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ORIGINAL ARTICLE

Effect of Mix Design on Restrained Shrinkage of Concrete

Yousef Zandi
Department of Civil Engineering, Tabriz Branch, Islamic Azad University, Tabriz, Iran.
Email: Zandi@iaut.ac.ir

ABSTRACT

The impetus for this research came from a project that involved the reconstruction of Twelve bridge decks in Tabriz, East Azerbaijan, IRAN that was completed in the summer of 2009. Shortly after construction was completed, shrinkage cracks were observed on 8 of the 12 bridge decks. Such cracking can cause long term durability problems by facilitating chemical ingress and moisture penetration that may aggravate problems such as alkali-silica reaction and corrosion of the reinforcing steel . Shrinkage cracks can also increase deterioration caused by cyclic loadings. Any of these problems can decrease the service life of a bridge deck . The mixture used in the bridge decks had a w/c+p ratio of 0.33 and contained 26.2% fly ash (Class F). Although the mixture was not intended to be a high performance concrete (HPC) mixture, it did have characteristics similar to HPC mixtures. As the use of HPC becomes more common, studies on the effect of pozzolanic materials and the ability of admixtures to reduce concrete shrinkage are needed to ensure durability of the structures. This paper presents results from an experimental study conducted to determine how certain mixture proportion parameters influence concrete shrinkage. In particular, the free shrinkage of concrete mixtures with varying amounts of fly ash, shrinkage reducing admixture (SRA), expansive cement, and fibers were studied.
Keywords: concrete, shrinkage, fly ash, shrinkage reducing admixture, expansive cement, fibers

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INTRODUCTION

Volume changes in concrete are a result of drying caused by the environment and internal reactions within the concrete [2]. Volume changes can be caused by fluctuations in concrete temperature (thermal shrinkage or expansion), by water loss to the external environment (drying shrinkage), as a result of the hydration products occupying less volume than the reactants (chemical shrinkage), or by drying caused by internal water being used for the hydration reaction (self-desiccation component of autogenous shrinkage). When fresh concrete is placed, solid particles in the concrete begin to settle and water rises to the surface. This phenomenon is referred to as bleeding of the concrete. After the bleed water dissipates (into either the atmosphere or the concrete), a complex series of menisci are formed [3]. This creates negative capillary pressures that cause the paste to contract and results in shrinkage [4]. Concrete shrinkage is primarily related to the pore structure of the concrete [4]. Any variables in the mixture proportions that influence the pore structure will also affect shrinkage. There are several constituents in concrete that can be adjusted to reduce concrete shrinkage. These variables include w/c+p ratio, cement content, fly ash content, type of cement, and SRA. Water content has a large influence on concrete shrinkage. Water content is used to determine the amount of cement paste in the concrete, which is directly related to shrinkage. Increasing the volume of the paste increases volume changes caused by autogenous and drying shrinkage. Additionally, increased cement contents produce more heat through hydration. This additional heat increases thermal shrinkage as the concrete cools. Fly ash can also have a substantial influence on concrete shrinkage. If fly ash is used as a replacement for cement, the reduced cement content produces smaller volume changes through hydration. Peak hydration temperatures will be lower, resulting in less thermal shrinkage. However, because the pores are smaller, surface tension caused by drying may be greater [4].

Certain attributes of the cement can also be used to control shrinkage. In particular, expansive (Type K) cement is known to reduce shrinkage by creating an increase in volume to offset the drying shrinkage that occurs just after set [1]. Type K cements contains calcium sulfoaluminate and anhydrite. By reacting with free lime, these compounds increase the rate of ettringite formation, causing expansion [3]. SRA's are another option for reducing shrinkage in concrete. SRA's reduce the capillary tension that develops in concrete pores, thereby reducing the shrinkage that occurs [5]. Fibers produce several beficial effects when used in concrete. They increase the strain energy needed to initiate cracks, increase the time that elapses prior to cracking, serve as reinforcement across open cracks (reduces crack width), and increase the ductility of the concrete[3,6]. Fibers are not generally considered to have a significant effect on shrinkage. However, it is believed that they cause the formation of large pores that reduce capillary pressure in the paste and reduce plastic shrinkage cracking [4]. HPC mixtures generally have high cement contents. Therefore, they have a high potential for shrinkage. Failing to address shrinkage in HPC applications can result in reduced serviceability and durability of a structure. Contraction joints are one way to accommodate shrinkage. However, even with adequate joint spacing, uneven shrinkage through the cross-section of a slab can cause curling [3]. Consequently, controlling shrinkage has become increasingly important. When evaluating the tendency of a certain concrete mixture towards cracking, it is reasonable to start by finding the unrestrained shrinkage of laboratory specimens. Greater shrinkage can be correlated with a greater tendency to crack in field conditions [7,8,9].

