Effect of Presoaked Expanded Perlite Aggregate on the Dimensional Stability and Mechanical Properties of Engineered Cementitious Composites

Suleyman Bahadir Keskin[1]; Kamaran Sulaiman[2]; Mustafa Sahmaran, Aff.M.ASCE[3]; and Ismail Ozgür Yaman[4]

Abstract: This paper reports on an investigation of the use of expanded perlite aggregate as saturated lightweight aggregate (LWA) with respect to the mechanical and dimensional stability properties of engineered cemetitious composites (ECC). Expanded perlite aggregate was soaked in water for 24 h before its use in ECC, and replaced 10, 20, and 30% of the aggregate that was used in ECC production. The mixture proportion of a standard ECC mixture with properties that have been extensively reported in the literature is used as a reference. The properties of the specimens are compared in terms of compressive strength, flexural strength, midspan beam deflection capacity, matrix fracture toughness, drying shrinkage, autogenous shrinkage, and restrained shrinkage. The compressive strength and flexural strength of the specimens were adversely affected with presoaked LWA replacement. Midspan beam deflection capacities were partially improved, whereas matrix fracture toughness values decreased by the presoaked LWA replacement, which is beneficial with respect to the multiple cracking behavior of ECC. Presoaked LWA replacement slightly increased the drying shrinkage with respect to the reference mixture. However, the use of presoaked expanded perlite aggregate in ECC production increased the age of restrained shrinkage cracking and decreased the autogenous shrinkage capacity significantly. Therefore, together with the comparable and enhanced composite mechanical, ductility, and dimensional properties of the standard ECC mixture, the use of presoaked LWA in ECC production should improve the durability and extend the service life of structures under environmental exposure. **DOI:** 10.1061/(ASCE)MT.1943-5533.0000553. *© 2013 American Society of Civil Engineers.*

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Introduction

Engineered cementitious composites (ECC) are a new class of composite materials that exhibit high ductility and durability. Its micromechanical design, based on controlled matrix fracture toughness, effective fiber bridging, and optimized fiber-matrix interface properties, is the reason for its high durability and ductility (Li 1998; Lin and Li 1997; Lin et al. 1999). Its supremacy with respect to ordinary concrete and fiber-reinforced concrete (FRC) is primarily its flexural and tensile performance that is designed to exhibit a strain-hardening property and high tensile strain capacity between the ranges of 3–5%, which is approximately 300–500× greater than that of ordinary concrete (Li 1998; Li et al. 2001; Li 2003). Furthermore, in contrast with ordinary concrete and most FRC, ECC exhibits self-controlled crack widths. Such cracks remain less than 100 μm in width under increasing loads regardless of the ultimate tensile strain, and have a volumetric fiber content of approximately 2% (Li 1998; Lin et al. 1999). The tight crack widths and high tensile ductility of this construction material are the key parameters of its high durability with respect to severe environmental conditions.

A mixture proportion of ECC is determined in accordance with the micromechanical design principles to satisfy strength and energy criteria and attain a high composite tensile ductility through the use of individual ingredient properties (Li 1998; Lin and Li 1997; Lin et al. 1999; Yang and Li 2006). To impart the desired interfacial properties and exhibit multiple cracking and a high tensile ductility, a standard ECC mixture (termed M45) exhibits a relatively low water-to-cementitious material ratio (W/CM). Furthermore, the W/CM of an ECC mixture should be low to attain an adequate plastic viscosity value that enables a uniform distribution of fibers, and hence adequate tensile strength and tensile ductility (Yang et al. 2009; Fischer and Li 2003; Lepech and Li 2005). Fiber bridging in an ECC mixture is developed as an interfacial bond that is built up with respect to time. Because of the low W/CM and high quantity of cementitious materials in the mixture, ECC exhibits high autogenous shrinkage. High autogenous shrinkage together with insufficient interfacial bonding that may not provide enough fiber bridging at early ages, bring about early age cracking. This is a problematic issue for ECC. Internal and external restraints yield tensile stresses inside the material and given that the material is insufficiently ductile at early ages to tolerate these stresses, cracks

[1]Assistant Professor, Dept. of Civil Engineering, Mugla Sitki Kocman Univ., 48000 Mugla, Turkey; formerly, Ph.D. Candidate, Dept. of Civil Engineering, Middle East Technical Univ., Ankara, Turkey.

[2]M.Sc. Student, Dept. of Civil Engineering, Gaziantep Univ., Gaziantep 27310, Turkey.

[3]Associate Professor, Dept. of Civil Engineering, Gaziantep Univ., Gaziantep 27310, Turkey (corresponding author). E-mail: sahmaran@gantep.edu.tr

[4]Professor, Dept. of Civil Engineering, Middle East Technical Univ., Ankara 06800, Turkey.

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larger than 100 μm may open up easily. Because ECC matrix is too dense to enable water transport, conventional curing methods are unsatisfactory to prevent early-age cracking (Bentz and Snyder 1999). Internal curing, through the use of presoaked and saturated lightweight aggregates (LWA), is one of the most commonly used methods of mitigating early-age autogeneous shrinkage. In this method, normal-weight aggregates are replaced with presoaked lightweight aggregate (LWA) for internal curing. This method has been reported in the literature, especially for mitigating the shrinkage deformation of low W/CM high-performance concrete (Sahmaran et al. 2009; Hammer 1992; Takada et al. 1992; Bentur et al. 2001; Duran-Herrera et al. 2007; Akçay and Taşdemir 2009; Lura et al. 2004).

