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Evaluation of shrinkage induced cracking performance of low shrinkage engineered cementitious composite by ring tests

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ABSTRACT

In this study, shrinkage induced cracking performance of low shrinkage engineered cementitious composite (LSECC) and traditional ECC is evaluated comparatively by ring tests. The development of free shrinkage and interior humidity of LSECC and traditional ECC under plastic film sealed and drying conditions were experimentally measured. The anti-cracking performance of both materials under shrinkage load was examined with ring tests by measuring the compressive strain along circle direction in the steel ring and by observation on the ring specimen. The experimental results show that the shrinkage of LSECC is significantly reduced comparing with that of traditional ECC. Under the same restraint and environmental drying conditions, LSECC presents super anti-cracking performance that behaves as no visible cracks on the ring specimen can be observed. By contrast, there are number of fine cracks are observed on traditional ECC specimen. The mechanisms of super anti-cracking performance of LSECC are interpreted by shrinkage induced stress analyses with ECC-steel composite ring specimen.

1. Introduction

Concrete is a typical brittle material that behaves as decaying load and immediate localizing the deformation at the location of first cracking after the peak load. Therefore, in normal concrete structures, as the stress exceeds the tensile strength of concrete, a single crack forms and the crack width quickly achieves a macro visible level in order to dissipating the large deformation requirement from both mechanical and environmental loads. Cracking in structures reduces the load-carrying capacity, and allows water and other chemical agents, such as deicing salt, to go through the cover layer to come into contact with the reinforcements, finally leads the structure failure due to the durability of concrete. Many methods have been proposed to improve the durability of concrete structures in the past, but, however few solutions have focus on that to overcome the brittle and tensile softening natures of concrete, which leads the formation of single crack with large opening. To effectively solve this problem, a fundamental solution reducing the brittle nature of concrete, especially reducing the crack width in concrete during its service stage must be found [1].

In last twenty years, a class of high performance fiber reinforced cementitious composite, called Engineered Cementitious Composites (ECCs), which are defined by an ultimate strength higher than their first cracking strength and the formation of multiple cracking during the inelastic deformation process has been developed [2]. After first cracking, tensile load-carrying capacity continues to increase, resulting in strain-hardening accompanied by multiple cracking. The development of individual crack width can be described as that first increases steadily up a certain level, thereafter the crack width stabilizes and tends to remain constant. Further increasing in strain capacity is obtained by the formation of additional cracks until the material is saturated. After that, a single crack localizes and the load slowly drops with increased deformation. The spacing between multiple cracks in a typical ECC is about 3–6 mm, and the crack opening at the saturated stage is around 60 μm [2]. With this magnitude of crack width, the durability of material can be improved compared to the conventional concrete material with the similar deformation capacity. However, in order to obtain this strain-hardening and multiple cracking behaviors, only a small amount of fine sand is allowed to be applied in the matrix in order to control fracture toughness of matrix [3–6]. Coarse aggregates are eliminated in the mixture also, resulting in higher cement content compared with conventional concrete. As a result of this special requirement, a high drying shrinkage strain must be developed during setting and hardening of the composite. For normal concrete, an ultimate drying shrinkage strain with magnitude of 400 μm/m to 600 μm/m will be produced under normal drying conditions of 20 °C and 60% relative humidity [7]. By contrast, the ultimate drying shrinkage strain of conventional ECC is approximately 1200 μm/m to 1800 μm/m under the similar

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drying conditions [8,9]. Due to this great difference in shrinkage deformation, more shrinkage induced cracking may happen as applying the ECC material in structures. These shrinkage cracks in structure may still lead long term durability problems even with small crack opening compared to the case without any cracks. Indeed, we always wish less cracks occur in structures. Desired situation should be the case there is no cracking also in the structure made of ECC as no cracking happens in the structure made of normal concrete under the similar environmental conditions. Therefore, developing new generation of ECC materials with drying shrinkage deformation comparable to normal concrete, but maintaining the excellent strain-hardening and multiple cracking performances becomes a new challenge to material designers and inventors. Recently, a new class of ECC with characteristic of low drying shrinkage, named low shrinkage ECC (LSECC) is developed [10–11]. The experimental results show that by applying the new type of cementitious matrix, the drying shrinkage of the composite can be greatly reduced. The drying shrinkage strain at 28 days is only 109 μm/m to 242 μm/m, while the average ultimate tensile strain is still able to achieve 2.5% [10].

