Mineral Admixtures, Curing, and Concrete Shrinkage – An Update

「礦物掺料、養護與混凝土收縮」之近期相關研究

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本文旨在介紹堪薩斯大學近期有關混凝土自由收縮行為之相關研究成果，本研究係以養護時間、礦物摻料取代部分水泥比例與骨材種類等作為探討混凝土自由收縮(free shrinkage)行為之參數。研究中所使用的礦物摻料包括矽灰、水淬高爐石粉與飛灰，分別以兩種重量比例取代部分水泥，並配合高吸水率(2.5~3.0%)與低吸水率(小於 0.7%)之兩類粗骨材以拌製混凝土。研究結果顯示，在使用高吸水率粗骨材的情形下，摻用矽灰或高爐石粉以取代部分水泥，會使混凝土在所有齡期的收縮量均有降低的現象，至於摻用飛灰的情形，則會增加混凝土早齡期的收縮量，在長齡期時則無明顯效應；在使用低吸水率粗骨材的情形下，摻用矽灰或高爐石粉以取代部分水泥，會使僅溼養 7 天的混凝土之早齡期收縮量有增加的趨勢，當溼養時間從 7 天延長至 14 天，相同的礦物摻料取代水泥比例下，各齡期之混凝土收縮量則呈現減少的趨勢。前述的兩種養護條件下，使用飛灰的混凝土之收縮量，在各齡期則均呈現增加的效應。上述研究結果顯示，高吸水率之石灰石骨材因其內部孔隙水可提供作為額外的養護水份，因此，使得矽灰或高爐石粉取代部分水泥時，可有助於降低混凝土之收縮量。

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Abstract

Work currently underway at the University of Kansas to evaluate free shrinkage of concrete as a function of the length of curing prior to drying, mineral admixtures as a replacement for portland cement, and aggregate type is presented. Silica fume, ground-granulated blast furnace slag (GGBFS), and fly ash at two levels of replacement are evaluated with a high-absorption coarse aggregate (2.5 to 3.0%) and a low-absorption coarse aggregate (less than 0.7%). The results show that when cast with a high-absorption coarse aggregate, the addition of either silica fume or GGBFS results in a reduction in shrinkage at all ages, while the addition of fly ash increases early-age shrinkage and does not have a significant effect on long-term shrinkage. For mixtures containing a low-absorption coarse aggregate, the addition of silica fume or GGBFS results in increased early-age shrinkage if the specimens are only cured for seven days. These same mixtures exhibit reduced shrinkage at all ages when the curing period is doubled from seven to fourteen days. In either case the addition of fly ash increases shrinkage at all ages. Based on these results, it appears that the high-absorption limestone provides internal curing water, which results in a reduction in the shrinkage of mixtures containing GGBFS or silica fume.

Keywords: concrete, curing, fly ash, free shrinkage, ground granulated blast furnace slag, mineral admixtures, silica fume

Introduction

Cracks can form in concrete for many reasons, principal among which is restrained drying shrinkage. For this reason, the factors that affect drying shrinkage have been studied for over 80 years. Crack formation is usually accommodated in the structural design, but there are specific cases in which design considerations alone cannot ameliorate the negative effects of cracks. In these cases, the problem must be addressed by altering the materials or the construction processes. A prime example is that of bridge decks exposed to deicing chemicals. In the U.S., the majority of transportation agencies prefer to use exposed reinforced concrete decks. The decks are regularly treated with deicing chemicals during the winter months to help keep them free of ice and snow. Cracks in these decks tend to occur directly over the reinforcing steel and represent a major challenge in terms of providing corrosion protection for the reinforcement and limiting the detrimental effects of freezing and thawing cycles.

The University of Kansas is leading a long-term program that includes the construction of 20 low-cracking high-performance concrete bridge decks. A portion of the laboratory work supporting that effort involves the evaluation of concrete free shrinkage and the cracking tendency of concrete mixtures as a function of mineral admixture type as a replacement for portland cement, length of curing prior to drying, and aggregate type. This paper presents a summary of current findings as they apply to these parameters, with special attention to the role of mineral admixtures, aggregate type, and curing on concrete free shrinkage. Of particular interest are observations from previous studies that the duration of moist curing has little impact on concrete shrinkage.[1–3] This observation is not supported by the current study.