Different types of natural and artificial LWA materials that exhibit a significant internal porosity may be used as containers for internal curing water. Sahmaran et al. (2009) applied internal curing by using volcanic pumice aggregate as presoaked LWA to decrease ECC autogeneous shrinkage. In their paper, the water that was retained in presoaked volcanic pumice aggregate, with respect to ECC mixtures with a fly ash–portland cement ratio (FA/PC) of 1.2, was insufficient to completely eliminate autogenous shrinkage; however, it did significantly reduce its magnitude. This may be attributed to the inadequate water absorption capacity of the volcanic pumice aggregate, which had a water absorption capacity of 31.3% at 24 h under water at 20°C. From the standpoint of the effectiveness in mitigating autogenous shrinkage by internal curing, the water absorption capacity of LWA should be as high as possible. This paper reports on an investigation of the effect of expanded perlite aggregate replacement as presoaked LWA on the dimensional stability and mechanical properties of ECC. The W/CM and fly ash-to-cement ratio of ECC that were used in the research were kept constant for all of the mixtures (0.27 and 1.2, respectively). Relative to the volcanic pumice with a similar aggregate gradation, expanded perlite aggregate is significantly more effective in terms of moisture content after prewetting. Three replacement levels of presoaked LWA with normal-weight siliceous sand (10, 20, and 30%) were investigated. Dimensional stability properties, restrained shrinkage, drying shrinkage, and autogeneous shrinkage of the ECC mixtures were determined along with the compressive and flexural performance, and compared with the standard ECC mixture that did not contain any presoaked LWA.

Experimental Program

Materials and Mixture Proportions

The ingredients of the produced standard ECC mixture were CEM I 42.5-R-type [European Committee for Standardization (CEN) (2000)] portland cement [similar to *ASTM C150/C150M-12* (ASTM 2012b) Type I]; fly ash [Class F in accordance with *ASTM C618a* (ASTM 2012a)]; polycarboxylate ether-type high-range water reducer (HRWR) with a specific gravity of 1.1 and 40% solid content; siliceous sand with a maximum size aggregate (MSA) of 0.4 mm, water absorption capacity of 0.3%, and specific gravity of 2.60; and polyvinyl alcohol (PVA) fibers (8 mm length, 39 μm diameter), with a nominal tensile strength of 1,610 MPa and specific gravity of 1.3, as reported by the manufacturer. The surfaces of the PVA fibers were coated with 1.2% by weight of hydrophobic oil to reduce the bond strength between the matrix and fiber for strain-hardening performance (Li et al. 2002). Table 1 presents the chemical and physical properties of the cementitious materials. Fig. 1 presents the particle size distributions of the cementitious materials and aggregates that the writers used for this paper.

Table 1. Chemical and Physical Properties of Portland Cement and Fly Ash

Chemical composition and physical properties	Cement	Fly ash
CaO (%)	61.43	1.64
SiO_2 (%)	20.77	56.22
Al_2O_3 (%)	5.55	25.34
Fe_2O_3 (%)	3.35	7.65
MgO (%)	2.49	1.80
SO_3 (%)	2.49	0.32
K_2O (%)	0.77	1.88
Na_2O (%)	0.19	1.13
Loss on ignition (%)	2.20	2.10
Specific gravity	3.06	2.31
Blaine fineness (m^2/kg)	325	290

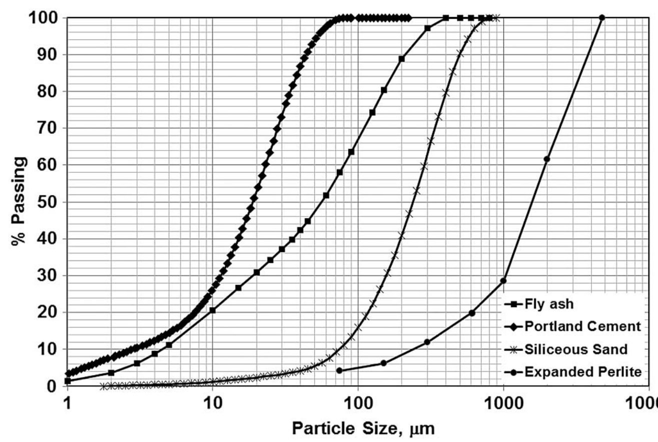

Fig. 1. Particle size distributions of portland cement, fly ash, and aggregates

The lightweight aggregate that the writers report in this paper was commercially produced expanded perlite. Perlite is a siliceous volcanic glass, the volume of which can expand substantially when heated. The perlite consisted primarily of approximately 75 and 13% SiO_2 and Al_2O_3, respectively. When heated above 900°C, its volume increases up to 35× that of the original volume. As a result of this volume increase, the absorption of the expanded perlite aggregate is significantly large. The expanded perlite aggregate had a water absorption capacity of 80 and 144% (by mass) at 1 and 24 h, respectively. Moreover, the specific gravity of the expanded perlite aggregate at saturated surface dry conditions is very small (0.850). Fig. 1 presents the particle size distribution of the expanded perlite aggregate. The particle size ranges from 0.1–5 mm, and it has a quasi-spherical shape. To investigate the effect of presoaked LWA on the dimensional stability and mechanical properties of ECCs, the writers prepared a control mixture without any LWA replacement and three different ECC mixtures with 10, 20, and 30% replacement levels of 24-h presoaked LWA (by weight) (Fig. 2). The mixture proportion of a standard ECC mixture (M45) with properties that have been extensively reported in the literature was used as a reference in the ECC mixture design (Lepech and Li 2005; Sahmaran et al. 2009). In accordance with the extent of internal curing (IC) provided by LWA replacement, LWA replacement levels were also designated as low, medium, and high IC for 10, 20, and 30% replacement levels, respectively. Table 2 presents designations and the proportions of ingredients that the writers used in the mixture design.

