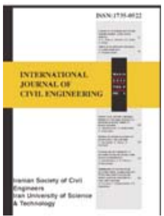

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Internal curing of high strength self consolidating concrete by saturated lightweight aggregate - effects on material properties

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Abstract

Self-desiccation is the major source of autogenous shrinkage and crack formation in low water-binder ratio (w/b) concretes which can be reduced by internal curing. In this paper performance of high strength self consolidating concrete (HS-SCC) with w/b of 0.28 and 0.33 including autogenous shrinkage, drying shrinkage, compressive strength, and resistance to freezing-thawing was investigated. Then, for the purpose of internal curing, 25% of normal weight coarse aggregate volume was replaced with saturated lightweight aggregate (LWA) of the same size; and its effects on the material properties was studied. Two modes of external curing, moist and sealed, were applied to test specimens after demoulding. Autogenous shrinkage from 30 minutes to 24 hours after mixing was monitored continuously by a laser system. The initial and final setting time were manifested as a change of the slope of the obtained deformation curves. Shrinkage after initial setting was 860 and 685 microstrain (με) for 0.28 and 0.33 w/b mixtures, respectively. The saturated LWA reduced these values to 80 and 295 με, respectively. By LWA Substitution the 28-day compressive strength of 0.28 w/b mixture was reduced from 108 to 89 and 98 to 87 MPa for moist and sealed cured specimen, respectively. The corresponding values for 0.33 w/b mixture was 84 to 80 and 82 to 70 MPa. Shrinkage of 0.28 w/b mixture without LWA after moist and sealed cured specimen dried for 3 weeks was about 400 με. Shrinkage of moist and sealed cured specimen containing LWA was reduced 9% and 25%, respectively. On the contrary for 0.33 w/b mixture an increase was noticed. Freezing-thawing resistance was improved by sealed curing, decreasing w/b and substituting LWA.

Keywords: High strength self consolidating concrete, Autogenous shrinkage, Drying shrinkage, internal curing, Saturated lightweight aggregate, Freezing-thawing resistance

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1. Introduction

During the last two decades, self consolidating concrete (SCC) has revolutionized the way that concrete construction is performed. This high performance concrete (HPC) with low water-binder ratio (w/b) has been increasingly promoted for use in civil engineering infrastructure due to its potential improvements in rheology, strength and durability. However reduced amount of water and increased content of cement and pozzolanic admixtures such as silica fume along with high paste volume used in SCC mixture design, contribute to development of considerable autogenous shrinkage leading to early age cracking [1-8]. Mazloom and Ramezanian Pour [4] investigated the effects of binder systems containing different levels of silica fume on behavior of high-strength concrete. They found that the autogenous shrinkage of concrete increased as the amount of silica fume increased. Reduction of water cement ratio in concrete with silica fume makes the concrete more sensitive in cracking. Ghoddousi et.al. [7] investigated the effect of silica fume on early age shrinkage and cracking of concrete. The results showed that in terms of crack initiation time, crack width and total cracking area, concrete containing silica fume is more severe than concrete with no silica fume. Autogenous shrinkage originates from chemical shrinkage and self desiccation of created pores during hydration process. It is defined as the unrestrained external bulk deformation taking place under isothermal and sealed conditions [3]. Autogenous shrinkage is inversely proportional to w/b of concrete. Compared to drying shrinkage, it is negligible in concrete with high w/b. But in concrete with low w/b, autogenous shrinkage can be as large as drying shrinkage. Autogenous

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shrinkage develops very early and if it is not controlled, concretes with a low w/b can severely crack [5]. Conventional curing techniques are not effective in eliminating this type of cracking; since water migration into the concrete is hampered by the tightness of the cement paste [5,9]. For instance, the Denver airport runways had noticeable concrete cracks 7 days after placing, though curing techniques were as specified with a continuous water spraying system [1].

Over the years, several methods have been proposed to reduce autogenous shrinkage and the internal stress that might be induced. Some of the mitigation strategies discussed by Bentz and Jensen [10] include: the addition of shrinkage-reducing admixtures more commonly used to control drying shrinkage, control of the cement particle size distribution, modification of the mineralogical composition of the cement and internal curing. However in terms of durability of concrete, internal water curing is the safest and most efficient method to reduce autogenous shrinkage [11]. Internal water curing consists of introducing a well-dispersed, water-saturated material in concrete that will release water during cement hydration to increase degree of hydration and mitigate autogenous shrinkage [11].

In 1991, Philleo [12] was the first to show that partial replacement of normal weight aggregate (NWA) by saturated lightweight aggregate (LWA) can provide an internal source of water to immediately replace the capillary water consumed during cement hydration and thereby reduce autogenous shrinkage. Lightweight aggregates typically have 24-hour absorptions in the range of 5% to 25% and, if properly preconditioned prior to their introduction into the mixture, can provide additional internal water for curing the concrete [13]. Philleo's suggestion gained some recognition in the mid-1990's with considerable amount of work being done on the use of internal curing methods to alleviate autogenous shrinkage [11-23].

Several techniques to implement internal water curing have been proposed in the literature, such as the use of water saturated lightweight fine aggregate [12-14], water saturated lightweight coarse aggregate [13,15,16], super-absorbent polymers [16,17], porous ceramic waste aggregates [18], recycled concrete aggregate [19] and wood-derived powders and fibers [20]. An extensive bibliography of related literature, compiled by Bentz [21], is available on line. A reasonable explanation of how the saturated LWA reduces or eliminates autogenous shrinkage is provided by Weber and Reinhardt [15]. For a comprehensive introduction to internal water curing, the reader is referred to the work of RILEM Technical Committee 196-ICC: Report 41 [22] and ACI SP-256 [23].

Internal curing with LWA has been successfully used recently in large construction projects. For example, in January 2005, about 190,000 m^3 of internally cured concrete was used in a large paving project in Hutchins, Texas [24]. Field observations reported satisfactory results regarding crack prevention, and tests indicated that 7-day flexural strengths reached 90–100% of the required 28-day flexural strength due to an improved cement hydration. They also found that the compressive strengths of air-cured cylinders were similar to those of wet-cured cylinders at all ages, suggesting that concrete with internal curing is less sensitive to poor external curing practices or unfavorable ambient conditions [24]. In another project, internal curing was utilized to combat autogenous shrinkage of a high performance fiber reinforced self consolidating concrete developed for a pavilion built for the FIFA World Cup 2006 in Germany which is situated in Kaiserslautern, one of the host cities [25].

