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Effects of Internal Curing, Slag, and Silica Fume on Concrete Shrinkage

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The shrinkage of mixtures containing replacements of total aggregate with prewetted lightweight aggregate (LWA) (0, 8, and 10% by volume) and replacements of cement with Grade 100 slag cement (0 and 30% by volume) and silica fume (0, 3, and 6% by volume) is evaluated. The results show that internal curing provided by prewetted LWA reduces the tendency of the mixtures to develop shrinkage strains. Further reductions are observed as slag is added in conjunction with prewetted LWA and as silica fume is added in conjunction with the prewetted LWA and slag.

Keywords: internal curing; prewetted lightweight aggregate; shrinkage; silica fume; slag cement.

INTRODUCTION

Concrete bridge deck deterioration caused by the corrosion of reinforcing steel is a serious problem that can considerably reduce structure service life and cause numerous maintenance problems. Concrete cracking caused by shrinkage accelerates this deterioration by providing a path for corrosive agents, water, and oxygen to penetrate the deck and reach the reinforcement (Schmitt and Darwin 1999; Lindquist et al. 2006; Darwin et al. 2004, 2010; Pendergrass and Darwin 2014). Furthermore, research has demonstrated that even bars with a protective epoxy coating are susceptible to disbondment and corrosion in cracked concrete (O'Reilly et al. 2011; Darwin et al. 2011).

It is well-established that minimizing shrinkage can greatly reduce the cracking potential of concrete bridge decks (Schmitt and Darwin 1999; Darwin et al. 2004, 2010). One technique increasingly used to reduce shrinkage is the addition of prewetted lightweight aggregate as a source of internal curing (IC) water (Browning et al. 2011; De la Varga et al. 2012). IC was first suggested by Philleo (1991), who proposed that a partial replacement of normalweight aggregate with prewetted vacuum-saturated (PVS) lightweight aggregate (LWA) can reduce autogenous shrinkage in concretes with low water-cementitious materials ratios (w/cm). Weber and Reinhardt (1997) demonstrated the effectiveness of IC in reducing shrinkage and improving hydration of high-performance concretes with water-cement ratio (w/c) as low as 0.30. Browning et al. (2011) demonstrated the effectiveness of IC with the use of PVS LWA to reduce shrinkage in concretes typically used in bridge decks (w/cm greater than or equal to 0.42).

Slag cement and silica fume are supplementary cementitious materials (SCMs) that have been used in concrete for decades. Reduced concrete permeability has been observed with the addition of slag (Rose 1987) and silica fume (Maage 1984; Maage and Sellevold 1987) to concrete, with decreased permeability as the proportions of each are increased. The lower permeability is due to a change in the pore structure of the cement paste matrix.

Drying shrinkage, a primary concern for bridge decks, is caused by the loss of water in the capillary pores of hardened cement paste as water is lost to the environment. Bentur et al. (1988) explained that concrete containing silica fume experiences a slower rate of water loss during drying as a result of the reduced permeability. If sufficient internal curing water is supplied to the concrete through the use of prewetted lightweight aggregate, the reduced permeability provided by the silica fume and slag could reduce drying shrinkage because water within the cement paste constituent of concrete is unable to quickly reach the surface and, thus, evaporate. Over time, this internal water becomes tied up in hydration products and is no longer available to evaporate.

Studies conducted to compare the shrinkage of concretes made with portland cement with that of concrete made with a partial slag cement replacement of portland cement have yielded differing results. Fulton (1974) concluded that the use of slag cement in concrete increases shrinkage. Similarly, Lee et al. (2006) found that partial replacement of cement with slag increases early-age shrinkage. A study conducted by Klieger and Isberner (1967) resulted in similar shrinkage values for mixtures with and without slag cement, while Tazawa et al. (1989) observed less shrinkage in mixtures with slag when cured for 28 days and greater shrinkage when cured for 3 or 7 days. Li et al. (1999) observed no significant change in concrete shrinkage with a 50% replacement of the cement with slag. It should be noted that the mixtures just described were proportioned based on an equal-weight substitution of cement with slag. As a result of the lower specific gravity of slag cement compared to portland cement, these mixtures contained a greater volume of cement paste, the constituent undergoing shrinkage, than those without slag. Therefore, to evaluate the effects of material substitutions, comparisons should be based on a volume replacement rather than weight basis. Using the work reported in 32 references, Hooton et al. (2009) assembled a database of 62 concrete mixtures to investigate the effect of slag cement on the shrinkage of concrete. Slag cement was either a partial replacement of cement or the only cementitious

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material. Hooton et al. (2009) concluded that the shrinkage of the mixtures containing slag cement was about the same as that of concretes without slag cement. When the shrinkage results were adjusted by taking into account the volume of the paste, concretes containing slag cement showed approximately 3% less shrinkage.

Ghasemzadeh et al. (2014) evaluated the shrinkage of concrete mixtures with paste contents between 29.5 and 30% and a *w/cm* of 0.38, with and without cement replacements with slag and silica fume. The results indicated that after 365 days, shrinkage was significantly reduced (by approximately 180 microstrain) for mixtures containing a slag cement replacement (25.8% by volume of binder) compared to mixtures with 100% portland cement. An additional small reduction (approximately 20 microstrain) in shrinkage was observed when a small amount (9.8% by volume of binder) of silica fume was used in conjunction with slag cement.

Yuan et al. (2015) compared the shrinkage of concrete mixtures containing different volume replacements of cement with slag cement with that of concrete mixtures made with 100% portland cement. The *w/cm* (0.44) and paste volume (24.1%) of the cementitious material were constant for all mixtures. They found that a partial replacement of cement with slag cement reduced shrinkage—a reduction that was greatest at early ages and increased as the replacement level of slag was increased. Yuan et al. (2015) also found, as did Darwin et al. (2007) and Lindquist et al. (2008), that when slag cement was used in conjunction with a saturated porous limestone coarse aggregate, which provided internal curing, a greater reduction in shrinkage was observed than obtained in mixtures containing a low-absorption coarse aggregate.

This paper evaluates the shrinkage of mixtures containing different combinations of prewetted LWA, Grade 100 slag cement, and silica fume. The mixtures evaluated in this study have paste contents between 23.7 and 24% by volume and a *w/cm* of 0.44 or 0.45.

RESEARCH SIGNIFICANCE

Previous studies have found inconsistent results when evaluating the shrinkage of concrete containing slag cement. These inconsistencies are likely attributed to evaluating the shrinkage of mixtures with different paste volumes. In addition, the beneficial effects on shrinkage performance of IC through the use of prewetted LWA have not been evaluated in conjunction with both slag cement and silica fume. Slag and silica fume, when combined with internal curing, can provide a significant reduction in shrinkage.

EXPERIMENTAL INVESTIGATION

Materials

Type I/II portland cement was used for all mixtures in this study. Grade 100 slag cement and silica fume were used as partial replacements by volume of cement in some mixtures. Granite, with an absorption between 0.6 and 0.8%, was used as the coarse aggregate. Pea gravel was used as an intermediate aggregate, and river run sand was used as the fine aggregate. Pea gravel-sized and sand-sized LWA were used in different mixtures as a partial aggregate replacement to provide a source of IC water in some of the mixtures.

Table 1—Chemical composition and specific gravity of cementitious materials, %

Component	Portland cement-1*	Portland cement-2*	Grade 100 slag cement	Silica fume
SiO_2	20.26	20.00	43.46	94.49
Al_2O_3	4.81	5.00	8.61	0.07
Fe_2O_3	3.07	2.98	0.37	0.1
CaO	63.52	62.99	31.13	0.53
MgO	1.41	1.58	12.5	0.62
SO_3	2.78	2.94	2.24	0.11
Na_2O	0.24	0.17	0.21	0.09
K_2O	0.44	0.41	0.4	0.54
TiO_2	0.33	0.33	0.32	—
P_2O_5	0.14	0.13	—	—
Mn_2O_3	0.09	0.09	0.35	0.02
SrO	0.11	0.11	0.04	0.01
Cl^-	—	—	—	0.05
LOI	3.11	3.77	0.37	3.21
Total	100.31	100.5	99.9	99.9
Specific gravity	3.15	3.20	2.86	2.20

*Portland cement-1 was used for mixtures in Series A and Portland cement-2 was used for mixtures Series B and C.

The gradations for the two types of LWA are presented in Appendix A.* The chemical compositions and specific gravities of the portland cement, slag cement, and silica fume are given in Table 1. A tall oil-based air-entraining admixture (AEA) was used in all mixtures. A polycarboxylate-based high-range water-reducing admixture (HRWRA) was used when necessary to achieve the desired concrete slump.

Concrete mixtures

Three series of concrete mixtures, a total of 13 individual mixtures, were used to evaluate the effect on shrinkage of internal curing with and without additions of slag and silica fume. Mixture proportions are shown in Table 2. Mixtures designated as "Control" contained no prewetted LWA, slag, or silica fume. Mixtures with 8 and 10% volume replacements of total aggregate with LWA, but no additions of slag or silica fume, are designated as "8% LWA" and "10% LWA," respectively. The mixture with a 10% LWA volume replacement of total aggregate and a 30% volume replacement of cement with slag cement is designated as "10% LWA-30% Slag." Mixtures with a 10% LWA volume replacement of total aggregate, a 30% volume replacement of cement with slag cement, and a 3 or 6% volume replacement of cement with silica fume are designated as "10% LWA-30% Slag-3% SF" and "10% LWA-30% Slag-6% SF," respectively. A letter is added at the end of a mixture designation to indicate the series in which the concrete was cast. For example, 10% LWA-30% Slag-3% SF-B describes the mixture containing

*The Appendix is available at **www.concrete.org/publications** in PDF format, appended to the online version of the published paper. It is also available in hard copy from ACI headquarters for a fee equal to the cost of reproduction plus handling at the time of the request.