Experimental Work

Materials

Cementitious materials included Type I/II portland cement (meets the specification for ASTM C 150 Type I normal portland cement and Type II modified portland cement), densified silica fume, Class F fly ash, and Grades 100 and 120 ground granulated blast furnace slag (GGBFS). Aggregates included a relatively porous limestone (with an absorption between 2.5 and 3.0%) and granite (with an absorption below 0.7%).

The concrete mixtures were designed to have limited shrinkage. The percentage of paste by volume for each mixture is reported in the Results section.

Specimen Fabrication and Testing

The study involves the fabrication and testing of ASTM C 157 shrinkage specimens that were subjected to drying conditions at 23° ± 2° C (73.4° ± 3° F) and 50% ± 4% relative humidity for periods of up to one year. Concrete was mixed and the specimens were prepared in accordance with

ASTM C 192. The fine aggregate was batched with excess free surface moisture, and the coarse aggregate was batched in the saturated-surface-dry (SSD) condition, except for some batches designed to evaluate the effects of internal curing in which coarse aggregate was batched in the oven-dry condition. Batch water was adjusted to account for deviations from the SSD condition. The results described next represent the average of three shrinkage specimens for each parameter with day zero being the initiation of drying.

Results

This section summarizes the free shrinkage test results as a function of curing period, aggregate type, and mineral admixture type.

Curing Period

The effect of curing period on shrinkage is illustrated in Figure 1. For concrete with a paste volume equal to 30% of the concrete volume, *w/c* = 0.45 and 5% entrained air, an increase in the curing period from 3 to 28 days results in a decrease in shrinkage. The greatest reduction in shrinkage is obtained with an increase in the curing period from 3 to 7 days (approximately 180 με at 1 year). Reductions of 20 and 60 με at one year are obtained for increases in curing period from 7 to 14 days and from 14 to 28 days, respectively. These observations are in contrast with those of Tremper and Spellman,[1] Carlson,[2] and Powers[3] in which curing was reported to have little effect on the long-term shrinkage of concrete.

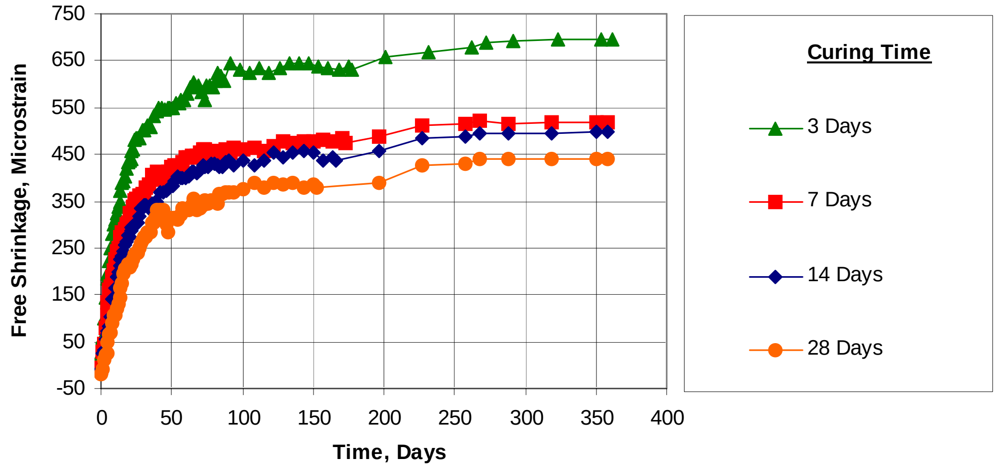

Figure 1 Average free shrinkage for specimens moist-cured from between 3 to 28 days

Mineral Admixtures

Mineral admixture replacements are reported by volume of cementitious materials rather than by weight. Because concrete shrinkage is largely controlled by the paste content, with the *w/cm* playing a lesser role,[4] the *w/cm* and paste content are kept constant for each batch in this series. The *w/cm* equals 0.42, and the paste content equals 23.26%, a volume percentage equal to that obtained with a cement content of 317 kg/m^3 (535 lb/yd^3) and a *w/c* of 0.42. All mixtures had a slump of 50 to 100 mm (2 to 4 in.) and an air content of 7.9 to 8.9%.

