig. 7-25). The Grade A-FA fly ash concrete mixtures containing SRA-3, due to their relatively low W/Cm, showed somewhat higher compressive strength than the reference (no SRA) Grade A-FA fly ash concrete mixture (Fig. 7-26). SRA-3 itself does not seem to have affected the compressive strength of concrete considerably.

Compared with Grade A no-ash concrete mixtures, Grade A-FA fly ash concrete mixtures showed a lower compressive strength at ages of up to 14 days, and a similar compressive strength at 28 days and beyond (Fig. 7-27).

Table 7-6. Compressive Strength of Concrete (Chemical 3)

Age (days)	Compressive strength (psi)											
	S3-00	S3-27	S3-38	S3-00-FA	S3-27-FA	S3-38-FA	S3-00-FA-H	S3-27-FA-H	S3-00-FA-A2	S3-27-FA-A2	S3-00-FA-A3	S3-27-FA-A3
1	2450	2280	2430	670	1280	1290	1500	1990	740	800	1060	960
3	4490	3940	4600	3430	3400	3620	3290	4810	2840	2670	3990	3120
7	5300	5160	5300	4700	4510	4760	4270	5890	3760	3760	5620	4790
14	6000	5740	5720	5110	5270	5360	5120	6630	4400	4700	6380	5630
28	6360	6250	6410	6140	6690	6040	5940	7890	4920	5330	7900	6470
91	7710	7190	7400	7090	8200	7030	7480	9020	5520	6440	9250	7690
182	7525	7580	…	6720	8420	7660	7630	9210	5900	7230	10320	8830

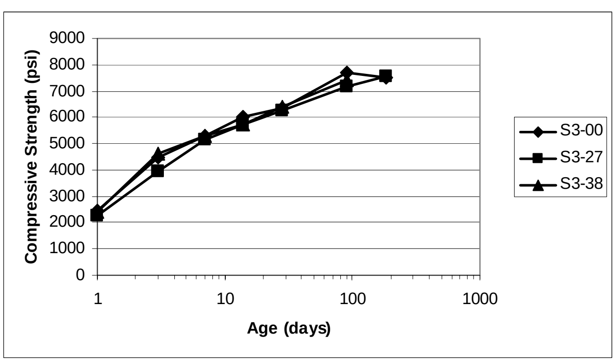


Fig. 7-25. Compressive strength of Grade A no-ash concrete vs. age (Chemical 3, Aggregate 1)

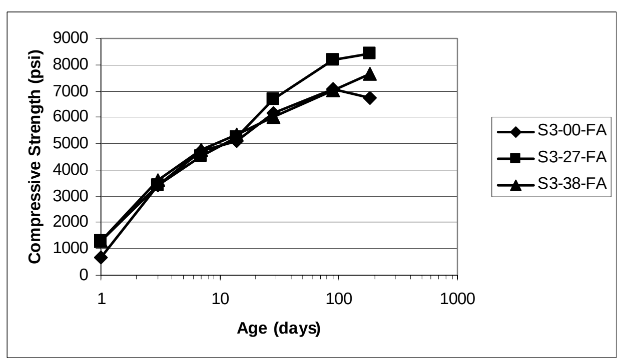


Fig. 7-26. Compressive strength of Grade A-FA fly ash concrete vs. age (Chemical 3, Aggregate 1)

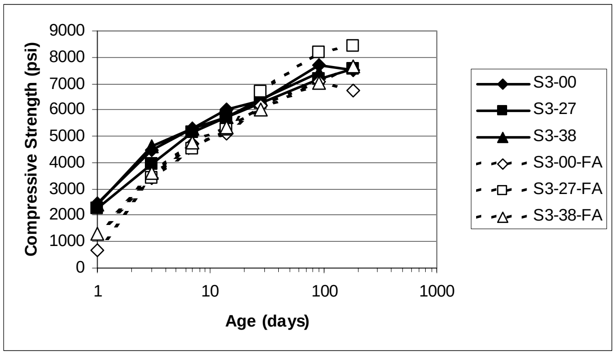


Fig. 7-27. Compressive strength of Grade A no-ash concrete and Grade A-FA fly ash concrete vs. age (Chemical 3, Aggregate 1)

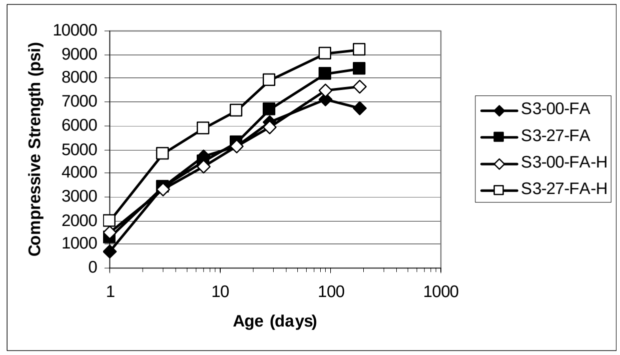


Fig. 7-28. Compressive strength of Grade A-FA fly ash concrete and high-Cm concrete vs. age (Chemical 3, Aggregate 1)

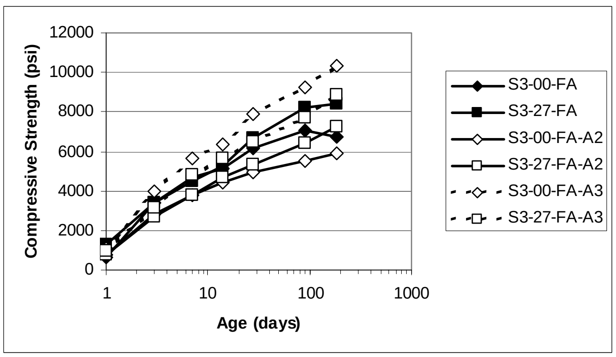


Fig. 7-29. Compressive strength of Grade A-FA fly ash concrete made with A1, A2, A3 vs. age (Chemical 3; Aggregates 1, 2, 3)

The reference (no SRA) high-Cm concrete mixture showed a slightly higher compressive strength than the reference (no SRA) Grade A-FA fly ash concrete mixture (Fig. 7-28). When SRA-3 was used in the high-Cm concrete, the compressive strength increased significantly due to a reduction in W/Cm. The compressive strength of the concrete S3-27-FA-H was about 1,100 psi higher compared with the concrete S3-27-FA. Compared with the reference (no SRA) Grade A no-ash concrete, the reference (no SRA) high-Cm concrete generally showed a lower compressive strength especially at early ages (Table 7-6). Compared with the Grade A no-ash concrete S3-27, the high-Cm concrete S3-27-FA-H showed a higher compressive strength at 3 days and later (Table 7-6).

The concrete mixtures made with Aggregates 1 and 3 (both crushed stone) showed generally higher compressive strength than the concrete mixtures made with Aggregate 2 (semi-crushed river gravel) (Fig. 7-29). The mixtures made with Aggregate 3 showed the highest compressive strength, followed by those made with Aggregate 1.

7.5 Splitting-Tensile Strength (Chemical 3)

The test results for splitting-tensile strength of concrete containing chemical admixtures from Source 3 are shown in Table 7-7, and Fig. 7-30 through Fig. 7-33.

Table 7-7. Splitting-Tensile Strength of Concrete (Chemical 3)

Age (days)	Splitting-tensile strength (psi)							
	S3-00	S3-27	S3-38	S3-00-FA	S3-27-FA	S3-38-FA	S3-00-FA-H	S3-27-FA-H
1	340	300	340	100	200	160	220	270
3	450	470	500	420	440	420	420	500
7	510	530	560	520	490	500	480	520
14	570	530	570	480	560	570	540	570
28	630	600	630	630	600	600	510	630
91	680	700	700	670	700	690	690	710
182	670	700	730	670	710	680	710	750

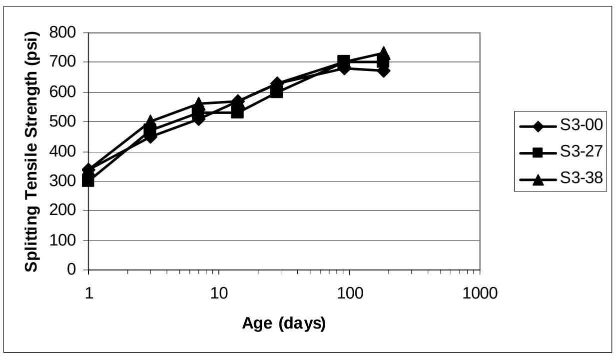


Fig. 7-30. Splitting strength of Grade A no-ash concrete vs. age (Chemical 3, Aggregate 1)

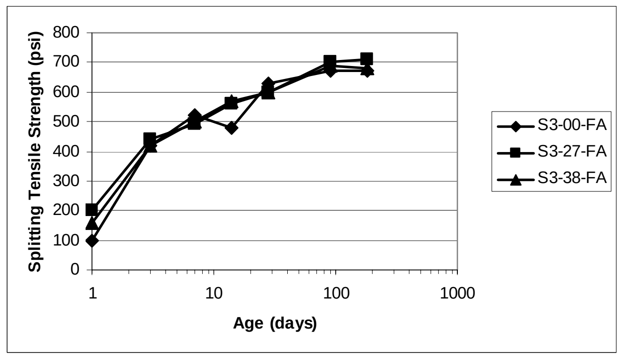


Fig. 7-31. Splitting strength of Grade A-FA fly ash concrete vs. age (Chemical 3, Aggregate 1)

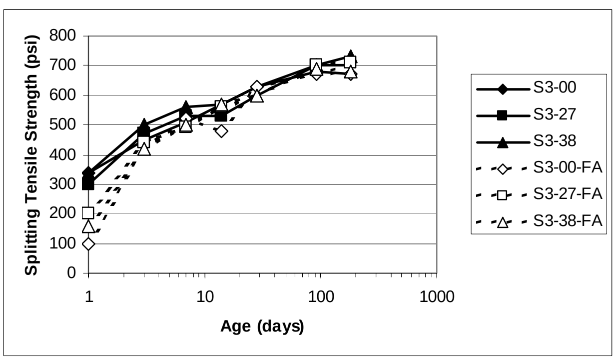


Fig. 7-32. Splitting-tensile strength of Grade A no-ash concrete and Grade A-FA fly ash concrete vs. age (Chemical 3, Aggregate 1)

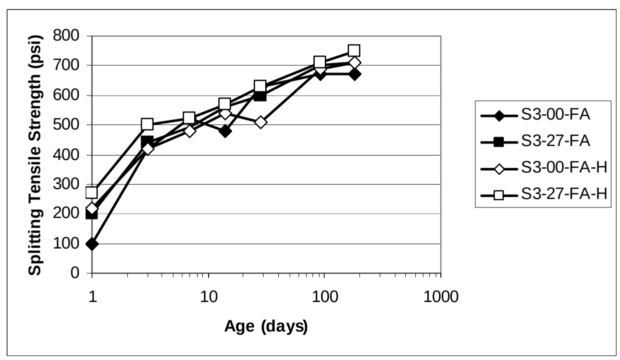


Fig. 7-33. Splitting-tensile strength of Grade A-FA fly ash concrete and high-Cm concrete vs. age (Chemical 3, Aggregate 1)

In trends, the splitting-tensile strength was similar to the compressive strength. SRA-3 did not noticeably affect the splitting-tensile strength of Grade A no-ash concrete (Fig. 7-30). The Grade A-FA fly ash concrete mixtures containing SRA-3 showed a higher 1-day splitting-tensile strength than the reference (no SRA) Grade A-FA fly ash concrete mixture (Fig. 7-31).

Compared to Grade A no-ash concrete mixtures, Grade A-FA fly ash concrete mixtures showed a lower splitting-tensile strength at 1 day, and a similar splitting-tensile strength at 3 days and afterward (Fig. 7-32). The high-Cm concrete mixtures showed a higher 1-day splitting-tensile strength than Grade A-FA fly ash concrete mixtures (Fig. 7-33).

7.6 Chloride-Ion Penetrability (Chemical 3)

The test results for electrical indication of chloride-ion penetrability into concrete are shown in Table 7-8, and Fig. 7-34 through Fig. 7-43.

Table 7-8. Chloride-Ion Penetrability into Concrete (Chemical 3)

Age (days)	Chloride-ion penetrability (Coulomb)											
	S3-00	S3-27	S3-38	S3-00-FA	S3-27-FA	S3-38-FA	S3-00-FA-H	S3-27-FA-H	S3-00-FA-A2	S3-27-FA-A2	S3-00-FA-A3	S3-27-FA-A3
28	4390	2490	2000	4510	2910	1840	2980	2050	2900	2640	4020	2950
56	3010	1710	1750	2400	1640	980	1750	1090	1470	1620	2440	1630
182	2250	1520	1250	840	650	520	560	410	690	850	790	690

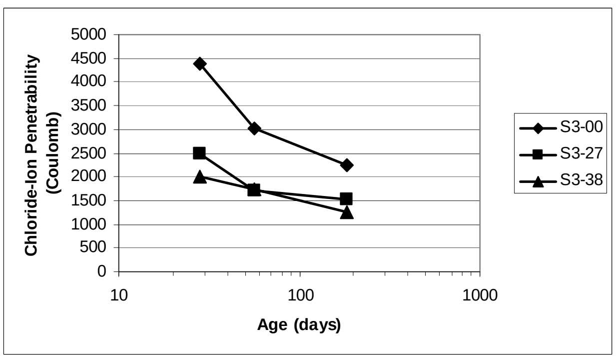


Fig. 7-34. Chloride-ion penetrability into Grade A no-ash concrete vs. age (Chemical 3, Aggregate 1)

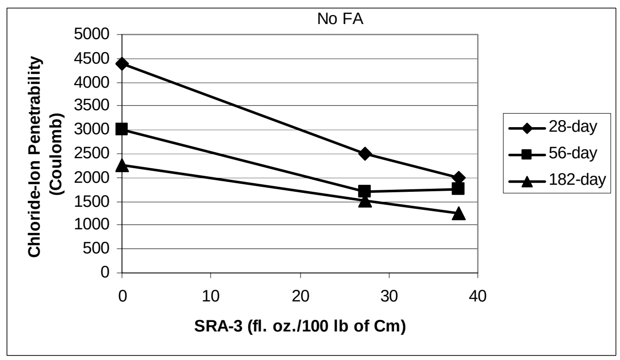


Fig. 7-35. Chloride-ion penetrability into Grade A no-ash concrete vs. SRA dosage rate (Chemical 3, Aggregate 1)

