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Self-healing properties of cement-based and alkali-activated slag-based fiber-reinforced composites

Huy Hoàng Nguyễn [a], Jeong-Il Choi [a], Keum-Il Song [a], Jin-Kyu Song [a], Jungwon Huh [b], Bang Yeon Lee [a,*]

[a] School of Architecture, Chonnam National University, 77 Yongbong-ro, Buk-gu, Gwangju 61186, Republic of Korea
[b] Department of Ocean Civil Engineering, Chonnam National University, 50 Daehak-ro, Yeosu 59626, Republic of Korea

HIGHLIGHTS

- The self-healing properties of cement-based and slag-based fiber-reinforced composites are investigated.
- Slag-based composites have advantages in terms of a reduction of relative crack width.
- Slag-based composites have low resonant frequency recovery.
- Calcium carbonate is the dominant healing material for cement-based and slag-based composites.

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ABSTRACT

This paper presents an experimental study of the self-healing properties of cement-based and alkali-activated slag-based fiber-reinforced composites with controlled crack width. Two types of binder, i.e. cement and alkali-activated slag-based polyethylene fiber-reinforced composites with identical water-to-binder ratios, were designed. Compressive strength and uniaxial tension tests were performed to measure the mechanical properties of the composites, and the self-healing performance was investigated by observation of the crack width and by measuring resonance frequency. Scanning electron microscopy and energy-dispersive X-ray spectroscopy were also adopted to analyze the morphology and chemical composition of the healing materials. The test results showed that alkali-activated slag-based composites have advantages compared to cement-based composites in terms of a reduction of relative crack width; however, cement-based composites have a higher resonant frequency recovery than alkali-activated slag-based composites. It is also observed that calcium carbonate is the dominant healing material of cement-based and slag-based composites.

1. Introduction

Along with the development of humanity, upgrading infrastructure is a strategically important issue. Furthermore, improving the quality of concrete structures is a matter of extreme urgency. Concrete is the world's most widely used construction material on the basis of its reliability and commercial value [1]. However, the deterioration of concrete in term of cracks happening over time is one of the major factors causing a reduction of the quality of concrete structures. Cracks on concrete structures can occur during the service life due to external and internal factors such as over-load, environmental exposure, shrinkage, or design error [2]. The cost of repair and maintenance of construction projects is quite large, and thus concepts to develop a new building material that recovers damage automatically to ensure the service life have been extensively studied in recent years [3].

A self-healing characteristic is a universal phenomenon that occurs in the human body, and occurs naturally without being affected by any external factors [3]. Concrete is also a special material with the ability to heal cracks by itself under natural conditions over time [2]. The target of designing autogenic healing concrete is to overcome problematic constructions to give a longer lifespan. Neville (1995) and Hearn (1997) pointed out that the tiny cracks in concrete could be sealed completely under a moist environment due to the delayed hydration of cement [4,5]. Edvardsen (1999) mentioned that calcium carbonate crystals are the main healing material within the crack width [6]. From a review of the literature [4–6], there are two primary definitions that should be noted on the self-healing mechanism of deteriorating concrete structures, autogenous healing and engineered repair. Autogenous healing is a phenomenon that takes place by a natural process [7]. It can be

* Corresponding author.
E-mail address: bylee@jnu.ac.kr (B.Y. Lee).

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described by the hydration process of the unhydrated cementitious materials, blockage of cracks caused by solid substances in the water, swelling of C—S—H in the crack flanks, and crystallization of calcium carbonate [8]. Meanwhile, engineered repair is activated by artificial healing materials or through intentional methods from human intervention to accomplish the healing process [7,9]. There are various approaches to improve the self-healing capacity of a concrete structure that has suffered damage including the use of bacteria, chemical admixtures, or microencapsulation [10–12].

In recent years, engineered cementitious composite (ECC) has been recognized as a unique construction material with the formation of multiple fine cracks, providing remarkable potential to achieve self-healing efficiency [8]. Developing enhanced techniques to upgrade the self-healing ability of ECC has been an important topic of study. Yang et al. (2009) introduced the mechanical recovery and healing rate of ECC through wet-dry cycles [13]. Sisomphon et al. (2013) clarified the self-healing mechanism of ECC incorporating a cementitious admixture [14]. Hung et al. (2017) reported that self-healing can be achieved in ECC through the effect of natural weathering with intrinsic tight crack width [15]. Qiu et al. (2016) developed an advanced method of improving the self-healing capacity of a cementitious composite based on the addition of blast furnace slag and the alkalinity condition [16]. They all concluded that the permissible crack width, which was smaller than 50 μm, achieved healing cracks [13–16]. Diminished self-healing was observed in the range of cracks between 50 μm and 150 μm; nevertheless if the crack width exceeded 150 μm, the self-healing ability vanished due to the appearance of serious damage to the matrix structure.

