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Self-healing capability of large-scale engineered cementitious composites beams

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ABSTRACT

Engineered Cementitious Composites (ECC) is a material which possesses advanced self-healing properties. Although the self-healing performance of ECC has been revealed in numerous studies, only small-scale, laboratory-size specimens have been used to assess it under fixed laboratory conditions and curing techniques. In order to evaluate the effect of intrinsic self-healing ability of ECC on the properties of structural-size, large-scale reinforced-beam members, specimens with four different shear span to effective depth (a/d) ratios, ranging from 1 to 4, were prepared to evaluate the effects of shear and flexural deformation. To ensure a realistic assessment, beams were cured using wet burlap, similar to on-site curing. Each beam was tested for mechanical properties including load-carrying capacity, deflection capacity, ductility ratio, yield stiffness, energy absorption capacity, and the influence of self-healing, by comparing types of failure and cracking. Self-healed test beams showed higher strength, energy absorption capacity and ductility ratio than damaged test beams. In test beams with an a/d ratio of 4 in which flexural behavior was prominent, self-healing application was highly successful; the strength, energy absorption capacity and ductility ratios of these beams achieved the level of undamaged beams. In addition, flexural cracks healed better, helping recover the properties of beams with predominantly flexural cracks rather than shear cracks.

1. Introduction

Concrete is the most widely used construction material in the world. However, its brittle behavior and low tensile strength affect not only mechanical performance, but also influence durability through cracking, limiting the service life of reinforced concrete structures and requiring maintenance and repair to ensure serviceability. Repairing concrete structures is not an easy task; it is expensive and requires specialized expertise and materials. For example, approximately $5.2 billion is spent each year to maintain existing bridges in the United States [1]; the estimated budget for reconstructing them is between $20 billion and $200 billion [2,3]. The situation is similar around the globe; 45% of the construction and building budget in the United Kingdom is spent on repair and maintenance applications [4]. Annual maintenance and repair costs are also substantial for the European Union countries, with actual spending of around $1 billion for the maintenance of bridges, with an estimated $20 billion for all infrastructure types [5]. However, over the last two decades, the self-healing capabilities of cementitious materials have become an attractive solution for reducing maintenance and repair costs; materials with self-healing ability have the potential of recovering their properties after cracking. Studies have shown that the mechanical performance and transport properties of these kinds of materials can be re-attained, and that even after substantial damage, the self-healing mechanism can help the material reach its initial properties and behave as if it had never been subjected to damage. Numerous self-healing techniques have emerged, some requiring unconventional ingredients such as hollow fibers, encapsulation with chemicals, bacteria, expansive agents and shape memory materials [6,7]. One mechanism is autogenous or intrinsic self-healing, which involves the plugging of cracks with materials incorporated into the cementitious

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composite, without any additional process or agent. It has been reported that the mechanism of intrinsic self-healing is a consequence of the chemical, mechanical and physical closure of existing cracks. This kind of self-healing is generally attributed to the hydration of previously unhydrated cementitious material, calcite formation, expansion of concrete in the crack flanks, crystallization, closing of cracks by solid matter in the water, and closing of cracks by spalling of loose concrete particles resulting from cracking [8]. Self-healing should be taken into account when specifying tolerable crack widths. Jacobsen et al. [8], Reinhardt and Joss [9], Sahmaran and Yaman [10], Edvardsen [11], Aldea et al. [12] and Clear [13] have proposed maximum crack widths of 5–10 μm, 100 μm, 200 μm, 205 μm and 300 μm, respectively, for a crack to seal itself completely. Overall, the most serious challenge for complete healing is tolerable crack width. Since conventional concrete has the tendency to deform in a brittle manner under mechanical loading, attaining such small crack widths is a major concern. However, the situation is different for ECC, which deforms in a ductile manner and is characterized by tensile strain hardening and flexural deflection hardening properties. These are the result of self-controlled multiple tight cracks that remain under 100 μm, and are likely to promote intrinsic self-healing ability. In addition, ECC material contains large amounts of supplementary cementitious materials, which also make it possible for unhydrated cementitious material to exist in the structure, allowing further hydrates to fill up the microcracks. ECC is a prominent intrinsic self-healing construction material, well-documented in the literature [7].

