Experimental Study on Self-Healing Capability of Cracked Ultra-High-Performance Hybrid-Fiber-Reinforced Cementitious Composites

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ABSTRACT

High-performance fiber-reinforced cementitious composites demonstrate very good self-healing capability after immersion in water due to the closely spaced multiple cracks. To investigate the self-healing capability of ultra-high-performance hybrid-fiber-reinforced cementitious composite (UHP-HFRCC), some experiments were carried out that focused on the recovery of the air permeability coefficient and chemical precipitation on the crack surface. After cracks were introduced, the specimens were placed under uniaxial tensile load, inducing up to 0.2% strain; these cracked specimens were then immersed in water to initiate self-healing. The self-healing performance of the specimens was investigated by means of microscopic observation and an air permeability test. As a result, UHP-HFRCC was confirmed to have crystallization products within its cracks and its air permeability coefficient was recovered significantly, which means UHP-HFRCC has great potential for self-healing.

Keywords. UHP-HFRCC, self-healing, Torrent test, air permeability test

1. INTRODUCTION

There has been interest in the development and application of ultra-high-performance fiber-reinforced cementitious composite (UHP-FRCC) due to their superior tensile strain hardening behavior compared with normal fiber-reinforced composite and concrete. In addition, UHP-FRCC has higher fracture resistance capacity than ordinary concrete or regular fiber-reinforced concrete. An important feature of UHP-FRCC exhibiting strain hardening and multiple cracking behaviors **(Figure 1)** is the increase in post-cracking strength beyond the first crack strength accompanied by the development of closely spaced multiple cracks. UHP-FRCC containing mono fibers (Chanvillard *et al.* 2003, Wuest *et al.* 2008, Wille *et al.* 2011) and hybrid fibers has also been developed (Rossi, P. 1997, Benson, S.D.P. and Karihaloo, B.L. 2005). In particular, a strain-hardened cementitious composite, ultra-high-performance hybrid-fiber-reinforced cementitious composite (UHP-HFRCC), has been developed with a compressive strength of 182 MPa and additionally exhibits self-consolidation properties that provide good workability, significantly higher tensile strength (12–20 MPa), and strain capacity (0.073%–1.06%) (Kwon *et al.* 2013). UHP-HFRCC exhibits superior crack width and spacing control in

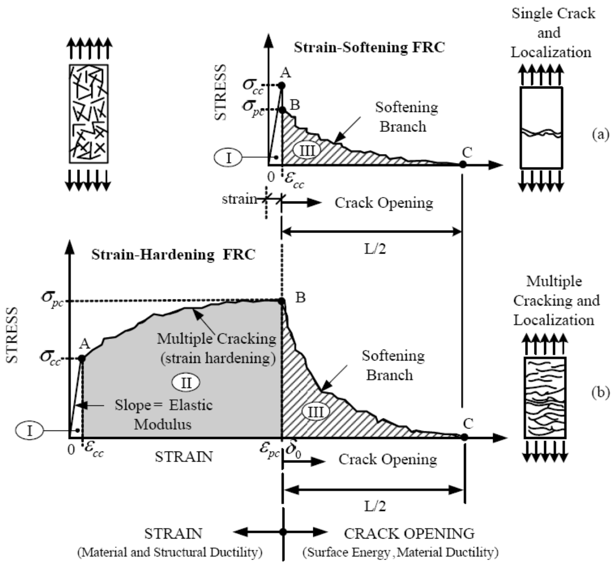
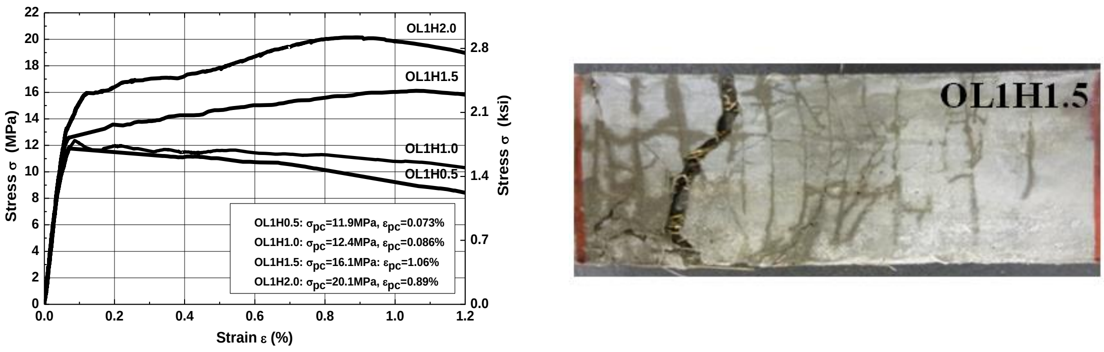