EXPERIMENTAL PROGRAM

Concrete prism specimens were prepared to assess how variations in w/c+p ratio, fly ash content, fiber content, SRA dosage, and cement type influenced shrinkage [3,4].

Materials

Type I/II Portland cement, expansive (Type K) Portland cement, and Class F fly ash were used as cementations materials in this study. The aggregates used in this study were obtained from the alluvial source used to obtain aggregates from Tabriz. Physical properties for these aggregates are provided in Tab. 1. Drinking water is used in the mixing and cure. A shrinkage-reducing admixture was also used for two sets of mixtures. Polypropylene fibers, 19 mm in length, were used in one series.

Table. 1. The granulometry of aggregates used in production of concretes

Granulometric class	0-7 (mm)	0-5 (mm)	5-15 (mm)	15-22 (mm)
Total Weight (%)	30,8	20	23,4	25,8

Mixture Proportions

Six sets of concrete mixtures were investigated. The mixture proportions were obtained by varying the proportions used for the. The mixture proportions used in construction are presented as Mixture A4 in Tab. 2. These proportions included 26.2% fly ash by mass of cement. The fly ash was used as an addition to the cement, not as a replacement. The first series of mixtures (Series A) included four mixtures with constant water and cement contents, but decreasing fly ash content. Mixtures A3-A1 had fly ash contents of 20, 10, and 0%, respectively. Since the water content remained constant, w/c+p ratios for the mixtures in Series A were 0.33, 0.35, 0.38, and 0.42. Each of the other five sets of mixtures contained four mixtures with these fly ash contents. In the second series of mixtures (Series B), the cementations materials content and w/c+p ratio were kept constant. Consequently, the cement content increased as the fly ash content decreased. The w/c+p ratio for these mixtures was 0.38. The third series of mixtures was designated as Series C. The mixtures in Series C had the same mixture proportions as the mixtures in Series B, but the Type I/II cement was replaced with a shrinkage compensating cement (Type K). The fourth series (Series D) repeated variations in Series B, but also contained the manufacturer's minimum recommended dosage of SRA. The fifth series (Series E) also repeated the variations in Series B, but contained the manufacturer's recommended dosage of the SRA for optimal shrinkage reduction. The sixth series (Series F) repeated variations in Series A, but 1% polypropylene fibers by volume were included in each mixture. The mixture proportions for all mixtures are presented in Tab. 2.

Preparation of Test Specimens

For each mixture, six prisms (76.2 x 102 x 406 mm) and three cylinders (102 by 204 mm) were prepared. The cylinders and three of the prisms were used for measurements of compressive and flexural strength, respectively. The remaining three prisms had 19.1 mm gage studs embedded in their ends to facilitate length change measurements. After placement, the specimens were left in the molds and covered in plastic for 24 ± 4 hours. After removal from the molds, the prisms with gage studs were moist cured for seven days, and then air-cured for the remainder of testing. The prisms and cylinders used for strength testing were moist cured for 28 days. The prisms with gage studs were monitored for length changes to an age of 56 days, and then oven-dried to obtain total shrinkage.

Length Measurements

Initial length measurements for each specimen were performed immediately after they were removed from the molds. Length measurements were conducted at ages of 3, 5, and 8 days. The specimens were kept in the moist-cure environment during this time. After the 8-day measurements were performed, the specimens were left in the open air at 22ºC and a relative humidity of 35 percent. Length measurements were performed on each specimen twice a week until they reached an age of 56 days. After the readings at 56 days, the specimens were placed in an oven at 110±5ºC. After oven drying for 48 hours, final lengths of the specimens were measured and the total shrinkage was calculated.

