LIGHTWEIGHT AGGREGATES AS AN INTERNAL CURING AGENT FOR LOW-CRACKING HIGH-PERFORMANCE CONCRETE

By

Diane Reynolds

JoAnn Browning

David Darwin

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Abstract

The use of lightweight aggregates to supply a source of internal curing for Low Cracking, High Performance Concrete (LC-HPC) is evaluated. Prior research is used as a basis to estimate the amount of with lightweight aggregate replacement needed to optimize the amount of moisture available in the mix for internal curing. An aggregate optimization program (*KU Mix*) is revised to include modifications for the addition of aggregate with different specific gravities, such as lightweight aggregate, for the purposes of internal curing.

Fourteen concrete mixes are designed to evaluate the free shrinkage and strength properties of LC-HPC mixes with lightweight aggregate for the purposes of internal curing. Six mixes in Program I are used to evaluate different replacement levels of lightweight aggregate. Eight mixes in Program II are used to evaluate the use of lightweight aggregate with Grade 100 slag. All mixes have a water/cement ratio of 0.44, 24.7% paste content (equivalent to a cement content of 540 lb/yd^3) and an air content of 8%. Both 7-day and 14-day curing periods are evaluated for the free shrinkage specimens. Cylinders are cast for every batch and tested for the 28-day strength.

The effect of adding lightweight aggregate does not significantly decrease the strength of any one mix. The addition of the lightweight aggregate increases the amount of internal curing water available and reduces shrinkage. The recommended mixes to reduce free shrinkage from Programs I and II were the 14-day cured

lightweight aggregate mix with the highest level of replacement and the 14-day cured lightweight aggregate mix with a 30% cement replacement of slag, respectively.

Key Words: bridge decks, concrete mix design, cracking, curing, durability, free shrinkage, high-performance concrete, internal curing, KU Mix, lightweight aggregate, slag, vacuum saturation.

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Chapter 1 Introduction and Background

1.1 General Information

Internal curing is a means of supplying an internal water source for concrete that promotes more cement hydration. There are many benefits associated with internal curing that include increased cement hydration, higher strength, less autogenous shrinkage and cracking, reduced permeability and higher durability. Internal curing can be provided by adding small amounts of saturated lightweight fine aggregates or superabsorbent polymers to the concrete (Bentz et al., 2005).

Internal curing can be very beneficial for Low Cracking, High Performance Concrete (LC-HPC). LC-HPC takes advantage of a reduced paste content, an optimized aggregate gradation, a water/cement ratio (*w/c*) of 0.45, air content of 8 ± ½%, slump between 1 ½ in. and 3 in. (3.8-7.6 cm), with controlled concrete temperature and improved curing methods to reduce cracking. Introducing a material to supply internal curing may further reduce shrinkage and increase workability in an optimized aggregate gradation.

There are many variables that affect the need and the amount of lightweight aggregates to be used for internal curing. The efficiency of such aggregates in a concrete mix is primarily dependent on the amount of water in the aggregates, the lightweight aggregate spacing (distance between aggregate particles) and the pore structure (amount and size of the capillaries in the aggregates) (Hammer et al., 2004). Internal curing is of particular use for combating autogenous shrinkage (also known as chemical shrinkage) in concrete, which reduces the internal relative humidity in the concrete so as to increase shrinkage and early age cracking (Bentz and Snyder, 2005). Internal relative humidity is a measure of the amount of internal water that is available for cement hydration in the cement paste (Lura et. al., 2005). Self-desiccation is the process that occurs in concrete mixes with low *w/c* ratios (<0.3) when internal drying occurs as the concrete cures. Self-desiccation then results in bulk or autogenous shrinkage (Mindess et. al., 2003).

To combat the shrinkage that results from self-desiccation and the associated drop in internal relative humidity, the minimum amount of water needed to supply internal curing is equal to the volume of water that is needed to fill the empty pore space that results from autogenous shrinkage associated with cement hydration. The amount of shrinkage increases with decreasing pore size, decreasing water/cementitious (*w/cm*) ratios and increasing amounts of silica fume (Hammer et al., 2004). Mixes that contain lightweight aggregate to supply internal curing increase the internal relative humidity of the concrete, reduce autogenous shrinkage and therefore reduce total shrinkage and the potential for cracking.

Internal curing can be particularly useful in mixes with relatively low *w/cm* ratios (ratios below 0.36) (Villarreal and Crocker, 2007). As the degree of water saturation increases, the coefficient of thermal expansion is reduced. A higher degree of water saturation also reduces the effects of self-desiccation and increases the resistance to frost damages and chloride ingress. Drying time of concrete in buildings tends to decrease with higher water saturation while compressive strength does not decrease significantly (Hammer et al., 2004).

A number of studies have been completed to analyze the effects of internal curing provided by lightweight aggregates for concrete and are reviewed in this chapter. The articles summarized here present different applications of lightweight aggregates and equations that can be used to determine the amount of replacement material needed to sufficiently supply internal curing. Although much of the previous research evaluating internal curing has focused on alleviating the autogenous shrinkage that occurs at low *w/cm* ratios (≤0.36), it has been shown that even at higher *w/cm* ratios it is important to provide an adequate supply of water during curing (Taylor, 1997). Previous work at the University of Kansas has also shown that internal curing can help reduce drying shrinkage in concrete with higher *w/cm* ratios (0.42-0.45). This work is also reviewed and a test program is designed to further evaluate the benefits of internal curing at higher *w/cm* ratios.

1.2 Development of Aggregate Replacement Methodologies

The articles reviewed in this section discuss internal curing as a means of supplying an internal water source for concrete that promotes more cement hydration and results in less paste shrinkage. By supplying internal curing through the use of lightweight aggregates the internal relative humidity of the concrete increases, autogenous shrinkage is reduced and therefore reduces overall shrinkage and the potential for cracking. The efficiency of such aggregates in a concrete mix is dependent on the amount of water in the aggregates, the lightweight aggregate spacing and the pore structure. Much of the previous research evaluating internal curing has focused on alleviating the autogenous shrinkage that occurs at low *w/cm* ratios though it has been shown that even at higher *w/cm* ratios it is important to provide an adequate supply of water during curing.

1.2.1 Internal Relative Humidity and Autogenous Shrinkage

Internal relative humidity and autogenous shrinkage were monitored in a number of experiments conducted by Ye et al. (2006). Internal relative humidity was tested by casting a specimen, that was $5.9 \times 5.9 \times 5.9$ in. ($150 \times 150 \times 150$ mm), in which a 1.2 in. (30 mm) plastic pipe was inserted to a depth of 3.0 in. (75 mm). The pipe was sealed during curing. A probe was inserted into the hole and was properly sealed so that it measured relative humidity to the nearest 0.1%. The concrete evaluated had a *w/cm* ratio of 0.34, contained both cement and fly ash and used lightweight aggregate to replace the normal-weight gravel by 10%, 20%, 30%, and 40%. The lightweight aggregate used was expanded clay aggregate that ranged in size from 0.2-0.6 in. (5-16 mm). It had a crushing strength of 1,130 psi (7.8 MPa). Figure 1-1 shows the relationship between the water absorption rate and time in hours.

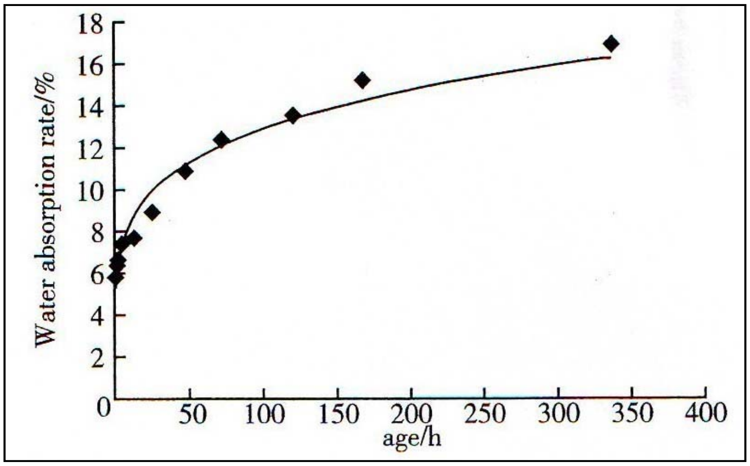

Figure 1-1: Water Absorption vs. Time [Ye et al. (2006)]

Table 1-1 shows the results from the material evaluation of concrete containing different aggregate replacement levels of expanded shale aggregate. Replacement levels ranged from 0-40% which correlated to 0-359.0 lb/yd^3 (0-213.0 kg/m^3) of lightweight aggregate. Based on an absorption rate of 5.73% in half an hour, 0-20.6 lb/yd^3 (0-12.2 kg/m^3) of water was available for internal curing. The compressive strength results of the concrete showed that after the replacement level exceeded 20% the strengths decreased rapidly.

Table 1-1: Test Results [Ye et al. (2006)]

No.	**Replacement Percentage** %	**Lightweight Aggregate** lb/yd^3 (kg/m^3)	**Carrying Water** lb/yd^3 (kg/m^3)	**Crushed Limestone** lb/yd^3 (kg/m^3)	**Compressive Strength** ksi (MPa)	**Elastic Modulus** ksi (GPa)
#1	0	-	-	1,795.3 (1,065.1)	9.7 (67.0)	5,640 (38.9)
#2	10	89.8 (53.3)	5.1 (3.05)	1,615.8 (958.6)	8.9 (61.1)	5,400 (37.2)
#3	20	179.5 (106.5)	10.3 (6.11)	1,436.3 (852.1)	8.4 (58.1)	5,370 (37.0)
#4	30	269.4 (159.8)	15.4 (9.15)	1,256.7 (745.6)	7.1 (48.8)	5,260 (36.3)
#5	40	359.0 (213.0)	20.6 (12.2)	1,077.2 (639.1)	6.8 (46.6)	5,130 (35.4)

*0.34 *w/cm* ratio, 713.8 lb/yd^3 (423.5 kg/m^3) of cement and 178.5 lb/yd^3 (105.9 k/m^3) of fly ash

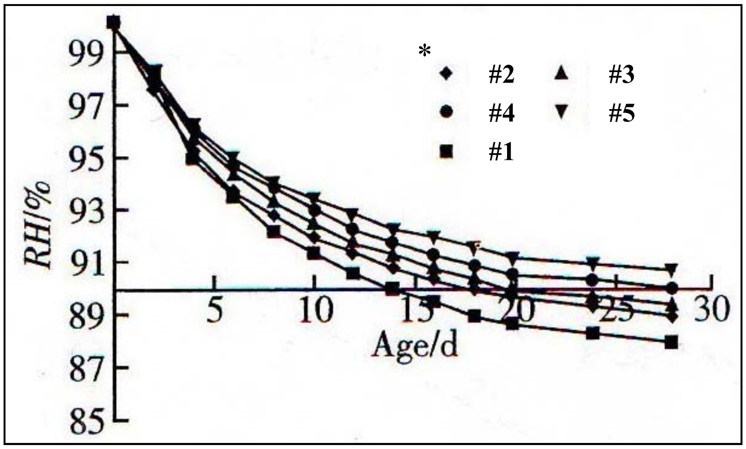

Figure 1-2: Relative Humitiy vs. Time [Ye et al. (2006)]

*Legend refers to mixes in Table 1-1

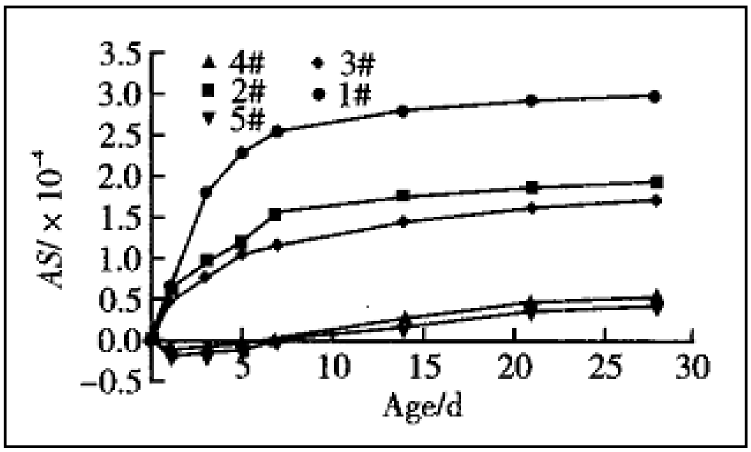

Figure 1-3: Shrinkage vs. Time [Ye et al. (2006)]

The results showed that as the amount of lightweight aggregate increased, the internal relative humidity increased (Figure 1-2). In addition, a linear relationship exists between internal relative humidity and the amount of water provided by the lightweight aggregates. Free shrinkage tests of the mixes shown in Table 1-1 showed that higher replacement of lightweight aggregate yielded lower amounts of shrinkage (Figure 1-3). Finally, the amount of shrinkage decreased with increasing internal relative humidity of the concrete.

1.2.2 Optimizing the Effects of Lightweight Aggregates

The work done by Zhutovsky et al. (2002) describes how to optimize the size and porosity of lightweight aggregate to achieve a minimum amount of effective internal curing.

The amount of water needed to supply internal curing and offset autogenous shrinkage can be determined as follows:

$$W_{cur} = C \times \alpha_{\max} \times CS \tag{1-1}$$

where W_{cur} is the water content, C is the cement content, α_{max} is the maximum degree of hydration of the cement, and CS is the chemical shrinkage (autogenous shrinkage).

Recent studies have shown that the amount of water needed is actually higher than that predicted by Eq. (1-1). Based on the research that was reviewed from Takada et al. (1998), Bentur et al. (2001) and Schwesinger and Sickert (2000), Eq. (1-1) predicted water contents in the range of 30 to 39 lb/yd^3 (18 to 23 kg/m^3) where levels of 50 to 67 lb/yd^3 (30 to 40 kg/m^3) were required to overcome self-desiccation because not all of the water that is absorbed in the lightweight aggregate is effective against self-desiccation. The aggregate property that describes how easily the absorbed water within the aggregate is able to be released back into the mix, is known as desorption.

The desorption of an aggregate is affected by a couple of factors, including the pore size of the aggregate as well as the spacing between aggregate particles. Equation (1-1) can be modified as follows to help account for some of these influences:

$$LWA = \frac{W_{cur}}{\phi \times S \times \eta} \quad \textbf{(1-2)}$$

where LWA is the content of the lightweight aggregate, ϕ is the aggregate absorption by weight, S is the degree of saturation of the aggregate and η is an efficiency factor that accounts for how much water in the aggregate is available to counteract the effects of self-desiccation. In order to maximize the efficiency factor, a small aggregate with a large pore structure must be used.

The work by Zhutovsky et al. (2002) determined how to obtain $\eta = 1$ by using a minimum amount of lightweight aggregate and without sacrificing strength. The lightweight aggregate used was Pumice sieved into three different sizes: Pumice0 – No. 100 to No. 16 (0.15 to 1.18 mm), Pumice1 – No. 16 to No. 8 (1.18 mm to 2.36 mm) and Pumice2 – No. 8 to No. 4 (2.36 mm to 4.75 mm). Two variables were then studied with the aggregates: aggregate size and aggregate replacement level. First, three mixes were developed with the three different aggregate sizes proportioned so that they provided the amount of water calculated from Eq. (1-1). The degree of hydration of the cement was determined to be 65% [α_{max} = 0.65]. The chemical shrinkage, based on literature, was estimated at 0.06 lb water/lb cement hydrated (0.06 kg water/kg cement hydrated) [CS = 0.06], and the cement content was 853 lb/yd^3 (506 kg/m^3) [C = 506]. This resulted in a required amount of internal water of 34 lb/yd^3 (20 kg/m^3) to offset autogenous shrinkage. All mixes used fully saturated aggregates [S = 1] and the absorption varied based on the amount of internal water that was needed. All mixes had 853 lb/yd^3 (506 kg/m^3) of ASTM Type I cement and a *w/c* ratio of 0.33.

Using the larger-sized aggregate (Pumice2), three more mixes were developed such that 50%, 100% and 150% of the required water for internal curing to offset autogenous shrinkage was provided. Two reference mixes were also cast without any lightweight aggregate; the first using air-dried aggregates and the second using saturated-surface-dried (SSD) aggregates. Free shrinkage specimens were used to compare the results.

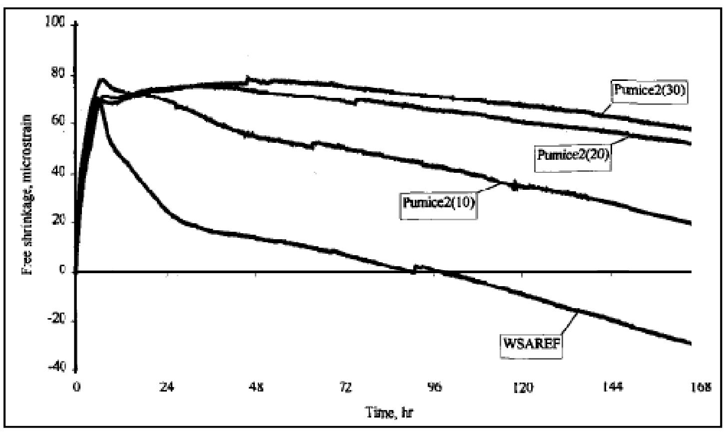

Figure 1-4: Pumice2 Free Shrinkage Results* [Zhutovsky et al. (2002)]
*Expansion is positive

Figure 1-4, shows that the large Pumice2 aggregate proved to be the most effective at achieving $\eta = 1$, and this was likely because almost all of the autogenous shrinkage was eliminated. Little change was noted in the amount of shrinkage from increasing the provided water from 100% (Pumice2(20)) to 150% (Pumice2(30)), indicating that the extra water was not needed for internal curing. When comparing the amount of free shrinkage from mixes with 50% (Pumice2(10)) to 100% (Pumice2(20)), a large difference can be noted because there was not enough water to overcome autogenous shrinkage with the 50% aggregate volume level. WSAREF in Figure 1-4 was the control mix with aggregates that were presoaked to the SSD condition without any lightweight aggregate. The WSAREF mix had the most amount of free shrinkage (contraction) even though the absorbed water content in the normal weight aggregate was 32 lb/yd^3 (19 kg/m^3) and was close to the calculated required internal water content.

Overall, test results proved the benefits of using lightweight aggregate to supply internal curing. An efficiency factor of $\eta = 1$ is achievable using a larger-sized lightweight aggregate.

1.2.3 Influence of Pore Structure on Internal Curing

Hammer et al. (2004) evaluated the efficiency of lightweight aggregates to provide internal curing by examining three factors through the review of published papers: (1) Total amount of water in the LWA, (2) the LWA particle spacing factor and (3) the LWA pore structure. The literature review included a number of studies with *w/cm* ratios that ranged from 0.2 to 0.4. The three factors were examined by first considering the autogenous shrinkage that occurs in concrete as estimated with Eq. (1-3):

$$V_{sd} = V_{cs} = 0.058 \times \alpha \times c \qquad \textbf{(1-3)}$$

where V_{sd} is the volume of self-desiccated pores which is the same as V_{cs} or the volume of chemical shrinkage (autogenous shrinkage), α is the degree of hydration of the cement and c is the cement content. For example, if the cement content is 674 lb/yd^3 (400 kg/m^3) and the degree of hydration is 65%, the resulting volume of self-desiccation (and therefore the amount of water that must be replaced) is close to 25 lb/yd^3 (15 l/m^3) of concrete.

The volume of pore space that is estimated using Eq. (1-3), however, is usually less than the amount of water that can be supplied by lightweight aggregates. Hammer et al. (2004) found that there are three conditions that will determine whether internal curing will take place:

(1) The amount of water in the lightweight aggregates. This must be larger than or equal to V_{cs}.

(2) The aggregate spacing.

(3) The pore structure of the aggregate versus the pore structure of the cement paste.

Desorption experiments were used to determine the pore structure of the lightweight aggregate. An experiment that examined two different lightweight aggregates was completed to evaluate the desorption. The first aggregate was Leca, evaluated at two total water contents: 7.0% (where the aggregate was initially dry) and 29.0% (where the aggregate was pre-saturated for one day and pressurized at 0.735 ksi (50 atm)). The second aggregate was Stalite and the corresponding total water contents that were evaluated were 3.0% and 10.6%. The rest of the concrete was comprised of sand, a low-alkali pure portland cement, and 5% silica fume. The *w/cm* was 0.40. The results of the tests showed that the aggregate with a higher initial total moisture content maintained a higher concrete moisture content when compared with concrete having normal weight aggregate.

Particle spacing was evaluated by a series of free shrinkage specimens that had a range of size fractions of No. 100 to No. 16, No. 16 to No. 8, No. 8 to No. 4 (0.15 - 1.2 mm, 1.2 - 2.4 mm, and 2.4 - 4.8 mm) so that when the mixes were proportioned they yielded the same total absorbed water. The *w/c* ratio in all of the mixes was 0.33. The tests showed that the largest of the aggregate series (and therefore larger pore structure) was the most efficient because the series of free shrinkage specimens with the largest size fraction shrank the least.

It was determined that the most critical of the three factors evaluated by Hammer et al. (2004) was the pore structure of the lightweight aggregates. Water that is supplied by the sand and coarse aggregate in the mix was also shown to have a significant influence in the early hydration phase.

Another important aspect of internal curing as examined by Bentz and Snyder (2005) is the proximity of the cement paste (that part of the mix requiring the water) to the surface of the lightweight fine aggregate. This is similar to the concept of air entrained concrete, where it is important to know how much cement paste is within a certain distance of an air bubble. The distribution was considered by looking at a 3D model of the microstructure of concrete that had previously been developed by Bentz, Garboczi and Snyder (1999). From this model, the volume of the cement paste within a certain proximity of a piece of lightweight fine aggregate can be determined. A study was completed with two different aggregate gradations based on the limits set forth in ASTM C33. The simulation results showed that, similar to well-dispersed air voids, well-dispersed lightweight fine aggregate yields the greatest benefits of internal curing.

1.2.4 Mixture Proportioning

Bentz and Snyder (2005) used a method similar to Zhutovsky et al. (2002) to determine the required amount of lightweight aggregate to provide adequate internal curing. The following equation was used to determine the volume of water that must be supplied from the lightweight fine aggregate to reach complete curing (when cement reaches the highest degree of saturation given the space limitations that result from the products that are formed during hydration in low *w/c* ratio mixtures):

$$V_{wat} = \frac{C_f \times CS \times \alpha_{\max}}{\rho} \tag{1-4}$$

where V_{wat} (m^3 water/m^3 concrete or ft^3 water/yd^3 concrete) is the volume of water that is "consumed" during the hydration process due to chemical shrinkage, C_f is the cement content, *CS* is the chemical shrinkage of the concrete that occurs during the hydration process (usually about 0.06 lb H_2O per lb of cement hydrated or kg of H_2O per kg of cement hydrated), α_{max} represents the maximum degree of hydration and can be estimated as (*w/c*)/0.40 for *w/c* ratios below 0.40, and ρ is the density of water. The total volume of required lightweight fine aggregate is given by the following equation:

$$V_{LWFA} = \frac{V_{wat}}{S \times \phi_{LWFA}} \tag{1-5}$$

where V_{LWFA} is the total volume fraction of the lightweight fine aggregate that is needed, S is the degree of saturation of the lightweight fine aggregate (relative to the absorption of the aggregate), and ϕ_{LWFA} is the porosity of the lightweight fine aggregate (a porosity of 0.15 was used as an example in the research). It is important to note that this equation assumes that all available water in the lightweight aggregate is available for the cement hydration and that the specific gravity of the lightweight aggregate is 1.0.

Bentz et al. (2005) improved previous work (Bentz and Snyder, 2005) with the following equation to estimate how much lightweight aggregate is needed to supply enough water for internal curing in mix design:

$$M_{LWA} = \frac{C_f \times CS \times \alpha_{\max}}{S \times \phi_{LWA}} \qquad \textbf{(1-6)}$$

where M_{LWA} is the mass of the dry fine lightweight aggregate per unit volume of the concrete, C_f is the cement factor (content) for the concrete mixture, CS is the chemical shrinkage of the concrete (in this study 0.07 lb of water/lb of cement or g/g), α_{max} is the maximum expected degree of hydration of the cement, S is the degree of saturation of the aggregate (ranging from 0 to 1), and ϕ_{LWA} is the absorption (total moisture content) of the lightweight aggregate. When the *w/c* ratio is less than 0.36, the maximum expected degree of hydration can be estimated as (*w/c*)/0.36. When the *w/c* ratio is greater than 0.36, the maximum expected degree of hydration can be estimated as one. Complete saturation of the aggregate would be represented by a value of S equal to one.

Refinements to the parameters in Eq. (1-6) were evaluated to more accurately estimate the optimal amount of lightweight aggregate to be used in the mix. This was done by examining the differences in chemical shrinkage due to the phase composition of portland cement and the selection of an appropriate value for the absorption of the lightweight aggregate, as described next.

The amount of chemical shrinkage that is necessary to balance the hydration reaction is related to the cement phase, as shown in Table 1-2. The value of chemical shrinkage was calculated based on the phase composition of the cement. This was done by determining the molar volumes of each cement phase and knowing the expected degree of hydration for each phase. By performing a volume balance of each reaction, chemical shrinkage is defined as the difference between the hydration products volume and the reactants. Curing temperature also has an effect on chemical shrinkage; as the curing temperature increases, the amount of shrinkage is reduced. The calculated values in Table 1-2 have been verified through many laboratory tests on a wide variety of portland cements.

Table 1-2: Chemical Shrinkage due to Cement Phase [Bentz et al. (2005)]

Cement Phase	**Coefficient** [lb water/lb solid cement phase or g/g]
C_3S	0.0704
C_2S	0.0724
C_3A	0.171* 0.115†
C_4AF	0.117* 0.086†
Silica Fume	0.20

*Assuming sufficient sulfate to convert all of the aluminate phases to ettringite
†Assuming total conversion of the aluminate phases to monosulfate

The amount of water available from lightweight aggregates for internal curing is another important aspect when trying to determine how much aggregate to use in a mix because it is not possible for the aggregate to release all of the absorbed water.

As concrete cures, the relative internal humidity can drop to the range of 85 to 90%. It is important that the lightweight aggregates release the water to provide internal curing before this drop in humidity can occur. A desorption (amount of water an aggregate releases over time) test was described to determine the reliability of an aggregate to release water in the hardened concrete. First, the aggregates are pre-soaked to a certain moisture content (a condition similar to batching) and then the amount of water that was released at a lower relative humidity was measured. If an alternate test is needed, measuring the rate of cumulative absorption over time may also be indicative of how much water can be released over time.

For internal curing to be effective, a number of factors need to be considered. The lightweight aggregate mechanical strength, shape and gradation are all important, as well as making sure the aggregate is well blended and evenly distributed throughout the concrete. This is more easily achieved by using fine aggregates as opposed to coarse aggregates.

1.2.5 Benefits of Internal Curing in Sealed and Unsealed Conditions

Henkensiefken et al. (2008) examined the effects of using saturated lightweight aggregates for internal curing and the differences in shrinkage between sealed and unsealed curing conditions. Shrinkage performance with varied amounts of lightweight aggregates is also examined.

A total of seven mortar mixes were designed to evaluate the effects of including the saturated lightweight aggregate. A plain mortar mix and two mixes each of varying amounts of lightweight aggregates (7.3%, 14.3%, 25.3% by volume) were designed. Table 1-3 lists the mix proportions for the tests. The effective *w/c* ratio was 0.30. The total volume of lightweight aggregate and sand was kept constant at 55% because only the sand was replaced with lightweight aggregate. Specimens were evaluated on both a sealed and unsealed basis (with and without lightweight aggregate). Free shrinkage, restrained shrinkage, internal relative humidity (sealed case only) and mass loss (unsealed case) were monitored in this experiment.

Table 1-3: Mixture Proportions (lb/yd^3 (kg/m^3)) [Henkensiefken et al. (2008)]

MATERIAL	Plain	7.3%	11.0%	14.3%	25.3%
Cement	1,228 (728)	1,228 (728)	1,228 (728)	1,228 (728)	1,228 (728)
Water	368 (218)	368 (218)	368 (218)	368 (218)	368 (218)
Fine Aggregate	2,390 (1,418)	2,072 (1,229)	1,913 (1,135)	1,755 (1,041)	1,360 (807)
LWA	0 (0)	192 (114)	289 (171)	384 (228)	624 (370)
Water from LWA	0 (0)	20 (12)	30 (18)	40 (24)	66 (39)

The results showed that including a sufficient amount of lightweight aggregate can reduce self-desiccation and autogenous shrinkage and can delay or prevent cracking. The sealed specimens in the experiment showed that higher internal relative humidity resulted from the larger replacements of lightweight aggregate. The rate of shrinkage as well as total shrinkage was also reduced with the addition of lightweight aggregate. Free shrinkage results from the plain mixture and the low replacement of lightweight aggregate mixture indicated that there was not enough lightweight aggregate to sufficiently supply internal curing. The unsealed specimens showed that (1) a larger mass loss was associated with larger replacement levels of lightweight aggregate, (2) the lightweight aggregate reduced the amount of total shrinkage seen in the first 28 days, and (3) the time to cracking was increased with the higher replacement levels of lightweight aggregate.

1.2.6 Optimum Replacement Levels of LWA for Internal Curing

A study by Cusson and Hoogeveen (2008) evaluated the use of lightweight aggregate for internal curing to reduce the amount of autogenous shrinkage cracking in high-performance concrete (HPC). Four concrete mixes were tested. The study included a reference mix (Mix-0) that contained no lightweight aggregate, a mix containing a low amount of pre-soaked lightweight aggregate (Mix-L), a mix containing a medium amount of pre-soaked lightweight aggregate (Mix-M), and a mix containing a high amount of pre-soaked lightweight aggregate (Mix-H). Pre-soaked expanded shale lightweight aggregate sand was used to replace part of the normal-density sand for each mix. The lightweight aggregate had a dry-bulk density of 1,551 lb/yd^3 (920 kg/m^3) and a water content of 15% by mass of dry material. The lightweight aggregate was slightly bigger than the normal-density sand that was used, which helped improved the combined gradation of the mix. Each mix contained 758 lb/yd^3 (450 kg/m^3) of ASTM Type I cement, a 0.34 *w/c* ratio, and a cement-sand-coarse aggregate ratio of 1:2:2 by mass.

The total *w/c* ratio was held constant by considering both mix water and water within the lightweight aggregate. This in turn, meant that as the amount of lightweight aggregate increased, the effective *w/c* ratio decreased. There were two primary reasons for calculating the effective *w/c* ratio. First, the effective *w/c* ratio was monitored to prevent any reduction in concrete strength and stiffness with the addition of the lightweight aggregate. Second, it was desired to create an environment with high autogenous shrinkage demands (with severe self-desiccation as in found in lower *w/cm* mixes) so that the effect of internal curing would be more pronounced.

Equation (1-7) was used to estimate the amount of internal curing water provided in the mix.

$$\left(\frac{w}{c}\right)_{ic} = 0.18 \times \left(\frac{w}{c}\right) \tag{1-7}$$

where $(w/\mathrm{c})_{\mathrm{ic}}$ was the mass ratio of internal curing water to cement and (w/c) was the mass ratio of mix water to cement. For the tested mix designs, the percentage of required water for internal curing was 0%, 34%, 74% and 120% for mixes Mix-0, Mix-L, Mix-M and Mix-H respectively.

For each batch, a total of four test samples were cast. Two large scale specimens, 7¾ × 7¾ × 39¼ in. (200 × 200 × 1000 mm), and 3 × 3 × 11½ in. prisms (75 × 75 × 295 mm) were used to determine the thermal expansion coefficient, and 4 × 8 in. (100 × 200 mm) cylinders were used to determine the strength. One of the large scale specimens was used to monitor free shrinkage while the other was used to monitor restrained shrinkage. Immediately after casting all of the specimens were covered with plastic to avoid external drying.

Based on the results of the tests, a number of conclusions were drawn. Autogenous shrinkage is most critical at very early ages and measures must be taken to prevent this shrinkage. Mix-H was able to provide an internal relative humidity similar to that provided by saturated curing. Mix-L, however, was insufficient for providing internal curing by providing 90% internal relative humidity at 7 days (the control mix provided 92% internal relative humidity at 7 days). Mix-H almost entirely eliminated autogenous shrinkage. Strength and the modulus of elasticity did not decrease with any of the replacement values of lightweight aggregate, as shown in Table 1-4. The specimens that contained the pre-soaked lightweight aggregate experienced autogenous swelling that resulted in beneficial compressive stresses.

Table 1-4: Hardened Concrete Properties

Concrete Mix	Compressive Strength ksi (MPa)	Compressive Modulus of Elasticity ksi (GPa)
Mix-0	7.25 (50)	4,580 (31.6)
Mix-L	7.25 (50)	4,530 (31.2)
Mix-M	7.83 (54)	4,640 (32.0)
Mix-H	8.27 (57)	4,550 (31.4)

*Properties measured at 7 days

1.3 Applications of Internal Curing

The studies discussed in this section investigate practical applications of internal curing to reduce shrinkage and improve hardened concrete properties.

1.3.1 Pavement Application

Work by Villarreal and Crocker (2007) shows that a ready mix plant in Texas has successfully integrated the use of lightweight aggregates into concrete mixtures for residential applications. The lightweight aggregate was used to replace a portion of the fine and coarse aggregates and has resulted in improved cement hydration as well as an improved aggregate gradation. The next step was to integrate the lightweight aggregate into concrete pavements. The following describes the research that was used to implement the internal curing application in the field.

A laboratory study was first completed to select an appropriate mix for field application. Expanded shale was the lightweight aggregate that was used in the study ranging in size between 3/8 in. and No. 8 (9.5 and 2.4 mm). The pre-wetted bulk density of the aggregate was 60 lb/ft^3 (961 kg/m^3) with a fineness modulus of 5.51. The aggregate was tested in the laboratory by using a replacement of 3, 5 and 7 ft^3/yd^3 (0.11, 0.19 and 0.26 m^3/m^3) of the normal weight aggregate. Workability, density and compressive strength were all analyzed as a result of the substitutions. The results showed that at the 3 and 5 ft^3/yd^3 (0.11 and 0.19 m^3/m^3) replacement levels, compressive strength and workability increased while they decreased at the 7 ft^3/yd^3 (0.26 m^3/m^3) replacement level. Some of the test cylinders were air-cured while some were standard-cured. Because the results from these cylinders showed that the strengths were similar to each other, it was inferred that internal curing was providing adequate water for internal hydration.

The technology from the preliminary study was adapted to field use by developing a mix that contained the 5 ft^3/yd^3 (0.19 m^3/m^3) replacement level which corresponded to 16.0% by volume. This corresponded to replacing about 300 lb/yd^3 (178 kg/m^3) of the coarse aggregate and 200 lb/yd^3 (119 kg/m^3) of the fine aggregate with the lightweight aggregate. The mix has been used in a number of projects in Texas and has shown promising results. The average compressive strength in the mixes used in the field was approximately 1,000 psi (6.9 MPa) more than the compressive strength of mixtures without lightweight aggregate (as seen in Table 1-5). In addition, the amount of cracking caused by plastic or drying shrinkage was minimal. Class C fly ash was used to replace 20% of the cement in the mixes tested by Villarreal and Crocker (2007). The fly ash addition was implemented because pozzolans reportedly increase the efficiency of internal curing (Holm, 1980).

Currently, the use of lightweight aggregates as an internal curing agent has significantly improved concrete performance in the Dallas-Fort worth area. Cement hydration and concrete compressive strength have increased. This has resulted in a reduction or elimination of cracking caused by plastic or drying shrinkage as noted from qualitative surveys. The total weight of a cubic yard of concrete has also been reduced by about 200 lbs/yd^3 (119 kg/m^3) of concrete, which increases the amount of concrete that can be carried by a single truck and reduces the number of trips, increases fuel savings, and decreases equipment wear.