Autogenous shrinkage, if not controlled, can reach very high values within the first 24 hours after start of hydration reactions leading to rapid failure under restrained shrinkage [26]. During this time concrete has the lowest strain capacity and is most sensitive to internal stresses. This early age shrinkage must be quantified in order to elucidate its mechanism and its contribution to total shrinkage for taking proper action with regard to crack prevention [5]. Early age shrinkage measurements provide a challenge, due to the difficulty in making accurate measurements of the concrete deformation prior to demoulding. The shrinkage must be measured as soon as possible after casting in a mould which permits constant readings without disturbing the concrete [27].

Different types of measuring errors may be involved [28]. Varieties of measurement methods (differences in: mould shape and size, vertical or horizontal setup and measuring device) are utilized by researchers and there is no general agreement on the time zero for starting the measurement [2]. Therefore, in literature the reported magnitude of autogenous deformation varies enormously [29,30]. In the present research, monitoring of shrinkage started 30 minutes after mixing and was registered automatically in 5-minute intervals for 24 hours. Because of the special test setup some of the error sources mentioned in reference 28, such as mechanical coupling between the fresh SCC and the sensor as well as the friction between the mould and specimen, were eliminated. The influence of internal curing by saturated LWA on the early age shrinkage of HS-SCC with w/b of 0.28 and 0.33 was quantified. In addition, the effects of partial replacement of NWA by saturated LWA on drying shrinkage, compressive strength and freeze/thaw resistance of test specimens subjected to two modes of external curing (sealed and moist) was studied.

2. Research significance

With the advent of low w/b high performance concretes such as HS-SCC early age cracking, primarily due to autogenous shrinkage, has occurred with greater frequency. A proper curing regime for the mitigation of autogenous shrinkage is crucial for achieving the desired durability of these concretes. In this study the effectiveness of saturated LWA as internal curing agent in reducing the early age autogenous shrinkage of HS-SCC was evaluated by measuring its very early age shrinkage via a laser system. Also effect of internal and external curing on compressive strength, drying shrinkage and resistance to freezing-thawing was studied. Understanding the influence of curing on SCC performance is critical to developing rational curing practices and integrating curing into the mixture design process.

3. Experimental program

3.1. Materials

Portland cement type I-425 and silica fume (12.5% of cement weight), as binder (b), and micronized quartzite (density=2.65), as filler, were used in all mixtures. The chemical composition and properties of cement and silica fume are given in table 1. The particle size distributions of cement, silica fume and micronized quartzite, obtained by laser diffraction technique, are presented in figure 1. Crashed limestone with maximum nominal size (MNS) of 12.5 mm and natural siliceous sand with MNS of 4.75 mm were used as normal weight coarse aggregate (NWCA) and normal weight fine aggregate (NWFA), respectively. For the purpose of internal curing, a commercial (Leca) lightweight coarse aggregate (LWCA) of a single fraction (4.5–9 mm) in saturated surface dry (SSD) condition was used to replace 25% by volume of NWCA of similar size. The absorption capacity and density of aggregates are shown in table 2; and their particle size distributions are presented in figure 2. The high range water reducing admixture (HRWRA) was based on carboxylic ether polymer with density of 1.07 and 40% solid content.

Table 1. Chemical composition of portland cement and silica fume

Composition	Portland cement %	Silica fume %
SiO_2	19.94	94.0
Al_2O_3	4.12	1.0
Fe_2O_3	4.08	0.1
MgO	4.25	0.6
CaO	60.15	1.0
SO_3	2.03	1.2
LOI	4.10	-
C_3S	54.02	-
C_2S	16.41	-
C_3A	4.01	-
Na_2Oeq	0.96	-

3.2. Mix proportions

Four SCC mixtures designated by 28LWA00, 33LWA00, 28LWA25 and 33LWA25 were designed. The number before LWA (28 or 33) indicates the percentage of w/b by weight and the number after that (00 or 25) stands for the percentage by volume of lightweight aggregate substitution. A three phase procedure, described in reference [31], was adopted for designing SCC mixtures. First a paste with adequate viscosity was designed. Then effect of paste volume on mortar workability was studied and a mortar with 55% paste volume was selected. Finally effect of mortar volume on workability of SCC was investigated and a stable SCC with mortar volume of 72% was chosen for this study (paste volume in SCC was 55%*72%=39.6%). The amount of solid HRWRA used was 0.45% of binder weight. The normal weight aggregates were in air dry state and the appropriate moisture correction was taken into account for trial batches. For accurate calculation of w/b, the water in HRWRA was accounted for. Mix design, shown in table 3, was based on volume proportioning and the spread sheet software Excel was utilized to perform the calculations.

Table 2. Aggregates properties

Aggregate Type	SSD Density	Absorption Capacity %
NWFA	2.59	3.24
NWCA	2.58	1.97
LWA	1.04	11.7

N: Normal, L: Light, W: Weight, F: Fine, C: Coarse, A: Aggregate

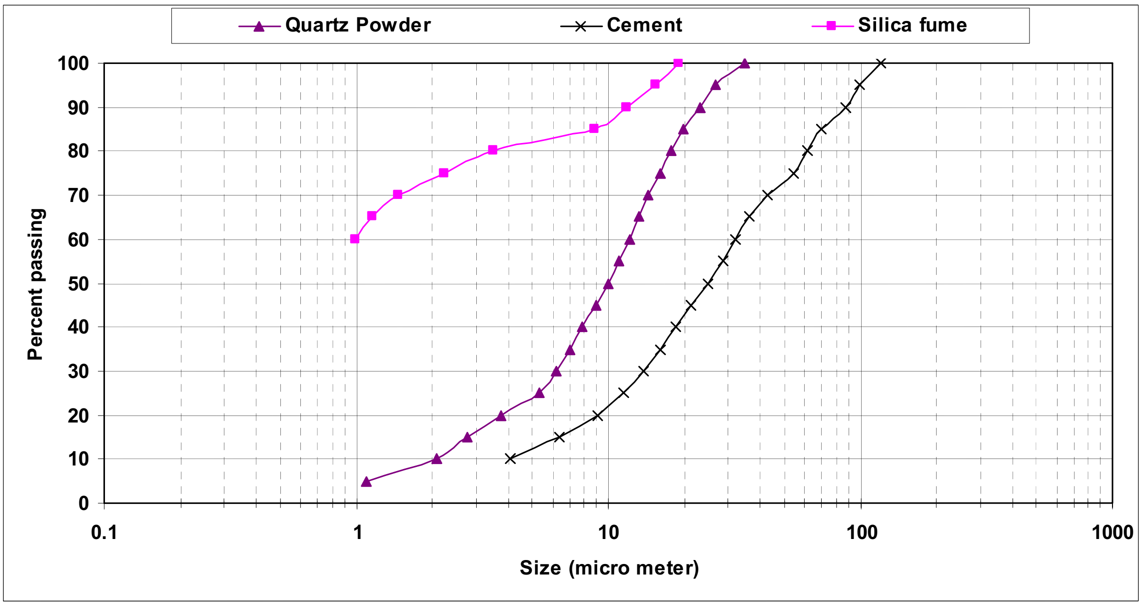


Fig. 1. Particles size distributions for cement, silica fume and micronized quartzite