Figure 2 compares the shrinkage results for concrete with limestone coarse aggregate containing 0, 30, or 60% volume replacements of cement with Grade 120 ground granulated blast furnace slag (GGBFS). Mixtures were cured for 7 or 14 days. For mixtures cured for 14 days, an increase in the GGBFS content from 0 to 30% resulted in a decrease in shrinkage of 50 με after 30 days of drying and by approximately 30 με for periods greater than 90 days. A similar reduction in shrinkage was obtained with an increase in the GGBFS content from 30 to 60%. In each case, specimens cured for 7 days exhibited greater shrinkage than those cured for 14 days. The 30% GGBFS mixture cured for 7 days exhibited similar shrinkage as the control mixture (0% GGBFS) cured for 7 days, and the 60% GGBFS mixture cured for 7 days exhibited similar shrinkage as the control mixture cured for 14 days.

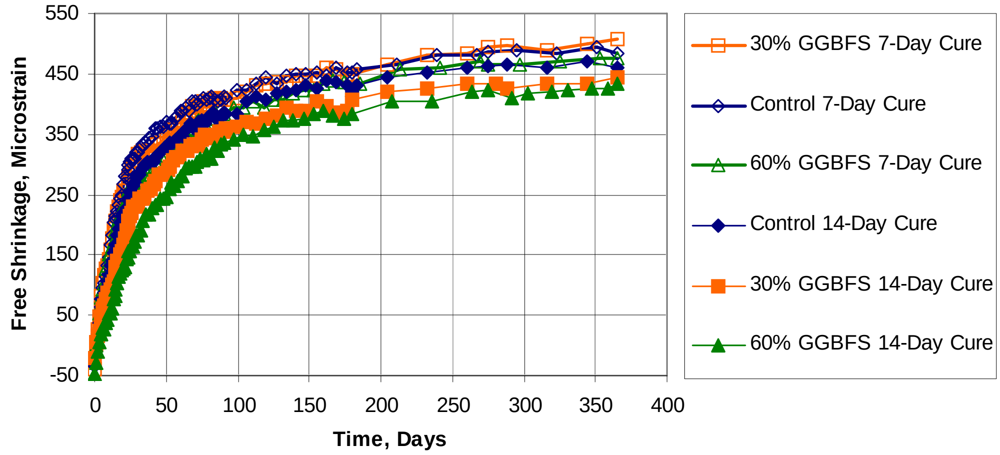

Figure 2 Average free shrinkage for specimens cast with Grade 120 ground granulated blast furnace slag (GGBFS) and limestone coarse aggregate

Additional testing with granite, which has a significantly lower absorption than the limestone (less than 0.7%), indicates that some of the reduced shrinkage observed for the mixtures containing GGBFS may be due to the availability of water within the limestone pores, which provides internal curing. The results in question are illustrated in Figure 3, which compares a limestone control mixture (0% GGBFS) with granite and limestone mixtures containing a 60% Grade 100 GGBFS replacement of cement. The paste content is maintained at 23.26% with a 0.42 *w/cm*. For the comparison shown in Figure 3, the least shrinkage throughout the drying period is for the limestone mixture with 60% Grade 100 GGBFS. At 16 days, the shrinkage of the granite mixture with 60% Grade 100 GGBFS equals and then drops below the shrinkage exhibited by the limestone control mix. It can also be seen that the shrinkage for the mixture containing granite appears to be stable after approximately 100 days, while the limestone mixture containing 60% GGBFS exhibits continued shrinkage through about 200 days.

