Cement and Concrete Research 39 (2009) 893–901

Contents lists available at ScienceDirect

Cement and Concrete Research

journal homepage: http://ees.elsevier.com/CEMCON/default.asp

Internal curing of engineered cementitious composites for prevention of early age autogenous shrinkage cracking

Mustafa Şahmaran [a], Mohamed Lachemi [b,*], Khandaker M.A. Hossain [b], Victor C. Li [c]

[a] Department of Civil Engineering, Gaziantep University, Gaziantep, Turkey
[b] Department of Civil Engineering, Ryerson University, Toronto, ON, Canada
[c] Department of Civil and Environmental Engineering, Michigan University, Ann Arbor, MI, United States

ARTICLE INFO

Article history:
Received 24 October 2008
Accepted 9 July 2009

Keywords:
Autogenous shrinkage
Drying shrinkage
Engineered cementitious composites (ECC)
Internal curing
Uniaxial tensile test
Flexural test

ABSTRACT

This investigation was carried out to study the effects of using a replacement percentage of saturated lightweight fine aggregate (LWA) as an internal curing agent on the shrinkage and mechanical behavior of Engineered Cementitious Composites (ECC). ECC is a micromechanically-based, designed high-performance, fiber-reinforced cementitious composite with high ductility and improved durability due to tight crack width. Standard ECC mixtures are typically produced with micro-silica sand (200 μm maximum aggregate size). Two replacement levels of silica sand with saturated LWA (fraction 0.59–4.76 mm) were adopted: the investigation used 10 and 20% by weight of total silica sand content, respectively. For each LWA replacement level, two different ECC mixtures with a fly ash-to-Portland cement ratio (FA/PC) of 1.2 and 2.2 were cast. In a control test series, two types of standard ECC mixtures with only silica sand were also studied. To investigate the effect of replacing a portion of the silica sand with saturated LWA on the mechanical properties of ECC, the study compared the results of uniaxial tensile, flexure and compressive strength tests, crack development, autogenous shrinkage and drying shrinkage. The test results showed that the autogenous shrinkage strains of the control ECCs with a low water-to-cementitious material ratio (W/CM) (0.27) and high volume FA developed rapidly, even at early ages. The results also showed that up to a 20% replacement of normal-weight silica sand with saturated LWA was very effective in reducing the autogenous shrinkage and drying shrinkage of ECC. On the other hand, the partial replacement of silica sand with saturated LWA with a nominal maximum aggregate size of 4.76 mm is shown to have a negative effect, especially on the ductility and strength properties of ECC. The test results also confirm that the autogenous shrinkage and drying shrinkage of ECC significantly decreases with increasing FA content. Moreover, increasing FA content is shown to have a positive effect on the ductility of ECC.

1. Introduction

The recent trend in concrete technology towards so-called High-Performance Fiber-Reinforced Cementitious Composites (HPFRCC) with a low water-to-cementitious material ratio (W/CM) is characterized by superior tensile properties and enhanced durability against severe environmental conditions. Engineered Cementitious Composite (ECC) is a recently developed HPFRCC designed with micromechanical principles [1–3]. Micromechanics allows optimization of the composite for high performance – represented by extreme tensile strain capacity – while minimizing the amount of reinforcing fibers, typically less than 2% by volume. Unlike ordinary cement-based materials, ECC strain-hardens after first cracking, similar to a ductile metal, and demonstrates a strain capacity 300–500 times greater than normal concrete (Fig. 1). Even at large imposed deformation, the crack widths of ECC remain small (less than 60 μm) (Fig. 1). The tight crack width in hardened ECC is a result of controlled matrix fracture toughness and effective fiber bridging provided by the micro polymer fibers and optimized fiber/matrix interface properties. This fiber bridging is quantified through the stress versus crack opening relation (σ-δ relation), which develops with time as a result of interfacial bond build-up. In most cases, prior to applying mechanical loads to the material, the σ–δ relation has already developed enough to resist any localized cracking.

Because ECC is different from conventional concrete, the W/CM is a more important parameter. In standard ECC mix design, a low W/CM has been determined (through micromechanics) to satisfy proper interface properties. Increasing W/CM can reduce cementitious particle concentration, resulting in relatively loose microstructure, and therefore introducing a lower interface frictional bond [4]. This weak interface bonding can potentially generate lower fiber-bridging stress, which can result in low ultimate tensile strength and tensile strain capacity. In addition, W/CM has the most significant influence on the plastic viscosity of ECC mortar [5]. A high W/CM can substantially decrease the plastic viscosity of ECC mortar and may

* Corresponding author. Tel.: +1 416 979 5000x6465; fax: +1 416 979 5308.
E-mail address: mlachemi@ryerson.ca (M. Lachemi).

0008-8846/$ – see front matter © 2009 Elsevier Ltd. All rights reserved.
doi:10.1016/j.cemconres.2009.07.006

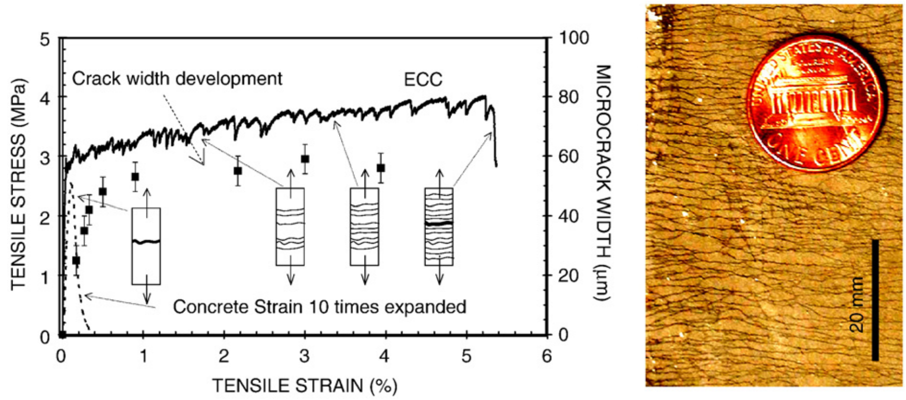

Fig. 1. Typical tensile stress-strain curve and crack width development of ECC.

result in poor fiber distribution, and low ultimate tensile strength and tensile strain capacity. Therefore, based on past experience [6,7], a reasonable W/CM should be in the range of 0.25 ± 0.05.

Because of their very low W/CM ($\leq$0.30), one of the major problems with ECC mixtures is their increased tendency to undergo early-age cracking, which is a consequence of increased autogenous shrinkage. Typically, strong fiber bridging associated with strong interfacial bond development provides strong resistance to cracking, and once mechanical loads are applied to the material, the crack bridging stress versus crack opening (σ–δ) relation has already developed enough to resist any localized cracking. At early ages, however, the σ–δ curve has not been fully developed to withstand internal stresses caused by the external and internal restraints, and thus insufficient tensile strain and autogenous deformation may lead to the formation of some microcracks (>100 μm). While this cracking may or may not compromise the mechanical properties of composites, it may affect their long-term durability. Traditional external curing techniques are not effective in eliminating early age cracking, since water transportation into the ECC is hindered by the tightness of the matrix [8]. A potentially effective strategy to overcome this problem is the use of pre-soaked lightweight aggregates (LWA) as internal water reservoirs. Several studies on this topic have been published in recent years, and have generally been focused on mitigating autogenous shrinkage by replacing normal weight aggregates with saturated lightweight aggregate (LWA) [9–14]. In those studies, internal curing by means of pre-soaked LWA has been effective in reducing autogenous shrinkage in high performance concrete with a low water-to-cement ratio.

