# Self-healing Capability of Ultra-High-Performance Fiber-Reinforced Concrete (UHP-FRC)

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**ABSTRACT**
UHP-FRC (ultra-high-performance fiber-reinforced concrete) is being successfully developed in the last decade, which shows the high strength and high durability due to its very dense microstructures. Moreover, incorporation of fibers in the mix design of UHP-FRC exhibits the high ductility and high energy absorption capacity. The high ductility of UHP-FRC materials shows pseudo-strain hardening behavior and multiple cracking after the occurrence of the first crack under uniaxial tension. Generally, presence of cracks is not desirable from durability viewpoint. That is, presence of cracks should be recovered in order to sustain durability of UHP-FRC. Here, self-healing phenomena might be strongly helpful to coexistence of the characteristics of multiple cracks. In this study, the potential of self-healing capability of UHP-FRC was investigated. As a result, it is confirmed that cracked UHP-FRC could be recovered by precipitation of calcium carbonate crystals.

## 1. INTRODUCTION

One of the most important features of UHP-FRC is strain hardening behavior, which increases tensile stress beyond the first crack strength accompanied by the development of closely spaced multiple cracks. However, cracks in the UHP-FRC structure may allow the ingress of aggressive agents (e.g., chloride ions and/or $CO_2$), which may lead to corrosion of reinforcements. Such corrosion brings about deterioration of the concrete structure including decrease in structural safety. Therefore, self-healing technique might be effective to solve durability problems of UHP-FRC because multiple cracks have generally small enough width. So far, various techniques for self-healing of cracks in concrete have been proposed. For durability performance, even just filling cracks may be sufficient for preventing the permeation of water and aggressive substance [1]. Some research papers reported that ECC (engineered cementitious composites) demonstrates very good self-healing performance due to the tiny width of multiple cracks [2]. While a few studies on the self-healing of FRCC using steel fiber have been done, most of studies were limited to synthetic fibers (e.g. polyvinyl alcohol, polyethylene, and polypropylene fiber). Homma et al. (2009) [3] carried out microscopic observation on cracked surfaces of FRCC containing steel cord. By observing the crack surface, it was confirmed that corrosion of steel cord was observed in exposed steel cords not only on the surface of specimens but also inside of the crack with rather wider width. The objective of this study was to investigate the self-healing capability (i.e. filling the crack to prevent deterioration of durability) of UHP-FRC containing only steel fibers, where UHP-FRC in this study employed two types of steel fibers together.

## 2. EXPERIMENTAL PROCEDURE

In order to investigate the self-healing capability (i.e. filling the crack to prevent deterioration of durability) of the UHP-FRCC, the following experiments were carried out. Firstly, uniaxial tension test was carried out to form cracks. Then, water curing was performed. The crack width and the healing products were observed by microscopic observation. Chemical compositions of the healing products were analyzed by energy dispersive X-ray spectroscope (EDX) and Raman spectroscopy.

## 3. MATERIALS AND METHODS

UHP-FRC consists of the matrix and two types of steel fibers. Table 1 shows the mix proportion of the matrix. The short fiber was straight steel fiber with the length of 6 mm (i.e. S-fiber), and the long fiber was hooked steel fiber with the length of 30 mm (i.e. H-fiber). The diameter of the S-fiber was 0.16 mm, and that of the H-fiber was 0.38 mm. The mechanical properties of the fibers are shown in Table 2. The volume fractions of S-fiber and H-fiber were $V_{sf}$ = 1.0% and $V_{hf}$ = 1.5%, respectively.

Table 1: Mix proportion.

| W/B | S/B | Wo/B | SP/B | D/B |
|---|---|---|---|---|
| 0.15 | 0.35 | 0.13 | 0.017 | 0.0002 |

[Note] B: Low-heat cement and silica fume were premixed at mass fraction of 82 and 18 (Blaine fineness: 6,555 $cm^2$/g, density: 3.01 g/$cm^3$), W: Tap water, S: Silica sand #6 (density: 2.61 g/$cm^3$, average diameter: 0.212 mm), Wo: Wollastonite microfibers (density: 2.9 g/$cm^3$), SP: Super plasticizer (polycarboxylic acid ether system, density: 1.05 g/$cm^3$), Anti-foaming agents (polyether system, density: 1.05 g/$cm^3$)

Table 2: Mechanical properties of the fibers.