Figure 1. Typical tensile strain softening and hardening behavior of fiber-reinforced composite, HPFRCC, and UHP-FRCC (Naaman, A.E. and Reinhardt, H.W. 1996)



(a) **(b)**

Figure 2. Examples of tensile stress-strain response with different fiber content (a) Pseudo strain-hardening of UHP-HFRCC (b) Example of multiple cracking (Kwon *et al.* 2013)

the pseudo strain-hardening phase, as depicted in **Figure 2 (a)**. A typical example of multiple cracking of UHP-HFRCC in uniaxial tension is shown in **Figure 2 (b)**. However, those cracks might have causes such as drying shrinkage, external force, and freezing and thawing. Apart from these causes, cracks in the UHP-HFRCC structure allow the ingress of aggressive agents (e.g., chloride ions and CO_2), which could lead to steel fiber corrosion. Such corrosion brings about not only a decrease in structural strength but also an increase in crack width. A few research papers reported that high-performance fiber-reinforced cementitious composite

Table 1. Properties of different fibers used in this study

Notation	Form	Specific gravity (g/cm^3)	Length (mm)	Diameter (μm)	Aspect ratio (L/D)	Tensile strength (MPa)	Young's modulus (GPa)
OL6	Straight	7.85	6.0	160	37.5	~2000	206
HDR	Hooked	7.85	30.0	380	78.9	3000	206

Table 2. Mixtures for UHP-HFRCC used in this study

Notation	Mixture						Fiber		
	B	S/B	Wo/B	W/B	SP/B	D/B	ℓ_f (mm)	d_f (mm)	V_f (%)
OL1H1.5	100	35	13	14.3	1.7	0.02	6.0 30.0	0.16 0.38	Smooth 1.0 Hooked 1.5

Note: B: binder, S: sand, Wo: wollastonite, W: water, SP: superplasticizer, D: antifoaming agent

(HPFRCC) demonstrates very good self-healing performance due to the tiny width of multiple cracks (Yang *et al.* 2009, Qian *et al.* 2009). It was also reported that the multiple micro-cracks of HPFRCC provide favorable conditions for the self-healing capacity of HPFRCC because the width of multiple micro-cracks is maintained under certain limits as the elongation of the HPFRCC specimen increases. However, those studies were limited to synthetic fibers (e.g., polyvinyl alcohol, polyethylene fiber). The objective of this paper is to investigate the self-healing capability of UHP-HFRCC reinforced only with steel fibers. The capability is evaluated by microscopic observation and an air permeability test.

2. SELF-HEALING MECHANISM

Self-healing of cracks is one phenomenon that acts positively in durability problems of concrete. There are some assumptions regarding the reactions of healing (Ramm, W. and Biscoping, M. 1998): (1) occurrence of further hydration of un-hydrated clinker available in the microstructure of the hardened concrete (important for concrete with a low water/cement ratio); (2) expansion of the concrete in the crack flanks; (3) the formation of calcium carbonate crystals on the crack surface; (4) closing of the cracks by solid matter in the water; (5) closing of the cracks by spalling of concrete particles as a result of the cracking. As a result, crack width is reduced and after a certain time, the crack is repaired.

3. EXPERIMENTAL PROGRAM

3.1 Materials and specimen preparation

The UHP-HFRCC mixture was developed in our laboratory by optimizing several constituent material parameters, resulting in the mixture having a compressive strength of 182 MPa. The mixture also exhibited self-consolidating properties that provide good workability. Commercial silica fume cement (SFC), which contained a blend of low-heat cement (82 wt.%) and silica fume (18 wt.%), was used in the mixture. The density and blaine fineness of SFC were 3.01 g/cm^3 and 6,555 cm^2/g, respectively. As an aggregate, well-graded very fine natural