The literature proposes different methods of internal curing, however, no information is currently available on the effect of internal curing with pre-soaked LWA on the performance of ECC. This study investigates the development of autogenous and drying shrinkages of ECC mixtures having a W/CM of 0.27, when pre-soaked LWA are included for internal curing. The experimental program includes several variables — 10% and 20% replacements of normal-weight silica sand with an equal weight of pre-soaked LWA (made of porous volcanic pumice aggregate) and two different fly ash (FA) replacement levels with a FA/PC of 1.2 and 2.2. Additionally, the effects of including pre-soaked LWA on the uniaxial tensile and flexural properties, ductility, crack development and compressive strength of ECC were evaluated.

2. Experimental investigations

2.1. Materials and mixture proportions

The materials used in the production of standard ECC mixtures were Type-I Portland cement (PC), Class-F fly ash (FA) with a lime content of 5.57%, normal-weight micro silica sand with an average and maximum grain size of 110 μm and 200 μm respectively, water, polyvinyl-alcohol (PVA) fibers, and a polycarboxylic-ether type high range water reducing admixture (HRWR) with a solid content of approximately 30%. Chemical composition and physical properties of Portland cement and fly ash are presented in Table 1. The PVA fibers – with a diameter of 39 μm and a length of 8 mm – are purposely manufactured with a tensile strength (1620 MPa), elastic modulus (42.8 GPa), and maximum elongation (6.0%) matching those needed for strain-hardening performance. Additionally, the surface of the PVA fibers is coated with a proprietary oiling agent 1.2% by mass to tailor the interfacial properties between fiber and matrix for strain-hardening performance [15].

The lightweight aggregate (LWA) used was volcanic pumice sand, which was initially sieved and divided into different fractions to obtain optimum efficiency for internal curing. From the point of view of the effectiveness in mitigating autogenous shrinkage, the water absorption capacity of LWA should be as high as possible, and its size should be as fine as possible [16]. The optimum efficiency was achieved with volcanic pumice LWA of size in the range of 0.59 to 4.76 mm. The same aggregate with finer size was significantly less effective in terms of water absorption. The saturated-surface-dry (SSD) weight of pumice was measured according to ASTM C128-97 and the maximum absorption was determined. The LWA of the fraction between 0.59 and 4.76 mm has an SSD specific gravity of 1.33 after 24 h absorption, and a measured absorption capacity of 31.3% by mass as measured by drying an SSD sample. The particle size distributions of the silica sand and LWA are presented in Fig. 2, which shows that the LWA has significantly coarser grading than the silica sand.

In order to investigate the influence of internal curing with saturated LWA on the performance of ECC, six ECC mixtures having a constant W/CM of 0.27 were designed in the present study. The water content in HRWR was also accounted for in the calculation of W/CM.

Table 1
Chemical composition and physical properties of Portland cement and fly ash.

Chemical composition, %	Cement	Fly ash
CaO	61.80	5.57
SiO_2	19.40	59.50
Al_2O_3	5.30	22.20
Fe_2O_3	2.30	3.90
MgO	0.95	–
SO_3	3.80	0.19
K_2O	1.10	1.11
Na_2O	0.20	2.75
Loss on ignition	2.10	0.21
Physical properties		
Specific gravity	3.15	2.18
Retained on 45 μm (0.002 in.), %	12.9	9.6
Water requirement, %	–	93.4

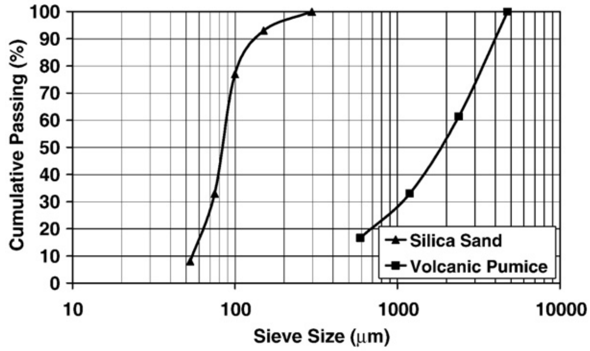

Fig. 2. Sieve analysis of volcanic pumice and silica sands.

The designation and components of the mixtures are provided in Table 2. The variable parameters in these mixtures were the LWA replacement level and FA replacement level (FA/C of 1.2 and 2.2 by weight, respectively). Two replacement levels of silica sand with SSD LWA (fraction 0.59–4.76 mm) at 10 and 20% by weight of total silica sand content were adopted. In a control test series, two types of standard ECC mixtures with only silica sand and an FA/PC of 1.2 (ECC1_0) and 2.2 (ECC2_0) by mass were also studied. All mixtures were prepared using a standard mortar mixer, and the amount of cementitious materials (cement + fly ash) was held constant. HRWR was added to the mixture until the desired fresh ECC characteristics were visually observed; as a result, the HRWR admixture content was not kept constant, and was observed to change between 1.8 and 2.3 kg/m^3 (Table 2). Previous studies have shown that, in general, the incorporation of HRWR slightly affects the drying shrinkage whereas it does not have any influence on the swelling and autogenous shrinkage [17,18]. Moreover, the effects of the HRWR dosage are minor on autogenous shrinkage of cement paste [18]. Therefore, it can be accepted that the ECC mixtures produced for this study had nearly the same HRWR content, and varying HRWR requirement is not a factor on the measured shrinkage capacities of ECC.

As seen in Table 2, ECC mixtures with an FA/PC of 1.2 had higher HRWR demand than ECC mixtures with an FA/PC of 2.2. The smooth surface characteristics and spherical shape of the FA improved the workability characteristics of ECC mixtures, so that similar workability properties at constant W/CM were achieved by using a lower HRWR content at higher FA replacement level.

2.2. Test specimen preparation, testing and basic properties

From each mixture, six 50-mm cubic specimens were prepared for the compressive strength test, eight 203 × 76 × 13 mm coupon specimens were prepared for the direct tensile test and six 355 × 50 × 76 mm prism specimens were prepared for the four-point bending test. The density of hardened ECC at 28 days was also measured for all mixes, which ranged from 2373 kg/m^3 to 2199 kg/m^3. The replacement of the normal weight silica sand with saturated LWA up to 20% by weight led to a reduction of unit weight of up to 100 kg/m^3, as demonstrated in Table 3.

All specimens were demolded at the age of 24 h, and moist cured in plastic bag at 95 ± 5% RH, 23 ± 2 °C for 7 days. The specimens were then air cured in laboratory condition at 50 ± 5% RH, 23 ± 2 °C until the age of 28 days. Direct tensile tests were conducted using an MTS machine with 25-kN capacity under displacement control at a rate of 0.005 mm/s. Prior to testing, aluminum plates were glued to both ends of the coupon specimen to facilitate gripping. After direct tensile testing, all residual crack widths were also measured in the unloaded stage. Crack widths were measured on the surface of the specimens using a portable microscope. A four-point bending test was also performed under displacement control at a loading rate of 0.005 mm/s on a closed-loop controlled servo-hydraulic material test system. The span length of flexural loading was 304.8 mm with a 101.6 mm center span length. During the flexural tests, the load and the mid-span deflection were recorded on a computerized data recording system.

