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

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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

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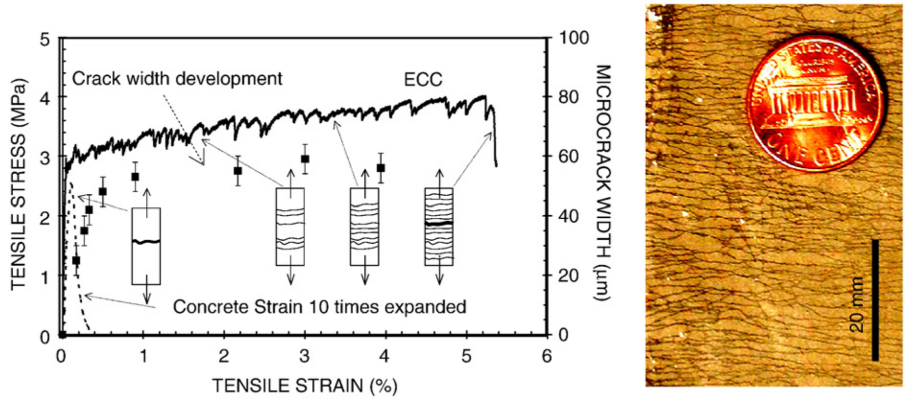

Fig. 1. Typical tensile stress-strain curve and crack width development of ECC.

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 (≤ 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