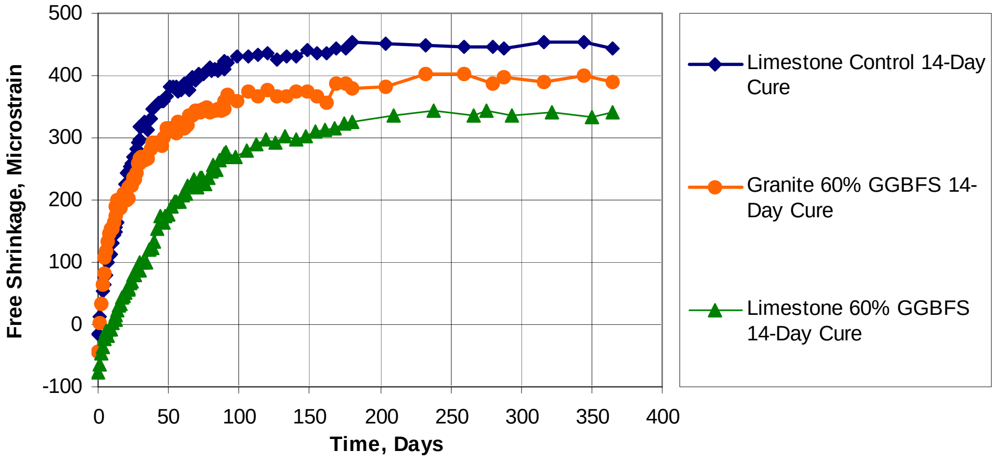

Figure 3 Average free shrinkage for specimens cast with Grade 100 GGBFS and limestone or granite coarse aggregates

The results illustrated in Figures 1 through 3 represent the performance of mixtures in which the aggregate moisture content at the time of batching is at least saturated-surface-dry (SSD). The effect of internal curing on shrinkage is shown in Figure 4, where control mixtures with SSD limestone, cured for 7 and 14 days, are compared with mixtures cast with Grade 100 GGBFS and limestone that was either in an SSD or an oven-dry condition at the time of casting. For these mixtures, the total water content was adjusted to account for the absorption of the oven-dry aggregate. As shown in Figure 4, the mixtures cast with SSD limestone containing 60% Grade 100 GGBFS exhibit less shrinkage than the corresponding mixtures cast with oven-dried limestone. The mixtures batched with oven-dry limestone (also containing 60% GGBFS) exhibit less shrinkage than the control mixture (0% GGBFS). Longer curing results in lower shrinkage in all cases. Presumably, the oven-dry limestone absorbed water during the mixing process allowing a portion of that water to be available for internal curing once the concrete hardened. All of the water added to bring the oven-dry aggregate to an SSD condition, however, was probably not absorbed, resulting in an increased paste content and *w/cm* ratio, as well as less water available for internal curing compared to the mixtures cast with SSD aggregate, which translates into increased shrinkage.

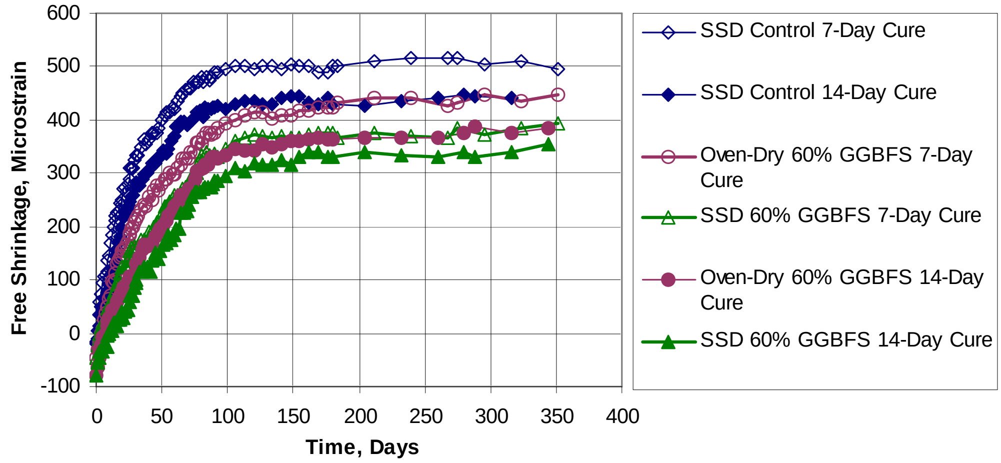

Figure 4 Average free shrinkage for specimens cast with Grade 100 GGBFS and limestone in the saturated-surface dry (SSD) or oven-dry condition

Figure 5 compares the shrinkage results for concrete with granite and 0, 30, or 60% volume replacements of cement with GGBFS. At 30 days, shrinkage ranges from 190 με for the 60% volume replacement mixture cured for 14 days, to 300 με for the 30% GGBFS mixture cured for 7 days. This difference decreases to about 50 με at 150 days, but the trend clearly illustrates the importance of extended curing periods for mixtures containing GGBFS. Unlike the comparisons with limestone shown in Figure 2, when only cured for 7 days, the addition of GGBFS (30 or 60% replacement) to granite mixtures results in increased shrinkage at 30 days compared to the control mixture. After 80 days of drying, the shrinkage of the control mixture cured for 7 days equals and then exceeds the shrinkage of both GGBFS mixtures cured for 7 days. When cured for 14 days, however, high-volume percentage replacements of cement with GGBFS can greatly reduce shrinkage, especially at early ages when the majority of shrinkage occurs.

