- Technical Paper -

INFLUENCE OF SAND FINENESS ON SELF HEALING BEHAVIOR OF HIGH PERFORMANCE FIBER REINFORCED CEMENT COMPOSITES

Dong Joo Kim [*1], Seok Hee Kang [*2], and Tae-Ho Ahn [*3]

ABSTRACT

This research investigated the influence of sand fineness on tensile behavior and self healing behavior of High Performance Fiber Reinforced Cementitious Composites. Two types of sand were investigated and two types of deformed high strength steel fibers were applied to produce strain hardening behavior accompanied with multiple micro-cracks. The type of sands and fibers generated clear influence on both tensile behavior and self healing behavior of High Performance Fiber Reinforced Cementitious Composites [HPFRCC].

Keywords: Strain hardening, Sand fineness, High Performance Fiber Reinforced Cementitious Composites, Fiber type, Self healing.

1. INTRODUCTION

There has been much interest on the development and application of High Performance Fiber Reinforced Cementitious Composites [HPFRCC] due to their superior tensile strain hardening behavior compared with normal FRC and concrete. The strain hardening behavior of HPFRCC generates much favorable performance such as high load carrying capacity, high energy absorption capacity and high durability as shown in Fig. 1. (Naaman and Reinhardt [1])

The condition for strain hardening behavior of HPFRCC is that post cracking strength σ_{cc} should be higher than first cracking strength σ_{pc} as illustrated in Fig. 1. Both first and post cracking strength of HPFRCC are functions of equivalent bond strength as described in Equations 1 and 2 and the equivalent bond strength. (Naaman and Reinhardt [1])

$$\sigma_{cc} = \sigma_{mu}\left(1 - V_f\right) + \alpha\tau_{eq}V_f\left(L_f / d_f\right) \quad [1]$$

$$\sigma_{pc} = \Lambda\tau_{eq}V_f\left(L_f / d_f\right) \quad [2]$$

Where, V_f = fiber volume fraction, L_f = fiber length, d_f = fiber diameter, σ_{mu} = tensile strength of matrix, τ = bond strength, α = factor equal to the product of several coefficients for considering average stress, random distribution and fiber orientation, Λ = factor equal to the product of several coefficients for considering average pullout length, group reduction and orientation effect.

In addition to the superior tensile performance of HPFRCC, the self healing performance of HPFRCC has been recently carried out. A few research papers reported that HPFRCC demonstrated very good self healing performance due to the tiny width of multiple cracks. (Yang et al. [2], Qian et al. [3]) It was also reported that the multiple micro-cracks of HPFRCC provided favorable condition for the self healing capacity of HPFRCC since the width of multiple

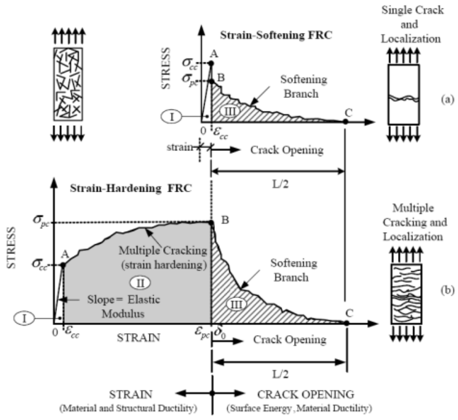


Fig. 1 – Typical tensile strain softening and hardening behavior of FRC, HPFRCC and UHP-FRC (Naaman and Reinhardt [1])

micro-cracks has been maintained under certain limit as the elongation of HPFRCC specimen increased.

The multiple micro-cracking behavior of HPFRCC is characterized by the number of multiple cracks within gage length, average crack spacing and the equivalent crack width. A strong correlation between the tensile cracking behavior of HPFRCC and single fiber pullout behavior was reported by Kim et al. [4] T-fiber reinforced HPFRCC produced better multiple cracking behavior than H- fiber reinforced HPFRCC because the pullout energy of T- fiber was 2-5 times higher than that of H- fiber in a 56MPa mortar matrix due to the higher slip capacity. Equivalent bond strength could be obtained from the pullout load – versus – slip curves as described in Equation 3. In Equation 3, it is assumed that the average embedment length of fibers is the half of fiber length.

$$\tau_{eq} = 8E_{pullout} \big/ \pi d_f L_f^{\,2} \quad [3]$$

Where, $E_{pullout}$ is the area under pullout load – slip curve, L_f = fiber length, d_f = fiber diameter.