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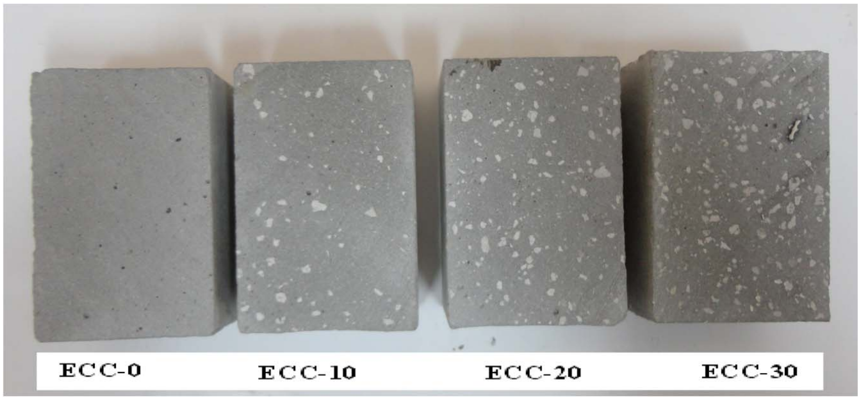

Fig. 2. Typical view of LWA distribution throughout the cross sections

Given that the LWA replacement is a function of weight, the aggregate-paste ratio of the ECC mixtures increases with the increase in LWA replacement rate, which is in the range of 21–34%. Therefore, the shrinkage test results should be interpreted by considering the change in the aggregate-paste ratio of the ECC mixtures. The quantity of HRWR was arranged to obtain a mixture with a consistency that enabled uniform distribution of the fibers and workability. The HRWR quantity has a slight effect on shrinkage properties (Roncero et al. 2000; Tawaza and Miyazawa 1995). Given that the quantity of HRWR varies in the range of 0.3 kg/m^3 for the ECC mixtures that are reported in this paper, the effect of HRWR can be considered to be ineffective. The total W/CM ratio of all of the mixtures was kept constant (0.27). The total effective W/CM of all of the mixtures was also calculated by taking the water supplied by internal curing into consideration (Table 2). The writers kept the quantity of the PVA fibers constant (2% by volume), which was anticipated through micromechanical design analysis of ECC to ensure superior tensile properties. Table 2 reports unit weights of the mixtures.

Test Specimen Preparation and Testing

In the research reported in this paper, compressive and flexural strengths of the ECC mixtures were determined at the test ages of 28 and 90 days in addition to the flexural deformations. Furthermore, the matrix (ECC without PVA fiber) fracture toughness of the mixtures was determined at the age of 28 days. For compressive strength tests, 12.50-mm^3 specimens were prepared. For flexural strength and fracture toughness tests, six $360 \times 50 \times 75$-mm prism specimens were cast for each test and testing age. Specimens were demolded 24 h after casting stored in plastic bags at $95 \pm 5\%$ relative humidity (RH), $23 \pm 2°C$, for 7 days, and moisture-cured by preventing moisture transfer from or to the system. For flexural strength determination, prismatic specimens were loaded under four-point bending loading. Specimens were placed on two supports that were 304 mm away from each other and loaded symmetrically from two loading points 101 mm apart on a closed-loop testing system with a loading rate of 0.005 mm/s. For all of the flexural testing specimens, the writers attached a linear variable differential transformer (LVDT) to the specimen, and through the use of a data acquisition system, load and deflection data were collected simultaneously during the tests.

Table 2. ECC Mixture Proportions

Constituent	Quantity (kg/m^3) ECC-0, no IC	ECC-10, low IC	ECC-20, medium IC	ECC-30, high IC
Total water (W)	332	323	313	303
Portland cement (C)	559	542	525	510
Fly ash (FA)	671	651	631	612
Quartz sand	446	385	332	282
LWA (perlite)	0.0	43	83	121
PVA fiber	26.0	26.0	26.0	26.0
HRWR[a]	4.00	4.00	3.90	3.70
Volumetric mass	2,038	1,973	1,913	1,857
Total[b]	0.27	0.27	0.27	0.27
Internal curing (IC)[b]	0.00	0.02	0.04	0.06
Effective[b]	0.27	0.29	0.31	0.33
LWA/total sand	0.00	0.10	0.20	0.30

[a]Unlike the other quantities, HRWR is in units of kilograms.
[b]In reference to the formula W/(C+FA).

The prismatic specimens (dimensions $360 \times 75 \times 50$ mm) that were used for matrix fracture toughness were comprised of the same ingredients, except the PVA fibers. There is no standard test method with respect to measuring the fracture toughness of cementitious materials. The writers adopted the standard test method *ASTM E399* (ASTM 2003) in the research that is reported in this paper. This standard has previously been implemented in cementitious materials with a maximum aggregate size ≤1 mm, as used in this research, and justified based on the relatively small process zone size relative to laboratory specimen size (Li et al. 1995). For each mixture, the writers prepared six prisms with 30-mm deep notches, created with a diamond saw immediately prior to the experiments, for each testing age. These samples were then tested in a three-point bending configuration at a loading rate of 0.002 mm/s. After this test, the fracture toughness of the matrix (K_Q) was then calculated in accordance with following formula:

$$K_Q = \frac{P_Q S}{BW^{3/2}} \cdot f\left(\frac{a}{W}\right) \tag{1}$$

where P_Q = ultimate load; S = span width; B = specimen height; W = specimen depth; a = notch depth; and $f(\frac{a}{w})$ is a geometric calibration factor that varies between 1.91 and 2.18 in accordance with the exact depth of the specimens (Li et al. 1995).