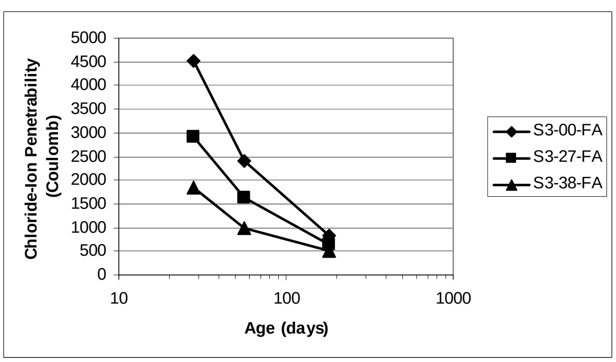


Fig. 7-36. Chloride-ion penetrability into Grade A-FA fly ash concrete vs. age (Chemical 3, Aggregate 1)

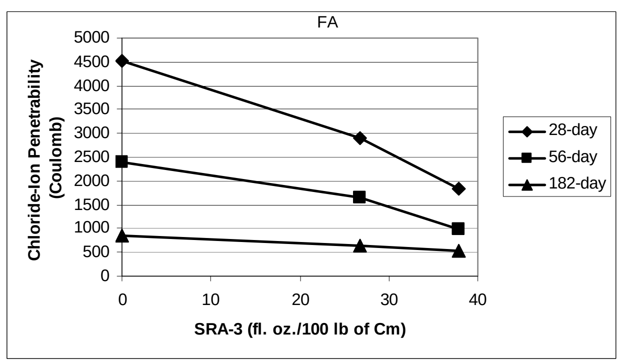


Fig. 7-37. Chloride-ion penetrability into Grade A-FA fly ash concrete vs. SRA dosage rate (Chemical 3, Aggregate 1)

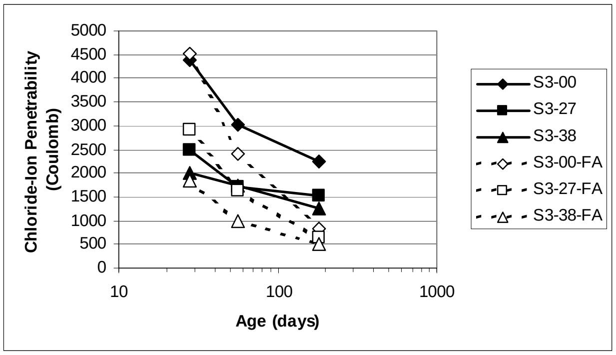


Fig. 7-38. Chloride-ion penetrability into Grade A no-ash concrete and Grade A-FA fly ash concrete vs. age (Chemical 3, Aggregate 1)

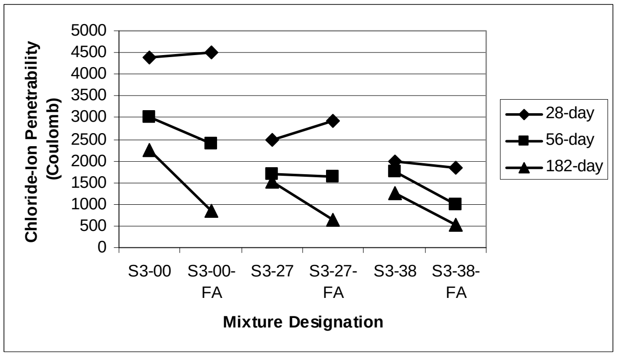


Fig. 7-39. Chloride-ion penetrability into no-SRA concrete and SRA concrete vs. fly ash content (Chemical 3, Aggregate 1)

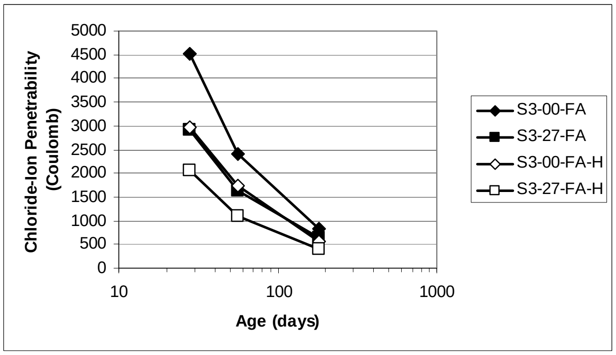


Fig. 7-40. Chloride-ion penetrability into Grade A-FA fly ash concrete and high-Cm concrete vs. age (Chemical 3, Aggregate 1)

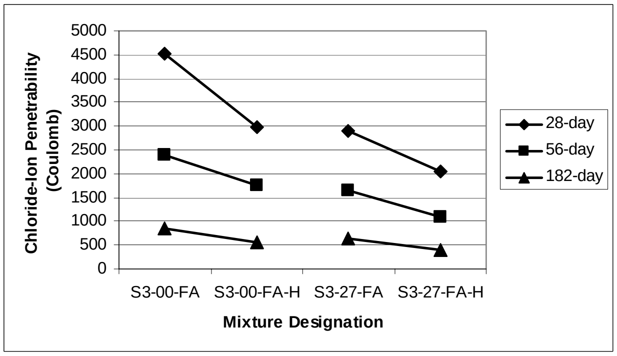


Fig. 7-41. Chloride-ion penetrability into concrete vs. cementitious materials content (Chemical 3, Aggregate 1)

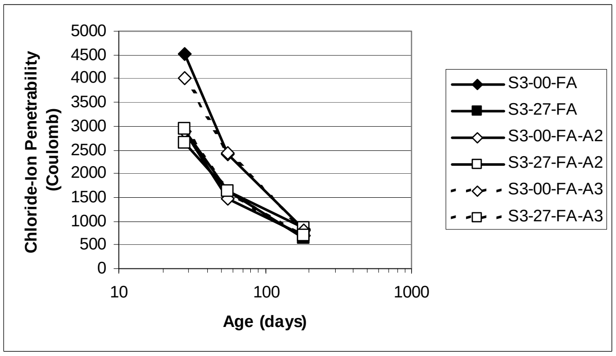


Fig. 7-42. Chloride-ion penetrability into Grade A-FA fly ash concrete made with A1, A2, A3 vs. age (Chemical 3; Aggregates 1, 2, 3)

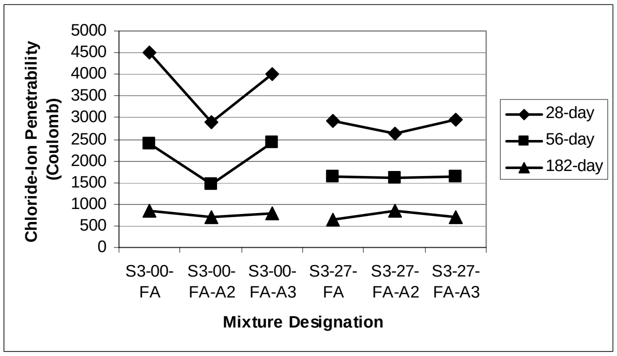


Fig. 7-43. Chloride-ion penetrability into Grade A-FA fly ash concrete vs. aggregate type (Chemical 3; Aggregates 1, 2, 3)

As the age increased, the chloride-ion penetrability decreased due to improvement in microstructure of cementitious paste in concrete.

Use of SRA-3 reduced the chloride-ion penetrability into concrete (a higher resistance to penetration) for all of the concrete mixtures at all ages, except in the case of the Grade A-FA fly ash concrete mixtures made with Aggregate 2 for which SRA-3 did not affect the chloride-ion penetrability noticeably (Table 7-8).

The chloride-ion penetrability into Grade A-FA fly ash concrete mixtures was lower (a higher resistance to penetration) compared with corresponding Grade A no-ash concrete mixtures at 56 and 182 days (Fig. 7-38, Fig. 7-39). Use of higher amounts of cementitious materials decreased the chloride-ion penetrability into concrete (Fig. 7-40, Fig. 7-41).

When used without SRA-3, use of Aggregate 2 led to the lowest chloride-ion penetrability (the highest resistance to penetration) at 28 and 56 days (Fig. 7-42, Fig. 7-43); the 182-day chloride-ion penetrability was similar regardless of the type of coarse aggregate. When used with SRA-3, the chloride-ion penetrability was not noticeably influenced by the aggregate type.

7.7 Air Content and Slump Losses (Chemical 3)

The SRA concrete mixtures S3-27 and S3-27-FA were repeated in the laboratory, and the changes in their air content and slump during the first hour were measured and compared against those of the reference (no SRA) concrete mixtures S3-00 and S3-00-FA that were also repeated. The mixture proportions of the concrete mixtures are shown in Table 7-9, including the initial air content and slump of fresh concrete. SRA-3 had a water-reducing effect and reduced the MRWRA-3 demand.

Table 7-9. Mixture Proportions of Concrete for Air Content (Chemical 3)

Mixture designation*	S3-00-air	S3-27-air	S3-00-FA-air	S3-27-FA-air
Laboratory mixture designation	A-3-air	A-S3-air	A-FA-3-air	A-FA-S3-air
Cement (lb/yd^3)	561	558	393	393
Class C Fly Ash (lb/yd^3)	0	0	169	169
Water (lb/yd^3)	231	227	229	219
Fine aggregate, SSD (lb/yd^3)	1410	1410	1400	1400
Coarse aggregate, ≤ 3/4 in., SSD (lb/yd^3)	1710	1700	1690	1690
W/Cm	0.41	0.41	0.41	0.39
MRWRA-3 (fl. oz./yd^3)	132.8	16.5	41.7	0.5
AEA-3 (fl. oz./yd^3)	1.7	2.5	3.7	3.2
SRA-3 (fl. oz./yd^3)	0	152	0	153
Slump (in.)	2	2.75	3.5	3.875
Air content (%)	5.4	6.1	6.4	6.8
Air temperature (°F)	68	70	67	68
Concrete temperature (°F)	0	64	0	0
Density (lb/ft^3)	145	145	144	144

* The number following S3- indicates the approximate dosage rate of SRA-3 in fl. oz./100 lb of cementitious materials. See Section 1.5 for more details.

The changes in air content and slump of fresh concrete mixtures are shown in Table 7-10, and Fig. 7-44 and Fig. 7-45.

Table 7-10. Changes in Air Content and Slump of Fresh Concrete (Chemical 3)

Time (minutes)	Air content (%)				Slump (in.)			
	S3-00-air	S3-27-air	S3-00-FA-air	S3-27-FA-air	S3-00-air	S3-27-air	S3-00-FA-air	S3-27-FA-air
0	5.4	6.1	6.4	6.8	2.00	2.75	3.50	3.88
10	4.8	5.6	6.4	7.2	0.88	2.25	3.13	3.88
20	4.6	5.0	6.3	7.0	0.88	1.75	2.75	3.00
30	4.3	4.7	5.8	6.0	0.88	1.75	2.50	3.50
40	3.8	4.3	5.7	6.2	0.63	1.25	2.25	3.25
50	3.9	4.1	5.5	6.4	0.63	1.19	2.00	2.00
60	3.7	3.8	5.2	5.6	0.50	1.00	1.63	2.25

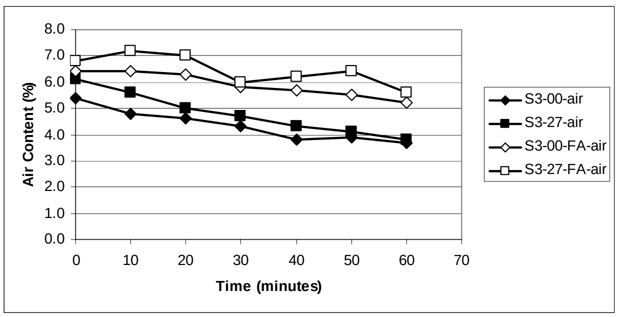


Fig. 7-44. Change in air content of fresh concrete (Chemical 3)

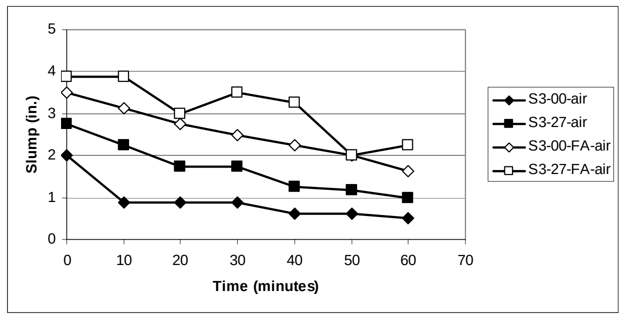


Fig. 7-45. Change in slump of fresh concrete (Chemical 3)

The air content of Grade A no-ash concrete mixtures decreased by 1.7 to 2.3% and reached a final air content of almost 4%. The air content of Grade A-FA fly ash concrete mixtures was relatively stable and decreased by 1.2% in one hour. SRA-3 did not noticeably affect the loss of air content.

The slump of concrete mixtures decreased by 1 to 1.9 inches in one hour and reached a final slump of 0.5 to 2.25 inches. The concrete mixtures containing SRA-3 retained slump somewhat better than their no-SRA counterparts.

Chapter 8. Comparison of Concrete Mixtures (Chemicals 1, 2, 3)

8.1 MRWRA and AEA Demands (Chemicals 1, 2, 3)

In general, SRA-1 and SRA-3 had a water-reducing effect and reduced either the MRWRA demand, or W/Cm, or both of concrete (Fig. 8-1 to Fig. 8-5). As a whole, SRA-2 did not have a water-reducing effect, except in the case of the Grade A-FA fly ash concrete made with Aggregate 3, as shown in Fig. 8-5.