Autogeneous shrinkage measurements were made on all ECC mixtures. After casting, specimen surfaces were coated with a curing membrane to prevent water from evaporating. The autogeneous shrinkage of three 285 × 25 × 25 mm bars was measured up to 28 days after an initial curing of 16 ± 0.5 h in the mould for all ECC mixtures. Immediately after demolding, the autogenous shrinkage specimens were sealed with two layers of adhesive aluminum tape to prevent moisture loss, and specimen length was measured immediately. This value was regarded as the initial length during calculation of the autogeneous shrinkage. The specimens were stored in a controlled room at a temperature of 23 ± 2 °C, and a relative humidity of 50 ± 4% during testing. Changes in length and mass were measured daily for the first week, and then weekly until the age of 28 days. The mass changes of the sealed specimens remained relatively constant over time (less than 0.07% of the weight at 16 ± 0.5 h. during this test) demonstrating that the sealing method was very effective in preventing moisture loss.

Temperature changes in ECC specimens can cause thermal expansion and contraction, which can have significant effects on autogenous shrinkage measurements [19]. For this reason, the temperature variations in the ECC mixes were also measured. Measurements were taken at the center of the 150 × 300 mm cylinder of fresh ECC that had been placed in an autogenous curing chamber along with a temperature logger immediately after casting. After mixing, the temperature of all ECC mixtures was about 25 °C. It was continuously monitored for the first 72 h after mixing to characterize the quantitative heat of hydration for each mixture (Fig. 3). The maximum temperature rise measured for all ECC mixtures during that time period are shown in Table 3. As seen in this table, the maximum temperature rise for ECC mixtures with an FA/PC of 1.2 ranged from 22.0 to 24.4 °C, and the maximum rise for ECC mixtures with an FA/PC of 2.2 was considerably lower, ranging from 13.1 to 15.6 °C. This difference demonstrates the potential of the high volume FA–ECC system for reducing temperature increase in massive members, owing

Table 2
Mixture composition of ECCs.

Mix ID	ECC1_0	ECC1_10	ECC1_20	ECC2_0	ECC2_10	ECC2_20
Cement, kg/m^3	558	549	540	375	369	363
Fly ash, kg/m^3	669	659	649	823	811	798
Water, kg/m^3	326	321	316	318	313	309
PVA, kg/m^3	26	26	26	26	26	26
Sand (dry), kg/m^3	446	395	345	435	386	338
Pumice sand (SSD), kg/m^3	–	44	86	–	43	85
HRWR, kg/m^3	2.3	2.3	2.2	2.0	1.9	1.8
FA/PC	1.20	1.20	1.20	2.20	2.20	2.20
W/CM[a]	0.27	0.27	0.27	0.27	0.27	0.27
W/CM (including water in pumice)	0.27	0.28	0.29	0.27	0.28	0.29

[a] CM: Cementitious Materials (Cement + Fly Ash).

Table 3
Properties of ECCs.

FA/PC	Mix ID	Temperature rise, °C	Density at 28 days, kg/m^3	Compressive strength at 28 days., MPa
1.2	ECC1_0	22.5	2373	62.5
	ECC1_10	24.4	2320	58.9
	ECC1_20	22.0	2278	53.9
2.2	ECC2_0	15.6	2301	54.1
	ECC2_10	14.3	2256	45.0
	ECC2_20	13.1	2199	40.7

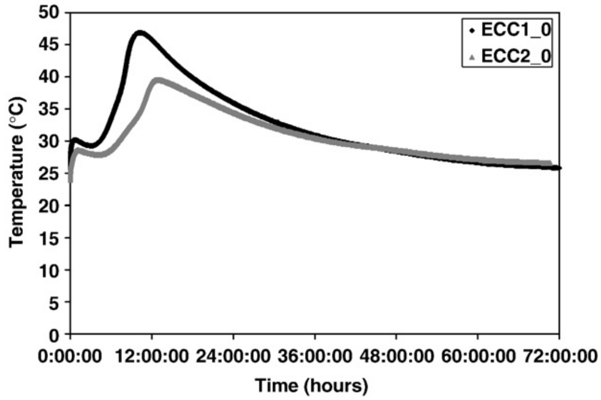

Fig. 3. Typical temperature development with time from ECC mixing.

to its low cement content and the slow pozzolanic activity of the low lime fly ash. On the other hand, the temperature data in Table 3 show no definite trends of maximum temperature increase with a saturated LWA replacement ratio.

Drying shrinkage measurements were also made on all ECC mixtures. The drying shrinkage of three 285×25×25 mm bars was measured up to 90 days after an initial curing of one day in the mould and 27 days in lime saturated water in accordance with ASTM C157 for all ECC mixtures. The drying shrinkage specimens were stored in a drying room at 23±2 °C, and at 50±4% relative humidity.

3. Results and discussions

3.1. Autogenous shrinkage

Fig. 4 is a plot of the free autogenous shrinkage of ECC mixtures measured from 16 h after mixing as a function of age up to 28 days. Each point in Fig. 4 represents the average free autogenous shrinkage measurements of three specimens. The results show that most of the autogenous shrinkage caused by internal self-desiccation developed within the first week of hydration. This effect appears to decrease after one week as the hydration process slows down with time. This observation, therefore, suggests that the prevention of excessive self-desiccation and autogenous shrinkage cracking in ECC structures should involve techniques that are effective for at least one week after mixing.

As clearly seen in Fig. 4, all ECC mixtures with an FA/PC of 2.2 showed significantly lower autogenous shrinkage at given ages compared with the ECC mixtures with an FA/PC of 1.2 at the same W/CM; the higher the FA replacement percentage, the lower the autogenous shrinkage. At the age of 28 days, when the pre-soaked LWA percentage was either 0, 10 or 20%, autogenous shrinkage of ECC2 specimens was lower (between 21 and 58%) compared with the ECC mixtures with an FA/PC of 1.2. This reduction in autogenous shrinkage can be attributed to a dilution effect caused by a reduction in cement content because part of the PC was replaced by FA [20]. When FA is used as a supplementary cementitious material in ECC, not only does it lead to less hydration, but the pozzolanic reaction can only occur when calcium hydroxide is present as a by-product from the cement hydration. In the case of ECC2, the amount of PC is only about 30% of the total cementitious material content. Combined with the low W/CM of 0.27, it limits the production of calcium hydroxide from the cement hydration process that is needed to activate the pozzolanic reaction of FA. An alternative mechanism contributing to the reduction of autogenous shrinkage is that unhydrated FA particles serve as an inert inclusion that restrains the shrinkage deformation. Based on the scanning electron microscope observation, a larger amount of unhydrated fly ash particles is observed in ECC2 specimens (Fig. 5) compared with ECC1 at the end of 28 days curing. In addition, since FA retains much more free water than cement particles due to particle shape characteristics, the autogenous shrinkage reduction noted in the case of higher volume of FA–ECC mixtures (ECC2) can also be attributed to the availability of more free water in their matrix. As seen in Table 2, the ECC mixture with the lower FA/PC content (1.2) resulted in a higher HRWR demand. Since autogenous shrinkage is the result of water consumption due to cement hydration, the larger free water content results in less autogenous shrinkage. Another reason for the observed lower autogenous shrinkage in the presence of a higher amount of FA may also be the maintenance of a more open pore structure containing larger pores [21]. This has been proved from the pore structure test results presented in Fig. 6. Mercury intrusion porosimetry (MIP) test were used to obtain information about the pore structure, including the porosity and pore size distribution of ECC mixtures. The figure clearly indicates that the increase of FA content significantly increased the porosity in almost all pore ranges.