Table 2—Concrete mixture proportions, lb/yd^3

Series	Mixtures	*w*/*cm*	Cement	Slag	Silica fume	Mixture water	Paste content, %	Sand	Pea gravel	LWA	IC water*	Coarse aggregate 3/4 in.	Coarse aggregate 1 in.	AEA, fl oz/yd^3
A	Control-A	0.45	520	0	0	234	23.69	944†	551#	0	0.00	565##	923#	3.0
A	8% LWA-A	0.44	520	0	0	229	23.39	1044†	213##	142&	5.68	454††	1046#	2.0
A	10% LWA-A	0.44	520	0	0	229	23.39	1044†	153##	177&	6.49	454#	1046#	2.0
A	10% LWA-30% Slag-A	0.44	374	146	0	229	23.67	1028††	84##	177&	6.70	454#	1110#	3.0
A	10% LWA-30% Slag-3% SF-A	0.44	359	144	11	226	23.46	1031††	153##	177&	6.49	454#	1045#	3..0
A	10% LWA-30% Slag-6% SF-A	0.44	342	146	22	224	23.36	1033††	153##	177&	6.11	456#	1047#	3.0
B	Control-B	0.45	520	0	0	234	23.69	1033†	646†	0	0.00	398Δ	948Δ	2.0
B	10% LWA-B	0.45	520	0	0	234	23.69	1082†	287†	178&	5.80	359Δ	1002Δ	3.0
B	10% LWA-30% Slag-3% SF-B	0.45	359	145	11	231	23.78	1033†	287†	177&	6.68	359Δ	1000Δ	3.0
B	10% LWA-30% Slag-6% SF-B	0.45	341	145	22	228	23.56	1083†	287†	177&	7.11	360Δ	1003Δ	3.0
C	10% LWA-C	0.45	520	0	0	234	23.69	892†	381$	198&&	7.49	533†	907†	7.0
C	10% LWA-30% Slag-C	0.45	373	147**	0	234	23.97	888†	380$	197&&	7.14	531†	903†	7.0
C	10% LWA-30% Slag-3% SF-C	0.45	362	147**	11	234	24.06	831†	507$	197&&	7.13	457†	906†	7.0

*Percentage of weight (mass) of cementitious material
**Specific gravity of slag =2.89
†Bulk specific gravity (SSD) = 2.62
††Bulk specific gravity (SSD) = 2.61
#Bulk specific gravity (SSD) = 2.59
##Bulk specific gravity (SSD) = 2.60
$Bulk specific gravity (SSD) = 2.63
&Bulk specific gravity (SSD) = 1.54
&&Bulk specific gravity (SSD) = 1.72
ΔBulk specific gravity (SSD) =2.64
Mixture designation: X% LWA-Y% Slag-Z% SF- γ
X = Percent replacement by volume of total aggregate with lightweight aggregate.
Y = Percent replacement by volume of cement with slag.
Z = Percent replacement by volume of cement with silica fume.
γ = series the mixture is in (A, B, or C).
Notes: 1 lb/yd^3 = 0.59 kg/m^3; 1 fl oz/yd^3 = 38.66 mL/m^3.

the 10% LWA, 30% slag, and 3% silica fume replacements in Series B. Series A included Control, 8% LWA, 10% LWA, 10% LWA-30% Slag, 10% LWA-30% Slag-3% Silica Fume, and 10% LWA-30% Slag-6% Silica Fume mixtures. Series B included the same mixtures as Series A, with the exception of 8% LWA and 10% LWA-30% Slag. Series C included three mixtures: 10% LWA, 10% LWA-30% Slag, and 10% LWA-30% Slag-3% Silica Fume.

The mixtures containing prewetted LWA in Series A and B were made with a pea gravel-size LWA, while those in Series C were made with a sand-size fine LWA. The gradations for the two types of LWA are provided in Table A1 in Appendix A. The LWA used in Series A and B was vacuum-saturated, while the LWA used in Series C was soaked in water at atmospheric pressure for 72 hours prior to mixing. Detailed descriptions of the vacuum saturation equipment and operation procedures are provided by Reynolds et al. (2009). The absorption of the vacuum-saturated and soaked LWAs, found according to ASTM C128, used in the batches ranged from 21.4 to 26.3% in Series A, 20.3 to 25.5% in Series B, and 23.2 to 24.7% in Series C, providing internal curing water content by weight (mass) of cementitious material ranging from 5.7 to 6.7% in Series A, 5.8 to 7.1% in Series B, and 7.1 to 7.5% in Series C (Table 2). Concrete properties are shown in Table 3.

The mixtures in Series A had a *w*/*cm* of 0.44, with the exception of the Control mixture, which had a *w*/*cm* of 0.45. The mixtures in Series B and C had a *w*/*cm* of 0.45. Paste contents, based on an air content of 8%, for the 13 mixtures ranged from 23.36 to 24.06% by volume, with a maximum variation for mixtures in a single series of under 0.4%. The mixtures were designed to remain within a small range of paste contents by volume to minimize the effect of paste volume on shrinkage. The low paste contents were based on the recommendations by Schmitt and Darwin (1995, 1999) resulting from a study of 33 bridge deck placements, which showed a clear relationship between paste content and bridge deck cracking. Schmitt and Darwin (1995, 1999) concluded that cracking will increase significantly when the volume of the paste exceeds 27%. Based on the work by Schmitt and Darwin, coupled with follow-on studies (Darwin et al. 2004; Lindquist et al. 2005), a series of low-cracking high-performance concrete (LC-HPC) bridge decks were constructed with paste contents between 22.8% and 24.6%. The benefits of using a lower paste content

Table 3—Properties of concrete mixtures

Series	Mixture	Air content, %	Slump, in.	Temp, °F (°C)	Unit wt., lb/ft³	28-day strength, psi
Series A	Control-A	9.00	3	72 (22.2)	—	—
	8% LWA-A	8.00	1-3/4	72 (22.2)	136.7	5050
	10% LWA-A	8.50	2-1/4	70 (21.1)	136.0	4260
	10% LWA-30% Slag-A	8.75	3	69 (20.6)	—	4440
	10% LWA-30% Slag-3% SF-A	8.00	1-1/2	69 (20.6)	134.0	5660
	10% LWA-30% Slag-6% SF-A	8.00	1-3/4	75 (23.9)	134.7	5370
Series B	Control-B	7.00	2-1/2	68 (20.0)	145.9	4290
	10% LWA-B	8.25	2-3/4	75 (23.9)	138.5	4980
	10% LWA-30% Slag-3% SF-B	9.00	2-1/2	61 (16.1)	137.2	4290
	10% LWA-30% Slag-6% SF-B	8.00	2-1/4	62 (16.7)	138.7	4720
Series C	10% LWA-C	8.50	2-3/4	71 (21.7)	135.7	3760
	10% LWA-30% Slag-C	8.75	3	60 (15.6)	135.0	3770
	10% LWA-30% Slag-3% SF-C	7.25	1-1/2	60 (15.6)	138.0	4270

Notes: — = not measured. 1 in. = 25.4 mm; 1 lb/ft³ = 16.02 kg/m³; 1 psi = 6.90 kPa.

Table 4—Net shrinkage versus drying time, με*

		Drying period, days				
	Mixture	0	30	90	180	365
Series A	Control-A	–33	397	530	550	567
	8% LWA-A	–33	347	443	463	480
	10% LWA-A	–33	327	440	463	503
	10% LWA-30% Slag-A	–70	230	360	435	470
	10% LWA-30% Slag-3% SF-A	–77	180	300	370	417
	10% LWA-30% Slag-6% SF-A	–50	200	307	367	400
Series B	Control-B	–73	390	537	583	613
	10% LWA-B	–60	340	470	523	566
	10% LWA-30% Slag-3% SF-B	–53	263	377	437	493
	10% LWA-30% Slag-6% SF-B	–63	227	350	393	446
Series C	10% LWA-C†	25	400	515	545	570
	10% LWA-30% Slag-C	–50	297	420	467	480
	10% LWA-30% Slag-3% SF-C‡	–53	217	365	395	400

*Average of three specimens unless otherwise noted. Negative values indicate swelling during wet-curing period.
†Average of two specimens.
‡After 84 days of drying = average of two specimens.

(less than 26%) in mitigating bridge deck cracking, irrespective of other factors, has been observed in multiple field evaluations of concrete bridge decks in Kansas and Virginia (Polley et al. 2015; Darwin et. al 2016).

Length change measurements

Unrestrained length changes of specimens were measured in accordance with ASTM C157. Three test specimens with dimensions of 3 x 3 x 11-1/4 in. (76 x 76 x 286 mm) were cast for each mixture. The mixtures are compared based on the average results for the three specimens. The specimens were dried at 73° ± 3°F (23° ± 2°C) and 50 ± 4% relative humidity. Length change measurements were taken using a mechanical dial gauge length comparator. Initial readings were taken when the specimens were demolded 24 ± 1 hour after casting and when the specimens were first subjected to drying at 14 days. Subsequent length measurements were taken every day for the first 30 days, every other day between 30 and 90 days, once a week between 90 and 180 days, and once a month between 180 and 365 days.