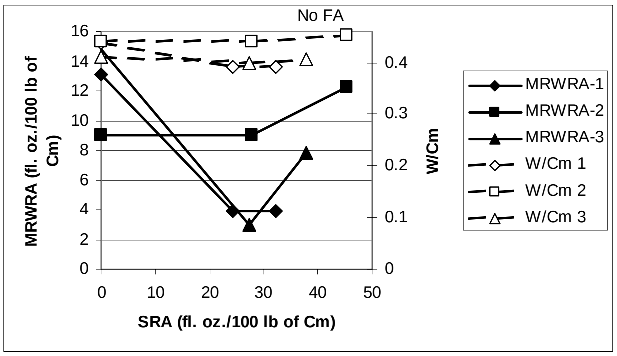


Fig. 8-1. MRWRA demand and W/Cm of Grade A no-ash concrete vs. SRA dosage rate (Chemicals 1, 2, 3; Aggregate 1)

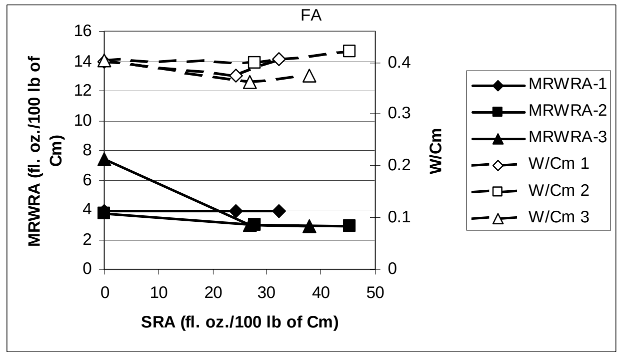


Fig. 8-2. MRWRA demand and W/Cm of Grade A-FA fly ash concrete vs. SRA dosage rate (Chemicals 1, 2, 3; Aggregate 1)

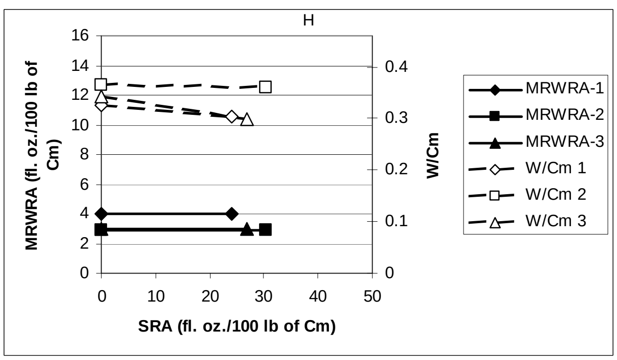


Fig. 8-3. MRWRA demand and W/Cm of high-Cm concrete vs. SRA dosage rate (Chemicals 1, 2, 3; Aggregate 1)

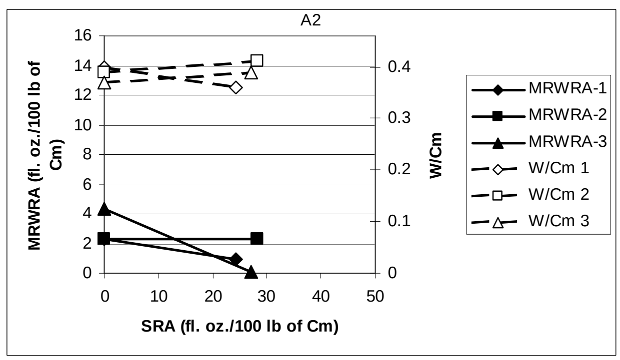


Fig. 8-4. MRWRA demand and W/Cm of Grade A-FA fly ash concrete vs. SRA dosage rate (Chemicals 1, 2, 3; Aggregate 2)

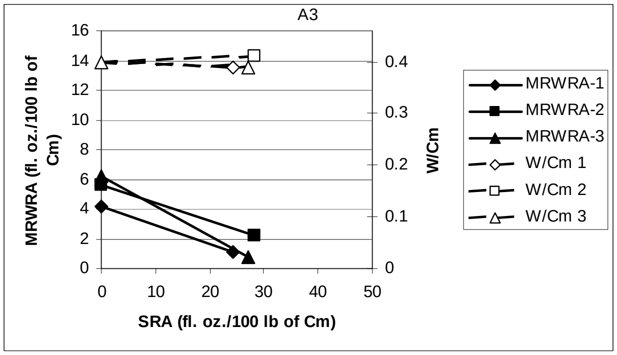


Fig. 8-5. MRWRA demand and W/Cm of Grade A-FA fly ash concrete vs. SRA dosage rate (Chemicals 1, 2, 3; Aggregate 3)

As discussed in Sections 5.1 and 7.1, SRA-1 reduced the AEA-1 demand (Fig. 8-6 to Fig. 8-10). When SRA-3 was used at its maximum dosage, it increased the AEA-3 demand (Fig. 8-6, Fig. 8-7). But the AEA-1 and AEA-3 demands were very small regardless of the dosages of SRA-1 and SRA-3.

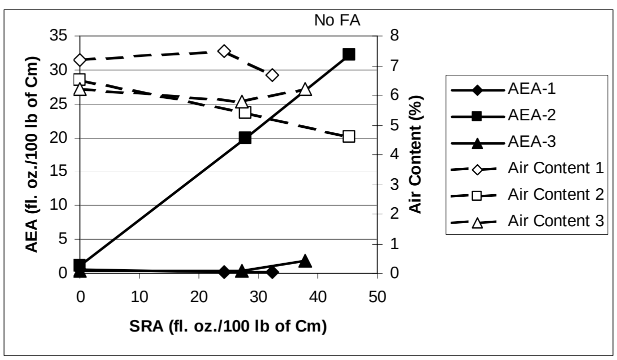


Fig. 8-6. AEA demand and air content of Grade A no-ash concrete vs. SRA dosage rate (Chemicals 1, 2, 3; Aggregate 1)

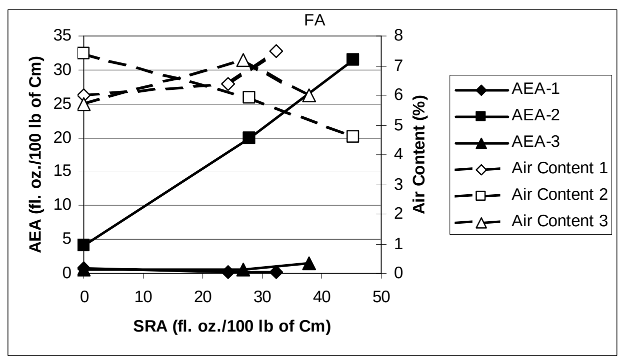


Fig. 8-7. AEA demand and air content of Grade A-FA fly ash concrete vs. SRA dosage rate (Chemicals 1, 2, 3; Aggregate 1)

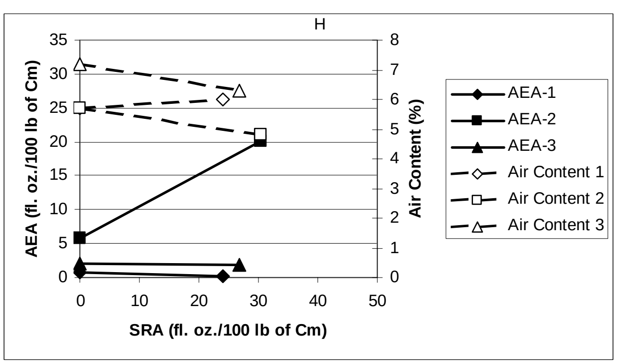


Fig. 8-8. AEA demand and air content of high-Cm concrete vs. SRA dosage rate (Chemicals 1, 2, 3; Aggregate 1)

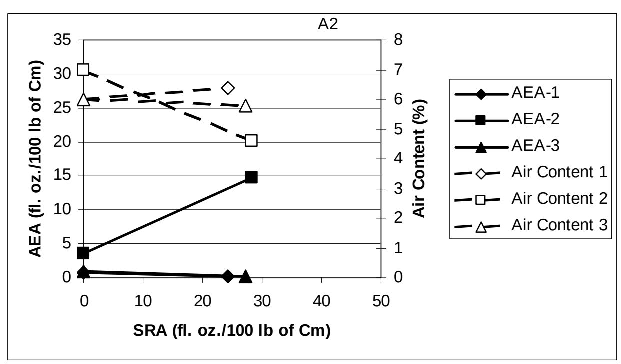


Fig. 8-9. AEA demand and air content of Grade A-FA fly ash concrete vs. SRA dosage rate (Chemicals 1, 2, 3; Aggregate 2)

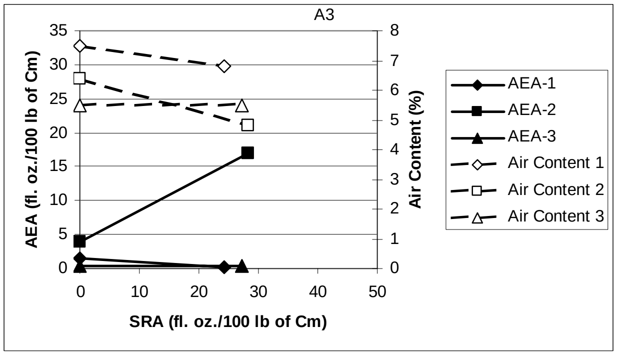


Fig. 8-10. AEA demand and air content of Grade A-FA fly ash concrete vs. SRA dosage rate (Chemicals 1, 2, 3; Aggregate 3)

When SRA-2 was used together with AEA-2 and MRWRA-2, the AEA-2 dosage had to be increased greatly in proportion to SRA-2 dosage. In spite of the very high AEA-2 dosage, the air content of the concrete mixtures containing SRA-2 and AEA-2 was rather low, many times just above the minimum requirement of 4.5%. Use of SRA-2 with other brands of AEA and MRWRA may help to solve this problem.

8.2 Autogenous Shrinkage (Chemicals 1, 2, 3)

Many times, the 14-day autogenous shrinkage roughly represented the trend in autogenous shrinkage of various concrete mixtures produced in this research. The autogenous shrinkage measurements were taken at 0.7, 1, 3, 7, 14, 28, and 56 days.

When the 14-day autogenous shrinkage of concrete mixtures was compared (Fig. 8-11 to Fig. 8-15), as a whole, SRA-1, SRA-2, and SRA-3 showed comparable performance in reducing the autogenous shrinkage. The 14-day autogenous shrinkage of Grade A no-ash concrete mixtures containing chemical admixtures from Source 2 was higher compared with other Grade A no-ash concrete mixtures (Chemicals 1, 3) (Fig. 8-11).

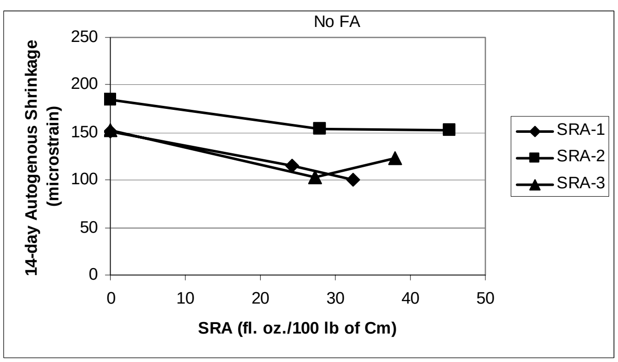


Fig. 8-11. Autogenous shrinkage of Grade A no-ash concrete vs. SRA dosage rate (Chemicals 1, 2, 3; Aggregate 1)

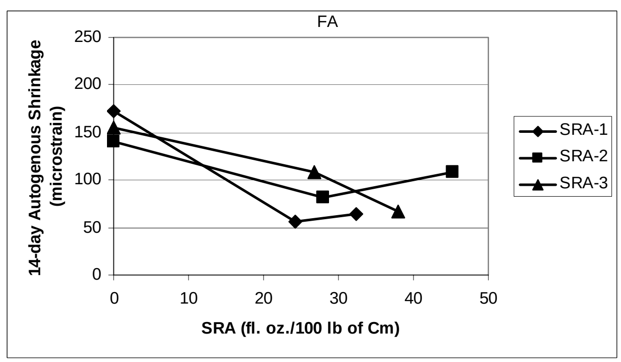


Fig. 8-12. Autogenous shrinkage of Grade A-FA fly ash concrete vs. SRA dosage rate (Chemicals 1, 2, 3; Aggregate 1)

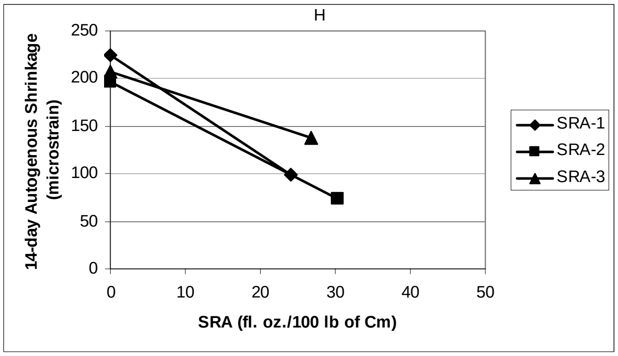


Fig. 8-13. Autogenous shrinkage of high-Cm concrete vs. SRA dosage rate (Chemicals 1, 2, 3; Aggregate 1)

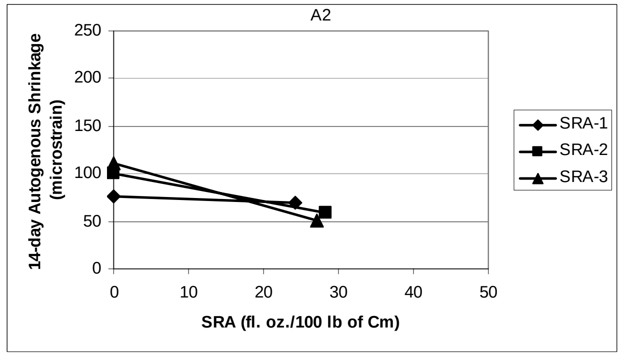


Fig. 8-14. Autogenous shrinkage of Grade A-FA fly ash concrete vs. SRA dosage rate (Chemicals 1, 2, 3; Aggregate 2)

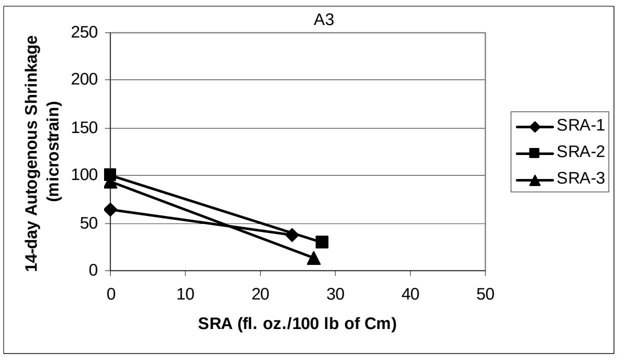


Fig. 8-15. Autogenous shrinkage of Grade A-FA fly ash concrete vs. SRA dosage rate (Chemicals 1, 2, 3; Aggregate 3)

As for the influence of the type of coarse aggregate on the 14-day autogenous shrinkage of Grade A-FA fly ash concrete mixtures, use of Aggregate 3 resulted in the lowest shrinkage (Fig. 8-12), followed by Aggregate 2 (Fig. 8-14), and Aggregate 1 (the highest 14-day autogenous shrinkage) (Fig. 8-15).