Table 1-5: Field Results [Villarreal and Crocker (2007)]

Mixture*	Cementitious material content	Average Slump	f'_c at 28 Days	No. of field tests	Average Compressive Strength	% of Reference	Difference
	lb (kg)	in. (mm)	psi (MPa)		psi (MPa)		psi (MPa)
8204 SF	517 (235)	2 (50)	3,000 (21)	98	5,130 (35.4)	---	---
8204 SFX	517 (235)	2 (50)	3,000 (21)	106	6,070 (41.9)	118%	940 (6.5)
8206	564 (256)	5 (125)	4,500 (31)	91	5,230 (36.1)	---	---
8206 X	564 (256)	5 (125)	4,500 (31)	68	6,510 (44.9)	124%	1,280 (8.8)
8206 SF	564 (256)	2 (50)	4,500 (31)	65	5,750 (39.6)	---	---
8206 SFX	564 (256)	2 (50)	4,500 (31)	110	6,750 (46.5)	117%	1,000 (6.9)

*Mixtures denoted with an ‘X’ designate a mixture that used lightweight aggregate.

1.3.2 Field Application Challenges

Villarreal (2008) reviews previous work by Villarreal and Crocker (2007) and discusses actual implementation and challenges of using lightweight aggregate in the field. The most critical step for using lightweight aggregate in the field for the purposes of internal curing is to correctly determine the moisture content of the aggregate. The aggregate must be saturated evenly and uniformly so that pumping of concrete with lightweight aggregate is not affected. Using a water sprinkler system works best to saturate the aggregate. It is important for the aggregate to be turned and mixed while saturating so that the aggregate is evenly saturated. If the lightweight aggregate stockpile is resting on the ground it is important to be aware that soil can turn to mud and contaminate the aggregate. By using lightweight aggregate that is properly saturated and the absorption of the lightweight aggregate has accurately been accounted for, concrete mixtures are noted to pump easily, have increased workability and are placed faster. Reduced plastic shrinkage cracking and improved finishing have been observed with concrete that contains lightweight aggregate for the purposes of internal curing.

Proper handling of the lightweight aggregate is important, however, to avoid numerous problems that may occur in the field. Villarreal (2008) notes several of the problems that may arise from improper use and handling of lightweight aggregate:

- If the aggregate is not completely saturated or the total moisture content of the aggregate is not accurately calculated, the yield of the lightweight aggregate will be over estimated. This results in concrete batches with more lightweight aggregate than required.
- Lightweight aggregate that is dry will absorb mix water and result in slump loss for the concrete.
- Lightweight aggregate that is not properly saturated can result in difficulty with pumping. The high pressure of the concrete pump may

drive mix water into the pores of the aggregate and result in slump loss and pump line blockage. Villarreal (2008) recommends using a minimum of a 5 in. (12.7 cm) pump line.

- Due to the lower density of the dry aggregate, the aggregate can segregate from a concrete mixture and float to the back of the mixing truck. This results in the last portion of concrete in a truck having a disproportionately large amount of lightweight aggregate.
- The lower density of lightweight aggregate can result in the lightweight aggregate floating to the top of a concrete, which happens more often with high-slump concrete.
- Dry lightweight aggregate can result in difficulty in finishing because lightweight aggregate near the surface of the concrete can absorb the bleed water.

1.3.3 New York Department of Transportation

The New York Department of Transportation has successfully integrated the use of lightweight aggregate in concrete bridge decks for the purpose of internal curing. The fine lightweight aggregate must meet the gradation requirements of the standard concrete sand gradation requirements set forth by the New York State Department of Transportation Materials Bureau. This requires the amount of aggregate finer than the No. 100 (150 μm) sieve of the combined aggregate gradation is no more than 3%, by weight. Special Specification Items 557.51XX0018, 557.52XX0018 and 557.54XX0018 in the Standard Specifications from the New

York State Department of Transportation Specification outline the use of lightweight aggregate for internal curing. The specification requires 30% of the normal-weight fine aggregate is to be replaced by lightweight aggregate by volume.

The lightweight aggregate is conditioned for high moisture content prior to batching. The lightweight aggregate is kept wet using soaker hoses or sprinklers for 48 hours or until the moisture content is at least 15% by weight. After a sufficient moisture content has been achieved, the hoses are turned off for 12 to 15 hours and the material is retested for moisture prior to batching. Test method NY 703-19E was developed by the New York State Department of Transportation Materials Bureau to test the moisture content of the lightweight aggregate.

Mix proportioning, including the approximate amount of lightweight aggregate, are determined using an automated batching system. The system bases the amount of lightweight aggregate for the mix on the SSD condition of the aggregates and compensates for the free moisture on the fine lightweight aggregate.

1.4 Previous Work at KU

Previous work at the University of Kansas has shown that even at higher *w/cm* ratios, the benefits of internal curing are realized through a reduction of free shrinkage.

A free shrinkage test series at the University of Kansas by Lindquist (2008) evaluated six test programs with 56 individual concrete batches. The test program, part of a larger study evaluating various mix designs that would result in lower cracking potential, evaluated the addition of mineral admixture replacements for Type

I/II cement. The admixtures that were examined included silica fume, Class F fly ash, and Grade 100 and 120 slag cement.

G120 slag cement was used in three batches as a partial replacement for Type I/II portland cement: one batch with limestone and a 60% G120 replacement (by volume) and two batches (one repeated batch) with quartzite and 60% G120 replacement (by volume). Each batch had a 0.42 *w/cm* ratio and a 23.3% paste content.

Figure 1-5 shows the results of the free shrinkage tests using G120 slag replacement through the first 30 days. The vertical axis plots free shrinkage (in με) of the specimens. The horizontal axis plots time in days. The batches plotted include a 7-day and 14-day cure for a 60% G120 slag replacement with quartzite (plotted twice for a repeated batch) and a 7-day and 14-day cure for a 60% G120 slag replacement with limestone.

From Figure 1-5, the average 30-day shrinkage for the 7-day cured 60% G120 slag with limestone was 193 με and was 163 με for the 14-day cured specimens. The average 30-day shrinkage for the 7-day cured 60% G100 batch with quartzite was 330 με and was 247 με for the 14-day cured 60% G100 batch with quartzite. The average 30-day shrinkage for the 7-day cured 60% G100 repeated batch with quartzite was 307 με and was 247 με for the 14-day cured 60% G100 repeated batch with quartzite.

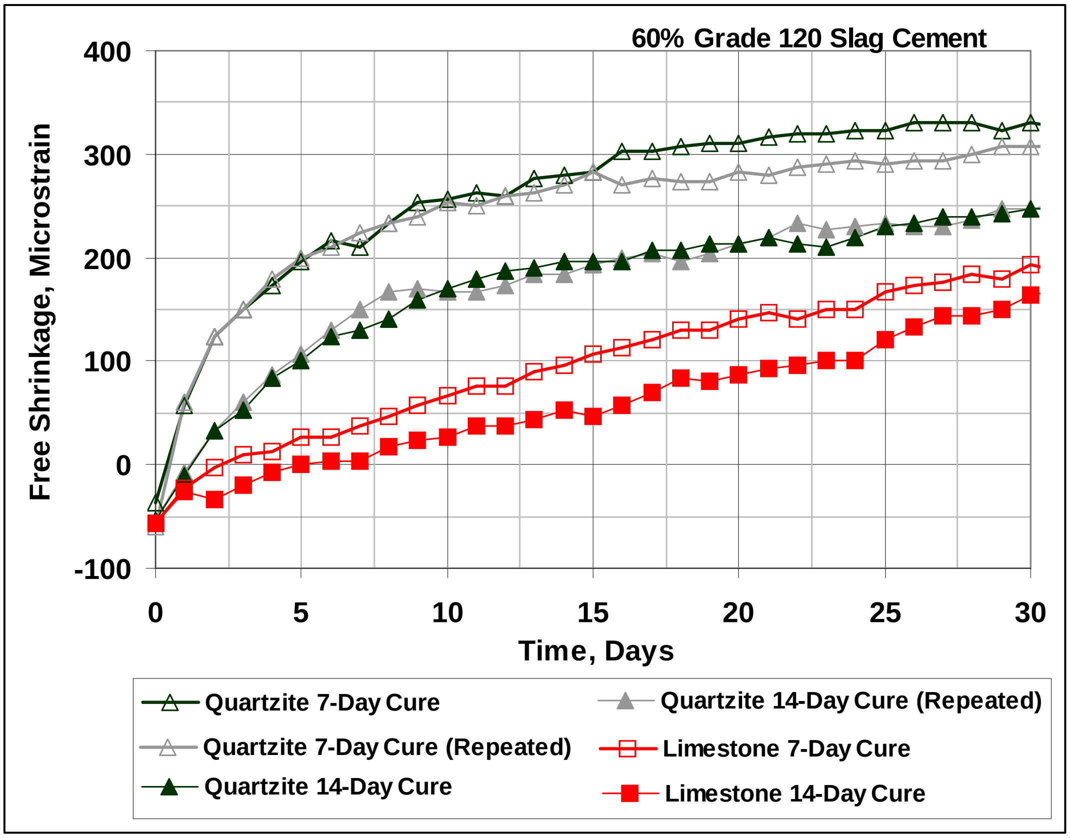

Figure 1-5: 60% G120 Slag - 30 day Free Shrinkage Results [Lindquist (2008)]

Figure 1-6 shows the results of the test for all 365 days. The vertical axis plots free shrinkage (in με) of the specimens. The horizontal axis plots time in days. The batches plotted include both a 7-day and 14-day cure for a 60% G120 slag replacement with quartzite (twice for a repeated batch) and both a 7-day and 14-day cure for a 60% G120 slag replacement with limestone.

From Figure 1-6, the average 365-day shrinkage for the 7-day cured 60% G120 slag with limestone was 413 με and was 393 με for the 14-day cured specimens. The average 365-day shrinkage for the 7-day cured 60% G100 batch with quartzite was 437 με and was 373 με for the 14-day cured 60% G100 batch with quartzite. The average 365-day shrinkage for the 7-day cured 60% G100 repeated batch with quartzite was 420 με and was 377 με for the 14-day cured 60% G100 repeated batch with quartzite.

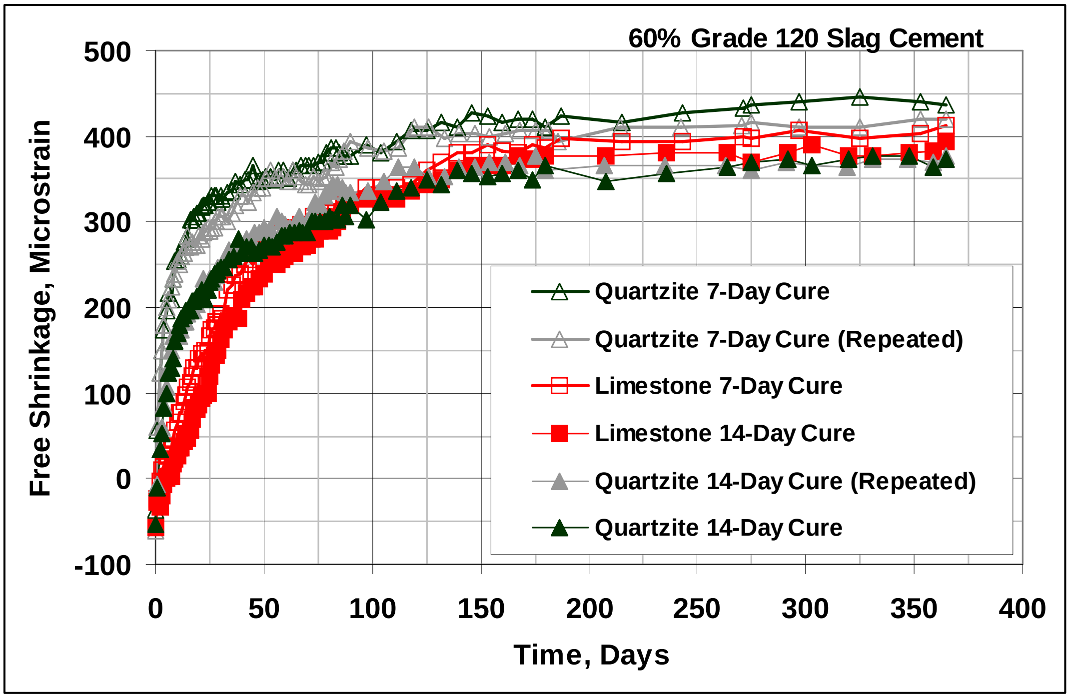

Figure 1-6: 60% G120 Slag - 365-day Free Shrinkage Results [Lindquist (2008)]

The results show that the addition of G120 slag with limestone, when cured for 7 or 14 days, reduced the amount of shrinkage when compared with the shrinkage measured for batches with quartzite, and especially at an early age (30 days). This is most likely the result of the presence of internal curing available from moisture in the limestone, which lengthened the curing period of the slag.

G100 slag cement was used in three batches as a partial replacement for Type I/II portland cement with either limestone or granite coarse aggregate: a limestone control (with no slag replacement), limestone with 60% G100 replacement (by volume) and granite with 60% G100 replacement (by volume). Each batch had a 0.42 *w/cm* ratio and a 23.3% paste content.

Figure 1-7 shows the results of the test through the first 30 days. The vertical axis plots free shrinkage (in με) of the specimens. The horizontal axis plots time in days. The batches plotted include a limestone control, 60% G100 slag replacement with granite and 60% G100 slag replacement with limestone. The plotted results are for a 14-day cure only.

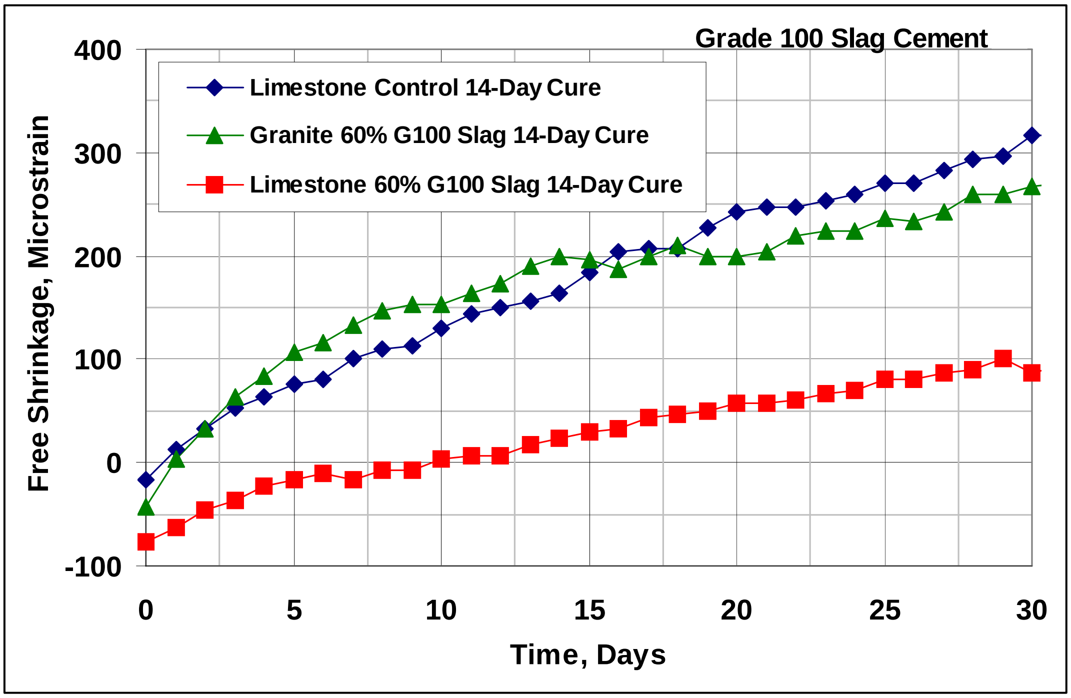

Figure 1-7: G100 Slag - 30 day Free Shrinkage Results [Lindquist (2008)]

From Figure 1-7, the average 30-day shrinkage for the 14-day cured control batch was 317 με. The average 30-day shrinkage for the 14-day cured 60% G100 slag with limestone batch was 87 με. The average 30-day shrinkage for the 14-day cured 60% G100 slag with granite batch was 267 με.

Figure 1-8 shows the results of the tests for all 365 days. The vertical axis plots free shrinkage (in με) of the specimens. The horizontal axis plots time in days. The batches plotted include a limestone control, 60% G100 slag replacement with granite and 60% G100 slag replacement with limestone. The plotted results are for a 14-day cure only.

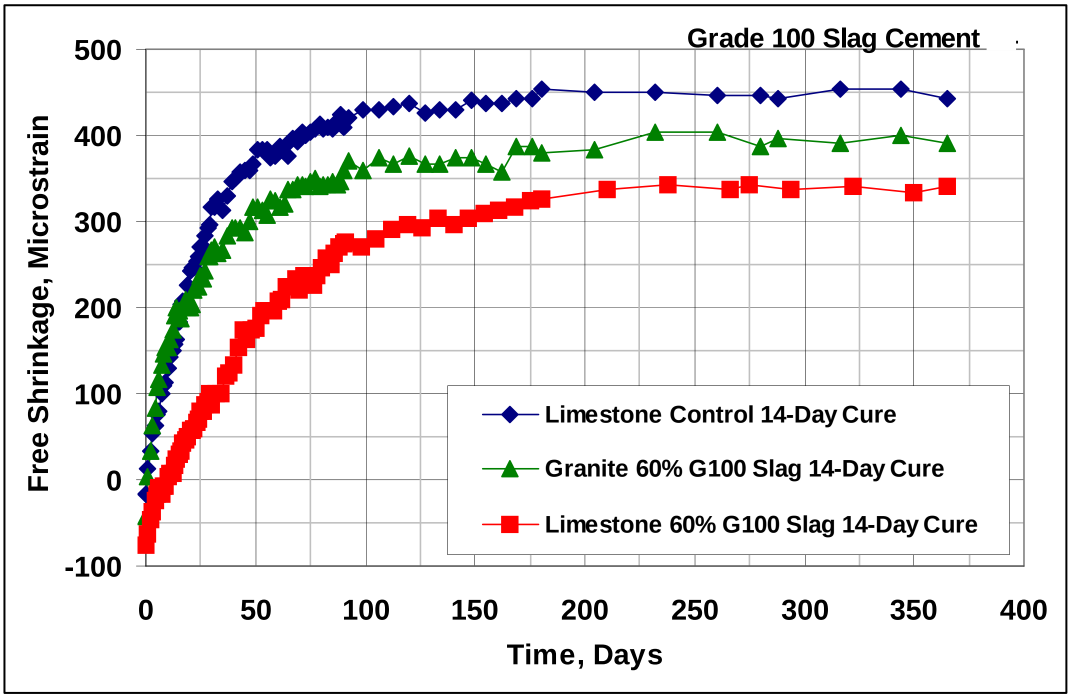

Figure 1-8: G100 Slag - 365-day Free Shrinkage Results [Lindquist (2008)]

From Figure 1-8, the average 365-day shrinkage for the 14-day cured control batch was 443 με. The average 365-day shrinkage for the 14-day cured 60% G100 slag with limestone batch was 340 με. The average 365-day shrinkage for the 14-day cured 60% G100 slag with granite batch was 390 με.

Similar to the results of the previous set, the results show that the addition of 60% G100 slag with limestone reduced the amount of shrinkage when compared with the shrinkage from the control batch (without slag) and the 60% G100 slag with granite batch. This is especially true at early ages (30 days). The reduction in shrinkage, once again, is most likely the result of the presence of internal curing made available from moisture in the limestone, which lengthened the curing period of the slag.

Three batches with different replacement levels of G100 slag and containing granite were studied: a granite control mix, granite with 30% G100 replacement (by volume), and a granite with 60% G100 replacement (by volume). Each batch had a 0.42 *w/cm* ratio and a 23.3% paste content.

Figure 1-9 shows the results of the free shrinkage tests through the first 30 days. The vertical axis plots free shrinkage (in με) of the specimens. The horizontal axis plots time in days. The three batch results plotted include a control, 30% G100 slag replacement and a 60% G100 slag replacement. Both 7-day and 14-day curing times were evaluated.

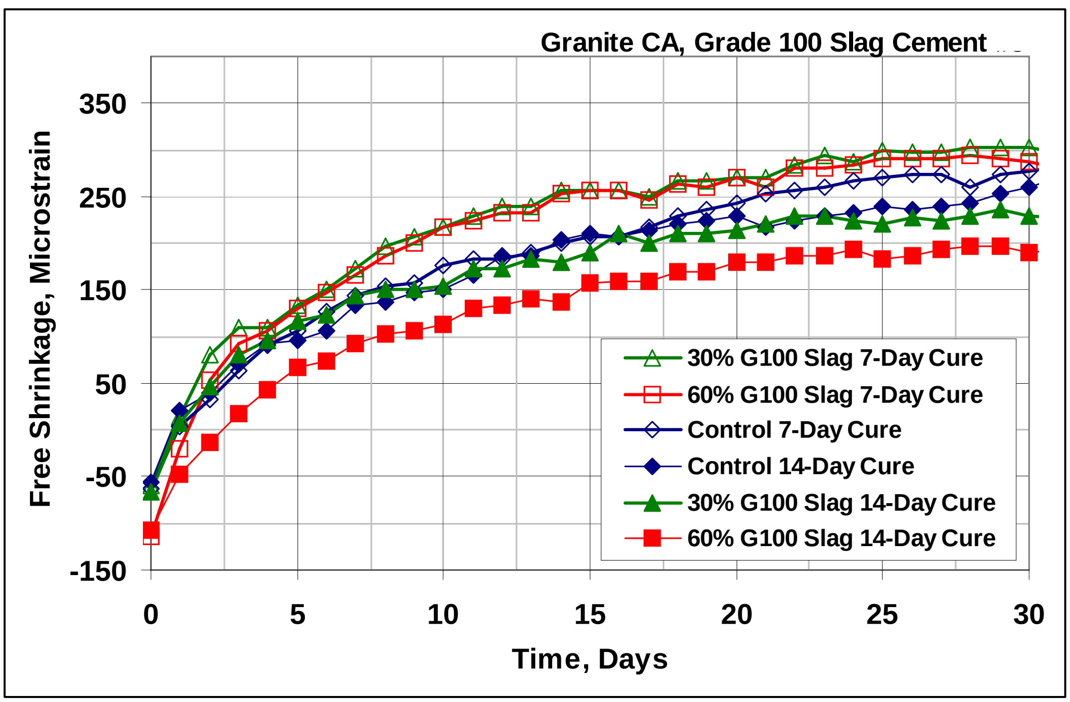

Figure 1-9: Granite - 30 day Free Shrinkage Results [Lindquist (2008)]

From Figure 1-9, the average 30-day shrinkage for the 7-day cured control batch was 277 με and was 260 με for the 14-day cured control. The average 30-day shrinkage for the 7-day cured 30% G100 batch was 303 με and was 230 με for the 14-day cured 30% G100 batch. The average 30-day shrinkage for the 7-day cured 60% G100 batch was 287 με and was 190 με for the 14-day cured 60% G100 batch.

Figure 1-10 shows the results of the test through 365 days. The vertical axis plots free shrinkage (in με) of the specimens. The horizontal axis plots time in days. The three batches plotted include a control, 30% G100 slag replacement and a 60% G100 slag replacement.

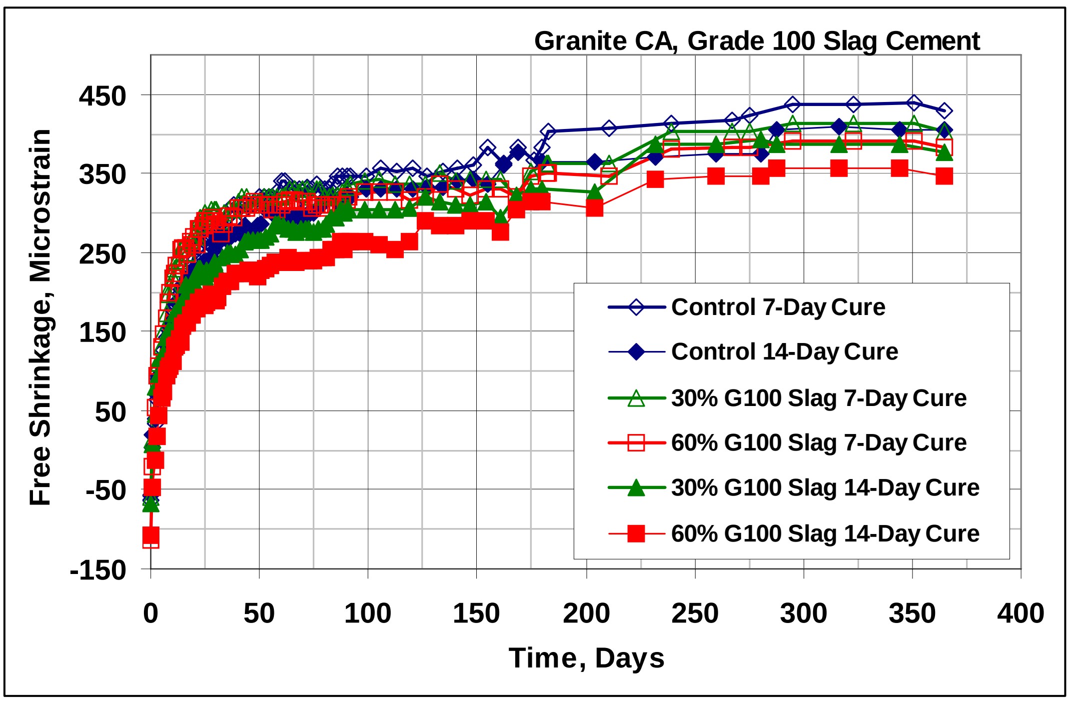

Figure 1-10: Granite - 365-day Free Shrinkage Results [Lindquist (2008)]

From Figure 1-10, the average 365-day shrinkage for the 7-day cured control batch was 430 με and was 420 με for the 14-day cured control. The average 365-day shrinkage for the 7-day cured 30% G100 batch was 403 με and was 377 με for the 14-

day cured 30% G100 batch. The average 365-day shrinkage for the 7-day cured 60% G100 batch was 383 με and was 347 με for the 14-day cured 60% G100 batch.

The results show that the addition of G100 slag, when cured for 14 days, reduced the amount of shrinkage when compared with the control batch shrinkage (without slag). The reduction was more pronounced for early age shrinkage (30 days). When the specimens were cured for only 7 days, however, an increase in shrinkage was seen when compared with the control batch shrinkage (without slag).

1.5 Summary

Upon review of various methodologies for lightweight aggregate replacement to provide internal curing, the literature is in agreement for predicting the required amount of replacement, and the mechanism of internal curing is well understood. One simplified equation may be used as follows:

$$V_{LWA} = \frac{C \times \alpha \times CS}{S \times \phi \times SG \times \rho} \quad \textbf{(1-8)}$$

where V_{LWA} is the volume of the lightweight aggregate (ft^3/yd^3 or m^3/m^3), C is the cement content (lb/yd^3 or kg/m^3), α is the degree of hydration (1.0), CS is the chemical shrinkage (0.07 lb water/lb of cement or kg water/kg of cement), S is the saturation (1.0), ϕ is the absorption of the lightweight aggregate, SG is the specific gravity of the lightweight aggregate, and ρ is the density of water (62.4 lb/yd^3 or 1000 kg/m^3). The amount of water, W (lb/yd^3 or kg/m^3), that is available for internal curing is defined by (1-9):

$$W = C \times \alpha \times CS \quad \textbf{(1-9)}$$

The percentage of aggregate replacement (R_{LWA}) can then be calculated as follows:

$$R_{LWA} = \frac{V_{LWA}}{V_{Total}} \times 100 \tag{1-10}$$

where V_{Total} is the total volume of aggregate (ft^3/yd^3 or m^3/m^3). The amount of aggregate defined using Eq. (1-10) is intended to provide enough absorbed water in the mix to compensate for the negative effects of autogenous shrinkage at low *w/cm* ratios. This water should also help provide better hydration of the cementitious material and thus reduce shrinkage in mixes with higher *w/cm*. The purpose of this study is to evaluate the benefits of using lightweight aggregate for internal curing of concrete with higher *w/cm* (0.44) that will also result in reduced cracking when used in concrete bridge decks.

A review of the literature reveals several primary lessons for efficient use of lightweight aggregates to provide internal curing:

- There is an optimal amount of aggregate replacement that will ensure that internal curing can occur. Increasing the aggregate replacement beyond this value has only a small effect on improving shrinkage properties and may have a detrimental effect on other important concrete properties (such as strength and abrasion resistance) (Ye et al., 2006).
- Lightweight aggregate replacement beyond 20% by volume of the total aggregate may significantly reduce strength (Ye et al., 2006).

- The efficiency of the aggregate is dependent upon the aggregate pore structure. Generally, larger aggregates have a larger pore structure, which results in more efficient internal curing (Hammer et al., 2004).
- Similar to the idea that properly dispersed air bubbles improves durability, properly dispersed lightweight aggregate improves internal curing. Smaller aggregate sizes are better dispersed than larger aggregates (Bentz and Snyder, 2005).
- The desorption property of the lightweight aggregate indicates the ability of the aggregate to release water back into the concrete for internal curing. This is a measure of both the efficiency of the aggregate and can be related to absorption (Zhutovsky et al., 2002).
- Beneficial compressive stresses results from the swelling of concrete specimens that contain pre-soaked lightweight aggregate (Cusson and Hoogeveen, 2008).
- Consideration to the amount of water that is available from the aggregates that are not lightweight aggregate may need to be considered (Hammer et al., 2004).
- Proper handling in the field is an important consideration that influences the estimation of the LWA moisture content, even saturation of the LWA, and contamination of the aggregate. Attention to proper handling techniques must be provided to avoid

problems with yield, slump loss, pumping, and finishing (Villarreal, 2009).

Therefore, moderately sized aggregates (aggregates with large pores that can be well dispersed) at an optimal replacement level (preferably less than or equal to 20% by volume) is needed to ensure proper internal curing. It is also important to determine how the amount of aggregate replacement will affect the strength and durability of the concrete.

1.6 Scope

This research includes the evaluation of several mixes to determine the effectiveness of lightweight aggregates as an internal curing agent. Free shrinkage specimens and strength cylinders are evaluated to determine the effects of the lightweight aggregates. The mixes have a cement content of 540 lb/yd^3, a 0.44 water/cement ratio, 24.7% paste content and 8% air content. Both a 7-day and 14-day curing period are evaluated for the free shrinkage specimens.

Two programs are described. A total of six mixes are included in Program I: two control mixes and four mixes to evaluate lightweight aggregate for internal curing. Three mixes are used to evaluate three different replacement levels of the intermediate lightweight aggregate: a low, medium and high level of replacement. A total of eight mixes are included in Program II: two control mixes, four mixes with lightweight aggregate and G100 slag, and two mixes with limestone and G100 slag.

Chapter 2 Experimental Program

2.1 General

This chapter describes the procedures used in the laboratory, the materials, and equipment used to perform the evaluation of the mix designs as well as the test programs. The free shrinkage of a concrete mix is affected by several factors including the paste content, the water-cementitious material (*w/cm*) ratio, the cement type and fineness, the mineral admixture content, the aggregate type and content, the use of superplasticizers and duration of curing. Two test programs with 14 batches were evaluated. Test Program I evaluated different amounts of lightweight aggregate replacement for internal curing. Test Program II evaluated the use of lightweight aggregate with ground granulated blast furnace slag (slag). Both test programs included two control mixes; one granite mix and one limestone mix. The limestone mix was used to compare the effects of internal curing on reducing shrinkage between batches with lightweight aggregate and batches with limestone. The free shrinkage test results from the mixes using lightweight aggregates are compared to standard LC-HPC mixes with granite to evaluate the performance with the addition of the lightweight aggregate for internal curing.

2.2 Materials

The materials used in this study include granite, limestone, pea gravel, sand, a lightweight expanded shale, slag, Type I /II cement, water reducing admixture and air entraining agent. Each time a new aggregate sample was obtained, a new sieve analysis and specific gravity test were performed. The following sections describe the materials used in the study. The list of materials for each batch is summarized in Table 2-1.

Table 2-1: Material Summary

Batch No.	Description	Cement[1]	Slag[2]	Coarse Aggregate[3]	Pea Gravel[4]	Sand[5]	LWA[6]
	PROGRAM I						
#619	Granite Control	Type I/II #7	N/A	G-15 (a/b)	PG-14	S-15	N/A
#620	Limestone Control	Type I/II #7	N/A	LS-9	PG-14	S-15	N/A
#622	LWA (Low)[7]	Type I/II #7	N/A	G-15 (a/b)	PG-14	S-15	LW-A2
#628	LWA (Medium)[8]	Type I/II #7	N/A	G-20 (a/b)	PG-14	S-15	LW-A2
#654	FLWA (Medium)[9]	Type I/II #8	N/A	G-20 (a/b)	PG-14	S-16	FLW-A1
#634	LWA (High)[10]	Type I/II #7	N/A	G-20 (a/b)	PG-14	S-15	LW-A2
	PROGRAM II						
#639	Granite Control	Type I/II #8	N/A	G-20 (a/b)	PG-14	S-16	N/A
#640	30% G100 Slag, LWA	Type I/II #8	G100 Slag	G-20 (a/b)	PG-14	S-16	LW-A3
#655	30% G100 Slag, FLWA	Type I/II #8	G100 Slag	G-20 (a/b)	PG-14	S-16	FLW-A1
#642	60% G100 Slag, LWA	Type I/II #8	G100 Slag	G-20 (a/b)	PG-14	S-16	LW-A3
#648	60% G100 Slag II, LWA	Type I/II #8	G100 Slag	G-20 (a/b)	PG-14	S-16	LW-A3
#645	Limestone Control	Type I/II #8	N/A	LS-9	PG-14	S-16	N/A
#646	30% G100 Slag, Limestone	Type I/II #8	G100 Slag	LS-9	PG-14	S-16	N/A
#647	60% G100 Slag, Limestone	Type I/II #8	G100 Slag	LS-9	PG-14	S-16	N/A

Notes:

1 – Table 2-2
2 – Table 2-3
3 – Table 2-5
4 – Table 2-4
5 – Table 2-4
6 – Lightweight Aggregate Table 2-6 and Table 2-8
7 – Low replacement amount of lightweight aggregate
8 – Medium replacement amount of lightweight aggregate
9 – Fine lightweight aggregate
10 – High replacement level of lightweight aggregate

2.2.1 Cement

Two samples of Type I/II portland cement were obtained during this study. The cement was produced by Ashgrove in Chanute, Kansas. The first sample, denoted as Type I/II #7, had a specific gravity of 3.20 and a Blaine fineness of 1,875 ft^2/lb (384 m^2/kg). Type I/II #7 was used in batches #619, #620, #622, #628 and

#634. The second sample, denoted as Type I/II #8, had a specific gravity of 3.15 and a Blaine fineness of 1,655 ft^2/lb (339 m^2/kg). Type I/II #8 was used in batches #639, #640, #642, #645, #646, #647, #648, #654 and #655. The chemical composition of each sample of cement is shown in Table 2-2. The batches containing each cement are summarized in Table 2-1.

Table 2-2: Type I/II Portland Cement Characteristics

	Type I/II #7	Type I/II #8
C_3S	55%	54%
C_2S	20%	18%
C_3A	6%	6%
C_4AF	10%	11%
Blaine (m^2/kg)	384	339
Specific Gravity (SSD)	3.20	3.15

2.2.2 Mineral Admixtures

Test Program II used mineral admixture; slag. The ground granulated blast-furnace grade 100 slag (G100 Slag) was obtained from Holcim in Theodore, Alabama. The slag had a specific gravity of 2.86 and was used in batches #640, #642, #646, #647, #648, and #655. The chemical composition of the G100 slag is shown in Table 2-3. The batches containing the slag are summarized in Table 2-1.