EXPERIMENTAL RESULTS AND DISCUSSION

The test results are described in two ways, in terms of drying shrinkage and in terms of net shrinkage. Drying shrinkage is the length change caused by the loss of moisture, while net shrinkage represents the length change due to the combination of drying shrinkage and any swelling that takes place during the curing period. Net shrinkage is discussed first.

The average net shrinkage strains for the mixtures after 0, 30, 90, 180, and 365 days of drying are summarized in Table 4. The values for the individual specimens are presented in Appendix B.

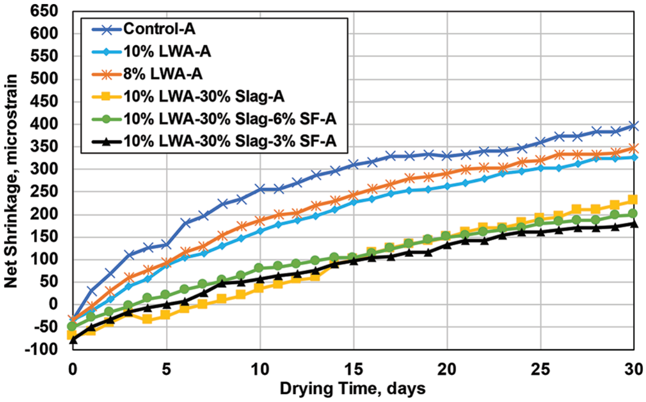

Fig. 1—Net shrinkage versus drying time through 30 days for mixtures in Series A.

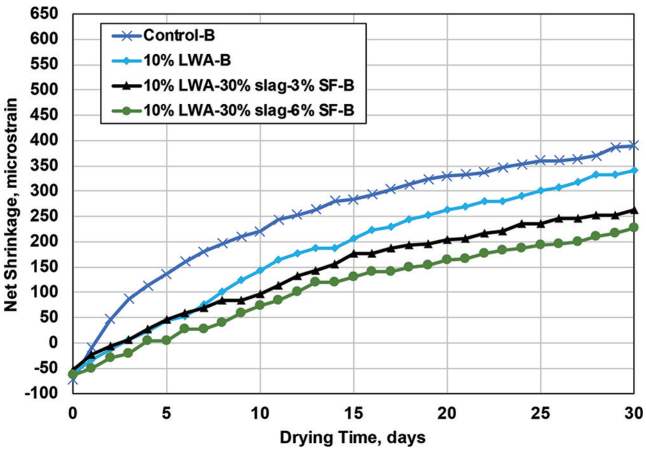

Fig. 2—Net shrinkage versus drying time through 30 days for mixtures in Series B.

Student's t-test is used to determine the statistical significance of differences in the performance of individual mixtures. The t-test is a parametric analysis used when sample sizes are small to verify whether the difference in the means of two samples, X_1 and X_2, represents a difference in the population means, μ_1 and μ_2. There are several ways to describe the outcome of a t-test. In this paper, the results are described based on the probability p that the difference between two means could have arisen by chance. Traditionally, values of p less than 0.02 or 0.05 and sometimes 0.10 are treated as indicative that the difference between two means is statistically significant (that is, unlikely to have arisen by chance). Values above 0.20 are universally accepted, as indicating that the difference between means is not statistically significant (that is, likely to have arisen by chance). The values of p for individual comparisons are shown in Appendix A. In the comparisons that follow, the differences are statistically significant unless otherwise noted.

Net shrinkage through 30 days

Figures 1, 2, and 3 show the average net shrinkage during the first 30 days of drying for the mixtures in Series A, B, and C, respectively. The figures illustrate a general trend—that is, the use of prewetted LWA as a partial replacement of normalweight aggregate reduces the tendency of the mixtures to develop shrinkage strain; additional reduction occurs when slag cement is used as a partial replacement for cement in conjunction with prewetted LWA; and shrinkage is further reduced when silica fume is used as a partial replacement for cement in conjunction with slag and LWA.

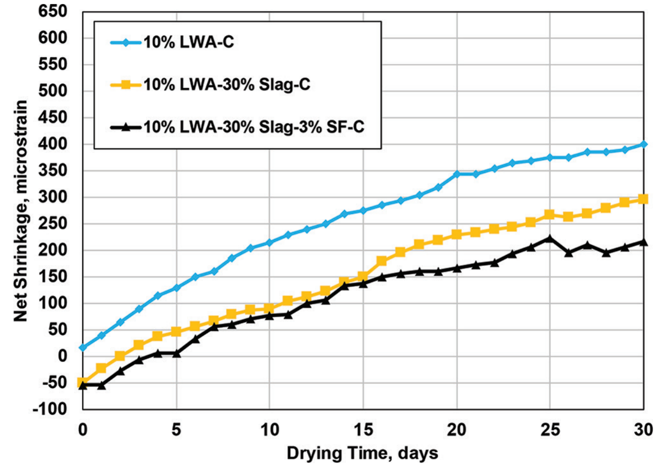

Fig. 3—Net shrinkage versus drying time through 30 days for mixtures in Series C.

In Series A (Fig. 1) after 14 days of wet curing and 30 days of drying, the mixtures containing prewetted LWA (referred to hereafter as LWA) exhibited less net shrinkage than the control mixture. The mixtures containing 8 and 10% LWA (8% LWA-A and 10% LWA-A), respectively, had 50 and 70 microstrain less net shrinkage than the control mixture (Control-A). The difference of 20 microstrain in net shrinkage between 8% LWA-A and 10% LWA-A, is not statistically significant. The mixture containing 10% LWA and 30% Slag (10% LWA-30% Slag-A) had 166 microstrain less net shrinkage than Control-A and 96 microstrain less net shrinkage than 10% LWA-A. The incorporation of silica fume in conjunction with slag and LWA resulted in further reductions in net shrinkage. The mixture containing 3% silica fume (10% LWA-30% Slag-3% SF-A) exhibited 50 microstrain less net shrinkage than the 10% LWA-30% Slag-A mixture, and 216 microstrain less net shrinkage than the Control-A mixture. The mixture containing 6% silica fume (10% LWA-30% Slag-6% SF-A) had 30 microstrain less net shrinkage than the 10% LWA-30% slag-A mixture, and 196 microstrain less net shrinkage than the Control-A mixture. The net shrinkage of the two mixtures containing silica fume differed by 20 microstrain, a difference that is not statistically significant.

In Series B (Fig. 2) after 30 days of drying, the addition of 10% LWA helped reduce net shrinkage by 50 microstrain when compared to the control mixture. Cement replacements with slag and silica fume reduced net shrinkage in this series as well. The mixture containing 3% silica fume (10% LWA-30% Slag-3% SF-B) had 77 microstrain less net shrinkage than 10% LWA-B, and 127 microstrain less net shrinkage than Control-B. The mixture containing 6% silica fume (10% LWA-30% Slag-6% SF-B) had 114 microstrain less net shrinkage than 10% LWA-B, and 164 microstrain less net shrinkage than Control-B. Increasing silica fume content from 3% to 6% resulted in 37 microstrain less net shrinkage, a difference that is not statically significant.

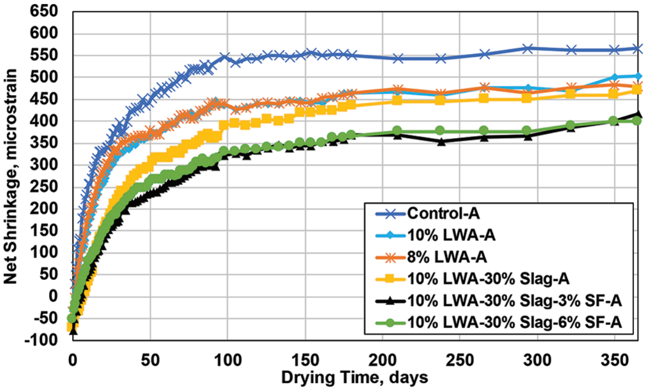

Fig. 4—Net shrinkage versus drying time through 365 days for mixtures in Series A.

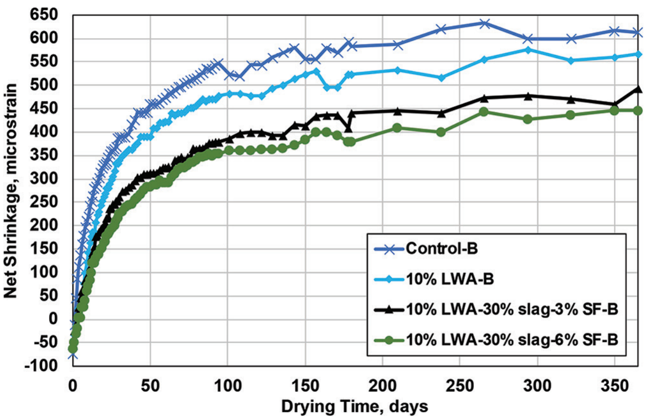

Fig. 5—Net shrinkage versus drying time through 365 days for mixtures in Series B.

A similar trend to that seen in Series A and B was observed for the three mixtures in Series C. As shown in Fig. 3, at 30 days, the mixture containing LWA and slag (10% LWA-30% Slag-C) had 104 microstrain less net shrinkage than the mixture containing only LWA (10% LWA-C). Also, the mixture containing LWA, slag, and silica fume (10% LWA-30% Slag-3% SF-C) had 80 microstrain less net shrinkage than the 10% LWA-30% Slag-C mixture and 184 microstrain less net shrinkage than the 10% LWA-C mixture.