3.3 Test methods

3.3.1 Fresh SCC properties

For each mixture a batch of 80 liters was made in a pan mixer of 100-liter capacity. The fresh SCC properties including slump flow, V funnel flow time and L box height ratio were determined according to European guidelines [32]. Unit weight and air content of fresh mixtures were measured according to ASTM C138 [33] and ASTM C231 [34], respectively. The test results are given in table 4. No rodding or vibration (for compacting) was applied in any of the tests performed in this research.

3.3.2 Early age deformation

To quantify the early age shrinkage behavior of SCC mixtures, a laser system equipped with data logger was utilized so that automatic measurement could be started immediately after casting. The test set up and mould shape was similar to that used by J. Kaufmann [35]. A special formed specimen container in the form of a cone with base inner diameter of 149 mm and inner height of 129 mm was used in a vertical setup with the base facing up. An advantage of this setup was the possibility of overcoming the friction between the specimen and the mould, a problem that exists in most other setups. The coned shape mould made it easy to fit a plastic foil of similar shape (cut from the corner of a plastic bag) into the mould to prevent direct contact of concrete and mould. The plastic foil was very smooth, thin and flexible so that it could deform with the specimen and therefore the friction between the specimen and mould was reduced to nearly zero. The presence of gravity force in the vertical setup also helped to overcome the friction force. The cone was filled with SCC without vibration. A light small reflector plate was slightly pressed into the fresh SCC at the center of the base. Any change of the specimen height was measured touch-less via a reflected laser beam and was registered automatically in 5 minutes intervals for 24 hours. A cone is a special geometry (unlike cylinder or prism), where the volume change and the height change are in a direct mathematical correlation i.e. $v'/v = (h'/h)^3$, where h and v are the original height and volume while h' and v' are the height and volume after shrinkage. Hence, even though change in specimen height is measured, it correlates well with volume change. The experiment was carried out in a controlled environment room with relative humidity and air temperature of 50±5% and 23±1°C respectively. A picture of the apparatus and the setup is presented in figure 3 and the measurement results are shown in figures 4a and 4b.

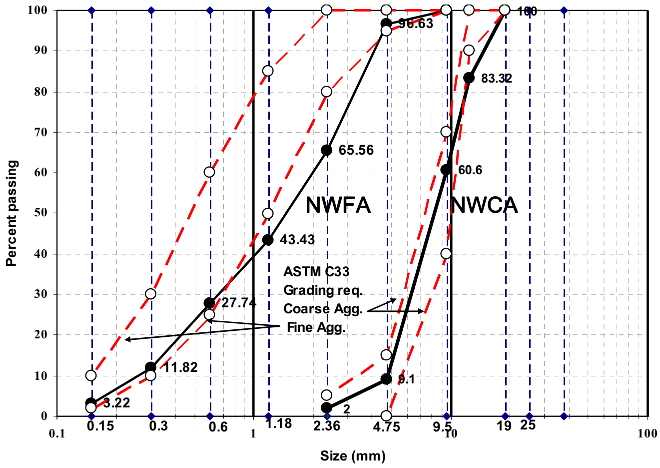


Fig. 2. Particles size distributions for normal fine and coarse aggregates

3.3.3 Compressive strength

The compressive strength of 100 mm. cubes at the ages of 7 and 28 days were determined according to the procedure described in EN 12390 [36]. For each mixture, 12 cubic moulds were cast and covered with wet burlap and plastic sheet while they were left at laboratory conditions. After demoulding at age of 24 hours, six specimens were cured in lime-saturated water at 23 °C and six specimens were sealed by wrapping them in aluminum foil and plastic sheet and were kept in room temperature of 23±1°C until the time of testing. The results, averaged from 3 specimens, appear in figure 5.

Table 3. Self consolidation concrete mixture proportions

Mixture ID	w/b	Constituent content (kg/m^3)							
		Cement Type I	Silica fume	Micronized quartzite	Water	HRWRA	NWFA SSD	NWCA SSD	LWA SSD
28LWA00	0.28	522.2	65.3	37.5	158.3	8.1	866.9	722.4	0.0
28LWA25	0.28	522.2	65.3	37.5	158.3	8.1	866.9	541.8	72.8
33LWA00	0.33	481.6	60.2	32.5	176.1	7.5	866.9	722.4	0.0
33LWA25	0.33	481.6	60.2	32.5	176.1	7.5	866.9	541.8	72.8

Table 4. Fresh self consolidating concrete properties

Mixture ID	Slump-flow (mm)	T_{500mm} Slump-flow(sec)	V-funnel flow time (sec)	V-funnel flow time @5min (sec)	L-Box Passing ratio	Unit weight kg/m^3	Air content%
28LWA00	670	3.0	5.0	9.5	0.85	2352	1.2
28LWA25	600	4.0	8.0	20.0	0.80	2187	2.4
33LWA00	660	2.7	4.2	15.0	0.85	2319	1.2
33LWA25	610	1.5	6.0	9.3	0.96	2204	2.0