*1 Assistant Professor, Dept. of Civil and Environmental Eng., Sejong University, Seoul, Korea, JCI Member
*2 Graduate Student, Dept. of Civil and Environmental Eng., Sejong University, Seoul, Korea,
*3 Assist.Prof./Research Associate, Dept. of Human & Social Systems,The University of Tokyo, JCI Member

Pullout energy ($E_{pullout}$), the area under the pullout load – slip curve, of deformed steel fibers during fiber pullout is much influenced by bond properties at the interface between fiber and matrix.

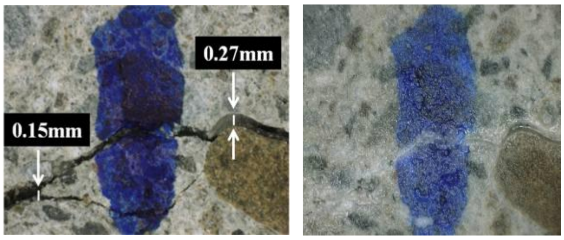
One of main parameters influencing the properties at the interface between fiber and matrix is sand fineness or mortar fineness since the packing density surrounding the fiber generates material properties at the Interface Transition Zone (ITZ). (Gurrero and Naaman [5] In addition, the influence of aggregate type and size on the ductility and mechanical properties of Engineered Cementitious Composites using PVA fibers was investigated by Sahmaran et al. [6]. They reported that the ECC mixture mixed with crushed limestone sand or gravel sand with higher maximum aggregate size, instead of micro silica sand, also produced strain hardening with multiple cracks.

However, there is still not enough information about the influence of sand fineness on the tensile behavior of HPFRCC with high strength deformed steel fibers and especially about the multiple cracking behavior, e.g., the number of cracks within gage length and crack width. Since the self healing capacity is highly dependent upon the width of crack, it is also questioned whether the sand fineness in the matrix composition of HPFRCC would generate any influence on the multiple cracking behavior and thus self healing behavior of HPFRCC.

The objective of this paper is to investigate the influence of sand fineness on the multiple cracking and self healing behavior of HPFRCC. The detailed objectives are: 1) to provide a tensile stress – strain response of HPFRCCs with different sand fineness; 2) to investigate the influence of the sand fineness on the multiple cracking behavior of HPFRCC with different deformed steel fibers; and, 3) to estimate the self healing behavior of HPFRCC according to the different types of sand and fiber.

2. SELF HEALING BEHAVIOR

Self healing behavior of concrete is as shown in Fig. 2. Lauer and Slate [7] reported that the healing of cement paste was mainly caused by formation of crystals of calcium carbonate and calcium hydroxide in the cracks and it occurred more rapidly under water than in air. Hannat and Keer [8] investigated antogeneous healing of thin cement based sheet. They reported that the tensile strength of the healed cracks after two years exposure to natural weathering was about 50% of the tensile strength of the uncracked samples. Gray [9] reported autogeneous healing of bond at the interface between steel fiber and a mortar matrix under continued water curing. Hearn [10] discussed the sources of healing and sealing differently if the phenomenon was permanent or not. Edvardsen [11] also insisted that the main cause for the autogeneous healing of the cracks is the formation of calcite in the cracks. In addition to continued hydration and carbonation reaction, various methods have been developed to enhance the healing capacity.



(a) Crack (b) 33days

Fig. 2- Self healing behavior of Concrete (Ahn and Kishi [12])

Recently, the self healing behavior of ECC, one of HPFRCCs, has been intensively reported. The tiny width of multiple micro-cracks of HPFRCC provides favorable condition for self healing. (Yang et al. [2], Qian et al. [3]) In this study, the self healing behavior of HPFRCC with high strength deformed steel fibers is reported and the influence of sand fineness on the tensile and healing behavior of HPFRCC is discussed.

3. TENSILE BEHAVIOR OF HPFRCC

Two types of sand were investigated as shown in Fig. 3: Sand A is crushed sands and Sand B is micro silica sand. As shown in Fig. 4, two types of high strength steel fibers, Hooked (H-) and Twisted (T-), with slip hardening pull-out behaviour, were used in high strength cementitious matrices with 2% fiber by volume contents. Direct tensile tests were carried out using a universal material testing machine running in displacement control. The loading velocity applied is 1mm/min.