After 30 days of drying, the net shrinkage values for the mixtures ranged from 180 to 400 microstrain, as shown in Table 4. The results indicate that: 1) internal curing using prewetted lightweight aggregate reduces the tendency of the mixtures to develop shrinkage strains at early ages; and 2) the reduction is significantly enhanced when internal curing is combined with slag cement or slag cement and silica fume. As observed by Darwin et al. (2007), Lindquist et al. (2008), and Yuan et al. (2015), when a partial replacement of cement with slag cement is combined with internal curing provided by porous limestone coarse aggregate, there appears to be a synergistic effect when combining slag and silica fume with internal curing.

Net shrinkage through 365 days

As shown in Fig. 4 through 6 and Table 4, a trend similar to that observed at earlier drying times (through 30 days) is seen after 365 days of drying. In all three series, the tendency

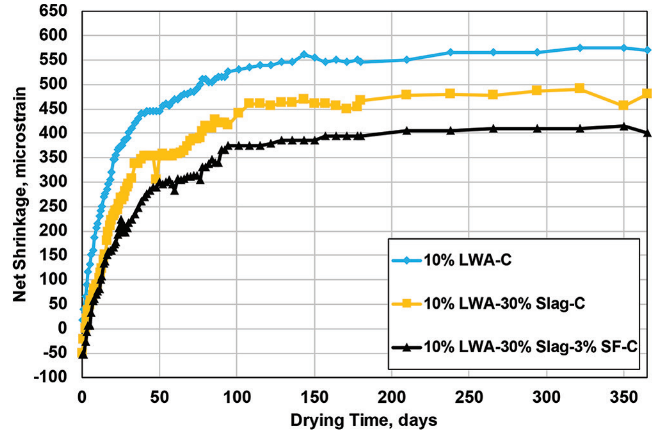

Fig. 6—Net shrinkage versus drying time through 365 days for mixtures in Series C.

to develop shrinkage strain was progressively reduced with additions of prewetted LWA, slag, and silica fume.

In Series A (Fig. 4 and Table 4) after 365 days of drying, the use of prewetted LWA continued to reduce the net shrinkage when compared to the control mixture. The 8% LWA-A and 10% LWA-A mixtures had 87 and 64 microstrain less net shrinkage than Control-A. The 10% LWA-A mixture had 23 microstrain more net shrinkage than 8% LWA-A, but the difference is not statistically significant. The 10% LWA-30% Slag-A mixture had 97 microstrain less net shrinkage than the Control-A mixture and 33 microstrain less net shrinkage than the 10% LWA-A mixture; the latter difference is not statistically significant. As at earlier ages, when silica fume was added in conjunction with slag and LWA, a further reduction in net shrinkage was observed. The 10% LWA-30% Slag-3% SF-A mixture had 53 microstrain less net shrinkage than the 10% LWA-30% slag-A mixture and 150 microstrain less net shrinkage than the Control-A mixture. The 10% LWA-30% Slag-6% SF-A mixture had 70 microstrain less net shrinkage than the 10% LWA-30% Slag-A mixture, and 167 microstrain less net shrinkage than the Control-A mixture. The 10% LWA-30% Slag-6% SF-A mixture had 17 microstrain less net shrinkage than the 10% LWA-30% Slag-3% SF-A mixture, but the difference is not statistically significant.

In Series B (Fig. 5 and Table 4) after 365 days of drying, the addition of 10% LWA resulted in a reduction in net shrinkage by 47 microstrain compared to the control mixture, but the difference barely meets the threshold of statistical significance. As observed at 30 days, cement replacements with slag and silica fume reduced net shrinkage in this series. The 10% LWA-30% Slag-3% SF-B mixture had 73 microstrain less net shrinkage than the 10% LWA-B mixture and 120 microstrain less net shrinkage than the Control-B mixture. The 10% LWA-30% Slag-6% SF-B mixture had 120 microstrain less net shrinkage than the 10% LWA-B mixture, and 167 microstrain less net shrinkage than the Control-B mixture. Increasing the silica fume content from 3% to 6% resulted in 47 microstrain less net shrinkage, but, as at 30 days, this difference is not statistically significant.

A similar trend to those for the mixtures in Series A and B is observed for the mixtures in Series C. As shown in Fig. 6,

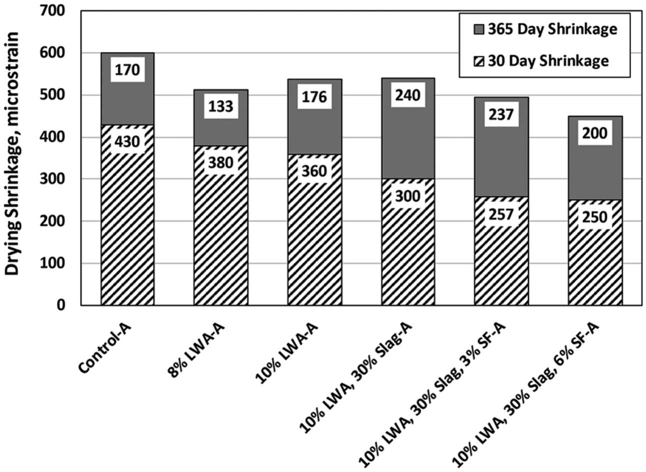

Fig. 7—Drying shrinkage for mixtures in Series A.

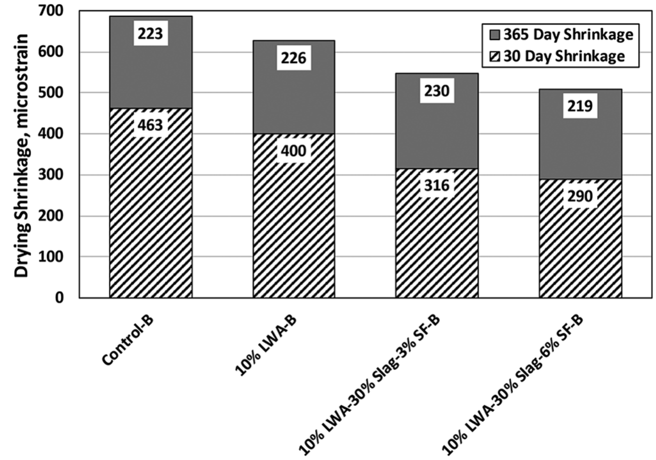

Fig. 8—Drying shrinkage for mixtures in Series B.

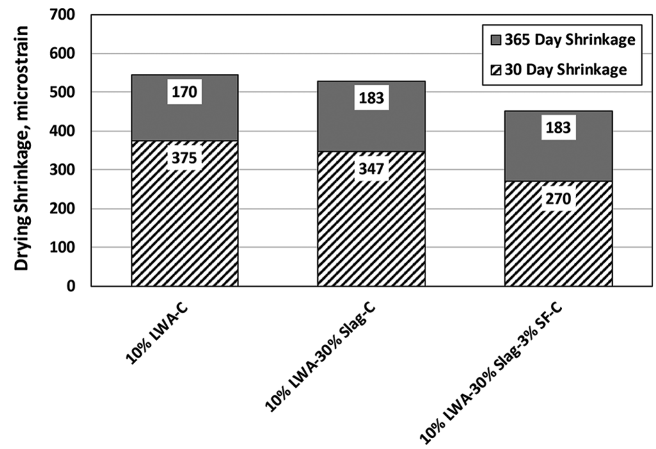

Fig. 9—Drying shrinkage for mixtures in Series C.

the use of LWA and slag (10% LWA-30% Slag-C) resulted in a reduction in net shrinkage of 90 microstrain compared to the mixture containing only the LWA replacement LWA (10% LWA-C). The use of a silica fume replacement for cement in conjunction with LWA and slag resulted in the lowest net shrinkage within this series; the 10% LWA-30% Slag-3% SF-C mixture had 80 microstrain less net shrinkage than the 10% LWA-30% Slag-C mixture and 170 microstrain less net shrinkage than the 10% LWA-C mixture.

Early-age versus later-age drying shrinkage

Figures 7, 8, and 9 show drying shrinkage during two time periods, termed early-age (0 to 30 days) and later-age (30 to 365 days), for mixtures in Series A, B, and C, respectively. The values in these figures *do not include the effect of swelling*. Thus, the comparisons are made only on the basis of drying shrinkage, which occurs beginning with exposure of the specimens to drying conditions. As shown in the figures, in each series of mixtures, the internally cured mixtures (8% LWA-A, 10% LWA-A, and 10% LWA-B) had lower early-age drying shrinkage than the comparable mixtures without internal curing (Control-A and Control-B) in that series. The reduction of drying shrinkage observed in mixtures containing prewetted LWA results from the release of water from prewetted LWA to the surrounding paste, which limits the decrease in internal relative humidity. The mixtures containing slag or slag and silica fume had lower 30-day drying shrinkage than the mixtures without these SCMs. The amount of drying shrinkage during the 30-to-365-day drying period, however, did not follow this trend. In fact, in numerous cases, the mixtures containing slag and silica fume exhibited *greater shrinkage* during the 30-to-365-day drying period than the mixtures without slag and silica fume. This point is demonstrated by the mixtures in Series A (Fig. 7). The three mixtures containing slag and silica fume—10% LWA-30% Slag-A, 10% LWA-30% Slag-3% SF-A, and 10% LWA-30% Slag-6% SF-A—had, respectively, 240, 237, 200 microstrain drying shrinkage during the 30-to-365-day drying period, while the mixtures with no slag and silica fume, 8% LWA-A, 10% LWA-A, and Control-A, had, respectively, 133, 176, and 170 microstrain drying shrinkage, demonstrating that slag and silica fume provide greatest advantage early during drying. This observation also holds true for Series B and C, as shown in Fig. 8 and 9; in these cases, drying shrinkage was similar for the mixtures within each series during the 30-to-365-day drying period, with the major advantage of replacing cement with slag and silica fume apparent during the first 30 days. Among the mixtures containing slag or slag and silica fume, a greater amount of silica fume (6% versus 3% and 0%) always resulted in both lower early-age (0 to 30 days) and lower later-age (30 to 365 days) drying shrinkage. Overall, using slag or slag and silica fume with IC substantially reduced early-age drying shrinkage.

