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# Lightweight Aggregate as Internal Curing Agent to Limit Concrete Shrinkage

by JoAnn Browning, David Darwin, Diane Reynolds, and Benjamin Pendergrass

*The effectiveness of prewetted, vacuum-saturated (PVS) lightweight aggregate (LWA) as an internal curing agent to reduce concrete shrinkage is evaluated for curing periods of 7 and 14 days. Normalweight aggregate is replaced by LWA at volume replacement levels ranging from 8.9 to 13.8%. Some mixtures contain a partial replacement of portland cement with slag cement while maintaining the paste content at approximately 24.1% of concrete volume. Comparisons are made with mixtures containing low-absorption granite and high-absorption limestone normalweight coarse aggregates. At the replacement levels used in this study, PVS LWA results in a small reduction in concrete density, no appreciable effect on concrete compressive strength, and a substantial decrease in concrete shrinkage for drying periods up to 365 days. Increasing the curing period from 7 to 14 days reduces concrete shrinkage. Thirty and 60% volume replacements of portland cement by slag cement result in reduced shrinkage when used with a porous LWA or normalweight aggregate. After 30 and 365 days of drying, all mixtures with LWA exhibited less shrinkage than the mixtures with either low- or high-absorption normalweight aggregates.*

**Keywords:** bridge decks; cracking; curing; drying shrinkage; lightweight aggregate; slag cement; vacuum saturation.

## INTRODUCTION

Drying shrinkage is a principal cause of cracking in concrete structures. For a wide variety of structures, however, the cracking can be accommodated (such as with joints in slabs-on-ground) or modified (such as through minimum reinforcement in structural slabs) so that the performance of the overall structure is not affected. One significant case where this is not true is bridge decks, where drying shrinkage cracking combines with plastic shrinkage, settlement, and thermal cracking to lower the durability of the decks by allowing water and deicing chemicals to penetrate the concrete and increase the susceptibility of the reinforcing steel to corrosion.<sup>1-3</sup>

A key aspect of work underway at the University of Kansas to minimize cracking in bridge decks is to develop concrete mixtures that will minimize concrete shrinkage. It is well established that the lower restraint provided by lightweight aggregates (LWAs) can lead to increased drying shrinkage compared with mixtures containing normalweight aggregates,<sup>4</sup> and if not adequately prewetted, the unsaturated pores lead to greater water demand during construction and result in inadequate water for hydration. Because of the absorption and desorption properties of the aggregate,<sup>5</sup> however, vacuum-saturated LWAs can readily provide an internal source of water to increase hydration and lessen the drying effects on a concrete mixture. Efforts to reduce autogenous shrinkage in concretes with low water-cementitious material ratios ( $w/cm$ ), first suggested by Philleo,<sup>6</sup> have demonstrated the success of using a partial replacement of normalweight aggregate with prewetted,

vacuum-saturated (PVS) LWA.<sup>7-11</sup> Autogenous shrinkage, however, is not a concern at the  $w/cm$  used in bridge decks, which are typically greater than 0.42.

Research using porous normalweight aggregates in combination with slag cement as a partial replacement for portland cement has demonstrated that the combination can significantly reduce shrinkage compared to concretes containing porous normalweight aggregate without slag or nonporous normalweight aggregate with slag.<sup>12-15</sup>

In this study of concretes with a  $w/cm$  typical of that used in bridge decks and at which autogenous shrinkage should not occur, the use of PVS LWA as a partial replacement for normalweight aggregate is investigated to determine its effectiveness at reducing shrinkage both with and without slag cement. Control mixtures without LWA containing normalweight coarse aggregates with both low and high absorptions are also tested.

Powers<sup>16</sup> observed that the length of curing has little effect on concrete shrinkage. His work was based, however, on cements that were not ground as finely as those currently in use. The effect of an increased curing period on drying shrinkage is included in this study.

## RESEARCH SIGNIFICANCE

This study demonstrates that a partial replacement of normalweight aggregate with PVS LWA will reduce drying shrinkage and that the effectiveness of the LWA is enhanced through the use of slag cement. This study also demonstrates the positive impact of extended curing on reducing shrinkage. Taken together, the results provide the basis for a combined strategy to reduce drying shrinkage—and by extension, the cracking that accompanies it—in reinforced concrete bridge decks.

## EXPERIMENTAL INVESTIGATION

### Materials

The concretes in this study contained Type I/II portland cement, river-run sand and pea gravel, 3/4 in. (19 mm) maximum-size crushed granite (with an absorption of 0.71 to 0.76%) or limestone (with an absorption of 3.07%) coarse aggregate, a polycarboxylate-based high-range water-reducing admixture (HRWRA), and a tall oil (liquid rosin)-based air-entraining agent. The LWA was expanded shale. Because the concrete is intended for use in low-cracking mixtures with low paste contents, an intermediate-sized

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(rather than fine) aggregate gradation (97% of particles pass the 3/8 in. [9.5 mm] sieve and are retained on the No. 16 [1.18 mm] sieve) was selected for ease of handling and placing during bridge deck construction and ease of handling in the laboratory. Some mixtures contained Grade 100 slag cement as a partial replacement for portland cement.