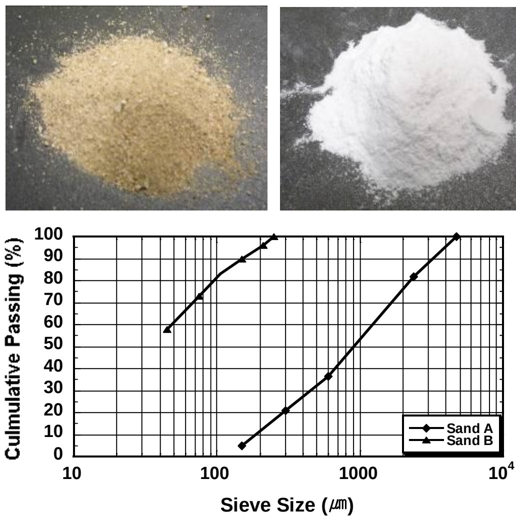


Fig. 3- Sand A and Sand B

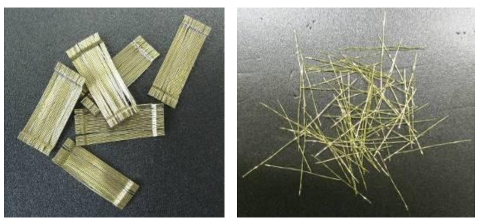


Fig. 4- Hooked and Twisted fibers

3.1 Materials and specimen preparation

The matrix mix composition and compressive strength are shown in Table 1, and the properties of fibers are shown in Table 2. The compressive strength of the matrix was measured from 100x200 mm cylinders and this matrix composition is self-consolidating mixture.

Table 1 - Composition of Matrix Mixtures by weight ratio and compressive strength

	Cement (Type III)	Fly ash	Sand A	Sand B	Silica Fume	Super - Plasticizer	Water	$f_c^{'}$ (MPa)
Matrix A	0.80	0.20	1.00	-	0.07	0.04	0.26	81
Matrix B	0.80	0.20	-	1.00	0.07	0.04	0.26	113

Table 2 – Properties of fibers

Fiber Type	Diameter (mm)	Length (mm)	Density, g/cc	Tensile strength, (MPa)	Elastic Modulus, (GPa)
Hooked	0.375	30	7.9	2311	200
Twisted	0.300*	30	7.9	2428**	200

* Equivalent diameter ** Tensile strength of the fiber after twisting

3.2 Test set-up and procedure

The geometry of tensile test specimen and test set up are shown in Fig. 5. In order to avoid the failure of specimen out of gage length and at the grip, two layers of steel wire mesh were used to reinforce the bell shaped ends. The section of tensile specimens is 50mm by 25mm and the gage length was selected to be 175mm. A special aluminium cage is attached to the tensile specimen to install two LVDTs to measure elongation during testing. The signals obtained from two LVDTs were averaged to estimate the tensile strain.

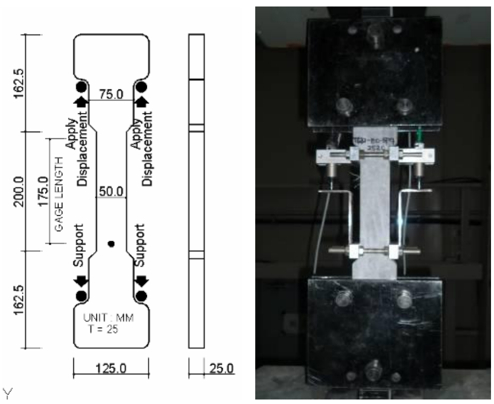
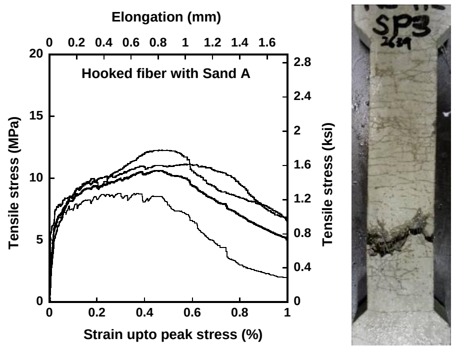