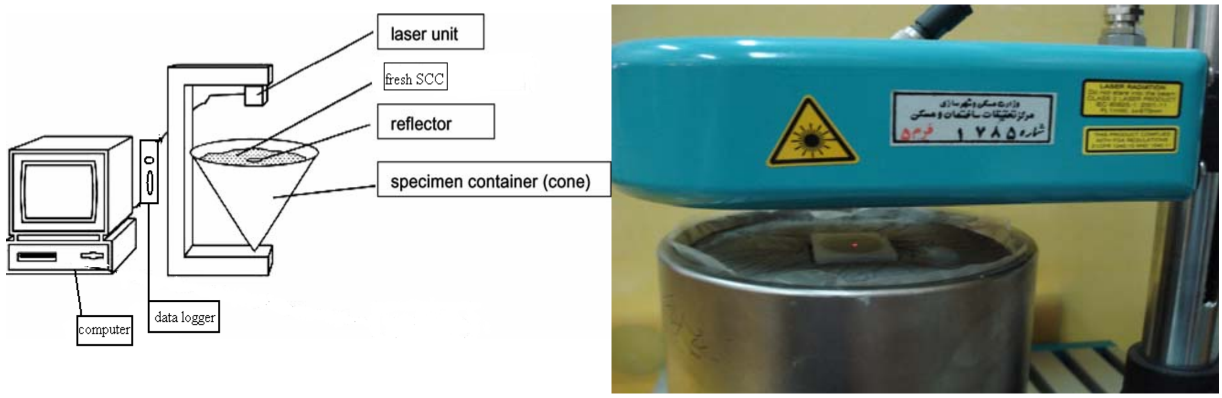
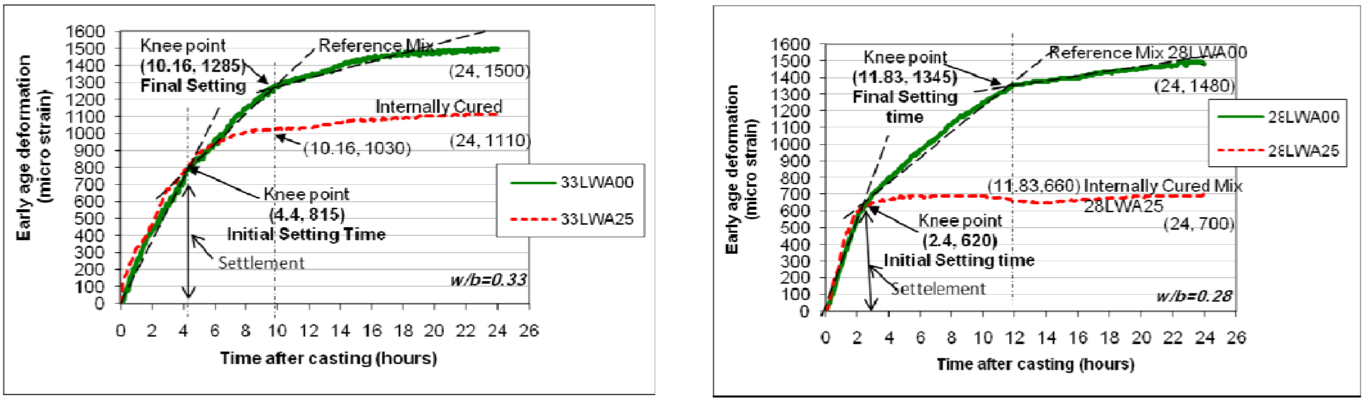


Fig. 3. Picture of test apparatus and the setup for measurement of early age shrinkage



(a) (b)

Fig. 4. a) Early age shrinkage of reference SCC and internally cured SCC (w/b=0.28) deformation curve is divided into liquid/skeleton formation/rigid stages by knee points. b) Early age shrinkage of SCC and internally cured SCC (w/b=0.33) deformation curve is divided into liquid/skeleton formation/rigid stages by knee points.

3.3.4 Drying shrinkage

Drying shrinkage was measured according to the procedure described in ASTM C157 [37]. Curing conditions (sealed and moist) were similar to those of compressive strength test specimen. For each mode of curing 3 specimens (75*75*285mm.) were made and after demoulding at age 24 hours they were cured in wet or sealed condition till age of 28 days. Thereafter, these samples were removed from water or unsealed and maintained at 23±1°C and 50±5% relative humidity (RH) environment. The specimens' weight loss and length change due to drying were recorded for 3 weeks. Unfortunately the measurement was halted earlier than planed schedule, because control of room temperature and humidity was no longer possible due to an unforeseen problem. The relative weight loss vs. drying time of all mixtures is shown in figure 6. Drying shrinkage vs. relative weight loss is presented in figure 7. The plot of drying shrinkage for 0.28 and 0.33 water to binder ratio mixtures vs. drying time are shown in figures 8 and 9, respectively.

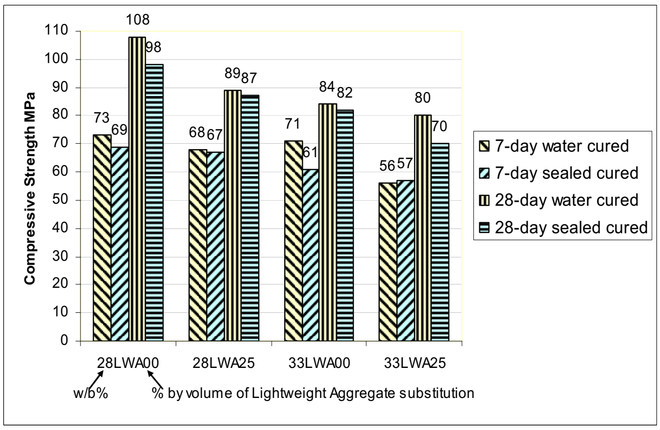


Fig. 5. The 7 and 28 day compressive strength of SCC mixtures with and without pre-saturated LWA subjected to moist and sealed external curing (water to binder ratio is: w/b= 0.28 and 0.33)

3.3.5 Resistance to rapid freezing and thawing

The resistance of SCC mixtures to freezing and thawing degradation was quantified through the use of the ASTM C666-97 (Procedure B) standard test method [38]. For each mixture three test specimens (76- by 102- by 406-mm) were cast. They were left in laboratory covered with wet burlap and plastic sheet. After demoulding at age 24 hours, the specimens were moist cured in 23 °C lime saturated water until age of 14 days. Due to equipment limitation, sealed curing (in addition

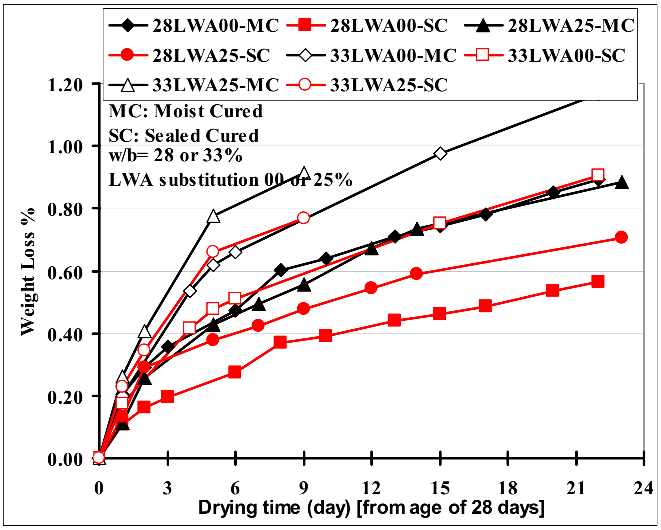


Fig. 6. Weight loss relative to the first weight measurement vs. time after drying started