The LWA was prewetted using a vacuum saturation process and used in a nominally surface-dry condition (PVS-SD). The river sand and pea gravel were batched in a wet condition, with appropriate corrections to the mixture water, and the normalweight coarse aggregates were batched in a saturated surface-dry (SSD) condition. The aggregate properties and mixture proportions are summarized in the concrete mixtures section.

Two Type I/II portland cements were used. The cement used for Program I (described in the following) had a specific gravity of 3.20 and a Blaine fineness of 384 m<sup>2</sup>/kg (1875 ft<sup>2</sup>/lb), while the cement used for Program II had a specific gravity of 3.15 and a Blaine fineness of 339 m<sup>2</sup>/kg (1655 ft<sup>2</sup>/lb). The Grade 100 slag cement had a specific gravity of 2.86.

Further details on the material properties are presented in Reference 17.

### Vacuum saturation

To provide water for internal curing, the LWAs were prewetted at a vacuum of 5.9 psi (0.041 MPa) for 1 hour. After vacuum saturation, the intermediate-sized LWA was prepared to a PVS-SD condition by drying it with cloth towels. The nominal specific gravity of the LWA (specific gravity factor)—1.54—was found using a pycnometer.<sup>18</sup> The water absorbed by the LWA ranged from 24.7 to 30.0% based on the dry weight of the aggregate.

### Concrete mixtures

The mixtures used in this study were based on low-shrinkage mixtures with low cement paste contents and optimized aggregate gradations that are currently in use in the field.<sup>15,19</sup> This study involved two programs, summarized in Table 1, which shows the concrete mixture proportions, the total water in all the aggregates, and the paste content as a percentage of concrete volume. The water in the aggregates represents the water held within the aggregate pores at the time of batching—water that is available to aid internal curing while not affecting the *w/cm*. The aggregates in the granite coarse control mixtures contained approximately 19 lb/yd<sup>3</sup> (11 kg/m<sup>3</sup>) of water. The aggregates in the other mixtures contained considerably more water—45 lb/yd<sup>3</sup> (26.7 kg/m<sup>3</sup>) for the mixtures containing a limestone coarse aggregate

**Table 1—Mixture proportions, lb/yd<sup>3</sup>**

Mixture	Cement	Slag	Water	Sand*	Pea gravel†	LWA	Coarse aggregate	Water in aggregate	Paste percentage by volume
Program I									
Granite coarse aggregate-control	540	—	238	1074	685	—	1226‡	19	24.10
Limestone coarse aggregate-control	540	—	238	1241	522	—	1215§	45	24.10
LWA-low replacement	540	—	238	1074	433	148	1226#	46	24.10
LWA-medium replacement	540	—	238	1057	305	199**	1285#	55	24.10
LWA-high replacement	540	—	238	1057	230	243††	1285#	70	24.10
Program II									
Granite coarse aggregate-control	540	—	238	925	812	—	1239#	19	24.29
LWA-30% slag	384	149	235	923	564	195‡‡	1243#	62	24.18
LWA-60% slag	226	303	233	933	617	195§§	1178#	58	24.26
Limestone coarse aggregate-control	540	—	238	1058	661	—	1253§	46	24.29
Limestone coarse aggregate-30% slag	384	149	235	1075	713	—	1190§	45	24.18
Limestone coarse aggregate-60% slag	226	303	233	1070	715	—	1188§	45	24.26

\*Bulk specific gravity (SSD) is 2.62; absorption (dry) is 0.33%.

†Bulk specific gravity (SSD) is 2.61; absorption (dry) is 0.93%.

‡Granite; bulk specific gravity (SSD) is 2.60; absorption (dry) is 0.76%.

§Limestone; bulk specific gravity (SSD) is 2.59; absorption (dry) is 3.07%.

||Nominal specific gravity (PVS-SD) is 1.54; moisture content (% dry weight) is 24.7%.

#Granite; bulk specific gravity (SSD) is 2.60; absorption (dry) is 0.71%.

\*\*Nominal specific gravity (PVS-SD) is 1.54; moisture content (% dry weight) is 25.2%.

††Nominal specific gravity (PVS-SD) is 1.54; moisture content (% dry weight) is 29.5%.

‡‡Nominal specific gravity (PVS-SD) is 1.54; moisture content (% dry weight) is 30.0%.