The writers conducted autogenous shrinkage measurements by using shrinkage drains that were linear prismatic molds (Fig. 3). A shrinkage drain is comprised of an inner and outer mold. The inner mold (dimensions $1{,}000 \times 60 \times 90$ mm) is located inside the outer mold. The writers covered the interior surfaces of the inner mold with Teflon sheets to minimize friction. One end of the mold was free, in which a LVDT was attached for length change measurements (Fig. 3). A similar autogenous shrinkage test setup was also used by Wei (2008) for autogenous shrinkage measurements. A thermocouple that was under the inner mold monitored

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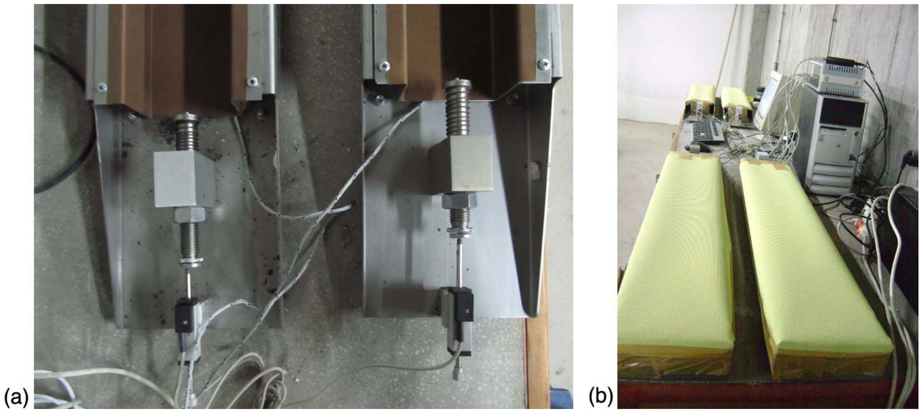

Fig. 3. Autogenous shrinkage test setup

the temperature variations during the tests. Before pouring ECC mixtures inside the drain, aerosol Teflon was sprayed over the Teflon sheet and the inner surfaces were covered with another layer of plastic sheet, which was used to cloth all of the surfaces of the fresh mixture after placing. Given that the fresh ECC mixture has a low viscosity and high consistency, to prevent the loss of fresh material and bleed water, the open end of the drain was closed with styrofoam. A small metal plate that was brought in contact with the LVDT during the test was attached on the interior side of this styrofoam. After placing the fresh mixture inside the drain, the top surface of the fresh mixture was immediately closed with the plastic sheet. The top surface of the drain was then covered with another sheet of Teflon. Given that the setting time of a fibrous cementitious mixture cannot be accurately determined with conventional test methods, for the first 12 h only temperature measurements were taken. After 12 h, the styrofoam that was placed to close the open end of the drain to hold the fresh mixture was removed, and the metal plate was brought in contact with the rod surrounded with a spring which is connected to the LVDT. The LVDT and temperature measurements were both started afterwards. The maximum heat that was measured on a specimen was taken as the initial reading, which was approximately 16 h after placing the fresh mixtures into the drains. The length changes of the autogenous shrinkage specimens were monitored every 10 min with a data acquisition system during the first 28 days. Shrinkage drains were kept in an isolated room that was equipped with an air conditioning system at a fixed ambient temperature at 23 ± 2°C. Two replicates of the specimens were cast for autogenous shrinkage measurements of each mixture.

For the drying shrinkage tests, the writers used $285 \times 25 \times 25$-mm bar specimens. Drying shrinkage measurements were conducted in accordance with the standard *ASTM C157/C157M-08* (ASTM 2008). For each ECC mixture, six specimens were cast and after 24 h inside the molds, the specimens were demolded and stored in lime-saturated water for 27 days. Afterwards, the specimens were stored at 23 ± 2°C and $50 \pm 5\%$ RH throughout the test. The writers measured the length changes of the specimens for 112 days after moist curing, in addition to the change in the weights of the specimens every day for the first week and once each week after the first week until the end of the test with a digital comparator.

The restrained shrinkage ring test was in accordance with *AASHTO PP-34-99.66* (1999). The writers used steel restrained shrinkage rings to evaluate the effect of LWA replacement on the dimensional stability of ECC. This setup consists of two concentric steel rings comprised of a rigid steel tube, in which the fresh ECC mixtures were cast in between to form a ring that is 25.4 mm thick and 140 mm high. The inside diameter, height, and thickness of the inner steel ring were 280, 140, and 12.5 mm, respectively. Following the placement of fresh mixtures between the rings, the outer ring was removed after 24 h to enable drying from the outer circumferential surface of ECC ring, which was kept at 23 ± 2°C and $50 \pm 5\%$ RH. Immediately after removing the outer ring, the top surface of the ECC ring was covered with a silicone-based sealant. The short curing time and early-age testing were intended to reflect in situ performance. The onset time of cracking, increase in the crack width, and number of cracks was monitored for 28 days. The writers conducted measurements through use of a hand-held portable microscope with an accuracy of 5 μm every 24 h from three different points on a crack. Two replicates of ring specimens were cast for each mixture and tested for shrinkage cracking behavior to derive reliable conclusions.