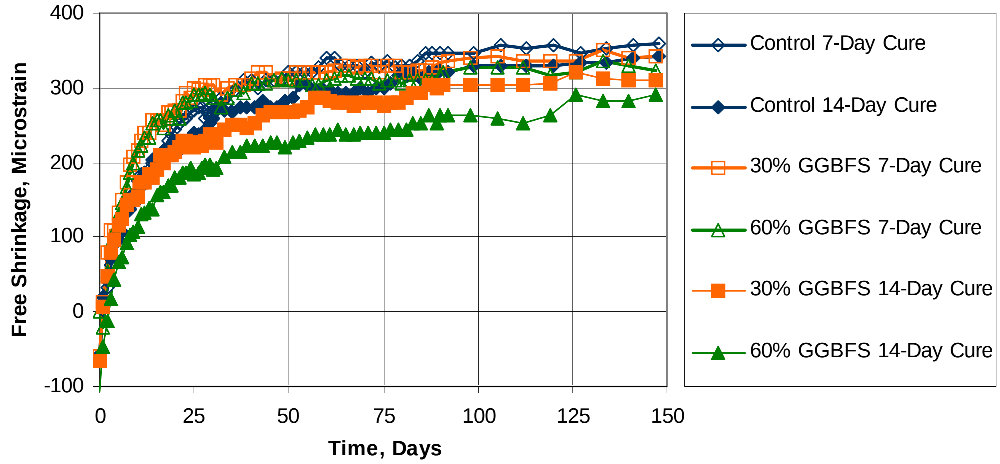

Figure 5 Average free shrinkage for specimens cast with Grade 100 GGBFS and granite coarse aggregate

Figure 6 compares the shrinkage results for concrete containing limestone and 0, 3, or 6% volume replacements of cement with densified silica fume. For mixtures cured for 14 days, an increase in the silica fume content from 0 to 3% resulted in a decrease in shrinkage by approximately 30 με for periods greater than 90 days. An even greater reduction in shrinkage (about 60 με for periods of 90 days and longer) was obtained with an increase in the silica fume content from 3 to 6%. Specimens cured for 7 days exhibited greater shrinkage than those cured for 14 days. The 3% silica fume mixture cured for 7 days exhibited the same shrinkage as the control mixture (0% silica fume) cured for 7 days, and the 6% silica fume mixture cured for 7 days exhibited slightly higher shrinkage than the 3% silica fume mixture cured for 14 days. A comparison of the effect of the curing period length shows the importance of increased curing (to obtain reduced shrinkage) as the quantity of silica fume increases.

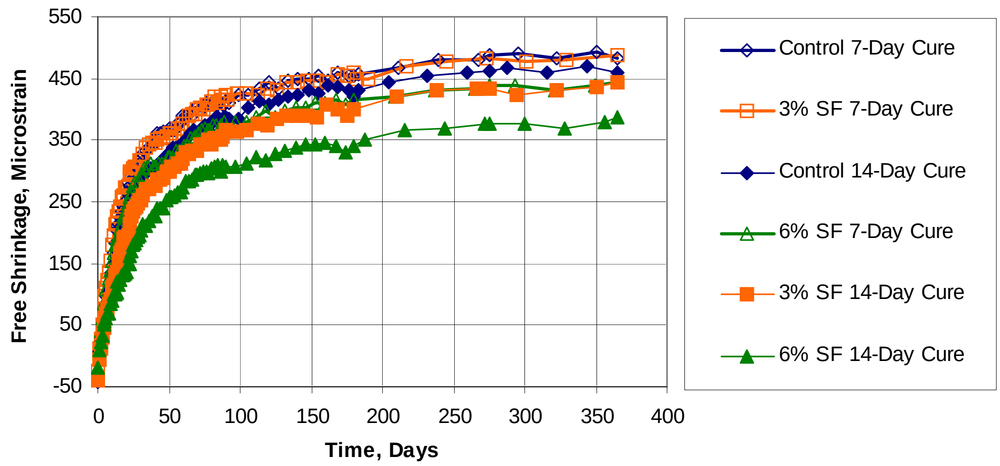

Figure 6 Average free shrinkage for specimens cast with silica fume (SF) and limestone coarse aggregate