In the present paper, cracking sensitivity under shrinkage load of newly developed LSECC and traditional ECC are evaluated comparatively with steel-ECC composite ring tests by measuring the compressive strain along circle direction in the steel ring and by observation of cracking status on the ring specimen. The development of shrinkage strain and interior humidity with age of LSECC and traditional ECC under plastic film sealed and drying conditions were experimentally measured in order to assess the anti-cracking performance of the materials. The mechanism of super anti-cracking performance of LSECC is interpreted by shrinkage induced stress analyses with ECC-steel composite ring specimen. From the shrinkage stress analyses, the stress relaxation behavior at early-age of LSECC and traditional ECC under tension are discussed by comparing the difference between the calculated shrinkage strain that taking creep of material into account and the free shrinkage strain.

2. Experimental program

Two parts of tests are involved in the experimental program. First, the development of shrinkage and interior humidity with age of LSECC and traditional ECC under plastic film sealed and drying conditions were experimentally measured using the newly developed testing method for shrinkage and interior humidity measurements [12]. The influences of curing condition on the shrinkage and interior humidity of the two kinds of composites were quantified from this test. Second, cracking sensitivity of LSECC and traditional ECC under shrinkage load was assessed by ring tests through recording the compressive strain along the steel ring that resulted from shrinkage of composite and through observation on the cracking status of the ring specimen.

2.1. Materials

In the present investigation, two types of cements, ordinary Portland cement used for traditional ECC matrix and the newly developed composite cement with low drying shrinkage characteristic used for LSECC matrix. Silica sand with average particle size 0.1 mm were used to form the matrix. Polyvinyl Alcohol fiber (PVA) supplied by Kuraray Company in Japan was employed as reinforcement and the fiber properties are listed in Table 1. Mixture proportions of LSECC adopted in this study and traditional ECC used for comparison are listed in Tables 2 and 3 respectively. In our tests, the workability for different mixture was adjusted by adding superplasticizer to maintain a similar fresh composite flowability. The mixing procedure of the composite material consists of the following steps: (1) Matrix preparation: The matrix was prepared in a mortar mixer. First, the cementitious material and silica sand were mixed together for 2 min at low speed. Then water with superplasticizer and viscous agent (methyl cellulose) mixed in were gradually added, and mixing was continued for 2 min which results in a uniform fluid matrix. Within this period, the bottom of the mixing bowl should be scraped manually to ensure that no solid materials stick to the bottom. After such scraping, the matrix was mixed at a higher speed for 1 min before addition of fibers. (2) Addition of fibers: the fibers were gradually spread into the mixer by hand as the matrix was mixed at a slow speed. The fibers must be added slowly to ensure proper distribution with no fibers bundled together.

Table 1
Parameters of the PVA fiber.

Density (g/cm^3)	Tensile strength (MPa)	E (GPa)	Diameter (mm)	Length (mm)
1.2	1620	42.8	0.039	12

Table 2
Mix proportion of LSECC.

Composite cement	Water	Sand	Super plasticizer	Fiber (volume, %)
1.0	0.35	0.3	0.012	1.7

Table 3
Mix proportion of traditional ECC.

Portland cement	Fly ash	Water	Sand	Fiber (volume, %)
1.0	0.25	0.5	0.8	1.7

2.2. Specimens, curing and testing procedures

2.2.1. Shrinkage tests

In shrinkage tests, the mold used to cast the specimens was made of plexiglass with inner dimensions of 60 × 100 × 400 mm. The four inner sides of the mold were covered with four pieces of removable plastic sheets with 2 mm thickness and the bottom of the mold was covered with a thin vinyl sheet with 1 mm thickness to reduce the frictional resistance between the mold and the concrete. After initial set of the concrete, the inner four removable plastic sheets were lifted to create the “free restraint” conditions of the shrinkage test. In the test, the humidity at the center of the specimen was measured. A resistance based digital humidity sensor with measuring accuracies of 3% was used for interior humidity measurement. In order to maintain the sensor at the designated location in the concrete, a PVC tube with an inner diameter of 15 mm was used to hold the sensor. One end of the PVC tube was covered with a plastic sheet glued to the end. To maintain the moisture exchange with the surrounding concrete, three rectangular holes were made at the surface of the PVC tube. In order to prevent fresh cement paste from flowing into the tube through the rectangular holes, a steel bar with a little smaller diameter than that of the PVC tube was placed into the tube first during concrete casting. A few minutes after casting, the steel bar was removed from the tube and the sensor was inserted. To ensure the measured humidity and temperature reflect the real values inside the concrete, two rubber O-rings with a 2 mm thickness were used to isolate the free gap between the PVC tube and the sensor bar. The O-ring was just above the sensory section of the sensor. In the mean time, at the top of the tube, the gap was sealed by an