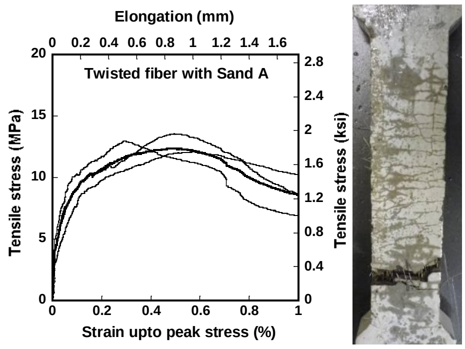
Fig. 5- The geometry of tensile test specimen and set-up

3.3 Test results

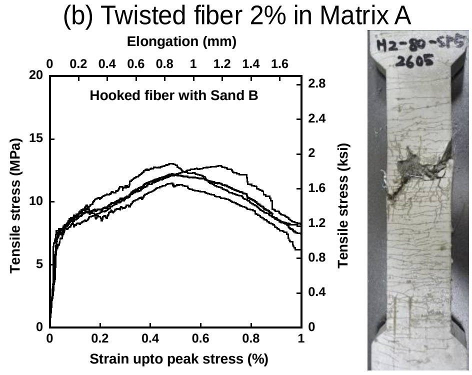
Fig. 6 shows tensile stress – strain curves and photos illustrating the number of cracks and crack spacing for each test series.



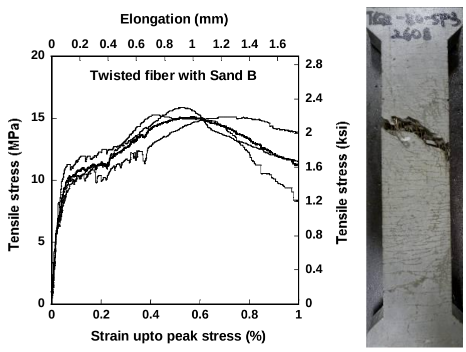
(a) Hooked fiber 2% in Matrix A



(b) Twisted fiber 2% in Matrix A



(c) Hooked fiber 2% in Matrix B



(d) Twisted fiber 2% in Matrix B

Fig. 6- Tensile stress – strain curves

The test results for H- fiber 2% in matrix A, T- fiber 2% in matrix A, H- fiber 2% in matrix B, T- fiber 2% in matrix B are shown in Fig. 6a, 6b, 6c and 6d, respectively. All of test series showed strain hardening behavior and multiple micro cracking behavior as shown in Fig. 6.

Averaged numerical values of several tensile parameters describing tensile response, e.g. first cracking strength, maximum post cracking strength, strain capacity at maximum post cracking strength and number of cracks (and related crack spacing) are summarized in Table 3. These numerical values are also averaged from at least three specimens.

Table 3 – Tensile parameters of HPFRCC

Fiber type & Volume fraction	First cracking strength MPa	Post Cracking Strength MPa	Strain Capacity %	Number of cracks EA	Crack Spacing mm	Average Crack Width micrometer
H- 2% in Matrix A	7.814	10.738	0.451	18	9.91	44.80
T- 2% in Matrix A	8.779	12.876	0.450	23	7.68	33.76
H- 2% in Matrix B	7.879	12.595	0.546	42	4.17	22.91
T- 2% in Matrix B	9.707	15.361	0.519	47	3.73	19.41

4. SELF HEALING BEHAVIOR OF HPFRCC

4.1 Crack self healing examination methods

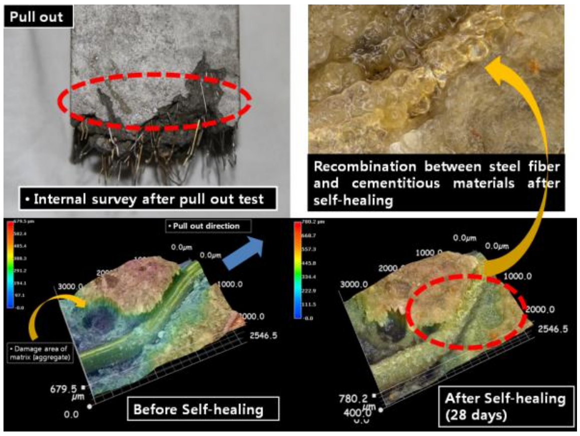
HPFRCC for the verification of self-healing capability were prepared following tensile test. Crack width was controlled by tensile test and then some specimens were fully pulled out in order to survey interfacial matrix damage as shown in Fig. 7.a. And the specimens were water cured for 28 days with pH 7 condition.(water submersion) Digital 3D Microscopy and SEM with EDS-detector were carried out to investigate the morphology, shape, and size of re-hydration products of HPFRCC.