Results and Discussion

Compressive Strength

Table 3 presents the results of the compressive strength tests performed at 28 and 90 days in accordance with *ASTM C39/C39M-12a* (ASTM 2012c). The results are the averages of six specimens of each ECC mixture for each testing age. Table 3 indicates that the increase with respect to the presoaked LWA content significantly decreases the compressive strength. However, the lowest

Table 3. Fundamental Mechanical Properties of the ECC Mixtures

	ECC-0		ECC-10		ECC-20		ECC-30	
Mechanical properties	28 days	90 days	28 days	90 days	28 days	90 days	28 days	90 days
Compressive strength (MPa)	60.8	72.9	53.6	61.8	48.6	58.7	39.8	49.1
Flexural strength (MPa)	12.5	12.7	10.9	11.2	9.2	9.8	8.7	9.5
Midspan deflection (mm)	4.52	4.04	5.29	5.10	5.42	5.28	4.58	4.45
Matrix fracture toughness ($\mathrm{MPa \cdot m^{1/2}}$)	0.742	—	0.597	—	0.496	—	0.468	—

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28-day compressive strength is 39.8 MPa, which reveals that even 30% presoaked LWA replacement yields a suitable concrete for most civil engineering applications. Because of the improved interfacial transition zone (ITZ), enhanced hydration, and absence of shrinkage cracks, LWA replacement is expected to increase the compressive strength, as in the studies that were conducted with pumice aggregate as saturated LWA with high-performance concrete (Lura et al. 2004). However, in this paper, there is nearly a 35% decrease between the control and ECC-30 specimens. Expanded perlite-type LWA replacement has a negative effect on the compressive strength of ECC mixtures. This effect can be attributed to large aggregate sizes, which aggravate the compact aggregate size distribution and significantly reduce the strength of the expanded perlite with respect to siliceous sand and pumice, which has been used as LWA (Lura et al. 2004). The replacement levels of presoaked LWA with normal-weight siliceous sand in this paper are significantly higher than those in the research of Lura et al. (2004). Larger aggregate particles of perlite aggregate relative to siliceous sand may also behave as stress concentrators in which the cracks are likely to initiate during loading. Additionally, large aggregate particles may hinder the uniform distribution of fibers and cause fiber bundles, which act as voids. Another possible reason for the lower compressive strength results with respect to higher LWA replacement is the greater local water-to-cement ratio in the interfacial transition zone, which is attributable to a higher maximum aggregate size with respect to siliceous sand and consequently the lower compressive strength (Mehta and Monteiro 2006). However, when the compressive strength development is taken into consideration, the increase in compressive strengths of specimens between 28 and 90 days were 19.9, 15.2, 20.6, and 23.4% for ECC-0, ECC-10, ECC-20, and ECC-30, respectively. This increase may be related to the continuing pozzolanic reaction with the presence of moisture that was provided by internal curing of presoaked LWA.

Flexural Performance

A four-point bending test was used to evaluate the flexural performance of ECC mixtures by means of flexural strength (modulus of rupture [MOR]), ultimate midspan beam deflection capacity and flexural stress-midspan beam deflection curves. For a strain-hardening material, deflection capacity under bending load can be correlated with tensile strain capacity in a direct manner (Qian and Li 2007). Table 3 represents the flexural strength and midspan beam deflections of ECC beams as averages of six specimens. Fig. 4 presents typical flexural stress-midspan beam deflection curves for each ECC mixture at test age of 28 days. All of the ECC mixtures exhibited strain-hardening behavior. There is a significant drop of flexural strength as the level of presoaked LWA replacement increases, which can be attributed to large aggregate sizes and the low strength of expanded perlite, which act as a stress concentrator and hinders the uniform fiber distribution, as noted previously. Furthermore, bundling of the fibers results in inadequate coating of the fibers by the matrix and reduces the fiber-matrix bonding, thereby decreasing the flexural load-carrying capacity. Considering the flexural strength development, the increase in flexural strength between 28 and 90 days was 1.8, 2.3, 5.9, and 8.2% for ECC-0, ECC-10, ECC-20, and ECC-30, respectively; this is very low relative to compressive strength development. Given that the tensile properties are primarily in accordance with fiber and fiber-matrix interface properties in addition to fiber volume, the development in matrix properties therefore has a limited effect on flexural strength. Furthermore, the highest flexural strength development was observed on the ECC-30 specimen, which may also be correlated with the expected beneficial effects of LWA replacement, as noted in the compressive strength results.

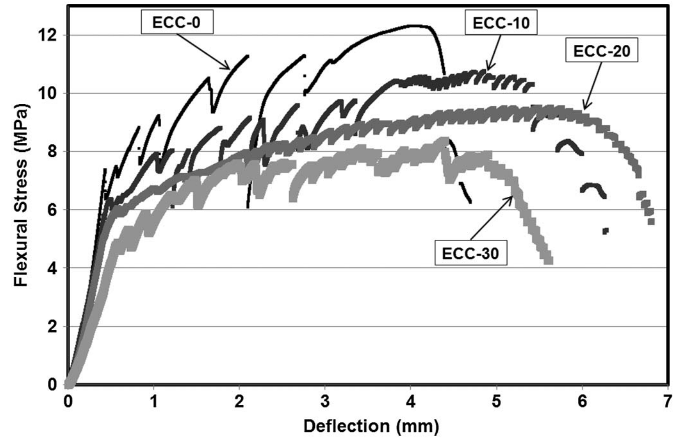

Fig. 4. Typical flexural stress-midspan beam deflection curves of the ECC mixtures at an age of 28 days

The first crack strength is defined as the point at which the stress-midspan beam deflection curve deviates from linearity. As indicated by Fig. 4, the first crack strength of the ECC mixtures decreases as the LWA replacement level increases. The stiffness of the ECC beams can be represented by the slope of the initial elastic portion of the stress-midspan beam deflection curves. The slope decreases significantly with the increase in LWA replacement level, which is contrary to literature results (Cetin and Carrasquillo 1998; Baalbaki et al. 1991; Aïtcin and Mehta 1990). The decrease in stiffness of the ECC beams with the increase in expanded perlite aggregate replacement level can be attributed to the same reasons as those noted previously for the decrease in the compressive strength test results.