However, studies focusing on the influence of self-healing on a structural scale are limited. One study into reinforced large-scale structural members was performed by Tran Diep et al. [14], in which four-point bending tests were performed on relatively large beams (125 mm × 200 mm × 2000 mm) containing encapsulated epoxy. Dry [15] also investigated the possibility of obtaining autonomous crack healing in a real-scale concrete bridge deck (76 mm × 1220 mm × 6096 mm) using adhesive-filled glass tubes. However, no study has been conducted into the self-healing ability of ECC on a structural scale. Numerous studies into ECC's self-healing capability are restricted by their use of small specimens with no reinforcement and single-type microcracks formed by tensile or flexural loading. However, the authors believe that a study into the effects of self-healing behavior of large-scale ECC members on important structural parameters such as strength, stiffness, ductility, energy absorption capacity and failure mechanism should be conducted to promote the use of such a successful self-healing material in real structures. Although ECC is a perfect material in terms of ductility and self-healing as determined under laboratory conditions, yet studies on large scale ECC members are quite limited. This deprives construction industry from the benefits of structural use of ECC. This study may help ECC to be recognized as a structural material and pave the way for a successful use of ECC in structural members. Successful and widespread implementation of ECC may yield more ductile hence more durable structures with smaller construction budgets for repair and retrofitting [16].

In addition, any construction material can be damaged in an earthquake or due to induced stresses originating from durability concerns and unpredicted load conditions. However, ECC has the potential to eliminate the need for repair as a result of its intrinsic self-healing capability. For this reason, beams were subjected to curing for as little as 30 days after being damaged to assess whether self-healing mechanisms of ECC can replace repair, which would be a great benefit for the construction industry. ECC is composite material type, and theoretical modeling of composite structures using this type of materials should be investigated [17–22].

This paper outlines an experimental investigation into the self-healing performance of large-scale reinforced ECC beam specimens. The main variables investigated were the shear span to effective depth (a/d) ratios of the reinforced ECC beams. This was mainly intended to reflect real-life cracking behavior of reinforced composites; crack formation is possible due to both shearing and bending effects. For this purpose, four different a/d ratios were chosen, ranging between 1 and 4. To examine the self-healing performance of reinforced ECC beams, twelve beam specimens, including three beams from each test group, were tested under four-point bending loading. The study investigated the effect of self-healing performance on structural characteristics such as strength, stiffness, ductility ratio, energy absorption capacity and failure mechanisms of test members and the way they are influenced by self-healing.

2. Experimental program

2.1. Test specimens and material properties

To evaluate self-healing characteristics of large-scale reinforced ECC beams, specimens with different shear span (a) to effective depth (d) ratios were tested under the four-point bending test. The a/d ratios of reinforced ECC beam specimens ranged from 1 to 4 so that shearing effects could be observed. According to Fig. 1 [23], which describes the changes in failure modes of reinforced concrete beams with respect to a/d ratio, as a/d ratio decreased, the possibility of shear failure increased. Therefore, a low ratio between 1 and 3 was selected to promote shear failure and monitor the behavior of test specimens under the influence of shear forces. Additionally, a high a/d ratio of 4 was used to obtain a different failure mode, which was expected to be a combination of shear and flexural failure mechanisms.

All test beams were produced with the same amount of reinforcement, obtained from the same supplier throughout the study. Geometric dimensions and steel reinforcement details of test specimens are shown in Fig. 2. Main longitudinal tensile reinforcements of 2φ16 were used for all a/d ratios. The yield strength (f_{sy}), ultimate strength (f_{su}) and elastic modulus (E) of φ16 ribbed steel bars were determined as 520 MPa, 625 MPa and 205 GPa, respectively. Only a small amount of shear reinforcement was placed at the support regions to prevent local failure at those points. No additional shear reinforcement was applied along the beam length. Shear reinforcing bars had a 10 mm diameter, with 428 MPa yield strength, 535 MPa ultimate strength and 198 GPa elastic modulus. The main test specimen parameters are presented in Table 1.

Three groups of reinforced beam specimens with four a/d ratios were produced and tested for the study. The main aim was to examine the effects of self-healing performance on major residual structural parameters such as load-deformation behavior, strength, stiffness, ductility ratio and energy absorption capacity. The effects of the change in a/d ratio on self-healing performance of beams were also examined. In the nomenclature of the test members provided in Table 1, the first three characters show the a/d ratio, while the last three characters designate the test age: 28 or 58 days (28D or 58D). “V” in the beam notations means that the beam is virgin, i.e. it is the reference value. “PL” refers to the fact that a preloading up to 50% of the maximum load-carrying capacity was applied on the beam specimens. “SH”, which appears in the last four test members, means that the self-healing process was applied on those beams.

In the first test group, one reference beam was tested until failure for each a/d ratio at the end of 28 days of standard curing to determine load-carrying capacities (specimens 1, 2, 3 and 4). Two sets of experiments were performed on specimens 5, 6, 7 and 8 (second test group). At 28 days, those specimens were preloaded up