4.2 Influence of sand fineness on interfacial matrix damage during fiber pullout

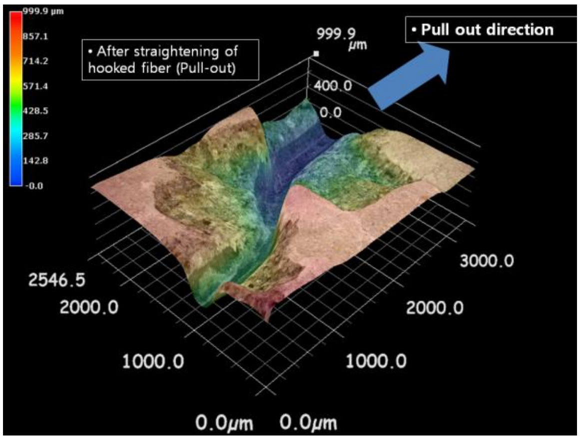
The straightening process of an end hook of H-fiber in cement mortar matrix can generate interfacial matrix damage although the degree of damage is dependent upon the strength of matrix. Thus, the sand fineness of cement mortar matrix is also one of governing parameters influencing the interfacial properties.

Fig. 7a shows a clear damage in the interfacial zone surrounding fiber in matrix A (containing sand A) before pullout of H- fiber. However, H- fiber in matrix B (containing sand B) shows no damage after complete pullout of H- fiber as shown in Figure 7b, i.e., the use of micro silica sand in matrix improved the interfacial properties.

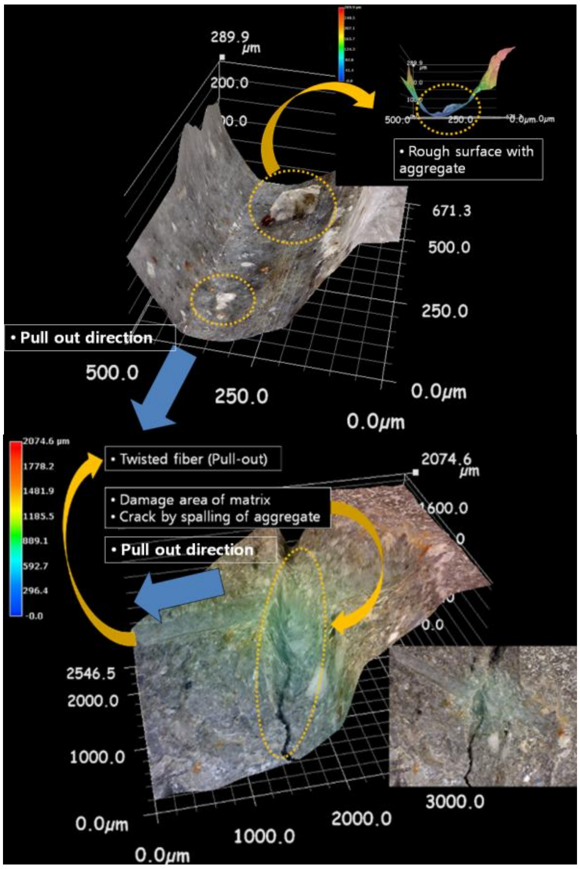
T- fiber, unlike H- fiber, should be untwisted during fiber pullout to be pulled out. During pullout, there might be matrix damage at the interface between fiber and matrix. Thus, the interfacial matrix damage during T- fiber pullout is also dependent upon the sand fineness of matrix. Fig. 7c and 7d shows interfacial zone surrounding T- fiber after complete pull-out of T-fiber in matrix A and B, respectively.