Results for concrete mixtures containing granite and a partial replacement of cement with silica fume are shown in Figure 7. The results are qualitatively very similar to the results obtained for mixtures containing a partial replacement of cement with GGBFS and granite (Figure 5). The addition of silica fume decreases shrinkage at all ages provided that the specimens are cured for 14 days. For these specimens, an increase in the silica fume content from 0 to 6% resulted in a small reduction in shrinkage (about 20 με) at 30 days that increased to about 60 με for periods of 90 days and longer. When only cured for 7 days, however, the addition of 3 or 6% silica fume resulted in an increase in early-age shrinkage (approximately 20 με at 30 days). For periods greater than 90 days, the 3% silica fume mixture cured for 7 days exhibited similar shrinkage as the control mixture (0% silica fume) cured for 7 days, and the 6% silica fume mixture cured for 7 days exhibited similar behavior as the control mixture cured for 14 days.

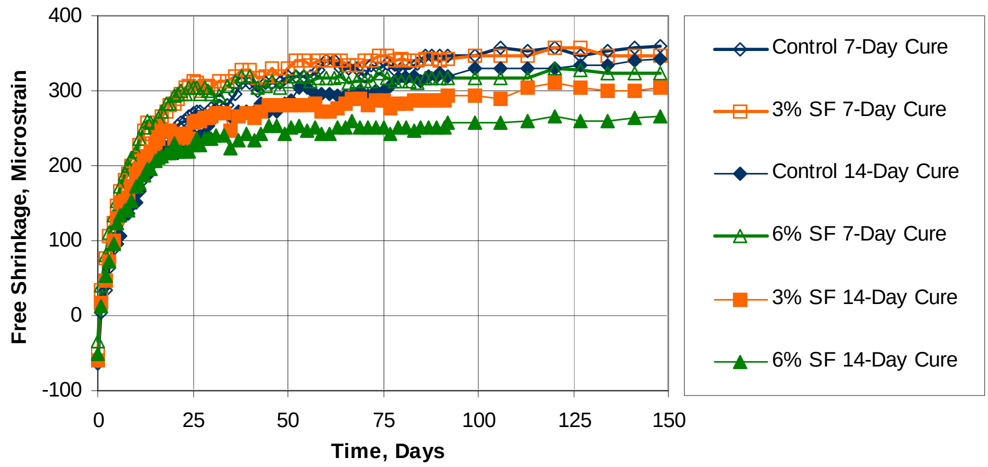

Figure 7 Average free shrinkage for specimens cast with silica fume (SF) and granite coarse aggregate

Results for concrete containing 0, 20, or 40% volume replacements of cement with Class F fly ash are shown in Figures 8 and 9. Figure 8 compares specimens cast with limestone coarse aggregate, while Figure 9 compares specimens cast with granite. In both cases, the addition of fly ash results in slightly increased long-term shrinkage as compared to the control mixture (0% fly ash). Higher percentage replacements of fly ash resulted in increased long-term shrinkage when cast with limestone coarse aggregate (Figure 8). The highest long-term shrinkage for mixtures with granite coarse aggregate was obtained for specimens containing a 20% replacement of cement with fly ash and cured for 7 days. As with the earlier observations, longer curing periods coincide with lower free shrinkage, although the differences are lower for concrete containing fly ash than for specimens containing GGBFS or silica fume.