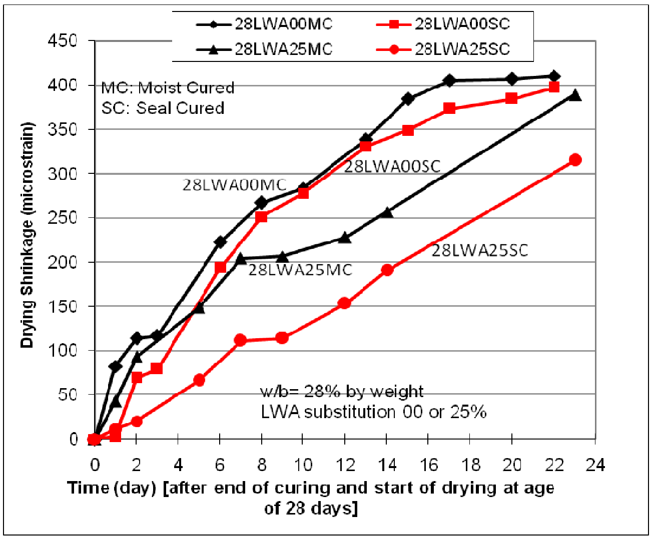


Fig. 8. Drying shrinkage vs. drying time of SCC mixtures after 28 days of moist and sealed curing

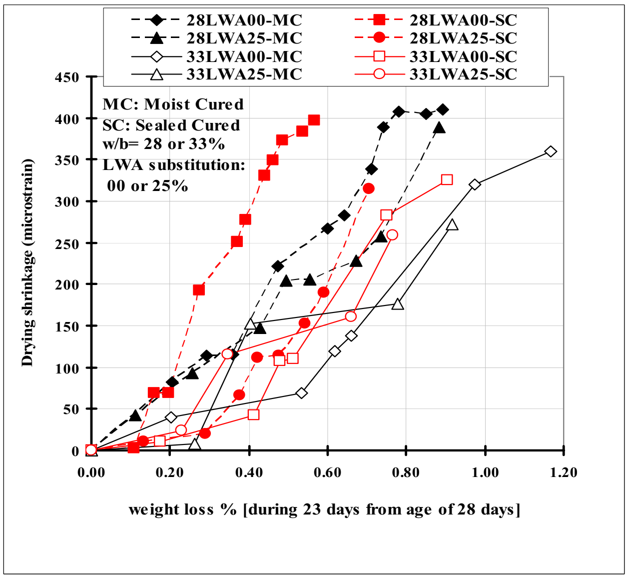


Fig. 7. Drying shrinkage vs. relative weight loss of sealed and moist cured specimens

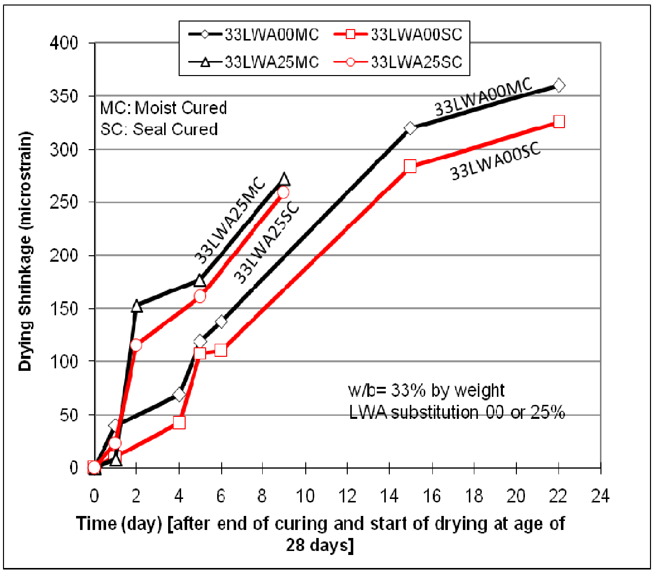


Fig. 9. Drying shrinkage vs. drying time of SCC mixtures after 28 days of moist and sealed curing

to moist curing) was only applied to specimens with w/b of 0.28 and no LWA (28LWA00). The fundamental transverse frequency and weight of each specimen were measured prior to starting the freeze-thaw cycles. Six cycles per day and total of 320 cycles of freeze/thaw were applied to all specimens. Specimens were removed from the freeze-thaw cabinet at intervals of approximately every 24 cycles to measure their fundamental transverse frequency and weight after thawing. The relative dynamic modulus of elasticity, P_c (in percent), after c cycles of freezing and thawing was calculated according to ASTM C666 as follows: $P_c = (n_1^2/n^2) \times 100$ where: n and n1=fundamental transverse frequency at 0 and after c cycles of freezing-thawing, respectively. The relative weight change and relative dynamic modulus of elasticity, averaged from results of 3 specimens, are shown in figures 10 and 11, respectively.

4. Results and discussion

4.1 Fresh SCC properties

The fresh properties of mixtures, shown in table 4, indicate that the conformity criteria for the properties of SCC, specified in the European guidelines for self compacting concrete [32], are satisfied.

There was no segregation or any halo of paste present around the slump flow.

There was some concern about the possibility of LWA flotation, but saturation of LWA as well as appropriate viscosity and amount of the paste helped to minimize this problem. As expected, the unit weight of mixtures with LWA was slightly reduced and the entrapped air in all mixtures was quite low.

