Third International Conference on Sustainable Construction Materials and Technologies http://www.claisse.info/Proceedings.htm

# Evaluation of Self-Healing Capability of FRCC using PVA as Reinforcing Fiber and Admixture

Tomoya Nishiwaki[1*], Makoto Yamada[1], Takatsune Kikuta[1] and Hirozo Mihashi[1]

[1]*Architecture and Building Science, School of Engineering, Tohoku University, Japan*
**6-6-11-1205 Aoba, Aramaki, Aoba-Ku, Sendai 980-8579, Japan, ty@archi.tohoku.ac.jp*

## ABSTRACT

Experimental studies were carried out to evaluate the self-healing capability of fiber reinforced cementitious composite (FRCC), to enhance its durability. For this purpose, polyvinyl alcohol (PVA) was used not only as a reinforcing fiber but also as an extra admixture. It was confirmed in a recent study that PVA fiber that had the high polarity of a synthetic composite could enhance self-healing capability of FRCC. In this study, FRCC specimens were subjected to uniaxial tension test in order to generate a crack in them, and the cracked specimens were then immersed in water. In order to evaluate their self-healing capability, water permeability test and microscopic observation were then carried out. It was found that the addition of an extra dose of PVA as an admixture could improve ductility of a specimen, as measured in the tension test, and also increase the complexity of the crack flanks. It was also found that it could enhance the chemical precipitation on the cement matrix of the crack flanks, so the coefficient of permeability could be restored to the point it was previous to the crack generation. Thus, an admixture of PVA might be expected to enhance the self-healing capability of cracks.

**Keywords.** self-healing, FRCC, PVA, calcite precipitation, water permeability

## 1. INTRODUCTION

Year by year it becomes more obvious how important it is to construct a sustainable society, and how the high durability of our infrastructures plays a large role in this. One obstacle to such durability is the cracking of concrete, which is inherent in reinforced concrete structures, and leads to serious damage that diminishes their durability. This can take such form as increased permeability, the ingress of aggressive agents and the corrosion of reinforcing steel within the concrete. To prevent such damage and deterioration, it is important to perform periodic and/or detailed inspections, as well as make the appropriate repairs. The cost of such maintenance, though, will not only become higher, but will assume huge proportions in terms of the direct expense incurred in making these inspections and repairs, as well as the indirect economic loss, e.g., the need to substitute structures, periods in which the use of structures is suspended, etc. One factor that runs counter to this tendency is that, even in the case of ordinary concrete, cracks with a small width, that is, a width of 0.1 mm or narrower, tend to close autogenously in the presence of moisture due to the precipitation of calcium carbonate (Edvardsen 1999). Thus, the self-healing of cracks is one favorable phenomenon that facilitates the durability of concrete. Such self-healing phenomena can be expected to be effective in the case of fiber reinforced cementitious composite (FRCC), which has been recognized as a material that is conducive to autonomic healing. FRCC has a mechanical property that is able to control crack propagation in the cement matrix via bridging with short fibers. Although the self-healing process requires crack widths that are sufficiently narrow, it is expected that FRCCs will be able to demonstrate great self-healing capability. Li et al. (1998) conducted experimental studies on the self-healing capability of engineered cementitious composites (ECC), and concluded that cementitious materials with an inherently tight crack width were effective at self-healing. Kan et al. (2010) demonstrated that self-healing products of ECC were identified as consisting mainly of C-S-H and calcium carbonate based on ESEM-EDS and TEM observations. Mihashi et al. (2011) reported FRCC demonstrated better resistance to the corrosion of steel bar than mortar because of the fiber bridging of cracks and the self-healing of some of these cracks. Homma et al. (2009) confirmed that reinforcing fibers bridging the crack surface serve not only to control crack width, but also provide a core for the deposition of chemical products. They also reported that the larger the numbers of bridging fibers, the more effective was the self-healing capability. Koda et al. (2011) concluded that different types of fibers showed different levels of self-healing performance. In particular, a fiber that has a polarity (e.g., poly vinyl alcohol, PVA) promotes the deposition of crystallization products on the crack surface more effectively than other types of fibers. Nishiwaki (2012) revealed that the chemical properties (polarity) of the reinforcing fiber alone were not sufficient, but that both the chemical and mechanical properties of FRCC, together, could lead to better self-healing. The specific mechanism involved is as follows: the complexity of the crack flanks that occurs as a result of ductile behavior under tensile stress facilitates the precipitation of calcite.