8.3 Drying Shrinkage (Chemicals 1, 2, 3)

In most cases, the 14-day drying shrinkage (subsequent to 28 days of moist curing) roughly corresponded to the average of the drying shrinkage measurements were taken at 4, 7, 14, 28, 56, and 112 days of air storage.

In general, when the 14-day drying shrinkage of concrete mixtures was compared, SRA-1, SRA-2, and SRA-3 showed quite similar performance in reducing the drying shrinkage (Fig. 8-16 to Fig. 8-20). In the high-Cm concrete (Fig. 8-18) and Grade A-FA concrete made with Aggregate 3 (Fig. 8-20), SRA-2 was somewhat less effective than SRA-1 or SRA-3.

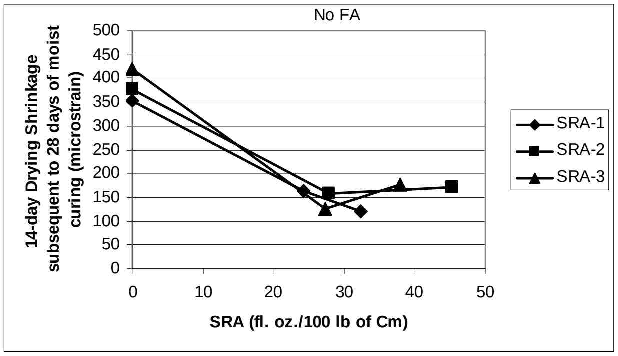


Fig. 8-16. Drying shrinkage of Grade A no-ash concrete vs. SRA dosage rate (Chemicals 1, 2, 3; Aggregate 1)

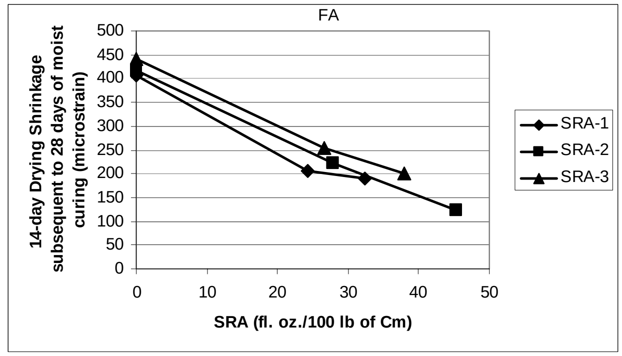


Fig. 8-17. Drying shrinkage of Grade A-FA fly ash concrete vs. SRA dosage rate (Chemicals 1, 2, 3; Aggregate 1)

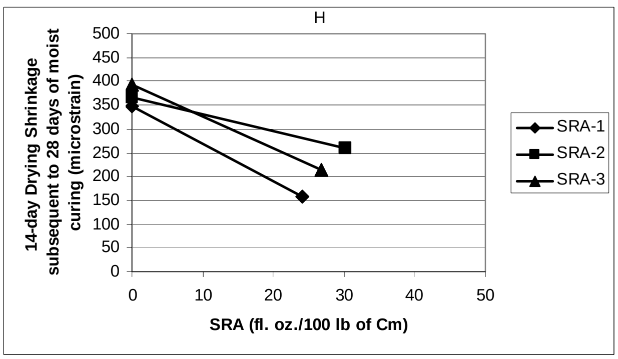


Fig. 8-18. Drying shrinkage of high-Cm concrete vs. SRA dosage rate (Chemicals 1, 2, 3; Aggregate 1)

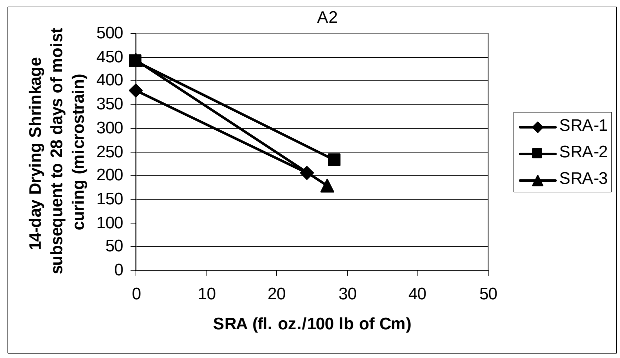


Fig. 8-19. Drying shrinkage of Grade A-FA fly ash concrete vs. SRA dosage rate (Chemicals 1, 2, 3; Aggregate 2)

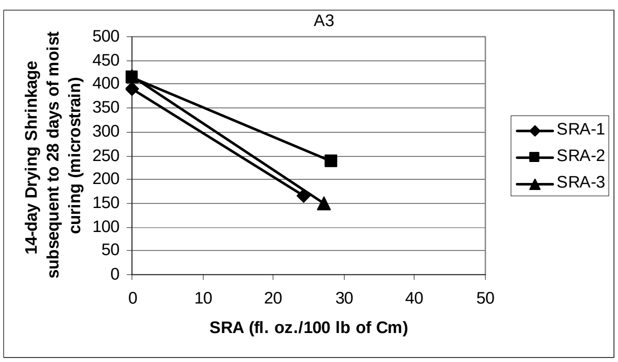


Fig. 8-20. Drying shrinkage of Grade A-FA fly ash concrete vs. SRA dosage rate (Chemicals 1, 2, 3; Aggregate 3)

The optimum dosage rate of SRA seems to be about 25 fl. oz./100 lb of cement (1.1 gal./yd^3) for Grade A no-ash concrete (Fig. 8-16), and about 40 fl. oz./100 lb of cementitious materials (1.8 gal./yd^3) for Grade A-FA fly ash concrete (Fig. 8-17), regardless of the source of SRA. To achieve similar drying shrinkage, more SRA was needed in Grade A-FA fly ash concrete than in Grade A no-ash concrete.

The use of higher amounts of cementitious materials slightly reduced the 14-day drying shrinkage (Fig. 8-17 vs. Fig. 8-18).

The type of coarse aggregate did not have any considerable effect on the 14-day drying shrinkage (Fig. 8-17, Fig. 8-19, Fig. 8-20). But, as discussed in Sections 5.3, 6.3, and 7.3, the use of Aggregate 3 often led to the lowest early-period (e.g., 7-day) drying shrinkage, followed by Aggregate 2, and Aggregate 1 (the highest early-period shrinkage). However, the late-period (e.g., 56-day) drying shrinkage of the concrete mixtures made with Aggregate 2 or 3 became about the same or higher compared with the concrete mixtures made with Aggregate 1. In fact, use of Aggregate 2 often resulted in the highest late-period drying shrinkage.

8.4 Compressive Strength (Chemicals 1, 2, 3)

In general, the concrete mixtures made with chemical admixtures from Source 2 showed a relatively low compressive strength (Fig. 8-21 to Fig. 8-25). An increase in SRA-2 dosage either did not affect or lowered the compressive strength. As discussed earlier in Section 8.1, the concrete mixtures containing SRA-2 had a relatively high W/Cm compared with the concrete mixtures containing SRA-1 and SRA-3.

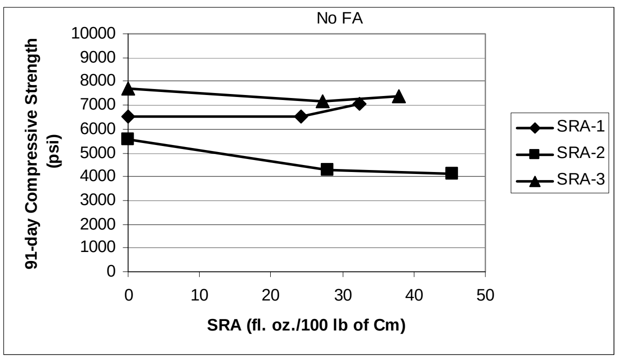


Fig. 8-21. Compressive strength of Grade A no-ash concrete vs. SRA dosage rate (Chemicals 1, 2, 3; Aggregate 1)

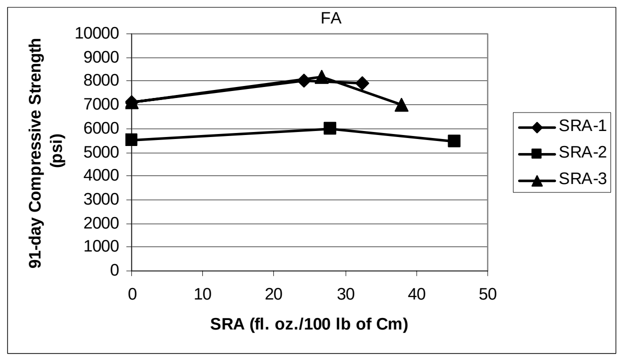


Fig. 8-22. Compressive strength of Grade A-FA fly ash concrete vs. SRA dosage rate (Chemicals 1, 2, 3; Aggregate 1)

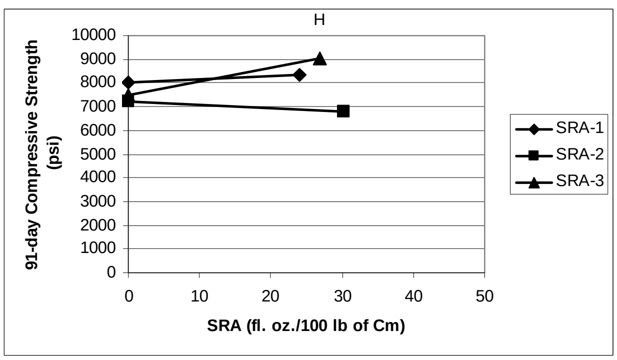


Fig. 8-23. Compressive strength of high-Cm concrete vs. SRA dosage rate (Chemicals 1, 2, 3; Aggregate 1)

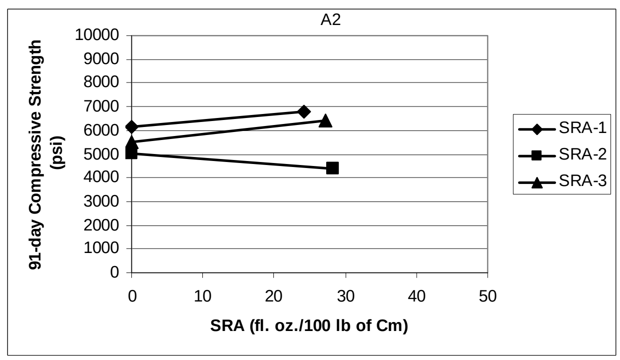


Fig. 8-24. Compressive strength of Grade A-FA fly ash concrete vs. SRA dosage rate (Chemicals 1, 2, 3; Aggregate 2)

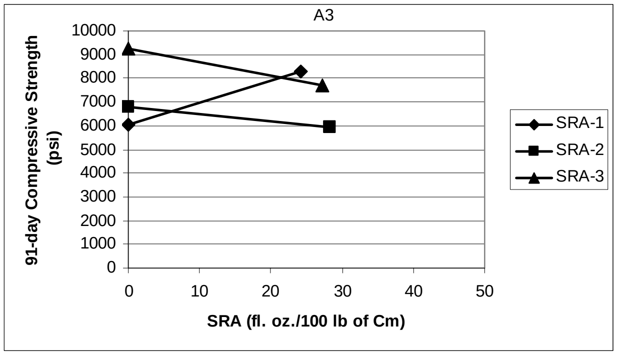


Fig. 8-25. Compressive strength of Grade A-FA fly ash concrete vs. SRA dosage rate (Chemicals 1, 2, 3; Aggregate 3)

An increase in SRA-1 dosage either did not affect or increased the compressive strength. Use of SRA-3 either did not affect or increased the compressive strength in most of the cases. In one case, the compressive strength of the Grade A-FA fly ash concrete made with Aggregate 3 (crushed dolomitic limestone) and SRA-3 was lower when compared with the unusually high strength of its reference (no SRA) Grade A-FA fly ash concrete made with Aggregate 3 (Fig. 8-25).

Use of Aggregate 3 led to the highest 91-day compressive strength of concrete (Fig. 8-25), followed by Aggregate 1 (crushed quartzite stone) (Fig. 8-22), and Aggregate 2 (semi-crushed river gravel) (Fig. 8-24).

8.5 Splitting-Tensile Strength (Chemicals 1, 2, 3)

Fig. 8-26 to Fig. 8-28 show the 91-day splitting-tensile strength of concrete mixtures made with Aggregate 1. The splitting-tensile strength was similar to the compressive strength in trend. The concrete mixtures containing chemical admixtures from Source 2 showed a lower splitting-tensile strength compared with the other concrete mixtures (Chemical 1, 3). A higher splitting-tensile strength can help to reduce the extent of shrinkage cracking.