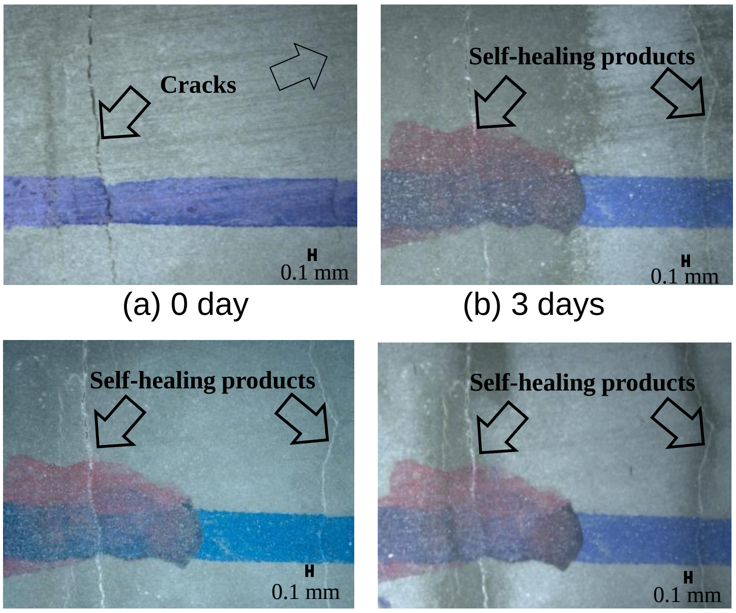
| Notation | Specific gravity (g/$cm^3$) | Length (mm) | Diameter (mm) | Aspect ratio (L/D) | Tensile strength (MPa) | Young's modulus (GPa) |
|---|---|---|---|---|---|---|
| S | 7.85 | 6.0 | 0.16 | 37.5 | 2000 | 206 |
| H | 7.85 | 30.0 | 0.38 | 78.9 | 3000 | 206 |

The geometry of the specimens was a plate of 150 × 200 × 30 $mm^3$. Two specimens of UHP-FRCC were tested. There were two rebars of D6 (SD295, fy = 356 MPa) embedded in the specimen to impart stable crack formation. The rebars of D10 (SD295A) were also embedded in both specimen's ends to allow the specimen to be held by the testing machine. The specimens were cured in a moist curing room (temperature: 20ºC, more than 95%RH) for 1 day. After demolding, the specimens were cured in a steam chamber for 24 h with the temperature at 90ºC. After the steam curing, the specimens were stored in the moist curing room (20ºC and more than 95%RH) until the day of the loading test. Tensile load was applied up to 0.2% of strain. After the tensile loading, the crack surface was observed by means of a digital microscope and the maximum crack width was measured (i.e. 76.1μm). Furthermore, multiple cracks were observed in the measurement area. After the microscopic observation, all specimens were kept for 28 days in a water tank at 20°C, which are the usual conditions for standard curing. In order to investigate the effects of self-healing on the cracks, microscopic measurements were conducted again at 3, 7, 14, 21, and 28 days.

## 4. RESULTS AND DISCUSSION

### Microscopic observation

Fig. 1(a)-(d) show the healing process of the cracked UHP-FRCC that was in the curing water tank for the planned elapsed time from 0 days (immediately after the tension test and before immersion in water) to 28 days. There were no chemical products on the surfaces of the specimens at 0 day as shown in Fig. 1(a). However, after water curing, small amount of self-healing products appeared at the age of 3 days (Fig. 1(b)). After 14 days, in the crack surfaces of the specimens, many self-healing products were confirmed (Fig. 1(c)). The result of 28 days as shown in Fig. 1(d) demonstrated no difference from that in 14 days (Fig. 1(c)). In addition, corrosion of steel fiber was not confirmed. From above results, the cracked UHP-FRC with steel fiber has a high self-healing capability, but does not have corrosion of steel fiber.