The reduction in drying shrinkage at early ages and the similarity and, in some cases, increase in drying shrinkage at later-ages observed when slag was used as a partial replacement for cement, may be due to a slower rate of hydration at early ages and a greater rate of hydration at later ages (that can be directly tied to internal water demand) experienced by these mixtures compared to the mixtures with 100% portland cement (De la Varga et al. 2012). The further reduction in drying shrinkage that was observed when small amounts of silica fume were used may be due to the reduced permeability attained by adding silica fume, which slows the movement of internal water to the surface of concrete, preventing it from contributing to shrinkage through evaporation (Bentur et al. 1988). This reduction has the potential to improve the cracking performance of concrete bridge decks, where the early-age cracking is a controlling factor.

SUMMARY AND CONCLUSIONS

This study evaluated both the drying shrinkage (length change due to the loss of moisture) and the net shrinkage (length change due to the combination of drying shrinkage and any swelling that takes place during curing) of 13 concrete mixtures containing different quantities of total aggregate with prewetted lightweight aggregate (0, 8, and 10% by volume), replacements of cement with Grade 100 slag cement (0 and 30% by volume), and replacements of cement with silica fume (0, 3, and 6% by volume). The internal curing water provided by prewetted LWA ranged from 5.7 to 7.5% by weight (mass) of cementitious material. The mixtures had a *w/cm* of 0.44 or 0.45 and paste contents between 23.36 and 24.06% by volume.

The following conclusions are made based on the results and analysis presented in this paper:

1. Replacement of a portion of total aggregate with prewetted lightweight aggregate, providing a source of internal curing water, reduces net shrinkage at both early (to 30 days) and later (to 365 days) ages.
2. The partial replacement of portland cement with slag cement in conjunction with prewetted lightweight aggregate further reduces net shrinkage.
3. An additional reduction in net shrinkage is obtained as silica fume is used as a partial replacement of cement in conjunction with prewetted lightweight aggregate and slag cement.
4. The use of the slag and silica fume in conjunction with internal curing contributes to a reduction in drying shrinkage only at early ages, although this reduction continues to result in lower net shrinkage, at least out to 365 days.
5. Among the mixtures containing slag or slag and silica fume, an increase in the amount of silica fume (6% versus 3% and 0%) results in both lower early-age (0 to 30 days) and lower later-age (30 to 365 days) drying shrinkage.

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NOTES:

Appendix A

Table A1– Gradations of LWA used in this study

Sieve Number	Percent of Weight Retained on Sieve	
	LWA-1*	LWA-2**
No. 4	22.04%	4.49%
No. 8	75.92%	25.70%
No. 16	1.47%	36.51%
No. 30	0.08%	17.15%
No. 50	0.02%	9.10%
No. 100	0.02%	3.68%
No. 200	0.04%	1.52%
Pan	0.41%	1.84%

*: LWA-1 was used in Series A and Series B. The fineness modulus of LWA-1 is 5.18.
**: LWA-2 was used in Series C. The fineness modulus of LWA-2 is 3.75.

Table A2–*p*-values based on a two-tailed test used to establish statistical significance of differences in 30-day and 365-day free shrinkage between mixtures in Series A

Series A		*p*	
		30-Day	**365-Day**
Control	8% LWA	0.116	0.090
	10% LWA	0.045	0.191
	10% LWA-30% Slag	0.000	0.001
	10% LWA-30% Slag-3% SF	0.000	0.001
	10% LWA-30% Slag-6% SF	0.000	0.005
8% LWA	10% LWA	0.583	0.691
	10% LWA-30% Slag	0.012	0.807
	10% LWA-30% Slag-3% SF	0.003	0.186
	10% LWA-30% Slag- 6% SF	0.007	0.168
10% LWA	10% LWA-30% Slag	0.021	0.449
	10% LWA-30% Slag-3% SF	0.005	0.103
	10% LWA-30% Slag-6% SF	0.010	0.101
10% LWA, 30% Slag	10% LWA-30% Slag-3% SF	0.038	0.016
	10% LWA-30% Slag-6% SF	0.192	0.076
10% LWA, 30% Slag, 3% SF	10% LWA-30% Slag-6% SF	0.355	0.622

Table A3– *p*-values based on a two-tailed test used to establish statistical significance of differences in 30-day and 365-day free shrinkage between mixtures in Series B

Series B		***p***	
		30-Day	**365-Day**
Control	10% LWA	0.089	0.199
	10% LWA-30% Slag-3% SF	0.003	0.004
	10% LWA-30% Slag-6% SF	0.001	0.001
10% LWA	10% LWA-30% Slag-3% SF	0.045	0.129
	10% LWA-30% Slag-6% SF	0.010	0.045
10% LWA, 30% Slag, 3% SF	10% LWA-30% Slag-6% SF	0.184	0.265

Table A4– *p*-values based on a two-tailed test used to establish statistical significance of differences in 30-day and 365-day free shrinkage between mixtures in Series C

Series C		***p***	
		30-Day	**365-Day**
10% LWA	10% LWA-30% Slag	0.120	0.057
	10% LWA-30% Slag-3% SF	0.029	0.057
10% LWA, 30% Slag	10% LWA-30% Slag-3% SF	0.067	0.075

Appendix B

The following tables show the shrinkage measurements for each specimen.

Table B.1 – Shrinkage measurements of Control-A, 8% LWA-A, and 10% LWA-A

Days After Cast	Days of Drying	Shrinkage (microstrain)											
		Control-A				8% LWA-A				10% LWA-A			
		A	B	C	Average	A	B	C	Average	A	B	C	Average
1		0	0	0	0	0	0	0	0	0	0	0	0
14	0	-30	-70	0	-33	-60	-20	-20	-33	0	-50	-50	-33
15	1	40	-10	60	30	-30	10	10	-3	-20	-20	0	-13
16	2	80	30	100	70	0	50	40	30	10	10	20	13
17	3	120	70	140	110	30	80	70	60	30	40	50	40
18	4	120	70	190	127	50	80	100	77	60	60	50	57
19	5	130	80	190	133	70	110	100	93	80	90	90	87
20	6	180	150	210	180	80	130	140	117	90	110	110	103
21	7	200	160	230	197	100	130	160	130	100	120	120	113
22	8	230	190	250	223	120	150	190	153	130	140	120	130
23	9	240	200	260	233	140	170	210	173	140	160	140	147
24	10	260	220	290	257	150	190	220	187	160	180	150	163
25	11	260	230	280	257	160	210	230	200	170	200	160	177
26	12	280	230	300	270	180	190	240	203	180	210	170	187
27	13	290	260	310	287	180	230	250	220	190	220	180	197
28	14	290	280	320	297	200	230	260	230	200	230	200	210
29	15	300	300	330	310	210	250	270	243	210	250	220	227
30	16	300	310	340	317	220	270	280	257	230	250	220	233
31	17	310	320	360	330	230	280	290	267	240	270	230	247
32	18	310	320	360	330	240	300	300	280	250	280	230	253
33	19	310	330	360	333	240	300	310	283	250	290	230	257
34	20	320	310	360	330	250	310	310	290	260	300	230	263
35	21	330	310	360	333	260	320	320	300	270	300	240	270
36	22	340	320	360	340	260	330	320	303	270	310	260	280
37	23	340	320	360	340	260	330	320	303	280	320	270	290
38	24	350	330	360	347	280	340	330	317	290	330	270	297
39	25	360	350	370	360	280	350	330	320	300	340	270	303
40	26	380	360	380	373	290	360	350	333	300	340	270	303
41	27	370	370	380	373	290	360	350	333	310	350	280	313
42	28	380	380	390	383	290	360	350	333	320	360	290	323
43	29	380	380	390	383	290	370	350	337	320	360	290	323
44	30	390	390	410	397	300	380	360	347	320	370	290	327

Table B.1 (continued) – Shrinkage measurements of Control-A, 8% LWA-A, and 10% LWA-A

