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Internal curing using lightweight fine aggregate

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Internal Curing Using Lightweight Fine Aggregate

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Introduction

Curing refers to the process of maintaining the hydration of the concrete as it hardens, or sets. Concrete is cured so that hydration continues which reduces concrete porosity. A reduction in concrete porosity increases concrete strength while reducing permeability. Proper curing also reduces cracking due to concrete shrinkage. There are three main types of shrinkage that can occur in concrete: plastic, drying, and autogenous shrinkage. Plastic shrinkage occurs because of capillary tension in the pore water of the fresh concrete. Drying shrinkage refers to the reduction in volume of concrete due to the loss of water during the drying process (Kolver & Zhutovsky, 2006). Autogenous shrinkage occurs internally in concrete due to a limited amount of water in the concrete for hydration. The concrete rapidly draws out water of the cement matrix to complete the hydration cycle, causing internal drying of concrete (Jensen & Kovler, 2005). This research project focuses on reducing autogenous shrinkage in a bridge deck mix design. There are two types of curing: external and internal. External curing utilizes water from external sources such as saturated burlap mats, ponding, or fogging. Internal curing supplies water from an internal source inside the concrete such as saturated fine light weight aggregate (FLWA) (Jensen & Kovler, 2005). For this research project, FLWA are used as an internal source of water. FLWA pores are generally much larger than the pores of the hydrated cement paste (Henkensiefken et al, 2009). These pores serve as an internal source of water which therefore reduces concrete cracking due to autogenous shrinkage.

For concrete internally cured with FLWA, the first water lost due to hydration after setting is lost from the FLWA inside the concrete. This is due to the pre-saturated FLWA having larger pores than the cement paste. The water in the large pores of the FLWA is removed through capillary action and moves into the much smaller pores in the cement paste (Bentz et al, 2010). There is little information on the optimum quantity of pre-wet FLWA necessary for proper hydration. Too much pre-saturated FLWA will decrease concrete compressive strength, whereas too little pre-saturated FLWA will increase compressive strength and decrease autogenous shrinkage by properly hydrating the cement (Crocker & Villarreal, 2007). This proposed research program will experimentally examine the optimum amount of FLWA required to reduce shrinkage in concrete mixtures used typically in bridge decks in Arkansas.

Background

Concrete is cured to increase strength, reduce permeability, improve durability and improve a host of other concrete properties (Cusson & Hoogeveen, 2008). As stated above, internal curing refers to the process in which the cement is hydrated through the availability of water from an internal source other than the water in the mix design. Proven benefits of internal curing consist of higher strength, reduced autogenous shrinkage and cracking, increased durability, and a lowered permeability; all qualities needed in a concrete mixture used in bridge decks (Bentz & Lura, 2005). Internal curing is a more efficient, and enhanced, method of curing concrete because of the process that the concrete undergoes. Where external curing requires constant maintenance of the concrete to keep it hydrated, internal curing can potentially require no maintenance due to the presence of pre-saturated FLWA within the cement matrix. Sustainability is another beneficial aspect of using FLWA. Researchers have suggested an improved performance of concrete containing fly ash and slag cement which are becoming more integrated in concrete mixture due to their “greener” properties (Henkensiefken et al, 2009). Research conducted in 2004 and 2005 has similarly advocated that high-performance concrete (HPC) using internal curing can potentially yield a concrete with a life-span of up to 150 years when compared to conventional concrete with a design life of 50 years (Roberts, 2006).

Since the FLWA is saturated prior to mixing, water lost due to hydration is only from the FLWA. This reduces and/or eliminates autogenous shrinkage and increases the concrete’s service life. FLWA are more preferred as opposed to coarse LWA because the fines are more evenly distributed throughout the concrete mixture and therefore provides more water to the cement paste (Henkensiefken et al, 2009).

Bentz and Lura developed an equation to determine the proper quantity of FLWA to use in a mix to supply the ideal amount of internal curing (Bentz & Lura, 2005). There are several variables that affect the amount of FLWA to be used. This equation was developed through computer simulations and assumes that the concrete is in a sealed curing condition; not exposed to any field conditions that could potentially be encountered during construction. It is suggested that for a water to cementitious materials ratio (w/cm) greater than 0.45, conventional external curing methods be used for efficiency and practicality reasons. It is also said that as the w/cm ratio approaches 0.45, the equation becomes more and more unreliable; therefore, this equation was not taken into serious consideration in this project. Using the equation developed by Bentz and Lura, 221 lb/yd^3 (131 kg/m^3) of FLWA would be the optimal amount to add the mixture in this project.