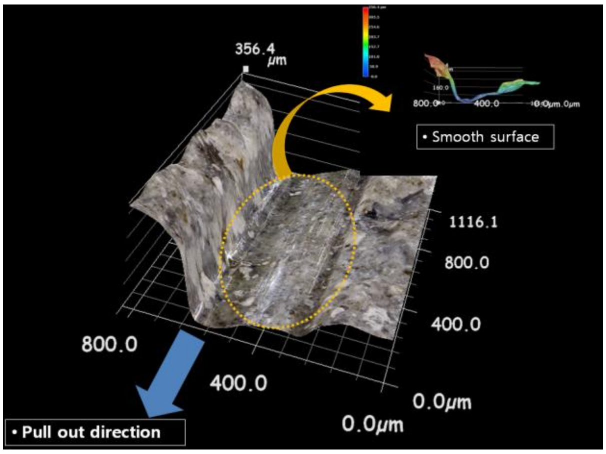
(a) Hooked fiber 2% in Matrix A



(b) Hooked fiber 2% in Matrix B



(c) Twisted fiber 2% in Matrix A



(d) Twisted fiber 2% in Matrix B

Fig. 7. Relationship between crack and pull-out behaviour of steel fibers on influence of sand fineness

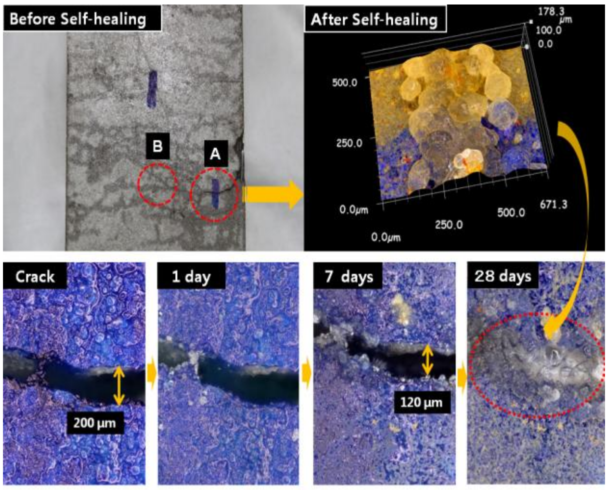
T- fiber, with a proper twist ratio, tends to untwist during fiber pullout from surrounding matrix. As shown in Figure 7, T- fiber produced little damage to the surrounding matrix in comparison with H- fiber. Although T- fiber generated little damage than H- fiber, the sand fineness in mortar matrices surrounding T- fiber also generate different interfacial characteristics as shown in Fig. 7c and 7d. In case of matrix A, tunnel of matrix has rough surface with aggregate as shown in Fig. 7c. This indicates that normal sand could be extracted, during T- fiber pullout, from matrix tunnel. Actually, this crack formation as shown in Fig. 7c seems to be related to these reactions when T- fibers is pulled out. In case of matrix B, the surface of matix tunnel is smoother than in matrix A as shown in Fig. 7d. Thus, it could be concluded that the matrix B (with micro silica sand) has a better damage resistance than matrix A (with normal sand). Moreover, it was found that self-healing phenomenon occurred under the water submersion condition as shown in Fig 7a. It is considered that HPFRCC also has a high potential for self-healing capability. These results are reported and discussed in the following section.

4.3 Influence of crack width on self-healing behavior of HPFRCC

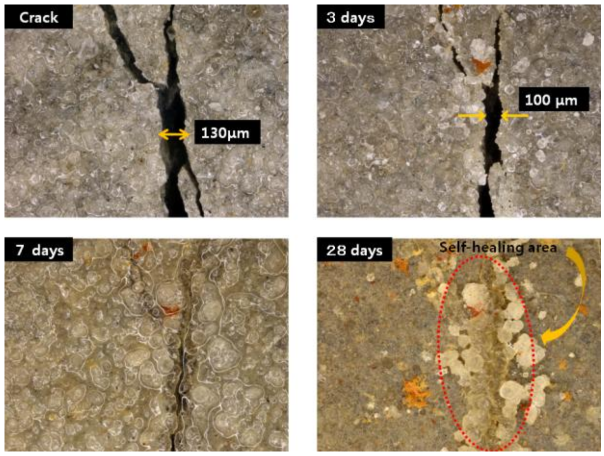
The self healing behavior of HPFRCC with a low water to binder ratio (W/B =0.26) was investigated according to the different types of sand and fiber.