The effects of pre-soaked LWA replacement level on the autogeneous shrinkage of ECC are also shown in Fig. 4. In each case, the partial replacement of silica sand by SSD LWA provides a significant reduction in the observed autogenous deformation during the first 28 days of sealed curing. With increased amounts of pre-soaked LWA used in the ECC specimens, the free autogenous shrinkage is further reduced. For the ECC mixtures with an FA/PC of 2.2, internal curing with 20% pre-soaked LWA replacement (ECC2_20) nearly eliminates the autogenous shrinkage (microstrains of less than 250 at 28 days). On the other hand, for the ECC mixes with an FA/PC of 1.2 and 20% pre-soaked LWA (ECC1_20) substantial autogenous shrinkage is observed (591 με after 28 days of sealed curing). Therefore, the water retained in pre-soaked LWA – especially in the case of ECC mixtures with an FA/PC of 1.2 (ECC1) – was not sufficient to

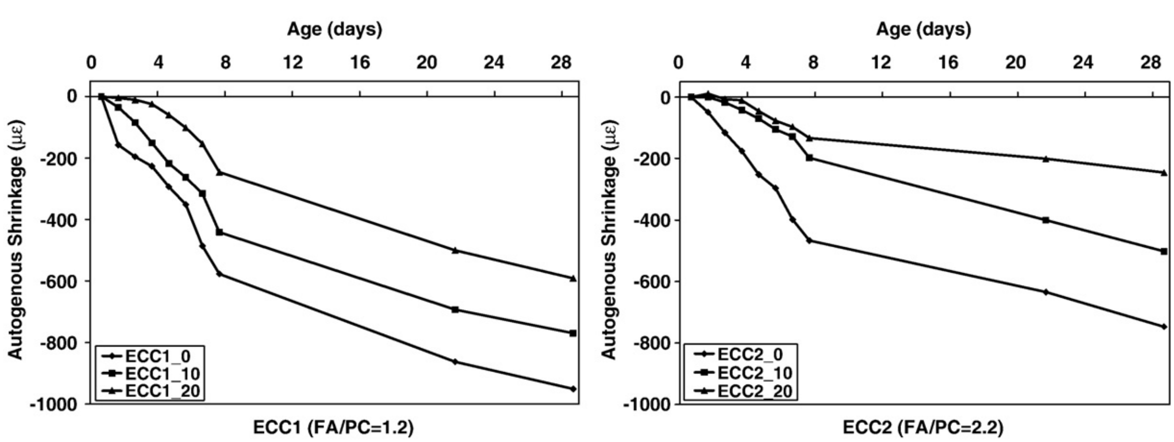

Fig. 4. Autogenous shrinkage development of ECC containing various replacement percentages of FA and LWA.

Fig. 5. SEM micrograph of ECC2_0 specimens after 28 days curing.

eliminate autogenous shrinkage, although it did significantly reduce its magnitude. The greater rate of shrinkage of ECC1 at early ages can likely be attributed to the greater cement content, which is accompanied by a considerably larger amount of heat and thus rate of hydration (Fig. 3). Moreover ECC specimens with an FA/PC of 2.2 including pre-soaked LWA showed slight early expansion, which is also frequently reported in the literature [11,12]. While the mechanisms of internal curing contributing to a reduction in autogenous shrinkage are well known, the mechanisms leading to an early-age expansion are not well understood. The expansion was most likely due to the crystallization pressure caused by the ettringite formation and/or swelling of the gel hydration products, which are generally considered as a principal cause of early-age expansion [22,23]. Additional mechanisms responsible for the observed early-age expansion may also be considered that re-absorption of bleed water may also lead to swelling [24]. No external bleeding was observed in the present research, but the occurrence of internal bleeding might be present.

3.2. Drying shrinkage

The results of drying shrinkage testing at the age of 90 days are shown in Fig. 7. Each value in Fig. 7 represents the average drying shrinkage measurements of three specimens. The ECC mixtures produced for this study had the same W/CM, so a varying water requirement was not a factor for drying shrinkage. The drying shrinkage strains at the age of 90 days ranged from 859 to 1698 micro-strain. As in autogenous shrinkage, ECC mixtures with an FA/PC of 1.2 without internal curing (ECC1_0) exhibited the highest drying shrinkage of 1698 microstrain at the end of 90 days. The general trend in Fig. 7 shows that the increase in the FA content can effectively

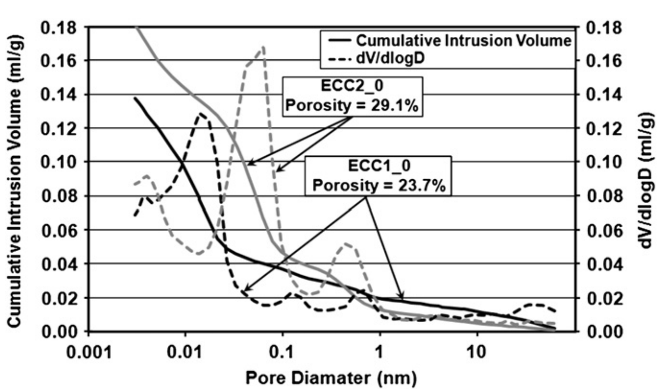

Fig. 6. Pore size distributions of ECC1_0 and ECC2_0 after 28 days curing.

reduce free drying shrinkage deformation. Similar results have been reported for high volume FA concrete [25]. In the present study, a reduction of up to 20% of drying shrinkage depending on the pre-soaked LWA replacement rate was found when the FA/PC ratio was increased from 1.2 to 2.2. A possible mechanism contributing to the reduction of drying shrinkage in ECCs is unhydrated fly ash particles, which serve as fine aggregates to restrain the shrinkage deformation [25–27].

As in the case of autogenous shrinkage, the advantage of substituting part of the silica sand with pre-soaked LWA can also clearly be seen in Fig. 7. The substitution of 10 and 20% silica sand by pre-soaked LWA (regardless of FA/PC) leads to a reduction of up to 28% and 37% of drying shrinkage at the ages of 90 days, respectively. According to Zhang et al. [28], the drying shrinkage of lightweight and normal-weight aggregate concrete is similar, and the lower shrinkage of lightweight aggregate concrete exposed to a dry environment is due to its lower autogeneous shrinkage compared with that of normal-weight concrete. Therefore, the water absorbed by the LWA can also contribute internally to the curing of the ECC even after 28 days and compensate for water loss when the drying shrinkage specimens are stored in a drying room at 23 ± 2 °C, and 50 ± 4% humidity.

