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Correlation between the viscoelastic properties and cracking potential of engineered cementitious composites

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HIGHLIGHTS

- Both microcracking and viscous shear theories are related to the deformability of ECC.
- Dimensional compatibility depends on tensile creep, elastic and shrinkage properties.
- Cracking potentials calculated by tensile creep and shrinkage tests reflected the real behavior.
- The type and amount of mineral admixture have significant effect on dimensional and mechanical properties.

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ABSTRACT

Although Engineered Cementitious Composites (ECC) offer a number of advantages over ordinary and fiber reinforced concrete in many respects, it is not cost-effective to build a whole structure with ECC, currently. Thus, ECC can potentially be used in repair systems or in bi-material systems which require it to be used together with a dimensionally stable material. High shrinkage, together with the restraining effect brings about cracking a critical phenomenon for ECC. In this study, along with the mechanical properties of ECC, viscoelastic properties like autogenous shrinkage, drying shrinkage and tensile creep which were used to calculate ECC's cracking potential were studied. At the same time, the tendency of ECC mixtures to crack under restrained shrinkage conditions was also investigated using restrained shrinkage rings. It was concluded that creep, elastic properties, and shrinkage data should be together used to evaluate the dimensional compatibility.

1. Introduction

As new civil engineering materials, cementitious materials of different types being developed and brought onto the scene with the goal of constructing safer and more durable structures. Engineered Cementitious Composites (ECC), which possesses high ductility and durability, may be the most striking of those materials. Although ECC is similar to conventional fiber reinforced concrete in terms of ingredients, the characteristics of the materials such as aggregate size, fiber type etc. used in its production lead to superior tensile ductility properties. To provide those properties, ECC is designed using a micromechanical design method that elaborates the properties of each single ingredient to achieve composite properties. In addition, the compressive strength of ECC is high enough to be used in all engineering structures. Its main advantage over ordinary and fiber reinforced concrete is tensile strain capacity, which is 200–500 times greater than that of conventional concrete accompanied with tensile strain hardening property; hence ECC can be considered as a ductile material [1–4]. Another important property of ECC is that self-controlled crack widths remain under 100 μm under tensile stress regardless of ultimate tensile strain, which is the key property behind the material's enhanced durability [5].

Despite the superior properties that make ECC a preferable material in most respects, special constituents make it too costly to use instead of concrete in whole structures. For this reason, ECC is generally used in critical parts of structures or for repair work. Potential uses of ECC have been demonstrated in multiple studies, and include bridge deck, coupling beams, bridge deck link slabs, patch repairs, retrofits, layered repair systems or overlays, stud connections, shotcrete repair systems, high early strength

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repairs and ductile strips [6–13]. These applications all require ECC to be used adjacent to another material like concrete or steel, which brings about early restrained cracking problems. Durability of a repair material or a material used in bi-material systems is dependent on its dimensional compatibility with the substrate, repaired material or the materials which are in contact with it. When a material is placed on or adjacent to a dimensionally stable material – which has lower shrinkage due to long-term exposure to environmental conditions and advanced hydration – the repair material should have appropriate shrinkage, tensile creep and elastic properties. However, due to the high amount of binder, low water to binder ratio and lack of coarse aggregate, ECC may potentially suffer from dimensional instability problems.

Several researchers have investigated the required properties for cementitious materials to be used for repair purposes, as well as factors affecting their performance. In general, compatibility of the repair material to the substrate – especially dimensional compatibility – was emphasized. Shrinkage, creep and instantaneous elastic properties [14,15] and strength [16–18] were suggested to be effective on compatibility. Also criteria for repair materials in terms of strength, shrinkage, creep, and elasticity properties were suggested by researchers [19,20].

Dimensional compatibility may be the most important property of a material used for repair purposes or in bi-material systems. If there is a mismatch between adjacent materials, any variations in the conditions such as temperature, hydration, environmental, loading and restraining effect yield internal stresses resulting in the formation of tension cracks. Li [21] and Li and Stang [22] defined cracking potential as superposition of time-dependent strains and formulated the cracking potential of a strain-hardening material under restrained shrinkage conditions as:

$$p = \varepsilon_{sh} - (\varepsilon_e + \varepsilon_i + \varepsilon_{cp})$$

where ε_{sh} is the shrinkage strain, ε_e is the elastic strain capacity, ε_i is the inelastic tensile strain capacity and ε_{cp} is the tensile creep strain. According to the given formulation, shrinkage (autogenous, plastic, drying and carbonation, thermal) is the main driver for cracking potential, while the resistors are elastic and inelastic strain capacity and material creep. Cracking due to lack of dimensional compatibility may be reduced or even prevented by altering the material parameters that affect cracking potential [17,21–23].

Although the mechanical properties of ECC have been studied intensively in the literature, there are limited studies concerning its viscoelastic properties. Despite the fact that autogenous shrinkage [24,25] and tensile creep [26–29] of ECC have attracted the attention of researchers, the results of these studies were not correlated to cracking potential. This paper presents the results of the experimental study that concentrated on the cracking potential of ECC, together with the viscoelastic properties that affect the cracking potential. Viscoelastic properties including drying and autogenous shrinkage and tensile creep were studied along with mechanical properties. Cracking potential values of the tested ECC specimens were calculated using experimentally determined shrinkage and creep values in accordance with the formulation given in Li [21] and Li and Stang [22]. All specimens were subjected to restrained shrinkage, and the tendency of the specimens to cracking was determined by this way. Calculated values of cracking potential (p) were then compared with the results of the restrained shrinkage test.

