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Engineered cementitious composite with characteristic of low drying shrinkage

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ABSTRACT

This paper reports a new class of engineered cementitious composite (ECC) with characteristics of low drying shrinkage, tight crack opening and high tensile strain capacity. Research emphasis is placed on the influence of different cementitious matrix on drying shrinkage, tensile property and early age cracking behavior of the composites. Experimental results show that drying shrinkage of the composite is greatly reduced as using the low shrinkage cementitious material in matrix, while the composite remains strain-hardening and multiple cracking characteristics. The measured drying shrinkage strain at 28 days is only 109×10^{-6} to 242×10^{-6} for low shrinkage ECCs. For traditional ECC, the shrinkage strain at 28 days is nearly 1200×10^{-6}. The average tensile strain capacity after 28 days curing is 2.5% of the low shrinkage ECC with tensile strength of 4–5 MPa. Further, in the strain-hardening and multiple cracking stage, cracks with much smaller width compared to the traditional ECC are formed in the low shrinkage ECC.

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 serious 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 recent years, a class of high performance fiber reinforced cementitious composite, called Engineered Cementitious Composites (ECC), 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 to 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 [3–5]. 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 400×10^{-6} to 600×10^{-6} will be produced under normal drying conditions of 20 °C and 60% relative humidity [6]. By contrast, the ultimate drying shrinkage strain of conventional ECC is approximately 1200×10^{-6} to 1800×10^{-6} under the similar drying conditions [7,8]. 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

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Table 1
Chemical contents of the composite cement (%).

CaO	SiO_2	Al_2O_3	Fe_2O_3	MgO	K_2O	Na_2O	TiO_2	LOI
33.75	19.63	18.03	0.47	1.28	0.50	0.28	0.62	6.26

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.

In the present paper, a new class of ECC with characteristic of low drying shrinkage is present. The experimental results show that by applying the new type of cementitious matrix, the composite drying shrinkage can be greatly reduced. The drying shrinkage strain at 28 days is only 109×10^{-6} to 242×10^{-6}, while the average ultimate tensile strain is still able to achieve 2.5%. In addition, the crack width in the strain-hardening stage of the low shrinkage ECC is much smaller than that in traditional ECC. The new ECC can be characterized as low drying shrinkage, tight crack opening and high tensile strain capacity.

2. Experimental program

Three parts of investigation are involved in the experimental program. First, the influence of the type of cementitious matrix, as well as the mixture parameters, such as water to cementitious material ratio (w/c) and sand to cementitious material ratio (s/c), on drying shrinkage of the composite were experimentally quantified. Second, the influence of cementitious binder, as well as mixture parameters of w/c and s/c, on the composite tensile behavior was evaluated and compared between traditional and newly developed ECCs. Third, the influence of drying shrinkage deformation on early age cracking behavior of ECC under restrict condition was assessed. Three types of tests, drying shrinkage, uniaxial tension and two direction restricted plate drying tests were carried out in the experimental program.

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 new ECC matrix. The chemical content of the composite cement is list in Table 1. Silica sand with average particle size 0.1 mm was 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 2. Mixture proportions for low shrinkage ECC adopted in this study and for traditional ECC are given in Tables 3 and 4 respectively. For low shrinkage matrix, three different water to cementitious material ratio (w/c) of 0.45, 0.50, 0.55 and three different sand to cementitious material ratio (s/c) of 0.8, 1.1, 1.4 were used to investigate the effect of w/c and s/c on material properties, including drying shrinkage deformation, tensile performance. In our tests, the workability for different mixture was adjusted by adding superplasticizer to maintain a similar fresh composite flowability.

Table 2
Mix proportions of low shrinkage ECCs.

Mixture no.	Composite cement	Water	Sand	Super plasticizer	Fiber (vol.%)
1	1.0	0.45	0.8	0.012	1.7
2	1.0	0.45	1.1	0.018	1.7
3	1.0	0.45	1.4	0.022	1.7
4	1.0	0.50	0.8	0.011	1.7
5	1.0	0.50	1.1	0.013	1.7
6	1.0	0.50	1.4	0.020	1.7
7	1.0	0.55	0.8	0.010	1.7
8	1.0	0.55	1.1	0.011	1.7
9	1.0	0.55	1.4	0.016	1.7

Table 3
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

2.2. Specimens, curing and testing procedures

For drying shrinkage test, a prism shape specimen measuring $40\times40\times160$ mm with two embedded copper heads at the two long ends for length measurement was used. After removing from their molds (24 h after casting), the specimens were stored in the room with constant temperature and relative humidity of 25 ± 2 °C and 60 ± 1.5% for drying shrinkage deformation measurement. The length measurement starts immediately after specimen demolding until 28 days after casting.

The uniaxial tensile tests give tensile stress–strain performance and related mechanical parameters, such as tensile strength and strain of materials. Rectangular coupon specimens with size of $40\times160\times15$ mm were used to conduct uniaxial tensile test for each mixture at age of 3, 7 and 28 days. The molds used to cast the tensile specimens were made of steel. After removing from their molds, the tensile specimens were stored in water at 20 ± 2 °C for curing until tensile tests were carried out. The tensile specimens were tested in uniaxial tension with displacement control in a 250 kN capacity MTS 810 material testing system with hydraulic wedge grips. Aluminum plates were epoxy glued onto the ends of the specimens prior to loading at least 6 h to enhance the ends for gripping. The actuator displacement rate used for controlling the test was 0.0025 mm/s. The strain was measured by two extensometers mounted on the surface of the specimen. The measured gage length of extensometer was 50 mm. The tensile test set-up and specimen with aluminum plates glued and extensometers mounted is shown in Fig. 1. The raw data consisted of time, load, position of the piston and displacement from each extensometer. The tensile behavior can then be determined from these test data.

To evaluate the influence of drying shrinkage deformation on early age cracking behavior of new developed and traditional ECCs, two direction restricted plate tests were conducted also in the present study. A square plate with dimension of $600\times600\times63$ mm was used in the test. The restriction to the plate specimen is provided by two layers of steel bolts with 100 mm in length and 8 mm in diameter, one end fixed with the boundary steel beam and the other end exposed inside the casting mold. A total of 56 steel bolts were used along the four boundary beams. After casting material into the mold, the dimension of the plate can then be regarded as approximately fixed without length changing. Thus shrinkage induced cracking should occur immediately as long as the shrinkage deformation developed in the composite is sufficiently large and the restricted action provided by the steel bolts is effective. The mold before material casting is shown in Fig. 2. The test was carried out in a room with temperature and relative humidity of 25 ± 5 °C and 40%–60%. After specimen casting, the plate surface were covered with plastic sheet for one day

Table 4
Mix proportion of traditional ECC.

Mixture no.	Portland cement	Fly ash	Water	Sand	Fiber (vol.%)
10	1.0	0.25	0.5	0.8	1.7