3.3. Compressive strength

Table 3 presents the average of the compressive strength as determined from six cubic specimens at the age of 28 days according to the procedure described in ASTM C39. As seen in Table 3 and as expected, the compressive strength of ECC mixtures decreased with increasing FA content. However, even at about 70% replacement of cement with FA (FA/PC = 2.2) (ECC2), the compressive strength of ECC at 28 days is still more than 40 MPa, considered more than adequate for many structural applications.

With plain high performance concrete (HPC), in spite of the fact that pumice is much weaker than the normal weight silica sand it substitutes, the compressive strength of HPC containing saturated LWA is expected to produce higher strength than HPC mixtures with normal-weight fine silica [14]. This is due to improvement of the interfacial transition zone, enhanced hydration because of internal curing, and absence of shrinkage-induced microcracking. However, as seen in Table 3, the compressive strength of ECC mixtures incorporating saturated LWA was lower than that for control ECC mixtures with silica sand (ECC1_0 and ECC2_0). These results also indicate that increasing the replacement level of LWA from 10 to 20% at a constant FA/PC further reduced the ECC compressive strength. Therefore, unlike conventional concrete, in the case of ECC, aggregate characteristics and internal curing negatively influence compressive properties. The higher strength in mixtures with only normal-weight fine silica sand (ECC1_0 and ECC2_0) may be due to the more uniform dispersion of fibers, which is also one of the major reasons for the obtained higher tensile properties in these mixtures (see Sections 3.4 and 3.5). Another possible explanation is that, the light weight pumice aggregate is much weaker than the normal-weight fine silica sand it substitutes. Moreover, the maximum size of LWA is much larger than the silica sand they substitute (up to 4.76 mm in size, vs. 200 µm of the silica sand). The LWA acts as the biggest defects in the matrix where stresses will concentrate and cracking initiate.

3.4. Uniaxial tensile performance

After an initial seven-day moist curing, uniaxial tensile tests were performed on ECC coupon specimens cured in air at 28 days of age to confirm the ductile strain-hardening performance of ECC mixtures containing pre-soaked LWA with a nominal maximum aggregate size of 4.76 mm. Table 4 displays test results in terms of ultimate tensile strength, ultimate tensile strain at the peak stress and residual crack width. Typical stress-strain curves are presented in Fig. 8. To facilitate

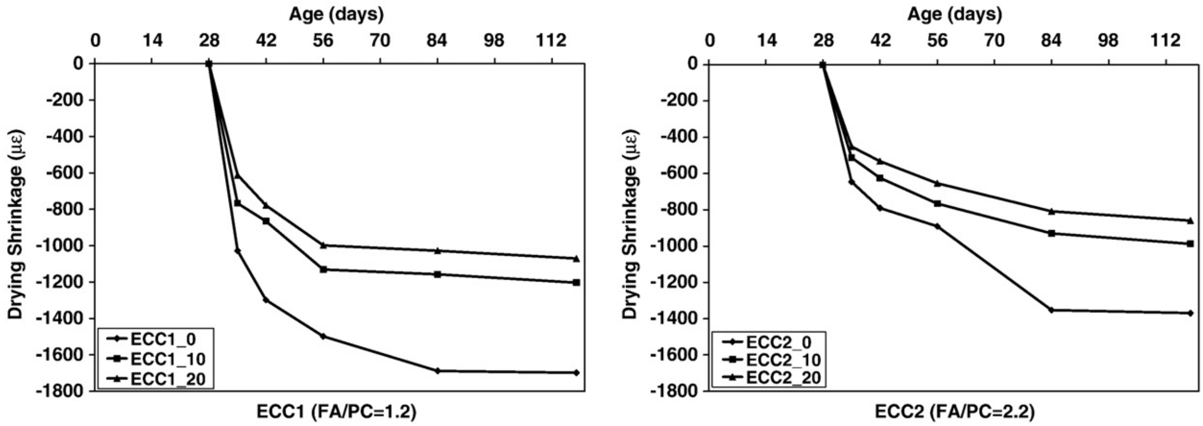

Fig. 7. Drying shrinkage strain versus drying time for ECCs after 28 days moist curing.

the comparison between test results for different ECC mixtures, the same scales for both axes have been used for the graphs. Each result in Table 4 is an average of six to eight specimens. As seen in both Fig. 8 and Table 4, all ECC mixtures developed in this study show strain-hardening behavior with development of multiple cracks with small crack spacing. They show a sustained increase in load capacity beyond the first matrix crack, with strain capacities from 1.64% to 2.99%, which are in the range of 164 to 300 times the ductility of conventional concrete and normal fiber reinforced concrete. Fig. 8 also shows that the first crack strengths vary from 3.0 to 4.5 MPa with the variation of the FA/PC and saturated LWA replacement rate. After the first cracking, the uniaxial tensile load continues to rise accompanied by multiple cracking with small crack spacing and tight crack widths (<0.060 mm). This contributes to the inelastic strain as stress increases; as the tensile strength was approached, one of the cracks started to open up.

As can be demonstrated in Fig. 8, regardless of the pre-soaked LWA replacement level, the increase of the FA/PC ratio from 1.2 to 2.2 significantly improves the tensile strain of ECC at 28 days of age. The improvement in tensile strain can be attributed to the fact that the increase in FA content tends to reduce the PVA fiber/matrix interface chemical bond and matrix toughness, while increasing the interface frictional bond in favor of attaining high tensile strain capacity [29]. On the other hand, the increase in FA content reduces the tensile strength (Table 4). ECC specimens with an FA/PC of 1.2 exhibit a higher ultimate tensile strength (up to 12% higher depending on the LWA replacement ratio), while the ECC specimens with an FA/PC of 2.2 exhibits more ductile behavior. However, even at about 70% replacement of cement by FA (FA/PC = 2.2), the uniaxial tensile strength of ECC at 28 days was not significantly different from that of fiber reinforced concrete.

As shown in Fig. 8, the typical tensile stress – tensile strain curves of ECC specimens containing pre-soaked LWA reveal that the effects of pre-soaked LWA replacement (regardless of FA/PC) on the stress – strain curves, tensile strain (ductility) and tensile strength of the ECC specimen are significant, which is surprising. Tensile strain capacity and uniaxial tensile strength of the ECC mixtures with pre-soaked LWA is lower than that of the control ECC mixtures without LWA (ECC1_0 and ECC2_0), in spite of the fact that the pumice is much weaker than the normal weight silica sand it substitutes. Moreover, as the replacement rate of pre-soaked LWA increases, the tensile properties decrease further. It is widely accepted that the use of LWA generally produces lower fracture energy for plain concrete, and therefore lower matrix toughness [13], which – according to micromechanics theory of ECC – is expected to contribute to the tensile strain capacity. According to micromechanical principles, lower matrix toughness is favorable for strain-hardening [1]. The reduced properties, especially ductility, might be due to the lack of uniform dispersion of fibers. The balling of fibers encouraged by significantly coarser LWA (compared with silica sand at constant sand content) prevents sufficient coating of fibers by the matrix, and thus reduces fiber-to-matrix bonding, which is an important factor influencing ductility. Moreover, even without balling, the fiber dispersion uniformity would still be disturbed by the physical presence of larger aggregates. Fortunately, as discussed above, the increase in the replacement rate of FA in ECC significantly increases tensile ductility. Therefore by adjusting the FA content in ECC mixtures made with the addition of saturated LWA, tensile properties can easily be optimized.