2. Experimental program

2.1. Materials and mixture proportions

The Portland cement (PC) used in ECC production was European type CEM I 42.5R, which is similar to ASTM Type I. Fly ash (FA) corresponding to Class-F (according to ASTM C 618 standard) and ground granulated blast furnace slag (GGBFS) were also used as binders. Physical properties and chemical compositions of the PC, FA and GGBFS can be found in Table 1. Aggregate used in the production of ECC was silica sand with a SiO_2 content of 99.8%. Specific gravity and absorption capacity of the silica sand were 2.60 and 0.3%, respectively. Although silica sand with maximum and average aggregate sizes of 250 µm and 110 µm are used in the production of standard ECC mixtures [30], maximum and average aggregate sizes of the locally available silica sand used in this study were about 400 µm and 200 µm. Polyvinyl alcohol (PVA) fibers 8 mm in length and 39 µm in diameter, which are commonly used in ECC production, were also used. Nominal tensile strength and specific gravity of the fibers were 1610 MPa and 1.3, respectively, as reported by the manufacturer. PVA fibers were provided coated with a 1.2% (by weight) hydrophobic oiling agent. In order to obtain a workable fresh mixture with adequate plasticity for uniform fiber distribution without bundling of fibers, polycarboxylate ether type high range water reducing admixture (HRWR) with a solid content of 40% and specific gravity of 1.1 was used, as the water to binder ratio of the ECC mixtures was quite low.

In order to investigate the effect of mixture proportions on time-dependent and mechanical properties, four different ECC mixtures were prepared. For an ECC specimen to attain strain hardening behavior with multiple fine microcracks, mixture proportions are determined by a micromechanical design principle which utilizes strength and energy criteria [3,31,32]. In the literature the ECC mixture named "M45" satisfying both criteria is comprehensively studied and is frequently referred. For this reason "M45", exhibiting an average crack width of about 60 µm and tensile strain capacity of about 5% under direct tensile stress, was selected as one of the mixtures in this study [5]. In addition to the "M45" (F 1.2 in this study), having a fly ash to cement ratio of 1.2 where about 55% of the total cementitious materials is fly ash, the amount of FA was increased to about 70% of the cementitious materials in F 2.2, to observe the effect of mineral admixture amount while the proportions of other ingredients (except HRWR) were kept constant. The remaining two mixtures replicated the first two mixtures, except the mineral admixture used was GGBFS instead of FA. All four mixtures possessed a water to binder ratio of 0.27, and the amount of silica sand was kept constant, for a sand to binder ratio of 0.36. An adequate amount of the HRWR, varied for all mixtures, was used to reach the required consistency. All mixtures contained 2% of PVA fibers by volume. Proportions and designations of the ECC mixtures are provided in Table 2.

2.2. Test specimen preparation and testing

All ECC mixtures were prepared in a planetary type mixer with a 25-liter capacity. All solid materials were introduced and blended in the mixer, and water was added afterwards. Following the preparation of the stiff mortar, HRWR was added until the desired consistency was achieved. Finally, PVA fibers were added and the mixing operation was continued until reaching a fiber distribution without bundling of fibers.

The compressive and flexural strengths of the specimens were determined at 7, 14, 28 and 90 days. Cubic specimens with 50 mm side lengths were prepared for compressive strength tests. The flexural strengths of the mixtures were determined on 360 × 75 × 50 mm beam specimens under four point bending. Specimens were demolded 24 h after casting. For the first seven days, they were kept in 95 ± 5% relative humidity (RH) at 23 ± 2 °C in plastic bags to avoid moisture transfer, and stored at 50 ± 5% RH at 23 ± 2 °C until the age of testing.

During the four-point bending tests, beams were placed on two supports 300 mm away from each other, and load was applied symmetrically from two 100 mm spaced points with a loading rate of 0.005 mm/s on a deformation controlled closed-loop testing machine. A linear variable differential transformer (LVDT) was attached to each flexural strength specimen and mid-span deflections of the beams were recorded simultaneously during loading.

The viscoelastic and dimensional properties of the ECC mixtures determined in this study include autogenous and drying shrinkage and tensile creep. Additionally, restrained shrinkage tests were performed to experimentally evaluate the cracking potential of the produced ECCs. Free autogenous shrinkages of the specimens were

Table 1
Chemical composition and physical properties of the cementitious materials.

Chemical composition	PC	FA	GGBFS
CaO (%)	61.43	1.64	34.48
SiO_2 (%)	20.77	56.22	38.4
Al_2O_3 (%)	5.55	25.34	10.96
Fe_2O_3 (%)	3.35	7.65	0.81
MgO (%)	2.49	1.8	7.14
SO_3 (%)	2.49	0.32	1.48
K_2O (%)	0.77	1.88	0.86
Na_2O (%)	0.19	1.13	0.18
Loss on ignition (%)	2.2	2.1	3.0
Specific gravity	3.06	2.31	2.79
Blaine fineness (m^2/kg)	325	290	425