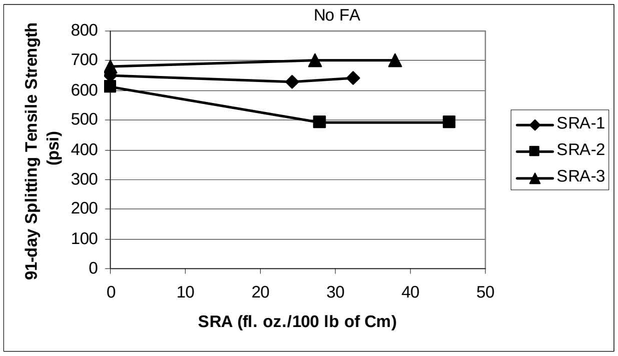


Fig. 8-26. Splitting-tensile strength of Grade A no-ash concrete vs. SRA dosage rate (Chemicals 1, 2, 3; Aggregate 1)

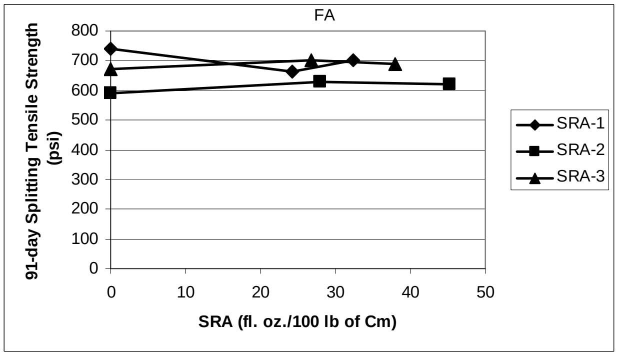


Fig. 8-27. Splitting-tensile strength of Grade A-FA fly ash concrete vs. SRA dosage rate (Chemicals 1, 2, 3; Aggregate 1)

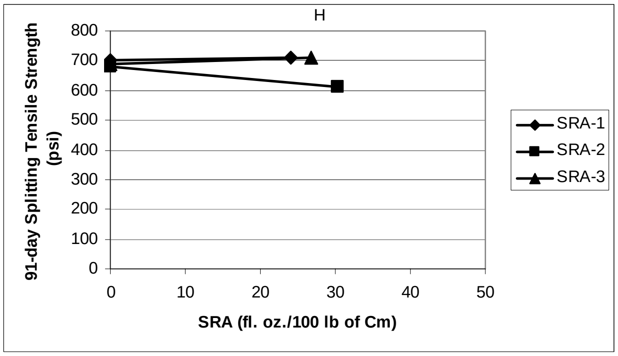


Fig. 8-28. Splitting-tensile strength of high-Cm concrete vs. SRA dosage rate (Chemicals 1, 2, 3; Aggregate 1)

SRA-1 and SRA-3 did not affect the 91-day splitting-tensile strength. SRA-2 either did not affect (Fig. 8-27) or lowered (Fig. 8-26, Fig. 8-28) the 91-day splitting-tensile strength.

8.6 Chloride-Ion Penetrability (Chemicals 1, 2, 3)

Overall, the influence of SRA-1 and SRA-2 on the 182-day chloride-ion penetrability was not significant (Fig. 8-29 to Fig. 8-33). Use of SRA-3 either did not considerably affect the 182-day chloride-ion penetrability (Fig. 8-31 to Fig. 8-33) or reduced it (a higher resistance to penetration) (Fig. 8-29, Fig. 8-30).

In general, the concrete mixtures containing chemical admixtures from Source 1 showed the lowest 182-day chloride-ion penetrability (the highest resistance to penetration). The concrete mixtures containing chemical admixtures from Source 2 generally showed the highest 182-day chloride-ion penetrability (the lowest resistance to penetration) due to their relatively low strength.

Use of Class C fly ash greatly reduced the chloride-ion penetrability into concrete (significantly higher resistance to penetration) (Fig. 8-29 vs. Fig. 8-30).

The effect of the type of coarse aggregate on the 182-day chloride-ion penetrability into Grade A-FA fly ash concrete was not significant (Fig. 8-30, Fig. 8-32, Fig. 8-33).

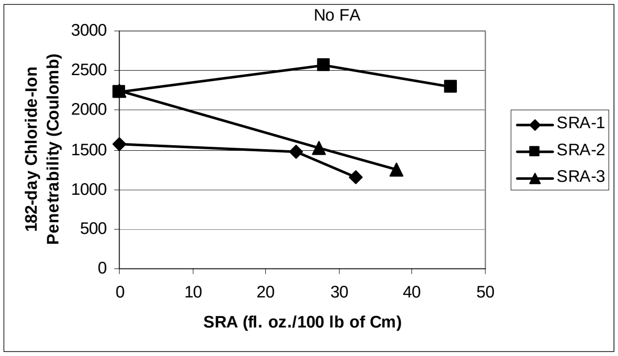


Fig. 8-29. 182-day chloride-ion penetrability into Grade A no-ash concrete vs. SRA dosage rate (Chemicals 1, 2, 3; Aggregate 1)

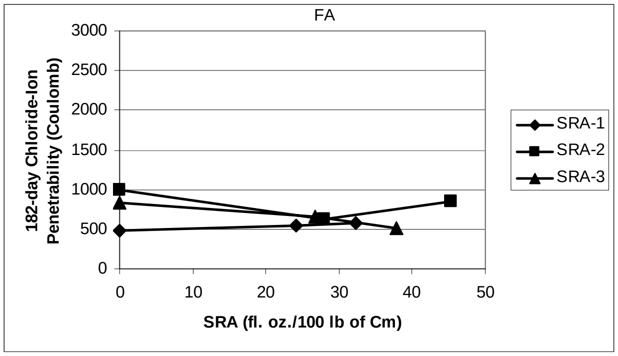


Fig. 8-30. 182-day chloride-ion penetrability into Grade A-FA fly ash concrete vs. SRA dosage rate (Chemicals 1, 2, 3; Aggregate 1)

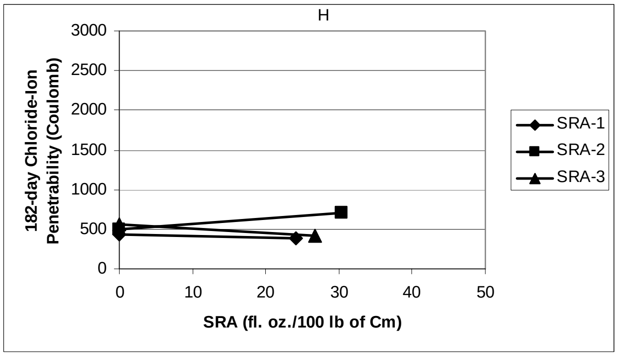


Fig. 8-31. 182-day chloride-ion penetrability into high-Cm concrete vs. SRA dosage rate (Chemicals 1, 2, 3; Aggregate 1)

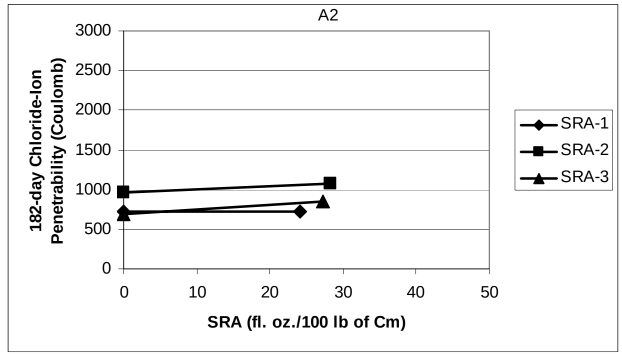


Fig. 8-32. 182-day chloride-ion penetrability into Grade A-FA fly ash concrete vs. SRA dosage rate (Chemicals 1, 2, 3; Aggregate 2)

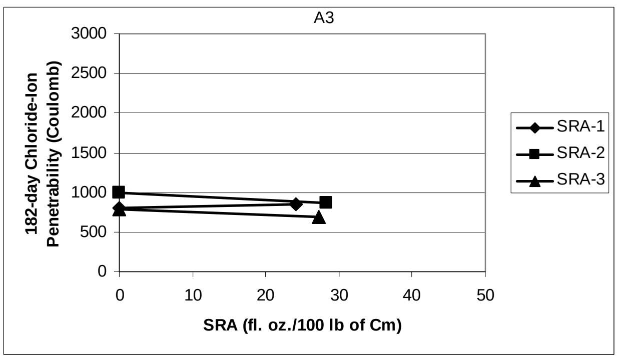


Fig. 8-33. 182-day chloride-ion penetrability into Grade A-FA fly ash concrete vs. SRA dosage rate (Chemicals 1, 2, 3; Aggregate 3)

8.7 Air Content and Slump Losses (Chemicals 1, 2, 3)

Fig. 8-34 and Fig. 8-35 show the change in air content of the concrete mixtures whose designations end with "-air", during the first hour (Sections 5.7, 6.7, 7.7). For each SRA, the dosage rates used were: (1) zero (reference); and (2) the average of the minimum and maximum dosage rates recommended by its manufacturer. The air content of eight out of the 12 mixtures was quite stable. The air content of the Grade A no-ash concrete mixtures containing chemical admixtures from Source 1 was stable (Fig. 8-34). All of the concrete mixtures made with fly ash showed a good retention of air content (Fig. 8-35).

Overall, use of SRA-1, SRA-2, and SRA-3 at their manufacturers' recommended average dosages did not affect the loss of air content of fresh concrete. The loss of air content was about the same regardless of whether or not SRA was used.

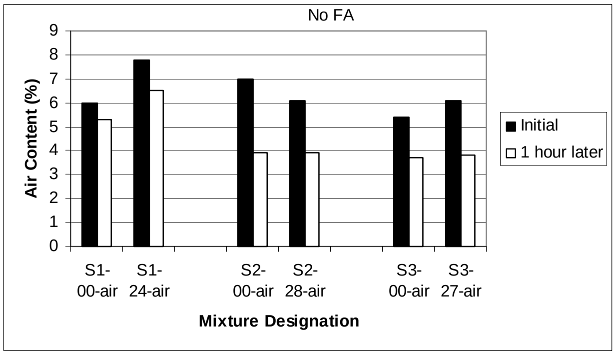


Fig. 8-34. Change in air content of Grade A no-ash concrete vs. SRA dosage rate (Chemicals 1, 2, 3; Aggregate 1)

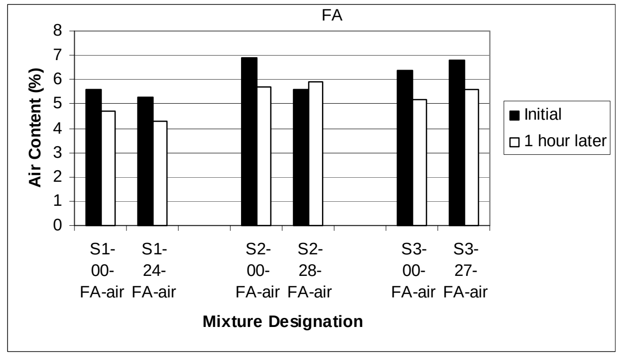


Fig. 8-35. Change in air content of Grade A-FA fly ash concrete vs. SRA dosage rate (Chemicals 1, 2, 3; Aggregate 1)

Fig. 8-36 and Fig. 8-37 show the loss of slump of the concrete mixtures. In general, SRA-1, SRA-2, and SRA-3 did not affect the loss of slump of the concrete mixtures. The slump decreased by about the same amount regardless of whether SRA was used or not. Mixture S1-00-FA-air showed exceptionally good slump retention (Fig. 8-37). Otherwise, chemical admixtures from Sources 1, 2, and 3 showed similar performance in terms of slump retention.

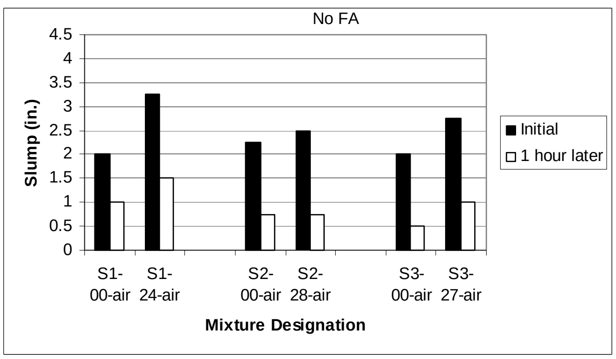


Fig. 8-36. Change in slump of Grade A no-ash concrete vs. SRA dosage rate (Chemicals 1, 2, 3; Aggregate 1)

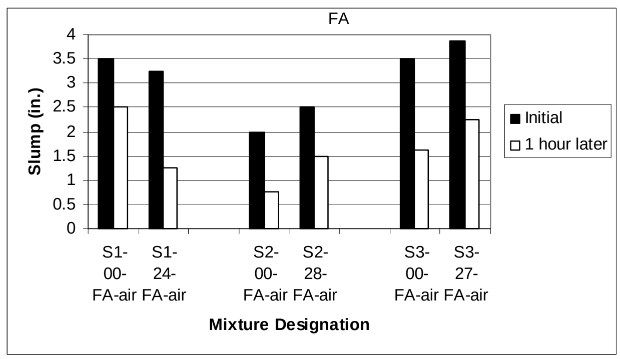


Fig. 8-37. Change in slump of Grade A-FA fly ash concrete vs. SRA dosage rate (Chemicals 1, 2, 3; Aggregate 1)

Chapter 9. Summary and Recommendations on Use of Shrinkage-Reducing Admixtures

The main objective of this research, within the scope of the project funded by Wisconsin Highway Research Program (WHRP), was to evaluate and compare the effectiveness of three different brands of shrinkage-reducing admixtures (SRA-1, SRA-2, and SRA-3) for reducing autogenous shrinkage and drying shrinkage of concrete made with and without fly ash. In addition, the effects of the SRAs on concrete air content, slump, initial setting time, compressive strength, splitting-tensile strength, chloride-ion penetrability, and changes in air content and slump during the first hour after concrete production were investigated.

Concrete mixtures were made based on mixture proportions of WisDOT Grade A, Grade A-FA, and a high-cementitious concrete mixture. Grade A concrete contained no supplementary cementitious materials (fly ash or ground granulated blast furnace slag). In Grade A-FA and the high-cementitious concrete, Class C fly ash was used to replace 35% of cement. The high-cementitious concrete contained 30% more cement and fly ash than Grade A-FA concrete.

The coarse aggregate used in this research conformed to the gradation requirements of WisDOT Size No. 1 (AASHTO No. 67) (0.75" maximum size). A majority of WisDOT paving concrete contains a blend of WisDOT No. 1 and No. 2 (1.5" maximum size) coarse aggregates. However, the shrinkage-reducing effects of SRAs are the results of their functioning in the cementitious paste.

Effects of three types of coarse aggregate were also evaluated using Grade A-FA mixture proportions: Aggregate 1, crushed quartzite stone; Aggregate 2, semi-crushed river gravel; and Aggregate 3, crushed dolomitic limestone.

Fresh concrete mixtures had an air content of 6 ± 1.5% and slump of 1 to 4 inches. Sealed beam specimens were used to evaluate the autogenous shrinkage of concrete up to the age of 56 days following JSCE procedure. ASTM standard test method (C 157) was used to evaluate the drying shrinkage of concrete. The drying shrinkage test results were collected for air-storage period of up to 112 days (subsequent to 28 days of moist curing) for all of the concrete mixtures.

In this research project, several sources of shrinkage-reducing admixtures (SRAs) were identified. The following three were selected and evaluated:
(1) SRA-1: Eucon SRA from Euclid Chemical Company;
(2) SRA-2: Eclipse Plus from Grace Construction Products; and
(3) SRA-3: Tetraguard AS20 from Degussa (formerly Master Builders).