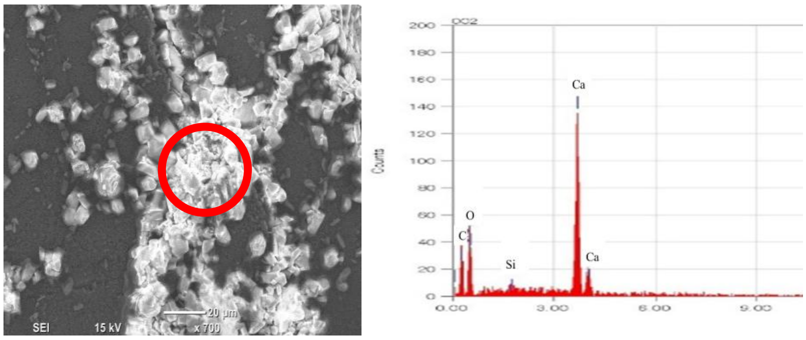

(a) 0 day (b) 3 days

(c) 14 days (d) 28 days

Fig. 1 Time dependence of self-healing

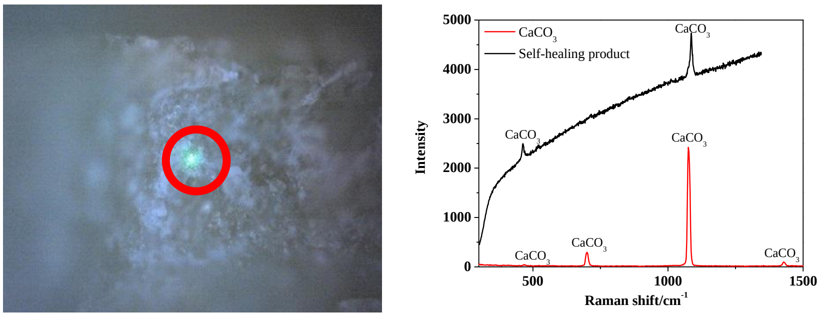
### Analyses of chemical compositions

Fig. 2(a) shows the SEM image of the surface composition of a crack path. The crystallization products (i.e. self-healing products) in the crack path were analyzed by energy dispersive X-ray spectroscope (EDX) analysis. The result of EDX spectrum is shown in Fig. 2(b). The analysis of surface chemical composition based on EDX shows that the healing products on the surface of the crack at the age of 28 days are composed of Ca, C and O. Therefore, chemical composition of self-healing product was assumed to be $CaCO_3$. The result of Raman spectroscopy is shown in Fig. 3. The self-healing product (i.e. black line in Fig. 3(b)) showed the same as Raman spectroscopy spectrum with pure calcium carbonate crystals ($CaCO_3$). Therefore, the chemical composition of the self-healing product was also confirmed to be $CaCO_3$. From the analyzed results of crystallization products, it was confirmed that the majority of the self-healed products in cracked UHP-FRC was $CaCO_3$.



(a) (b)

Fig. 2 (a) SEM image of self-healing product and (b) corresponding EDX spectrum



(a) (b)

Fig. 3(a) Microscopic observation and (b) corresponding Raman spectroscopy spectrum

## 5. CONCLUSION

This study presented the experimental results on the self-healing capability of UHP-FRCC which can eliminate durability problems due to multiple cracks. Based on the experimental results, the following conclusions were obtained:

(1) High self-healing potential of UHP-FRC was confirmed

(2) No corrosion of steel fiber was confirmed during water curing for self-healing.

(3) The chemical composition of the self-healing product was confirmed to be $CaCO_3$ by means of EDX analyses and Raman spectroscopy.

(4) Durability problems of UHP-FRC can be avoided by self-healing-even if multiple cracking is essential for the ductile performance.

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