Days After Cast	Days of Drying	Shrinkage (microstrain)											
		Control-A				8% LWA-A				10% LWA-A			
		A	B	C	Average	A	B	C	Average	A	B	C	Average
45	31	360	400	350	370	310	380	370	353	330	370	290	330
46	32	350	400	380	377	310	380	370	353	330	380	300	337
47	33	360	390	380	377	320	380	370	357	330	380	300	337
49	35	370	410	420	400	320	390	380	363	340	390	310	347
51	37	380	450	440	423	320	390	380	363	340	390	310	347
53	39	390	440	440	423	320	400	380	367	350	400	320	357
55	41	390	450	450	430	320	400	380	367	350	410	320	360
57	43	390	450	450	430	320	400	380	367	350	410	320	360
59	45	400	470	480	450	320	400	380	367	350	420	320	363
61	47	390	460	460	437	330	420	390	380	360	420	320	367
63	49	390	470	470	443	330	400	380	370	370	420	330	373
65	51	420	470	470	453	340	400	380	373	370	420	330	373
67	53	430	480	480	463	330	400	380	370	370	420	340	377
69	55	430	480	490	467	340	430	400	390	380	430	340	383
71	57	430	500	500	477	340	430	400	390	380	430	340	383
73	59	420	490	490	467	340	430	400	390	390	440	350	393
75	61	440	490	500	477	350	440	400	397	390	440	350	393
77	63	440	500	500	480	350	440	400	397	390	450	350	397
79	65	460	500	500	487	360	450	410	407	400	460	360	407
81	67	470	500	500	490	360	460	420	413	400	460	370	410
83	69	480	520	510	503	360	460	420	413	410	460	370	413
85	71	480	520	510	503	370	460	420	417	410	460	370	413
87	73	470	510	510	497	360	450	410	407	410	470	380	420
89	75	490	530	530	517	360	450	410	407	400	460	370	410
91	77	500	530	530	520	360	460	420	413	400	460	370	410
93	79	500	530	530	520	370	470	430	423	410	470	380	420
95	81	500	530	530	520	370	470	430	423	410	480	380	423
97	83	500	530	530	520	380	470	430	427	410	480	390	427
99	85	500	550	540	530	390	480	440	437	420	480	390	430
101	87	490	530	530	517	390	490	450	443	430	490	400	440
102	88	490	540	530	520	390	480	440	437	430	500	410	447
104	90	510	550	530	530	390	490	440	440	430	490	390	437
112	98	530	560	550	547	390	490	440	440	430	490	390	437
119	105	510	550	540	533	380	470	430	427	410	480	390	427
126	112	520	560	550	543	380	480	430	430	420	490	390	433

Table B.1 (continued) – Shrinkage measurements of Control-A, 8% LWA-A, and 10% LWA-A

Days After Cast	Days of Drying	Shrinkage (microstrain)											
		Control-A				8% LWA-A				10% LWA-A			
		A	B	C	Average	A	B	C	Average	A	B	C	Average
133	119	520	560	550	543	390	490	440	440	430	500	390	440
140	126	540	560	550	550	390	500	440	443	430	500	390	440
147	133	540	560	550	550	390	490	440	440	430	500	390	440
154	140	530	560	550	547	400	500	440	447	430	510	400	447
161	147	540	560	550	550	400	490	440	443	430	510	400	447
168	154	550	560	560	557	400	490	440	443	430	510	390	443
175	161	530	560	560	550	400	510	450	453	430	510	390	443
182	168	540	560	560	553	400	520	450	457	440	520	400	453
189	175	530	560	570	553	410	520	450	460	450	530	410	463
194	180	530	560	560	550	410	520	460	463	450	530	410	463
224	210	510	560	560	543	420	530	470	473	450	540	410	467
252	238	510	560	560	543	410	520	460	463	450	520	410	460
280	266	520	570	570	553	430	530	470	477	460	540	430	477
308	294	540	580	580	567	410	520	460	463	460	540	430	477
336	322	540	580	570	563	420	540	470	477	440	540	430	470
364	350	540	580	570	563	420	550	480	483	480	570	450	500
379	365	550	580	570	567	420	550	470	480	480	580	450	503

Table B.2 – Shrinkage measurements of 10%-LWA-30%-Slag-10%-LWA-A, 30%-Slag-3%-SF-A, and 10%-LWA-30% Slag-6% SF-A

Days After Cast	Days of Drying	Shrinkage (microstrain)											
		10%-LWA-30%-Slag-A				10%-LWA-30%-Slag-3%-SF-A				10%-LWA-30%-Slag-6% SF-A			
		A	B	C	Average	A	B	C	Average	A	B	C	Average
1		0	0	0	0	0	0	0	0	0	0	0	0
14	0	-100	-20	-40	-70	-110	-80	-40	-77	-60	-50	-40	-50
15	1	-90	0	-30	-60	-70	-50	-30	-50	-40	-30	-20	-30
16	2	-70	20	-10	-40	-60	-30	-10	-33	-30	-20	0	-17
17	3	-40	60	0	-20	-40	-20	10	-17	-20	-10	20	-3
18	4	-40	70	-30	-35	-30	-10	20	-7	0	10	30	13
19	5	-30	80	-20	-25	-20	-10	30	0	0	20	40	20
20	6	-10	100	-10	-10	-20	0	40	7	10	30	60	33
21	7	0	120	0	0	10	20	50	27	20	40	70	43
22	8	10	130	10	10	30	40	70	47	30	50	80	53
23	9	20	140	20	20	40	50	60	50	40	60	90	63
24	10	30	150	40	35	40	60	70	57	60	80	100	80
25	11	40	150	50	45	50	60	80	63	60	80	110	83
26	12	50	170	60	55	50	70	90	70	70	80	120	90
27	13	50	170	70	60	60	70	100	77	80	90	120	97
28	14	90	190	90	90	80	80	110	90	80	100	130	103
29	15	100	190	100	100	80	100	110	97	80	100	130	103
30	16	110	220	120	115	80	110	120	103	90	110	140	113
31	17	110	220	140	125	90	110	120	107	100	120	150	123
32	18	120	230	150	135	100	120	130	117	110	130	160	133
33	19	120	230	160	140	100	120	130	117	120	140	170	143
34	20	130	240	170	150	120	130	150	133	130	140	180	150
35	21	140	250	180	160	140	130	160	143	130	150	180	153
36	22	150	260	190	170	140	130	160	143	140	150	190	160
37	23	150	260	190	170	140	150	170	153	150	160	190	167
38	24	160	270	200	180	150	150	180	160	140	170	200	170
39	25	170	280	210	190	150	150	180	160	160	170	210	180
40	26	170	280	220	195	160	150	190	167	170	170	210	183
41	27	190	290	230	210	160	160	190	170	170	170	220	187
42	28	190	300	230	210	160	160	190	170	170	170	220	187
43	29	200	300	240	220	160	170	190	173	180	180	230	197
44	30	210	310	250	230	160	180	200	180	180	190	230	200
45	31	220	330	260	240	160	190	260	203	180	200	240	207
46	32	220	330	260	240	170	200	220	197	190	210	250	217
47	33	230	330	270	250	200	210	230	213	200	220	260	227

Table B.2 (Continued) – Shrinkage measurements of 10%-LWA-30%-Slag-10%-LWA-A, 30%-Slag-3%-SF-A, and 10%-LWA-30% Slag-6% SF-A

Days After Cast	Days of Drying	Shrinkage (microstrain)											
		10%-LWA-30%-Slag-A				10%-LWA-30%-Slag-3% SF-A				10%-LWA-30%-Slag-6% SF-A			
		A	B	C	Average	A	B	C	Average	A	B	C	Average
49	35	250	350	280	265	200	210	230	213	200	220	270	230
51	37	260	360	290	275	200	210	240	217	210	230	280	240
53	39	270	360	290	280	200	220	240	220	220	240	280	247
55	41	280	380	300	290	210	220	240	223	220	240	280	247
57	43	280	380	300	290	210	220	250	227	220	240	280	247
59	45	280	380	310	295	210	230	260	233	220	240	290	250
61	47	280	380	310	295	210	230	270	237	230	250	300	260
63	49	300	390	320	310	220	230	270	240	240	260	300	267
65	51	300	390	330	315	220	230	270	240	240	260	300	267
67	53	300	400	330	315	220	250	270	247	240	260	300	267
69	55	300	410	330	315	230	250	270	250	240	260	300	267
71	57	300	410	330	315	230	250	280	253	250	270	310	277
73	59	300	410	330	315	240	250	290	260	250	270	310	277
75	61	310	420	340	325	250	250	280	260	250	270	310	277
77	63	320	420	340	330	250	250	290	263	250	270	300	273
79	65	320	420	340	330	240	260	300	267	250	270	310	277
81	67	310	420	340	325	250	260	300	270	260	280	320	287
83	69	320	430	350	335	260	260	310	277	260	280	320	287
85	71	340	440	350	345	260	270	310	280	260	280	320	287
87	73	340	440	350	345	260	280	320	287	260	280	330	290
89	75	340	440	350	345	260	290	320	290	270	280	340	297
91	77	340	440	360	350	260	290	320	290	280	300	340	307
93	79	340	450	370	355	260	300	330	297	280	300	340	307
95	81	350	460	380	365	280	290	320	297	280	310	350	313
97	83	350	460	380	365	280	290	330	300	270	300	340	303
99	85	360	460	380	370	280	290	330	300	270	300	350	307
101	87	350	450	370	360	280	290	330	300	270	300	350	307
102	88	350	460	370	360	260	290	340	297	280	300	360	313
104	90	350	460	380	365	290	320	360	323	280	310	360	317
112	98	370	490	410	390	290	320	360	323	300	320	370	330
119	105	380	490	410	395	300	320	360	327	300	320	370	330
126	112	380	490	400	390	300	310	360	323	300	330	380	337
133	119	380	490	410	395	310	320	370	333	300	330	380	337
140	126	390	500	420	405	320	330	370	340	300	340	380	340
147	133	390	500	410	400	330	340	370	347	300	340	380	340