Other research has suggested that controlling autogenous expansion during the first 48 hours will significantly reduce the amount of shrinkage and cracking in concrete over its lifetime. It was also found in the same study that 300 lb/yd^3 (178 kg/m^3) of pre-soaked LWA sand almost eliminated all autogenous shrinkage of specimens cast at a w/cm of 0.36 (Cusson & Hoogeveen, 2008). Cusson and Hoogeveen suggest that the total w/cm should be held constant through testing and list an equation to determine how much of the w/cm will be applied to the internal curing of the concrete.

FLWA has been used in several field applications. There have been multiple paving projects in Texas, particularly the Dallas-Fort Worth area, that have used this new technology. By substituting 5ft^3/yd^3 of LWA, one project increased a typical load of concrete delivered to the site by 0.5yd^3 due to the reduction in weight of the concrete mix. This reduction in weight was accompanied by the enhancement of concrete performance the FLWA provided. The performance improvements include enhanced workability, better consolidation and a minimal amount of reports of plastic and drying shrinkage (Crocker & Villarreal, 2007).

The American Society of Civil Engineers Report Card for the U.S.'s infrastructure was a C for bridges in 2009. They go on to say that 25%, or one in every four, of Arkansas' bridges are either structurally deficient or functionally obsolete (ASCE, 2010). Bridge decks must transfer the vehicles loads to the girders and eventually into the substructure. As bridge decks deteriorate, they contribute to the bridges overall rating of "structurally deficient." By incorporating FLWA in our concrete mixtures, concrete quality and performance will improve which will hopefully reduce the number of structural deficient bridges in Arkansas.

Experimental Procedure

The materials and mixture proportioning for the research project were performed according to the Arkansas State Highway and Transportation Department's (AHTD) bride deck mix design (AHTD, 2003). For concrete used in bridge decks, AHTD requires a minimum cement content of 611 lb/yd^3 (362 kg/m^3) and a maximum w/cm of 0.44. AHTD also requires a slump of 1 to 4 inches (25 to 100 mm), an air content of 6 ± 2 percent, and a 28 day compressive strength of at least 4000 psi (28 MPa).

For this research program, a single source of Type I portland cement was used for all mixtures. Crushed limestone was the coarse aggregated and dredged river sand was the fine aggregate. The w/cm ratio of 0.44 was held constant for all mixtures. The FLWA was fine shale provided by Buildex Lightweight Aggregate of New Market, Missouri. The absorption capacity of the FLWA was 18% compared to 0.38% for the limestone coarse aggregate and 0.48% for the river sand, fine aggregate. The aggregate properties are listed below in Table 1. When necessary, a high-range water reduce (HRWR) was used to increase workability. HRWRs, also known as super-plasticizers, can improve workability without increasing the w/cm.

Table 1 Aggregate Properties

	Specific Gravity	Absorption Capacity
Fine Shale (FLWA)	1.35	18%
Limestone (Coarse)	2.68	0.38%
River Sand (Fine)	2.63	0.48%

The mixture proportions included in the study are shown below in Table 2. The research project examined three FLWA contents, 150 lb/yd^3 (FLWA-1, FLWA-2), 300 lb/yd^3 (FLWA-3), and 450 lb/yd^3 (FLWA-4.). As shown below in Table 2, the amount of rock was reduced from 1790 lb/yd^3 in the control mixture to 1700 lb/yd^3 in the mixtures containing FLWA. This is done to maintain adequate workability in the mixtures containing FLWA.

Table 2 Mixture Proportions (lb/yd^3)					
	Control	FLWA-1	FLWA-2	FLWA-3	FLWA-4
Cement (lb)	611	611	611	611	611
Rock (lb)	1790	1700	1700	1700	1700
Sand (lb)	1353	979	979	660	572
Water (lb)	269	269	269	269	269
HRWR (fl oz)	2	6	2	0	0
FLWA (lb)	--	150	150	300	450
w/cm	0.44	0.44	0.44	0.44	0.44

Prior to batching, the moisture content of the coarse and fine aggregate were determined To determine aggregate moisture content, samples of the coarse aggregate and fine aggregate were weighed and dried to a constant weight (approximately 24 hours). The aggregate and water content were then adjusted based on this information.

The FLWA was submerged in water 24 hours prior to batching. Immediately prior to batching, the excess water would be removed from the FLWA bucket as shown below in Figure 1. A sample of the FLWA was placed in the oven to determine the moisture content.