Table 2-3: G100 Slag Characteristics

	G100 Slag
SiO_2	43.36%
Al_2O_3	8.61%
Fe_2O_3	0.37%
CaO	31.13%
MgO	12.50%
SO_3	2.24%
Na_2O	0.21%
K_2O	0.40%
TiO_2	0.32%
Mn_2O_3	0.35%
SrO	0.04%
LOI	0.37%
Specific Gravity (SSD)	2.86

2.2.3 Admixtures

The super plasticizer used in this study to adjust the slump for each batch was obtained on June 3, 2008 from Master Builders Technologies called Glenium 3000 NS. The air entraining agent used was obtained on May 28, 2008 from BASF called Master Builders MicroAir.

2.2.4 Fine Aggregate

Two samples of sand were obtained from Lawrence Ready Mix (LRM). The first sample, denoted as S-15, had a saturated surface dry (SSD) specific gravity of 2.61 and absorption (dry) of 0.33%. S-15 was used in batches #619, #620, #622, #628, and #634. The second sample, denoted as S-16, had a saturated surface dry (SSD) specific gravity of 2.61 and absorption (dry) of 0.33%. S-16 was used in batches #639, #640, #642, #645, #646, #647, #648, #654, and #655.

Table 2-4: Fine Aggregate Sieve Analysis, % Retained

	Sand		**Pea Gravel**
Sieve Size	S-15	S-16	PG-14
3/8 in. (9.5 mm)	0.00	0.00	0.00
No. 4 (4,750 μm)	1.52	1.20	11.28
No. 8 (2,360 μm)	12.58	6.97	57.36
No. 16 (1,180 μm)	23.85	16.07	29.30
No. 30 (600 μm)	28.15	24.82	1.47
No. 50 (300 μm)	28.09	37.73	0.34
No. 100 (150 μm)	5.55	12.01	0.11
No. 200 (75 μm)	0.20	0.73	0.05
Pan	0.06	0.47	0.09

One sample of pea gravel was obtained from LRM for this study. The pea gravel was KDOT classification UD-1 from Midwest Concrete Materials in Manhattan, Kansas. The sample, denoted as PG-14, had a saturated surface dry (SSD) specific gravity of 2.61 and absorption (dry) of 0.93%. PG-14 was used in every batch. A summary of the fine aggregate sieve analyses are shown in Table 2-4. The batches containing the fine aggregates are summarized in Table 2-1.

2.2.5 Coarse Aggregate

Two coarse aggregates were used in this study, granite and limestone. Two samples of granite were obtained from Fordyce in Kansas City, Kansas. Each granite had a maximum size aggregate (MSA) of 3/4 in. (19 mm). To aid in the optimization process, the granite samples were split on the 3/8 in. (9.5 mm) sieve. The aggregate that was 3/8 in. (9.5 mm) or larger was denoted with an 'a' and the aggregate that was No.4 (4,750 μm) or smaller was denoted with a 'b'. The first granite sample, denoted G-15a and G-15b, had an SSD specific gravity of 2.60 and absorption (dry) of 0.76%. The second granite sample, denoted G-20a and G-20b, had an SSD specific gravity of 2.60 and an absorption (dry) of 0.71%.

Table 2-5: Coarse Aggregate Sieve Analysis, % Retained

	Granite				**Limestone**
Sieve Size	G-15a	G-15b	G-20a	G-20b	LS-9
1½ in. (38.1 mm)	0.00	0.00	0.00	0.00	0.00
1 in. (25.4 mm)	0.00	0.00	0.00	0.00	0.00
¾ in. (19.0 mm)	0.00	0.00	0.00	0.00	0.00
½ in. (12.7 mm)	32.50	0.00	36.96	0.00	17.86
3/8 in. (9.5 mm)	65.93	0.00	59.28	0.00	28.92
No. 4 (4,750 μm)	0.00	92.47	0.00	85.46	46.14
No. 8 (2,360 μm)	0.00	5.38	0.00	10.48	4.58
No. 16 (1,180 μm)	1.57	2.15	3.76	4.06	0.00

One sample of KDOT approved limestone was obtained from LRM. The limestone also had a MSA of 3/4 in. (19 mm). The sample, denoted as LS-9, had an SSD specific gravity of 2.59 and absorption (dry) of 3.07%. The coarse aggregate sieve analyses are summarized in Table 2-5. The batches containing the coarse aggregates are summarized in Table 2-1.

2.2.6 Lightweight Aggregate

Six samples of lightweight aggregates were obtained from a local company, Buildex Incorporated located in Ottawa, Kansas. Buildex Incorporated supplies expanded shale aggregate from plants in Marquette, Kansas and New Market, Missouri. Six initial samples were obtained and included three different sizes of aggregates from both plants:

- ¼ x ⅛ in.
- ⅛ x 0 in.
- ⅛ x 0 in., Crushed

A number of variables were compared before choosing the appropriate aggregate for this study. First, based on the previous work done, larger lightweight aggregates have been shown to result in a larger pore structure which improves internal curing (Zhutovsky et al., 2002). Next, a comparison of combined gradation using *KU Mix* (an aggregate optimization and mix design program developed at KU) showed that the larger aggregate also improved the aggregate gradation. The last variable considered was the aggregate absorption. The absorption of the aggregate can be related to the desorption (the amount of water that can be supplied for internal curing) of the aggregate; i.e. a higher absorption implies a higher desorption property. Table 2-6 shows the properties for all of the aggregates, as reported from Buildex.

Table 2-6: Lightweight Aggregate Properties

Aggregate	Marquette, Kansas			New Market, Missouri		
	Specific Gravity	Density lb/ft^3 (kg/m^3)	Percent Absorption	Specific Gravity	Density lb/ft^3 (kg/m^3)	Percent Absorption
¼ x ⅛ in.	1.15	42 (25)	16	1.20	44 (26)	12
⅛ x 0 in.	1.50	47 (29)	10	1.80	58 (34)	8
⅛ x 0 in., Crushed	1.50	47 (29)	10	1.80	58 (34)	8

Table 2-7 shows the sieve analyses that were performed on the aggregate. After comparing the variables from Table 2-6 and Table 2-7, the ¼ × ⅛ in. aggregate from Marquette, Kansas, had the highest absorption and largest aggregate gradation and was used for the primary evaluation of internal curing for this study.

Table 2-7: Initial Lightweight Aggregate Sieve Analysis, % Retained

Sieve Size	Marquette, Kansas			New Market, Missouri		
	¼ x ⅛ in.	⅛ x 0 in.	⅛ x 0 in., Crushed	¼ x ⅛ in.	⅛ x 0 in.	⅛ x 0 in., Crushed
3/8 in. (9.5 mm)	0.00	0.00	0.00	0.00	0.00	0.00
No. 4 (4,750 μm)	39.52	0.14	0.03	24.98	0.00	0.00
No. 8 (2,360 μm)	60.05	18.77	18.19	70.52	4.08	3.47
No. 16 (1,180 μm)	0.09	36.19	42.68	4.06	53.95	31.09
No. 30 (600 μm)	0.04	23.87	19.80	0.05	29.20	23.99
No. 50 (300 μm)	0.04	13.40	8.34	0.03	9.32	14.51
No. 100 (150 μm)	0.02	4.87	3.41	0.02	1.25	6.92
No. 200 (75 μm)	0.05	1.29	2.04	0.03	0.49	4.53
Pan	0.20	1.46	5.51	0.30	1.72	15.49

Two samples of the ¼ × ⅛ in. from Marquette, Kansas were obtained, denoted as LW-A2 and LW-A3. In addition to these two samples, a smaller, crushed sample was obtained to determine whether a smaller sized aggregate had better internal curing capabilities. The smaller aggregate was denoted as FLW-A1. The aggregate gradations of the delivered materials are shown in Table 2-8. The batches containing the lightweight aggregate and fine lightweight aggregate (abbreviated LWA and FLWA, respectively) are summarized in Table 2-1. Lightweight aggregate total moisture contents and specific gravities are reported in *Section 2.3.7 Vacuum Saturation*.

Table 2-8: Final Lightweight Aggregate Sieve Analysis, % Retained

	Lightweight Aggregate		
Sieve Size	FLW-A1	LW-A2	LW-A3
3/8 in. (9.5 mm)	0.00	0.00	0.00
No. 4 (4,750 µm)	4.49	23.38	22.10
No. 8 (2,360 µm)	25.70	73.73	75.86
No. 16 (1,180 µm)	36.51	1.20	1.47
No. 30 (600 µm)	17.15	0.11	0.08
No. 50 (300 µm)	9.10	0.20	0.02
No. 100 (150 µm)	3.68	0.39	0.02
No. 200 (75 µm)	1.53	0.41	0.04
Pan	1.84	0.58	0.41

2.3 Laboratory Work

The free shrinkage test procedure outlined in ASTM C157 “Standard Test Method for Length Change of Hardened Hydraulic-Cement Mortar and Concrete” was followed for the casting and testing of the free shrinkage specimens. Every batch consisted of three specimens that were cured for seven days and three specimens that were cured for 14 days in a lime-saturated tank. All specimens were allowed to dry in a controlled temperature and humidity environment. In addition to six free shrinkage specimens per batch, ASTM C39 “Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens” was used to cast and test three 7-day strength cylinders and three 28-day strength cylinders.

2.3.1 ASTM C 157 Free-Shrinkage Specimens

The free shrinkage molds were cold-rolled steel molds that were purchased from Humboldt Manufacturing Company and shown in Figure 2-1.

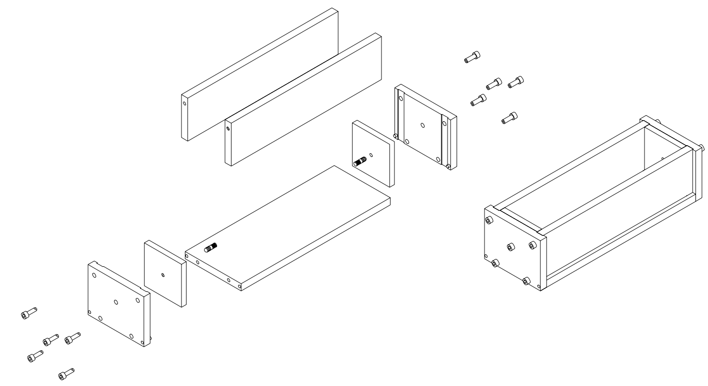

Figure 2-1: Free Shrinkage Molds [Tritsch et al. (2005)]

The free shrinkage specimens measured $3 \times 3 \times 11\frac{1}{4}$ in. ($76 \times 76 \times 286$ mm). Gage studs measured 10 in. (254 mm) between studs and are shown in Figure 2-2.

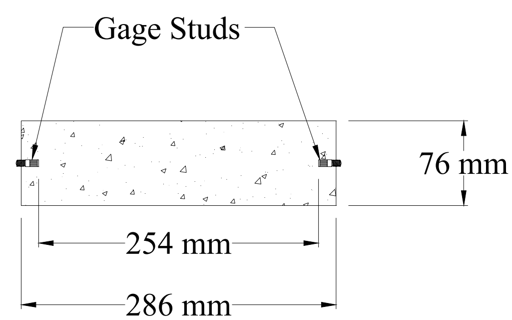

Figure 2-2: Free Shrinkage Specimens [Tritsch et al. (2005)]

2.3.2 Free Shrinkage Measurements and Data Collection

Free shrinkage readings were taken using the 10 in. (254 mm) Effective Length Comparator/Dial Indicator — H-3250, a mechanical dial gage length comparator, that was purchased from Humboldt Manufacturing Company (Figure 2-3). The comparator had a 0.4 in. (10 mm) range and is accurate to 0.0001 in.

(0.00254 mm). Each day, the comparator was set to a reference reading using a 10 in. (254 mm) calibration bar. A reference reading was then checked every nine readings. The reference bar, as well as the specimens, was carefully placed so that the orientation was the same for every reading. The readings were taken by spinning the calibration bar or specimen in the clockwise direction and reading the minimum number on the dial.

Figure 2-3: Length Comparator [www.humboldtmfg.com/c-4-p-274-id-4.html]

The initial reading was taken within 23½ ± ½ hours after casting prior to being placed in the curing tank. Free shrinkage was recorded in terms of shrinkage strain (measured in με). The strain was determined by dividing the change in length of the specimen by the gage length of 10 in. (254 mm). The change in length was found by taking the difference between the daily readings and the initial reading. Final results are presented as the average strain of the three specimens.

Unlike the ASTM standard, readings were taken more frequently than recommended. For the first 30 days, readings were taken every day. From days 31-90, readings were taken every other day. After 91 days, readings were taken once a week. Specimens were monitored for 180 days for both test programs.

2.3.3 Casting

Specimens were cast immediately following the testing of the concrete slump and air. After the molds were coated with a layer of baby oil (to help in the removal of the specimens), concrete was placed within the molds in approximately two equal layers. After adding each layer of concrete, the concrete was consolidated on a vibrating table with an amplitude of 0.006 in. (0.15 mm) and a frequency of 60 Hz for 30 seconds. The molds were then struck off using a 2 × 5½ in. (50 × 135 mm) steel screed. After the molds were cleaned, they were moved to an environmentally-controlled lab for the initial curing.

2.3.4 Curing

After the six specimens were cleaned and moved to the environmentally controlled lab, they were sealed with 6 mil (152 μm) Marlex® strips, followed by 3.5 mil (89 μm) plastic sheets that were secured with rubber bands. The specimens were grouped together in sets of three and covered again with ½ in. (12.7 mm) thick Plexiglas® plates and four 6 × 12 in. (152 × 305 mm) cylinders were placed on top.

All six specimens were demolded within 23½ ± ½ hours after casting and were immediately wrapped in wet towels and placed under running water to prevent moisture loss. The initial length readings were taken and the specimens were placed in the lime-saturated tank for 6 or 13 days (making the total curing time 7 or 14 days). After curing, the specimens were allowed to dry in a controlled temperature and humidity environment.

2.3.5 Drying

Specimens were allowed to dry in a fabricated environmental tent. The tent was kept at 73° ± 3°F (23° ± 2°C) and 50% ± 4% relative humidity. Changes in conditions due to the season were stabilized through the use of a humidifier (mainly during the winter) and a dehumidifier (mainly during the summer). The specimens were placed on wooden racks and were placed with at least 1 in. (25 mm) of clearance to allow for proper air circulation. The specimens were not removed from the tent after being placed in the tent.

2.3.6 ASTM C39 Strength Cylinders

Six strength cylinders were cast simultaneously with the free shrinkage specimens; three 7-day strength cylinders and three 28-day strength cylinders. Cylinders were 4 × 8 in. (102 × 203 mm) in dimension. Concrete was placed in accordance with ASTM C39, struck off and sealed with 3.5 mil (89 μm) plastic sheets that were secured with rubber bands for the initial curing periods. Cylinders were demolded 23½ ± ½ hours after casting and immediately placed in the lime-saturated tank for the remainder of the curing period (6 or 27 days). Three cylinders were tested at 7 days and three cylinders were tested at 28 days for strength.

2.3.7 Vacuum Saturation

Determining the appropriate values for total moisture content and specific gravity of the lightweight aggregate to be used in designing concrete mixes was a challenge. It was first necessary to find a repeatable and reliable way to infuse the aggregate with water. In the field, Buildex Incorporated offers vacuum saturated aggregate from the New Market, Missouri plant. After several attempts at saturating the aggregate from the Marquette, Kansas plant by soaking the aggregate in a bucket of water, a simple vacuum saturation device was developed, shown in Figure 2-4. The system was able to achieve total moisture content values in one hour that required approximately 16 hours of soaking without vacuum saturation.

The vacuum saturation system consisted of a Gast Rotary Vane air compressor/vacuum pump (Model #0211), a 19 × 28 in. (48 × 53 cm) steel barrel and a five gallon bucket. A ¼ in. (6 mm) plastic tube connected the steel barrel to both the vacuum pump and the five gallon bucket. A lid for the steel barrel was constructed out a sheet of scrap metal. The lid had valves for the vacuum pump line and the five gallon bucket line. It also had a pressure gage, two open areas for viewing and a valve that prevented the vacuum from reaching a pressure that could crush the barrel.

The system was very simple to operate. First, the aggregate that was to be saturated was placed in the steel barrel and the lid was placed on top. The five gallon bucket was then filled with water (to the water fill line) and the valve that connected the water to the barrel was closed. The valve that was connected to the vacuum was opened and the vacuum turned on. Once the gage on the barrel indicated that there was 5.9 psi (12 in. Hg) of vacuum, the valve to the water was opened. The water was then pulled into the barrel until it reached a designated mark on the barrel (water empty line) and the valve was closed. Care was taken to ensure that the water bucket did not completely empty of water, which would have released the vacuum within the barrel. The system was kept under constant pressure for one hour to saturate the aggregate. Timing was started once the water was introduced into the steel barrel.

Figure 2-4: Vacuum Saturation Equipment

After full saturation had been achieved, the fine and intermediate lightweight aggregates were prepared for batching in a slightly different manner from each other.

The intermediate sized aggregate (LW-A2 or LW-A3) was removed from the steel barrel and placed onto dry towels. The aggregate was 'dried' with the towels until the saturated surface dried (SSD) condition was met. This was defined when the aggregate no longer had a shine on the particles. At this point, the aggregate was weighed for batching. It was stored in a bucket covered in a wet towel until being added to the mixer.

The absorption of the aggregate (reported as 'total moisture content') was found by weighing a representative sample of the SSD aggregate (approximately 1.1 lb or 500 g) and placing it in the oven for a minimum of 24 hours. The absorption (Abs) was then defined as the quotient of the difference between the SSD weight (SSD_{wt}) and the oven-dried weight (OD_{wt}) and the oven-dried weight, as shown in Eq. (2-3).

$$Abs = \frac{SSD_{wt} - OD_{wt}}{OD_{wt}} \qquad \textbf{(2-1)}$$

The specific gravity of the sample was assumed to be constant during batching because the aggregate was prepared in the same manner for every batch. It is important to note this because the longer aggregate is allowed to soak, the more water it will absorb, and the specific gravity of the aggregate will increase. Specific gravity was determined through the use of a pycnometer. A representative sample of the SSD aggregate (approximately 1.1 lb or 500 g) was weighed and recorded as 'A'. The pycnometer was filled with water and its weight was recorded as 'B'. The pycnometer was then filled with the SSD sample and water and their total weight was recorded as 'C'. The specific gravity was then calculated using Eq.(2-2)

$$SG = \frac{A}{A + B - C} \qquad \textbf{(2-2)}$$

where *SG* is the specific gravity.

For the fine aggregate (FLW-A1), reaching an "SSD" condition was much more difficult because of the size of the particles. The proper method, as defined by ASTM C70 "Standard Test Method for Surface Moisture in Fine Aggregate", which involved the use of a blow dryer, was not employed because the blow dryer would have scattered the aggregate so that some particles would be lost.

Several trials were run until a repeatable and consistent method of preparing the aggregate was achieved. After the aggregate had been vacuum saturated, it was removed from the steel barrel and placed evenly in No. 50 (300 μm) sieves. After the sieves were full, they were tapped 25 times around the edge and set into a sink to allow for drainage. They were covered with a wet (but not dripping) towel and allowed to sit for 10 minutes. After 10 minutes, the sieves were set at an angle and allowed to drain for 30 seconds. The aggregate was then spread out very thin on newspaper that was four or five layers thick. The aggregate was once again allowed to sit for 10 minutes. After five minutes, the aggregate was rolled gently to ensure that all sides of particle were placed against the newspaper. After 10 minutes of rolling the aggregate, the aggregate was ready and weighed for batching. It was stored in a bucket covered by a wet towel until being added to the mixer. The absorption and specific gravity for the fine lightweight aggregate was determined using the same procedure as for the intermediate lightweight aggregate. This method resulted in fairly consistent results.

Working with the fine lightweight aggregate presented a number of problems. The aggregate had a large percentage of particles that were finer than the No. 50 (300 μm) sieve (7.05%), so that when draining the aggregate in No. 50 (300 μm) sieves many of the fine particles were lost. This also occurred when allowing the aggregate to dry on the newspaper. Accounting for this loss in particles was difficult. When visually inspecting the intermediate fine lightweight aggregate for an SSD condition, it was easy to see that there was not a shine on the particles. The fine lightweight aggregate, however, was so small that visually inspecting for the SSD condition was not possible.

Table 2-9: Lightweight Aggregate Total Moisture Contents

Batch No.	Batch Description	LWA Used	Specific Gravity	Total Moisture Content
#622	LWA (Low)	LW-A2	1.54	24.73%
#628	LWA (Medium)	LW-A2	1.54	25.18%
#654	FLWA (Medium)	FLW-A1	1.53	28.36%
#634	LWA (High)	LW-A2	1.54	29.49%
#640	30% G100 Slag, LWA	LW-A3	1.54	29.96%
#655	30% G100 Slag, FLWA	FLW-A1	1.53	25.41%
#642	60% G100 Slag, LWA	LW-A3	1.54	29.67%
#648	60% G100 Slag II, LWA	LW-A3	1.54	26.50%

The specific gravity used for analysis in this research was found by averaging several tests of the lightweight aggregates. The specific gravity for all intermediate lightweight aggregate (LW-A2 and LW-A3) was determined to be 1.54. The specific gravity for the fine lightweight aggregate (FLW-A1) was determined to be 1.53. The total moisture contents for the lightweight aggregate used in this research is reported in Table 2-9. The total moisture content ranged from 24.73% to 29.96% for the intermediate lightweight aggregate and 25.41% to 28.36% for the fine lightweight aggregate.

2.3.8 Mixing

All batches were mixed by hand using a counter-current pan mixer. The batch size for all of the batches was 0.04 yd^3 (0.03 m^3). All of the course aggregates were allowed to soak in water for a minimum of 24 hours and batched in the SSD condition. The lightweight aggregate was batched in the SSD condition as defined in *Section 2.3.7*. The pea gravel and sand were batched with excess free moisture that was measured in accordance with ASTM C70 "Standard Test Method for Surface Moisture in Fine Aggregate."

The mixing procedure was the same for each batch to minimize variation due to batching. The procedure was as follows:

1. The interior surfaces of the mixer were dampened with a wet sponge.
2. The coarse aggregate and eighty percent of the mixing water was added to the pan mixer and allowed to mix for 1½ minutes.
3. The cement and slag (if required) was slowly added and allowed to mix for 1½ minutes.
4. The sand, pea gravel and lightweight aggregate (if required) were added and allowed to mix for 2 minutes.
5. The super plasticizer was added with 10% of the mixing water and allowed to mix for 1 minute.

6. The air entraining agent was added with the remaining mix water for 1 minute.
7. The plastic concrete was mixed for 3 minutes.
8. The concrete was allowed a 5 minute rest, during which the pan was covered with damp towels.
9. The concrete was mixed for 3 more minutes.
10. The concrete was then ready for the slump and air test.

The temperature of the concrete was checked with a thermometer during the 5 minute resting period. Liquid nitrogen was used to cool the concrete if the temperature exceeded 70°F (21°C).

2.4 Internal Curing Application

2.4.1 Conventional LC-HPC Mix Design

All mixes in both test programs were prepared to satisfy the requirements of low-cracking high-performance concrete. The University of Kansas has developed concrete specifications to construct Low-Cracking High-Performance Concrete (LC-HPC) bridge decks in the field *[Lindquist (2008)]*. The goal of LC-HPC is to minimize the amount of cracking that a bridge deck will experience over its life. To achieve this, LC-HPC takes advantage of lower cement and water contents, a low slump, a low evaporation rate and better construction methods and materials. The concrete specifications define parameters for an optimized aggregate gradation: a low-absorption aggregate with 1 in. (25 mm) MSA; a cement content of 540 lb/yd^3

(320 kg/m^3) or less; a *w/c* ratio between 0.43 and 0.45; an air content between 6.5% and 9.5%; a slump between 1 ½ and 3 in. (38 and 76 mm); controlled concrete temperature and improved curing to minimize shrinkage. An Excel-based program (Microsoft® Office Excel® (2007)) was developed at the University of Kansas called *KU Mix* to optimize the aggregate gradation so as to improve workability, pumping, consolidation, finishing, and consistency with a minimized paste content in the concrete.

Two control mixes were used for each test program to compare shrinkage properties with concrete containing lightweight aggregate for internal curing. The control mix was designed according to the specifications for LC-HPC bridge decks and the aggregate was optimized using *KU Mix*. The conventional parameters that were used for the control mixes include the following:

▪ Cement Content:	540 lb/yd^3 (320 kg/m^3)
▪ Water/Cement Ratio:	0.44
▪ Maximum Size Aggregate:	1 in. (25 mm)
▪ Three aggregates for optimization:	Granite/Limestone
	Pea Gravel
	Sand

2.4.2 Internal Curing Equation

As shown in *Section 1.5*, a theoretical amount of required lightweight aggregate to supply sufficient internal curing to prevent self-desiccation and autogenous shrinkage can be determined based on the cement content and key properties of the lightweight aggregate. Although these values were developed considering mixes with lower *w/c* ratios than the 0.44 used in this study, the benefits of internal curing on reducing total shrinkage will still be realized at higher *w/c* ratios. The following equations were used to determine the theoretical replacement amount (by volume) for the lightweight aggregate to supply sufficient internal curing:

$$V_{LWA} = \frac{C \times \alpha \times CS}{S \times \phi \times SG \times \rho} \tag{1-8}$$

$$W = C \times \alpha \times CS \tag{1-9}$$

$$R_{LWA} = \frac{V_{LWA}}{V_{Total}} \times 100 \tag{1-10}$$

The following values were used to determine the theoretical replacement level. The cement factor (C) was 540 lb/yd^3 (320 kg/m^3); this is based on the LC-HPC specifications designated by the University of Kansas. The degree of hydration (α) was estimated as 1 because the *w/c* ratio was 0.44; this follows research by Bentz and Snyder (2005) and Bentz et al. (2005). Chemical shrinkage (CS) was estimated as 0.07 based on the work done by Bentz et al. (2005). The saturation (S) of the lightweight aggregate was estimated at 100%. The value for the aggregate absorption (ϕ) was 0.20 as determined through trials with the aggregate. The specific gravity (SG), as determined through trials with the aggregates, was 1.54 for the intermediate lightweight aggregate and 1.53 for the fine lightweight aggregate. The density of water (ρ) was 62.4 lb/yd^3 (1,000 kg/m^3).

2.4.3 KU Mix Design Application

KU Mix was used to compare an optimized aggregate gradation mix with mix designs used for evaluating internal curing. *KU* Mix, however, required some modifications to accommodate aggregates with different specific gravities. Originally, *KU Mix* assumed that all the aggregates had roughly the same specific gravity. This is almost true when dealing with normal weight aggregates for a concrete mix. The specific gravity of lightweight aggregates, however, can be as much as half that of a normal weight limestone or granite. *KU Mix* was modified so that calculations for the amounts of aggregates were based on volumes (accounting for the individual specific gravities) rather than weights.

The modifications to the program were simple. The first modification was to adjust the effective specific gravity. When determining the total weight of aggregate, the program previously found an effective specific gravity for each individual aggregate. Instead of finding an effective specific gravity, the modified program assumes that all aggregates have a specific gravity of 2.60 at the start of the optimization process. This essentially ignores the density of each aggregate and optimizes purely on volume to create a well-graded mix based on particle size rather than particle weight.

The other modification to the program was the process that determined the batch weights of the aggregates after the optimization was complete. Previously, the batch weight of the individual aggregates was determined as follows:

$$W_i = V_{agg} \times SG_{eff} \times UW_w \times MF_i \quad \textbf{(2-3)}$$

where W_i is the total weight of each individual aggregate, V_{agg} is the total volume of the aggregate, SG_{eff} is the effective specific gravity of all the aggregates, UW_w is the unit weight of water and MF_i is the individual aggregate mass fraction (determined through optimization). To account for the individual aggregate specific gravity, Eq. (2-3) was modified as follows:

$$W_i = V_{agg} \times \frac{SG_i}{2.60} \times UW_w \times MF_i \qquad \textbf{(2-4)}$$

where SG_i is the specific gravity of the individual aggregate. This modification individually corrects the batch weights for each aggregate based on the correct specific gravity for that aggregate.

KU Mix also evaluates every mix design using the Modified Coarseness Factor Chart (MCFC) which is shown in Figure 2-5. The Modified Coarseness Factor Chart (Shilstone, 2002) is a visual representation of the aggregate gradation based on comparing the Coarseness Factor (CF) to the Workability Factor (WF).

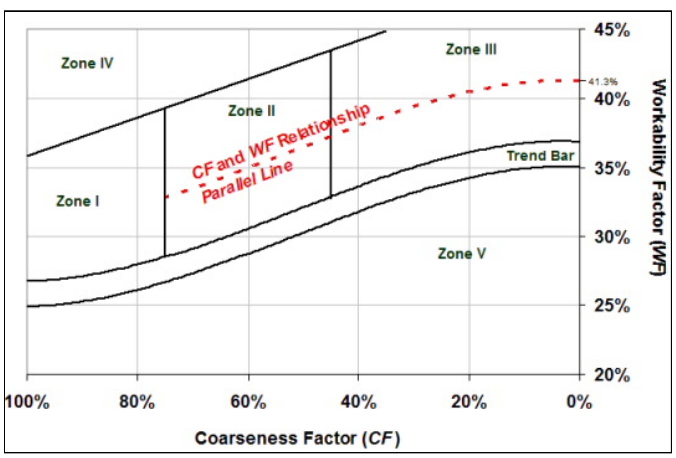

Figure 2-5: Modified Coarseness Factor Chart [Shilstone (2002)]

The CF is used to describe the relationship between the quality particles (Q) and the intermediate particles (I) of a mix. The quality particles are defined as the sum of the percents retained on sieves ⅜ in. through 1½ in. (9.5 mm through 38.1 mm). The intermediate particles are defined as the percents retained on the No. 4 and No. 8 (4,750 and 2,360 μm) sieve. The Coarseness Factor is the ratio of the *Q* particles to the sum of the *Q* particles and the *I* particles as shown in Eq. (2-5).

$$CF = \frac{Q}{Q+I} \tag{2-5}$$

The WF is used to describe a relationship between the *Q* particles, the *I* particles and the workability particles (*W*) of a mix. The workability particles are defined as the sum of the percents retained from the pan to the No. 16 (1,180 μm) sieve. WF quantifies the effect of all the particles that aid the workability of a mix. The WF is defined as the ratio of the *W* particles to the sum of the *Q* particles, the *I* particles and the *W* particles as shown in Eq. (2-6).

$$WF = \frac{W}{Q+I+W} \tag{2-6}$$

The MCFC has five zones that characterize different concrete properties and are shown in Figure 2-5:

where:

Zone I: Typically is a gap graded mixture, is non-cohesive and has a high potential for segregation.

Zone II: Optimal zone for mixes with maximum size aggregate (MSA) ranging from ¾ to 1½ in. (19 to 38 mm).

Zone III: Optimal zone for mixes with MSA less than ¾ in. (19 mm).

Zone IV: Produces concrete that has an excessive amount of fine aggregate. Mixes in this zone typically require fine aggregate with higher water contents and have some potential for segregation.

Zone V: Typically a rocky, harsh concrete that is non-plastic.

Trend Bar: The region where the maximum aggregate density is defined for a mix.

A point (CF, WF) that lies on a line parallel to the middle of Zone II and Zone III represents a mix that is most optimal for this research.

2.5 Free Shrinkage Test Programs

2.5.1 General

Several mixes were batched to determine the effectiveness of lightweight aggregates as an internal curing agent. Free shrinkage specimens were cast to evaluate the performance of concrete mixes with the addition of lightweight aggregates. The mixes were designed to have a cement content of 540 lb/yd^3 (320 kg/m^3), a 0.44 water/cement ratio, 24.7% paste content and 8% air content. Both a 7-day and 14-day curing period were evaluated. Strength cylinders were cast for every batch.

2.5.2 Program I

A total of six mixes were designed for Program I: two control mixes and four mixes to evaluate lightweight aggregate for internal curing. Three mixes evaluated three different replacement levels of the intermediate lightweight aggregate; a low level of replacement, a medium level of replacement and a high level of replacement. The replacement levels were chosen based on the previous research with autogenous shrinkage as discussed in *Chapter 1 Introduction and Background*. Even though the equations were developed for mixes with much lower *w/cm*, the benefits of internal curing to eliminate self-desiccation will still be realized in this program as a reduction in the total shrinkage. Using Eq. (1-8) the volume of lightweight aggregate needed for internal curing is as follows:

$$\begin{aligned} V_{LWA} &= \frac{C \times \alpha \times CS}{S \times \varphi \times SG \times \rho} \\ &= \frac{540^{lb/yd^3} \times 1.0 \times 0.07^{lb/lb}}{1.0 \times 0.20 \times 1.54 \times 62.4^{lb/yd^3}} \left[= \frac{320^{kg/m^3} \times 1.0 \times 0.07^{kg/kg}}{1.0 \times 0.20 \times 1.54 \times 37.0^{kg/m^3}} \right. \\ &= 1.97^{ft^3/yd^3} \qquad \left. = 0.0730^{m^3/m^3} \right] \end{aligned} \tag{1-8}$$

A volume of 1.97 ft^3/yd^3 (0.0730 m^3/m^3) results in the following amount of water available for internal curing by using Eq. (1-9):

$$\begin{aligned} W &= C \times \alpha \times CS \\ &= 540^{lb/yd^3} \times 1.0 \times 0.07^{lb/lb} \left[= 320^{kg/m^3} \times 1.0 \times 0.07^{kg/kg} \right. \\ &= 37.8^{lb/yd^3} \qquad \left. = 22.4^{kg/m^3} \right] \end{aligned} \tag{1-9}$$

Equation (1-10) was used to determine the percent replacement of the lightweight aggregate that is required to provide *W*:

$$\begin{aligned} R_{LWA} &= \frac{V_{LWA}}{V_{Total}} \times 100 \\ &= \frac{1.97^{ft^3/yd^3}}{18.33^{ft^3/yd^3}} \times 100 \left[= \frac{0.0730^{m^3/m^3}}{0.6789^{m^3/m^3}} \times 100 \right. \\ &= 10.7\% \qquad \left. = 10.7\% \right] \end{aligned} \tag{1-10}$$

The volume replacement (10.7%) was designated as the medium level of replacement (medium). A lower level (low), 75% of the medium level of replacement, and a high level (high), 125% of the medium level replacement, were the other two replacement levels. The lower level replacement was 8.0% by volume and the high level of replacement was 13.4% by volume. The batch that evaluated the fine lightweight aggregate was the same volume replacement as the medium level of replacement.

The intermediate lightweight aggregate replaced the pea gravel in each mix, which had a similar gradation to that of the intermediate lightweight aggregate. The fine lightweight aggregate was used to replace the sand. By only replacing the pea gravel in the mixes with the intermediate lightweight aggregate, all other variables were held constant (as compared with the Granite Control) and a fair comparison of shrinkage properties was made between the mixes with varying amounts of lightweight aggregate. These mixes were compared to 2 control mixes, one with all granite and the other with limestone. The following is a summary of the mixes that were cast for Program I:

- SSD Granite Control
- SSD Limestone Control
- SSD Granite with LWA (Low)
- SSD Granite with LWA (Medium)
- SSD Granite with LWA (High)
- SSD Granite with FLWA (Medium)

2.5.2.1 SSD Granite Control

Figure 2-6 shows the mix design containing granite that was optimized using *KU Mix* and was used as the control mix for Program I. The SSD Granite Control had an optimized aggregate gradation and used four aggregates (two granite sizes, pea gravel, and sand) and Type I-II portland cement.