Table B.2 (Continued) – Shrinkage measurements of 10%-LWA-30%-Slag-10%-LWA-A, 30%-Slag-3%-SF-A, and 10%-LWA-30% Slag-6% SF-A

Days After Cast	Days of Drying	Shrinkage (microstrain)											
		10%-LWA-30%-Slag-A				10%-LWA-30%-Slag-3%-SF-A				10%-LWA-30%-Slag-6% SF-A			
		A	B	C	Average	A	B	C	Average	A	B	C	Average
154	140	390	500	420	405	320	330	370	340	300	340	390	343
161	147	410	510	430	420	320	330	380	343	310	350	390	350
168	154	410	510	430	420	320	330	380	343	310	350	390	350
175	161	420	520	430	425	330	340	390	353	310	350	390	350
182	168	420	520	430	425	330	340	390	353	320	360	410	363
189	175	420	520	440	430	340	350	390	360	320	360	410	363
194	180	430	530	440	435	350	360	400	370	330	360	410	367
224	210	440	530	450	445	350	360	400	370	330	370	430	377
252	238	440	530	450	445	320	350	390	353	330	370	430	377
280	266	440	540	460	450	330	360	400	363	330	370	430	377
308	294	440	530	460	450	350	360	390	367	330	370	430	377
336	322	450	540	470	460	360	380	420	387	340	390	440	390
364	350	450	550	470	460	370	390	440	400	350	400	450	400
379	365	460	560	480	470	400	410	440	417	350	400	450	400

Table B.3– Shrinkage measurements of Control-B, 10% LWA-B, and 10% LWA-30% Slag-3% SF-B

Days After Cast	Days of Drying	Shrinkage (microstrain)											
		Control-B				10% LWA-B				10% LWA-30% Slag-3% SF-B			
		A	B	C	Average	A	B	C	Average	A	B	C	Average
1		0	0	0	0	0	0	0	0	0	0	0	0
14	0	-60	-70	-90	-73	-80	-50	-50	-60	-60	-50	-50	-53
15	1	-10	-30	10	-10	-50	-20	-30	-33	-30	-20	-20	-23
16	2	40	30	70	47	-30	0	-10	-13	-20	0	0	-7
17	3	80	70	110	87	-10	20	10	7	0	10	10	7
18	4	100	100	140	113	10	40	20	23	20	30	30	27
19	5	120	130	160	137	30	60	40	43	40	50	50	47
20	6	140	160	180	160	30	80	50	53	50	60	70	60
21	7	160	190	190	180	70	100	60	77	60	70	80	70
22	8	180	200	210	197	90	130	80	100	80	80	90	83
23	9	190	220	220	210	110	150	110	123	70	90	90	83
24	10	200	230	230	220	130	170	130	143	90	100	100	97
25	11	230	250	250	243	150	190	150	163	100	120	120	113
26	12	240	260	260	253	160	210	160	177	120	140	140	133
27	13	250	270	270	263	170	220	170	187	130	150	150	143
28	14	260	290	290	280	170	220	170	187	140	170	160	157
29	15	260	300	290	283	190	240	190	207	160	190	180	177
30	16	270	310	300	293	200	260	210	223	160	190	180	177
31	17	280	320	310	303	210	260	220	230	170	200	190	187
32	18	290	330	320	313	220	280	230	243	170	210	200	193
33	19	300	340	330	323	230	290	240	253	180	210	200	197
34	20	310	350	330	330	240	300	250	263	180	220	210	203
35	21	310	350	340	333	250	310	250	270	190	220	210	207
36	22	320	360	330	337	260	320	260	280	200	230	220	217
37	23	320	370	350	347	260	320	260	280	200	230	230	220
38	24	330	380	350	353	270	330	270	290	210	260	240	237
39	25	340	380	360	360	280	340	280	300	210	260	240	237
40	26	340	380	360	360	280	350	290	307	220	270	250	247
41	27	350	380	360	363	290	360	300	317	220	270	250	247
42	28	350	390	370	370	310	380	310	333	220	280	260	253
43	29	370	400	390	387	310	380	310	333	220	280	260	253
44	30	370	400	400	390	320	380	320	340	230	290	270	263
46	32	370	400	400	390	320	400	330	350	240	300	280	273
48	34	370	400	400	390	330	410	330	357	240	310	280	277

Table B.3 (Continued) – Shrinkage measurements of Control-B, 10% LWA-B, and 10% LWA-30% Slag-3% SF-B

Days After Cast	Days of Drying	Shrinkage (microstrain)											
		Control-B				10% LWA-B				10% LWA-30% Slag-3% SF-B			
		A	B	C	Average	A	B	C	Average	A	B	C	Average
50	36	380	410	400	397	330	420	340	363	250	320	280	283
52	38	400	430	420	417	330	420	340	363	250	320	290	287
54	40	410	440	430	427	340	430	350	373	260	330	300	297
56	42	430	460	440	443	350	430	350	377	260	340	310	303
58	44	420	460	440	440	360	450	360	390	260	340	310	303
60	46	420	460	450	443	360	450	360	390	270	340	320	310
62	48	420	460	450	443	360	450	360	390	270	340	320	310
64	50	440	480	460	460	360	450	360	390	280	340	320	313
66	52	440	480	460	460	380	470	380	410	280	340	320	313
68	54	440	480	460	460	380	470	380	410	280	340	320	313
70	56	440	480	470	463	390	480	390	420	300	340	320	320
72	58	450	490	470	470	390	480	390	420	290	340	340	323
74	60	450	490	480	473	400	480	390	423	290	340	340	323
76	62	460	500	490	483	400	480	390	423	290	350	340	327
78	64	460	500	490	483	410	500	410	440	280	340	330	317
80	66	470	500	500	490	410	500	400	437	300	370	350	340
82	68	480	510	500	497	410	500	410	440	300	370	360	343
84	70	480	510	500	497	410	500	410	440	310	370	360	347
86	72	490	520	500	503	410	510	410	443	300	360	360	340
88	74	490	520	510	507	420	510	420	450	310	370	360	347
90	76	490	530	510	510	420	520	420	453	320	370	360	350
92	78	500	530	510	513	420	520	420	453	330	400	370	367
94	80	510	530	510	517	430	520	420	457	320	400	370	363
96	82	520	530	520	523	430	530	430	463	330	400	370	367
98	84	520	530	530	527	440	540	430	470	330	400	370	367
100	86	530	540	540	537	440	530	430	467	330	400	380	370
102	88	530	530	540	533	440	540	430	470	340	410	380	377
104	90	540	530	540	537	440	540	430	470	340	410	380	377
106	92	550	530	550	543	440	540	430	470	340	410	390	380
108	94	550	540	550	547	440	550	440	477	340	410	390	380
115	101	510	540	520	523	450	550	450	483	340	420	400	387
122	108	510	540	510	520	450	550	450	483	350	420	420	397
129	115	540	540	550	543	440	540	450	477	350	420	430	400
136	122	540	540	550	543	440	540	450	477	350	430	420	400

Table B.3 (Continued) – Shrinkage measurements of Control-B, 10% LWA-B, and 10% LWA-30% Slag-3% SF-B

Days After Cast	Days of Drying	Shrinkage (microstrain)											
		Control-B				10% LWA-B				10% LWA-30% Slag-3% SF-B			
		A	B	C	Average	A	B	C	Average	A	B	C	Average
143	129	550	560	570	560	460	560	460	493	350	410	420	393
157	143	570	580	590	580	480	580	480	513	360	450	440	417
164	150	540	570	560	557	490	590	490	523	370	420	450	413
171	157	530	570	570	557	490	600	500	530	380	460	460	433
178	164	570	580	590	580	460	560	470	497	390	460	460	437
185	171	550	590	570	570	460	560	470	497	390	450	470	437
192	178	590	590	600	593	480	600	490	523	360	430	440	410
194	180	590	590	570	583	480	600	490	523	390	460	470	440
224	210	580	590	590	587	490	610	500	533	390	470	480	447
252	238	610	620	630	620	470	590	490	517	390	460	470	440
280	266	620	640	640	633	510	630	530	557	420	500	500	473
308	294	610	590	600	600	530	650	550	577	430	500	500	477
336	322	610	590	600	600	500	630	530	553	420	490	500	470
364	350	620	600	630	617	510	640	530	560	410	480	490	460
379	365	610	610	620	613	530	640	530	567	420	530	530	493

Table B.4– Shrinkage measurements of 10% LWA-30% Slag-6% SF-B, 10% LWA-C, and 10% LWA-30% Slag-C