As noted previously, given that midspan beam deflection can be directly correlated with the tensile strain capacity of a strain-hardening material, it reflects the level of ductility of the material. For all of the mixtures tested, there was a slight drop in the midspan deflection capacity with respect to time. This might be attributable to development of matrix and fiber-matrix interfacial properties. This drop in the ductility is likely to be limited with respect to time and reach a stable state as the maturity of the matrix stabilizes. As indicated by Table 3 and Fig. 4, the presoaked LWA replacement level was also effective on midspan beam deflection capacities. Up to the replacement level of 20%, the positive effect of presoaked LWA replacement is obvious. However, 30% replacement decreased the midspan beam deflection capacity, which was still higher than that of the control specimen. There is an optimum level of presoaked LWA replacement to obtain maximum ductility. The increase in midspan beam deflection capacity of ECC-10 and ECC-20 specimens can be attributed to the decrease in matrix fracture toughness, which will be discussed in a subsequent paragraph. Although the writers observed the lowest 28-day matrix fracture toughness in ECC-30, the corresponding midspan deflection is not the highest. The reason for this discrepancy may be the poor fiber distribution that was caused by the large quantity of coarser presoaked LWA replacement.

Fracture Toughness

As indicated by Table 3, matrix fracture toughness decreased as the level of internal curing increased. For instance, 10% LWA replacement decreased the fracture toughness 20%. This indicates that the energy required to open a crack on the ECC-10 matrix

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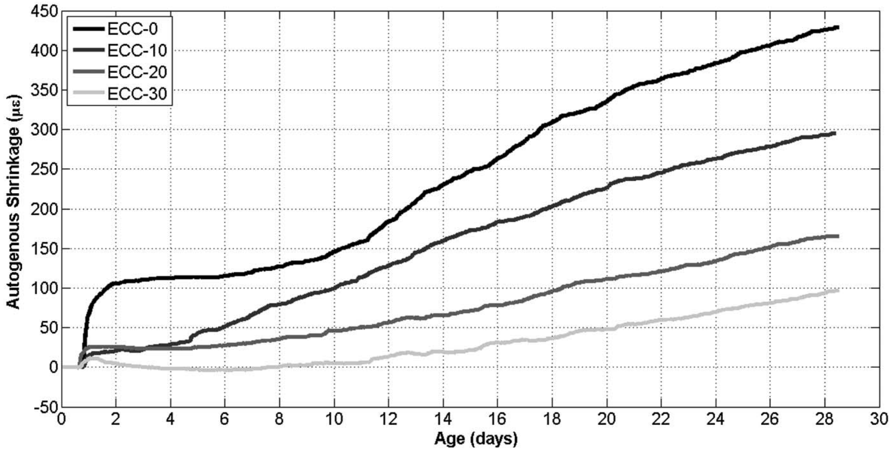

Fig. 5. Autogenous shrinkage of ECC mixtures with respect to time

specimen was nearly 20% lower than that of the control specimen. The decreases in fracture toughness values were 33 and 37% for the mixtures that had LWA replacement rates of 20 and 30%, respectively. The reason behind the lower fracture toughness values with incorporation of a higher LWA replacement rate may be correlated with the matrix maturity. Even if it was expected that the increase in LWA quantity would increase the maturity of matrix because of internal curing and further hydration considerations, the writers observed a similar trend for fracture toughness results as in compressive strength because there is a direct correlation between them. It is well-known that when concrete is loaded, cracks tend to propagate along the weaker zone or big pores in the matrix (Mehta and Monteiro 2006). As the crack meets a LWA particle, it can easily propagate through the weaker LWA. For ECC mixtures that incorporate presoaked LWA, the LWA was weaker than the rest of the matrix. Cracks therefore tended to propagate easily through the LWA particles. Consequently, when the LWA volume increases, a greater number of weak LWA particles are available in the path of crack, which results in a smoother cracking path and less energy required for cracking, and therefore lower values of fracture toughness. Given that a higher matrix toughness could be detrimental to achieving the desired mechanical properties and reduce the tendency to develop multiple cracking (Li et al. 1995), the use of LWA in ECC production should be helpful for achieving strain-hardening behavior (Davis and Alexander 1989, 1992; De Larrard and Belloc 1997).

Autogenous Shrinkage

Fig. 5 presents the results of autogenous shrinkage measurements for the ECC mixtures. The coefficient of variations (COV) of all of the autogenous shrinkage test results is less than 3%. Autogenous shrinkages were 441, 295, 166, and 97 $\mu\varepsilon$ for ECC-0, ECC-10, ECC-20, and ECC-30, respectively, at the end of 28 days. Relative to autogenous shrinkage of a standard ECC mixture that was measured by Sahmaran et al. (2009), the test results indicate that the standard ECC mixture tested in this study exhibit a significantly lower autogenous shrinkage than a 28-days-old specimen. The values of autogenous shrinkage that the writers found in the literature (Sahmaran et al. 2009) were determined with a different test method and ingredients with different chemical and physical properties.

As seen from Fig. 5, the control ECC mixture experienced an instantaneous shrinkage within several days after the initiation of the test, at which it reached approximately 25% of its total measured autogenous shrinkage. Thus, the early-age autogenous shrinkage should not be overlooked, because the ECC is most susceptible to cracking at early ages; this is attributable to its low fiber-matrix interface frictional bond. This weak interface bonding can potentially generate lower fiber-bridging stress, which can result in a low ultimate tensile strength and tensile strain capacity. After a week the writers observed another ascending trend. Until the end of the autogenous shrinkage measurements, the writers observed a slight concavity in the plot as the hydration reaction slows with respect to time. As seen from Fig. 5, incorporation of presoaked LWA had a significant effect on the autogenous shrinkage strain of ECC. As the level of LWA replacement increases, autogenous shrinkage decreased drastically. The contribution of LWA replacement can be observed at both early and late ages, which is evidence of its positive effect on autogenous shrinkage. Autogenous shrinkages of ECC-10 and ECC-20 are both approximately 25 $\mu\varepsilon$ at the end of 3 days, whereas it is greater than 100 and 10 $\mu\varepsilon$ for ECC-0 and ECC-30, respectively. As the level of LWA replacement increases, the concave portion of the diagram becomes a line. Furthermore, up to between days eight and nine, instead of shrinkage, ECC-30 exhibited swelling as a result of high internal curing. The test results of all of the ECC mixtures also indicate that the autogenous shrinkage phenomenon did not stabilize after 28 days. This point could be attributed to the secondary hydration that was caused by pozzolanic reaction of the fly ash.