Table 2. Mixture proportion

Series	Mixture No.	Water Reducing Admixture mL/m³	Coarse Aggregate kg/m³	Fine Aggregate kg/m3	Fly Ash %	Cement kg/m3	Water kg/m³	AEA mL/m³	SRA mL/m³
A	1 2 3 4	200 870 0 1535	985 985 985 985	670 625 580 550	0% 10% 20% 30%	362 362 362 362	152 152 152 152	466 466 466 622	0 0 0 0
B	1 2 3 4	579 0 0 0	985 985 985 985	550 525 500 500	0% 10% 20% 30%	362 385 421 457	174 174 174 174	466 466 466 466	0 0 0 0
C	1 2 3 4	1766 1766 1766 1766	985 985 985 985	600 575 550 500	0% 10% 20% 30%	316 330 356 386	174 174 174 174	466 466 466 466	0 0 0 0
D	1 2 3 4	1324 1413 1324 1324	985 985 985 985	545 530 515 500	0% 10% 20% 30%	362 385 421 457	174 174 174 174	706 706 883 883	2476 2476 2476 2476
E	1 2 3 4	1324 1324 1324 1766	985 985 985 985	545 530 515 500	0% 10% 20% 30%	362 385 421 457	174 174 174 174	883 680 889 466	7427 7427 7427 7427
F	1 2 3 4	1199 1766 1766 1766	985 985 985 985	670 625 580 550	0% 10% 20% 30%	362 362 362 362	152 152 152 152	466 466 466 466	466 466 466 466

Strength Testing
The drying shrinkage test was conducted according to ASTM C157 [10].

RESULTS AND DISCUSSION
Strength Comparisons
Flexural strength comparisons for all mixtures are presented in Fig. 1. Each value in Fig. 1 represents the average of the results from ASTM C157 tests performed on three prisms from each mixture[10]. These results show that fly ash content does not have a significant effect on the flexural strength of mixtures with Type I/II cement (Series A and Series B), the mixtures containing the SRA (Series D and Series E), or the Series C mixtures. Flexural strengths for the mixtures from Series F show a trend of increasing strength with increasing fly ash content. These results are typical for concrete containing fly ash because fly ash reacts slowly. Strength increases produced by fly ash are generally observed at ages later than 28 days [3,4].

Compressive strengths for all mixtures are illustrated in Fig. 2. The most important trend in Fig. 2 is that compressive strength increased as fly ash content increased in Series A. However, w/c+p decreased as the fly ash content increased in Series A. A similar trend is observed in the compressive strengths from Series F, which has mixture proportions similar to Series A. It appears that the expected trend of increasing strength with decreasing w/c+p ratio is primarily responsible for this trend because fly ash content does not have a significant effect on compressive strength for the remaining mixtures. As with flexural strength, fly ash was not expected to have a strong effect on compressive strength at 28 days.

Effects of w/c+p on shrinkage
Shrinkage results for mixtures with varying w/c+p due to varying fly ash contents are shown in Fig. 3. The water and cement content was held constant in these mixtures. Shrinkage strains for the various fly ash contents are similar. Mixture A20, with w/c+p = 0.35, exhibited approximately 120 microstrain less shrinkage than the other mixtures in Series A. Slump results for this mixture were similar to the other mixtures in this series, so an erroneous water content does not appear to be a factor in the lower shrinkage strains. The mixture with the lowest w/c+p, 0.33, exhibited shrinkage strains similar to the

mixture with the highest w/c+p. In very low w/c+p concrete, capillary shrinkage due to self-desiccation tends to be greater. However, shrinkage also increased as the w/c+p increased from 0.35. It is important to note that the increasing w/c+p and shrinkage were not accompanied by an increasing water content that would result in more cement paste. Because the fly ash was treated as an addition in this series, the paste content was decreasing as w/c+p increased. Consequently, it appears that the 20% fly ash content produced an optimal effect in terms of reducing capillary tension or limiting moisture loss.

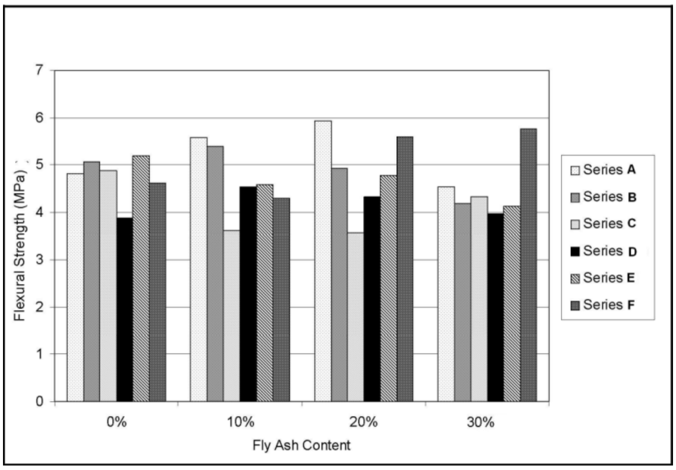

Fig. 1. Flexural strength with varying fly ash contents.