§§Nominal specific gravity (PVS-SD) is 1.54; moisture content (% dry weight) is 26.5%.

Notes: 1 lb/yd<sup>3</sup> = 0.5933 kg/m<sup>3</sup>; *w/c* = 0.44 for Program I and *w/cm* = 0.44 for Program II.

**Table 2—Mixture properties**

Mixture	Slump, in. (mm)	Air content, %	Temperature at batching, °F (°C)	Unit weight, lb/ft <sup>3</sup> (kg/m <sup>3</sup> )	7-day compressive strength, psi (MPa)	28-day compressive strength, psi (MPa)
<b>Program I</b>						
Granite coarse aggregate-control	4 (100)	8.90	70 (21)	139.3 (2231)	3700 (25.5)	4610 (31.8)
Limestone coarse aggregate-control	4 (100)	8.65	72 (22)	139.2 (2230)	3260 (22.5)	4460 (30.8)
LWA-low replacement	2 (50)	8.40	70 (21)	133.9 (2145)	3640 (25.1)	4450 (30.7)
LWA-medium replacement	3.25 (85)	8.90	67 (19)	132.1 (2116)	3370 (23.2)	4450 (30.7)
LWA-high replacement	3.25 (85)	8.15	69 (21)	130.5 (2091)	3950 (27.2)	4850 (33.4)
<b>Program II</b>						
Granite coarse aggregate-control	3.5 (90)	8.90	72 (22)	139.0 (2227)	2950 (20.3)	4140 (28.5)
LWA-30% slag	3.75 (95)	8.15	74 (23)	135.3 (2168)	3240 (22.3)	4950 (34.1)
LWA-60% slag	3.25 (85)	8.90	70 (21)	135.0 (2162)	2690 (18.5)	4910 (33.9)
Limestone coarse aggregate-control	2.25 (55)	7.90	72 (22)	138.9 (2225)	4060 (28.0)	4680 (32.3)
Limestone coarse aggregate-30% slag	3 (75)	8.90	76 (24)	138.7 (2222)	3150 (21.7)	4900 (33.8)
Limestone coarse aggregate-60% slag	4 (100)	8.65	73 (23)	138.3 (2215)	2730 (18.8)	4570 (31.5)

and between 46 and 70 lb/yd<sup>3</sup> (27.3 and 41.5 kg/m<sup>3</sup>) for the mixtures containing a partial replacement of normalweight aggregate with LWA.

Program I included LWA mixtures with three replacement levels of LWA—8.9, 11.3, and 13.8% by aggregate volume (designated as low, medium, and high)—and two mixtures that served as controls. The mixture with the low LWA replacement contained approximately the same aggregate water content as the mixtures in Programs I and II containing limestone coarse aggregate. Program II included two LWA mixtures (an LWA replacement of 8.4% by aggregate volume) containing Grade 100 slag cement, two mixtures containing limestone coarse aggregate and Grade 100 slag cement, and two mixtures that served as controls. The control mixtures for both programs contained a granite or limestone coarse aggregate combined with river-run pea gravel and sand. In the LWA mixtures, the LWA replaced a portion of the pea gravel.

The mixtures in Program I were proportioned using a water-cement ratio ( $w/c$ ) of 0.44, 540 lb/yd<sup>3</sup> (320 kg/m<sup>3</sup>) of Type I/II cement, a nominal air content of 8%, and an HRWRA to produce a slump of approximately 3 in. (75 mm). The total paste (cement plus water) content was 24.10% by volume. The mixtures in Program II had similar proportions, except those mixtures contained slag cement at either a 30 or 60% volume replacement of portland cement. The  $w/cm$  was 0.44, and the paste content ranged from 24.18 to 24.29% by volume. The paste contents, which are indicative of those used to produce low-shrinkage mixtures in the field,<sup>3,15,19</sup> were held within a narrow range to minimize the effect of paste content on drying shrinkage.

The concrete was mixed in a counter-current pan mixer in accordance with ASTM C192/C192M-07.<sup>20</sup>

### Free shrinkage and strength

The free shrinkage tests were performed in accordance with ASTM C157/C157M-08.<sup>21</sup> Six free shrinkage specimens were prepared for each batch of concrete; three were cured for 7 days and three were cured for 14 days. The specimens were demolded 23.5 ± 0.5 hours after casting, immediately wrapped in wet towels, and placed under running water to prevent moisture loss. Initial length readings were taken,

and the specimens were placed in lime-saturated water for 6 or 13 days (for a total curing time of 7 or 14 days). After curing, the specimens were dried at 73° ± 3°F (23° ± 2°C) and 50% ± 4% relative humidity for 1 year. The temperature and humidity varied somewhat during the tests, causing some fluctuations in the free shrinkage readings. The temperature and humidity, however, remained within the limits prescribed by ASTM C157/C157M-08.<sup>21</sup> Readings were taken daily for the first 30 days, every other day for Days 31 to 90, weekly for Days 91 to 180, and monthly thereafter.