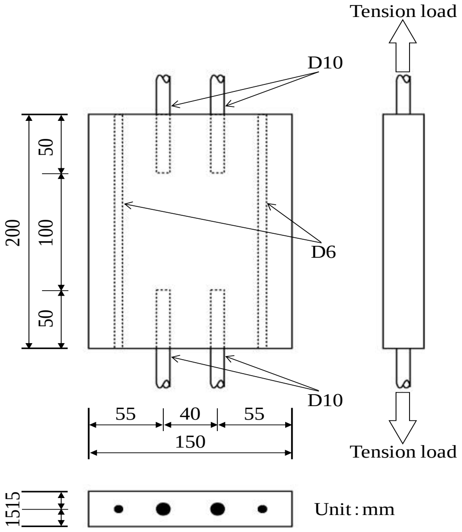


Figure 3. Uniaxial tensile loading: specimen shape

silica sand with an average particle size of 0.212 mm was used and wollastonite ($CaSiO_3$) was also substituted. The density of the wollastonite was 2.9 g/cm^3. Superplasticizer and anti-foaming agents were employed for reducing water dosage and air content. The steel fibers used in this study were 6 mm OL fiber, used as the micro-fiber, and 30 mm HDR fiber, used as the macro-fiber. The properties of the fibers are listed in **Table 1**. The volume content of OL fiber was maintained as 1.0 vol.% to maintain workability, while the volume content of HDR fiber was 1.5 vol.%. Which possessed an average tensile strength of 16.1 MPa and a tensile strain capacity of 1.06% (Kwon *et al.* 2013). **Table 2** lists the mixture proportion for the UHP-HFRCC used in this study. **Figure 3** shows the shape of the specimen used for the investigation on the self-healing properties of UHP-HFRCC. There were two rebars of D6 (SD295, F_y = 539 MPa) in the specimen to impart stable crack formation. Rebars of D10 (SD295A) were also embedded in both specimen ends to allow the specimen to be held by the testing machine (Kunieda *et al.* 2012). The specimens were cured in a steam chamber for 24 h. The steam curing conditions were as follows: the temperature was increased at a rate of 15 °C/h up to 90 °C, maintained at this value for 24 h, and then gradually cooled down to 20 °C. After steam curing, specimens were stored in a curing room at 20 °C and about 95% RH until the time of the tests.

3.2 Air permeability test

An air permeability test was conducted using the Torrent permeability tester (TPT), which was proposed by Torrent (1992). The characteristic features of the TPT test equipment are a two-chamber vacuum cell and a regulator that balances the pressure in the inner (measuring) chamber and the outer (guard-ring) chamber **(Figure 4)**. The outer guard ring prevents air from the surrounding areas from flowing into the pressure measurement chamber, which would influence the test results. During the test, the cell is placed on the concrete surface and vacuum is created using the pump. Owing to the external atmospheric pressure and the rubber rings, the cell is pressed against the surface and thus both chambers are sealed. The rate at which the pressure rises in the inner chamber is recorded, and this rate is related to the permeability of the underlying concrete. The air permeability coefficient is calculated according to Torrent's model (1992). In this study, air permeability tests were performed at the centers of the specimens.

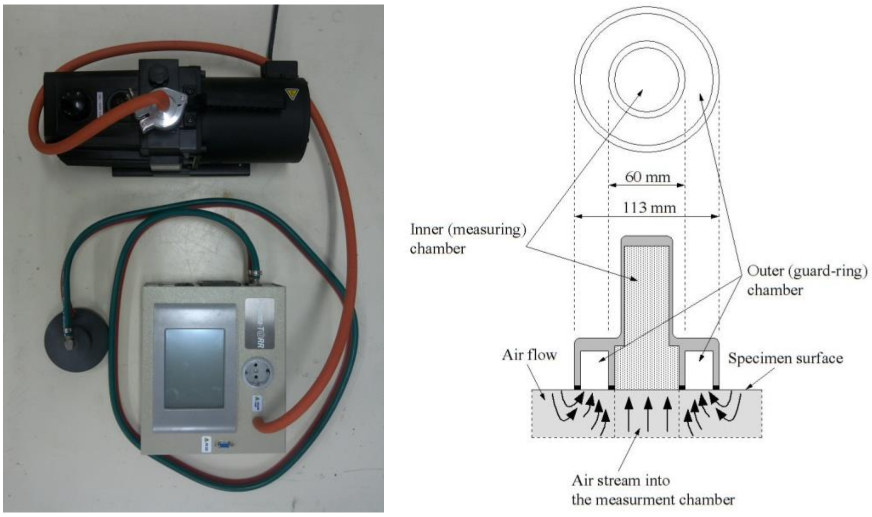


Figure 4. Torrent permeability tester (TPT)