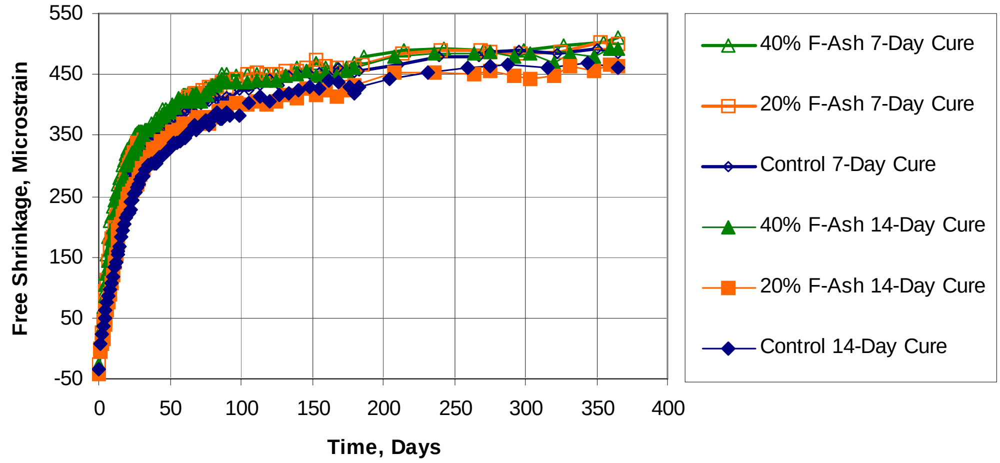

Figure 8 Average free shrinkage for specimens cast with Class F fly ash (F-Ash) and limestone coarse aggregate

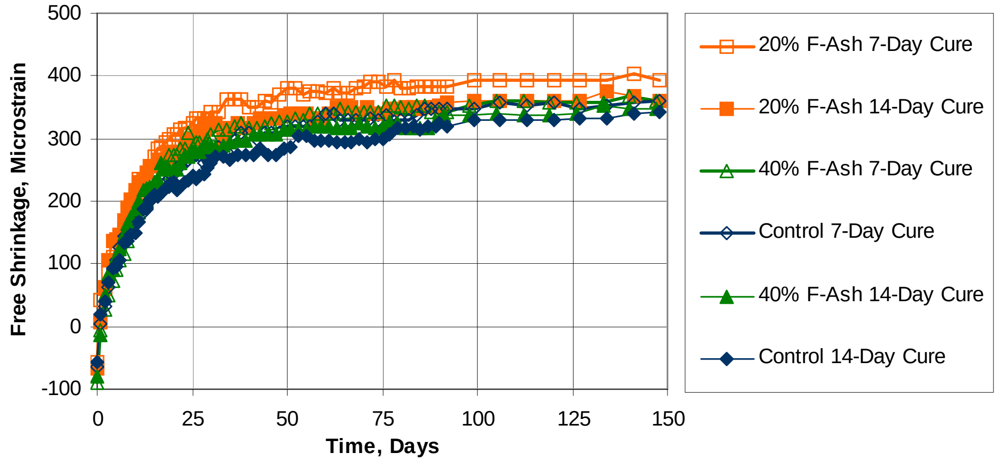

Figure 9 Average free shrinkage for specimens cast with Class F fly ash (F-Ash) and granite coarse aggregate

Early shrinkage is of special importance for bridge decks because the tensile stresses induced by long-term shrinkage are generally decreased due to the effects of tensile creep. The relative order of short-term shrinkage (through 30 days) for the fly ash mixtures are shown in Figures 10 and 11, and demonstrate that the addition of fly ash provides no special advantage, and in fact, increases the short-term shrinkage for all mixtures. This increase is exacerbated by reduced curing periods. For the limestone mixtures (Figure 10), the lowest shrinkage through 30 days is attained by the control mix (0% fly ash) cured for 14 days, and the highest shrinkage occurred for the 40% volume replacement mixture cured for 7 days. The total difference is approximately 80 με, which decreases to about 40 με for periods of 260 days and longer, as shown in Figure 8. The results are similar for the mixtures containing granite, except the highest early-age shrinkage occurred for the 20% volume replacement cured for 7 days and the lowest occurred for the control mix cured for 14 days. The total difference in this case is approximately 80 με at 30 days decreasing slightly to 60 με for periods of 90 days and longer (Figure 9).