Contractor: NORMALIZED SPECIFIC GRAVITIES
Project: #619: Control
Source of Concrete: Program I

Material / Source or Designation / Blend [1]	Quantity (SSD)	S.G.	Yield, ft^3
Type I/II / Ashgrove #7 / 100%	540 lb	3.20	2.70
Water	237 lb	1.00	3.80
CA-15 Granite >=3/8'' / G-15(a) / 24.36%	727 lb	2.60	4.48
CA-15 Granite <=3/8'' / G-15(b) / 16.72%	499 lb	2.60	3.08
Pea Gravel / PG-14 / 22.95%	685 lb	2.61	4.21
Sand / S-15 / 35.98%	1074 lb	2.62	6.57
1/4 X 1/8 Marq, KS / LW-A2 / 0%	0 lb	1.54	0.00
Total Air, percent	8%		2.16
MicroAir / Master Builders	1.6 fl oz (US)	1.01	0.00
Glenium 3000NS / Master Builders	12.6 fl oz (US)	1.08	0.01
			27.00

1 The blend percentage indicated (by weight) is listed separately for cementitious materials and aggregates.

Total Water Content (including water in admixtures), lb		238		
Water / Cementitious Material Ratio:		0.44		
Concrete Unit Weight, pcf		139.4		
Target Slump, in.		3 ± 0.5		
Paste Content, percent		24.10%		
Workability Factor (WF)	Target:	38.2	Actual:	38.2
Coarseness Factor (CF)	Target:	39.3	Actual:	39.3

Figure 2-6: SSD Granite Control (*KU Mix*)

Conversion Factors:
1 ft^3 = 0.0283 m^3
1 lb = 0.454 kg
1 in. = 2.54 cm
1 lb/ft^3 = 16.0 kg/m^3
1 fl oz = 29.6 mL

The total volume for each aggregate can be determined with Eq. (2-7).

$$V = \frac{M_{agg}}{SG \times \rho} \tag{2-7}$$

where V is the volume of the aggregate (ft^3/yd^3 or m^3/m^3), M_{agg} is the mass of the individual aggregate (lb/yd^3 or kg/m^3), SG is the specific gravity of the individual aggregate and ρ is the density of water (62.4 ft^3/yd^3 or 1,000 kg/m^3). Table 2-10 is a summary of the mix showing the batch weights, percentage by weight, the batch volumes and the percentage by volume for the SSD Granite Control mix.

Table 2-10: SSD Granite Control

Aggregate	Specific Gravity	Weight lb/yd^3 (kg/m^3)	% by Weight	Volume ft^3/yd^3 (m^3/m^3)	% by Volume
G-15 (a)	2.60	727 (431)	24.4	4.48 (0.166)	24.4
G-15 (b)	2.60	499 (296)	16.7	3.08 (0.114)	16.8
PG-14	2.61	685 (406)	22.9	4.21 (0.156)	23.0
S-15	2.62	1,074 (637)	36.0	6.57 (0.243)	35.8
TOTAL		**2,985 (1,770)**	**100**	**18.34 (0.679)**	**100**

Figure 2-7 shows that the mix had an optimized gradation. The aggregate gradation fell in Zone III which was optimal for this research.

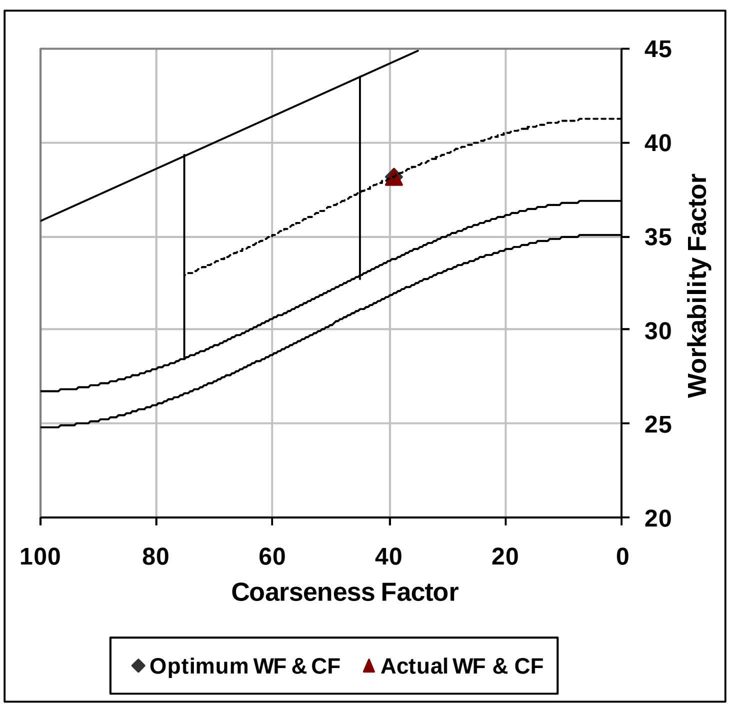

Figure 2-7: MCFC SSD Granite Control

2.5.2.2 SSD Limestone Control

Figure 2-8 shows the mix design containing limestone that was optimized using *KU Mix*. The SSD Limestone mix had an optimized aggregate gradation and used four aggregates (two sizes of Kansas Department of Transportation approved limestone, pea gravel and sand) and Type I-II portland cement.

Contractor:	NORMALIZED SPECIFIC GRAVITIES			
Project:	#620: Limestone			
Source of Concrete:	Program I			
Material / Source or Designation / Blend[1]		Quantity (SSD)	S.G.	Yield, ft^3
Type I/II / Ashgrove #7 / 100%		540 lb	3.20	2.70
Water		237 lb	1.00	3.80
KDOT Limestone / LS-9 / 40.8%		1215 lb	2.59	7.52
Pea Gravel / PG-14 / 17.53%		522 lb	2.61	3.21
Sand / S-15 / 41.67%		1241 lb	2.62	7.60
Total Air, percent		8%		2.16
MicroAir / Master Builders		1.6 fl oz (US)	1.01	0.00
Glenium 3000NS / Master Builders		12.6 fl oz (US)	1.08	0.01
1 The blend percentage indicated (by weight) is listed separately for cementitious materials and aggregates.				27.00

Total Water Content (including water in admixtures), lb		238		
Water / Cementitious Material Ratio:		0.44		
Concrete Unit Weight, pcf		139.1		
Target Slump, in.		3 ± 0.5		
Paste Content, percent		24.10%		
Workability Factor (WF)	Target: 38.2		Actual:	41.6
Coarseness Factor (CF)	Target: 39.2		Actual:	33.2

Figure 2-8: SSD Limestone Control (*KU Mix*)

Conversion Factors:
1 ft^3 = 0.0283 m^3
1 lb = 0.454 kg
1 in. = 2.54 cm
1 lb/ft^3 = 16.0 kg/m^3
1 fl oz = 29.6 mL

Table 2-11 is a summary of the mix showing the batch weights, percentage by weight, the batch volumes and the percentage by volume.

Table 2-11: SSD Limestone Control

Aggregate	Specific Gravity	Weight lb/yd^3 (kg/m^3)	% by Weight	Volume ft^3/yd^3 (m^3/m^3)	% by Volume
LS-9	2.59	1,215 (721)	40.8	7.52 (0.279)	41.0
PG-14	2.61	522 (310)	17.5	3.21 (0.119)	17.5
S-15	2.62	1,241 (736)	41.7	7.60 (0.281)	41.5
TOTAL		**2,978 (1,767)**	**100**	**18.33 (0.679)**	**100**

Figure 2-9 shows that the mix had an actual gradation that fell a little outside the optimized gradation. The gradation of the mix was adjusted manually to get a closer fit to the ideal haystack shape for a well graded mix, which is shown in Figure 2-9. The aggregate gradation, however, still fell in Zone III and did not prove to be a challenge when batching.

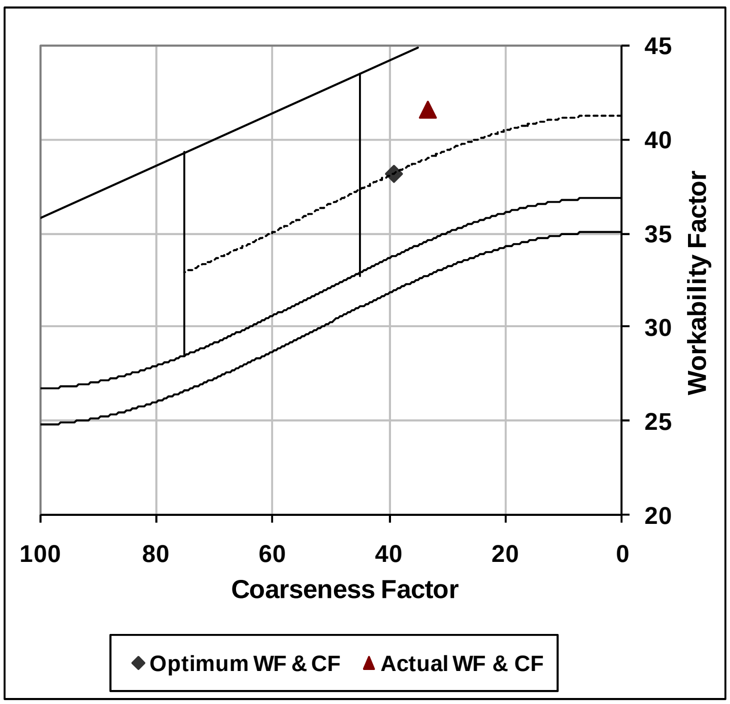

Figure 2-9: MCFC SSD Limestone Control

2.5.2.3 SSD Granite with LWA (Low)

The SSD Granite with LWA (low) mix was designed by replacing 8.0% of pea gravel in the optimized Granite Control with lightweight aggregate. Due to slight variations in actual total moisture content, the exact replacement level was 8.4% by volume. The goal of this replacement level was to achieve approximately 28.4 lb/yd^3 (16.8 kg/m^3) of water that could be available for internal curing. The mix used five aggregates (two sizes of granite, pea gravel, sand and the lightweight aggregate from Marquette, Kansas) and Type I-II portland cement. Figure 2-10 shows the actual mix design for this batch.

Contractor:	NORMALIZED SPECIFIC GRAVITIES		
Project:	#622: Low LWA Replacement		
Source of Concrete:	Program I		
Material / Source or Designation / Blend[1]	Quantity (SSD)	S.G.	Yield, ft^3
Type I/II / Ashgrove #7 / 100%	540 lb	3.20	2.70
Water	237 lb	1.00	3.80
CA-15 Granite >=3/8'' / G-15(a) / 25.23%	727 lb	2.60	4.48
CA-15 Granite <=3/8'' / G-15(b) / 17.32%	499 lb	2.60	3.08
Pea Gravel / PG-14 / 15.03%	433 lb	2.61	2.66
Sand / S-15 / 37.28%	1074 lb	2.62	6.57
1/4 X 1/8 Marq, KS / LW-A2 / 5.14%	148 lb	1.54	1.54
Total Air, percent	8%		2.16
MicroAir / Master Builders	1.6 fl oz (US)	1.01	0.00
Glenium 3000NS / Master Builders	12.6 fl oz (US)	1.08	0.01
1 The blend percentage indicated (by weight) is listed separately for cementitious materials and aggregates.			27.00

Total Water Content (including water in admixtures), lb		238		
Water / Cementitious Material Ratio:		0.44		
Concrete Unit Weight, pcf		135.0		
Target Slump, in.		3 ± 0.5		
Paste Content, percent		24.10%		
Workability Factor (WF)	Target:	38.2	Actual:	35.7
Coarseness Factor (CF)	Target:	39.3	Actual:	37.8

Figure 2-10: SSD Granite with LWA (Low) (*KU Mix*)

Conversion Factors:
1 ft^3 = 0.0283 m^3
1 lb = 0.454 kg
1 in. = 2.54 cm
1 lb/ft^3 = 16.0 kg/m^3
1 fl oz = 29.6 mL

Table 2-12 shows the content of aggregates by weights and by volumes for SSD Granite with LWA (low). All of the weights and volumes were the same as for the Granite Control with the exception of the pea gravel. The lightweight aggregate was used to replace some of the pea gravel in the mix.

Table 2-12: SSD Granite with LWA (Low)

Aggregate	Specific Gravity	Weight lb/yd^3 (kg/m^3)	% by Weight	Volume ft^3/yd^3 (m^3/m^3)	% by Volume
G-15 (a)	2.60	727 (431)	25.2	4.48 (0.166)	24.5
G-15 (b)	2.60	499 (296)	17.3	3.08 (0.114)	16.8
PG-14	2.61	433 (257)	15.0	2.66 (0.0985)	14.0
S-15	2.62	1,074 (637)	37.3	6.57 (0.243)	35.8
LW-A2	1.54	148 (88)	5.1	1.54 (0.0570)	8.9
TOTAL		**2,881 (1,709)**	**100**	**18.33 (0.679)**	**100**

Figure 2-11 shows the MCFC for the mix. The actual gradation of the mix fell within Zone III. It clearly did not match the optimized mix because the substitution of the lightweight aggregate changed the gradation, however, this did not cause any problems mixing and casting the specimens.

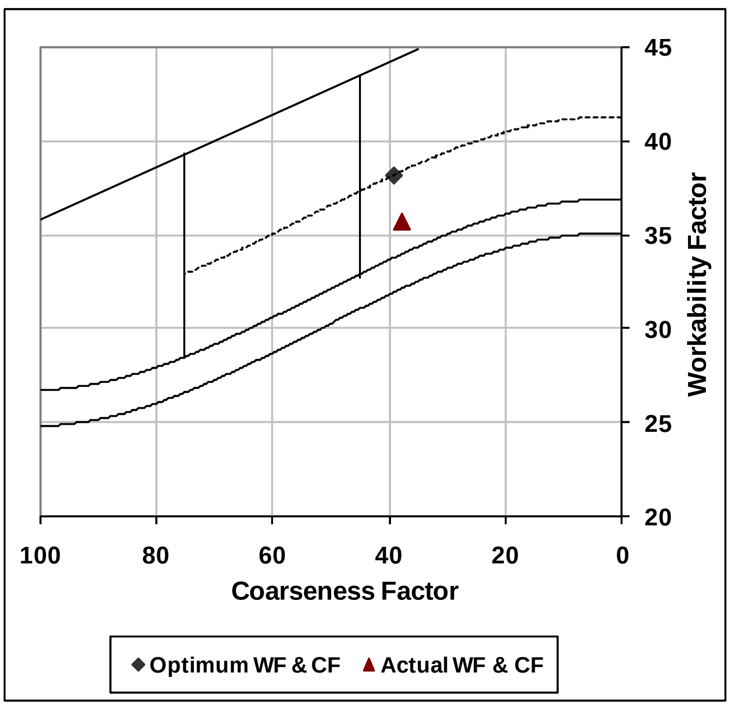

Figure 2-11: MCFC SSD Granite with LWA (Low)

2.5.2.4 SSD Granite with LWA (Medium)

The SSD Granite with LWA (medium) mix was designed by replacing 10.7% of pea gravel in the optimized Granite Control with lightweight aggregate. Due to slight variations in actual total moisture content, the exact replacement level was 11.3% by volume. The goal of this replacement level was to achieve approximately 37.8 lb/yd^3 (22.4 kg/m^3) of water that could be available for internal curing. The mix used five aggregates (two sizes of granite, pea gravel, sand and the lightweight aggregate from Marquette, Kansas) and Type I-II portland cement.

Figure 2-12 shows the actual mix design for this batch. For this mix a new sample of granite (G-20) was used, which changed the optimized gradation slightly. The volume of sand, however, was kept nearly constant between the (low) and (medium) mixes.

Table 2-13 shows the content of aggregates by weights and by volumes in the SSD Granite with LWA (medium) mix. All of the weights and volumes were the same as for the Granite Control with the exception of the pea gravel. The lightweight aggregate was used to replace some of the pea gravel in the mix.

Table 2-13: SSD Granite with LWA (Medium)

Aggregate	Specific Gravity	Weight lb/yd^3 (kg/m^3)	% by Weight	Volume ft^3/yd^3 (m^3/m^3)	% by Volume
G-20 (a)	2.60	743 (441)	26.1	4.58 (0.170)	25.0
G-20 (b)	2.60	542 (322)	19.0	3.34 (0.124)	18.2
PG-14	2.61	305 (181)	10.7	1.87 (0.0693)	10.2
S-15	2.62	1,057 (627)	37.1	6.47 (0.240)	35.3
LWh-A2	1.54	199 (118)	7.0	2.07 (0.0767)	11.3
TOTAL		**2,985 (1,771)**	**100**	**18.33 (0.679)**	**100**

Contractor: NORMALIZED SPECIFIC GRAVITIES			
Project: #626: Medium LWA Replacement			
Source of Concrete: Program I			
Material / Source or Designation / Blend[1]	Quantity (SSD)	S.G.	Yield, ft^3
Type I/II / Ashgrove #7 / 100%	540 lb	3.20	2.70
Water	237 lb	1.00	3.80
CA-20 Granite >=3/8" / G-20(a) / 26.11%	743 lb	2.60	4.58
CA-20 Granite <=3/8" / G-20(b) / 19.04%	542 lb	2.60	3.34
Pea Gravel / PG-14 / 10.72%	305 lb	2.61	1.87
Sand / S-15 / 37.14%	1057 lb	2.62	6.47
1/4 X 1/8 Marq, KS / LW-A2 / 6.99%	199 lb	1.54	2.07
Total Air, percent	8%		2.16
MicroAir / Master Builders	1.6 fl oz (US)	1.01	0.00
Glenium 3000NS / Master Builders	12.6 fl oz (US)	1.08	0.01
1 The blend percentage indicated (by weight) is listed separately for cementitious materials and aggregates.			27.00

Total Water Content (including water in admixtures), lb		238		
Water / Cementitious Material Ratio:		0.44		
Concrete Unit Weight, pcf		133.4		
Target Slump, in.		3 ± 0.5		
Paste Content, percent		24.10%		
Workability Factor (WF)	Target:	38.2	Actual:	34.9
Coarseness Factor (CF)	Target:	39.2	Actual:	37.3

Figure 2-12: SSD Granite with LWA (Medium) (*KU Mix*)

Conversion Factors:
1 ft^3 = 0.0283 m^3
1 lb = 0.454 kg
1 in. = 2.54 cm
1 lb/ft^3 = 16.0 kg/m^3
1 fl oz = 29.6 mL

Figure 2-13 shows the MCFC for the mix. The actual gradation of the mix remained within Zone III, although it was not as close to the optimal gradation as it was for the SSD Granite with LWA (Low) mix. Even though the gradation of the mix did not match the optimal gradation, there were not any problems with mixing and casting of specimens.

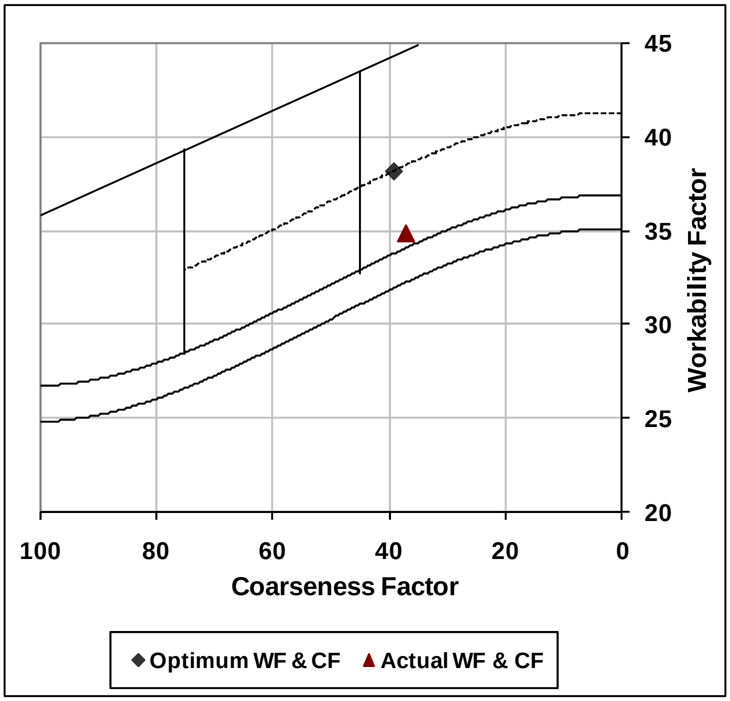

Figure 2-13: MCFC SSD Granite with LWA (Medium)

2.5.2.5 SSD Granite with LWA (High)

The SSD Granite with LWA (high) mix was designed by replacing 13.4% of pea gravel in the optimized Granite Control with lightweight aggregate. Due to slight variations in actual total moisture content, the exact replacement level was 13.8% by volume. The goal of this replacement level was to achieve approximately 47.3 lb/yd^3 (28.1 kg/m^3) of water that could be available for internal curing. The mix used five aggregates (two sizes of granite, pea gravel, sand and the lightweight aggregate from Marquette, Kansas) and Type I-II portland cement. Figure 2-14 shows the actual mix design for this batch. Table 2-14 shows the content of aggregates by weights and by volumes in the SSD Granite with LWA (high) mix. All of the weights and volumes were the same as for the Granite Control with the exception of the pea gravel. The lightweight aggregate was used to replace some of the pea gravel in the mix.

Contractor:	NORMALIZED SPECIFIC GRAVITIES		
Project:	#634: High LWA Replacement		
Source of Concrete:	Program I		

Material / Source or Designation / Blend[1]	Quantity (SSD)	S.G.	Yield, ft^3
Type I/II / Ashgrove #7 / 100%	540 lb	3.20	2.70
Water	237 lb	1.00	3.80
CA-20 Granite >=3/8" / G-20(a) / 26.39%	743 lb	2.60	4.58
CA-20 Granite <=3/8" / G-20(b) / 19.25%	542 lb	2.60	3.34
Pea Gravel / PG-14 / 8.17%	230 lb	2.61	1.41
Sand / S-15 / 37.55%	1057 lb	2.62	6.47
1/4 X 1/8 Marq, KS / LW-A2 / 8.63%	243 lb	1.54	2.53
Total Air, percent	8%		2.16
MicroAir / Master Builders	1.6 fl oz (US)	1.01	0.00
Glenium 3000NS / Master Builders	12.6 fl oz (US)	1.08	0.01
1 The blend percentage indicated (by weight) is listed separately for cementitious materials and aggregates.			27.00

Total Water Content (including water in admixtures), lb		238		
Water / Cementitious Material Ratio:		0.44		
Concrete Unit Weight, pcf		132.1		
Target Slump, in.		3 ± 0.5		
Paste Content, percent		24.10%		
Workability Factor (WF)	Target:	38.2	Actual:	34.2
Coarseness Factor (CF)	Target:	39.2	Actual:	36.9

Figure 2-14: SSD Granite with LWA (High) (*KU Mix*)

Conversion Factors:
1 ft^3 = 0.0283 m^3
1 lb = 0.454 kg
1 in. = 2.54 cm
1 lb/ft^3 = 16.0 kg/m^3
1 fl oz = 29.6 mL

Table 2-14: SSD Granite with LWA (High)

Aggregate	Specific Gravity	Weight lb/yd^3 (kg/m^3)	% by Weight	Volume ft^3/yd^3 (m^3/m^3)	% by Volume
G-20 (a)	2.60	743 (441)	26.4	4.58 (0.170)	25.0
G-20 (b)	2.60	542 (322)	19.3	3.34 (0.127)	18.2
PG-14	2.61	230 (136)	8.2	1.41 (0.0522)	7.7
S-15	2.62	1,057 (627)	37.6	6.47 (0.240)	35.3
LW-A2	1.54	243 (144)	8.6	2.53 (0.0937)	13.8
TOTAL		**2,815 (1,670)**	**100**	**18.33 (0.679)**	**100**

Figure 2-15 shows the MCFC for the mix. The actual gradation of the mix fell between Zone III and the trend bar. This indicated that there may be some difficulty with consolidation. There was not, however, a problem with mixing and casting of the free shrinkage specimens and strength cylinders.

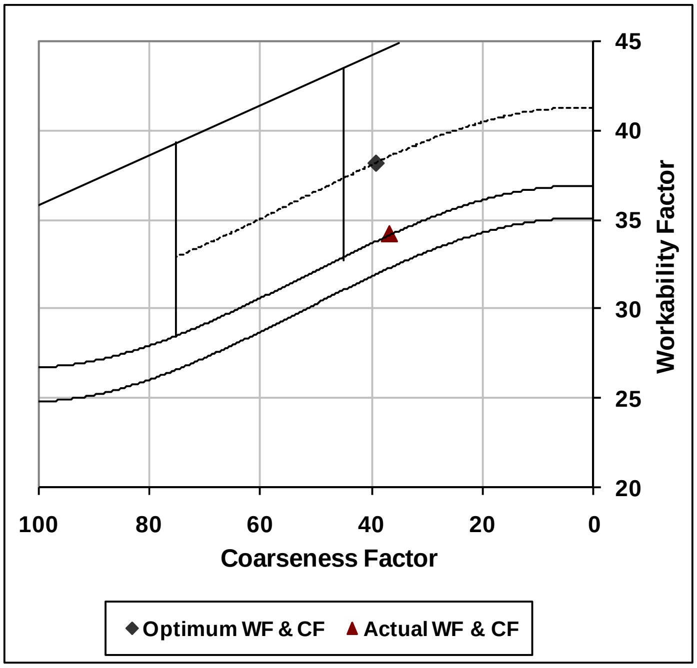

Figure 2-15: MCFC SSD Granite with LWA (High)

2.5.2.6 SSD Granite with FLWA (Medium)

The SSD Granite with FLWA (medium) mix was designed by replacing 10.7% of the sand in the optimized Granite Control with lightweight aggregate. Due to slight variations in actual total moisture content, the exact replacement level was 7.4% by volume. The goal of this replacement level was to achieve approximately 37.8 lb/yd^3 (22.4 kg/m^3) of water that could be available for internal curing. The mix used five aggregates (two sizes of granite, pea gravel, sand and the lightweight aggregate from Marquette, Kansas) and Type I-II portland cement. Figure 2-16 shows the actual mix design for this batch.

Contractor:	NORMALIZED SPECIFIC GRAVITIES			
Project:	# 654: Medium FLWA Replacment			
Source of Concrete:	Program I			
Material / Source or Designation / Blend[1]		Quantity (SSD)	S.G.	Yield, ft^3
Type I/II / Ashgrove #8 / 100%		540 lb	3.15	2.75
Water		237 lb	1.00	3.80
CA-20 Granite >=3/8" / G-20(a) / 25.72%		742 lb	2.60	4.57
CA-20 Granite <=3/8" / G-20(b) / 17.23%		497 lb	2.60	3.06
Pea Gravel / PG-14 / 28.15%		812 lb	2.61	4.98
Sand / S-16 / 24.44%		705 lb	2.62	4.31
1/4 X 1/8 Marq, KS / FLW-A1 / 4.47%		129 lb	1.53	1.35
Total Air, percent		8%		2.16
MicroAir / Master Builders		1.6 fl oz (US)	1.01	0.00
Glenium 3000NS / Master Builders		12.6 fl oz (US)	1.08	0.01
1 The blend percentage indicated (by weight) is listed separately for cementitious materials and aggregates.				27.00

Total Water Content (including water in admixtures), lb		238		
Water / Cementitious Material Ratio:		0.44		
Concrete Unit Weight, pcf		137.1		
Target Slump, in.		3 ± 0.5		
Paste Content, percent		24.29%		
Workability Factor (WF)	Target:	38.2	Actual:	36.6
Coarseness Factor (CF)	Target:	39.2	Actual:	38.2

Figure 2-16: SSD Granite with FLWA (Medium) (*KU Mix*)

Conversion Factors:
1 ft^3 = 0.0283 m^3
1 lb = 0.454 kg
1 in. = 2.54 cm
1 lb/ft^3 = 16.0 kg/m^3
1 fl oz = 29.6 mL

Table 2-15 shows the content of aggregates by weights and by volumes in the SSD Granite with FLWA (medium) mix. All of the weights and volumes were the same as for the Granite Control with the exception of the pea gravel. The lightweight aggregate was used to replace some of the sand in the mix, which was similar in gradation to the FLWA.

Table 2-15: SSD Granite with FLWA (Medium)

Aggregate	Specific Gravity	Weight lb/yd^3 (kg/m^3)	% by Weight	Volume ft^3/yd^3 (m^3/m^3)	% by Volume
G-20 (a)	2.60	742 (440)	25.7	4.57 (0.169)	25.0
G-20 (b)	2.60	497 (295)	17.2	3.06 (0.113)	16.7
PG-14	2.61	812 (482)	28.2	4.98 (0.184)	27.3
S-16	2.62	705 (418)	24.4	4.31 (0.160)	23.6
FLW-A1	1.53	129 (77)	4.5	1.35 (0.0500)	7.4
TOTAL		**2,885 (1,712)**	**100**	**18.27 (0.677)**	**100**

Figure 2-15 shows the MCFC for the mix. The gradation of the mix fell within Zone III. The gradation of the mix did not match the optimal gradation, though there were not problems mixing or casting of the concrete.

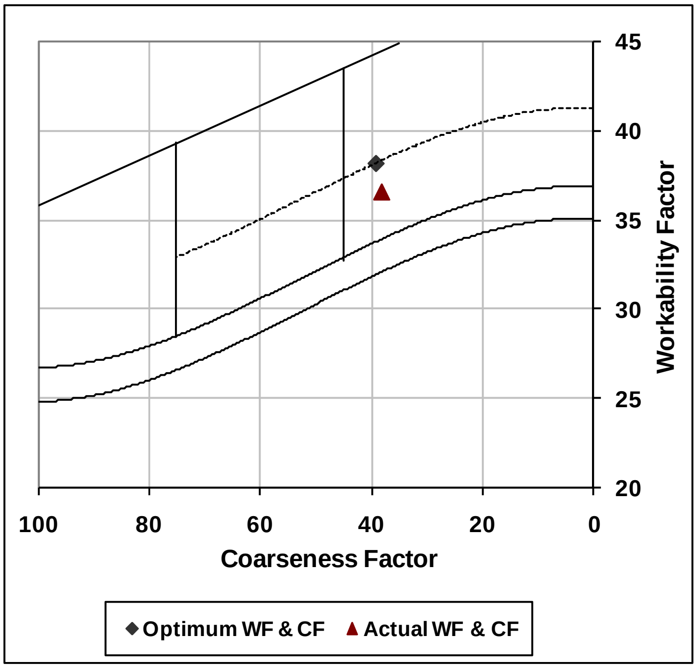

Figure 2-17: MCFC SSD Granite with FLWA (Medium)

2.5.2.7 Program I Summary

The paste content was held constant for every batch in Program I. As the gradations changed for the aggregates slightly, the mixes, however, changed slightly. The lightweight aggregate was consistently used to replace a portion of the pea gravel, and the fine lightweight aggregate was used to replace the sand. The batches are summarized in Table 2-16 showing the aggregate amounts by percent volume. The coarse aggregate volume was nearly constant for all mixes (41.0-43.2%), but the volume of pea gravel changed (7.7-27.3%) as the lightweight aggregate was used as a replacement. The volume of sand ranged from 35.3-41.2%, except for the mix with fine lightweight aggregate. The mix with fine lightweight aggregate had only 23.6% sand by volume because a portion of the sand was replaced by the fine lightweight aggregate.

Table 2-16: Program I – Batch Aggregates by Volume *(%)*

Aggregate	Granite Control	Limestone Control	Granite with LWA (Low)	Granite with LWA (Med)	Granite with LWA (High)	Granite with FLWA (Med)
Coarse	41.2	41.0	41.2	43.2	43.2	41.7
Pea Gravel	22.9	17.5	14.5	10.2	7.7	27.3
Sand	35.8	41.4	35.8	35.3	35.3	23.6
LWA	0	0	8.4	11.3	13.8	7.4
TOTAL	**100**	**100**	**100**	**100**	**100**	**100**

2.5.3 Program II

A total of eight mixes were designed for Program II; two control mixes, four mixes with lightweight aggregate and G100 slag, and two mixes with limestone and G100 slag. The replacement level for the batches with lightweight aggregate was calculated as described for Program I. After Program I was completed, however, the vacuum saturation procedure was modified to be more efficient and the obtained total moisture content was closer to 25% rather than the previously estimated 20%. Using Eq. (1-8) the volume of lightweight aggregate required for internal curing is as follows:

$$V_{LWA} = \frac{C \times \alpha \times CS}{S \times \phi \times SG \times \rho}$$

$$= \frac{540^{lb/yd^3} \times 1.0 \times 0.07^{lb/lb}}{1.0 \times 0.25 \times 1.54 \times 62.4^{lb/yd^3}} \left[= \frac{320^{kg/m^3} \times 1.0 \times 0.07^{kg/kg}}{1.0 \times 0.25 \times 1.54 \times 37.0^{kg/m^3}} \right. \tag{1-8}$$

$$= 1.57^{ft^3/yd^3} \qquad \left. = 0.0581^{m^3/m^3} \right]$$

A volume of 1.57 ft^3/yd^3 (0.0581 m^3/m^3) results in the following amount of water available for internal curing by using Eq. (1-9):

$$
\begin{aligned}
W &= C \times \alpha \times CS \\
&= 540^{lb/yd^3} \times 1.0 \times 0.07^{lb/lb} \quad \left[\begin{aligned} &= 320^{kg/m^3} \times 1.0 \times 0.07^{kg/kg} \\ &= 22.4^{kg/m^3} \end{aligned} \right] \\
&= 37.8^{lb/yd^3}
\end{aligned}
\tag{1-9}
$$

Equation (1-10) was used to determine the percent replacement of the lightweight aggregate that is required to provide *W*:

$$
\begin{aligned}
R_{LWA} &= \frac{V_{LWA}}{V_{Total}} \times 100 \\
&= \frac{1.57^{ft^3/yd^3}}{18.33^{ft^3/yd^3}} \times 100 \quad \left[\begin{aligned} &= \frac{0.0581^{m^3/m^3}}{0.6789^{m^3/m^3}} \times 100 \\ &= 8.6\% \end{aligned} \right] \\
&= 8.6\%
\end{aligned}
\tag{1-10}
$$

The volume replacement (8.6%) was designated as the level of replacement for the batches containing lightweight aggregate. The batch that evaluated the fine lightweight aggregate had the same volume replacement but for the sand.

The intermediate lightweight aggregate replaced the pea gravel in each mix, which had a similar gradation to that of the intermediate lightweight aggregate. The fine lightweight aggregate was used to replace the sand. Additional mixes were also cast with limestone as the coarse aggregate to compare the internal curing with limestone to lightweight aggregate. The following is a summary of the mixes that were cast for Program II:

- SSD Granite Control
- SSD Granite with LWA (30% G100 Slag)
- SSD Granite with FLWA (30% G100 Slag)
- SSD Granite with LWA (60% G100 Slag)
- SSD Granite with LWA (60% G100 Slag II)
- SSD Limestone Control

- SSD Limestone (30% G100 Slag)
- SSD Limestone (60% G100 Slag)

2.5.3.1 SSD Granite Control

Figure 2-18 shows the mix design containing granite that was optimized using *KU Mix*. The SSD Granite Control had an optimized aggregate gradation and used four aggregates (two granite sizes, pea gravel, and sand) and Type I-II portland cement.

Contractor:	NORMALIZED SPECIFIC GRAVITIES		
Project:	#639: Granite Control		
Source of Concrete:	Program II		
Material / Source or Designation / Blend[1]	Quantity (SSD)	S.G.	Yield, ft^3
Type I/II / Ashgrove #8 / 100%	540 lb	3.15	2.75
Water	237 lb	1.00	3.80
CA-20 Granite >=3/8" / G-20(a) / 24.93%	742 lb	2.60	4.57
CA-20 Granite <=3/8" / G-20(b) / 16.7%	497 lb	2.60	3.06
Pea Gravel / PG-14 / 27.28%	812 lb	2.61	4.99
Sand / S-16 / 31.08%	925 lb	2.62	5.66
1/4 X 1/8 Marq, KS / LW-A3 / 0%	0 lb	1.54	0.00
Total Air, percent	8%		2.16
MicroAir / Master Builders	1.6 fl oz (US)	1.01	0.00
Glenium 3000NS / Master Builders	12.6 fl oz (US)	1.08	0.01
1 The blend percentage indicated (by weight) is listed separately for cementitious materials and aggregates.			27.00

Total Water Content (including water in admixtures), lb		238		
Water / Cementitious Material Ratio:		0.44		
Concrete Unit Weight, pcf		139.0		
Target Slump, in.		3 ± 0.5		
Paste Content, percent		24.29%		
Workability Factor (WF)	Target:	38.2	Actual:	38.2
Coarseness Factor (CF)	Target:	39.2	Actual:	39.2

Figure 2-18: SSD Granite Control (*KU Mix*)

Conversion Factors:
1 ft^3 = 0.0283 m^3
1 lb = 0.454 kg
1 in. = 2.54 cm
1 lb/ft^3 = 16.0 kg/m^3
1 fl oz = 29.6 mL

Table 2-17 is a summary of the aggregate used in the mix showing the batch weights, percentage by weight, the batch volumes and the percentage by volume of each aggregate.