In addition to the free shrinkage specimens, six 4 x 8 in. (100 x 200 mm) cylinders were cast for testing in accordance with ASTM C39/C39M-09a.<sup>22</sup> Three cylinders were cured for 7 days and three were cured for 28 days. The cylinders were demolded 23.5 ± 0.5 hours after casting and immediately placed in lime-saturated water for the remainder of the curing period.

## EXPERIMENTAL RESULTS AND DISCUSSION

### Mixture properties

The properties of the mixtures in Programs I and II are shown in Table 2. The concrete slumps ranged from 2 to 4 in. (50 to 100 mm) and the air contents ranged from 7.9 to 8.9%, measured in accordance with ASTM C173/C173M-09<sup>23</sup> (volumetric method). The unit weights of the mixtures containing only normalweight aggregates were approximately 139 lb/yd<sup>3</sup> (2227 kg/m<sup>3</sup>), whereas those containing LWA ranged from 130.5 lb/ft<sup>3</sup> (2091 kg/m<sup>3</sup>) for the LWA-high replacement mixture in Program I to 135.3 lb/ft<sup>3</sup> (2168 kg/m<sup>3</sup>) for the LWA-30% slag mixture in Program II. At 7 days, the compressive strengths of the concretes without slag ranged from 2950 psi (20.3 MPa) for the control mixture containing granite coarse aggregate in Program II to 3700 psi (25.5 MPa) for the control mixture containing granite in Program I. At 7 days, the specimens containing slag exhibited strengths between 2690 psi (18.5 MPa) for the LWA-60% slag mixture in Program II to 3240 psi (22.3 MPa) for the LWA-30% slag mixture in the same program. The limestone mixtures containing slag exhibited strengths between those for the two LWA slag aggregate mixtures. At 28 days (with one exception), the compressive strengths ranged from 4450 to 4950 psi (30.7 to 34.4 MPa).

**Table 3—Average free shrinkage, Programs I and II,  $\mu\epsilon$ \***

Program I						Program II					
Mixture	Curing period, days	Drying period, days				Mixture	Curing period, days	Drying period, days			
		0	30	90	365			0	30	90	365
Granite coarse aggregate-control	7	-3	347	447	513	Granite coarse aggregate-control	7	-53	337	423	483
	14	-43	313	410	467		14	-53	297	393	433
Limestone coarse aggregate-control	7	-90	377	503	570	LWA-30% slag	7	-83	190	290	353
	14	-73	363	490	543		14	-83	120	263	310
LWA-low replacement	7	-17	300	413	477	LWA-60% slag	7	-97	113	243	313
	14	-63	253	373	440		14	-143	30	157	217
LWA-medium replacement	7	3	300	413	483	Limestone coarse aggregate-control	7	-53	317	423	457
	14	-47	260	370	427		14	-47	327	430	463
LWA-high replacement	7	-30	260	370	420	Limestone coarse aggregate-30% slag	7	-93	280	367	400
	14	-80	220	347	417		14	-63	217	323	377
						Limestone coarse aggregate-60% slag	7	-80	200	320	377
							14	-143	87	233	317

\*Values based on length measured upon removal from molds 23.5 ± 0.5 hours after casting.

The one exception was the granite control mixture in Program II with a compressive strength of 4140 psi (28.5 MPa). The three highest-strength mixtures contained slag cement with strengths of 4950, 4910, and 4900 psi (34.1, 33.9, and 33.8 MPa) for the LWA-30%, LWA-60%, and limestone-30% mixtures, respectively.

Overall, in the percentages used, the LWA resulted in a small reduction in concrete density and had no appreciable effect on compressive strength.

**Free shrinkage**

*Program I*—Program I was designed to compare the free shrinkage of mixtures containing varying replacement levels of PVS-SD LWA with that of control mixtures containing a low-absorption granite coarse aggregate and a high-absorption limestone coarse aggregate. The average shrinkage strains for the drying periods of 0, 30, 90, and 365 days and curing periods of 7 and 14 days are summarized in Table 3. The average free shrinkage is plotted as a function of the drying period for the mixtures in Program I over 30 and 365 days in Fig. 1 and 2, respectively. Shrinkage during the first 30 days is of particular importance for structures such as concrete bridge decks, in which dimensional change is restrained because of the high percentage of the total shrinkage that occurs and the relatively short period available for creep to reduce tensile stresses. In the figures, the mixtures/curing periods are shown in the key in the order of descending shrinkage at the end of 30 or 365 days.