Figure 1 Removal of Excess Water From FLWA

All concrete mixtures were batched in a rotating drum mixer with a capacity of 0.33 yd^3 (0.25 m^3). Once the concrete was batched, fresh concrete tests were performed on the concrete. The slump test was performed in accordance to ASTM C143 and the unit weight test was performed in accordance to ASTM C138. Nine cylinders were cast from each mixture. Three cylinders were tested in compression at 1, 7, and 28 days of age. The test cylinders were 4” x 8”. The cylinders were cured in an environmental chamber at 100 percent relative humidity and 73 F until testing. To assess concrete shrinkage, four prisms were cast from each mixture. A gage stud was imbedded in each end of the prism which allowed for the measurement of length change using a length change comparator. The testing and specimen molds were performed in accordance to ASTM C490. A test specimen and the length change comparator are shown below in Figure 2.

Figure 2 Shrinkage Testing Prism

Concrete shrinkage was measured at 1, 7, 14, 21, 28, 56, 90, and 112 days of age. All specimens were stored in an environmental chamber at a constant temperature of 73°F and at 50 percent relative humidity. The specimens were stored on wooden rollers which allowed the concrete to expand and contract freely. To conserve space in the environmental chamber, specimens were stored on top of one another as shown in Figure 3.

Figure 3 Shrinkage Specimens Storage

Results

In this research project, the fresh concrete tests that were performed were slump test and unit weight; the results of these tests are shown below in Table 3. Slump is based on the workability of the concrete and varies due to different w/cm, aggregate size, and the amount of fine aggregate versus coarse aggregate. Unit weight measures the density of the concrete mixture and will vary between mixtures due to the mixture proportioning. This includes the amount of coarse aggregate in the mixture, the amount of water in the mixture and the percent air. Unit weight is a measure of the specific gravity of the mixture, so the more materials with a higher specific gravity that are present in the mixture, the higher the unit weight will be. For this reason, as FLWA is added to the mixture, the unit weight will decrease. Table 3 adequately shows this relationship.

Table 3 Fresh Concrete Properties

	Control	FLWA-1	FLWA-2	FLWA-3	FLWA-4
Slump (in)	3.00	8.50	2.50	4.75	3.25
Unit Weight (lb/ft^3)	149.40	147.48	147.88	139.84	141.16

As previously mentioned, two mixtures, FLWA-1 and FLWA-2, were batched using 150 lb/yd^3 of FLWA. The reasoning is due to the high slump value for FLWA-1 as shown in Table 3. FLWA-1 was the first mixture batched and the proper dosage of HRWR to achieve a slump of approximately 1 to 4 inches was not known. Based on prior research at the University of Arkansas, a dosage rate of 6 fluid ounces per hundred pounds of cementitious material (fl oz/cwt) was chosen. This resulted in a mixture with a slump that was out of the targeted range. Mixture FLWA-2 had adequate workability without using a HRWR and therefore the remaining mixtures did not contain a HRWR. Table 3 also shows that the unit weight of the mixtures containing FLWA was less than that of the control mixture. This reduction was due to the lower specific gravity of the FLWA. The FLWA has a specific gravity of 1.35 compared to 2.63 for the normal weight fine aggregate (river sand). As said above, the lower unit weight will ultimately result in a higher volume of concrete brought to the site per truck, reducing the cost of construction and reducing truck emissions to the environment.

The hardened concrete testing consisted of compressive strength testing and shrinkage testing. Table 4 below shows the results of the compressive strength testing. Figure 4, also shown below, shows the relationship between compressive strength of the concrete and the amount of FLWA added to the mixture. The typical required compressive strength, f'c, of concrete for use in bridge decks is 4000 psi.