Days After Cast	Days of Drying	Shrinkage (microstrain)											
		10% LWA-30% Slag-6% SF-B				10% LWA-C				10% LWA-30% Slag-C			
		A	B	C	Average	A	B	C	Average	A	B	C	Average
1		0	0	0	0	-	0	0	0	0	0	0	0
14	0	-80	-70	-40	-63	-	-10	60	17	-80	-20	-50	-50
15	1	-70	-60	-20	-50	-	10	70	40	-60	10	-20	-23
16	2	-50	-40	0	-30	-	30	100	65	-40	40	0	0
17	3	-30	-30	0	-20	-	50	130	90	-10	50	20	20
18	4	-10	-10	30	3	-	80	150	115	10	70	30	37
19	5	-10	-10	30	3	-	100	160	130	20	80	40	47
20	6	10	20	50	27	-	110	190	150	30	90	50	57
21	7	10	20	50	27	-	130	190	160	40	100	60	67
22	8	20	40	60	40	-	150	220	185	60	110	70	80
23	9	40	60	80	60	-	170	240	205	70	120	70	87
24	10	50	70	100	73	-	180	250	215	70	120	80	90
25	11	60	80	110	83	-	200	260	230	90	130	90	103
26	12	80	100	120	100	-	210	270	240	100	140	100	113
27	13	100	120	140	120	-	210	290	250	110	150	110	123
28	14	100	120	140	120	-	230	310	270	130	160	130	140
29	15	110	130	150	130	-	230	320	275	140	170	140	150
30	16	120	140	160	140	-	240	330	285	150	170	220	180
31	17	120	140	160	140	-	250	340	295	160	190	240	197
32	18	130	150	170	150	-	260	350	305	170	210	250	210
33	19	130	160	170	153	-	280	360	320	180	220	260	220
34	20	140	170	180	163	-	310	380	345	190	230	270	230
35	21	140	170	190	167	-	300	390	345	200	230	270	233
36	22	150	180	200	177	-	310	400	355	210	230	280	240
37	23	150	190	210	183	-	320	410	365	220	220	290	243
38	24	160	190	210	187	-	320	420	370	230	220	310	253
39	25	160	200	220	193	-	330	420	375	250	230	320	267
40	26	170	200	220	197	-	330	420	375	250	220	320	263
41	27	170	200	230	200	-	340	430	385	260	220	330	270
42	28	180	210	240	210	-	340	430	385	270	240	330	280
43	29	190	220	240	217	-	340	440	390	280	250	340	290
44	30	200	230	250	227	-	350	450	400	290	260	340	297
46	32	200	230	260	230	-	360	460	410	300	270	350	307
48	34	210	240	270	240	-	370	470	420	300	360	350	337

Table B.4 (Continued) – Shrinkage measurements of 10% LWA-30% Slag-6% SF-B, 10% LWA-C, and 10% LWA-30% Slag-C

Days After Cast	Days of Drying	Shrinkage (microstrain)											
		10% LWA-30% Slag-6% SF-B				10% LWA-C				10% LWA-30% Slag-C			
		A	B	C	Average	A	B	C	Average	A	B	C	Average
50	36	210	250	270	243	-	380	480	430	310	350	350	337
52	38	210	250	280	247	-	390	490	440	320	360	360	347
54	40	220	260	290	257	-	390	490	440	330	370	360	353
56	42	230	260	290	260	-	390	500	445	330	370	360	353
58	44	230	270	300	267	-	390	500	445	330	370	360	353
60	46	240	280	310	277	-	390	500	445	340	360	360	353
62	48	250	290	310	283	-	380	510	445	300	330	280	303
64	50	250	290	310	283	-	380	510	445	340	370	350	353
66	52	250	290	320	287	-	390	520	455	340	370	360	357
68	54	250	290	320	287	-	390	530	460	340	370	350	353
70	56	260	300	330	297	-	380	530	455	340	370	350	353
72	58	250	300	330	293	-	390	540	465	340	370	350	353
74	60	250	300	330	293	-	400	540	470	340	370	360	357
76	62	250	300	330	293	-	400	540	470	340	370	360	357
78	64	260	310	340	303	-	410	540	475	340	370	370	360
80	66	270	320	340	310	-	420	540	480	350	370	370	363
82	68	290	320	350	320	-	420	540	480	360	380	380	373
84	70	290	330	350	323	-	430	540	485	370	390	390	383
86	72	290	330	350	323	-	430	540	485	380	390	390	387
88	74	300	330	360	330	-	440	540	490	380	390	390	387
90	76	300	340	370	337	-	460	540	500	390	390	390	390
92	78	300	340	370	337	-	470	550	510	390	430	390	403
94	80	300	350	370	340	-	470	550	510	400	440	400	413
96	82	310	350	380	347	-	460	550	505	390	440	400	410
98	84	310	350	380	347	-	460	550	505	390	440	400	410
100	86	310	360	380	350	-	460	560	510	410	450	420	427
102	88	310	360	390	353	-	460	570	515	410	440	410	420
104	90	310	360	380	350	-	460	570	515	410	440	410	420
106	92	310	360	390	353	-	460	570	515	410	440	410	420
108	94	320	360	380	353	-	470	580	525	400	440	410	417
115	101	320	370	390	360	-	480	580	530	420	450	450	440
122	108	320	370	390	360	-	490	580	535	440	470	470	460
129	115	320	370	390	360	-	500	580	540	440	470	470	460

Table B.4 (Continued) – Shrinkage measurements of 10% LWA-30% Slag-6% SF-B, 10% LWA-C, and 10% LWA-30% Slag-C

Days After Cast	Days of Drying	Shrinkage (microstrain)											
		10% LWA-30% Slag-6% SF-B				10% LWA-C				10% LWA-30% Slag-C			
		A	B	C	Average	A	B	C	Average	A	B	C	Average
136	122	330	370	390	363	-	500	580	540	440	460	470	457
143	129	330	370	390	363	-	510	580	545	440	470	480	463
150	136	330	380	390	367	-	510	580	545	440	470	480	463
157	143	340	380	400	373	-	520	600	560	450	480	480	470
164	150	340	400	410	383	-	520	590	555	440	470	470	460
171	157	360	410	430	400	-	510	580	545	440	470	470	460
178	164	360	410	430	400	-	520	580	550	440	470	460	457
185	171	350	400	430	393	-	510	580	545	430	460	460	450
192	178	340	390	410	380	-	520	580	550	440	460	460	453
194	180	340	390	410	380	-	510	580	545	450	470	480	467
224	210	370	420	440	410	-	520	580	550	450	490	490	477
252	238	360	410	430	400	-	530	600	565	460	490	490	480
280	266	400	450	480	443	-	530	600	565	450	490	490	477
308	294	400	430	450	427	-	530	600	565	460	500	500	487
336	322	400	440	470	437	-	540	610	575	470	500	500	490
364	350	410	460	470	447	-	540	610	575	440	470	460	457
379	365	410	460	470	447	-	540	600	570	460	510	470	480

Table B.5– Shrinkage measurements of 10% LWA-30% Slag-3% SF-C

Days After Cast	Days of Drying	Shrinkage (microstrain)			
		10% LWA-30% Slag-3% SF-C			
		A	B	C	Average
1		0	0	0	0
14	0	-50	-60	-50	-53
15	1	-30	-80	-50	-53
16	2	0	-60	-20	-27
17	3	30	-40	-10	-7
18	4	50	-30	0	7
19	5	20	-10	10	7
20	6	60	10	30	33
21	7	90	30	50	57
22	8	100	30	50	60
23	9	110	40	60	70
24	10	120	50	60	77
25	11	110	60	70	80
26	12	130	80	90	100
27	13	130	90	100	107
28	14	170	110	120	133
29	15	170	120	120	137
30	16	190	130	130	150
31	17	200	140	130	157
32	18	200	140	140	160
33	19	200	140	140	160
34	20	210	150	140	167
35	21	210	150	160	173
36	22	210	150	170	177
37	23	230	170	180	193
38	24	240	190	190	207
39	25	260	200	210	223
40	26	210	200	180	197
41	27	250	200	180	210
42	28	230	190	170	197
43	29	250	190	180	207
44	30	260	200	190	217
46	32	260	210	200	223
48	34	270	210	220	233

Table B.5 (Continued) – Shrinkage measurements of 10% LWA-30% Slag-3% SF-C

Days After Cast	Days of Drying	Shrinkage (microstrain)			
		10% LWA-30% Slag-3% SF-C			
		A	B	C	Average
50	36	290	220	230	247
52	38	300	230	250	260
54	40	310	250	250	270
56	42	320	250	260	277
58	44	330	260	260	283
60	46	330	270	270	290
62	48	330	270	270	290
64	50	340	280	280	300
66	52	330	280	280	297
68	54	340	280	280	300
70	56	340	290	280	303
72	58	340	280	270	297
74	60	330	270	250	283
76	62	340	290	290	307
78	64	330	300	280	303
80	66	340	300	280	307
82	68	350	300	280	310
84	70	350	300	280	310
86	72	350	300	290	313
88	74	350	300	290	313
90	76	340	290	280	303
92	78	360	310	320	330
94	80	360	310	320	330
96	82	360	320	330	337
98	84	360	330	-	345
100	86	360	320	-	340
102	88	360	320	-	340
104	90	390	340	-	365
106	92	390	340	-	365
108	94	400	350	-	375
115	101	400	350	-	375
122	108	400	350	-	375
129	115	400	350	-	375

Table B.5 (Continued) – Shrinkage measurements of 10% LWA-30% Slag-3% SF-C

Days After Cast	Days of Drying	Shrinkage (microstrain)			
		10% LWA-30% Slag-3% SF-C			
		A	B	C	Average
136	122	410	350	-	380
143	129	410	360	-	385
150	136	410	360	-	385
157	143	410	360	-	385
164	150	410	360	-	385
171	157	420	370	-	395
178	164	420	370	-	395
185	171	420	370	-	395
192	178	420	370	-	395
194	180	420	370	-	395
224	210	440	370	-	405
252	238	440	370	-	405
280	266	440	380	-	410
308	294	440	380	-	410
336	322	440	380	-	410
364	350	450	380	-	415
379	365	430	370	-	400