Table 2-17: SSD Granite Control

Aggregate	Specific Gravity	Weight lb/yd^3 (kg/m^3)	% by Weight	Volume ft^3/yd^3 (m^3/m^3)	% by Volume
G-20(a)	2.60	742 (440)	24.9	4.57 (0.169)	25.0
G-20(b)	2.60	497 (295)	16.7	3.06 (0.113)	16.7
PG-14	2.61	812 (482)	27.3	4.99 (0.185)	27.3
S-16	2.62	925 (549)	31.1	5.66 (0.210)	31.0
TOTAL		**2,976 (1,766)**	**100**	**18.28 (0.677)**	**100**

Figure 2-19 shows that the mix had an optimized gradation. The aggregate gradation fell in Zone III which was optimal for this research.

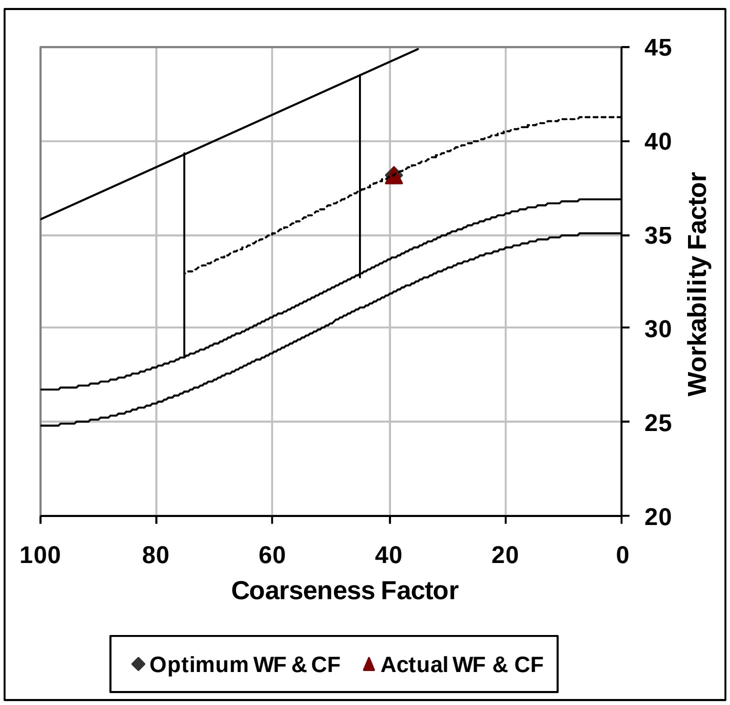

Figure 2-19: MCFC SSD Granite Control

2.5.3.2 SSD Granite with LWA (30% G100 Slag)

The SSD Granite with LWA (30% G100 slag) mix was designed by replacing 8.0% of pea gravel in the optimized Granite Control with lightweight aggregate. Due to slight variations in actual total moisture content, the exact replacement level was 8.4% by volume. The goal of this replacement level was to achieve approximately 37.8 lb/yd^3 (22.4 kg/m^3) of water that could be available for internal curing. The mix used five aggregates (two sizes of granite, pea gravel, sand and the lightweight aggregate from Marquette, Kansas), Type I-II portland cement and 30% G100 Slag. Figure 2-20 shows the actual mix design for this batch.

Contractor:	NORMALIZED SPECIFIC GRAVITIES		
Project:	#640: SSD Granite + LWA; 30% G100 Slag		
Source of Concrete:	Program II		
Material / Source or Designation / Blend[1]	Quantity (SSD)	S.G.	Yield, ft^3
Type I/II / Ashgrove #8 / 72%	384 lb	3.15	1.95
Slag / Slag / 28%	149 lb	2.90	0.82
Water	234 lb	1.00	3.75
CA-20 Granite >=3/8" / G-20(a) / 25.44%	744 lb	2.60	4.59
CA-20 Granite <=3/8" / G-20(b) / 17.06%	499 lb	2.60	3.08
Pea Gravel / PG-14 / 19.28%	564 lb	2.61	3.46
Sand / S-16 / 32.56%	923 lb	2.62	5.65
1/4 X 1/8 Marq, KS / LW-A3 / 6.67%	195 lb	1.54	1.54
Total Air, percent	8%		2.16
MicroAir / Master Builders	1.6 fl oz (US)	1.01	0.00
Glenium 3000NS / Master Builders	12.6 fl oz (US)	1.08	0.01
1 The blend percentage indicated (by weight) is listed separately for cementitious materials and aggregates.			27.00

Total Water Content (including water in admixtures), lb			235	
Water / Cementitious Material Ratio:			0.44	
Concrete Unit Weight, pcf			136.7	
Target Slump, in.			3 ± 0.5	
Paste Content, percent			24.18%	
Workability Factor (WF)	Target:	38.2	Actual:	35.7
Coarseness Factor (CF)	Target:	39.2	Actual:	37.7

Figure 2-20: SSD Granite with LWA, 30% G100 Slag (*KU Mix*)

Conversion Factors:
1 ft^3 = 0.0283 m^3
1 lb = 0.454 kg
1 in. = 2.54 cm
1 lb/ft^3 = 16.0 kg/m^3
1 fl oz = 29.6 mL

Table 2-12 shows the content of aggregates by weights and by volumes. The lightweight aggregate was used to replace the pea gravel in the mix.

Table 2-18: SSD Granite with LWA, 30% G100 Slag

Aggregate	Specific Gravity	Weight lb/yd³ (kg/m³)	% by Weight	Volume ft³/yd³ (m³/m³)	% by Volume
G-20 (a)	2.60	744 (441)	25.4	4.59 (0.170)	25.0
G-20 (b)	2.60	499 (296)	17.1	3.08 (0.114)	16.8
PG-14	2.61	564 (335)	19.3	3.46 (0.128)	18.9
S-16	2.62	923 (548)	32.6	5.65 (0.209)	30.9
LW-A3	1.54	195 (116)	6.7	1.54 (0.057)	8.4
TOTAL		**2,925 (1,735)**	**100**	**18.31 (0.678)**	**100**

Figure 2-21 shows the MCFC for the mix. The actual gradation of the mix fell within Zone III. It clearly did not match the optimized mix because the substitution of the lightweight aggregate changed the gradation, however, this did not cause any problems with mixing and casting of the free shrinkage specimens and strength cylinders.

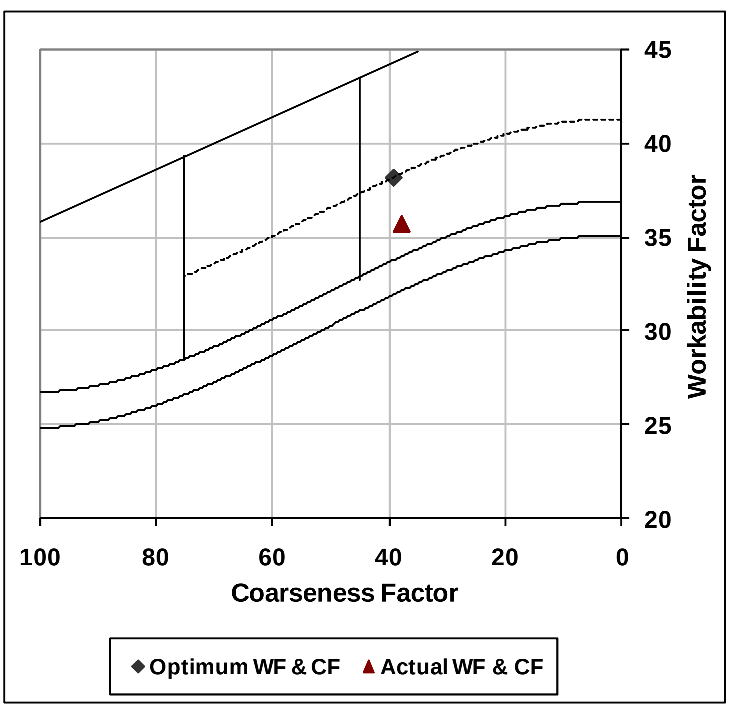

Figure 2-21: MCFC SSD Granite with LWA; 30% G100 Slag

2.5.3.3 SSD Granite with FLWA (30% G100 Slag)

The SSD Granite with FLWA (30% G100 slag) mix was designed by replacing 8.0% of pea gravel in the optimized Granite Control with lightweight aggregate. Due to slight variations in actual total moisture content, the exact replacement level was 7.4% by volume. The goal of this replacement level was to achieve approximately 37.8 lb/yd^3 (22.4 kg/m^3) of water that could be available for internal curing. The mix used five aggregates (two sizes of granite, pea gravel, sand and the fine lightweight aggregate from Marquette, Kansas), Type I-II portland cement and 30% G100 Slag. Figure 2-22 shows the actual mix design for this batch.

Contractor: NORMALIZED SPECIFIC GRAVITIES
Project: #655: SSD Granite + FLWA; 30% G100 Slag
Source of Concrete: Program II

Material / Source or Designation / Blend[1]	Quantity (SSD)	S.G.	Yield, ft^3
Type I/II / Ashgrove #8 / 72%	384 lb	3.15	1.95
Slag / Slag / 28%	149 lb	2.90	0.82
Water	234 lb	1.00	3.75
CA-20 Granite >=3/8" / G-20(a) / 25.42%	744 lb	2.60	4.59
CA-20 Granite <=3/8" / G-20(b) / 17.05%	499 lb	2.60	3.08
Pea Gravel / PG-14 / 27.84%	815 lb	2.61	5.01
Sand / S-16 / 23.92%	700 lb	2.62	4.28
1/4 X 1/8 Marq, KS / FLW-A1 / 5.77%	169 lb	1.53	1.35
Total Air, percent	8%		2.16
MicroAir / Master Builders	1.6 fl oz (US)	1.01	0.00
Glenium 3000NS / Master Builders	12.6 fl oz (US)	1.08	0.01
1 The blend percentage indicated (by weight) is listed separately for cementitious materials and aggregates.			27.00

Total Water Content (including water in admixtures), lb		235		
Water / Cementitious Material Ratio:		0.44		
Concrete Unit Weight, pcf		136.8		
Target Slump, in.		3 ± 0.5		
Paste Content, percent		24.18%		
Workability Factor (WF)	Target:	38.2	Actual:	36.5
Coarseness Factor (CF)	Target:	39.2	Actual:	38.2

Figure 2-22: SSD Granite with FLWA, 30% G100 Slag (*KU Mix*)

Conversion Factors:
1 ft^3 = 0.0283 m^3
1 lb = 0.454 kg
1 in. = 2.54 cm
1 lb/ft^3 = 16.0 kg/m^3
1 fl oz = 29.6 mL

Table 2-19 shows the content of aggregates by weights and by volumes. The lightweight aggregate was used to replace the sand in the mix.

Table 2-19: SSD Granite with FLWA, 30% G100 Slag

Aggregate	Specific Gravity	Weight lb/yd^3 (kg/m^3)	% by Weight	Volume ft^3/yd^3 (m^3/m^3)	% by Volume
G-20 (a)	2.60	744 (441)	25.4	4.59 (0.170)	25.1
G-20 (b)	2.60	499 (296)	17.1	3.08 (0.114)	16.8
PG-14	2.61	815 (484)	27.8	5.01 (0.186)	27.3
S-16	2.62	700 (415)	23.9	4.28 (0.159)	23.4
FLW-A1	1.53	169 (100)	5.8	1.35 (0.0500)	7.4
TOTAL		**2,927 (1,737)**	**100**	**18.31 (0.678)**	**100**

Figure 2-23 shows the MCFC for the mix. The actual gradation of the mix fell within Zone III. It clearly did not match the optimized mix because the substitution of the lightweight aggregate changed the gradation, however, this did not cause any problems with mixing and casting of the free shrinkage specimens and strength cylinders.

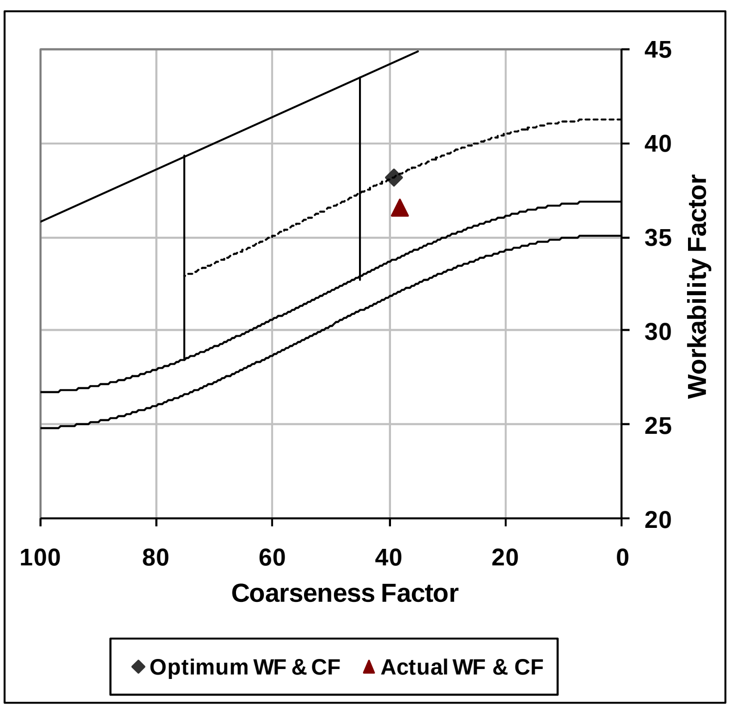

Figure 2-23: MCFC SSD Granite with FLWA; 30% G100 Slag

2.5.3.4 SSD Granite with LWA (60% G100 Slag)

The SSD Granite with LWA (60% G100 slag) mix was designed by replacing 8.0% of pea gravel in the optimized Granite Control with lightweight aggregate. Due to slight variations in actual total moisture content, the exact replacement level was 8.4% by volume. The goal of this replacement level was to achieve approximately 37.8 lb/yd^3 (22.4 kg/m^3) of water that could be available for internal curing. The mix used five aggregates (two sizes of granite, pea gravel, sand and the lightweight aggregate from Marquette, Kansas), Type I-II portland cement and 30% G100 Slag. Figure 2-24 shows the actual mix design for this batch.

Contractor:	NORMALIZED SPECIFIC GRAVITIES			
Project:	#642: SSD Granite + LWA; 60% G100 Slag			
Source of Concrete:	Program II			
Material / Source or Designation / Blend[1]		Quantity (SSD)	S.G.	Yield, ft^3
Type I/II / Ashgrove #8 / 42.7%		226 lb	3.15	1.15
Slag / Slag / 57.3%		303 lb	2.90	1.67
Water		232 lb	1.00	3.72
CA-20 Granite >=3/8" / G-20(a) / 25.47%		744 lb	2.60	4.59
CA-20 Granite <=3/8" / G-20(b) / 17.56%		513 lb	2.60	3.16
Pea Gravel / PG-14 / 18.66%		545 lb	2.61	3.35
Sand / S-16 / 31.63%		924 lb	2.62	5.65
1/4 X 1/8 Marq, KS / LW-A3 / 6.68%		195 lb	1.54	1.54
Total Air, percent		8%		2.16
MicroAir / Master Builders		1.6 fl oz (US)	1.01	0.00
Glenium 3000NS / Master Builders		12.6 fl oz (US)	1.08	0.01
1 The blend percentage indicated (by weight) is listed separately for cementitious materials and aggregates.				27.00

Total Water Content (including water in admixtures), lb		233		
Water / Cementitious Material Ratio:		0.44		
Concrete Unit Weight, pcf		136.4		
Target Slump, in.		3 ± 0.5		
Paste Content, percent		24.26%		
Workability Factor (WF)	Target: 38.2		Actual:	35.8
Coarseness Factor (CF)	Target: 39.1		Actual:	37.7

Figure 2-24: SSD Granite with LWA, 60% G100 Slag (*KU Mix*)

Conversion Factors:
1 ft^3 = 0.0283 m^3
1 lb = 0.454 kg
1 in. = 2.54 cm
1 lb/ft^3 = 16.0 kg/m^3
1 fl oz = 29.6 mL

Table 2-20 shows the content of aggregates by weights and by volumes. The lightweight aggregate was used to replace the pea gravel in the mix.

Table 2-20: SSD Granite with LWA, 60% G100 Slag

Aggregate	Specific Gravity	Weight lb/yd^3 (kg/m^3)	% by Weight	Volume ft^3/yd^3 (m^3/m^3)	% by Volume
G-20 (a)	2.60	744 (441)	25.5	4.59 (0.170)	25.1
G-20 (b)	2.60	513 (304)	17.6	3.16 (0.117)	17.3
PG-14	2.61	545 (323)	18.7	3.35 (0.124)	18.3
S-16	2.62	924 (548)	31.6	5.65 (0.209)	30.9
LW-A3	1.54	195 (116)	6.7	1.54 (0.0570)	8.4
TOTAL		**2,925 (1,735)**	**100**	**18.29 (0.677)**	**100**

Figure 2-25 shows the MCFC for the mix. The actual gradation of the mix fell within Zone III. It clearly did not match the optimized mix because the substitution of the lightweight aggregate changed the gradation, however, this did not cause any problems with mixing and casting of the free shrinkage specimens and strength cylinders.

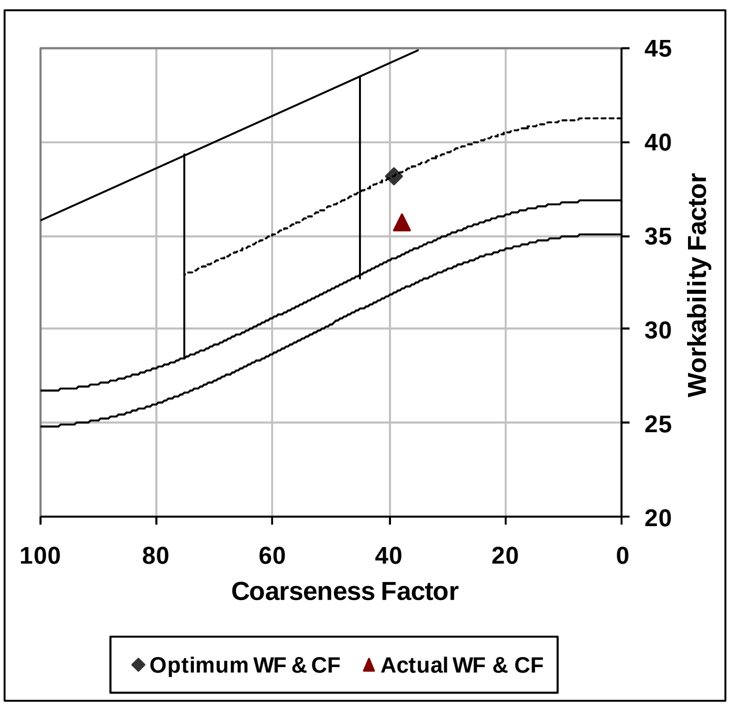

Figure 2-25: MCFC SSD Granite with LWA; 60% G100 Slag

2.5.3.5 SSD Granite with LWA (60% G100 Slag II)

Due to unreasonably low free shrinkage results of the SSD Granite with LWA (60% G100 slag) mix, the SSD Granite with LWA (60% G100 slag) mix was rebatched (60% G100 slag II). The mix had the same parameters as the previous mix. The mix used five aggregates (two sizes of granite, pea gravel, sand and the lightweight aggregate from Marquette, Kansas), Type I-II portland cement and 30% G100 Slag. Figure 2-26 shows the actual mix design for this batch.

Contractor:	NORMALIZED SPECIFIC GRAVITIES		
Project:	#648: SSD Granite + LWA; 60% G100 Slag		
Source of Concrete:	Program II		

Material / Source or Designation / Blend[1]	Quantity (SSD)	S.G.	Yield, ft^3
Type I/II / Ashgrove #8 / 42.7%	226 lb	3.15	1.15
Slag / Slag / 57.3%	303 lb	2.90	1.67
Water	232 lb	1.00	3.72
CA-20 Granite >=3/8" / G-20(a) / 24.87%	727 lb	2.60	4.48
CA-20 Granite <=3/8" / G-20(b) / 15.43%	451 lb	2.60	2.78
Pea Gravel / PG-14 / 21.11%	617 lb	2.61	3.79
Sand / S-16 / 31.92%	933 lb	2.62	5.71
1/4 X 1/8 Marq, KS / LW-A3 /6.67%	195 lb	1.54	1.54
Total Air, percent	8%		2.16
MicroAir / Master Builders	1.6 fl oz (US)	1.01	0.00
Glenium 3000NS / Master Builders	12.6 fl oz (US)	1.08	0.01
1 The blend percentage indicated (by weight) is listed separately for cementitious materials and aggregates.			27.00

Total Water Content (including water in admixtures), lb		233		
Water / Cementitious Material Ratio:		0.44		
Concrete Unit Weight, pcf		136.4		
Target Slump, in.		3 ± 0.5		
Paste Content, percent		24.26%		
Workability Factor (WF)	Target:	38.2	Actual:	36.7
Coarseness Factor (CF)	Target:	39.1	Actual:	37.3

Figure 2-26: SSD Granite with LWA, 60% G100 Slag II (*KU Mix*)

Conversion Factors:
1 ft^3 = 0.0283 m^3
1 lb = 0.454 kg
1 in. = 2.54 cm
1 lb/ft^3 = 16.0 kg/m^3
1 fl oz = 29.6 mL

Table 2-21 shows the content of aggregates by weights and by volumes. The lightweight aggregate was used to replace the pea gravel in the mix.

Table 2-21: SSD Granite with LWA, 60% G100 Slag II

Aggregate	Specific Gravity	Weight lb/yd³ (kg/m³)	% by Weight	Volume ft³/yd³ (m³/m³)	% by Volume
G-20 (a)	2.60	727 (431)	24.9	4.48 (0.166)	24.5
G-20 (b)	2.60	451 (268)	15.4	2.78 (0.103)	15.2
PG-14	2.61	617 (366)	21.1	3.79 (0.140)	20.7
S-16	2.62	933 (554)	31.9	5.71 (0.211)	31.2
LW-A3	1.54	195 (116)	6.7	1.54 (0.0570)	8.4
TOTAL		**2,923 (1,734)**	**100**	**18.30 (0.678)**	**100**

Figure 2-27 shows the MCFC for this mix. The actual gradation of the mix fell within Zone III. It clearly did not match the optimized mix because the substitution of the lightweight aggregate changed the gradation, however, this did not cause any problems with mixing and casting of the free shrinkage specimens and strength cylinders.

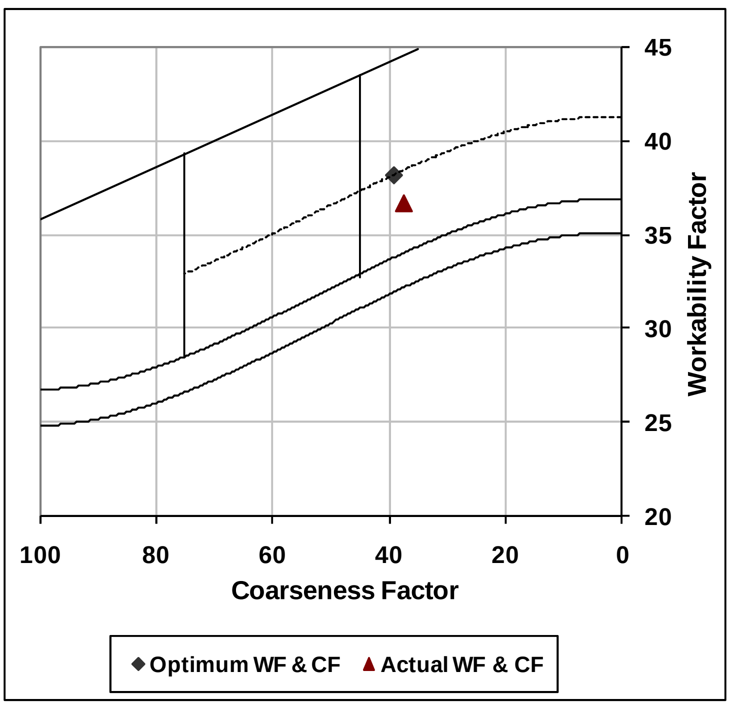

Figure 2-27: MCFC SSD Granite with LWA; 60% G100 Slag II

2.5.3.6 SSD Limestone Control

Figure 2-28 shows the mix design for the SSD Limestone Control mix that was optimized using *KU Mix*. The SSD Limestone Control had an optimized aggregate gradation and used three aggregates (limestone, pea gravel, and sand) and Type I-II portland cement.

Contractor:	NORMALIZED SPECIFIC GRAVITIES		
Project:	#645: Limestone Control		
Source of Concrete:	Program II		
Material / Source or Designation / Blend[1]	Quantity (SSD)	S.G.	Yield, ft^3
Type I/II / Ashgrove #8 / 100%	540 lb	3.15	2.75
Water	237 lb	1.00	3.80
KDOT Limestone / LS-9 / 42.16%	1253 lb	2.59	7.75
Pea Gravel / PG-14 / 22.24%	661 lb	2.61	4.06
Sand / S-16 / 35.6%	1058 lb	2.62	6.47
Total Air, percent	8%		2.16
MicroAir / Master Builders	1.6 fl oz (US)	1.01	0.00
Glenium 3000NS / Master Builders	12.6 fl oz (US)	1.08	0.01
1 The blend percentage indicated (by weight) is listed separately for cementitious materials and aggregates.			27.00

Total Water Content (including water in admixtures), lb		238		
Water / Cementitious Material Ratio:		0.44		
Concrete Unit Weight, pcf		138.9		
Target Slump, in.		3 ± 0.5		
Paste Content, percent		24.29%		
Workability Factor (WF)	Target:	38.2	Actual:	40.1
Coarseness Factor (CF)	Target:	39.2	Actual:	33.4

Figure 2-28: SSD Limestone Control (*KU Mix*)

Conversion Factors:
1 ft^3 = 0.0283 m^3
1 lb = 0.454 kg
1 in. = 2.54 cm
1 lb/ft^3 = 16.0 kg/m^3
1 fl oz = 29.6 mL

Table 2-22 is a summary of the aggregates in the Limestone Control and shows the batch weights, percentage by weight, the batch volumes and the percentage by volume.

Table 2-22: SSD Limestone Control

Aggregate	Specific Gravity	Weight lb/yd^3 (kg/m^3)	% by Weight	Volume ft^3/yd^3 (m^3/m^3)	% by Volume
LS-9	2.59	1,253 (743)	42.2	7.75 (0.287)	42.4
PG-14	2.61	661 (392)	22.2	4.06 (0.150)	22.2
S-16	2.62	1,058 (628)	35.6	6.47 (0.240)	35.4
TOTAL		**2,972 (1,763)**	**100**	**18.28 (0.677)**	**100**

Figure 2-29 shows that this mix had an actual gradation that fell a little outside of the optimized gradation. The gradation of the mix was adjusted manually to get a closer fit to the ideal haystack shape for a well graded mix, which is shown in Figure 2-29. The aggregate gradation, however, remained within Zone III and did not prove to be a challenge when batching.

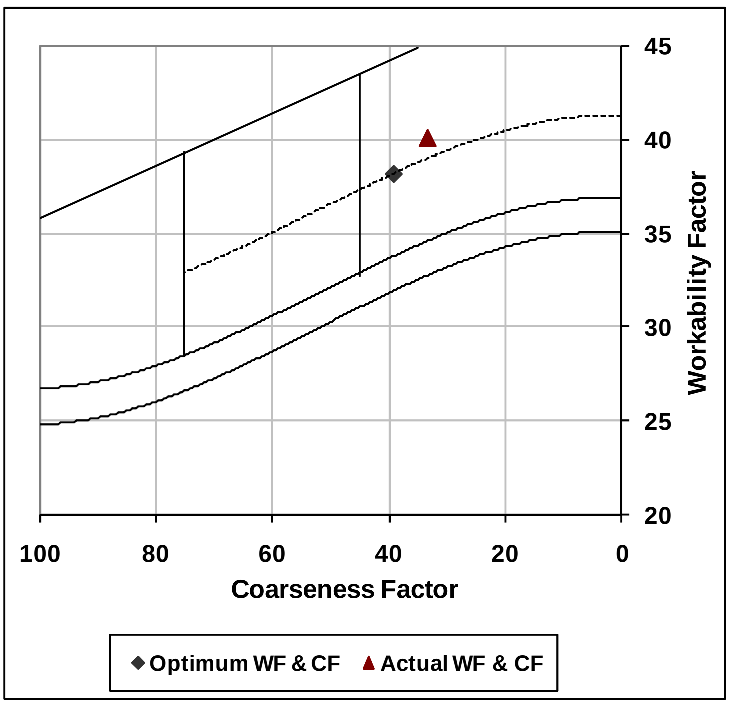

Figure 2-29: MCFC SSD Limestone Control

2.5.3.7 SSD Limestone (30% G100 Slag)

Figure 2-30 shows the mix design for the SSD Limestone (30% G100 Slag) mix that was optimized using *KU Mix*. The SSD Limestone (30% G100 Slag) had an optimized aggregate gradation and used three aggregates (limestone, pea gravel, and sand), Type I-II portland cement and 30% G100 slag.

CONCRETE MIX DESIGN

Contractor:	NORMALIZED SPECIFIC GRAVITIES
Project:	#646: Limestone; 30% G100 Slag
Source of Concrete:	Program II

Material / Source or Designation / Blend[1]	Quantity (SSD)	S.G.	Yield, ft^3
Type I/II / Ashgrove #8 / 72%	384 lb	3.15	1.95
Slag / Slag / 28%	149 lb	2.90	0.82
Water	234 lb	1.00	3.75
KDOT Limestone / LS-9 / 39.96%	1190 lb	2.59	7.36
Pea Gravel / PG-14 / 23.94%	713 lb	2.61	4.38
Sand / S-16 / 36.1%	1075 lb	2.62	6.57
Total Air, percent	8%		2.16
MicroAir / Master Builders	1.6 fl oz (US)	1.01	0.00
Glenium 3000NS / Master Builders	12.6 fl oz (US)	1.08	0.01
1 The blend percentage indicated (by weight) is listed separately for cementitious materials and aggregates.			27.00

Total Water Content (including water in admixtures), lb			235	
Water / Cementitious Material Ratio:			0.44	
Concrete Unit Weight, pcf			138.7	
Target Slump, in.			3 ± 0.5	
Paste Content, percent			24.18%	
Workability Factor (WF)	Target:	38.2	Actual:	41.1
Coarseness Factor (CF)	Target:	39.2	Actual:	32.1

Figure 2-30: SSD Limestone, 30% G100 Slag (*KU Mix*)

Conversion Factors:
1 ft^3 = 0.0283 m^3
1 lb = 0.454 kg
1 in. = 2.54 cm
1 lb/ft^3 = 16.0 kg/m^3
1 fl oz = 29.6 mL

Table 2-23 is a summary of the aggregate in the mix and shows the batch weights, percentage by weight, the batch volumes and the percentage by volume.

Table 2-23: SSD Limestone, 30% G100 Slag

Aggregate	Specific Gravity	Weight lb/yd^3 (kg/m^3)	% by Weight	Volume ft^3/yd^3 (m^3/m^3)	% by Volume
LS-9	2.59	1,190 (706)	40.0	7.36 (0.273)	40.2
PG-14	2.61	713 (423)	23.9	4.38 (0.162)	23.9
S-16	2.62	1,075 (638)	36.1	6.57 (0.243)	35.9
TOTAL		**2,978 (1,767)**	**100**	**18.31 (0.678)**	**100**

Figure 2-31 shows that the mix had an actual gradation that fell a little outside of the optimized gradation. The gradation of the mix was adjusted manually to get a closer fit to the ideal haystack shape for a well graded mix, which is shown in Figure 2-31. The aggregate gradation, however, still fell in Zone III and did not prove to be a challenge when batching.

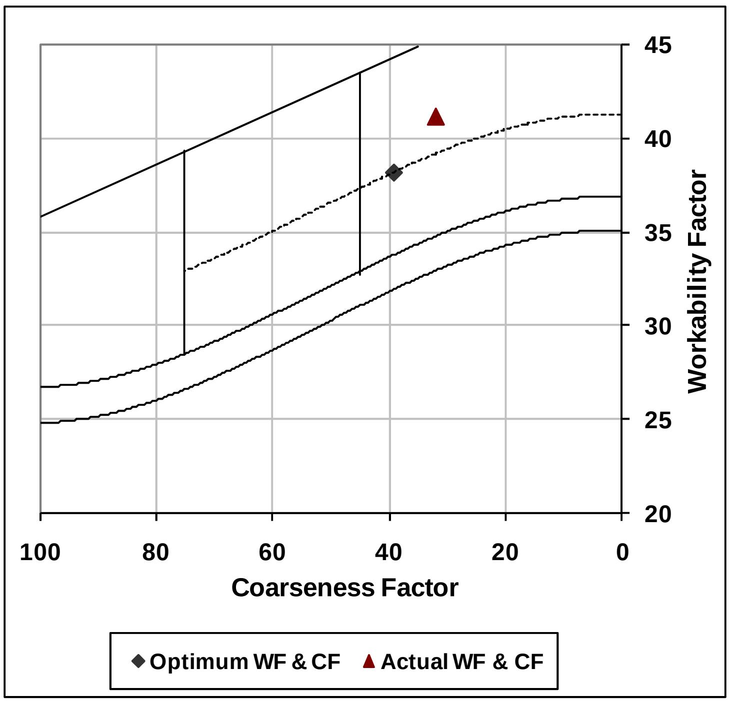

Figure 2-31: MCFC SSD Limestone, 30% G100 Slag

2.5.3.8 SSD Limestone (60% G100 Slag)

Figure 2-32 shows the mix design for the SSD Limestone (60% G100 Slag) mix that was optimized using *KU Mix*. The SSD Limestone (60% G100 Slag) had an optimized aggregate gradation and used three aggregates (limestone, pea gravel, and sand), Type I-II portland cement and 60% G100 slag.

Contractor:	NORMALIZED SPECIFIC GRAVITIES		
Project:	#647: Limestone; 60% G100 Slag		
Source of Concrete:	Program II		

Material / Source or Designation / Blend[1]	Quantity (SSD)	S.G.	Yield, ft^3
Type I/II / Ashgrove #8 / 42.7%	226 lb	3.15	1.15
Slag / Slag / 57.3%	303 lb	2.90	1.67
Water	232 lb	1.00	3.72
KDOT Limestone / LS-9 / 39.96%	1188 lb	2.59	7.35
Pea Gravel / PG-14 / 24.05%	715 lb	2.61	4.39
Sand / S-16 / 35.99%	1070 lb	2.62	6.55
Total Air, percent	8%		2.16
MicroAir / Master Builders	1.6 fl oz (US)	1.01	0.00
Glenium 3000NS / Master Builders	12.6 fl oz (US)	1.08	0.01
1 The blend percentage indicated (by weight) is listed separately for cementitious materials and aggregates.			27.00

Total Water Content (including water in admixtures), lb		233		
Water / Cementitious Material Ratio:		0.44		
Concrete Unit Weight, pcf		138.3		
Target Slump, in.		3 ± 0.5		
Paste Content, percent		24.26%		
Workability Factor (WF)	Target: 38.2		Actual:	41.2
Coarseness Factor (CF)	Target: 39.2		Actual:	32.1

Figure 2-32: SSD Limestone, 60% G100 Slag (*KU Mix*)

Conversion Factors:
1 ft^3 = 0.0283 m^3
1 lb = 0.454 kg
1 in. = 2.54 cm
1 lb/ft^3 = 16.0 kg/m^3
1 fl oz = 29.6 mL

Table 2-24 is a summary of the mix aggregates and shows the batch weights, percentage by weight, the batch volumes and the percentage by volume.