Each SRA was used with a mid-range water-reducing admixture (MRWRA) and air-entraining admixture (AEA) supplied by the same manufacturer as the SRA. SRA was added last into a concrete mixer after all the other ingredients were intermixed.

Based on the test results obtained from this experimental program and the interpretation of the results, the following summary of results and recommendations are given by the research team:

1. **Drying shrinkage and SRA dosage rates:** SRA-1, SRA-2, and SRA-3 showed similar performance in reducing the drying shrinkage of concrete. Drying shrinkage normally includes the effect of autogenous shrinkage.

(a) To minimize the drying shrinkage of concrete, the following amounts of SRA are recommended:
   (i) Up to 25 fl. oz./100 lb of cement (1.6 L/100 kg of cement), or 1.1 gal./yd^3 (5.5 L/m^3), for Grade A no-ash concrete; and
   (ii) Up to 40 fl. oz./100 lb of cementitious materials (2.6 L/100 kg of cementitious materials), or 1.75 gal./yd^3 (8.7 L/m^3), for Grade A-FA fly ash concrete.

   In November 2005, the market prices of SRAs ranged between \$15 to 20 per gallon (\$4.00 to 5.25 per liter). Taking the minimum price of \$15/gal. (\$4.00/L), the cost of SRA translates to about \$16/yd^3 (\$22/m^3) for Grade A no-ash concrete and \$26/yd^3 (\$35/m^3) for Grade A-FA fly ash concrete containing the maximum effective dosages of SRA.

(b) The drying shrinkage reduced in an approximately direct proportion to the amount of SRA used. When SRA is used in excess of the above recommended dosage rates, drying shrinkage may not reduce any further.

(c) SRA was most effective in reducing the drying shrinkage of concrete during early periods (up to about four days) of exposure to dry air when the rate of drying shrinkage is otherwise the highest. In effect, SRAs eliminated much of the initial high drying shrinkage of concrete.

(d) By using SRAs in Grade A and A-FA concrete mixtures, the 4-day drying shrinkage was reduced by up to 67 to 83%, and the 28-day drying shrinkage reduced by up to 48 to 66%.

(e) Compared with Grade A no-ash concrete, Grade A-FA fly ash concrete generally showed a slightly higher drying shrinkage when using the same SRA dosage and required more SRA to achieve similar drying shrinkage.

2. **Autogenous shrinkage:** Overall, SRA-1, SRA-2, and SRA-3 showed similar performance in reducing the autogenous shrinkage of concrete. As for the effect of fly ash on autogenous shrinkage, compared with Grade A no-ash concrete mixtures, Grade A-FA fly ash concrete mixtures (with and without SRA) usually exhibited a lower autogenous shrinkage at early ages and then a higher autogenous shrinkage starting from 14 to 56 days.
3. **MRWRA demand:** Many times, SRA-1 and SRA-3 had an effect similar to water-reducing admixtures and significantly reduced the required amounts of mid-range water-reducing admixtures (MRWRAs). SRA-2 generally did not have a noticeable water-reducing effect.
4. **AEA demand:** Each SRA had a different effect on the AEA demand.
   (a) SRA-1 reduced the AEA-1 demand significantly, bringing it close to zero.
   (b) When SRA-2 was used with AEA-2 and MRWRA-2, the AEA-2 demand increased sharply and the air content and strength of concrete generally decreased. Use of SRA-2 with some other AEA and MRWRA might help to solve this problem.
   (c) When SRA-3 was used at its maximum dosage, it increased the AEA-3 demand.
5. **Changes in air content and slump:** Fresh concrete mixtures had an initial air content of 6 ± 1.5%. SRAs did not significantly affect the changes in air content and slump of fresh concrete mixtures during the first hour after the concrete was mixed. The changes in air content and slump during the first hour were about the same regardless of whether SRAs were used or not. Thus, there was no adverse effect of the SRAs on the initial air content, air-content stability, and slump retention of fresh concrete.
6. **Compressive strength:**

(a) Usually, SRA-1 and SRA-3 either did not affect or increased the compressive strength.
(b) Concrete mixtures made with chemical admixtures from Source 2 showed a relatively low compressive strength. An increase in SRA-2 dosage either did not affect or lowered the compressive strength. This could be due to the significant increase in AEA-2 demand with increasing SRA-2 dosage.

7. **Splitting-tensile strength:**
   (a) SRA-1 and SRA-3 generally did not affect the splitting-tensile strength.
   (b) SRA-2 either did not affect or lowered the splitting-tensile strength.
8. **Chloride-ion penetrability:**
   (a) SRA-1 and SRA-3 either did not affect or improved the resistance of concrete to chloride-ion penetration (less chloride-ion penetration into concrete).
   (b) SRA-2 did not considerably affect the chloride-ion penetrability.
   (c) Concrete mixtures containing chemical admixtures from Source 1 showed the highest resistance to chloride-ion penetration (the least penetration). The concrete mixtures containing chemical admixtures from Source 2 generally showed the lowest resistance to chloride-ion penetration at 182 days (the highest penetration), most likely due to the relatively lower strength of these concrete mixtures.
9. **Effect of the type of coarse aggregate:**
   (a) Drying shrinkage:
      (i) Use of Aggregate 3 (crushed dolomitic limestone) often led to the lowest early-period (at 7 days) drying shrinkage, followed by Aggregate 2 (semi-crushed river gravel), and Aggregate 1 (crushed quartzite stone).
      (ii) However, the late-period (at 56 days) drying shrinkage of the concrete made with Aggregate 2 or 3 became either approximately the same as or higher than that of the concrete made with Aggregate 1. Often, use of Aggregate 2 resulted in the highest late-period drying shrinkage.
   (b) Autogenous shrinkage: Use of Aggregate 3 resulted in the lowest autogenous shrinkage, followed by Aggregate 2, and Aggregate 1 (the highest autogenous shrinkage), especially at early ages.
   (c) Compressive strength: Use of Aggregate 3 led to the highest compressive strength of concrete, followed by Aggregate 1, and Aggregate 2 (the lowest compressive strength).
   (d) Chloride-ion penetrability: The type of coarse aggregate did not noticeably affect the 182-day chloride-ion penetrability into concrete.
   (e) Thus, use of dolomitic limestone seems to be helpful in reducing early autogenous shrinkage and drying shrinkage compared with using river gravel or quartzite stone.
10. **Effect of higher cementitious materials:** Compared to Grade A-FA fly ash concrete, the high-cementitious concrete with a higher cementitious materials content (leading to lower W/Cm) generally exhibited either similar or higher autogenous shrinkage, either similar or lower drying shrinkage, higher compressive strength, and higher resistance to chloride-ion penetration.

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Chapter 11. Appendices

Appendix A – Setup and Test Methods for Autogenous Length Change

Test Apparatus and Setup for Autogenous Length Change

Fig. 11-1 to Fig. 11-4 show the test setup for early autogenous length change of concrete.

Steel molds: Steel molds were used to prepare concrete beam test specimens having nominal dimensions of 4" × 4" × 13 ¾".
Gauge plugs (pins): As shown in Fig. 11-1 to Fig. 11-4, the tip of the gauge plugs were used as contact points for length change measurements. Each gauge plug (pin) was made of a 3/32"-diameter × 2"-long dowel pin, with one end having a less round tip brazed into a 3/4" × 3/4" × 1/16" thick carbon steel plate. The more round tip (the other end) of the dowel pin touched the tip of the dial indicator.
Aluminum bushings: A gauge plug (pin) was inserted into an aluminum "bushing," which was placed in a 3/16"-diameter hole at each end plate of the steel mold.
Length-change comparators: Three length-change comparators were used for each concrete mixtures, one comparator for each beam. The "beams" of the length-change comparators were made of invar, which provided a reference length that was almost invariable with temperature change. The linear coefficient of thermal expansion of invar is about 1×10^{-6}/°C in the temperature range of 30 to 100°C. Dial indicators were used for autogenous length-change measurements. The brand of dial indicator used in this research was Mitutoyo No. 2358-50 having a total range of 0.5", a gradation of 0.0001", and modified to have a flat, carbide tipped, 2-mm diameter contact point.

For alignment of the tips of dial indicators with gauge plugs (pins), two 3/8"-diameter bolts on the left side and one 3/8"-diameter bolt on the right side were provided to adjust the height of each end of the comparator. A fine alignment of the tips of dial indicators with gauge plugs (pins) was done with the aid of a magnifying glass and a small wrench.

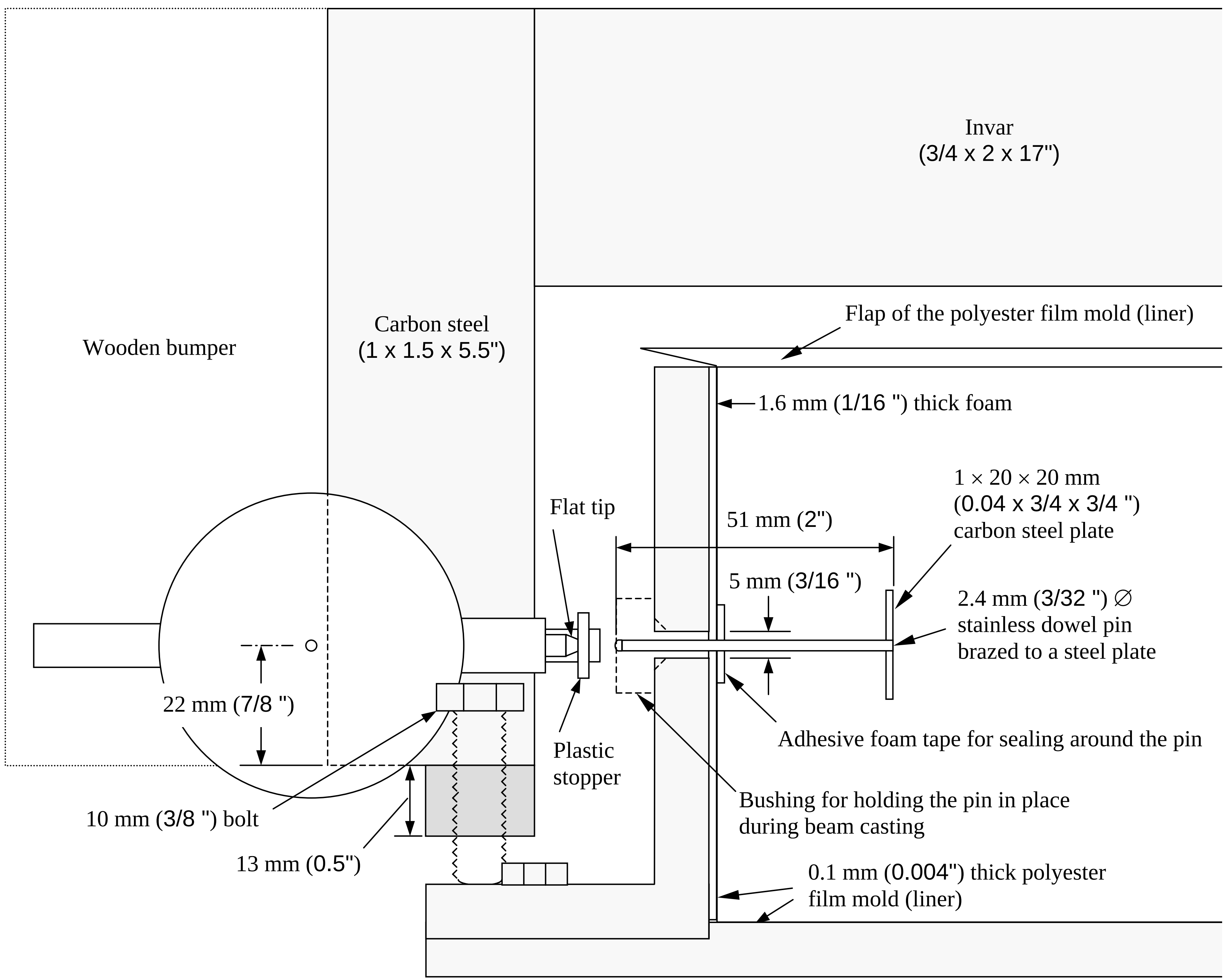


Fig. 11-1. Setup for early autogenous length change (Left, Side view) [UWM-CBU]

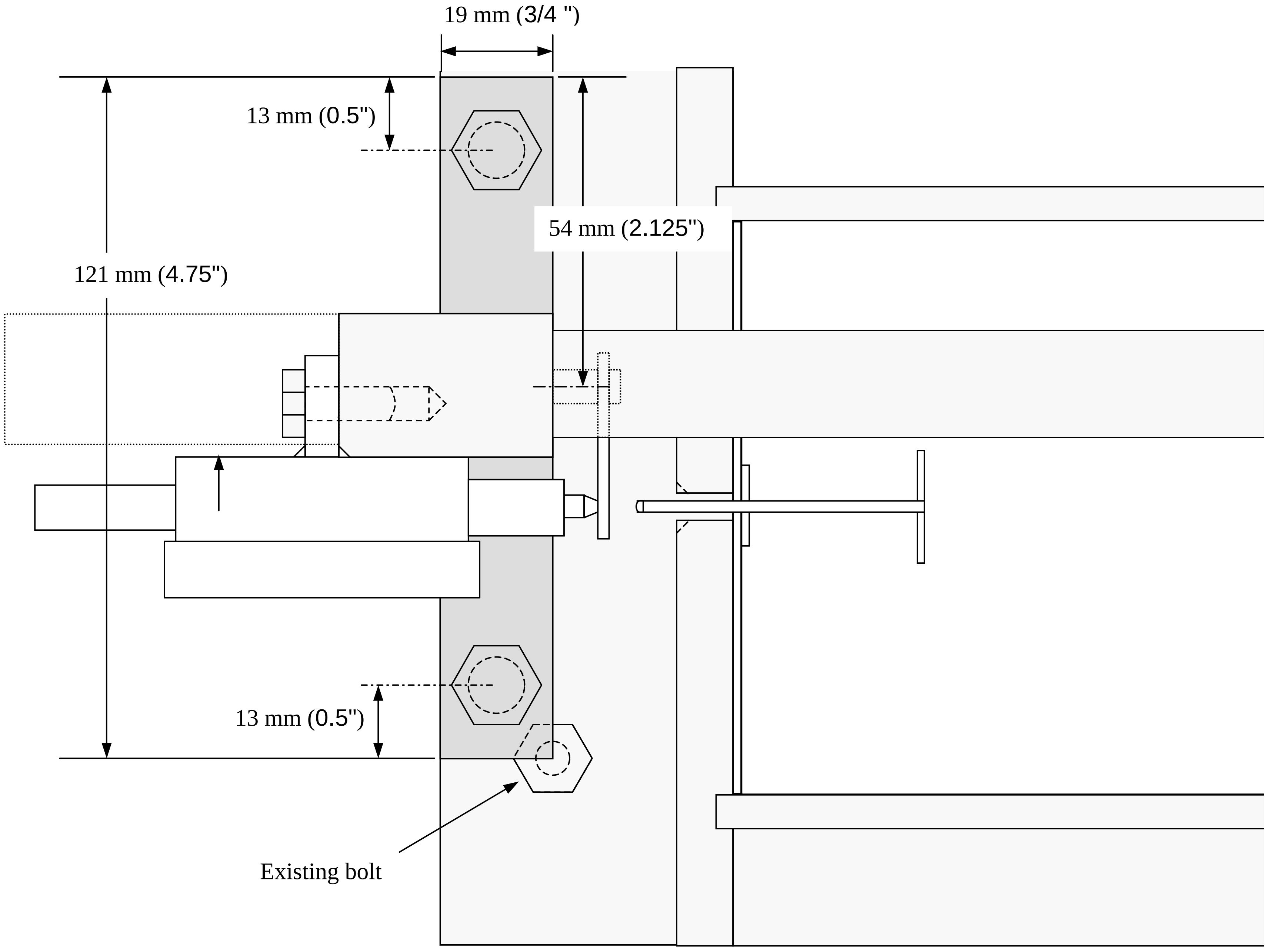


Fig. 11-2. Setup for early autogenous length change (Left,Top view) [UWM-CBU]