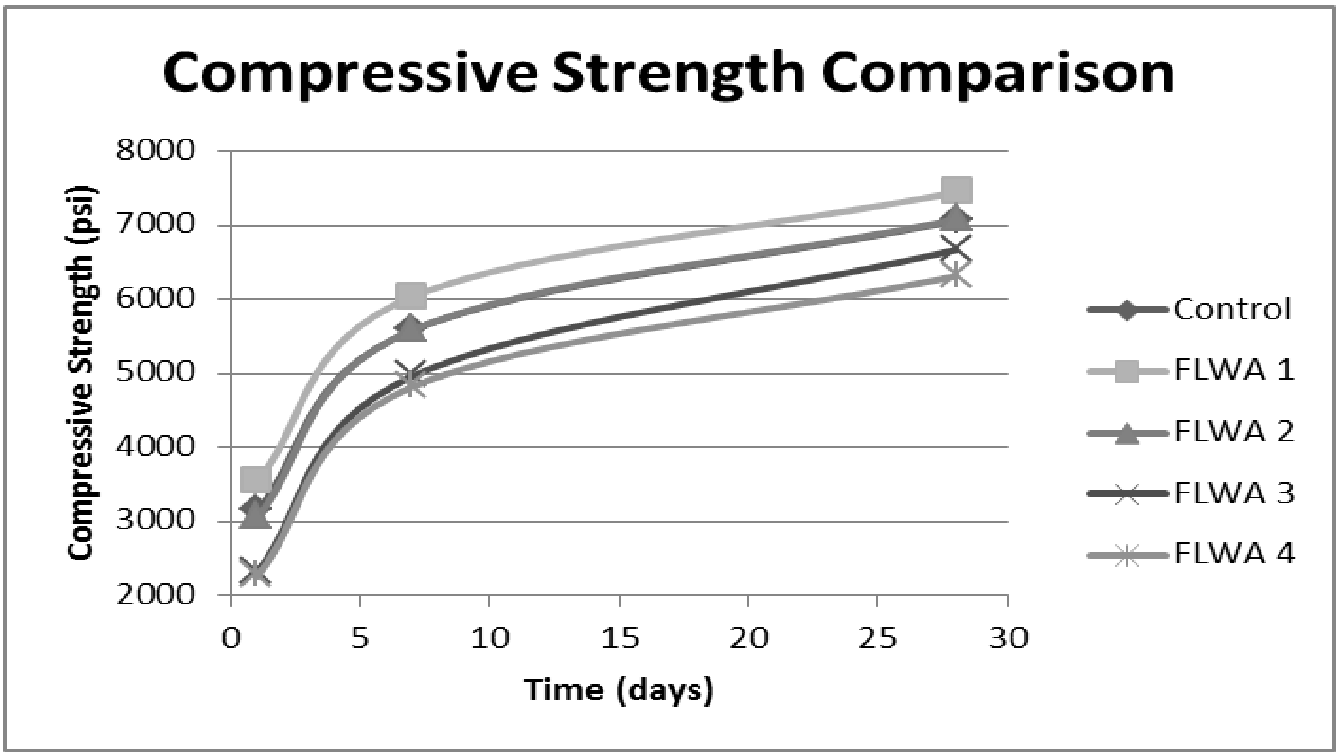

Figure 4 Compressive Strength Comparison

Compressive strength of the concrete, with the exception of the 150 lb/yd^3 replacement, decreased as FLWA was added. This is expected due to the addition of FLWA which has a lower specific gravity and therefore lower strength than normal weight fine aggregate. Even though the FLWA specimens have a lower compressive strength, the compressive strength is still much higher than the specified compressive strength of 4000 psi. Previous studies have shown that the long term compressive strength of the concrete (beyond 28 days) will increase with the use of internal curing, so it is likely that the FLWA specimens have higher 56 and 112 day compressive strengths than the control specimen (Bentz, 2007).

Table 4 Concrete Compressive Strength (psi)					
	Control	FLWA-1	FLWA-2	FLWA-3	FLWA-4
1 day	3140	3540	3050	2310	2260
7 days	5580	6040	5860	4960	4820
28 days	7060	7450	7080	6670	6310

Mitigating concrete shrinkage was the main objective of this study. Figure 5 shows the shrinkage curves for the all specimens. The curves for four of the five mixtures follow a very similar trend. The measured shrinkage at 112 days for the four mixtures (Control, FLWA-1, FLWA-2, FLWA-3) fell within a range of 310 to 340 microstrains. There is some variability in the curves and this was due to fluctuations in the air temperature and relative humidity in the environmental chamber. During testing, a circuit was blown which caused the temperature and humidity changes. Even with this being taken into consideration, FLWA-2 resulted in less shrinkage than the control mix, and FLWA-3 showed a great reduction in shrinkage at early-ages. FLWA-2 also showed a slower rate of shrinkage throughout the 112 day testing period. Table 5 shows the actual length change data of the specimens.