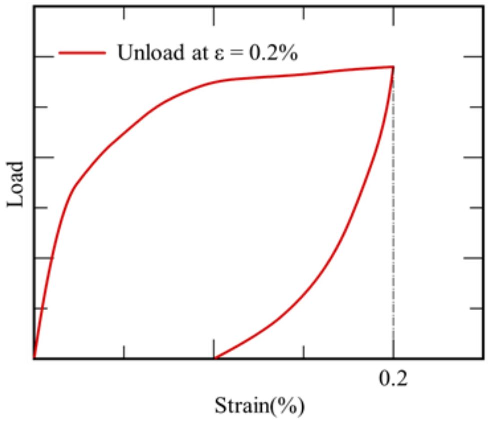


Figure 5. Schematic image of load versus strain relationship

Table 3. Tested specimens

Notation	Loaded strain (%)	Maximum crack width (μm)	Re-curing condition	Re-curing period
UHP-0	0	0	Water	3 days 7 days 14 days 21 days 28 days
UHP-0.2	0.2	76.1		

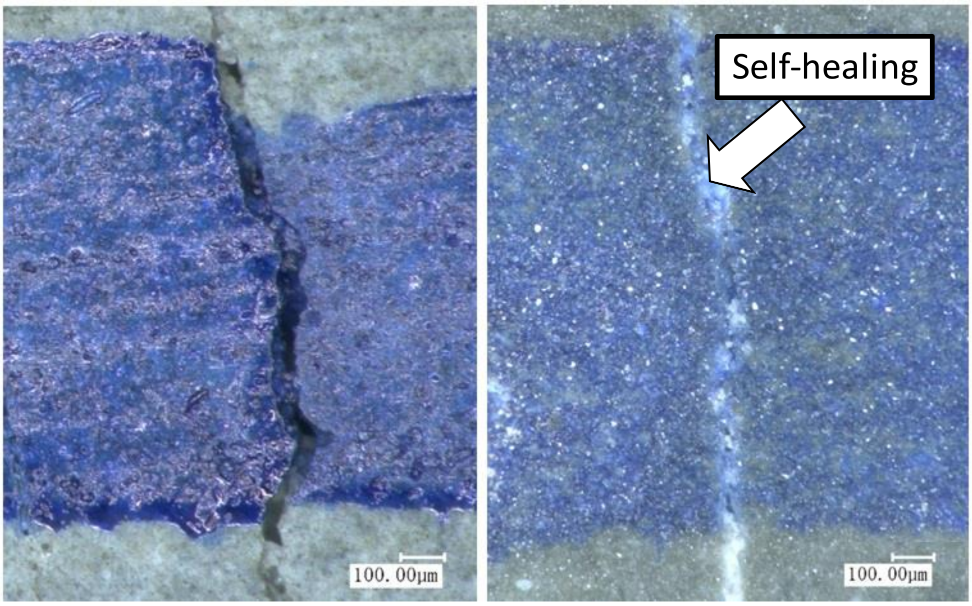
3.3 Induced crack and re-curing

Air permeability tests were carried out after curing for 7 days, and then, tensile loading was performed till up to 0.2% of strain **(Table 3)**. In **Figure 5**, the relationship between the strain and load under uniaxial tension is shown. After the tensile loading, the crack surface was observed by means of a digital microscope and the maximum crack width was measured **(Table 3)**. After the microscopic observation, the specimens were tested for air permeability again. After the air permeability tests, all specimens were kept for 28 days in a water tank at 20 °C, which are the usual conditions for standard curing. To investigate the effect of self-healing of the cracks, microscopic measurements and air permeability tests were conducted again at 3, 7, 14, 21, and 28 days. Multiple cracks were observed in the measurement area.