Previous studies developed high performance fiber-reinforced cementless composites called alkaline activated slag (AAS) based composites, characterized by high ductility and material greenness [17–19]. This technology also has played a role in innovating carbon dioxide emission control and sustainable green infrastructure due to the elimination of cement binder. While knowledge of self-healing in normal concrete is available, the self-healing of fiber-reinforced alkali-activated slag-based cementless composite has been fairly limited. In this light, it is necessary to develop a new construction material in term of enhanced ductility, greenness, and high self-healing potential based on an alkali-activated slag-based fiber-reinforced composite.

The purpose of this paper is to experimentally investigate the self-healing capacity of cement-based and alkali-activated slag-based fiber-reinforced composites with an identical water-to-binder ratio. The self-healing performance of the composites was evaluated by visual observation of crack width and measurement of the resonant frequency with time. Scanning electron microscope (SEM) and energy-dispersive X-ray spectroscopy (EDS) were also adopted to analyze the microstructure and chemical composition of the healing materials.

2. Materials and experimental methodology

2.1. Materials and mixture proportions

Two types of binder, i.e. cement and alkali-activated slag, were used in this study. The chemical compositions of cement and ground-granulated blast-furnace slag (GGBS) are listed in Table 1. Type I Portland cement was used, and the specific surface area and density of cement were 3297 cm^2/g and 3.14 g/cm^3, respectively. The specific surface area and density of GGBS were 4320 cm^2/g and 2.91 g/cm^3, respectively. The GGBS is the source material of a cementless composite and it was activated by alkali activators. The calcium hydroxide in a powder form was used as an alkali activator. The amount of calcium hydroxide was 11.1% of GGBS in terms of the mass ratio. Polyethylene (PE) fiber was used as a reinforcing fiber. The physical properties of PE fiber used in this study were a diameter of 12 μm, a fiber length of 18 mm, a tensile strength of 2700 MPa, a density of 0.97 g/cm^3, and an elastic modulus of 88 GPa. Superplasticizer (SP), viscosity modifying admixture (VMA), and anti-foaming agent are all in powder form, and are used as the additives for the mixtures. A superplasticizer (SP) and viscosity modifying admixture (VMA) were used to achieve controlled workability as well as to ensure good fiber dispersion of the fresh mixture. An anti-foaming agent was included in the mixture to diminish the amount of air bubbles. Table 2 lists the mixture proportions. The water-to-binder ratio of all mixtures was 0.3.

2.2. Mixing procedure and specimen preparation

Each powder type binder was mixed in a commercial planetary mixer for three minutes. Water was then slowly added and the mixture was mixed for another five minutes. Next, the SP and VMA were also added to the mixture. Once a homogeneous mixture was attained, PE fibers were slowly inserted into the mixture. The fresh mixture was then poured into molds for a compressive strength test (three 50 mm cube specimens for each mixture) and a self-healing test including uniaxial tension tests (four dog-bone shaped specimens for each mixture), and it was covered with plastic sheets to prevent the evaporation of water in air at the room temperature (23 °C ± 3 °C) for two days. Finally, the hardened specimens were removed from the molds and cured in water at a temperature of 23 °C ± 3 °C until the age of 28 days.

2.3. Mechanical tests and self-healing capacity evaluation

The compressive strength was measured using 50 mm cube specimens according to the ASTM C109 with three specimens for each mixture [20]. The tensile load by displacement control in accordance with a constant loading speed of 0.1 mm/min. was applied to each specimen to create cracks and investigate the tensile behavior using an electrical uniaxial testing machine with a capacity of 20 kN at the age of 28 days. Fig. 1 shows the specimen geometry and the test setup [21]. The specimens have a gauge length of 80 mm and the cross-sectional area within the gauge length is 390 mm^2 (30 mm × 13 mm). The tensile load was measured by a load cell attached to the top of the jig and the deformation within the gauge length was measured by two linear variable differential transducer attached to both sides of the specimens. According to the highly ductile characteristic of cement-based and slag-based composites, cracks of all specimens can be self-controlled below 100 μm. However, it should be noted that to evaluate the maximum self-healing capacity, most specimens were

Table 1
Chemical compositions of cement and GGBS.

Binder	Chemical composition (%)										
	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	TiO_2	K_2O	MnO	Na_2O	etc
Cement	18.5	4.5	3.3	65.8	3.4	2.2	0.3	1.1	–	–	0.9
GGBS	30.6	13.8	0.5	40.4	8.0	4.0	0.9	0.5	0.5	0.4	0.4