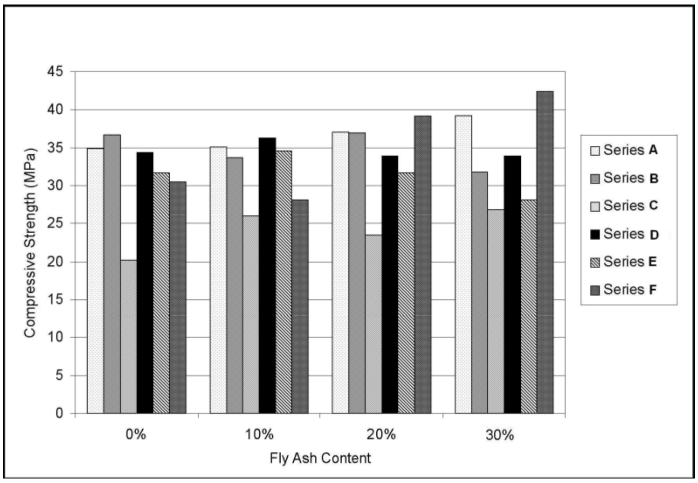

Fig. 2. Compressive strength with varying fly ash contents.

Effects of Fly Ash Content The effects of fly ash content on shrinkage can be seen in Fig. 4. Again, the mixture with 20% fly ash had the least shrinkage.

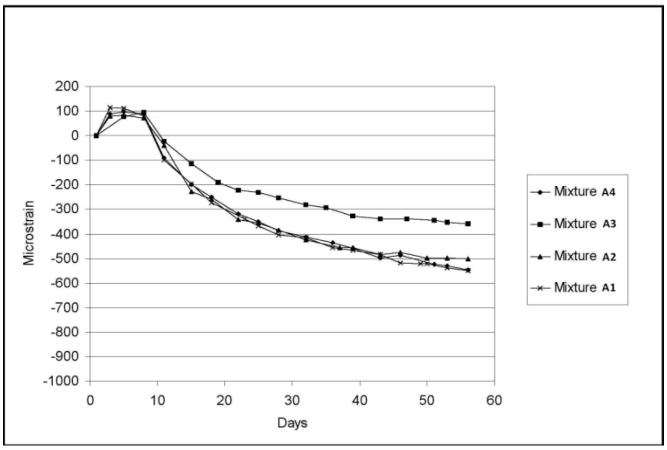

Fig. 3. Shrinkage strains for mixtures from Series A.

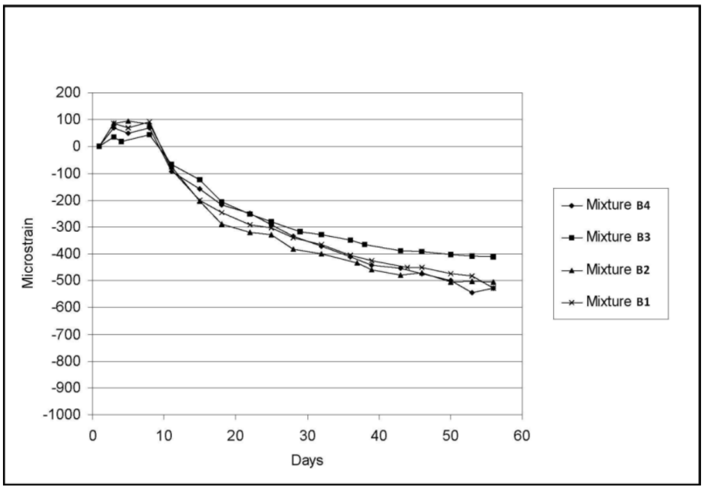

Fig. 4. Shrinkage strains for mixtures from Series B.

As fly ash content decreased from 20% to 0%, or increased to 30%, shrinkage strains increased. Mixture B3 experienced a reduction in shrinkage strains of approximately 100 microstrain compared to the other mixtures. Again, it appears that the moderate fly ash content (20%) produced an optimal effect that reduced shrinkage.