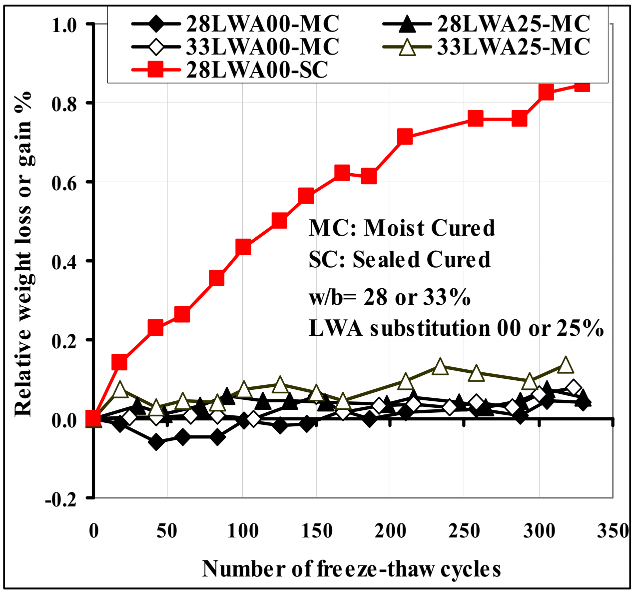


Fig. 10. Relative values of weight loss or gain of specimens subjected to freezing and thawing

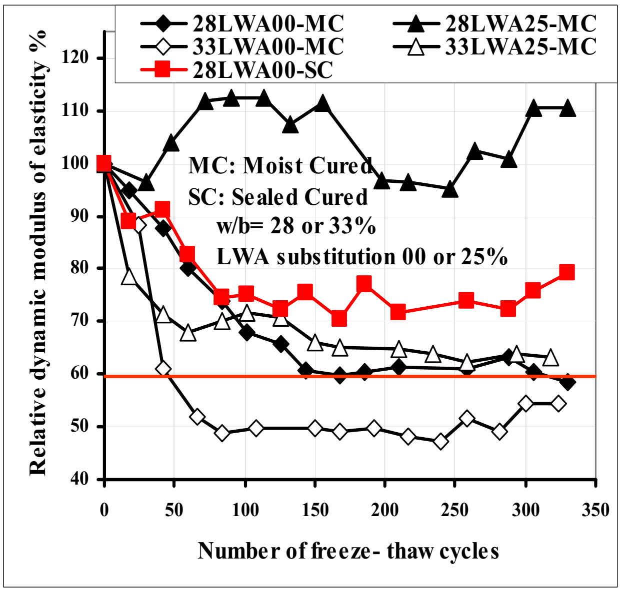


Fig. 11. Relative dynamic modulus of elasticity vs. number of freeze/thaw cycles

4.2 Early age deformation

The pattern of early age shrinkage curves of reference mixtures (without LWA), shown in figure 4, comprises three nearly linear line segments with different slopes; indicating the presence of three distinct stages with different rate of shrinkage occurring in each stage. It is suggested [8,39] that, when measuring the autogenous shrinkage from time of casting, the initial and final setting time may be manifested as points of the curve which a change of the slope of the deformation curve occurs. These points which are called the knee points, divide the early age shrinkage curve into 3 Phases: before setting or liquid stage, during setting or skeleton formation stage and after setting or hardening stage [1]. In figure 4, straight dashed lines are fitted over each segment of the shrinkage curve of reference mixtures and their intersections are shown as the knee points. It should be noted that the shrinkage measured is actually a combination of settlement, autogenous, drying and thermal deformation. However, according to Aitcin [40] because the mould is small the test condition can be considered as quasi-isothermal and hence thermal deformation is negligible in this case; also drying shrinkage is not dominating here because only the base of the coned shape specimen was subjected to drying. Therefore, the major part of the measured deformation can be considered as settlement and autogenous shrinkage. Settlement occurs at first few hours and before initial setting, while the concrete is liquid. According to Japan Concrete Institute (JCI) [41], in vertical setup the effect of gravity causes subsidence, defined as: "vertical length change in cementitious materials before initial setting, which is caused by bleeding, chemical shrinkage, and so on". It is argued [1,8,42] that before initial setting, concrete is liquid and any deformation will be immediately corrected by a shift in the position of the body with little consequence for the risk of cracking [1]. While, the shrinkage taking place after initial setting is considerably detrimental, because the concrete at skeleton formation and early hours of hardening stage has poorly developed tensile strain capacity [8,42]. JCI [41] suggests that measurement of autogenous shrinkage should start at initial setting time and therefore any volume change before this point shall be excluded and that all volume change beyond this point must be included. As shown in figure 4 the initial setting time of 0.28 and 0.33 w/b mixtures occurred 2.4 and 4.4 hours after casting with corresponding subsidence of 620 and 815 με, respectively. It has been shown by Justnes et al. [43] that setting time of pastes increased with an increased water/cement ratio (w/c). Holt studied early age autogenous shrinkage of HPC with w/c of 0.3 and 0.35 using rapid hardening cement. The initial setting time was shortened from 2.5 hours to 0.5 hour at the lower w/c ratio. This was attributed to the quicker hydration rate of lower w/c concrete.

Excluding the subsidence in liquid stage from the total values of 1480 and 1500 με at 24 hours, the first day autogenous shrinkage of mixtures without saturated LWA would be 860 με for the lower w/b SCC and 685 με for the higher w/b SCC. Even though in literature the reported magnitude of autogenous deformation varies enormously [29,30], there is a general agreement [2,6] that the lower the w/b is the higher the autogenous shrinkage would be. For the liquid phase no particular difference was observed with regard to the deformation behavior of the mixtures with and without saturated LWA. At the end of this phase, deformation curves of mixtures with saturated LWA diverged from their corresponding reference mixtures and grew very slowly then after. From initial setting time till 24 hours after casting, shrinkage of mixture 28LWA25 was 80 με (90% reduction) and that of mixture 33LWA25 was 295 με (57% reduction). It is clear that internal curing can be very effective in reducing autogenous shrinkage of young concrete. The degree of effectiveness depends on different factors. As reported by

Hammer [44], the efficiency of LWA as an internal curing agent for shrinkage reduction, primarily depends on the amount of water in the LWA, the LWA particle spacing, and pore structure. Even though these factors were intended to be similar but it is suspected that the LWA used in 33LWA25 mixture was dryer than SSD condition and therefore amount of water in LWA of this mixture was probably less than that of mixture 28LWA25. To obtain SSD aggregate, air dried LWA was immersed in a water bath for 24 hours after which time the water was decanted and LWA was spread out on a tray left in laboratory environment till the aggregate's surface moisture was dried. The desired SSD condition was checked by touching a paper towel to the aggregate and when it appeared the paper towel was no longer picking up moisture from the aggregate, it was presumed that SSD condition has been reached. However, determining when there was no more surface moisture on the aggregate was not easy and depending on how frequently the surface moisture is checked the variation of water stored in LWA from person to person could be rather large. The higher reduction of autogenous shrinkage in lower w/b SCC may also be due to smaller pore size of the lower w/b paste, generating higher capillary suction force.