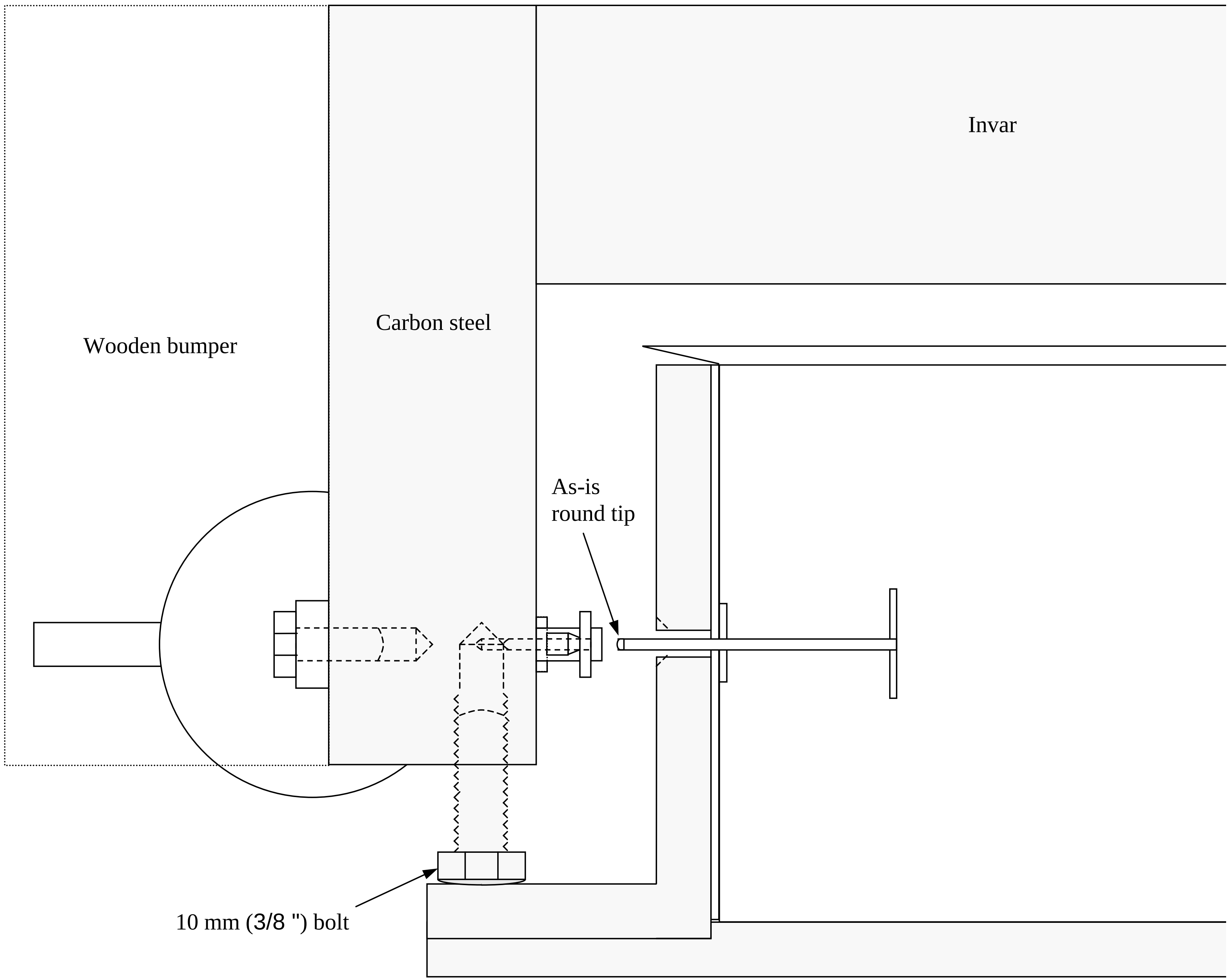


Fig. 11-3. Setup for early autogenous length change (Right, Side view) [UWM-CBU]

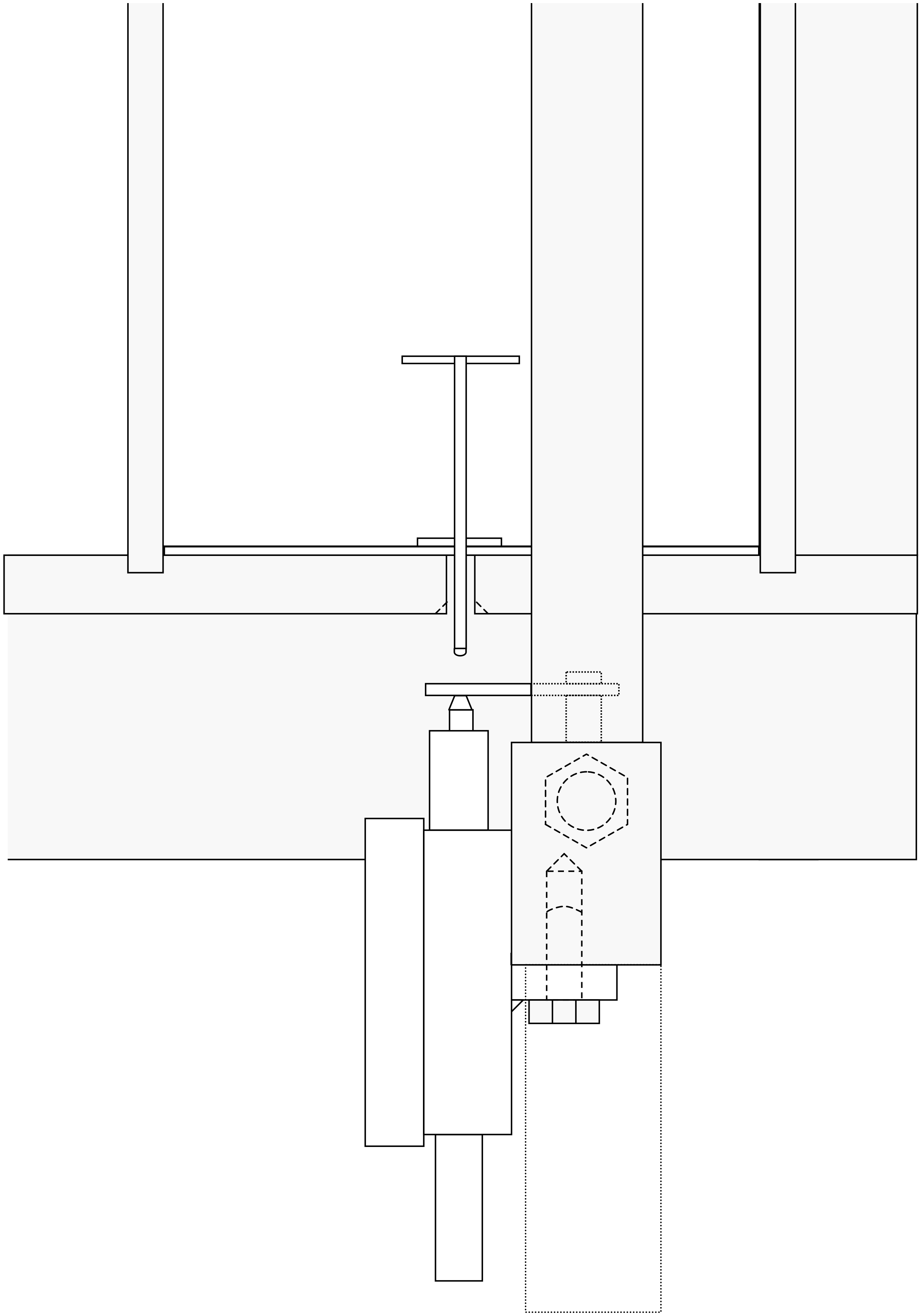


Fig. 11-4. Setup for early autogenous length change (Right, Top view) [UWM-CBU]

Polyester film molds (liners): Parts (a) through (i) of Fig. 11-5 show the details of preparation of the polyester film mold (liner) and the casting and sealing of beam. To seal the concrete beam used for autogenous length-change measurements, 0.1 mm (0.004") polyester film was used inside the steel mold. Fig. 11-5 (e) shows the top view of the polyester film mold. Each autogenous length-change test beam was cast and subsequently sealed in this polyester mold in steel mold, and kept in that condition for the first 24 hours. Fig. 11-5 (a) shows the dimensions of the liner used for sides and bottom of the steel mold. Fig. 11-5 (b) show dimensions of the liner used for end plate of the steel mold. Two end pieces were attached to the "side and bottom liner" using strips of duct tape for sealing, as shown in Fig. Fig. 11-5 (d). As shown in Fig. 11-5 (d), pieces of foam tape were used to seal around the gauge plugs (pins) that would be inserted through the holes in end pieces of the plastic liner.
Foam sheet: As shown in Fig. 11-1 to Fig. 11-4, between the steel mold and the plastic liner at each end of the beam, a 3 $^{15}/_{16}$" × 3 $^{15}/_{16}$" × 1/8"-thick foam sheet piece was placed so that the length change of the concrete beam specimen would not be restrained by the steel mold. Also to minimize the friction between the plastic liner and the steel mold, a 3 $^{15}/_{16}$" × 13 $^{13}/_{16}$" polyester film was placed along the bottom and the sides of the beam.
Polyester film covers (tops): As shown in Fig. 11-5 (h) and (i), after a concrete beam is cast, the polyester film mold was covered with a 0.1 mm (0.004") polyester film cover. Then the cover was attached to the flaps of the polyester liner using transparent tape and sealed.
Thermometer: As shown in Fig. 11-5 (c) and (h), to measure the temperature of the autogenous length-change concrete beam, a concrete thermometer was inserted into the center of the beam specimen.

Mold Assembly, Specimen Preparation, and Testing

Fig. 11-5 (e) shows the assembled polyester mold (liner). In the oiled steel mold, first 3-15/16" × 13-$^{13}/_{16}$" polyester film sheets were placed, one each on the inside bottom and sides of the steel mold. A 3 $^{15}/_{16}$" × 3 $^{15}/_{16}$" × 1/8"-thick foam piece was placed on each inside end of the steel mold. Now the assembled polyester mold (liner) was placed in the steel mold and the corners of the polyester mold were sealed with silicone sealant, as shown in Fig. 11-5 (f). In the 3/16"-diameter hole in each end plate of the beam mold, an aluminum "bushing" was inserted, and a gauge plug (pin) was inserted into the opening in the busing (Fig. 11 1 to Fig. 11 4, and Fig. 11-5 (g)).

Strips of duct tape were used to secure the bushings in position during the consolidation of beam specimens by a vibrating table. To keep the tips of gage plugs (pins) glue-free, the centers of the duct tape strips were covered with small pieces of transparent tape beforehand. As soon as casting was finished, the fresh concrete beam specimens were covered with the polyester film covers, and the attached concrete thermometers were inserted into specimens at the same time. Any air pockets between the top of the fresh concrete and the cover were removed. Each cover was attached to the flaps of the polyester mold (liner) and sealed using transparent tape. After moving the beams in molds into the autogenous length-change measuring room, the pieces of duct tape and the bushings were removed carefully. Any air gaps around the gauge plugs, created while removing the bushings, were closed by lightly tapping the sides of the steel molds with a rubber mallet.