As shown in Table 3 and Fig. 1, increasing the replacement percentage of normalweight aggregate with LWA and increasing the curing period from 7 to 14 days consistently reduces early-age shrinkage. By 30 days, the limestone control mixture, cured for 7 or 14 days, exhibits the highest shrinkage (377  $\mu\epsilon$  and 363  $\mu\epsilon$ , respectively), and the LWA-high replacement mixture cured for 14 days exhibits the lowest shrinkage (220  $\mu\epsilon$ ). It should be noted that the limestone control mixture and LWA-low replacement mixture have nearly the same internal water content (45 and 46 lb/yd<sup>3</sup> [26.7 and 27.3 kg/m<sup>3</sup>], respectively), but the LWA is much more effective in reducing free

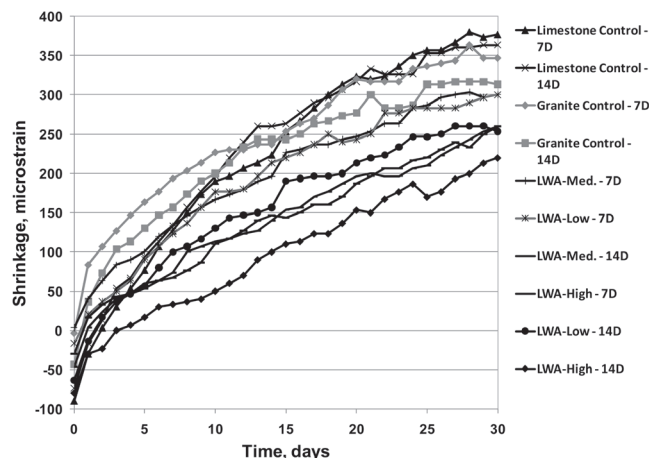


Fig. 1—Free shrinkage versus drying time through 30 days for concrete in Program I.

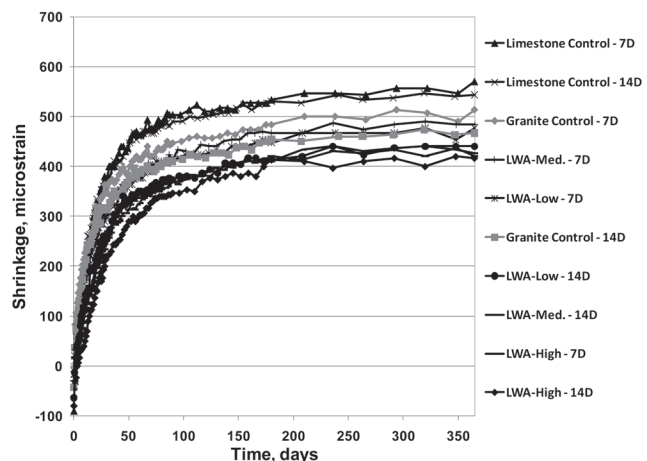


Fig. 2—Free shrinkage versus drying time through 365 days for concrete in Program I.

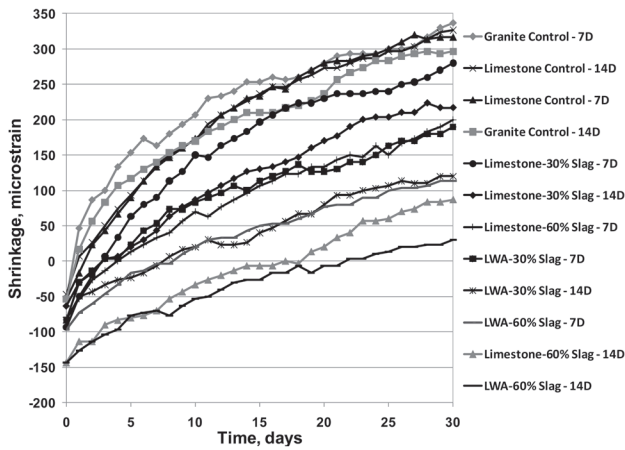


Fig. 3—Free shrinkage versus drying time through 30 days for concrete in Program II.