Restrained Shrinkage Cracking

Restrained shrinkage cracking is a critical problem in concrete construction. Free shrinkage tests alone cannot offer sufficient information with respect to the behavior of concrete structures because virtually every concrete structure is restrained in some manner, either by reinforcement or the boundary condition of the structure. In this paper, the writers used the method of the ECC ring cast next to a rigid steel ring to simulate restrained shrinkage cracking. Fig. 6 presents the development of the average crack widths of the tested ECC mixtures under restrained shrinkage tests. Table 4 also summarizes the restrained shrinkage test results. Table 4 indicates that each mixture exhibited some degree of multiple cracking. Cracks have widened quickly in several days following the first crack formation, and it stabilized afterwards. Fig. 6 illustrates that the standard ECC mixture began to crack after 5 days, and ECC mixtures that incorporated presoaked LWA after 6—7 days in accordance with the LWA replacement rate. The benefit of using LWA was immediately obvious in the observed increase in the age of first cracking. Moreover, the average width of the cracks decreased in accordance with LWA replacement.

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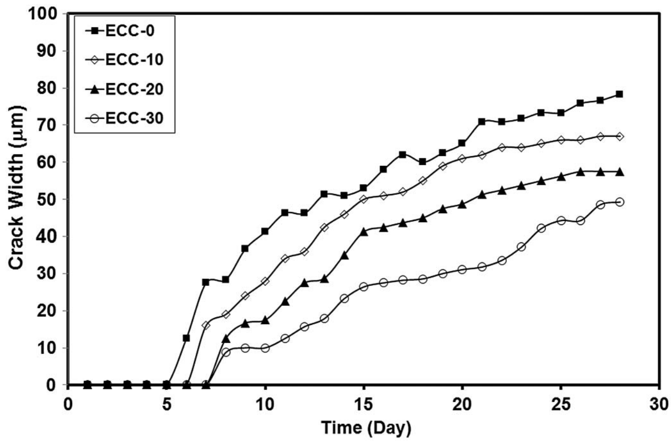

Fig. 6. Development of crack width in the restrained specimens with respect to time

Table 4. Restrained Shrinkage Crack Characterization of the ECC Mixtures

Mixture ID	Crack width (μm)			Number of cracks
	Average	Minimum	Maximum	
ECC-0	78	40	100	7
ECC-10	67	30	95	9
ECC-20	58	30	75	11
ECC-30	49	25	60	13

Furthermore, the presoaked LWA replacement resulted in a greater number of cracks. Therefore, presoaked LWA replacement had a significant effect on the restrained shrinkage cracking performance and improved the dimensional stability of ECC mixtures. Such consequences may be the result of lower matrix fracture toughness and higher midspan beam deflection capacity; these in turn can be considered as a measure of the ductility that was attained by presoaked LWA replacement. However, when the total crack width (number of cracks multiplied by the average crack width) of ECC mixtures are compared (Table 4), LWA replacement slightly increases the total crack width of the ECC mixtures. This can be attributed to the increased drying shrinkage capacity of ECC mixtures with the addition of presoaked LWA (discussed in a subsequent section). The maximum width of an individual crack, rather than the total crack width, is the primary factor that affects the durability and self-healing capability of cementitious composites (Sahmaran and Li 2009).

Drying Shrinkage

The writers evaluated the effects of presoaked LWA replacement on the free drying shrinkage of ECC mixtures with the goal of establishing guidelines to reduce cracking in ECC. Fig. 7 presents the average drying shrinkages and weight loss of three specimens of ECC mixtures that were developed in this research. The COV values for the drying shrinkage test results ranged from 3.8–5.9%. The specimens were cured 28 days under lime-saturated water and subjected to drying afterwards for 16 weeks (until the hygral equilibrium state), in accordance with *ASTM C157/C157M-08* (ASTM 2008). The drying shrinkage strains at the age of 112 days ranged between 1,233 and 1,391 $\mu\varepsilon$. The standard ECC mixture without presoaked LWA (ECC-0) exhibited the lowest drying shrinkage of