The development of autogenous shrinkage slowed down considerably about 22 hours after casting. It is important to pay attention to the high values of autogenous shrinkage in low w/b concretes in the first 24 hour. According to the findings of Mak et al., [45] the autogenous shrinkage strain obtained within the first 24 hours was more than the subsequent shrinkage measured over 1 year using standard procedures. Therefore, using standards such as ASTM C157 [37] for measuring shrinkage of low w/b concretes (without proper modification) is not valid, since in this standard measurement starts after demoulding at age of 24 hours. It has been emphasized by Aitcin [40] that a large part of autogenous shrinkage would have occurred by then. Recently ASTM has developed a standard method, ASTM C1698-09 [46], of measuring early age autogenous shrinkage which starts after casting of paste and mortar. This method is modified by some researchers [8,16] so that it could be applied to concrete.

4.3 Compressive strength

The 7 and 28 day compressive strength of mixtures, 28LWA25 and 33LWA25, along with their corresponding reference mixtures, 28LWA00 and 33LWA00, subjected to two different external curing conditions (sealed and moist) are given in figure 5. For both w/b mixtures with saturated LWA the mode of external curing made no difference in 7 and 28 day compressive strength (±1Mpa difference) except that the 28 day strength of 0.33 w/b mix with LWA (33LWG25) was higher when it was moist cured. This may be due to the lower efficiency of internal curing in 0.33 w/b mixture which was also noticed and discussed in section 4.2. Weber and Reinhardt [47] stated that wet curing of internally cured HPC has no paramount influence on the compressive strength and can, therefore, be neglected. In the present study the mixtures without saturated LWA gained more strength when external moist curing, instead of sealed curing, was applied.

Therefore if internal curing is applied, external water curing may be omitted without loss of strength; in this case sealed curing may be necessary and care should be taken to make sure enough curing water is provided by the Internal reservoir. Substituting 25% (by volume) of NWCA by saturated LWA lead to a moderate reduction of compressive strength. For example the 28-day strength of 0.28 w/b SCC was reduced from 108 to 89 MPa (18% reduction) for moist cured specimen and from 98 to 87 MPa (11% reduction) for sealed cured specimen. In literature reports of increase [22,47], decrease [16,22], and no change [14] of compressive strength due to saturated LWA substitution are registered. Theoretically, it is argued [47] that the moisture in LWA causes an increase in degree of hydration and decrease in porosity of the matrix and as a result the compressive strength should increase. However a strength ceiling may exist in concrete containing LWA which is independent of the matrix [48]. Maghsoudi et.al. [49] used Leca as lightweight aggregate and designed self consolidating lightweight concrete with 500 kg/m3 of binder including 10% silica fume. The 28-day compressive strength of this concrete with w/b of 0.35, was only 28.5 Mega Pascal; conforming the above statement that a ceiling may exist.

4.4 Drying shrinkage

In Figure 6 relative weight loss of all mixtures subjected to 28 days of moist and sealed curing is plotted against drying time. This figure shows that moist cured specimens and mixtures with higher w/b have a greater relative weight loss compared to sealed cured specimens and mixtures with lower w/b, respectively. Also mixtures with LWA have higher relative weight loss than mixtures without LWA. As expected these mixtures have higher potential for absorbing moisture and therefore loose more weight than their counterparts. However, this does not necessarily mean that these specimens experience much larger shrinkage. The rate of moisture loss is higher in the first few days and then drying continues at slower rate. This is perhaps an indication of free water evaporation from larger pores at the beginning. According to Neville [48], the shrinkage due to loss of adsorbed water held by hydrostatic tension in small capillaries (< 50 nm) is significantly greater than that associated with the loss of free water which occurs in the early stages of drying. Drying shrinkage vs. relative weight loss of all mixtures is plotted in figure 7. This figure shows that there is very little or no shrinkage for relative weight loss of up to 0.3%, confirming the loss of free water in the first hours of drying which causes little or no shrinkage. Romildo et al. [50] plotted the drying shrinkage of a cement mortar composite mixture against the normalized loss of mass (mass loss of time/final loss of mass) and observed that up to a normalised loss of mass of 0.12 there was no shrinkage. They concluded that up to this stage the loss of mass was mainly due to removal of free water. Shrinkage strain of 0.28 and 0.33 water to binder ratio mixtures vs. drying time are shown in figures 8 and 9, respectively. Mode of external curing did not make considerable difference in shrinkage development. Even though, comparing to the sealed cured specimens, much higher relative weight loss was observed in moist cured specimens, shrinkage of these specimens was only slightly higher than that of sealed cured specimens. With regards to the effect of LWA substitution on drying shrinkage, 45%, and 25% reduction was noticed for sealed cured specimens made of 0.28 w/b mixture after 2 and 3 weeks of drying, respectively. The reduction for similar but moist cured specimens was 30% and 9% during same drying time. On the contrary for 0.33 w/b mixture with LWA substitution about 45% increase was noticed for both moist and sealed cured specimens after the first week of drying.

It was found that the measurement of shrinkage is very sensitive to any change in the temperature and humidity of the room where experiment is carried on. Durán-Herrera, et al. [14] substituted 20% (by weight) of normal weight sand by saturated lightweight sand in a 0.35 w/b concrete mixture. They found that by this substitution, drying shrinkage reduced 40, 30, and 20% at the ages of 7, 28, and 91 days, respectively. Lam and Hooton [16] investigated the effect of internal curing methods on properties of mortar and concrete and concluded that the saturated lightweight aggregates (fine and coarse) did little in decreasing the total drying shrinkage of mortar and concrete.

4.5 Resistance to rapid freezing and thawing

Limited information on performance of internally cured mixtures subjected to freeze/thaw cycling is available. The possibility of higher degree of saturation due to wet LWA has raised concern regarding durability issues under freezing and thawing conditions; on the other hand LWA can provide the void volume required to release hydraulic pressure developed during cyclic freezing. The potential benefits or possible drawbacks of utilizing LWA for internal curing of SCC subjected to freezing and thawing condition were quantified using ASTM C666 test method and the results are summarized in figures 10 and 11.

The relative weight change of each mixture vs. the number of freeze/thaw cycles is presented in figure 10. The moist cured specimens showed very little weight change ranging from 0.06% weight loss to 0.14% weight gain corresponding to mixtures 28LWA00 and 33LWA25, respectively. In contrast, the relative weight change of sealed cured specimen cast from mixture 28LWA00 was considerably higher reaching to 0.85% weight gain after 330 cycles. The amount of weight gain of each specimen indicates how much water the specimens absorbed and observation of weight loss (which was negligible in this study) induces a degradation of specimens.