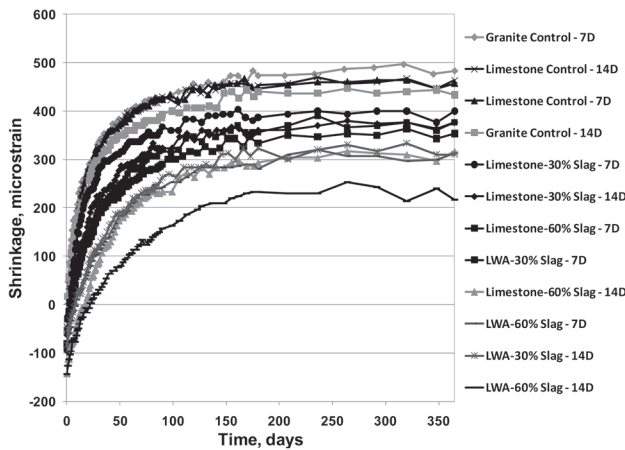


Fig. 4—Free shrinkage versus drying time through 365 days for concrete in Program II.

shrinkage (363  $\mu\epsilon$  and 253  $\mu\epsilon$ , respectively, after curing for 14 days). The low and medium replacement LWA mixtures exhibit similar values of shrinkage for the respective curing periods of 7 and 14 days, with the 14-day curing period producing 40 to 50  $\mu\epsilon$  less shrinkage than the 7-day curing period. The granite control mixture exhibits lower shrinkage than the limestone control mixture by 30  $\mu\epsilon$  and 50  $\mu\epsilon$  for curing periods of 7 and 14 days, respectively.

For a drying period of 365 days (Table 3 and Fig. 2), increasing the level of LWA replacement and increasing the curing period from 7 to 14 days continues to result in lower shrinkage, although the order of descending shrinkage changes to some extent. In addition, the reduction in shrinkage strain resulting from the increased curing period decreases compared to the reduction observed at 30 days, except for the granite control mixture, for which the specimens cured for 14 days exhibit 46  $\mu\epsilon$  lower shrinkage at 365 days compared to 34  $\mu\epsilon$  at 30 days. Overall, the LWA-high replacement mixture cured for 14 days continues to exhibit the lowest shrinkage at 365 days (417  $\mu\epsilon$ ), whereas the limestone control mixture cured for 7 days continues to exhibit the highest shrinkage (570  $\mu\epsilon$ ).

The lower shrinkage strain exhibited by the granite control mixture compared to the limestone control mixture is likely

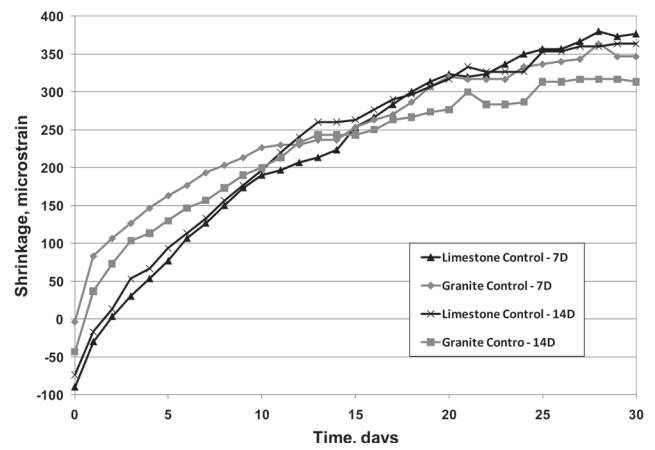


Fig. 5—Free shrinkage versus drying time through 30 days for control mixtures in Program I.

due to the greater restraint provided by the higher modulus of elasticity of the granite.

*Program II*—Program II was designed to compare mixtures containing 30 and 60% replacements of portland cement with slag cement, with internal curing provided by either LWA or porous limestone. The average values of free shrinkage are shown, along with those from Program I, in Table 3 and Fig. 3 and 4. Figures 3 and 4 cover the drying periods through 30 days and 365 days, respectively. At 30 days, an increase in slag replacement and, with one exception (the limestone control mixture), an increase in curing period resulted in a decrease in shrinkage. The lowest shrinkage is exhibited by the LWA-60% slag mixture, with a shrinkage of only 30  $\mu\epsilon$ , followed by the limestone-60% slag mixture, with a shrinkage of just 87  $\mu\epsilon$  (both were cured for 14 days). The highest shrinkage is exhibited by the granite control mixture cured for 7 days, with a shrinkage of 337  $\mu\epsilon$ . The LWA is more effective than the limestone in providing internal curing, at least in part because of the greater quantity of moisture held within the aggregate (approximately 60 versus 45 lb/yd<sup>3</sup> [36.6 versus 26.7 kg/m<sup>3</sup>]). The shrinkage strain of 30  $\mu\epsilon$  exhibited by the LWA-60% slag mixture appears to be abnormally low.

At 365 days (Table 3 and Fig. 4), the LWA-60% slag mixture cured for 14 days continues to exhibit the lowest shrinkage (217  $\mu\epsilon$ ), followed by the same mixture cured for 7 days (313  $\mu\epsilon$ ). The granite control mixture cured for 7 days exhibits the highest shrinkage (483  $\mu\epsilon$ ), followed by the limestone control mixtures cured for 14 and 7 days (463  $\mu\epsilon$  and 457  $\mu\epsilon$ , respectively) and the granite control mixture cured for 14 days (433  $\mu\epsilon$ ). Overall, increasing the percentage of slag replacement, using LWA, and curing for a longer period (with a single exception) results in reduced shrinkage (the exception: the limestone control mixture cured for 14 days exhibited slightly more shrinkage than the same mixture cured for 7 days at nearly all ages, as shown in Table 3).