Effects of Type K cement

Shrinkage comparisons of specimens containing Type K cement are shown in Fig. 5. shrinkage at 56 days was observed in the mixtures with Type K cement compared to mixtures in Series B. Initial expansion of the specimens made with Type K cement was greater in the specimens with 20% and 0% fly ash content and similar to the specimens with Type I/II cement for the other two fly ash contents. By 56 days, the Type K specimens had experienced about 50 microstrain more shrinkage than comparable specimens in Series B. Type K mixtures require higher w/c+p ratios to ensure the proper formation of ettringite, sometimes as high as 0.5 [1]. The w/c+p ratio used in this study for the mixtures with Type K cement was 0.44. As a result, greater shrinkage was observed in Set K because the expansive sulfoaluminates in the Type K cement did not have sufficient water to maximize expansion. The effects of fly ash content on shrinkage of Series C mixtures was similar to the effects observed for Series A and Series B. Excluding mixture C3, shrinkage strains at 56 days were similar for all the Type K specimens. Mixture C3, with 20% fly ash, had approximately 100 microstrain less shrinkage at 56 days than the Type K mixtures with other fly ash contents. This supports the observation that moderate amounts of fly ash are helpful in controlling shrinkage.

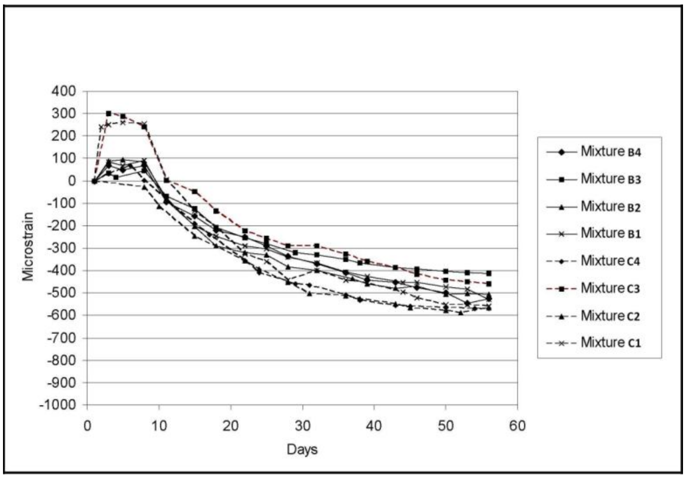

Fig. 5. Shrinkage strains for mixtures from Series K compared to mixtures with Type I/II cement.

Effects of SRA

The effects of two different dosages of SRA are shown in Fig. 6-7. Fig. 6 presents the shrinkage results for mixtures containing the manufacturer's minimum recommended dosage of the SRA. At this dosage, the SRA produced a minor reduction in shrinkage. Results for specimens with the minimum dosage of SRA initially run along the same curves as the results for specimens without SRA. Between 14 and 24 days, specimens with SRA began to show less shrinkage than the control specimens. Shrinkage strains in Series D, with a minimum dosage of SRA, were 50-90 microstrain less than shrinkage strains for similar mixtures in Series B at 56 days. Shrinkage results for mixtures containing the manufacturer's recommended dosage of SRA for optimal performance are presented in Fig. 7. At this dosage, there is a substantial difference in the shrinkage strains of the specimens with SRA compared to those without SRA. While the specimens were moist-cured, the length changes that occurred in two sets of SRA mixtures were similar to those in non-SRA mixtures. Differences in shrinkage strains became apparent in the first reading after the specimens began the dry-curing phase. Initial differences in shrinkage strains are small. However, differences in shrinkage strain increase significantly by 56 days for all mixtures except E4. E4 exhibited 60 micro strain less shrinkage than B26. The remaining mixtures in Series E experienced reductions in shrinkage strain of 230-260 microstrain. This is a reduction of approximately 50% when the manufacturer's optimal dosage of SRA was added to the mixture. Close inspection of Figg. 6-7 reveals that Mixtures MS20 and E3 experienced less shrinkage than the other mixtures in their respective sets. Again, this supports the observation that moderate amounts of fly ash produce less shrinkage.