Fig. 8a and 8b show the different healing process of cracked HPFRCC with 2% H- fibers in matrix A under water supply according to crack width. In Figure 8a, crack with an initial width of 200 ㎛ is still remained unhealed completely at early stage(A area). However, when the crack width was below 100 ㎛ as shown in Figure 8b, the crack was considerably healed by filling the crack with re-hydration products. Furthermore, the crack closed by formation of self-healing products after 7 days re-curing.

Fig. 9 and Fig. 10 show the effect of crack width on self-healing behavior clearly. As shown in Fig. 9, when the width of crack was around 50 ㎛, cementitious recrystallization and precipitation of calcium salts were heavily occurred in the cracks. Furthermore, when the width of cracks is below 20 ㎛ as shown in Fig. 10, it is very clear that the crack is completely self-healed in very early stages (within 3 days). This means that self-healing capability of HPFRCC is strongly dependent on the crack width.



(a) Crack width (200 ㎛) (A area)



(b) Crack width (130 ㎛, 100 ㎛) (B area)

Fig. 8- Process of self-healing on Matrix A with hooked fiber 2%

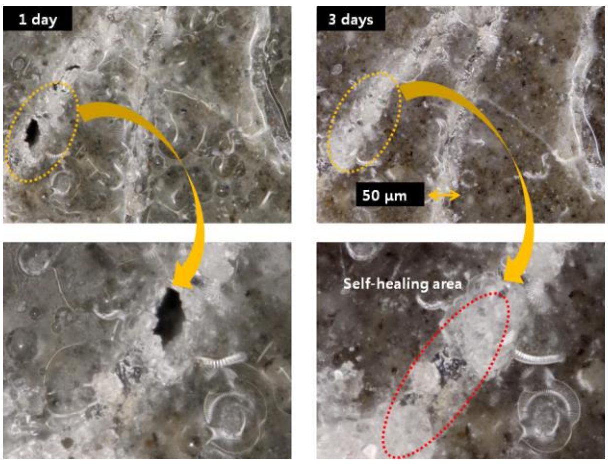


Fig. 9- Process of self-healing on Matrix A with twisted fiber 2% (Crack width 50 ㎛)

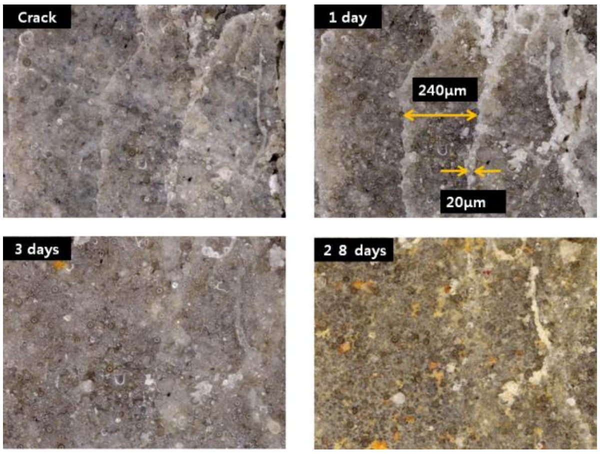


Fig. 10- Process of self-healing on Matrix B with twisted fiber 2% (Crack width 20 ㎛)

Therefore, the reasonable types of sand and fiber should be carefully applied in material design of HPFRCC for maximizing potential self-healing capacity of HPFRCC.

5. Summary and conclusions

In this study, two types of sand were investigated and two types of deformed high strength steel fibers were applied to develop strain hardening Fiber Rerinforced Cement Composites which accompany very fine multiple micro-cracks which are favorable condition for self healing.

1) The type of sands and fibers generated clear influence on both tensile behavior and self healing behavior of High Performance Fiber Reinforced Cementitious Composites [HPFRCC].
2) The type of sand significantly affected the crack width and eventually self-healing behavior of HPFRCC. Micro silica sand is more desirable for multiple micro cracks of HPFRCC because it increases resistance to pull-out without damage of surrounding matrix as well as improves the self-healing capability of HPFRCC.
3) Microscopy analysis results show that most of the cracks (below 50㎛) were fully filled by newly-formed hydration products in short term period. Self-healing capability of HPFRCC was largely dependent on the crack width.

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