Figures 5 and 6 illustrate the difference in very early-age shrinkage between the limestone and granite control mixtures for Programs I and II, respectively. The internal curing provided by the water in the pores of the limestone coarse aggregate, coupled with the ability of the water within the limestone to replace water lost due to evaporation, results in reduced shrinkage for approximately 12 days for the Program I specimens and for 10 to 25 days for the Program II

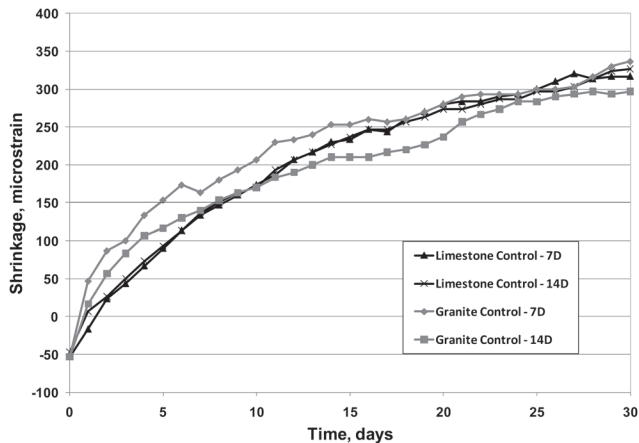


Fig. 6—Free shrinkage versus drying time through 30 days for control mixtures in Program II.

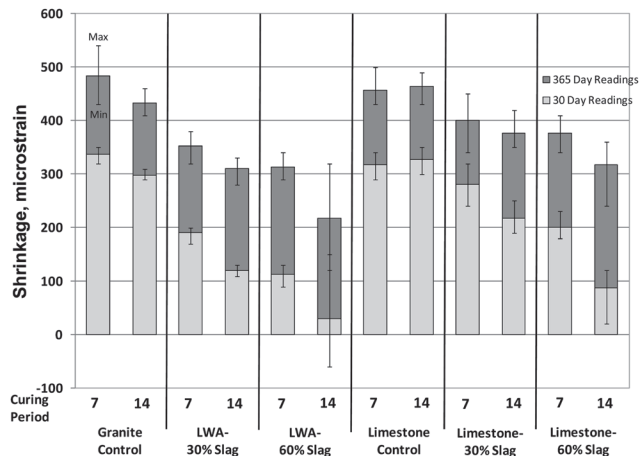


Fig. 8—Free shrinkage at 30 and 365 days for curing periods of 7 and 14 days for mixtures in Program II.

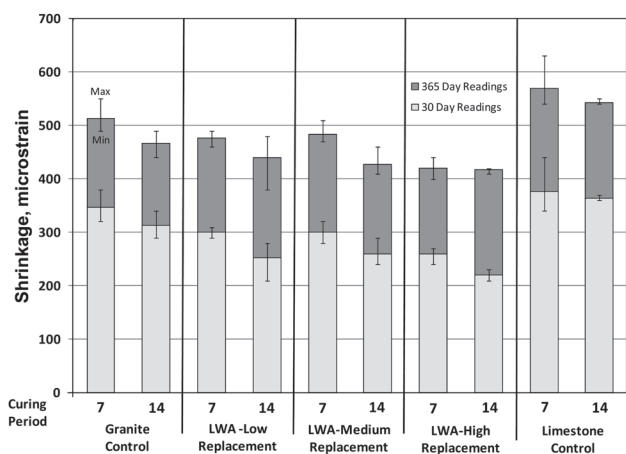


Fig. 7—Free shrinkage at 30 and 365 days for curing periods of 7 and 14 days for mixtures in Program I.

specimens, depending on the curing period. Afterward, the effect of the higher stiffness of the granite compared to the limestone in restraining shrinkage is apparent.