Table 2-24: SSD Limestone, 60% G100 Slag

Aggregate	Specific Gravity	Weight lb/yd^3 (kg/m^3)	% by Weight	Volume ft^3/yd^3 (m^3/m^3)	% by Volume
LS-9	2.59	1,188 (705)	40.0	7.35 (0.272)	40.2
PG-14	2.61	715 (424)	24.0	4.39 (0.163)	24.0
S-16	2.62	1,070 (635)	36.0	6.55 (0.243)	35.8
TOTAL		**2,973 (1,764)**	**100**	**18.29 (0.677)**	**100**

Figure 2-33 shows that this mix had an actual gradation that fell a little outside the optimized gradation. The gradation of the mix was adjusted manually to get a closer fit to the ideal haystack shape for a well graded mix, which is shown in Figure

2-33. The aggregate gradation, however, still fell in Zone III and did not prove to be a challenge when batching.

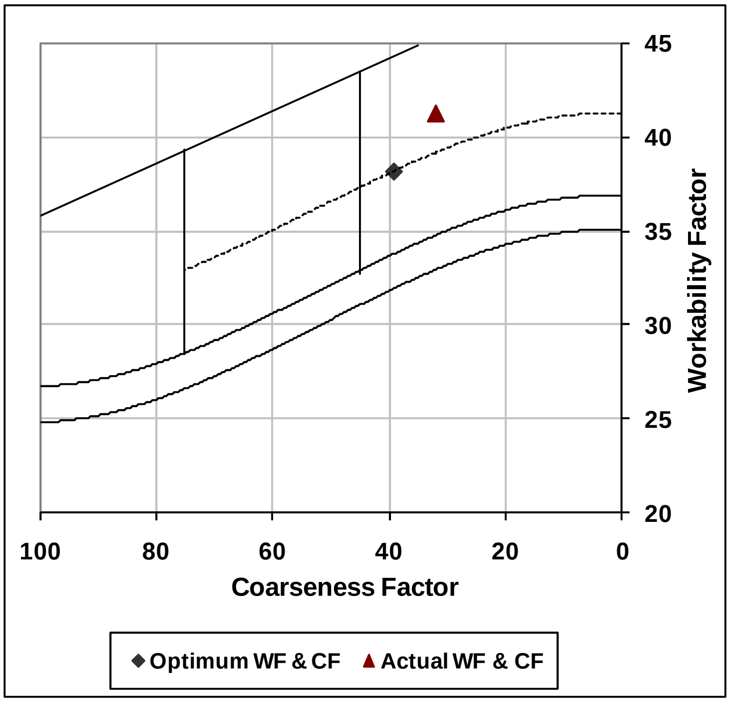

Figure 2-33: MCFC SSD Limestone, 60% G100 Slag

2.5.3.9 Program II Summary

The paste content was held constant for every batch in Program II. As new samples of aggregates were obtained, the gradations changed and the mix proportions changed slightly. The lightweight aggregate was consistently used to replace the pea gravel and the fine lightweight aggregate was used to replace the sand. The batches are summarized in Table 2-25 showing the aggregate amounts by percent volume. The coarse aggregate volume was nearly constant for all granite mixes (39.7% to 42.4%). For the mixes with LWA, the volume of pea gravel ranged from 18.3% to 27.3%. The volume of sand ranged from 30.8% to 31.2%, except for the mix with fine lightweight aggregate. The mix with fine lightweight aggregate had 27.3% pea gravel and only 23.4% sand by volume because a portion of the sand was replaced by the fine lightweight aggregate.

Table 2-25: Program II – Batch Aggregates by Volume

	Granite					Limestone		
Aggregate	**Control**	**LWA (30% Slag)**	**FLWA (30% Slag)**	**LWA (60% Slag)**	**LWA (60% Slag II)**	**Control**	**30% Slag**	**60% Slag**
Coarse	41.7	41.8	41.8	42.4	39.7	42.4	40.2	40.2
Pea Gravel	27.3	18.9	27.3	18.3	20.7	22.2	23.9	24.0
Sand	31.0	30.8	23.4	30.9	31.2	35.4	35.9	35.8
LWA	0	8.4	7.4	8.4	8.4	0	0	0
TOTAL	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**

The aggregate proportions for the limestone mixes were nearly constant. The volume of coarse aggregate for the limestone mixes ranged from 40.2% to 42.4%, the volume of pea gravel ranged from 22.2% to 24.0% and the volume of sand ranged from 35.4% to 35.9%.

Chapter 3 Results and Evaluation

3.1 General Information

This chapter presents the free shrinkage results from the two programs tested in this research. Special attention is given to the early shrinkage of the specimens because less early age shrinkage results in less overall shrinkage. Data for the 30-day results is shown. Test specimens are still being monitored in the lab, but results at 90 days are also presented. The behavior between 30 and 90 days has been steady and the relative results between specimens is anticipated to remain constant to the end of the 365-day test. Final results will be reported in future work.

All free shrinkage results that are presented represent the average shrinkage of three specimens, unless otherwise noted. Free shrinkage is plotted starting at time zero which represents the day the specimens are removed from the curing tank. Comparisons are made from each batch with respect to aggregate absorptions, available water for internal curing, compressive strength and unit weight. The free shrinkage results are reported in accordance to ASTM C 157.

The goal of this research is to determine how effective the use of lightweight aggregate is to combat early shrinkage in LC-HPC mixes. Free shrinkage specimens and strength cylinders were cast to determine the effects of the addition of lightweight aggregates. The mixes had a cement content of 540 lb/yd^3, a 0.44 water/cement ratio, 24.7% paste content and 8% air content. Both 7-day and 14-day curing periods were used for the free shrinkage specimens. Strength cylinders were tested at 28 days.

Two programs were designed to test the lightweight aggregate as an internal curing agent. The objective of Program I was to determine an appropriate level of lightweight aggregate that would supply a sufficient amount of internal curing to reduce shrinkage without sacrificing strength. A total of six mixes were batched in Program I: two control mixes and four mixes to evaluate lightweight aggregate for internal curing. Three mixes were used to evaluate three different replacement levels of the intermediate lightweight aggregate: a low level of replacement, a medium level of replacement and a high level of replacement.

The objective of Program II was to determine how the addition of lightweight aggregate affected a mix that includes a G100 slag. A total of eight mixes were included in Program II: two control mixes, four mixes with lightweight aggregate and G100 slag, and two mixes with limestone and G100 slag.

3.2 Statistical Analysis

The Student's T-Test is a statistical analysis that was used to determine whether the difference between two free shrinkage samples was statistically significant. The T-Test is able to statistically identify whether two tests are the same with respect to the tested variable. The test assumes that the data has a normal distribution and uses the means, standard deviation and number of data points in each sample for the two sample groups. The independent T-Test was used to compare each set of free shrinkage data. Eq. (3-1) is used to find the t-value (t_t) for each set of data points.

$$t_t = \frac{\overline{x_1} - \overline{x_2}}{\sqrt{\left(\frac{S_1 + S_2}{d_f}\right) \times \left(\frac{1}{n_1} + \frac{1}{n_2}\right)}} \tag{3-1}$$

where $\overline{x_1}$ and $\overline{x_2}$ are the means for sample 1 and 2, respectively, S_1 and S_2 are the sum of the squares for sample 1 and 2, respectively, d_f is the total degrees of freedom for both samples, and n_1 and n_2 are the number of variables in sample 1 and 2, respectively. The sum of the squares is calculated using Eq. (3-2)

$$S = \sum x^2 - \frac{\left(\sum x\right)^2}{n} \tag{3-2}$$

where x is the value of each variable in the given sample and n is the number of variables in the sample. The total degrees of freedom for the T-Test are determined using Eq. (3-3).

$$d_f = n_1 + n_2 - 2 \tag{3-3}$$

After calculating the t-value (t_t), the value is compared to the statistical t-value (t) at a given confidence level (α) to determine whether the test shows a significant difference between the two samples. If t_t is larger than t the test shows that there is a significant difference between the two samples at the given confidence level. For example, if t_t is found to be 3.62 for two sets of data and t (at a confidence level of $\alpha = 0.05$) is 2.78, the test shows that statistically, there is a significant difference between the two sets of data. The result is interpreted such that, with 95% ($\alpha = 0.05$) certainty, there is a significant difference between the two sets of data. All free shrinkage data is compared to four confidence levels (α = 0.2, 0.1, 0.05, 0.02). A standard notation is used to interpret the T-Test results and is as follows: a "Y" indicates that at the highest confidence level ($\alpha = 0.02$), with at least 98% certainty, the test shows a significant difference between test data. A "N" indicates that at the lowest confidence level ($\alpha = 0.2$), with at least 80% certainty, there is not a significant difference between test data. At confidence levels of at least $\alpha = 0.2$, $\alpha = 0.1$ and $\alpha = 0.05$, a statistically significant difference is noted by "80", "90" and "95", respectively.

3.3 Program I

A total of six mixes were included in Program I: two control mixes and four mixes to evaluate an appropriate level of lightweight aggregate for internal curing to reduce shrinkage without sacrificing strength. The program included two control mixes; one granite mix and one limestone mix. Three mixes were used to evaluate three different replacement levels of the intermediate lightweight aggregate: a low level of replacement, a medium level of replacement and a high level of replacement. One additional mix was cast to evaluate the use of a fine lightweight aggregate at a medium level of replacement.

Table 3-1 shows the properties of each batch mixed in Program I. Each slump, air content and temperature test proved to be within the given LC-HPC specifications. The average 28-day compressive strength for the Granite Control was 4,610 psi (31.8 MPa) and 4,460 psi (30.8 MPa) for the Limestone Control. The LWA (Low) had a compressive strength similar to that of the Limestone Control [4,450 psi (30.7 MPa)], 160 psi (1.1 MPa) lower than that of the Granite Control. The LWA

(Medium) was similar, with a 28-day compressive strength of 4,450 psi (30.7 MPa). The batch FLWA (Medium) had the lowest strength at 28 days of 4,160 psi (28.7 MPa). The LWA (High) actually had higher strength than the Granite Control at 4,850 psi (33.4 MPa). The unit weights for the batches ranged from 132.1 lb/ft^3 (2,116 kg/m^3) to 139.3 lb/ft^3 (2,231 kg/m^3).

Table 3-1: Mix Properties, Program I

Description	Slump	Air Content	Temp.	Compressive Strength		Unit Weight
	in. (cm)	%	°F (°C)	Avg. 7 Day psi (MPa)	Avg. 28 Day psi (MPa)	lb/ft^3 (kg/m^3)
Granite Control	4 (10.2)	8.90	70 (21.1)	3,700 (25.5)	4,610 (31.8)	139.3 (2,231)
Limestone Control	4 (10.2)	8.65	72 (22.2)	3,260 (22.5)	4,460 (30.8)	139.2 (2,230)
LWA (Low)	2 (5.1)	8.40	70 (21.1)	3,640 (25.1)	4,450 (30.7)	133.9 (2,145)
LWA (Medium)	3¼ (8.3)	8.90	67 (19.4)	3,370 (23.2)	4,450 (30.7)	132.1 (2,116)
FLWA (Medium)	2½ (6.4)	8.90	71 (21.7)	3,410 (23.5)	4,160 (28.7)	135.7 (2,174)
LWA (High)	3¼ (8.3)	8.15	69 (20.6)	3,950 (27.2)	4,850 (33.4)	130.5 (2,091)

The amount of water available to contribute to the mix is an important aspect of this research. Table 3-2 shows the total absorbed water from each aggregate of each material (See Table 3-3 for absorption values for each mix). The amount of water that was absorbed in each aggregate and potentially available for internal curing was calculated using Eq.(3-4):

$$W = M_{SSD} \times \frac{1}{1+\phi_{Aggregate}} \times \phi_{Aggregate} \tag{3-4}$$

where W is the amount of absorbed water (lb/yd^3), M_{SSD} is the total mass of the SSD aggregate in the mix and $\phi_{Aggregate}$ is the absorption of the aggregate. The total amount of absorbed water for a mix is equal to the sum of all the absorbed water for each aggregate in the mix.

Table 3-2: Available Water for Internal Curing, Program I

No.	Description	Coarse Aggregate	Pea Gravel	Sand	LWA	Water Excluding LWA	Water from all Aggregates
		lb/yd³ (kg/m³)	lb/yd³ (kg/m³)	lb/yd³ (kg/m³)	lb/yd³ (kg/m³)	lb/yd³ (kg/m³)	lb/yd³ (kg/m³)
#619	Granite Control	9.2 (5.5)	6.3 (3.7)	3.5 (2.1)	0	19.0 (11.3)	19.0 (11.3)
#620	Limestone Control	36.2 (21.5)	4.8 (2.8)	4.1 (2.4)	0	45.1 (26.7)	45.1 (26.7)
#622	LWA (Low)	9.2 (5.5)	4.0 (2.4)	3.5 (2.1)	29.7 (17.6)	16.7 (10.0)	46.4 (27.5)
#628	LWA (Medium)	9.1 (5.4)	2.8 (1.7)	3.5 (2.1)	40.2 (23.8)	15.4 (9.2)	55.6 (33.0)
#654	FLWA (Medium)	9.3 (5.2)	7.5 (4.4)	2.3 (1.4)	28.5 (16.7)	19.1 (11.2)	47.7 (28.0)
#634	LWA (High)	9.1 (5.5)	2.1 (1.2)	3.5 (2.1)	55.1 (32.7)	14.7 (8.7)	69.8 (41.4)

The total amount of absorbed water for the mixes ranged from 19.0 lb/yd^3 (11.3 kg/m^3) to 69.8 lb/yd^3 (41.4 kg/m^3). As discussed in *Chapter 1 Introduction and Background*, however, not all the absorbed water is available for internal curing. As the absorption of the aggregate increases, so does the size of the pore structure; the larger the pore structure the more readily available the absorbed water is to be re-introduced into the concrete mix for internal curing (Hammer et al., 2004). This desorption property can be related to the aggregate absorption (Zhutovsky et al. 2002) which are shown in Table 3-3. It is expected that the desorption value will be greater with higher aggregate absorption (or total moisture content) values. The aggregate with the lowest desorption capability (lowest absorption) will therefore be the sand, followed by the granite, pea gravel and limestone. The lightweight aggregates, having the highest absorption values, will have the greatest desorption value and be able to contribute the most water back to the mix for internal curing.

Table 3-3: Aggregate Absorption Values

Aggregate	Aggregate Absorption/Total Moisture Contents	
Granite	G-15: 0.76%	G-20: 0.71%
Limestone	LS-9: 3.07%	
Pea Gravel	PG-14: 0.93%	
Sand	S-15: 0.33%	S-16: 0.33%
Intermediate LWA	LW-A2: 24.73%-29.49%	LW-A3: 26.50%-29.96%
Fine LWA	FLW-A1: 25.41%-28.36%	

Even though the mixes with granite and lightweight aggregate have between 14.2 lb/yd^3 (8.4 kg/m^3) and 18.2 lb/yd^3 (10.8 kg/m^3) of absorbed water excluding the contribution from the lightweight aggregate, not all of this water will be available for internal curing because of the low absorption values related to these aggregates. The lightweight aggregate contributes between 29.7 lb/yd^3 (16.6 kg/m^3) and 55.1 lb/yd^3 (32.7 kg/m^3) of additional water to the mix, and will contribute the most to reduce free shrinkage.

Table 3-4: Free Shrinkage Summary for Program I

Days of Drying	Granite Control		Limestone Control		LWA (Low)		LWA (Medium)		FLWA (Medium)		LWA (High)	
	7-day Cure	14-day Cure	7-day Cure	14-day Cure	7-day Cure	14-day Cure	7-day Cure	14-day Cure	7-day Cure	14-day Cure	7-day Cure	14-day Cure
0	-3	-43	-90	-73	-17	-63	3	-47	-20	-27	-30	-80
30	347	313	377	363	300	253	300	260	337	280	260	220
60	413	387	463	460	377	350	390	327	403	358	337	303
90	447	410	503	490	413	373	413	370	450	393	370	347

Table 3-4 shows the summary of the free shrinkage data for the mixes in Program I at 0, 30, 60 and 90 days of drying and for both the 7-day and 14-day cured specimens. At 90 days, the least shrinkage was observed with the LWA (High), 14-day cure, with 347 με. The most shrinkage was observed with the Limestone Control, 7-day cure, with 503 με.

The average 30-day free shrinkage values shown in Table 3-4 ranged from 220 με to 377 με. The lowest shrinkage at 30-days was observed with the 14-day cured LWA (High) batch at 220 με, followed by the 14-day cured LWA (Low) batch at 253 με; 7-day cured LWA (High) batch at 260 με; 14-day cured LWA (Medium) batch at 260 με; 14-day cured FLWA (Medium) batch at 280 με; 7-day cured LWA (Medium) batch at 300 με; 7-day cured LWA (Low) batch at 300 με; 14-day cured Granite Control batch at 313 με; 7-day cured FLWA (Medium) batch at 337 με; 7-day cured Granite Control batch at 347 με; 14-day cured Limestone Control batch at 363 με and the 7-day cured Limestone Control batch at 377 με.

The average 90-day free shrinkage values shown in Table 3-4 ranged from 347 με to 503 με. The lowest shrinkage at 90-days was observed with the 14-day cured LWA (High) batch at 347 με, followed by the 7-day cured LWA (High) batch at 370 με; 14-day cured LWA (Medium) batch at 370 με; 14-day cured LWA (Low) batch at 373 με; 14-day cured FLWA (Medium) batch at 393 με; 14-day cured Granite Control batch at 410 με; 7-day cured LWA (Medium) batch at 413 με; 7-day cured LWA (Low) batch at 413 με; 7-day cured Granite Control batch at 447 με; 7-day cured FLWA (Medium) batch at 450 με; 14-day cured Limestone Control batch at 490 με and the 7-day cured Limestone Control batch at 503 με.

Figure 3-1 shows the results of the free shrinkage tests evaluating different replacement levels of lightweight aggregate through the first 30 days. The vertical axis plots free shrinkage (in με) of the specimens. The horizontal axis plots time in days. The batches plotted include both the 7-day (7D) and 14-day (14D) cured data for the Granite Control, Limestone Control, LWA (Low), LWA (Medium), FLWA (Medium) and LWA (High).

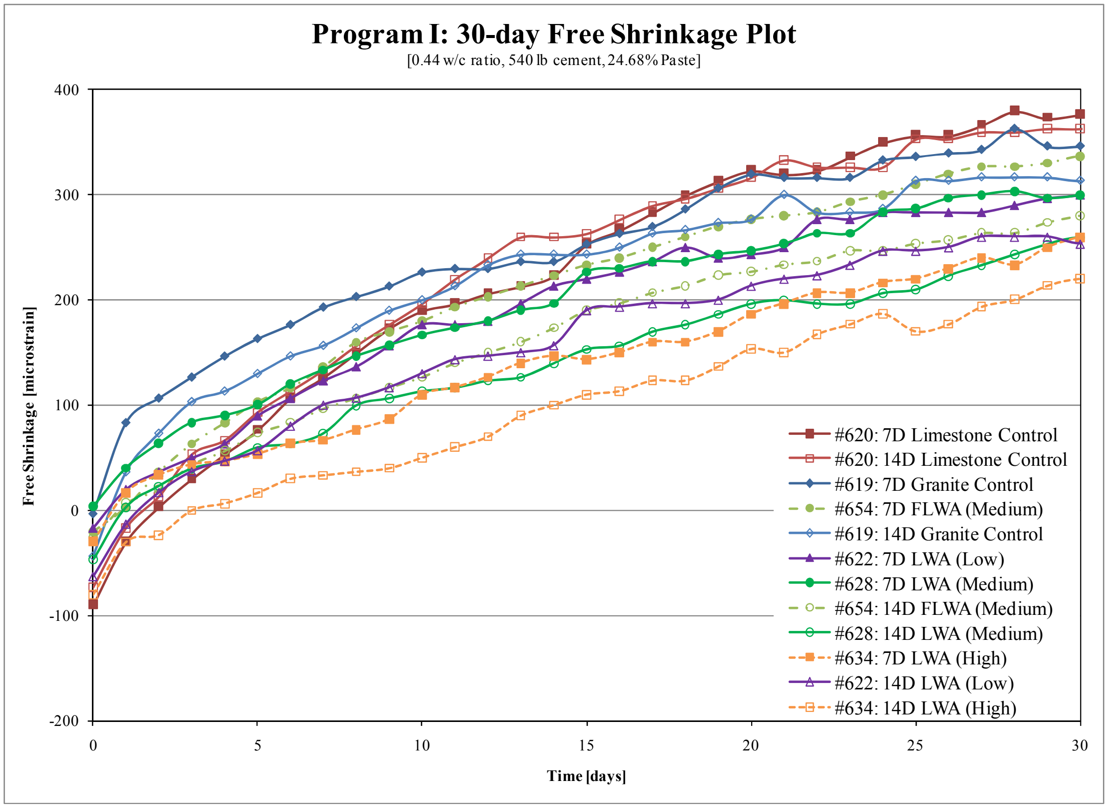

Figure 3-1: 30-day Free Shrinkage Plot, Program I

Figure 3-1 shows that in all cases, at 30-days, the 14-day cured specimens performed better with less free shrinkage than the associated 7-day cured specimens. The Limestone Control, however, showed less improvement between the 7-day cured specimens and 14-day cured specimens at 30-days compared to all other batches.

Comparing 7-day cured specimens, adding lightweight aggregate improved shrinkage when compared to the Granite Control. Shrinkage performance was improved with increasing amounts of lightweight aggregate. Of the four batches with lightweight aggregate, the 7-day cured FLWA (Medium) batch only showed a slight improvement when compared to the 7-day cured Granite Control (337 με compared to 347 με, respectively). No difference in shrinkage was observed between the 7-day cured LWA (Low) and 7-day cured LWA (Medium) at 30-days (300 με each). The 7-day cured LWA (High) showed the most improvement (260 με).

Comparing 14-day cured specimens, the trends were similar. The 14-day cured FLWA (Medium) still performed poorly compared to the other batches with lightweight aggregate. The 14-day cured LWA (Low) showed a little less shrinkage than the 14-day cured LWA (Medium) at 30 days, 253 με compared to 260 με, respectively. The 14-day cured LWA (High) still performed the best.

During the first 30 days, the batches with the fine lightweight aggregate did not perform as well as the batches with intermediate lightweight aggregate. The highest level of intermediate lightweight aggregate replacement performed the best out of the batches with lightweight aggregate. All batches containing lightweight aggregate showed less shrinkage than the corresponding 7-day or 14-day cured Granite Control. The Limestone Control batch had the largest amount of shrinkage.

Figure 3-2 shows the results of the free shrinkage tests evaluating different replacement levels of lightweight aggregate through the first 90 days. The vertical axis plots free shrinkage (in με) of the specimens. The horizontal axis plots time in days. The batches plotted include both the 7-day (7D) and 14-day (14D) cured data for the Granite Control, Limestone Control, LWA (Low), LWA (Medium), FLWA (Medium) and LWA (High).

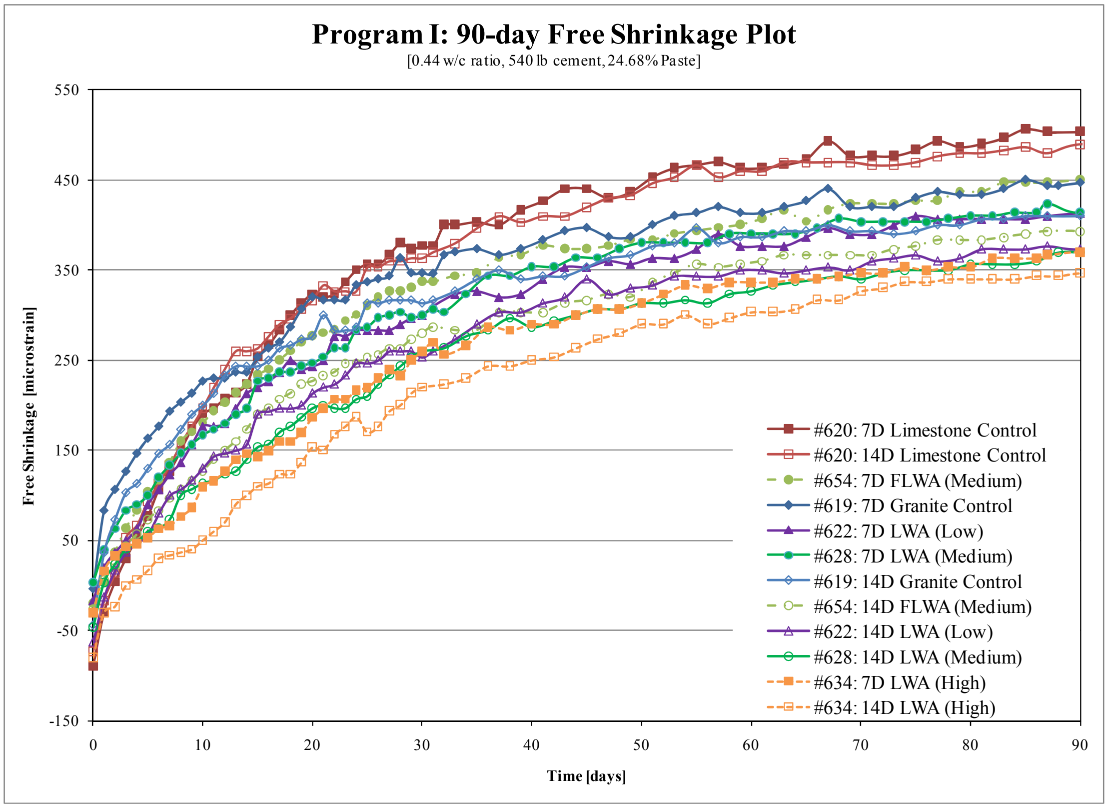

Figure 3-2: 90-day Free Shrinkage Plot, Program I

Trends at 90-days were similar to the 30-day trends. The 14-day cured specimens still performed better with less free shrinkage than the associated 7-day cured specimens. The Limestone Control still showed less improvement between the 7-day cured specimens and 14-day cured specimens at 30-days compared to all other batches.

Comparing 7-day cured specimens, adding lightweight aggregate improved shrinkage when compared to the Granite Control in almost all cases [except FLWA (Medium)]. Shrinkage performance was improved with increasing amounts of lightweight aggregate. Of the four batches with lightweight aggregate, the 7-day cured FLWA (Medium) batch shrank slightly more when compared to the 7-day cured Granite Control (450 με compared to 447 με, respectively). No difference in shrinkage was observed between the 7-day cured LWA (Low) and 7-day cured LWA (Medium) at 90 days (413 με each). The 7-day cured LWA (High) showed the most improvement (370 με) when compared to the free shrinkage of the 7-day Granite Control mix at 447 με. The 7-day cured LWA (High) batch outperformed all batches cured for 14 days except the 14-day cured LWA (High).

Comparing 14-day cured specimens, the trends were similar to the 7-day cured specimen behavior. The 14-day cured FLWA (Medium) batch still did not perform as well as batches with intermediate lightweight aggregate, but did have less shrinkage than the 14-day cured Granite Control (393 με vs. 410 με). The 14-day cured LWA (Medium) showed a little less shrinkage than the 14-day cured LWA (Low), 370 με compared to 373 με, respectively. The 14-day cured LWA (High) still performed the best.

During the first 90 days, the batches with the fine lightweight aggregate did not perform as well as the corresponding batches with intermediate lightweight aggregate. Both the 7-day cured and 14-day cured batch with the highest level of intermediate lightweight aggregate replacement performed better than all other batches. All batches containing intermediate lightweight aggregate showed less shrinkage than the corresponding 7-day or 14-day cured Granite Control. The Limestone Control batch had the largest amount of shrinkage.

The Student's T-Test was used to evaluate all the mixes at both the 30-day free shrinkage results and the 90-day free shrinkage results. The results are shown in

Table 3-5 and Table 3-6. The statistical analysis not only accounts for the difference between the means of the free shrinkage between the two mixes but the variability in the free shrinkage data points as well.

From Table 3-5, listed in order from highest to lowest relevance, are the mixes that showed statistically significant differences at the highest confidence level of 98% or better for the free shrinkage at 30 days. :

- #620 - 14D Limestone Control[†] and #634 - 14D LWA (High)
- #620 - 14D Limestone Control and #634 - 7D LWA (High)[‡]
- #622 - 7D LWA (Low) and #634 - 14D LWA (High)
- #620 - 14D Limestone Control and #622 - 7D LWA (Low)
- #654 - 7D FLWA (Medium) and #634 - 14D LWA (High)
- #620 - 14D Limestone Control and #654 - 14D FLWA (Medium)
- #619 - 7D Granite Control and #634 - 14D LWA (High)
- #620 - 14D Limestone Control and #628 - 14D LWA (Medium)
- #628 - 7D LWA (Medium) and #634 - 14D LWA (High)
- #619 - 14D Granite Control and #634 - 14D LWA (High)
- #620 - 14D Limestone Control and #628 - 7D LWA (Medium)
- #620 - 14D Limestone Control and #622 - 14D LWA (Low)
- #654 - 7D FLWA (Medium) and #634 - 7D LWA (High)
- #620 - 7D Limestone Control and #634 - 14D LWA (High)
- #654 - 14D FLWA (Medium) and #634 - 14D LWA (High)
- #619 - 7D Granite Control and #634 - 7D LWA (High)
- #628 - 14D LWA (Medium) and #654 - 7D FLWA (Medium)

[‡]7D: 7-day cured
[†]14D: 14-day cured

It is important to note that this list compares Granite Control with the lightweight aggregate mix with the highest level of replacement (including both the 7-day and 14-day curing periods) indicating that a statistically significant difference in shrinkage was seen between these mixes. The 14-day cured mix containing the lightweight aggregate at the highest level of replacement was the best shrinkage performing mix at 30 days.

Table 3-5: 30-day T-Test Results for Program I†

		30-day Free Shrinkage (με)	#619 - Granite Control		#620 – Limestone Control		#622 – LWA (Low)		#628 – LWA (Medium)		#654 – FLWA (Medium)		#634 – LWA (High)	
			7-day	14-day	7-day	14-day	7-day	14-day	7-day	14-day	7-day	14-day	7-day	14-day
#619	7-day	347		N	N	N	90%	95%	90%	95%	N	95%	Y	Y
	14-day	313			80%	95%	N	90%	N	90%	N	80%	95%	Y
#620	7-day	377				N	90%	95%	90%	95%	N	95%	95%	Y
	14-day	363					Y	Y	Y	Y	90%	Y	Y	Y
#622	7-day	300						80%	N	90%	90%	80%	95%	Y
	14-day	253							80%	N	95%	N	N	N
#628	7-day	300								80%	90%	N	90%	Y
	14-day	260									Y	N	N	90%
#654	7-day	337										95%	Y	Y
	14-day	280											N	Y
#634	7-day	260												95%
	14-day	220												

†See *3.2 Statistical Analysis* for explanation of terms

Table 3-6: 90-day T-Test Results for Program I†

		90-day Free Shrinkage (με)	#619 - Granite Control		#620 – Limestone Control		#622 – LWA (Low)		#628 – LWA (Medium)		#654 – FLWA (Medium)		#634 – LWA (High)	
			7-day	14-day	7-day	14-day	7-day	14-day	7-day	14-day	7-day	14-day	7-day	14-day
#619	7-day	447		N	N	80%	N	80%	N	90%	N	90%	95%	Y
	14-day	410			80%	Y	N	N	N	N	80%	N	90%	Y
#620	7-day	503				N	80%	90%	80%	90%	N	90%	95%	95%
	14-day	490					Y	Y	Y	Y	90%	Y	Y	Y
#622	7-day	413						N	N	80%	90%	80%	95%	Y
	14-day	373							N	N	90%	N	N	N
#628	7-day	413								80%	80%	80%	95%	Y
	14-day	370									90%	N	N	N
#654	7-day	450										95%	Y	Y
	14-day	393											80%	Y
#634	7-day	370												80%
	14-day	347												

†See *3.2 Statistical Analysis* for explanation of terms

From Table 3-5, listed in order from highest to lowest relevance, are the mixes that showed statistically significant differences at a confidence level of 95% or better for the free shrinkage at 30 days.

- #619 - 7D Granite Control and #628 - 14D LWA (Medium)
- #620 - 7D Limestone Control and #634 - 7D LWA (High)
- #634 - 7D LWA (High) and #634 - 14D LWA (High)
- #622 - 7D LWA (Low) and #634 - 7D LWA (High)
- #654 - 7D FLWA (Medium) and #654 - 14D FLWA (Medium)
- #619 - 14D Granite Control and #620 - 14D Limestone Control
- #622 - 14D LWA (Low) and #654 - 7D FLWA (Medium)
- #619 - 7D Granite Control and #622 - 14D LWA (Low)
- #620 - 7D Limestone Control and #628 - 14D LWA (Medium)
- #620 - 7D Limestone Control and #622 - 14D LWA (Low)
- #619 - 7D Granite Control and #654 - 14D FLWA (Medium)
- #619 - 14D Granite Control and #634 - 7D LWA (High)
- #620 - 7D Limestone Control and #654 - 14D FLWA (Medium)

From Table 3-5, listed in order from highest to lowest relevance, are the mixes that showed statistically significant differences at a confidence level of 90% or better for the free shrinkage at 30 days:

- #622 - 7D LWA (Low) and #654 - 7D FLWA (Medium)
- #628 - 7D LWA (Medium) and #634 - 7D LWA (High)
- #619 - 14D Granite Control and #628 - 14D LWA (Medium)
- #619 - 7D Granite Control and #622 - 7D LWA (Low)
- #628 - 14D LWA (Medium) and #634 - 14D LWA (High)
- #622 - 7D LWA (Low) and #628 - 14D LWA (Medium)
- #620 - 7D Limestone Control and #622 - 7D LWA (Low)
- #619 - 14D Granite Control and #622 - 14D LWA (Low)
- #620 - 7D Limestone Control and #628 - 7D LWA (Medium)
- #619 - 7D Granite Control and #628 - 7D LWA (Medium)
- #628 - 7D LWA (Medium) and #654 - 7D FLWA (Medium)
- #620 - 14D Limestone Control and #654 - 7D FLWA (Medium)

This list notably contains the comparison of the Granite Control mix with mixes containing low and medium level replacements of lightweight aggregate (both for 7-

day and 14-day curing periods) indicating that a statistically significant difference in shrinkage (at a confidence level of 90% or better) was observed between these mixes. The 7-day cured lightweight aggregate mix at the medium level of replacement also showed a statistically significant difference in shrinkage at a 90% confidence level with the 7-day cured fine lightweight aggregate mix at a medium level of replacement.

From Table 3-5, listed in order from highest to lowest relevance, are the mixes that showed statistically significant differences at a confidence level of 80% or better for the free shrinkage at 30 days:

- #628 - 7D LWA (Medium) and #628 - 14D LWA (Medium)
- #622 - 7D LWA (Low) and #622 - 14D LWA (Low)
- #622 - 14D LWA (Low) and #628 - 7D LWA (Medium)
- #619 - 14D Granite Control and #620 - 7D Limestone Control
- #619 - 14D Granite Control and #654 - 14D FLWA (Medium)
- #622 - 7D LWA (Low) and #654 - 14D FLWA (Medium)

This list notably contains comparisons between the 14-day cured Granite Control with the 14-day cured fine lightweight aggregate mix at a medium level of replacement indicating a statistically significant difference in shrinkage (at a confidence level of 80% or better) was observed between these mixes.