Table 4 also summarizes the effect of FA and saturated LWA replacement level on the residual crack width of ECC mixtures. After unloading, multiple microcracks with a small average crack width and fine crack spacing were observed, as shown in Fig. 9. It was also found that crack width reduces slightly as FA content increases. On the other hand, up to a 20% substitution of silica sand by the pre-soaked LWA did not influence the average residual crack width, which is less than 60 μm for all ECC mixtures studied. Crack width control is of primary importance for many reinforced concrete applications, since there is a close relationship between the mean or maximum crack widths and the durability of the structure. Moreover, the lower magnitude of crack width is expected to promote self-healing behavior, and thus the transport properties in cracked composites [30–37]. Consequently, in the serviceability limit state a mean or maximum crack width of less than about 0.1 mm is usually prescribed [38,39].

Table 4
Uniaxial tensile properties of ECC specimens at 28 days.

FA/PC	Mix ID	Tensile strain, %	Tensile strength, MPa	Residual crack width, μm
1.2	ECC1_0	2.09 ± 0.16	5.13 ± 0.31	~60
	ECC1_10	1.95 ± 0.17	4.65 ± 0.36	~56
	ECC1_20	1.64 ± 0.04	4.16 ± 0.27	~55
2.2	ECC2_0	2.99 ± 0.37	4.59 ± 0.28	~54
	ECC2_10	2.92 ± 0.50	4.27 ± 0.41	~50
	ECC2_20	2.46 ± 0.29	4.07 ± 0.35	~50

3.5. Flexural performance

Table 5 displays the test results of flexural strength (modulus of rupture — MOR) and ultimate mid-span deflection at the peak stress. The typical flexural stress-mid-span deflection curves for different saturated LWA and FA replacement levels of the ECC mixtures are shown in Fig. 10. Each result in Table 4 is the average of four to six specimens.

As seen in Fig. 10, under severe bending load, all ECC beams deforms similarly to a ductile metal plate through plastic deformation.

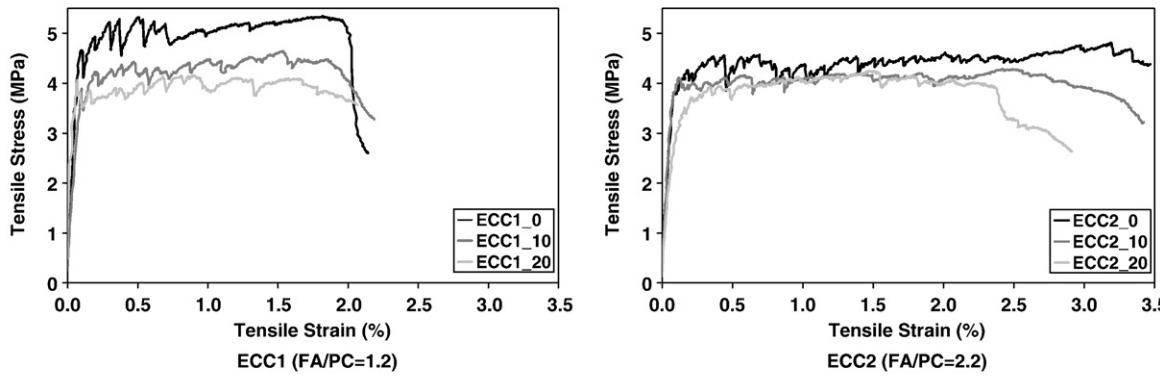

Fig. 8. Typical uniaxial tensile stress–tensile strain curves of ECC mixtures at age of 28 days.

In all ECC specimens, the first crack started inside the mid-span at the tensile face. The flexural stress increased at a slower rate along with multiple cracks with small crack spacing and tight crack widths (<0.1 mm) that developed from the first cracking point and spread. Bending failure in ECC occurred when the fiber bridging strength at one of the microcracks was reached, resulting in localized deformation at this section. As the MOR was approached, one of the cracks inside the mid-span started to open up.

Table 5 shows that the average ultimate flexural loads vary from 10.45 to 12.12 MPa and the total deflection of the ECC beams, which reflects the material ductility, vary from 3.66 to 4.56 mm depending on the FA and saturated LWA replacement levels. The flexural strength test results (Table 5) also show that the load carrying capacity and mid-span beam deflection value of the ECC mixtures with pre-soaked LWA are lower than that of the control ECC mixtures without LWA (ECC1_0 and ECC2_0). Moreover, as the amounts of pre-soaked LWA used in the ECC specimens increase from 10 to 20%, the flexural properties decrease further. For example, the flexural strength and mid-span beam deflection of ECC beams with saturated LWA replacement rate of 20% (ECC1_20 and ECC2_20) are about 90% and 81% that of the control ECC mixtures (ECC1_0 and ECC2_0) without saturated LWA, respectively. The possible reason for this negative effect of saturated LWA has already been discussed in Section 3.4. On the other hand, unlike the uniaxial tensile strength, increasing the FA replacement level from an FA/PC of 1.2 to 2.2 has only a minor effect on the flexural strength and total deflection of the ECC beam. This result may be attributed to the fact that in a flexural test, the response can be either due to the deflection hardening or strain hardening [40], and thus direct uniaxial tensile testing is considered the most convincing method of evaluating material strain-hardening behavior [41]. In bending, the dimensions of the specimen and the chosen set-up also significantly influence the behavior of a test specimen [41]. A thin specimen, for example, is more likely to show deflection hardening than a thick one. In uniaxial tension, the effects associated with non-uniform stress in the specimen section are eliminated. However, this observation requires further investigation before any firm conclusions can be drawn, and will not be discussed further in the present study.

The slope of the load-deflection curve represents the stiffness of the beams. It can be easily noted from Fig. 10 that the slope decreases with increasing saturated LWA content, thereby indicating a reduction in the stiffness of the ECC beams. The first crack load is defined as the load at which the load-deformation response deviated from linearity. For all ECC mixtures, the first crack load increases up to about 70% of the peak load for fiber composites. The increase in saturated LWA replacement ratio from 0 to 20% also reduces the first crack strength by an average of 45%. However, Fig. 10 shows that an increase in the FA/PC from 1.2 to 2.2 had little influence on the magnitude of the first crack loads and stiffness of the ECC beams, at least within the FA/PC ratio-range studied here.

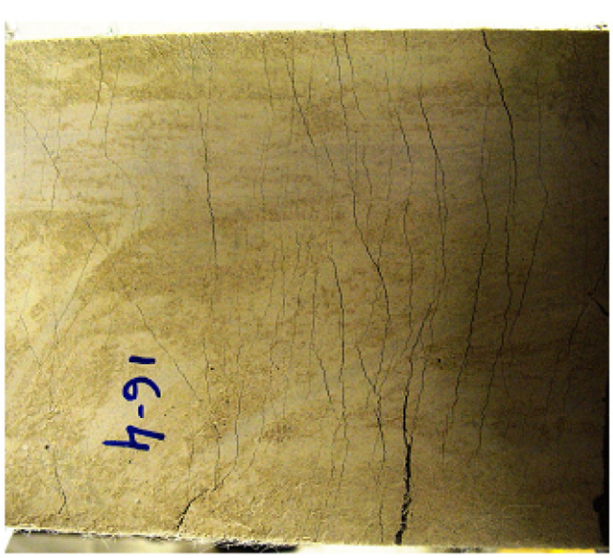

Fig. 9. Typical crack pattern on the surface of ECC coupon after uniaxial tensile load application (ECC2_20).