Figures 7 and 8 illustrate the degree to which using LWA as an internal curing agent and increasing the curing period resulted in reduced shrinkage in this study. In addition to the average values of free shrinkage, the figures also show the maximum and minimum values for the three specimens used for each parameter. For Program I (Fig. 7), the impact of both factors on lowering shrinkage is apparent in all cases at 30 and 365 days. This trend is consistent even when the maximum and minimum values shown in the graphs are considered. For Program II (Fig. 8), the observations are similar, except for the effect of the curing period on the limestone control mixture. Figure 8 also illustrates the major reductions provided by slag cement when used in combination with aggregates that provide internal curing, especially LWA. Thus, internal curing, longer curing, and slag cement, used in conjunction with internal curing, will result in reduced shrinkage. In this study, the difference is substantial. The maximum and minimum values support the trends, except the maximum value for the LWA-60% slag specimens with 14 days of curing and 30 days of drying overlaps with the minimum value at 365 days of drying. This is caused by the free shrinkage value of one specimen

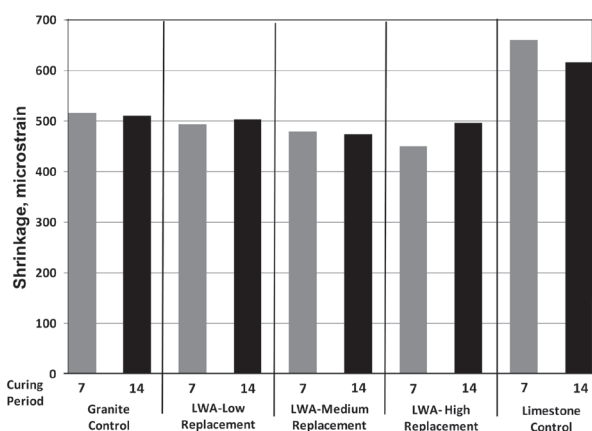


Fig. 9—Free shrinkage at 365 days based on total length change after curing for curing periods of 7 and 14 days for mixtures in Program I.

at 30 days of drying being much higher than the other two free shrinkage values.

As shown in Fig. 1 through 4, the specimens exhibit various amounts of swelling (negative shrinkage) at the end of the curing period. In this study, increasing the curing period from 7 to 14 days resulted in higher swelling for seven out of the 13 mixtures, identical or nearly identical swelling for five mixtures, and lower swelling for one mixture (limestone-30% slag). An increase in swelling is potentially beneficial in the case of concrete that is restrained, such as in bridge decks, because it places the concrete in compression.

Figures 9 and 10 show the average values of free shrinkage based on the total length change after curing through 365 days, thus discounting the effect of swelling. These figures illustrate that with one exception (the LWA-high replacement mixture from Program I), reduced shrinkage obtained through the use of an increased curing period, the use of LWA for internal curing, or the use of slag cement is maintained or improved over 365 days, independent of swelling.

## SUMMARY AND CONCLUSIONS

The effectiveness of prewetted, vacuum-saturated light-weight aggregate (PVS LWA) as an internal curing agent to reduce concrete shrinkage is evaluated using 11 concrete mixtures that cover the effects of LWA replacement levels

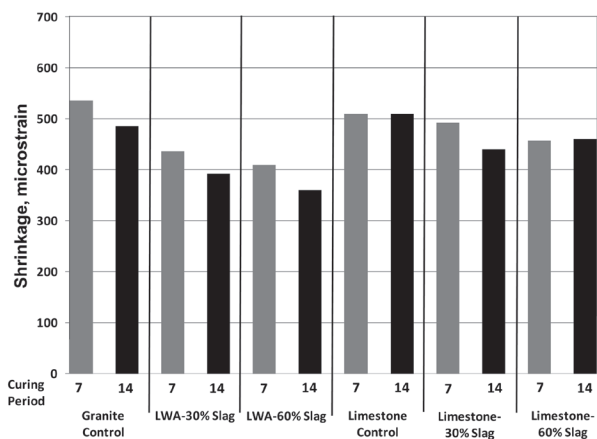


Fig. 10—Free shrinkage at 365 days based on total length change after curing for curing periods of 7 and 14 days for mixtures in Program II.

ranging from 8.9 to 13.8% based on volume and performance when used in conjunction with Grade 100 slag cement. Comparisons are made with mixtures containing a low-absorption (0.71 to 0.76%) granite coarse aggregate and a high-absorption (3.07%) limestone coarse aggregate. All mixtures have a  $w/cm$  of 0.44, a cement paste content of approximately 24.1%, and an air content of approximately 8%. Seven- and 14-day curing periods are evaluated and compressive strengths are compared at 7 and 28 days.

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

1. At the percentages used in this study to provide internal curing, PVS LWA results in a small reduction in concrete densities and has no appreciable effect on concrete compressive strength at 7 or 28 days.
2. When used as an internal curing agent, PVS LWA substantially decreases concrete shrinkage for periods of up to 365 days.
3. Increasing the curing period from 7 to 14 days reduces concrete shrinkage.
4. When used in conjunction with either porous limestone or PVS LWA to provide internal curing, 30 and 60% volume replacements of portland cement by slag cement results in reduced shrinkage.
5. Of the two porous aggregates tested, the PVS LWA is more effective than the porous limestone at reducing shrinkage in both the short and long term when used in conjunction with slag cement.

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