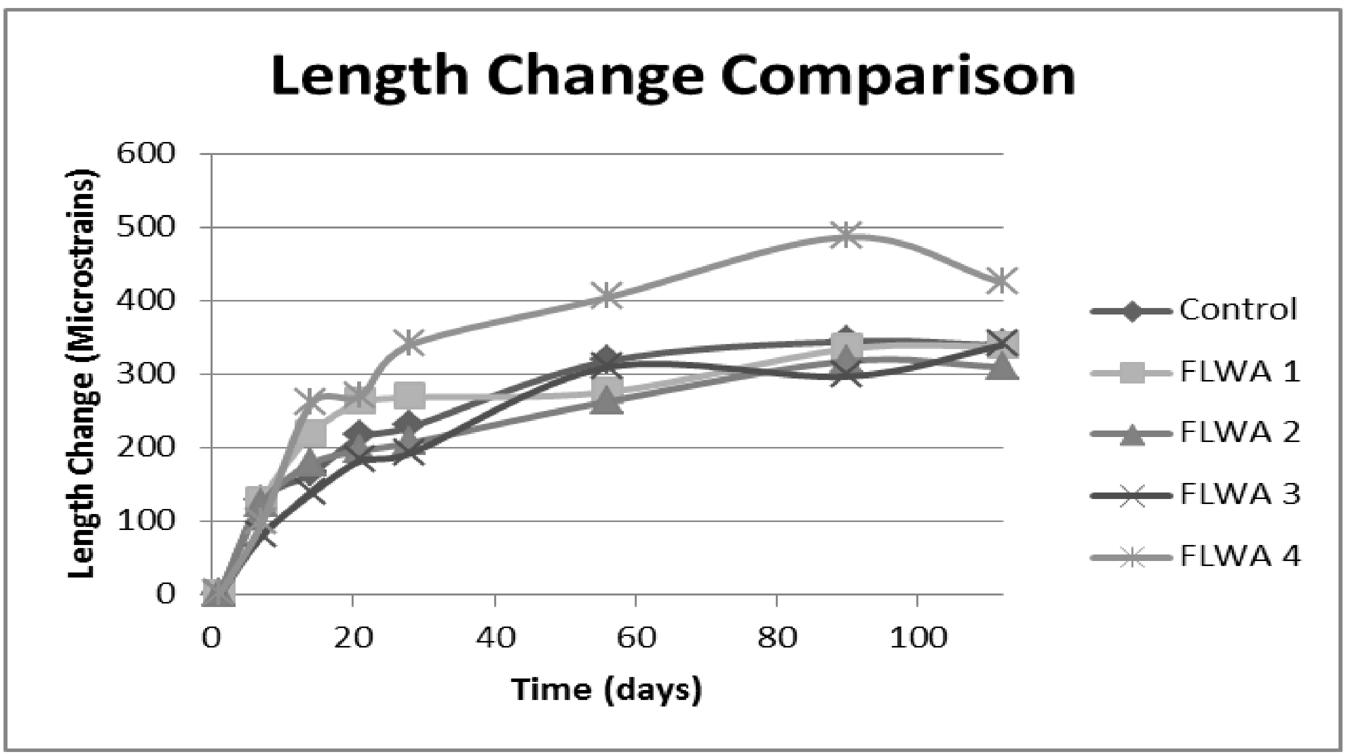

Figure 5 Length Change Comparison

Table 5 Concrete Length Change (Microstrains)					
	Control	FLWA-1	FLWA-2	FLWA-3	FLWA-4
7 days	127	127	123	80	97
14 days	165	219	178	138	260
21 days	215	263	197	183	270
28 days	228	269	207	193	340
56 days	318	276	263	310	405
90 days	345	335	318	298	488
112 days	340	339	310	340	425

Due to the fluctuation of values, it is hard to draw a solid conclusion on how some of the mixtures would react in the field. FLWA-3 shows the lowest amount of shrinkage through 28 days of testing and up until the 56 day testing where the shrinkage significantly increases due to the increase in temperature and reduction in relative humidity that was due to the blown circuit. The control mixture was the last mixture batched and therefore did not experience the blown circuit due to the timing of the circuit being blown. Had the curing conditions been uniform throughout the testing process, it is predicted that FLWA-3 would have the least amount of shrinkage of all of the specimens throughout the entire testing period. Further testing should be done narrowing down the amount of FLWA added to the mixture and in proper curing conditions.

Conclusions

Despite the curing conditions of the specimens in this research, it is still proven that adding FLWA to a mixture improves fresh and early-age hardened concrete properties as well as still reaching the design strength of 4000psi. The improvements provided by the FLWA include a lower unit weight, increased workability, and a reduction in the early-age autogenous shrinkage of the concrete, while showing no long-term increase in autogenous shrinkage. Adding 300 lb/yd^3 of fine shale as the FLWA to a bridge deck mix design yields the lowest amount of autogenous shrinkage at early ages and after 28 days of curing.

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