From Table 3-5, listed in order from highest to lowest relevance, are the mixes that showed no statistically significant differences (a confidence level of less than 80%) for the free shrinkage at 30 days:

- #622 - 14D LWA (Low) and #634 - 14D LWA (High)
- #619 - 7D Granite Control and #619 - 14D Granite Control
- #654 - 14D FLWA (Medium) and #634 - 7D LWA (High)
- #619 - 14D Granite Control and #654 - 7D FLWA (Medium)

- #628 - 7D LWA (Medium) and #654 - 14D FLWA (Medium)
- #620 - 7D Limestone Control and #654 - 7D FLWA (Medium)
- #622 - 14D LWA (Low) and #654 - 14D FLWA (Medium)
- #628 - 14D LWA (Medium) and #654 - 14D FLWA (Medium)
- #619 - 7D Granite Control and #620 - 14D Limestone Control
- #619 - 14D Granite Control and #622 - 7D LWA (Low)
- #619 - 7D Granite Control and #620 - 7D Limestone Control
- #619 - 14D Granite Control and #628 - 7D LWA (Medium)
- #619 - 7D Granite Control and #654 - 7D FLWA (Medium)
- #620 - 7D Limestone Control and #620 - 14D Limestone Control
- #622 - 14D LWA (Low) and #634 - 7D LWA (High)
- #622 - 14D LWA (Low) and #628 - 14D LWA (Medium)
- #622 - 7D LWA (Low) and #628 - 7D LWA (Medium)
- #628 - 14D LWA (Medium) and #634 - 7D LWA (High)

This list notably contains the comparison between the 7-day cured Granite Control with the 7-day cured fine lightweight aggregate mix at a medium level of replacement as well as the 14-day cured lightweight aggregate mix with the 14-day cured fine lightweight aggregate mix (both at a medium level of replacement) indicating there was not a statistically significant difference in shrinkage (at a confidence level of less than 80%) observed between these mixes.

From Table 3-6, listed in order from highest to lowest relevance, are the mixes that showed statistically significant differences at the highest confidence level of 98% or better for the free shrinkage at 90 days:

- #620 - 14D Limestone Control and #634 - 14D LWA (High)
- #620 - 14D Limestone Control and #654 - 14D FLWA (Medium)
- #620 - 14D Limestone Control and #622 - 7D LWA (Low)
- #620 - 14D Limestone Control and #634 - 7D LWA (High)
- #622 - 7D LWA (Low) and #634 - 14D LWA (High)
- #620 - 14D Limestone Control and #628 - 7D LWA (Medium)
- #628 - 7D LWA (Medium) and #634 - 14D LWA (High)
- #619 - 14D Granite Control and #620 - 14D Limestone Control
- #654 - 7D FLWA (Medium) and #634 - 14D LWA (High)

- #654 - 14D FLWA (Medium) and #634 - 14D LWA (High)
- #619 - 14D Granite Control and #634 - 14D LWA (High)
- #620 - 14D Limestone Control and #628 - 14D LWA (Medium)
- #619 - 7D Granite Control and #634 - 14D LWA (High)
- #620 - 14D Limestone Control and #622 - 14D LWA (Low)
- #654 - 7D FLWA (Medium) and #634 - 7D LWA (High)

It is important to note that this list compares the 14-day cured Granite Control with the 14-day cured lightweight aggregate mix at the highest level of replacement indicating a statistically significant difference in shrinkage (at the highest confidence level) was observed between these mixes. The 14-day cured LWA (High) mix was the best shrinkage performing mix at 90 days.

From Table 3-6, listed in order from highest to lowest relevance, are the mixes that showed statistically significant differences at a confidence level of 95% or better for the free shrinkage at 90 days:

- #620 - 7D Limestone Control and #634 - 14D LWA (High)
- #654 - 7D FLWA (Medium) and #654 - 14D FLWA (Medium)
- #622 - 7D LWA (Low) and #634 - 7D LWA (High)
- #619 - 7D Granite Control and #634 - 7D LWA (High)
- #628 - 7D LWA (Medium) and #634 - 7D LWA (High)
- #620 - 7D Limestone Control and #634 - 7D LWA (High)

This list notably compares the 7-day cured Granite Control with the 7-day cured lightweight aggregate mix at the highest level of replacement showing that a statistically significant difference in shrinkage (at a confidence level of 95% or better) was observed between these mixes.

From Table 3-6, listed in order from highest to lowest relevance, are the mixes that showed statistically significant differences at a confidence level of 90% or better for the free shrinkage at 90 days:

- #620 - 7D Limestone Control and #628 - 14D LWA (Medium)
- #628 - 14D LWA (Medium) and #654 - 7D FLWA (Medium)
- #620 - 14D Limestone Control and #654 - 7D FLWA (Medium)
- #620 - 7D Limestone Control and #622 - 14D LWA (Low)
- #620 - 7D Limestone Control and #654 - 14D FLWA (Medium)
- #622 - 14D LWA (Low) and #654 - 7D FLWA (Medium)
- #619 - 14D Granite Control and #634 - 7D LWA (High)
- #619 - 7D Granite Control and #654 - 14D FLWA (Medium)
- #619 - 7D Granite Control and #628 - 14D LWA (Medium)
- #622 - 7D LWA (Low) and #654 - 7D FLWA (Medium)

This list notably compares the 7-day cured lightweight aggregate mix with the 7-day cured fine lightweight aggregate mix (both at medium levels of replacement) showing that a statistically significant difference in shrinkage (at a confidence level of 90% or better) was observed between these mixes.

From Table 3-6, listed in order from highest to lowest relevance, are the mixes that showed statistically significant differences at a confidence level of 80% or better for the free shrinkage at 90 days:

- #619 - 7D Granite Control and #622 - 14D LWA (Low)
- #622 - 7D LWA (Low) and #654 - 14D FLWA (Medium)
- #619 - 14D Granite Control and #654 - 7D FLWA (Medium)
- #619 - 14D Granite Control and #620 - 7D Limestone Control
- #628 - 7D LWA (Medium) and #654 - 7D FLWA (Medium)
- #620 - 7D Limestone Control and #622 - 7D LWA (Low)
- #620 - 7D Limestone Control and #628 - 7D LWA (Medium)
- #619 - 7D Granite Control and #620 - 14D Limestone Control
- #634 - 7D LWA (High) and #634 - 14D LWA (High)
- #628 - 7D LWA (Medium) and #654 - 14D FLWA (Medium)
- #654 - 14D FLWA (Medium) and #634 - 7D LWA (High)
- #622 - 7D LWA (Low) and #628 - 14D LWA (Medium)
- #628 - 7D LWA (Medium) and #628 - 14D LWA (Medium)

From Table 3-6, listed in order from highest to lowest relevance, are the mixes that showed no statistically significant differences (a confidence level of less than 80%) for the free shrinkage at 90 days:

- #619 - 7D Granite Control and #619 - 14D Granite Control
- #619 - 7D Granite Control and #622 - 7D LWA (Low)
- #622 - 7D LWA (Low) and #622 - 14D LWA (Low)
- #622 - 14D LWA (Low) and #628 - 7D LWA (Medium)
- #619 - 7D Granite Control and #628 - 7D LWA (Medium)
- #619 - 14D Granite Control and #628 - 14D LWA (Medium)
- #619 - 14D Granite Control and #622 - 14D LWA (Low)
- #619 - 14D Granite Control and #654 - 14D FLWA (Medium)
- #619 - 7D Granite Control and #620 - 7D Limestone Control
- #620 - 7D Limestone Control and #654 - 7D FLWA (Medium)
- #622 - 14D LWA (Low) and #634 - 14D LWA (High)
- #628 - 14D LWA (Medium) and #634 - 14D LWA (High)
- #628 - 14D LWA (Medium) and #654 - 14D FLWA (Medium)
- #622 - 14D LWA (Low) and #654 - 14D FLWA (Medium)
- #620 - 7D Limestone Control and #620 - 14D Limestone Control
- #619 - 14D Granite Control and #622 - 7D LWA (Low)
- #619 - 14D Granite Control and #628 - 7D LWA (Medium)
- #619 - 7D Granite Control and #654 - 7D FLWA (Medium)
- #622 - 14D LWA (Low) and #634 - 7D LWA (High)
- #622 - 14D LWA (Low) and #628 - 14D LWA (Medium)
- #622 - 7D LWA (Low) and #628 - 7D LWA (Medium)
- #628 - 14D LWA (Medium) and #634 - 7D LWA (High)

This list notably contains comparisons between the Granite Control and fine and intermediate lightweight aggregate mixes at low and medium levels of replacement (both for 7-day cured and 14-day cured specimens) showing that there was not a statistically significant difference in shrinkage (at a confidence level of less than 80%) between these mixes at 90 days. The list also contains the comparison between the 14-day cured fine lightweight aggregate mix with the 14-day cured lightweight aggregate mix (both at medium levels of replacement).

3.3.1 Program I Results

From Table 3-1, it is evident that adding the lightweight aggregate did not significantly decrease the strength of any one mix compared to the Granite Control. In one case [LWA (High)], the 28-day strength was actually greater than the Granite Control.

From Table 3-2, the addition of the lightweight aggregate does increase the amount of internal curing water available for the mix. Although additional water may be available from other aggregates in the mix, the most likely contribution comes from the lightweight aggregate which has the highest absorption (total moisture content, which ranged from 24.73%-29.96%), followed by the limestone with an absorption of 3.07%.

In almost all cases (both at 30 days and 90 days), the addition of the lightweight aggregate improved the free shrinkage results regardless of how long the specimens were cured when compared to the Granite Control. The only exception at 90 days was the FLWA (Medium) 7-day cured mix, where the 90-day free shrinkage was 450 $\mu\varepsilon$ compared to the Granite Control 7-day cured mix where the 90-day free shrinkage was 447 $\mu\varepsilon$.

The most effective mix against shrinkage was the 14-day cured LWA (High) mix. At 30 days the free shrinkage of this mix was 220 $\mu\varepsilon$ and was 347 $\mu\varepsilon$ at 90 days. This mix had higher strength [4,850 psi (33.4 MPa)] than both the Granite Control [4,610 psi (31.8 MPa)] and Limestone Control [4,460 psi (30.8 MPa)] at 28 days. This mix proved to have statically significant differences with both the Granite

Control (7 and 14-day cured) and the Limestone Control (7 and 14-day cured) at the highest confidence level.

The second through fourth next best performing mixes at 90 days were the 7-day cured LWA (High), 14-day cured LWA (Medium), and 14-day cured LWA (Low) mixes with 370 $\mu\varepsilon$, 370 $\mu\varepsilon$ and 373 $\mu\varepsilon$ free shrinkage, respectively. The 7-day cured LWA (High) mix had a statistically significant difference in shrinkage from the 14-day cured Granite Control at a confidence level of 90%. The 14-day cured LWA (Low) and 14-day cured LWA (Medium) mixes, however, did not have a statistically significance difference in shrinkage with the 14-day cured Granite Control.

Even though the limestone had a high absorption of 3.07% when compared to the granite (0.71-0.76%) and was able to absorb a large amount of water, the use of lightweight aggregate was still more beneficial to combat free shrinkage. The percentage (by volume) of lightweight aggregate ranged from 8.4-13.8% and was able to contribute more water available to the mix for internal curing than the limestone (even with a coarse aggregate volume of 41.0%). The total amount of water from mixes with lightweight aggregate ranged from 46.4 lb/yd^3 (27.5 kg/m^3) to 69.8 lb/yd^3 (41.4 kg/m^3), whereas the Limestone Control had 45.1 lb/yd^3 (26.7 kg/m^3). When comparing the Limestone Control with 45.1 lb/yd^3 (26.7 kg/m^3) of water to the LWA (Low) mix with 46.4 lb/yd^3 (27.5 kg/m^3) of total available water, the amount of shrinkage decreases from 503 $\mu\varepsilon$ to 413 $\mu\varepsilon$ for the 7-day cured specimens (at a confidence level of 80%) and 490 $\mu\varepsilon$ to 373 $\mu\varepsilon$ for the 14-day cured specimens (at the highest confidence level) at 90 days. This reduction in shrinkage can be attributed to the ability of the lightweight aggregate to release more of the water that it absorbed than that of the limestone.

At 28 days, the Limestone Control had a strength of 4,460 psi (30.8 MPa), the intermediate lightweight aggregate mixes ranged in strength from 4,450 psi (30.7 MPa) to 4,850 psi (33.4 MPa) and the fine lightweight aggregate mix had a strength of 4,160 psi (28.7 MPa). This shows that using intermediate lightweight aggregate, at a volume ranging from 8.4%-13.8%, does not sacrifice strength to order to gain a reduction in free shrinkage. The use of fine lightweight aggregate does have a reduction in strength of 300 psi (2.1 MPa).

3.4 Program II

Test Program II evaluated the use of lightweight aggregate with ground granulated blast furnace slag (slag). A total of eight mixes were included in Program II: two control mixes, four mixes with lightweight aggregate and G100 slag, and two mixes with limestone and G100 slag. The two control mixes included one granite mix and one limestone mix. Due to unreasonably low free shrinkage results of the 60% G100 Slag, LWA mix, however, the mix was rebatched (60% G100 Slag II, LWA). Results for the 60% G100 Slag, LWA mix are presented but not used to compare the results. For comparison purposes, only results from 60% G100 Slag II, LWA are discussed.

Table 3-7 shows the properties of each batch in Program II. As in Program I, each slump, air content and temperature test proved to be within the given LC-HPC specifications. The average 28-day compressive strength for the Granite Control was

4,140 psi (28.5 MPa). The 30% G100 Slag, LWA had a compressive strength of 4,950 psi (34.1 MPa). The 30% G100 Slag, FLWA also had a 28-day compressive strength higher than the Granite Control with 4,470 psi (30.8 MPa). The 60% G100 Slag II, LWA had a 28-day compressive strength of 4,910 psi (33.9 MPa). The average 28-day compressive strength was 4,680 psi (32.3 MPa) for the Limestone Control. The 30% G100 Slag, Limestone had a compressive strength of 4,900 psi (33.8 MPa) at 28 days. The average 28-day strength of the 60% G100 Slag, Limestone batch was 4,570 psi (31.5 MPa). The unit weights for the batches ranged from 135.0 lb/ft^3 (2,162 kg/m^3) to 139.0 lb/ft^3 (2,227 kg/m^3).

Table 3-7: Mix Properties, Program II

Description	Slump	Air Content	Temp.	Compressive Strength		Unit Weight
	in. (cm)	%	°F (°C)	Avg. 7 Day psi (MPa)	Avg. 28 Day psi (MPa)	lb/ft^3 (kg/m^3)
Granite Control	3½ (8.9)	8.90	72 (22.2)	2,950 (20.3)	4,140 (28.5)	139.0 (2,227)
30% G100 Slag, LWA	3¾ (9.5)	8.15	74 (23.3)	3,240 (22.3)	4,950 (34.1)	135.3 (2,168)
30% G100 Slag, FLWA	2½ (6.4)	8.90	73 (22.8)	3,290 (22.7)	4,470 (30.8)	135.4 (2,169)
60% G100 Slag, LWA	3¼ (8.3)	8.15	71 (21.7)	2,900 (20.0)	5,160 (35.6)	136.4 (2,185)
60% G100 Slag II, LWA	3¼ (8.3)	8.90	70 (21.1)	2,690 (18.5)	4,910 (33.9)	135.0 (2,162)
Limestone Control	2¼ (5.7)	7.90	72 (22.2)	4,060 (28.0)	4,680 (32.3)	138.9 (2,225)
30% G100 Slag, Limestone	3 (7.6)	8.90	76 (24.4)	3,150 (21.7)	4,900 (33.8)	138.7 (2,222)
60% G100 Slag, Limestone	4 (10.2)	8.65	73 (22.8)	2,730 (18.8)	4,570 (31.5)	138.3 (2,215)

The total absorbed water for Program II was calculated in the same manner as for Program I, using Eq. (3-4). The results are shown in Table 3-8. The total amount of absorbed water for the mixes ranged from 19.3 lb/yd^3 (11.4 kg/m^3) for the Granite Control to 62.0 lb/yd^3 (36.8 kg/m^3) for the 30% G100 Slag, LWA. The goal of using the lightweight aggregate in this program was to attempt to have the same amount of internal water for each mix that included lightweight aggregate. The amount of water for mixes with intermediate lightweight aggregate ranged from 57.9 lb/yd^3 (34.3 kg/m^3) to 62.0 lb/yd^3 (36.8 kg/m^3). The mix containing the fine lightweight aggregate had slightly less total water at 52.8 lb/yd^3 (31.4 kg/m^3). The mixes containing limestone ranged from 45.5 lb/yd^3 (27.0 kg/m^3) to 46.9 lb/yd^3 (27.8 kg/m^3) of total available water. The total amount of water was held almost constant for comparable mixes.

Table 3-8: Available Water for Internal Curing, Program II

No.	Description	Coarse Aggregate	Pea Gravel	Sand	LWA	Water Excluding LWA	Water from all Aggregates
		lb/yd^3 (kg/m^3)	lb/yd^3 (kg/m^3)	lb/yd^3 (kg/m^3)	lb/yd^3 (kg/m^3)	lb/yd^3 (kg/m^3)	lb/yd^3 (kg/m^3)
#639	Granite Control	8.7 (5.2)	7.5 (4.4)	3.1 (1.8)	0	19.3 (11.4)	19.3 (11.4)
#640	30% G100 Slag, LWA	8.8 (5.2)	5.2 (3.1)	3.0 (1.8)	45.0 (26.7)	17.0 (10.1)	62.0 (36.8)
#655	30% G100 Slag, FLWA	8.8 (5.2)	7.5 (4.5)	2.3 (1.4)	34.2 (20.3)	18.6 (11.1)	52.8 (31.4)
#642	60% G100 Slag, LWA	8.9 (5.3)	5.0 (3.0)	3.0 (1.8)	44.6 (26.5)	16.9 (10.0)	61.5 (36.6)
#648	60% G100 Slag II, LWA	8.3 (4.9)	5.7 (3.4)	3.1 (1.8)	40.8 (24.2)	17.1 (10.1)	57.9 (34.3)
#645	Limestone Control	37.3 (22.1)	6.1 (3.6)	3.5 (2.1)	0	46.9 (27.8)	46.9 (27.8)
#646	30% G100 Slag, Limestone	35.4 (21.0)	6.6 (3.9)	3.5 (2.1)	0	45.5 (27.0)	45.5 (27.0)
#647	60% G100 Slag, Limestone	35.4 (21.0)	6.6 (3.9)	3.5 (2.1)	0	45.5 (27.0)	45.5 (27.0)

When considering the contribution of water from just the aggregates with the highest absorption in each mix, the amount of water was also comparative. For the mixes containing the intermediate lightweight aggregate, the available water for internal curing ranged from 40.8 lb/yd^3 (24.2 kg/m^3) to 45.0 lb/yd^3 (26.7 kg/m^3), the mix with the fine lightweight aggregate had 34.2 lb/yd^3 (20.3 kg/m^3), the limestone mixes ranged from 35.4 lb/yd^3 (21.0 kg/m^3) to 37.3 lb/yd^3 (22.1 kg/m^3), and the Granite Control had the least amount of water at 8.7 lb/yd^3 (5.2 kg/m^3). The water from the lightweight aggregate will be able to contribute the most water to combat free shrinkage because it also has the highest absorption value.

Table 3-9 shows the summary of the 7-day cured free shrinkage data for the mixes in Program II at 0, 30, 60 and 90 days of drying. At 90 days, the most shrinkage was observed with both the Granite Control and Limestone Control with 423 με. The least shrinkage was observed with the 60% G100 Slag II, LWA with 243 με.

Table 3-9: 7-day Cure Free Shrinkage Summary for Program II

Days of Drying	Granite Control	30% G100 Slag, LWA	30% G100 Slag, FLWA	60% G100 Slag, LWA	60% G100 Slag II, LWA	Limestone Control	30% G100 Slag, Limestone	60% G100 Slag, Limestone
0	-53	-83	-90	-190	-97	-53	-93	-80
30	337	190	240	87	113	317	280	200
60	380	253	295	172	207	388	337	280
90	423	290	340	207	243	423	367	320

Table 3-10 shows the summary of the 14-day cured free shrinkage data for the mixes in Program II at 0, 30, 60 and 90 days of drying. At 90 days, the most shrinkage was observed with the Limestone Control with 430 με. The least shrinkage was observed with the 60% G100 Slag II, LWA with 157 με.

Table 3-10: 14-day Cure Free Shrinkage Summary for Program II†

Days of Drying	Granite Control	30% G100 Slag, LWA	30% G100 Slag, FLWA	60% G100 Slag, LWA	60% G100 Slag II, LWA	Limestone Control	30% G100 Slag, Limestone	60% G100 Slag, Limestone
0	-53	-83	-67	-25	-143	-47	-63	-143
30	297	120	177	105	30	327	217	87
60	360	207	248	190	105	392	292	193
90	393	263	283	245	157	430	323	233

†Results given for 60% G100 Slag, LWA are presented as the average of only two specimens because the third specimen was damaged during casting.

The average 30-day free shrinkage values from Table 3-9 and Table 3-10 ranged from 30 με to 337 με. The lowest shrinkage at 30-days was observed with the 14-day cured 60% G100 Slag II, LWA at 30 με, followed by the 14-day 60% G100 Slag, Limestone batch at 87 με; 7-day cured 60% G100 Slag, LWA batch at 87 με; 14-day cured 60% G100 Slag, LWA batch at 105 με; 7-day cured 60% G100 Slag II, LWA batch at 113 με; 14-day cured 30% G100 Slag, LWA batch at 120 με; 14-day cured 30% G100 Slag, FLWA batch at 177 με; 7-day cured 30% G100 Slag, LWA batch at 190 με; 7-day cured 60% G100 Slag, Limestone batch at 200 με; 14-day cured 30% G100 Slag, Limestone batch at 217 με; 7-day cured 30% G100 Slag, FLWA batch at 240 με; 7-day cured 30% G100 Slag, Limestone batch at 280 με; 14-day cured Granite Control batch at 297 με; 7-day cured Limestone Control batch at 317 με; 14-day cured Limestone Control batch at 327 με; and the 7-day cured Granite Control batch at 377 με.

The average 90-day free shrinkage values ranged from 157 με to 430 με. The lowest shrinkage at 30-days was observed with the 14-day cured 60% G100 Slag II, LWA at 157 με, 7-day cured 60% G100 Slag, LWA batch at 207 με; followed by the 14-day 60% G100 Slag, Limestone batch at 233 με; 7-day cured 60% G100 Slag II, LWA batch at 243 με; 14-day cured 60% G100 Slag, LWA batch at 245 με; 14-day cured 30% G100 Slag, LWA batch at 263 με; 14-day cured 30% G100 Slag, FLWA batch at 283 με; 7-day cured 30% G100 Slag, LWA batch at 290 με; 7-day cured 60% G100 Slag, Limestone batch at 320 με; 14-day cured 30% G100 Slag, Limestone batch at 323 με; 7-day cured 30% G100 Slag, FLWA batch at 340 με; 7-day cured

30% G100 Slag, Limestone batch at 367 με; 14-day cured Granite Control batch at 393 με; 7-day cured Granite Control batch at 423 με; 7-day cured Limestone Control batch at 423 με; and the 14-day cured Limestone Control batch at 430 με.

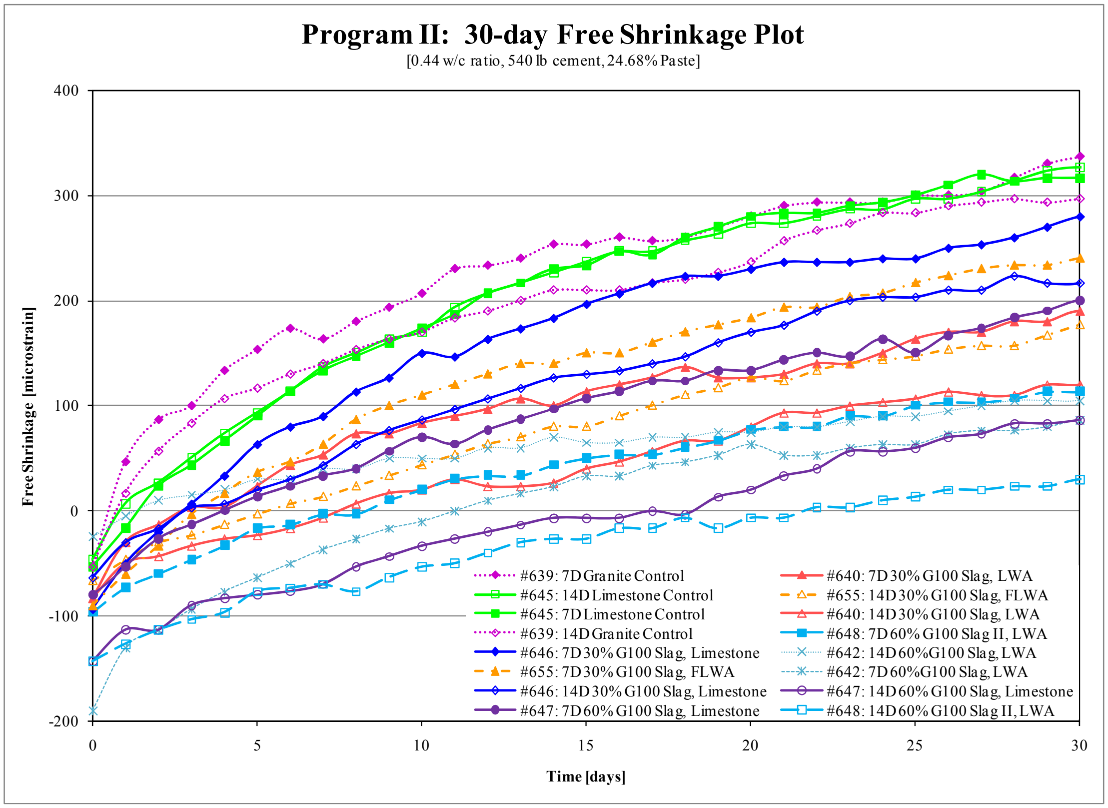

Figure 3-3: 30-day Free Shrinkage Plot, Program II

Figure 3-3 shows the results of the free shrinkage tests evaluating the use of a G100 Slag with lightweight aggregate through the first 30 days. The vertical axis plots free shrinkage (in με) of the specimens. The horizontal axis plots time in days. The batches plotted include a 7-day and 14-day cure for the Granite Control; 30% G100 Slag, LWA; 30% G100 Slag, FLWA; 60% G100 Slag, LWA; 60% G100 Slag II, LWA; Limestone Control; 30% G100 Slag, Limestone; and 60% G100 Slag, Limestone.

Figure 3-3 shows that in almost all cases at 30 days, the 14-day cured specimens performed better with less shrinkage than the associated 7-day cured specimens. The only exception being the Limestone Control batch where the 7-day cured specimens performed slightly better than the 14-day cured specimens (317 με compared to 327 με, respectively). The batches mixed with limestone showed that less shrinkage occurs with increasing amounts of G100 slag and longer curing periods. Curing batches with limestone for 14-days rather than 7-days lowers shrinkage by 63 με with 30% G100 slag and 113 με with 60% slag.

The addition of lightweight aggregate with 30% slag cured for 7 days outperformed 7-day cured 30% G100 Slag, Limestone, 14-day cured 30% G100 Slag, Limestone and 7-day cured 60% G100 Slag, Limestone batches. The improvement in shrinkage between curing for 7 days and 14 days is substantial with all lightweight aggregate mixes: 63 με for 30% G100 Slag, FLWA; 70 με for 30% G100 Slag, LWA; and 83 με for 60% G100 Slag, LWA. The least amount of shrinkage was seen with 60% G100 Slag, LWA cured for 14 days. In all cases, the use of lightweight aggregate when compared to the corresponding batch with limestone resulted in less shrinkage at 30 days. The use of fine lightweight aggregate was not as beneficial as the use of intermediate lightweight aggregate.

Figure 3-4 shows the results of the free shrinkage tests evaluating the use of a G100 Slag with lightweight aggregate through the first 90 days. The vertical axis plots free shrinkage (in με) of the specimens. The horizontal axis plots time in days. The batches plotted include a 7-day and 14-day cure for the Granite Control; 30%

G100 Slag, LWA; 30% G100 Slag, FLWA; 60% G100 Slag, LWA; 60% G100 Slag II, LWA; Limestone Control; 30% G100 Slag, Limestone; and 60% G100 Slag, Limestone.

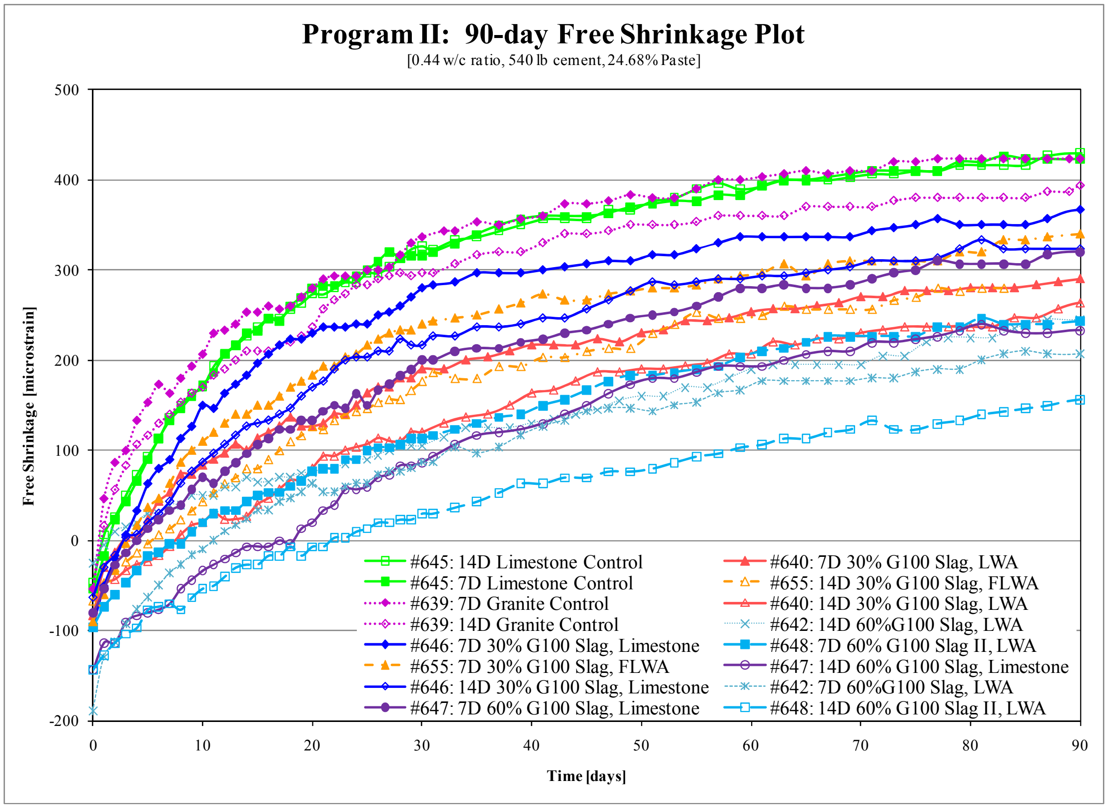

Figure 3-4: 90-day Free Shrinkage Plot, Program II

Figure 3-4 shows that in almost all cases at 90 days, the 14-day cured specimens performed better with less shrinkage than the associated 7-day cured specimens. The only exception being with the Limestone Control batch where the 7-day cured specimens performed slightly better than the 14-day cured specimens (423 $\mu\varepsilon$ compared to 430 $\mu\varepsilon$, respectively). The batches mixed with limestone showed that less shrinkage occurs with increasing amounts of G100 slag and longer curing periods. Curing batches with limestone for 14-days rather than 7-days lowers shrinkage by 44 με with 30% G100 slag and 87 με with 60% slag.

As at 30 days, the addition of lightweight aggregate with 30% slag cured for 7 days still outperformed 7-day cured 30% G100 Slag, Limestone; 14-day cured 30% G100 Slag, Limestone; and 7-day cured 60% G100 Slag, Limestone batches. The improvement in shrinkage between curing for 7 days and 14 days was substantial with all lightweight aggregate mixes: 57 με for 30% G100 Slag, FLWA; 27 με for 30% G100 Slag, LWA; and 86 με for 60% G100 Slag, LWA. The most improvement in shrinkage was seen with 60% G100 Slag, LWA cured for 14 days.

In all cases, the use of lightweight aggregate when compared to the corresponding batch with limestone resulted in less shrinkage at 90 days. The use of fine lightweight aggregate was not as beneficial as the use of intermediate lightweight aggregate.

The Student's T-Test was also used to evaluate all the mixes at both the 30-day free shrinkage results and the 90-day free shrinkage results for Program II. The results are shown in Table 3-11 and Table 3-12.