4. Conclusions

This paper presents the first results of a series of studies being performed to determine the effect of saturated lightweight aggregate (LWA) substitution (10 and 20% by weight of total silica sand) on autogenous shrinkage in a low W/CM Engineered Cementitious Composites (ECC) with two different fly ash contents (FA/PC of 1.2 and 2.2 by weight). Standard ECC mixtures with only normal-weight micro-silica sand were produced for control purposes. Additionally, the drying shrinkage, compressive, flexural and uniaxial tensile

Table 5
Flexural properties of ECC specimens at 28 days.

FA/PC	Mix ID	Flexural strength, MPa	Ultimate deflection, mm
1.2	ECC1_0	12.12 ± 0.86	4.51 ± 0.47
	ECC1_10	10.90 ± 1.37	4.10 ± 0.85
	ECC1_20	10.50 ± 0.27	3.66 ± 0.06
2.2	ECC2_0	11.48 ± 0.92	4.56 ± 0.05
	ECC2_10	10.83 ± 0.12	4.48 ± 0.89
	ECC2_20	10.45 ± 1.12	3.91 ± 0.31

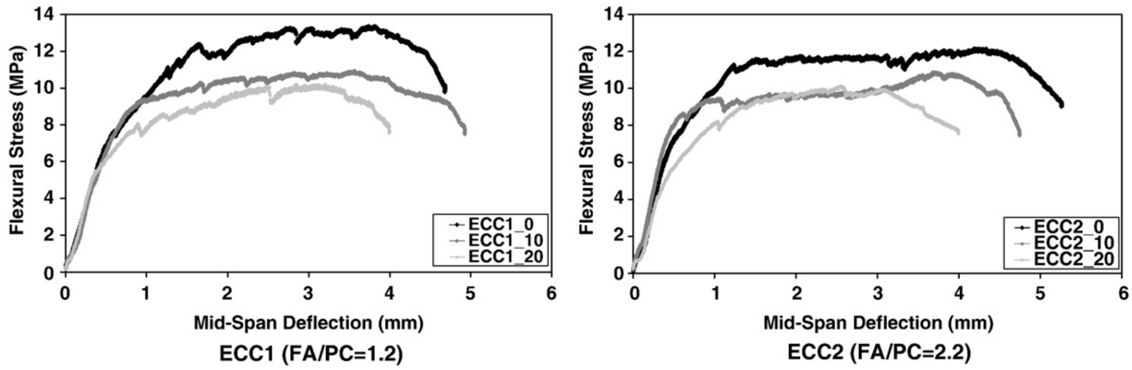

Fig. 10. Typical flexural strength-deflection curves of ECC mixtures at age of 28 days.

properties of these same materials were evaluated. Based on the experimental test results and discussion, the following conclusions can be drawn:

1. The incorporation of internal curing in ECC by the addition of saturated fine LWA is very beneficial in controlling the development of autogenous shrinkage of a 0.27 W/CM ECC. As much as a 67% reduction in autogenous shrinkage relative to control specimens at 28 days can be attained with a 20% substitution of silica sand by saturated LWA. An additional benefit of drying shrinkage reduction of 37% relative to control specimens at 90 days, has also been observed. On the other hand, the ductility and strength properties of ECCs are adversely affected by the partial replacement of normal-weight silica sand with saturated LWA. Nevertheless the observed ~2.0% strain capacity remains acceptable for an ECC, which is almost 200 times greater than the ductility of conventional concrete and normal fiber reinforced concrete.
2. Incorporating FA considerably reduced both autogenous shrinkage and drying shrinkage of ECC; the higher the FA content, the lower the autogenous shrinkage and drying shrinkage. It is hypothesized that the intrinsic characteristics of FA, such as its particle shape, diluent effect (especially at early ages and higher and coarser porosity because of delayed hydration), and inert characteristics at earlier ages, contribute to the reduction of autogenous shrinkage of ECC containing high volume of FA (ECC2). Moreover, increasing the levels of FA (FA/PC of 2.2) leads to further improvements in tensile strain capacity and flexural performance and reductions in crack width compared with the ECC mixture (ECC1–M45) with an FA/PC of 1.2.

Because autogenous shrinkage is one of the main reasons for early-age cracking of low W/CM ECC, it is to be expected that a partial replacement of normal-weight silica sand by saturated fine LWA with high volume FA would reduce such cracking under restraint conditions at an early age. The risk of drying shrinkage cracking may also be reduced due to the incorporation of saturated LWA in the mixture. For a complete understanding of ductility and mechanical performance of ECC containing saturated LWA with different replacement levels, it will be necessary to conduct further research on a micro-mechanical scale to determine changes in ECC matrix toughness and fiber/matrix interface properties, which is beyond the scope of this study.

Acknowledgments

The authors gratefully acknowledge the financial assistance of the Scientific and Technical Research Council (TUBITAK) of Turkey provided under Project: MAG-108M495, the Natural Sciences and Engineering Research Council (NSERC) of Canada, and the Canada Research Chair Program. Support from the U.S. National Science Foundation (NSF CI-Team OCI 0636300) for international collaborative research on ECC is gratefully acknowledged.