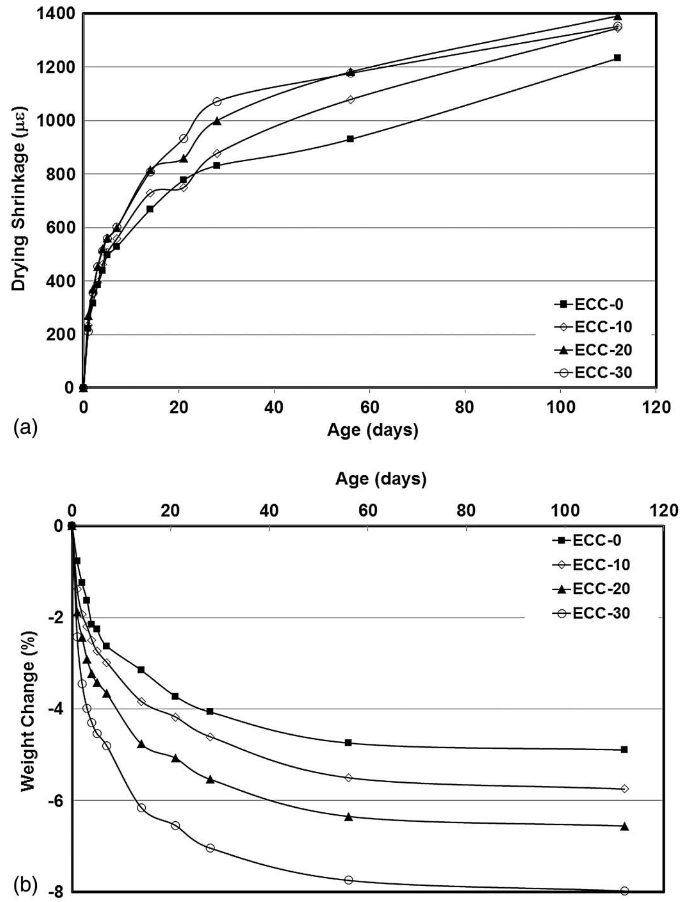

Fig. 7. Drying shrinkages and weight changes of the ECC mixtures with respect to time

1,233 $\mu\varepsilon$ at the end of 112 days. In contrast with the autogenous and restrained shrinkage, as seen from Fig. 7, the drying shrinkage of the specimens was not significantly affected by presoaked LWA replacement. The addition of presoaked LWA slightly increased the free-drying shrinkages of ECC mixtures. Zhang et al. (2005) suggested that the drying shrinkages of normal weight and lightweight aggregates would be similar, and when exposed to drying, LWA containing concrete would exhibit lower shrinkage because of its lower autogenous shrinkage. This controversy can probably be attributed to the greater water loss from ECC to the environment, which induces higher drying shrinkage when the presoaked LWA replacement ratio is increased. This was confirmed by the increased mass loss of the ECC with an increasing presoaked LWA ratio [Fig. 7(b)]. This is valid at all ages and the difference increases with age. Although the W/CM of all of the mixtures was kept constant, the effective W/CM ratios were 0.27, 0.29, 0.31, and 0.33 for ECC-0, ECC-10, ECC-20, and ECC-30 respectively, which is attributable to the high absorption capacity of the expanded perlite aggregate. Therefore, the effective water content should be considered during drying shrinkage measurement evaluation.

A comparison of Fig. 7(a) with Fig. 7(b) indicates that even though the ECC mixtures that incorporated presoaked LWA lost more water, the drying shrinkage values at 112 days can be accepted as virtually the same or slightly different. For example, the drying shrinkage of ECC-30 is similar to ECC-10 and lower than ECC-20; however, the percent weight change of ECC-30 is higher than ECC-10 and ECC-20. This would indicate that free shrinkage is related with other factors in addition to weight loss. One possible explanation may be that ECC which incorporates

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presoaked LWA has a lower autogenous shrinkage that may partially compensate for the increased drying shrinkage. The drying shrinkage may be somewhat different from the actual drying shrinkage in real structures because of size effects. Size should have some effects on the shrinkage. According to Bazant and Baweja (1995), a larger member requires much more time for shrinkage effects to reach its interior regions. Thus, larger members have a lower rate and total magnitude of shrinkage. Therefore, the results should be interpreted with care.

Conclusions

In this paper, the writers reported the effects of presoaked LWA replacement on the mechanical properties and dimensional stability of engineered cementitious composites. Presoaked expanded perlite as a LWA was replaced by 10, 20, and 30% by weight of the siliceous sand. The writers produced a similar mixture without replacement of LWA to compare the tested properties. The compressive strength, flexural strength, midspan beam deflection capacity, matrix fracture toughness, drying shrinkage, autogenous shrinkage, and restrained shrinkage of the ECC mixtures were determined. The writers present the following conclusions:

- Presoaked LWA replacement has a negative effect on compressive strength. This can be a collective result of large aggregate size and low strength of LWA with respect to siliceous sand. However, compressive strength development with respect to age is better for mixtures that contain presoaked LWA, which can be attributed to the better hydration, itself attributable to internal curing.
- Fracture toughness of ECC matrices decreases with the increase in presoaked LWA replacement ratio. Lower fracture toughness indicates a lower energy to onset a crack, which is beneficial for multiple cracking in accordance with the micromechanical-based design theory of ECC.
- Under flexural loading, all of the ECC mixtures exhibited strain-hardening behavior. However, flexural strengths were inversely proportional with the LWA replacement levels, which were attributed to weak LWA particles. However, the deflection capacity of the ECC increased with the LWA replacement level up to 20%. Although the lowest 28-day matrix fracture toughness was observed in ECC-30, the midspan deflection was not the highest. The reason for this discrepancy may be the poor fiber distribution that was caused by the large quantity of coarser presoaked LWA replacement. Therefore, at a 30% LWA replacement rate, the negative effect that is attributable to a lack of fiber distribution outweighs the positive effect that is attributable to the decrease in matrix fracture toughness.
- Autogenous shrinkage of ECC mixtures, both at early and late ages, were significantly affected by the LWA replacement. The writers observed an approximately 78% decrease in the autogenous shrinkage strain at the age of 28 days for ECC-30, which reveals that presoaked expanded perlite aggregate replacement can be used to almost eliminate autogenous shrinkage in ECC.
- Presoaked expanded perlite type LWA replacement improves the dimensional stability of ECC mixtures that were measured with a restrained shrinkage test. The first crack onset time and number of the cracks increased, whereas the average crack widths decreased as the presoaked LWA replacement level increased. This may be attributed to the greater ductility and dimensional stability (by reducing autogenous shrinkage) with presoaked LWA replacement.
- Drying shrinkage of the ECC specimens that incorporated presoaked LWA was slightly greater than the control specimens. The greater rate of measured free shrinkage can likely be attributed to the increased effective W/CM ratio with the increase in presoaked expanded perlite aggregate replacement rate.

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