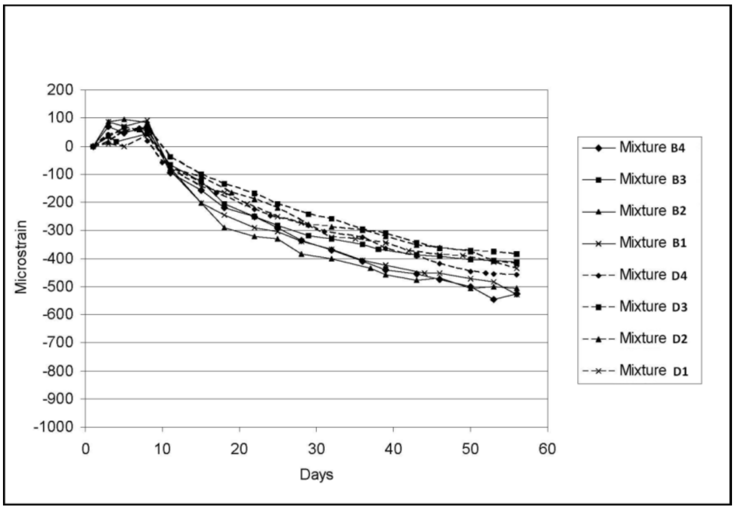

Fig. 6. Shrinkage strains for mixtures from Series D compared to mixtures without SRA.

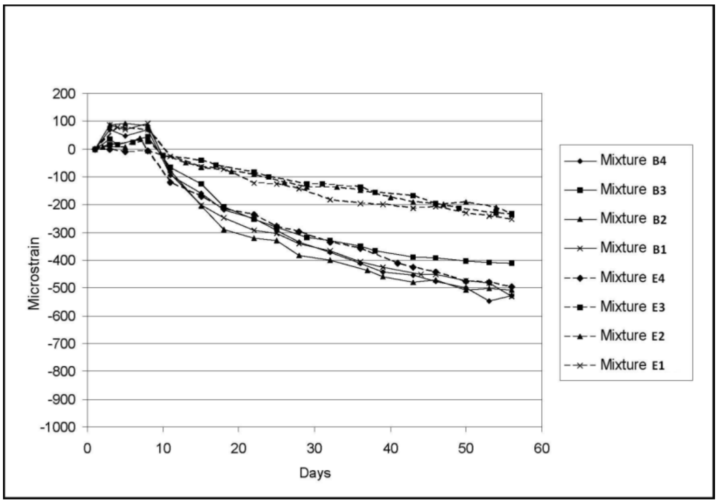

Fig. 7. Shrinkage strains for mixtures from Series E compared to mixtures without SRA.

Effects of Fibers

The effects of using fibers in the concrete mixture are shown in Fig. 8. The polypropylene fibers used in this study had little effect on shrinkage. Fly ash content in the fiber mixtures also had little effect on shrinkage. The lack of a trend for the Series F mixtures was not surprising since fibers are generally used to control cracking by limiting crack widths, not by reducing shrinkage [6].

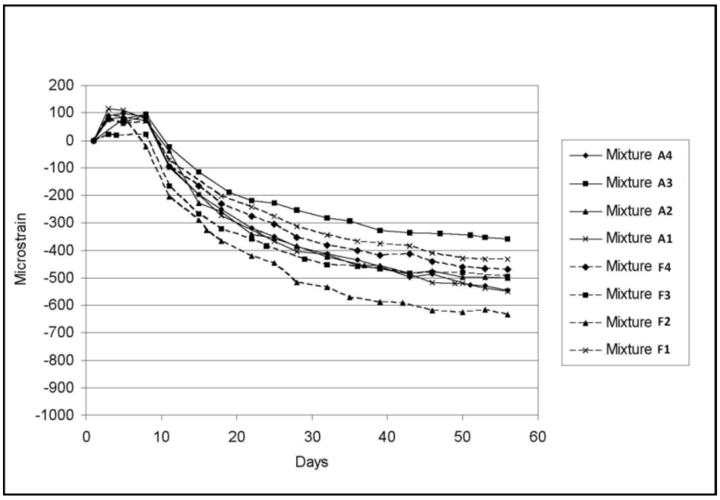

Fig. 8. Shrinkage strains for mixtures from Series F compared to mixtures without fibers.