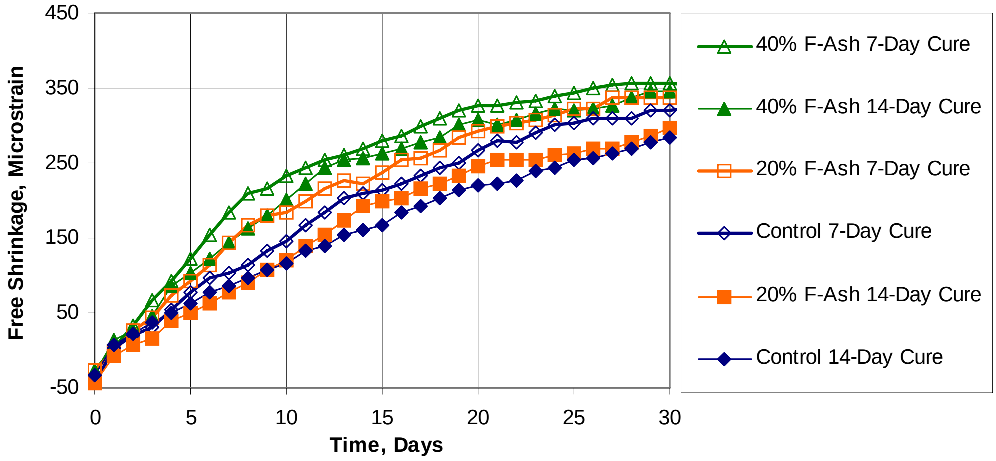

Figure 10 Early-age average free shrinkage for specimens cast with Class F fly ash (F-Ash) and limestone coarse aggregate

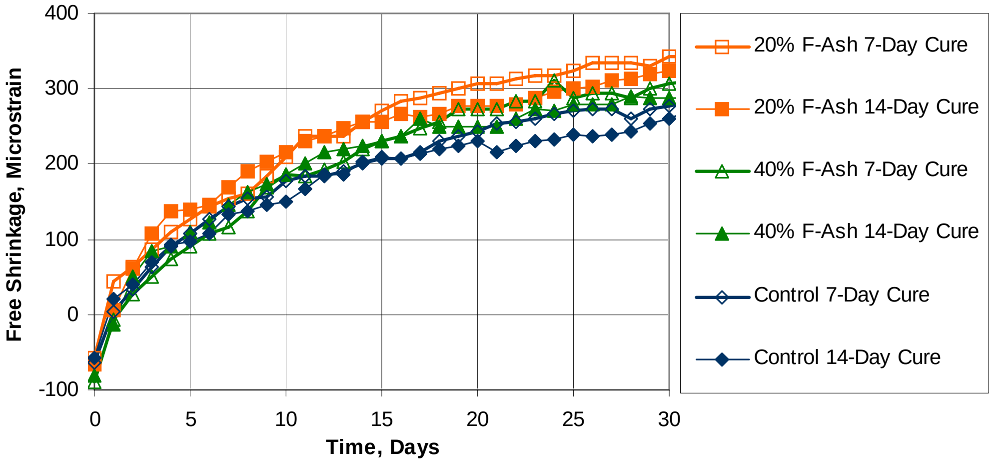

Figure 11 Early-age average free shrinkage for specimens cast with Class F fly ash (F-Ash) and granite coarse aggregate

Conclusions

The following conclusions are based on the limited test results reported in this paper.

1. Longer curing periods reduce concrete shrinkage.

2. When used with a coarse aggregate with a high absorption, such as 2.5-3.0% as used in this study, the addition of either silica fume or GGBFS results in a reduction in shrinkage at all ages, while the addition of fly ash increases early-age shrinkage (30 days) and does not have a significant effect on long-term shrinkage.

3. Internal curing provided by water held in the pores of coarse aggregate particles reduces the free shrinkage of concrete containing silica fume or ground granulated blast furnace slag as a replacement for portland cement.

4. When used with a low-absorption coarse aggregate, such as 0.7% in this study, mixtures

containing silica fume or GGBFS exhibit increased early-age shrinkage compared to a 100% portland cement mixture when only cured for 7 days. These same mixtures exhibit similar or slightly reduced shrinkage compared to the 100% portland cement mixture after approximately 90 days of drying.

5. For mixtures containing a low-absorption aggregate and cured for 14 days, the addition of either silica fume or GGBFS results in a reduction in shrinkage at all ages.

6. The addition of fly ash results in increased early-age shrinkage compared to the 100% portland cement mixture for concrete cast with either a low or high-absorption coarse aggregate and cured for either 7 or 14 days.

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