References

[1] V.C. Li, ECC — tailored composites through micromechanical modeling, in: Banthia, et al., (Eds.), Fiber Reinforced Concrete: Present and the Future, CSCE, Montreal, 1998, pp. 64–97.
[2] V.C. Li, On Engineered Cementitious Composites (ECC) — a review of the material and its applications, J. Adv. Concr. Tech. 1 (3) (2003) 215–230.
[3] V.C. Li, S. Wang, C. Wu, Tensile strain-hardening behavior of PVA-ECC, ACI Mater. J. 98 (6) (2001) 483–492.
[4] H.J. Kong, S. Bike, V.C. Li, Constitutive rheological control to develop a self-consolidating Engineered Cementitious Composite reinforced with hydrophilic poly(vinyl alcohol) fibers, Cem. Concr. Compos. 25 (3) (2003) 333–341.
[5] E. Yang, M. Şahmaran, Y. Yang, V.C. Li, Rheological control in the production of Engineered Cementitious Composites, ACI Mater. J. 106 (4) (2009) 357–366.
[6] G. Fischer, V.C. Li, Design of Engineered Cementitios Composites (ECC) for processing and workability requirement, vol. 7, BMC, Poland, 2003, pp. 29–36.
[7] M. Lepech, V.C. Li, Durability and long term performance of Engineered Cementitious Composites, Proceedings of International RILEM Workshop on HPFRCC in Structural Applications, Honolulu, Hawaii, 2005, pp. 165–174.
[8] D.P. Bentz, K.A. Snyder, Protected paste volume in concrete — extension to internal curing using saturated lightweight fine aggregate, Cem. Concr. Res. 29 (11) (1999) 1863–1867.
[9] T.A. Hammer, High strength LWA concrete with silica fume — effect of water content in the LWA on mechanical properties, Supplementary Papers in the 4th CANMET/ACI Int. Conf. On Fly Ash, Silica Fume, Slag and Natural Pozzolans in Concrete, Istanbul, Turkey, 1992, pp. 314–330.
[10] K. Takada, K. van Breugel, E.A.B. Koenders, N. Kaptijn, Experimental evaluation of autogenous shrinkage of lightweight aggregate concrete, "Autoshrink'98", Proceedings of an International Workshop, Hiroshima, Japan, E & FN SPON, London, 1999, pp. 221–230.
[11] A. Bentur, S. Igarashi, K. Kovler, Prevention of autogenous shrinkage in high strength concrete by internal curing using wet lightweight aggregates, Cem. Concr. Res. 31 (11) (2001) 1587–1591.
[12] A. Durand-Herrera, P.-C. Aitcin, N. Petrov, Effect of saturated lightweight sand substitution on shrinkage in 0.35 w/b concrete, ACI Mater. J. 104 (1) (2007) 48–52.
[13] B. Akçay, M.A. Tasdemir, Optimisation of using lightweight aggregates in mitigating autogenous deformation of concrete, Const. Build. Mat. 23 (1) (2009) 353–363.
[14] P. Lura, D.P. Bentz, D.A. Lange, K. Kovler, A. Bentur, Pumice aggregates for internal water curing, PRO 36: Proceedings of the International RILEM Symposium on Concrete Science & Engineering - A Tribute to Arnon Bentur, RILEM Publications S.A.R.L, 2004, pp. 137–151.
[15] V.C. Li, C. Wu, S. Wang, A. Ogawa, T. Saito, Interface tailoring for strain-hardening PVA-ECC, ACI Mater. J. 99 (5) (2002) 463–472.
[16] S. Zhutovsky, K. Kovler, A. Bentur, Efficiency of lightweight aggregates for internal curing of high strength concrete to eliminate autogenous shrinkage, Mater. Struct. 35 (2) (2002) 97–101.
[17] J. Roncero, R. Gettu, I. Carol, Effect of chemical admixtures on the shrinkage of cement mortars, Proc. 14th Engineering Mechanics Conference, American Society of Civil Engineers, EM2000, CD-ROM, 2000.
[18] E. Tazawa, S. Miyazawa, Influence of cement and admixture on autogenous shrinkage of cement paste, Cem. Concr. Res. 25 (2) (1995) 281–287.
[19] S.N. Lim, T.H. Wee, Autogenous shrinkage of ground-granulated blast-furnace slag concrete, ACI Mater. J. 97 (5) (2000) 587–593.
[20] H.K. Lee, K.M. Lee, B.K. Kim, Autogenous shrinkage of high-performance concrete containing fly ash, Mag. Concr. Res. 55 (6) (2003) 507–515.
[21] D.P. Bentz, Internal curing of high-performance blended cement mortars, ACI Mater. J. 104 (4) (2007) 408–414.
[22] D.P. Bentz, O.M. Jensen, K.K. Hansen, J.F. Olesen, H. Stang, C.J. Haecker, Influence of cement particle-size distribution on early-age autogenous strains and stresses in cement-based materials, J. Amer. Cer. Soc. 84 (1) (2001) 129–135.
[23] D.P. Bentz, G. Sant, W.J. Weiss, Early-age properties of cement-based materials: I. Influence of cement fineness, ASCE J. Mat. Civ. Eng. 20 (7) (2008) 502–508.
[24] D. Cusson, Effect of blended cements on effectiveness of internal curing of HPC, Proc., Internal Curing of High-Performance Concretes: Laboratory and Field Experiences, ACI SP-256, American Concrete Institute, Farmington Hills, MI, 2008, pp. 105–120.

[25] M. Şahmaran, İ.Ö. Yaman, M. Tokyay, Development of high volume low-lime and high-lime fly-ash-incorporated self consolidating concrete, Mag. Concr. Res. 59 (2) (2007) 97–106.
[26] M.N. Zhang, Microstructure, crack propagation, and mechanical properties of cement pastes containing high volumes of fly ashes, Cem. Concr. Res. 25 (6) (1995) 1165–1178.
[27] A. Bisaillon, M. Rivest, V.M. Malhotra, Performance of high-volume fly ash concrete in large experimental monoliths, ACI Mater. J. 91 (2) (1994) 178–187.
[28] M.H. Zhang, L. Li, P. Paramasivum, Shrinkage of high-strength lightweight aggregate concrete exposed to dry environment, ACI Mater. J. 102 (2) (2005) 86–92.
[29] S. Wang, V.C. Li, Engineered Cementitious Composites with high-volume fly ash, ACI Mater. J. 104 (3) (2007) 233–241.
[30] M. Şahmaran, M. Li, V.C. Li, Transport properties of Engineered Cementitious Composites under chloride exposure, ACI Mater. J. 104 (6) (2007) 604–611.
[31] M. Şahmaran, V.C. Li, Influence of microcracking on water absorption and sorptivity of ECC, Mater. Struct. 42 (5) (2009) 593–603.
[32] M.D. Lepech, V.C. Li, Water permeability of cracked cementitious composites, Paper 4539 of Compendium of Papers CD ROM, ICF 11, Turin, Italy, March, 2005.
[33] Y. Yang, M.D. Lepech, V.C Li, Self-healing of ECC under cyclic wetting and drying, Proceedings of Int'l Workshop on Durability of Reinforced Concrete under Combined Mechanical and Climatic Loads, Qingdao, China, 2005, pp. 231–242.
[34] M. Li, M. Şahmaran, V.C. Li, Effect of cracking and healing on durability of Engineered Cementitious Composites under marine environment, HPFRCC 5 - High Performance Fiber Reinforced Cement Composites, Stuttgart, Germany, Vol. 10-13, 2007, pp. 313–322.
[35] M. Şahmaran, V.C. Li, Durability of mechanically loaded Engineered Cementitious Composites under high alkaline environment, Cem. Concr. Res. 30 (2) (2008) 72–81.
[36] M. Şahmaran, V.C. Li, De-icing salt scaling resistance of mechanically loaded Engineered Cementitious Composites, Cem. Concr. Res. 39 (5) (2007) 1035–1046.
[37] Y. Yang, M.D. Lepech, E. Yang, V.C Li, Autogenous healing of engineered cementitious composites under wet–dry cycles, Cem. Concr. Res. 39 (5) (2009) 382–390.
[38] C. Evardsen, Water permeability and autogenous healing of cracks in concrete, ACI Mater. J. 96 (4) (1999) 448–454.
[39] H.W. Reinhardt, M. Jooss, Permeability and self-healing of cracked concrete as a function of temperature and crack width, Cem. Concr. Res. 33 (7) (2003) 981–985.
[40] A.E. Naaman, H.W. Reinhardt, Proposed classification of HPFRCC composites based on their tensile response, in: N. Banthia, T. Uomoto, A. Bentur, S.P. Shah (Eds.), 3rd International Conference on Construction Materials: Performance, Innovations and Structural Implications (ConMa*t '05*), Vancouver, Canada, 2005.
[41] H. Stang, Scale effects in FRC and HPRFCC structural elements, High Performance Fiber Reinforced Cementitious Composites, in: A.E. Naaman, H.W. Reinhardt (Eds.), RILEM Proceedings Pro 30, 2003, pp. 245–258.