Total Shrinkage Comparisons

All specimens were oven dried for 48 hours following the 56-day reading. After oven drying, a final length measurement was performed and total shrinkage strain was calculated. Total shrinkage results are shown in Fig. 9. The optimum dosage of SRA resulted in the lowest total shrinkage strain for each of the different fly ash contents, excluding 30% fly ash. Although a minimum dosage of SRA experienced more total shrinkage than Series E, these specimens generally exhibited less total shrinkage than any of the other sets. Specimens made with Type K cement exhibited similar or greater total shrinkage when compared to similar specimens made with Type I/II cement. There is no distinct trend in the total shrinkage strain of the specimens containing fibers. Mixtures with 20% fly ash had less shrinkage than comparable mixtures with other fly ash contents in four of the six sequences.

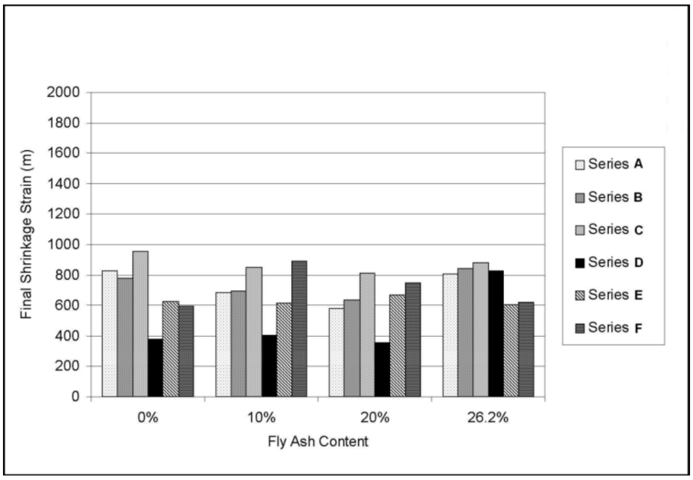

Fig. 9. Total shrinkage strains.

CONCLUSIONS

The results that were obtained in this study led to the following conclusions:

Shrinkage reducing admixtures produce an easily discernible reduction in shrinkage. Mixtures with the minimum dosage of SRA recommended by the manufacturer experienced 7 to 17% less shrinkage than comparable specimens without SRA. The mixtures did not exhibit decreased shrinkage immediately, but an improvement could be seen by the end of the 56-day test period.

When the SRA dosage was increased to the optimal dosage, differences in shrinkage strains could be seen as soon as air curing was initiated. Over 56 days, shrinkage differences continued to increase such that the SRA mixtures experienced approximately 40 to 50% less shrinkage at the end of the test period. Mixture E4 experienced shrinkage strains approximately 250 micro strain greater than the other mixtures in Series E. Consequently, the improvement of Mixture E4 over Mixture B4 was not as dramatic.

Moderate fly ash contents typically resulted in reduced shrinkage strains. Mixtures with 20% fly ash exhibited the least amount of shrinkage in five of the six cases. This indicates that the 20% fly ash content produced an optimal effect in either reducing moisture losses or reducing capillary tension, and possibly both.

Mixtures containing Type K cement generally had slightly greater shrinkage strains at 56 days than similar mixtures from Series B. Shrinkage over time and total shrinkage strains were both greater when the Type I/II cement was directly replaced with Type K cement. Type K cement requires that ample water be supplied to facilitate the formation of ettringite. This water should be provided as curing water as well as mixing water. Adequate curing water should also be available for at least seven days. Additionally, sufficient water should be provided in the mixture proportions to hydrate all of the cement. A minimum w/c+p ratio of

0.5 should be used with Type K cement. The mixture proportions for the Type K mixtures in this study had w/c+p=0.45. The water content for mixtures containing Type K cement was the same as the water content used for the Type I/II mixtures, as was the curing regimen. Therefore, the conditions were not favorable for the performance of the Type K cement. If more favorable conditions were provided, the performance of the Type K cement would be expected to improve.

Fibers in the concrete mixtures had little effect on shrinkage. They are intended to provide ductility and minimize crack width, so the results for fiber mixtures were not unexpected.

Patterns in the shrinkage strains between the mixtures emerged when the total shrinkage strains were calculated after the specimens were oven dried. Series D typically exhibited greater total shrinkage strains than Series E. However, both Series D and Series E generally experienced less total shrinkage than the other sets. Concrete made with Type K cement exhibited similar or greater total shrinkage strains when compared to Series B. The 20% fly ash content still produced the least shrinkage in four of the six cases.

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