4. EXPERIMENTAL RESULTS

4.1 Microscopic observation

The formation of a crystallization product that might be the source of self-healing was monitored just after the tension test and at the age of 14 days. Additionally, the crack width in specimens was measured by means of a digital microscope. **Figure 6** shows the healing process of the cracked UHP-HFRCC when it had been in the curing water tank for an elapsed time of 0 days (immediately after the tension test and before immersion in water) and 14 days. There were no chemical products on the surfaces of the specimens immediately after the tension test (0 days). After 14 days, however, in the crack surfaces of the specimens, many crystallization products were confirmed to be attached **(Figure 6 (b)**. These crystallization products might be hydration products of un-hydrated cement particles, made of silica fume, which activated the pozzolanic reaction and precipitation of $CaCO_3$. These minerals and chemical reactions might significantly affect the self-healing of specimens.



(a) Before immersion in water (0 days) (b) After curing immersion in water (14 days)

Figure 6. Self-healing process of UHP-HFRCC

4.2 Air permeability tests

The air permeability coefficient was used to evaluate the self-healing capability of UHP-HFRCC. Torrent (1992) proposed quality grading of concrete using a quality index. In the proposal, an air permeability coefficient of less than 0.1 × 10^{-16} m^2 indicates good quality concrete and a coefficient of less than 0.01 × 10^{-16} m^2 indicates very good quality concrete. Note that in his proposal, the resistivity of concrete was used for the total evaluation. On the basis of this proposal, the air permeability coefficient of UHP-HFRCC before the tensile loading is below 0.001 × 10^{-16} m^2, and hence, UHP-HFRCC can be classified as great quality concrete. The air permeability coefficients of the series of cracked specimens No.1 and No.2 after tensile loading were over 0.1 × 11^{-16} m^2 and 0.2 × 183^{-16} m^2, respectively. Air permeability coefficients dramatically increased in comparison with those of un-cracked specimens. After re-curing, however, the air permeability coefficients of all cracked specimens immersed in water decreased. These results might be affected by re-hydration of un-hydrated cement particles, a pozzolanic reaction of silica fume, and a precipitation of $CaCO_3$ within the cracks. Furthermore, **Figure 7** shows that the increasing speed of recovery of the air permeability coefficient during the first 3 days is higher than that after 14 days. This is because the Ca^{2+} diffusion speed from the inside of UHP-HFRCC reduced with time. In other words, the formation of the crystallization product layer may prevent diffusion (Edvardsen, C. 1999).

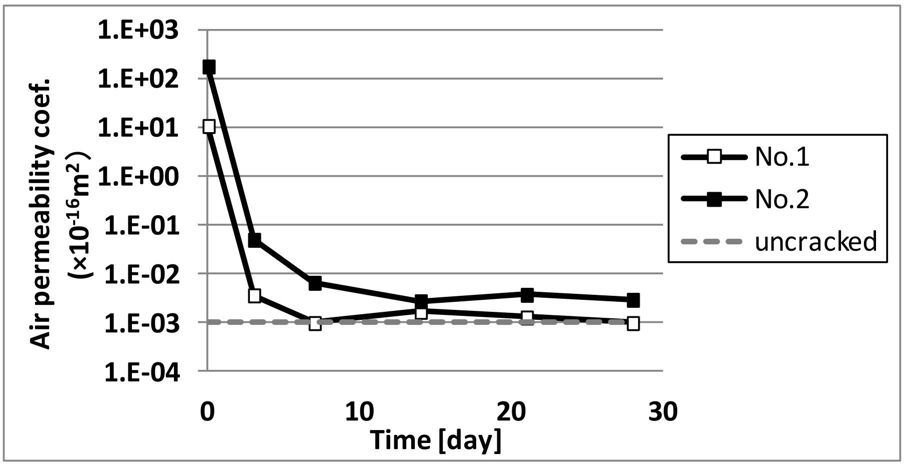


Figure 7. Time dependence of air permeability coefficient in cracked UHP-HFRCC

5. CONCLUSIONS

This paper presents results of experimental studies on the self-healing capability of UHP-HFRCC. Based on the experimental study results, the following conclusions were obtained:

1) Self-healing of cracks in UHP-HFRCC was confirmed.

2) UHP-HFRCC has potential self-healing capability. The air permeability coefficient decreases with an increase in the re-curing period.

3) Because of the self-healing, UHP-HFRCC could possibly protect itself against the ingress of aggressive agents, even if cracks occur.

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