From Table 3-11, listed in order from highest to lowest relevance, are the mixes that showed statistically significant differences at the highest confidence level of 98% or better for the free shrinkage at 30 days:

- #639 - 14D Granite Control and #642 - 7D 60% G100, LWA
- #639 - 7D Granite Control and #642 - 7D 60% G100, LWA
- #639 - 7D Granite Control and #640 - 14D 30% G100, LWA
- #639 - 14D Granite Control and #640 - 14D 30% G100, LWA
- #642 - 7D 60% G100, LWA and #645 - 14D Limestone Control

Table 3-11: 30-day T-Test Results for Program II[†]

		30-day Free Shrinkage (με)	**#639 - Granite Control**		**#640 – 30% G100 Slag, LWA**		**#655 – 30% G100 Slag, FLWA**		***#642 – 60% G100 Slag, LWA***		**#648 – 60% G100 Slag II, LWA**		**#645 – Limestone Control**		**#646 – 30% G100 Slag, Limestone**		**#647 – 60% G100 Slag, Limestone**	
			7-day	14-day	7-day	14-day	7-day	14-day	*7-day*	*14-day*	7-day	14-day	7-day	14-day	7-day	14-day	7-day	14-day
#639	7-day	337		95%	Y	Y	90%	Y	*Y*	*90%*	Y	Y	N	N	90%	Y	Y	Y
	14-day	297			Y	Y	N	Y	*Y*	*90%*	Y	Y	N	80%	N	Y	Y	Y
#640	7-day	190				Y	N	N	*Y*	*N*	Y	90%	Y	Y	95%	N	N	95%
	14-day	120					95%	Y	*Y*	*N*	N	N	Y	Y	Y	Y	Y	N
#655	7-day	240						80%	*Y*	*N*	95%	95%	80%	90%	N	N	N	95%
	14-day	177							*Y*	*N*	95%	90%	Y	Y	Y	80%	N	90%
#642	*7-day*	*87*								*N*	*90%*	*N*	*Y*	*Y*	*Y*	*Y*	*Y*	*N*
	14-day	*105*									*N*	*N*	*90%*	*90%*	*80%*	*N*	*N*	*N*
#648	7-day	113										N	Y	Y	Y	Y	Y	N
	14-day	30											Y	Y	Y	95%	90%	N
#645	7-day	317												N	N	Y	Y	Y
	14-day	327													80%	Y	Y	Y
#646	7-day	280														90%	95%	Y
	14-day	217															N	95%
#647	7-day	200																95%
	14-day	87																

[†]See *3.2 Statistical Analysis* for explanation of terms

Table 3-12: 90-day T-Test Results for Program II†

		90-day Free Shrinkage (με)	#639 - Granite Control		#640 – 30% G100 Slag, LWA		#655 – 30% G100 Slag, FLWA		*#642 – 60% G100 Slag, LWA*		#648 – 60% G100 Slag II, LWA		#645 – Limestone Control		#646 – 30% G100 Slag, Limestone		#647 – 60% G100 Slag, Limestone	
			7-day	14-day	7-day	14-day	7-day	14-day	*7-day*	*14-day*	7-day	14-day	7-day	14-day	7-day	14-day	7-day	14-day
#639	7-day	423		N	Y	Y	80%	Y	*Y*	*80%*	Y	Y	N	N	80%	95%	Y	Y
	14-day	393			Y	Y	N	Y	*Y*	*80%*	Y	Y	80%	80%	N	95%	Y	Y
#640	7-day	290				80%	N	N	*Y*	*N*	80%	80%	Y	Y	90%	N	N	N
	14-day	263					90%	N	*Y*	*N*	N	80%	Y	Y	Y	95%	95%	N
#655	7-day	340						80%	*Y*	*N*	90%	90%	90%	90%	N	N	N	80%
	14-day	283							*Y*	*N*	80%	80%	Y	Y	95%	80%	80%	N
#642	*7-day*	*207*								*N*	*80%*	*N*	*Y*	*Y*	*Y*	*Y*	*Y*	*N*
	14-day	*245*									*N*	*N*	*80%*	*80%*	*N*	*N*	*N*	*N*
#648	7-day	243										N	Y	Y	Y	95%	95%	N
	14-day	157											Y	Y	95%	90%	90%	N
#645	7-day	423												N	80%	Y	Y	Y
	14-day	430													80%	Y	Y	Y
#646	7-day	367														N	80%	95%
	14-day	323															N	90%
#647	7-day	320																90%
	14-day	233																

†See *3.2 Statistical Analysis* for explanation of terms

- #642 - 7D 60% G100, LWA and #645 - 7D Limestone Control
- #639 - 7D Granite Control and #648 - 7D 60% G100 II, LWA
- #639 - 14D Granite Control and #648 - 7D 60% G100 II, LWA
- #640 - 14D 30% G100, LWA and #645 - 14D Limestone Control
- #640 - 14D 30% G100, LWA and #645 - 7D Limestone Control
- #648 - 7D 60% G100 II, LWA and #645 - 14D Limestone Control
- #639 - 7D Granite Control and #640 - 7D 30% G100, LWA
- #648 - 7D 60% G100 II, LWA and #645 - 7D Limestone Control
- #639 - 7D Granite Control and #655 - 14D 30% G100, FLWA
- #640 - 7D 30% G100, LWA and #642 - 7D 60% G100, LWA
- #639 - 14D Granite Control and #640 - 7D 30% G100, LWA
- #642 - 7D 60% G100, LWA and #646 - 7D 30% G100, LS
- #639 - 14D Granite Control and #655 - 14D 30% G100, FLWA
- #640 - 7D 30% G100, LWA and #645 - 14D Limestone Control
- #639 - 7D Granite Control and #647 - 7D 60% G100, LS
- #655 - 14D 30% G100, FLWA and #645 - 14D Limestone Control
- #639 - 7D Granite Control and #647 - 14D 60% G100, LS
- #642 - 7D 60% G100, LWA and #647 - 7D 60% G100, LS
- #642 - 7D 60% G100, LWA and #646 - 14D 30% G100, LS
- #640 - 7D 30% G100, LWA and #645 - 7D Limestone Control
- #655 - 14D 30% G100, FLWA and #645 - 7D Limestone Control
- #640 - 14D 30% G100, LWA and #646 - 7D 30% G100, LS
- #645 - 14D Limestone Control and #647 - 14D 60% G100, LS
- #642 - 7D 60% G100, LWA and #645 - 7D Limestone Control
- #639 - 7D Granite Control and #648 - 7D 60% G100 II, LWA
- #639 - 14D Granite Control and #648 - 7D 60% G100 II, LWA
- #640 - 14D 30% G100, LWA and #645 - 14D Limestone Control
- #640 - 14D 30% G100, LWA and #645 - 7D Limestone Control
- #648 - 7D 60% G100 II, LWA and #645 - 14D Limestone Control
- #639 - 7D Granite Control and #640 - 7D 30% G100, LWA
- #648 - 7D 60% G100 II, LWA and #645 - 7D Limestone Control
- #639 - 7D Granite Control and #655 - 14D 30% G100, FLWA
- #645 - 7D Limestone Control and #647 - 14D 60% G100, LS
- #639 - 14D Granite Control and #647 - 14D 60% G100, LS
- #639 - 7D Granite Control and #646 - 14D 30% G100, LS
- #640 - 7D 30% G100, LWA and #640 - 14D 30% G100, LWA
- #645 - 14D Limestone Control and #647 - 7D 60% G100, LS
- #639 - 14D Granite Control and #647 - 7D 60% G100, LS
- #645 - 7D Limestone Control and #647 - 7D 60% G100, LS

- #640 - 14D 30% G100, LWA and #646 - 14D 30% G100, LS
- #640 - 14D 30% G100, LWA and #642 - 7D 60% G100, LWA
- #640 - 7D 30% G100, LWA and #648 - 7D 60% G100 II, LWA
- #640 - 14D 30% G100, LWA and #647 - 7D 60% G100, LS
- #639 - 7D Granite Control and #648 - 14D 60% G100 II, LWA
- #648 - 7D 60% G100 II, LWA and #646 - 14D 30% G100, LS
- #645 - 14D Limestone Control and #646 - 14D 30% G100, LS
- #646 - 7D 30% G100, LS and #647 - 14D 60% G100, LS
- #648 - 14D 60% G100 II, LWA and #645 - 14D Limestone Control
- #648 - 14D 60% G100 II, LWA and #645 - 7D Limestone Control
- #648 - 7D 60% G100 II, LWA and #647 - 7D 60% G100, LS
- #645 - 7D Limestone Control and #646 - 14D 30% G100, LS
- #639 - 14D Granite Control and #648 - 14D 60% G100 II, LWA
- #639 - 14D Granite Control and #646 - 14D 30% G100, LS
- #655 - 7D 30% G100, FLWA and #642 - 7D 60% G100, LWA
- #640 - 14D 30% G100, LWA and #655 - 14D 30% G100, FLWA
- #655 - 14D 30% G100, FLWA and #646 - 7D 30% G100, LS
- #648 - 14D 60% G100 II, LWA and #646 - 7D 30% G100, LS

It is important to note that statistically significant differences in shrinkage at the highest confidence level were observed between the Granite and Limestone Controls and the 30% and 60% slag mixes with intermediate lightweight aggregate (both for 7-day cured and 14-day cured specimens). These differences were also noted between the 14-day cured lightweight aggregate with 30% slag mix and the 14-day cured fine lightweight aggregate with 30% slag mix as well as the 14-day cured limestone with 30% slag mix. Finally this list contains the comparison between the fine lightweight aggregate with 60% slag mix and the limestone with 60% slag mix (at a 7-day curing period).

From Table 3-11, listed in order from highest to lowest relevance, are the mixes that showed statistically significant differences at a confidence level of 95% or better for the free shrinkage at 30 days:

- #639 - 7D Granite Control and #639 - 14D Granite Control
- #640 - 7D 30% G100, LWA and #646 - 7D 30% G100, LS
- #655 - 14D 30% G100, FLWA and #648 - 7D 60% G100 II, LWA
- #646 - 14D 30% G100, LS and #647 - 14D 60% G100, LS
- #655 - 7D 30% G100, FLWA and #648 - 7D 60% G100 II, LWA
- #640 - 14D 30% G100, LWA and #655 - 7D 30% G100, FLWA
- #647 - 7D 60% G100, LS and #647 - 14D 60% G100, LS
- #655 - 7D 30% G100, FLWA and #647 - 14D 60% G100, LS
- #640 - 7D 30% G100, LWA and #647 - 14D 60% G100, LS
- #646 - 7D 30% G100, LS and #647 - 7D 60% G100, LS
- #648 - 14D 60% G100 II, LWA and #646 - 14D 30% G100, LS
- #655 - 7D 30% G100, FLWA and #648 - 14D 60% G100 II, LWA

This list notably contains the comparison between the 7-day cured lightweight aggregate mix with 30% slag and the 7-day cured limestone mix with 30% slag, indicating a statistically significant difference in shrinkage at a confidence level of 95%.

From Table 3-11, listed in order from highest to lowest relevance, are the mixes that showed statistically significant differences at a confidence level of 90% or better for the free shrinkage at 30 days:

- #648 - 14D 60% G100 II, LWA and #647 - 7D 60% G100, LS
- #639 - 7D Granite Control and #642 - 14D 60% G100, LWA
- #640 - 7D 30% G100, LWA and #648 - 14D 60% G100 II, LWA
- #655 - 14D 30% G100, FLWA and #647 - 14D 60% G100, LS
- #639 - 7D Granite Control and #655 - 7D 30% G100, FLWA
- #642 - 14D 60% G100, LWA and #645 - 14D Limestone Control
- #642 - 14D 60% G100, LWA and #645 - 7D Limestone Control
- #655 - 14D 30% G100, FLWA and #648 - 14D 60% G100 II, LWA
- #639 - 7D Granite Control and #646 - 7D 30% G100, LS
- #639 - 14D Granite Control and #642 - 14D 60% G100, LWA
- #646 - 7D 30% G100, LS and #646 - 14D 30% G100, LS
- #642 - 7D 60% G100, LWA and #648 - 7D 60% G100 II, LWA
- #655 - 7D 30% G100, FLWA and #645 - 14D Limestone Control

From Table 3-11, listed in order from highest to lowest relevance, are the mixes that showed statistically significant differences at a confidence level of 80% or better for the free shrinkage at 30 days:

- #642 - 14D 60% G100, LWA and #646 - 7D 30% G100, LS
- #655 - 7D 30% G100, FLWA and #645 - 7D Limestone Control
- #639 - 14D Granite Control and #645 - 14D Limestone Control
- #655 - 14D 30% G100, FLWA and #646 - 14D 30% G100, LS
- #645 - 14D Limestone Control and #646 - 7D 30% G100, LS
- #655 - 7D 30% G100, FLWA and #655 - 14D 30% G100, FLWA

From Table 3-11, listed in order from highest to lowest relevance, are the mixes that showed no statistically significant differences (a confidence level of less than 80%) for the free shrinkage at 30 days:

- #639 - 14D Granite Control and #655 - 7D 30% G100, FLWA
- #640 - 14D 30% G100, LWA and #648 - 14D 60% G100 II, LWA
- #655 - 7D 30% G100, FLWA and #642 - 14D 60% G100, LWA
- #645 - 7D Limestone Control and #646 - 7D 30% G100, LS
- #640 - 7D 30% G100, LWA and #646 - 14D 30% G100, LS
- #648 - 7D 60% G100 II, LWA and #648 - 14D 60% G100 II, LWA
- #642 - 14D 60% G100, LWA and #646 - 14D 30% G100, LS
- #640 - 7D 30% G100, LWA and #655 - 7D 30% G100, FLWA
- #639 - 14D Granite Control and #645 - 7D Limestone Control
- #639 - 7D Granite Control and #645 - 7D Limestone Control
- #655 - 14D 30% G100, FLWA and #647 - 7D 60% G100, LS
- #642 - 14D 60% G100, LWA and #647 - 7D 60% G100, LS
- #640 - 7D 30% G100, LWA and #642 - 14D 60% G100, LWA
- #640 - 14D 30% G100, LWA and #647 - 14D 60% G100, LS
- #655 - 7D 30% G100, FLWA and #647 - 7D 60% G100, LS
- #642 - 7D 60% G100, LWA and #648 - 14D 60% G100 II, LWA
- #655 - 14D 30% G100, FLWA and #642 - 14D 60% G100, LWA
- #655 - 7D 30% G100, FLWA and #646 - 7D 30% G100, LS
- #648 - 14D 60% G100 II, LWA and #647 - 14D 60% G100, LS
- #640 - 7D 30% G100, LWA and #655 - 14D 30% G100, FLWA
- #648 - 7D 60% G100 II, LWA and #647 - 14D 60% G100, LS
- #646 - 14D 30% G100, LS and #647 - 7D 60% G100, LS

- #642 - 14D 60% G100, LWA and #648 - 14D 60% G100 II, LWA
- #639 - 14D Granite Control and #646 - 7D 30% G100, LS
- #639 - 7D Granite Control and #645 - 14D Limestone Control
- #655 - 7D 30% G100, FLWA and #646 - 14D 30% G100, LS
- #640 - 7D 30% G100, LWA and #647 - 7D 60% G100, LS
- #640 - 14D 30% G100, LWA and #648 - 7D 60% G100 II, LWA
- #645 - 7D Limestone Control and #645 - 14D Limestone Control
- #642 - 7D 60% G100, LWA and #642 - 14D 60% G100, LWA
- #642 - 14D 60% G100, LWA and #647 - 14D 60% G100, LS
- #640 - 14D 30% G100, LWA and #642 - 14D 60% G100, LWA
- #642 - 14D 60% G100, LWA and #648 - 7D 60% G100 II, LWA
- #642 - 7D 60% G100, LWA and #647 - 14D 60% G100, LS

This list notably contains comparisons between the 7-day cured lightweight aggregate mix with 30% slag and the 7-day cured fine lightweight aggregate mix with 30% slag, indicating no statistically significant difference in shrinkage. The list also shows that there was not a statistically significant difference in shrinkage between the lightweight aggregate mix with 60% slag and the limestone mix with 60% slag at a 14-day curing period.

From Table 3-12, listed in order from highest to lowest relevance, are the mixes that showed statistically significant differences at the highest confidence level of 98% or better for the free shrinkage at 90 days:

- #639 - 14D Granite Control and #642 - 7D 60% G100, LWA
- #642 - 7D 60% G100, LWA and #645 - 7D Limestone Control
- #642 - 7D 60% G100, LWA and #645 - 14D Limestone Control
- #639 - 14D Granite Control and #640 - 14D 30% G100, LWA
- #639 - 7D Granite Control and #642 - 7D 60% G100, LWA
- #640 - 14D 30% G100, LWA and #645 - 7D Limestone Control
- #640 - 14D 30% G100, LWA and #645 - 14D Limestone Control
- #648 - 7D 60% G100 II, LWA and #645 - 14D Limestone Control
- #648 - 7D 60% G100 II, LWA and #645 - 7D Limestone Control
- #639 - 14D Granite Control and #648 - 7D 60% G100 II, LWA
- #640 - 14D 30% G100, LWA and #642 - 7D 60% G100, LWA

- #655 - 14D 30% G100, FLWA and #645 - 14D Limestone Control
- #639 - 7D Granite Control and #640 - 14D 30% G100, LWA
- #655 - 14D 30% G100, FLWA and #645 - 7D Limestone Control
- #639 - 14D Granite Control and #655 - 14D 30% G100, FLWA
- #642 - 7D 60% G100, LWA and #647 - 7D 60% G100, LS
- #639 - 7D Granite Control and #648 - 7D 60% G100 II, LWA
- #640 - 7D 30% G100, LWA and #645 - 14D Limestone Control
- #640 - 7D 30% G100, LWA and #645 - 7D Limestone Control
- #655 - 14D 30% G100, FLWA and #642 - 7D 60% G100, LWA
- #642 - 7D 60% G100, LWA and #646 - 7D 30% G100, LS
- #639 - 7D Granite Control and #655 - 14D 30% G100, FLWA
- #639 - 14D Granite Control and #640 - 7D 30% G100, LWA
- #642 - 7D 60% G100, LWA and #646 - 14D 30% G100, LS
- #640 - 7D 30% G100, LWA and #642 - 7D 60% G100, LWA
- #639 - 7D Granite Control and #640 - 7D 30% G100, LWA
- #645 - 14D Limestone Control and #647 - 7D 60% G100, LS
- #645 - 14D Limestone Control and #647 - 14D 60% G100, LS
- #645 - 7D Limestone Control and #647 - 7D 60% G100, LS
- #645 - 7D Limestone Control and #647 - 14D 60% G100, LS
- #639 - 7D Granite Control and #647 - 14D 60% G100, LS
- #648 - 14D 60% G100 II, LWA and #645 - 14D Limestone Control
- #639 - 14D Granite Control and #647 - 14D 60% G100, LS
- #648 - 14D 60% G100 II, LWA and #645 - 7D Limestone Control
- #645 - 14D Limestone Control and #646 - 14D 30% G100, LS
- #639 - 14D Granite Control and #647 - 7D 60% G100, LS
- #639 - 7D Granite Control and #648 - 14D 60% G100 II, LWA
- #639 - 7D Granite Control and #647 - 7D 60% G100, LS
- #645 - 7D Limestone Control and #646 - 14D 30% G100, LS
- #648 - 7D 60% G100 II, LWA and #646 - 7D 30% G100, LS
- #640 - 14D 30% G100, LWA and #646 - 7D 30% G100, LS
- #655 - 7D 30% G100, FLWA and #642 - 7D 60% G100, LWA
- #639 - 14D Granite Control and #648 - 14D 60% G100 II, LWA

It is important to note that statistically significant differences in shrinkage at the highest confidence level were observed between the Granite and Limestone Controls and the 30% and 60% slag mixes with intermediate lightweight aggregate (both for 7-day cured and 14-day cured specimens).

From Table 3-12, listed in order from highest to lowest relevance, are the mixes that showed statistically significant differences at a confidence level of 95% or better for the free shrinkage at 90 days:

- #639 - 7D Granite Control and #646 - 14D 30% G100, LS
- #640 - 14D 30% G100, LWA and #647 - 7D 60% G100, LS
- #648 - 7D 60% G100 II, LWA and #647 - 7D 60% G100, LS
- #639 - 14D Granite Control and #646 - 14D 30% G100, LS
- #648 - 14D 60% G100 II, LWA and #646 - 7D 30% G100, LS
- #648 - 7D 60% G100 II, LWA and #646 - 14D 30% G100, LS
- #646 - 7D 30% G100, LS and #647 - 14D 60% G100, LS
- #655 - 14D 30% G100, FLWA and #646 - 7D 30% G100, LS
- #640 - 14D 30% G100, LWA and #646 - 14D 30% G100, LS

This list notably contains the comparison between the 14-day cured lightweight aggregate mix with 30% slag and the 14-day cured limestone mix with 30% slag, as well as the comparison between the lightweight aggregate mix with 60% slag and the limestone mix with 60% slag (7-day cured specimens) indicating a statistically significant difference in shrinkage at a confidence level of 95%.

From Table 3-12, listed in order from highest to lowest relevance, are the mixes that showed statistically significant differences at a confidence level of 90% or better for the free shrinkage at 90 days:

- #655 - 7D 30% G100, FLWA and #648 - 14D 60% G100 II, LWA
- #648 - 14D 60% G100 II, LWA and #647 - 7D 60% G100, LS
- #648 - 14D 60% G100 II, LWA and #646 - 14D 30% G100, LS
- #640 - 7D 30% G100, LWA and #646 - 7D 30% G100, LS
- #655 - 7D 30% G100, FLWA and #648 - 7D 60% G100 II, LWA
- #655 - 7D 30% G100, FLWA and #645 - 14D Limestone Control
- #655 - 7D 30% G100, FLWA and #645 - 7D Limestone Control
- #647 - 7D 60% G100, LS and #647 - 14D 60% G100, LS
- #640 - 14D 30% G100, LWA and #655 - 7D 30% G100, FLWA
- #646 - 14D 30% G100, LS and #647 - 14D 60% G100, LS

This list notably contains comparisons between the 7-day cured lightweight aggregate with 30% slag mix and the 7-day cured limestone 30% slag mix indicating a statistically significant difference in shrinkage at a confidence level of 90%.

From Table 3-12, listed in order from highest to lowest relevance, are the mixes that showed statistically significant differences at a confidence level of 80% or better for the free shrinkage at 90 days:

- #655 - 7D 30% G100, FLWA and #647 - 14D 60% G100, LS
- #640 - 7D 30% G100, LWA and #648 - 14D 60% G100 II, LWA
- #645 - 14D Limestone Control and #646 - 7D 30% G100, LS
- #642 - 14D 60% G100, LWA and #645 - 14D Limestone Control
- #639 - 14D Granite Control and #645 - 14D Limestone Control
- #639 - 7D Granite Control and #655 - 7D 30% G100, FLWA
- #642 - 7D 60% G100, LWA and #648 - 7D 60% G100 II, LWA
- #655 - 14D 30% G100, FLWA and #648 - 14D 60% G100 II, LWA
- #642 - 14D 60% G100, LWA and #645 - 7D Limestone Control
- #640 - 7D 30% G100, LWA and #648 - 7D 60% G100 II, LWA
- #639 - 7D Granite Control and #642 - 14D 60% G100, LWA
- #645 - 7D Limestone Control and #646 - 7D 30% G100, LS
- #655 - 14D 30% G100, FLWA and #647 - 7D 60% G100, LS
- #655 - 14D 30% G100, FLWA and #648 - 7D 60% G100 II, LWA
- #639 - 14D Granite Control and #645 - 7D Limestone Control
- #639 - 14D Granite Control and #642 - 14D 60% G100, LWA
- #640 - 14D 30% G100, LWA and #648 - 14D 60% G100 II, LWA
- #639 - 7D Granite Control and #646 - 7D 30% G100, LS
- #655 - 14D 30% G100, FLWA and #646 - 14D 30% G100, LS
- #640 - 7D 30% G100, LWA and #640 - 14D 30% G100, LWA
- #646 - 7D 30% G100, LS and #647 - 7D 60% G100, LS
- #655 - 7D 30% G100, FLWA and #655 - 14D 30% G100, FLWA

From Table 3-12, listed in order from highest to lowest relevance, are the mixes that showed no statistically significant differences (a confidence level of less than 80%) for the free shrinkage at 90 days:

- #639 - 14D Granite Control and #655 - 7D 30% G100, FLWA
- #640 - 14D 30% G100, LWA and #655 - 14D 30% G100, FLWA
- #640 - 7D 30% G100, LWA and #647 - 14D 60% G100, LS
- #640 - 7D 30% G100, LWA and #647 - 7D 60% G100, LS
- #648 - 7D 60% G100 II, LWA and #648 - 14D 60% G100 II, LWA
- #639 - 7D Granite Control and #639 - 14D Granite Control
- #642 - 14D 60% G100, LWA and #646 - 7D 30% G100, LS
- #640 - 7D 30% G100, LWA and #655 - 7D 30% G100, FLWA
- #646 - 7D 30% G100, LS and #646 - 14D 30% G100, LS
- #640 - 7D 30% G100, LWA and #646 - 14D 30% G100, LS
- #655 - 14D 30% G100, FLWA and #647 - 14D 60% G100, LS
- #648 - 14D 60% G100 II, LWA and #647 - 14D 60% G100, LS
- #640 - 14D 30% G100, LWA and #648 - 7D 60% G100 II, LWA
- #655 - 7D 30% G100, FLWA and #642 - 14D 60% G100, LWA
- #639 - 14D Granite Control and #646 - 7D 30% G100, LS
- #642 - 14D 60% G100, LWA and #646 - 14D 30% G100, LS
- #642 - 14D 60% G100, LWA and #647 - 7D 60% G100, LS
- #642 - 14D 60% G100, LWA and #648 - 14D 60% G100 II, LWA
- #642 - 7D 60% G100, LWA and #648 - 14D 60% G100 II, LWA
- #640 - 14D 30% G100, LWA and #647 - 14D 60% G100, LS
- #642 - 7D 60% G100, LWA and #647 - 14D 60% G100, LS
- #640 - 7D 30% G100, LWA and #642 - 14D 60% G100, LWA
- #655 - 7D 30% G100, FLWA and #646 - 7D 30% G100, LS
- #642 - 7D 60% G100, LWA and #642 - 14D 60% G100, LWA
- #655 - 14D 30% G100, FLWA and #642 - 14D 60% G100, LWA
- #655 - 7D 30% G100, FLWA and #647 - 7D 60% G100, LS
- #655 - 7D 30% G100, FLWA and #646 - 14D 30% G100, LS
- #640 - 14D 30% G100, LWA and #642 - 14D 60% G100, LWA
- #640 - 7D 30% G100, LWA and #655 - 14D 30% G100, FLWA
- #645 - 7D Limestone Control and #645 - 14D Limestone Control
- #639 - 7D Granite Control and #645 - 14D Limestone Control
- #642 - 14D 60% G100, LWA and #647 - 14D 60% G100, LS
- #648 - 7D 60% G100 II, LWA and #647 - 14D 60% G100, LS
- #642 - 14D 60% G100, LWA and #648 - 7D 60% G100 II, LWA
- #646 - 14D 30% G100, LS and #647 - 7D 60% G100, LS
- #639 - 7D Granite Control and #645 - 7D Limestone Control

This list notably contains comparisons between the lightweight aggregate mix with 30% slag and fine lightweight aggregate mix with 30% slag (for both 7-day cured and 14-day cured specimens) indicating no statistically significant difference in shrinkage.

The list also shows that there was not a statistically significant difference in shrinkage between the lightweight aggregate mix with 60% slag and the limestone mix with 60% slag at a 14-day curing period.

3.4.1 Program II Results

The results in Table 3-7 of Program II show the effect of adding the lightweight aggregate actually increases the average 28-day strength the mixes when compared to the Granite Control.

The addition of the lightweight aggregate increases the amount of internal water available for the mix, as shown in Table 3-8. In this program the total amount of water available from the lightweight aggregate mixes [52.8 lb/yd^3 (31.4 kg/m^3) – 62.0 lb/yd^3 (36.8 kg/m^3)] or limestone mixes [45.5 lb/yd^3 (27.0 kg/m^3) – 46.9 lb/yd^3 (27.8 kg/m^3)] was kept almost constant.

In all cases (both at 30 days and 90 days), the addition of the lightweight aggregate with G100 slag improved the free shrinkage results regardless of how long the specimens were cured when compared to the Granite Control. These differences were determined to be significant at the highest confidence level in almost all cases; the exception being 7-day cured 30% G100 Slag, LWA compared to the 7-day cured Granite Control which was statistically significantly different at a confidence level of 90% and the 7-day cured 30% G100 Slag, LWA was shown to not have a statistically significant difference with the 14-day cured Granite Control.

When compared to limestone mixes with G100 slag, the mixes containing lightweight aggregate and G100 slag performed better when cured for both 7 days and 14 days than the corresponding limestone mix. Only five of the eight batches with 30% G100 slag and 60% G100 slag at 90 days showed statistically significant differences when compared with the Limestone mixes with slag:

At the highest confidence level:
- #640 - 14D 30% G100, LWA and #646 - 7D 30% G100, LS

At a confidence level of 95%:
- #640 - 14D 30% G100, LWA and #646 - 14D 30% G100, LS
- #648 - 7D 60% G100 II, LWA and #647 - 7D 60% G100, LS

At a confidence level of 90%:
- #640 - 7D 30% G100, LWA and #646 - 7D 30% G100, LS
- #648 - 14D 60% G100 II, LWA and #647 - 7D 60% G100, LS

The most effective mix against shrinkage was the 14-day cured 60% G100 Slag II, LWA mix. At 30 days the free shrinkage of this mix was 30 με, and at 90 days was 157 με. This mix had higher strength [4,910 psi (33.9 MPa)] than both the Granite Control [4,140 psi (28.5 MPa)] and Limestone Control [4,680 psi (32.3 MPa)] at 28 days. This mix proved to have statically significant differences with both the Granite Control (7 and 14-day cured) and the Limestone Control (7 and 14-day cured) at the highest confidence level, at 90 days. The mix did not indicate a statistically significant difference in shrinkage at 90 days with the 60% G100 Slag, Limestone mix.

The most effective mix against shrinkage without a 60% G100 slag replacement was the 14-day cured 30% G100 Slag, LWA mix. At 30 days the free shrinkage of this mix was 217 με, and at 90 days was 323 με. This mix had higher strength [4,950 psi (33.9 MPa)] than both the Granite Control [4,140 psi (28.5 MPa)] and Limestone Control [4,680 psi (32.3 MPa)] at 28 days. This mix proved to have statically significant differences with both the Granite Control (7-day and 14-day cured) and the Limestone Control (7-day and 14-day cured) at the highest confidence level, at 90 days. The mix indicated a statistically significant difference in shrinkage at 90 days at a confidence level of 95% with the 14-day cured 30% G100 Slag, Limestone mix.

3.5 Other Considerations

Free shrinkage tests from Program I and Program II show promising results for using lightweight aggregate as an internal curing agent, but many tests should be considered for future work before lightweight aggregates should be used in the field. Useful tests for determining concrete bridge deck durability include scaling (BNQ NQ 2621-900 Annex B), freeze-thaw (ASTM C666 "Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing, Procedure B") and permeability (AASHTO T 260-97, "Standard Method of Test for Sampling and Testing for Chloride Ion in Concrete and Concrete Raw Materials"). Work by Toledo (2009) has shown, specifically, that the high substitution of 60% slag has resulted in scaling of concrete specimens outside the range of acceptable scaling standards, but that 30% slag stays within acceptable ranges of scaling. Work by McLeod (2009) shows that the use of 30% slag provides a statistically significant difference in permeability over the 60% slag replacement. Considering this, testing with 30% G100 slag should continue to determine its usefulness for field application. Scaling, freeze-thaw and permeability testing still should be completed with the lightweight aggregate with and without slag.

Further work is also needed to verify the usefulness of lightweight aggregate to reduce shrinkage of concrete mixes placed in the field. The challenges that must be considered include the methods for keeping aggregate piles saturated and methods to determine appropriate moisture contents of aggregate piles for batching purposes.

Chapter 4 Summary and Conclusions

4.1 Summary

Internal curing is a means of supplying an internal water source for concrete that promotes more cement hydration. Internal curing can be especially beneficial for Low Cracking, High Performance Concrete (LC-HPC). LC-HPC takes advantage of a reduced paste content, optimized aggregate gradation, water/cement ratio (*w/c*) of 0.45, air content of 8 ± ½%, slump between 1½ in. and 3 in. (3.8-7.6 cm), with controlled concrete temperature and improved curing methods to reduce cracking. Introducing a material to supply internal curing may further reduce shrinkage and increase workability of these mixes.

This research includes the evaluation of several mixes to determine the effectiveness of lightweight aggregates as an internal curing agent. Free shrinkage specimens and strength cylinders are evaluated to determine the effects of the addition of lightweight aggregates. All mixes have a cement content of 540 lb/yd^3, 0.44 water/cement ratio, 24.7% paste content and 8% air content. Free shrinkage specimens are evaluated for both 7- and 14-day curing periods. An aggregate optimization program (*KU Mix*) is also revised to include modifications based on aggregate specific gravities for the addition of the lightweight aggregate.

The first program evaluates different replacement amounts of lightweight aggregate for the purposes of internal curing to reduce free shrinkage. A total of six mixes are included in Program I: two control mixes and four mixes to evaluate lightweight aggregate for internal curing. Three of the four lightweight aggregate mixes are used to evaluate three different replacement levels of the intermediate lightweight aggregate: a low, medium and a high level of replacement. One mix evaluated the use of a fine lightweight aggregate at a medium level of replacement. The lightweight aggregate mixes were compared with a Granite and Limestone Control.

The second program evaluates the internal curing from lightweight aggregate in mixes containing Grade 100 (G100) slag. A total of eight mixes are included in Program II: two control mixes, four mixes with lightweight aggregate and G100 slag, and two mixes with limestone and G100 slag. The lightweight aggregate and limestone mixes contained two levels of G100 slag replacement, 30% and 60%. The mixes were compared to a Granite Control and a Limestone Control. Mixes containing lightweight aggregate and slag are compared to mixes containing limestone and slag to determine whether lightweight aggregate is more beneficial for internal curing of slag mixes than limestone.

4.2 Conclusions

The following are the observations and results from the programs studied in this report.

4.2.1 Program I

1. The effect of adding lightweight aggregate does not significantly decrease strength of any one mix.

2. The addition of the lightweight aggregate increases the amount of internal curing water available for the mix when compared to the Granite or Limestone Controls.
3. In almost all cases (both at 30 days and 90 days), the addition of the lightweight aggregate improved the free shrinkage results regardless of how long the specimens were cured when compared to the free shrinkage of the Granite Control mix.
4. Fine lightweight aggregate proves to be too difficult to handle and test. Trying to consistently account for the amount of water both in the aggregate as well as on the surface and maintaining a constant sample size during the handling process was difficult. Fine lightweight aggregate should not be used unless new testing makes it easier to determine properties and better methods of handling the aggregate are developed.
5. The most effective mix to reduce shrinkage was the 14-day cured LWA (High) mix. This mix proved to have statically significant differences with both the Granite Control (7 and 14-day cured) and the Limestone Control (7 and 14-day cured) at the highest confidence level of 98% or better.
6. Even though the limestone had a relatively high absorption of 3.07% when compared to the granite absorption (0.71-0.76%), the use of lightweight aggregate with a higher total moisture content (24.73-29.49%) was more beneficial to reduce free shrinkage even at lower replacement levels by

volume (8.4-13.8% for the lightweight aggregate versus 41.0% of coarse aggregate for the limestone mixes).

4.2.2 Program II

1. The addition of the lightweight aggregate increases the average 28-day strength of the mixes [4,470-5,160 psi (30.8-35.6 MPa)] when compared to the Granite Control [4,140 psi (28.5 MPa)].
2. The addition of the lightweight aggregate increases the amount of internal water available for the mix [from 19.3 lb/yd^3 (11.4 kg/m^3) for the Granite Control to 52.8-62.0 lb/yd^3 (31.4-36.8 kg/m^3) for the lightweight aggregate mixes].
3. The total amount of water available from the lightweight aggregate mixes or limestone mixes was kept almost constant.
4. As in Program I, fine lightweight aggregate proves to be too difficult to handle and test. Trying to consistently account for the amount of water both in the aggregate as well as on the surface and maintaining a constant sample size during the handling process was difficult. Fine lightweight aggregate should not be used unless new testing makes it easier to determine properties and better methods of handling the aggregate are developed.
5. In all cases (both at 30 days and 90 days), the addition of the lightweight aggregate with G100 slag reduced free shrinkage regardless of how long the specimens were cured (7 or 14 days) when compared to the free shrinkage of the Granite Control mix. These differences were determined to be significant

at the highest confidence level in almost all cases, except for the 7-day cured 30% G100 Slag, FLWA mix.

6. When compared to limestone mixes with G100 slag, the mixes containing lightweight aggregate and G100 slag performed better (less free shrinkage) when cured for both 7 days and 14 days than the corresponding limestone mix.
7. The most effective mix to reduce shrinkage was the 14-day cured 60% G100 slag II, LWA mix. At 30 days, the free shrinkage of this mix was 30 $\mu\varepsilon$ and was 157 $\mu\varepsilon$ at 90 days. This mix proved to have statically significant differences with both the Granite Control (7 and 14-day cured) and the Limestone Control (7 and 14-day cured) at the highest confidence level of 98% or better.
8. When considering the poor scaling performance of 60% slag replacement mixes (Todelo 2009), the 14-day cured 30% G100 slag, LWA mix performed the best. At 30 days, the free shrinkage of this mix was 177 $\mu\varepsilon$ and was 283 $\mu\varepsilon$ at 90 days. This mix proved to have statically significant differences with both the Granite Control (7 and 14-day cured) and the Limestone Control (7 and 14-day cured) at the highest confidence level of 98% or better.

4.3 Recommendations

Based on this study, the following is a list of recommendations to further evaluate the use of lightweight aggregate as an internal curing agent for LC-HPC bridge decks.

1. Further durability tests are needed to determine whether lightweight aggregate can be used as an internal curing agent in LC-HPC bridge design. These tests should include scaling (BNQ NQ 2621-900 Annex B), freeze-thaw (ASTM C666 "Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing, Procedure B") and permeability (AASHTO T 260-97, "Standard Method of Test for Sampling and Testing for Chloride Ion in Concrete and Concrete Raw Materials").
2. The use of 30% slag with lightweight aggregate should be tested further for durability (as described above).
3. Further testing programs similar to Program I need to be performed if quantities of more than 13.8% (the highest level of replacement used in Program I) replacement by volume of lightweight aggregate are needed, either because of a lower absorption of the lightweight aggregate or because more water is needed. This could change strength and durability properties of the mix.
4. Further work is needed to verify the usefulness of lightweight aggregate to reduce shrinkage of concrete mixes placed in the field. Challenges that must be considered include methods for keeping aggregate piles saturated and methods to determine appropriate moisture contents of aggregate piles for batching purposes.

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