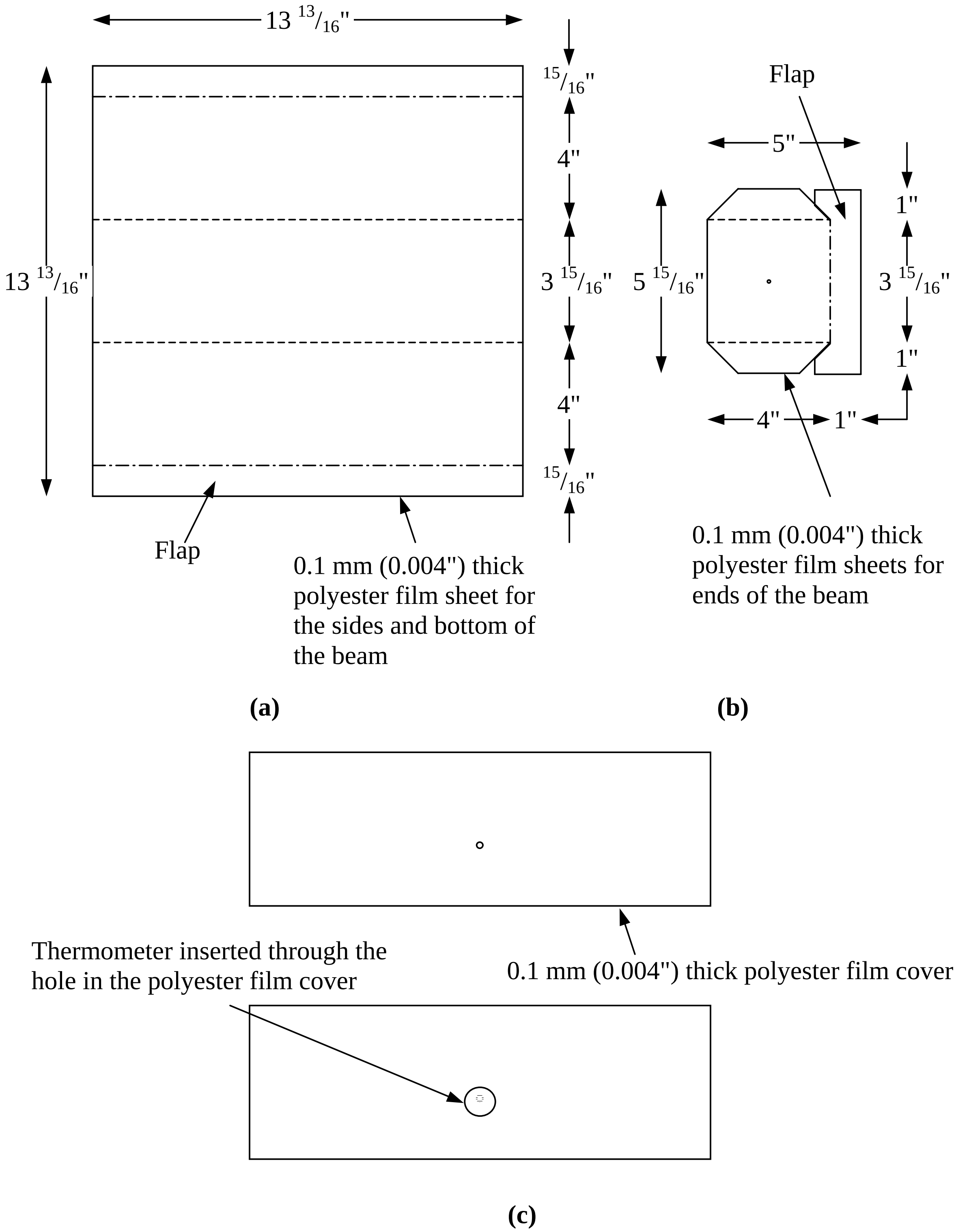
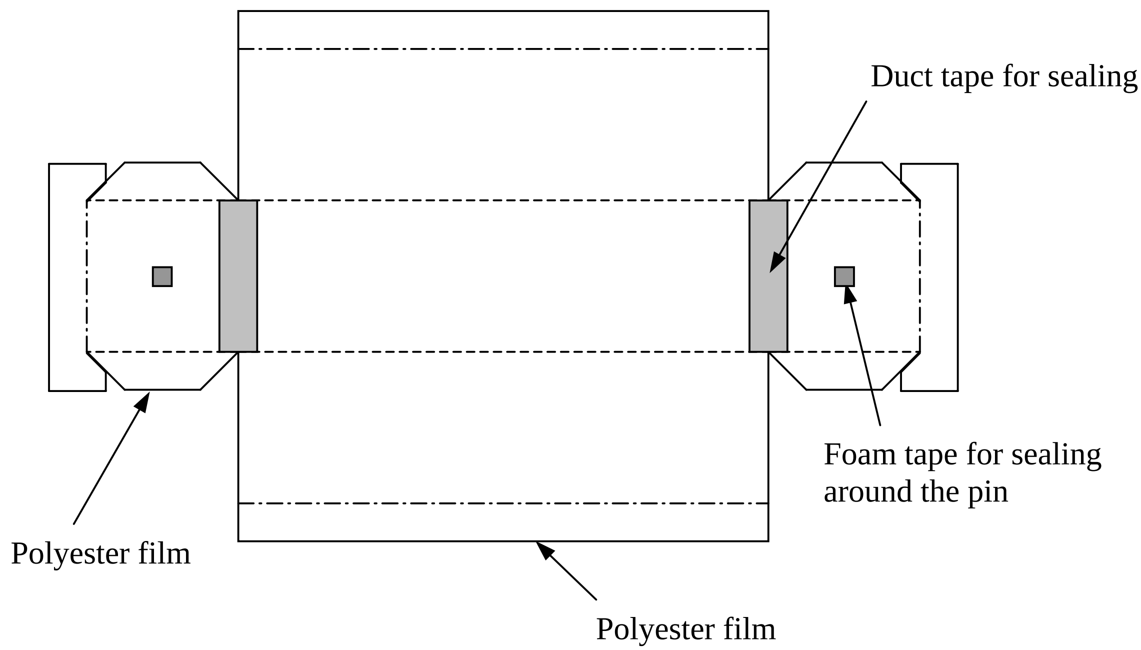
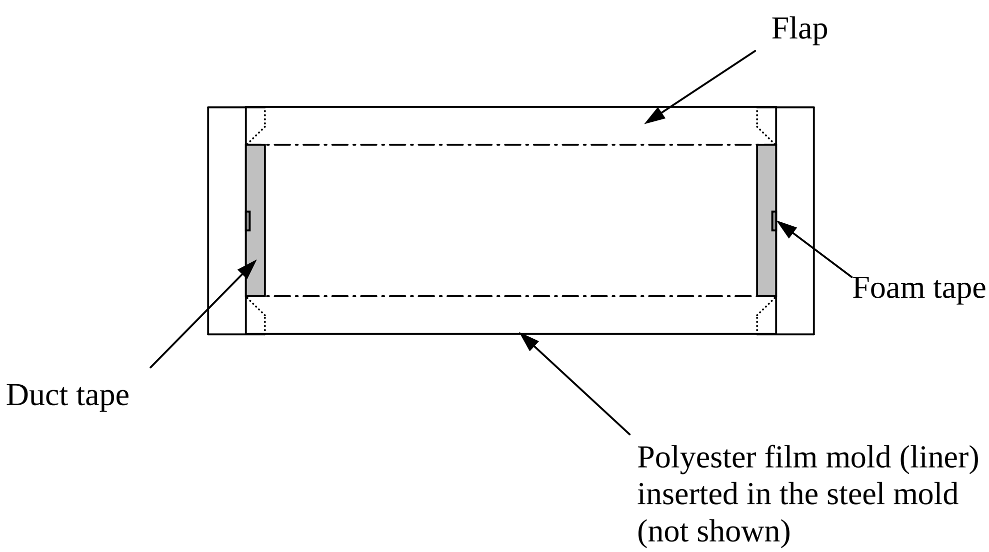


Fig. 11-5. Film mold (liner) and specimen preparation [UWM-CBU]

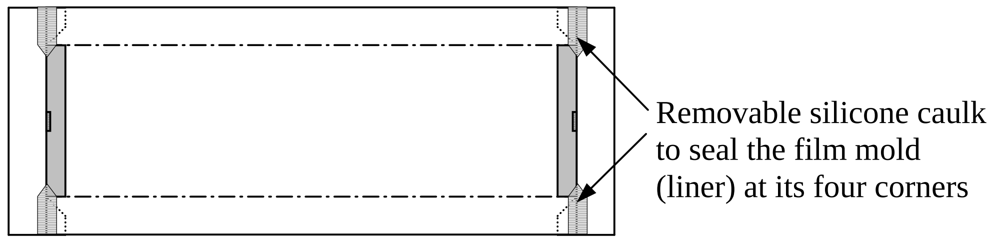


(d)

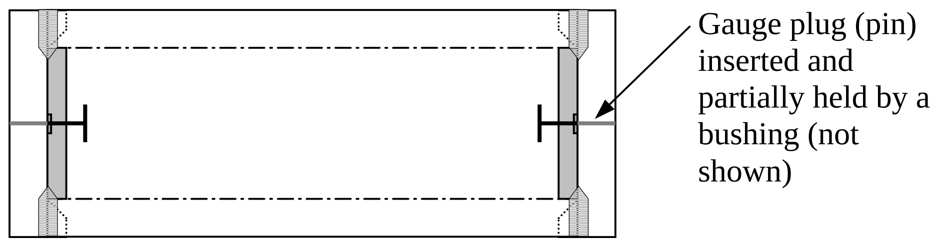


(e)

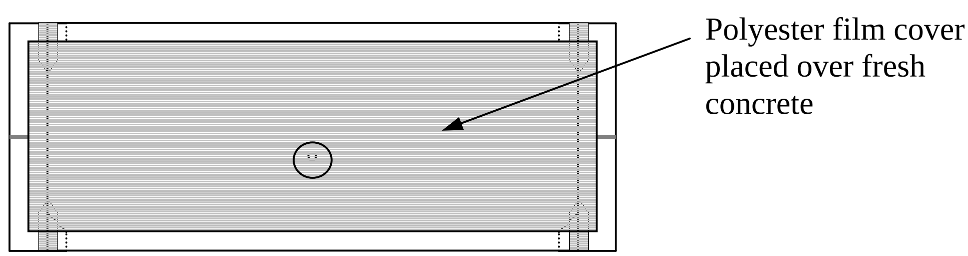
Fig. 11-5. Film mold (liner) and specimen preparation [UWM-CBU] (Cont'd)



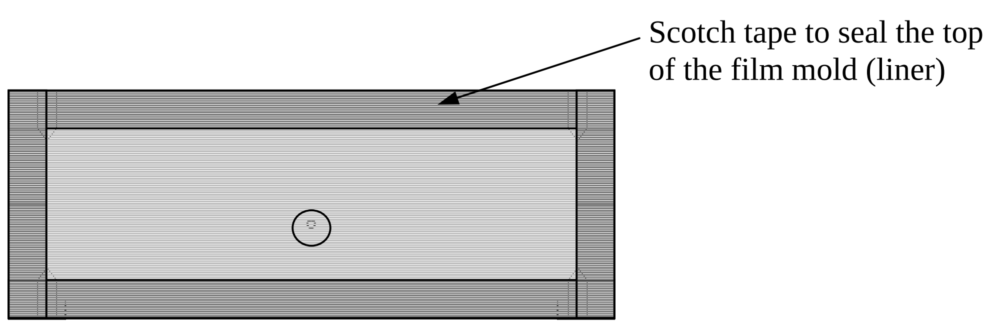
(f)



(g)



(h)



(i)

Fig. 11-5. Film mold (liner) and specimen preparation [UWM-CBU] (Cont'd)

Shortly after the time of initial setting of concrete was reached, the autogenous length-change comparators were set up in position and measurements of autogenous length change were started. After taking the reading up to the age of 24 hours, the steel molds and polyester molds (liners) were dissembled. Immediately the beams were sealed with aluminum adhesive tape. The same length-change comparators were used for further testing for autogenous length change of the concrete beams.

Calculation of Autogenous Length Change

For the calculations of the autogenous length change of concrete, the thermal strain caused by cementitious material hydration was deducted from the apparent length change measurements. The coefficient of thermal expansion of concrete was assumed as 10×10^{-6}/°C.

For calculation of autogenous length change of a concrete beam, the two readings of the dial indicators were recorded as X_{oa} and X_{ob} at the time of initial setting of concrete. Further readings of the dial indicators were recorded as X_{ia} and X_{ib}. The autogenous length change was calculated as the linear strain ΔL by the following equation:

$$\Delta L = \{[(X_{ia} + X_{ib}) - (X_{0a} + X_{0b})]/ L\} - \varepsilon_t$$

where,

L = 11.45", the distance between the innermost ends of gauge plugs (between little plates of the gauge plugs)

ε_t = Thermal strain calculated as $dT \times \alpha$ where, dT = change in concrete temperature, and α = coefficient of thermal expansion of concrete, which was assumed to be 10×10^{-6}/°C.

Appendix B – Expansion of Concrete During Moist Curing (Chemicals 1, 2, 3)

Table B-1 to Table B-3 show the expansion of concrete mixtures during moist curing from 1 to 28 days of age.

Table B-1. Expansion of Concrete During Moist Curing from 1 to 28 Days (Chemical 1)

Mixture designation	S1-00	S1-24	S1-32	S1-00-FA	S1-24-FA	S1-32-FA	S1-00-FA-H	S1-24-FA-H	S1-00-FA-A2	S1-24-FA-A2	S1-00-FA-A3	S1-24-FA-A3
Expansion during moist curing from 1 to 28 days (microstrain)	52	20	27	140	53	62	95	17	3	10	13	-3

Table B-2. Expansion of Concrete During Moist Curing from 1 to 28 Days (Chemical 2)

Mixture designation	S2-00	S2-28	S2-45	S2-00-FA	S2-28-FA	S2-45-FA	S2-00-FA-H	S2-30-FA-H	S2-00-FA-A2	S2-28-FA-A2	S2-00-FA-A3	S2-28-FA-A3
Expansion during moist curing from 1 to 28 days (microstrain)	25	25	90	33	50	27	18	92	40	23	37	110

Table B-3. Expansion of Concrete During Moist Curing from 1 to 28 Days (Chemical 3)

Mixture designation	S3-00	S3-27	S3-38	S3-00-FA	S3-27-FA	S3-38-FA	S3-00-FA-H	S3-27-FA-H	S3-00-FA-A2	S3-27-FA-A2	S3-00-FA-A3	S3-27-FA-A3
Expansion during moist curing from 1 to 28 days (microstrain)	47	50	13	52	48	47	47	68	20	27	77	23

In general, the concrete mixtures containing SRA-1 showed a lower expansion during moist curing than those mixtures that did not contain SRA-1 (Table B-1). When used with chemical admixtures from Source 1, the concrete mixtures made with Aggregate 2 or 3 showed a lower expansion during moist curing than the concrete mixtures made with Aggregate 1 (Table B-1). However, this cannot be generalized. SRA-2 and SRA-3 showed different effects.

Use of SRA-2 generally led to either a similar or higher expansion of concrete during curing in water from 1 to 28 days (Table B-2).

In general, SRA-3 did not affect the expansion of concrete during moist curing considerably (Table B-3). As an exception, the expansion of the concrete mixtures S3-38 and S3-27-FA-A3 during moist curing was considerably lower than that of their respective reference (no SRA) mixtures S3-00 and S3-00-FA-A3.

Wisconsin Highway Research Program
University of Wisconsin-Madison
1415 Engineering Drive
Madison, WI 53706
608/262-2013
www.whrp.org