The relative dynamic modulus of elasticity (RDM) of each mixture vs. the number of freeze/thaw cycles is shown in figure 11. The value of RDM For mixture 33LWA00 fell below the ASTM specified limit of 60% after 50 cycles but remained unchanged at about 50% after that. RDM of mixture 28LWA00 reached the value of 60% by 150 cycles of freeze/thaw and did not decrease further for the remaining 150 cycles. Perhaps a better performance would have been expected from these high strength concretes. But several factors are involved. According to Pigeon et al. [51] for high strength concrete and type I cement the limiting value of water to binder ratio below which air entrainment (AE) is not necessary for adequate frost protection is of order 0.25. The results of present study indicate that by reducing the w/b, the concrete's performance (freeze/thaw resistant) would be improved. In addition, the freeze/thaw performance of specimens was improved considerably by sealed curing compared to moist curing. This is attributed to self desiccation and lower degree of saturation of capillary pores. RDM of mixture 28LWA00 when sealed cured was reduced to 75% by about 100 cycles and did not decrease any further for more than 200 cycles that followed. Inclusion of silica fume may have also been a reason for the low performance of these non-AE mixtures. As reported by ACI committee 234 [52], some researchers have found the silica-fume concrete to be frost resistant even without entrained air while conflicting results have been produced by others. Malhotra et al. in their research [53] found that all non-AE silica fume concretes failed at less than 50 cycles regardless of w/b when moist cured 14 days prior to freezing. Gokce et al. [54] studied freezing and thawing resistance of air-entrained concrete incorporating recycled coarse aggregate and found that use of silica fume in concrete decreased its freezing and thawing resistance compared with the performance of the concrete containing only cement as binder. In general, it is assumed that when internal microcracks develop in test specimens subjected to freeze-thaw cycling, their resonant frequency will decrease. Therefore RDM reduction in a test specimen is an indication of concrete deterioration. However non of the prisms considered in this study showed any sign of deterioration throughout the test and the appearance of specimens relative to their original shape was unchanged after 300 cycles of freeze/thaw as per ASTM C666.

Freezing and thawing resistance of mixtures with internal curing by LWA substitution was improved compared to their corresponding reference mixtures. The RDM of 0.28 w/b mixture with 25% LWA substitution (28LWA25) remained close to 100% (varied between 95% to 110%). This improvement may be attributed to the void volume provided by LWA. These voids may similarly act like the entrained air which, according to powers [55], reduces the hydraulic pressure created during cyclic freezing. The minimum RDM value of reference mixture 33LWA00 was increased from 50% at 75 cycles to 65% at 150 cycles when 25% of NWCA was substituted with saturated LWA in mixture 33LWA25. Schlitter et al. [56] tested 3 mortar mixtures with w/b of 0.3 (the binder consisted of only type 1 cement). For the purpose of internal curing portions of the normal weight sand were replaced with manufactured rotary kilned expanded shale such that 11 % and 23.7 % of the total mixture volume comprised of LWA. ASTM C666 method of testing with 2 cycles of freeze/thaw per day was used. The specimens were sealed cured for 14 days prior to testing. They did not observe freeze-thaw damage after 300 cycles. Cusson and Margeson [57] also found that internally-cured air entrained concrete performed better than the reference concrete without internal curing under 300 rapid cycles of freezing and thawing in water, and 50 slow cycles of freezing and thawing in a solution of de-icing chemicals.

5. Conclusion

Four self consolidating concrete mixtures containing micronized quartz powder, silica fume and type 1 Portland cement with water to binder ratio of 0.28 and 0.33 and with or without 25% pre-saturated lightweight aggregate (LWA) substitution were made. The material property of each mixture including fresh property, early age autogenous shrinkage, drying shrinkage, compressive strength and resistance to freezing/thawing was investigated. Based on the results of this research the following conclusions may be drawn:

1. With the measurement setup in this study, the pattern of early age shrinkage curves of reference mixtures (without LWA) showed three distinct stages with different rate of shrinkage occurring in each stage. The initial and final setting time was manifested as points of the curve which a change of the slope of the deformation curve occurred.
2. The first day autogenous shrinkage of low w/b mixture without saturated LWA was quite high. By increasing the w/b, the autogenous shrinkage was decreased. The development of autogenous shrinkage slowed down considerably about 22 hours after casting. It is important to pay attention to the high values of autogenous shrinkage in low w/b concretes in the first 24 hour.
3. Internal curing with saturated surface dry (SSD) LWA was very effective in reducing early age autogenous shrinkage. However obtaining LWA in SSD condition was tedious and the amount of water stored in the LWA affected the efficiency of LWA as an internal curing agent.
4. The mode of external curing (moist and sealed) made no difference in compressive strength of mixtures containing saturated LWA.
5. The mixtures without saturated LWA gained more strength when external moist curing, compared to sealed curing, was applied. Therefore if internal curing is not utilized, external water curing should be used in order to gain maximum strength possible.
6. LWA Substitution led to a moderate reduction of compressive strength. For example the 28-day strength of 0.28 w/b SCC was reduced from 108 to 89 Mpa (18% reduction) for moist cured specimen and from 98 to 87 Mpa (11% reduction) for sealed cured specimen.
7. The relative weight loss of drying shrinkage specimens was higher in mixtures with higher w/b, moist cured and containing LWA compared to mixtures with lower w/b, sealed cured and without LWA, respectively. However the specimens with higher weight loss did not necessarily have higher shrinkage. This is attributed to the fact that evaporation of loose water from bigger pores causes little shrinkage.
8. Drying shrinkage of moist cured specimens was slightly higher than that of sealed cured specimens of same mixture. The largest difference, observed in 0.28 w/b mixture containing LWA (28LWA25), was 20%.
9. With regards to the effect of LWA substitution on drying shrinkage, 45%, and 25% reduction was noticed for sealed cured specimens made of 0.28 w/b mixture after 2 and 3 weeks of drying, respectively. The reduction for similar but moist cured specimens was 30% and 9% during same drying time. On the contrary for 0.33 w/b mixture with LWA substitution about 45% increase was noticed for both moist and sealed cured specimens after the first week of drying.
10. Performance of non air entrained high strength SCC containing silica fume subjected to repeated cycles of freezing/thawing was not satisfactory. However the following factors improved its resistance to freeze/thaw cycling: sealed curing instead of moist curing, decreasing w/b and substituting lightweight aggregate for normal weight aggregate. The voids of LWA may similarly act like the entrained air which reduces the hydraulic pressure created during cyclic freezing.

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