According to recent studies, FRCC with synthetic fibers, including PVA, offers great potential for the self-healing of cracks. It has already been confirmed that PVA is more conducive to crack closing with calcite precipitation than other types of synthetic fibers, because of its polarity property (Koda et al. 2011). However, the quantity of reinforcing fiber that can be added to FRCC is limited, owing to issues of workability. In this study, experimental studies using an additional dose of PVA as an admixture were carried out in order to enhance the self-healing function. The results obtained could help lead to the use of self-healing FRCC as a practical engineered material.

## 2. SELF-HEALING MECHANISM

There are some assumptions regarding the dynamics involved in the healing of cracks (Ramm et al. 1998): (1) further the hydration of un-hydrated cement; (2) expansion of the concrete in the crack flanks; (3) crystallization of calcium carbonate on crack surface; (4) the filling up of the crack by solid matter in the water and/or spalling-off of loose concrete particles that result from the cracking. Regarding FRCC used with synthetic fibers, the crystallization of calcium carbonate on the crack surface (flank) in the presence of moisture is the most influential factor. In this process, the dissolved $CO_2$ and the calcium ion in water combine with each other to produce calcium carbonate crystals. Homma (2009) revealed that the self-healing mechanism was accelerated in cracks that contained bridging fibers and that this could serve as the core of a precipitation site. Moreover, Koda (2011) showed that a greater quantity of precipitation was promoted in case of using synthetic fibers that have polarity because of attracting calcium ion.

## 3. EXPERIMENTAL PROGRAM

FRCC specimens using PVA as a reinforcing fiber and as an admixture were prepared and subjected to experimental study in order to confirm their self-healing capability. Uniaxial tension test was carried out in order to introduce cracks in the specimens, which were then cured again in a water tank. The cracked and re-cured specimens were subjected to water permeability test and microscopic observation. Calcite precipitation on the surface of the specimens and on the flanks of the cracks was observed with a digital microscope. **Table 1** shows the experimental series and the mix proportions. **Table 2** presents the employed materials and their properties. PVAs having different degrees of saponification were employed: a higher degree (99%) was used as a short reinforcing fiber, and a lower degree (96%) was dissolved in the mixing water as an admixture. As a result, the PVA-A series contained higher total volume content (3.5 vol. %) of PVA than the PVA-F series. the dissolved PVA could serve as a viscous agent to improve workability and distribution of reinforcing fibers. **Figure 1** shows an employed specimen and apparatus of a uniaxial tension test. The geometry of the specimen was a plate of 85 mm × 85 mm × 30 mm and four screw bars (M6) with an anchor nut at the tip are installed (Homma 2009). After casting, specimens were settled in a water tank at a temperature of 20 °C for 7 days. After the first curing step, each specimen was subjected to a uniaxial tensile test via the embedded screw bars to generate a crack, which had a maximum width of approximately 300 µm. The cracked specimens were then subjected to a water permeability test. After this test, the specimens were immersed under the same condition as in the first curing step (the second curing step). During the second curing step, the water permeability test was again carried out after 3, 14, and 28 days had passed from the start of the second curing step. During this time, the surface around the cracks was observed by the digital microscope. **Figure 2** shows the apparatus of this permeability test (an improvement upon that of Kishimoto 2007). The coefficient of the water permeability was calculated from the volume of water that permeated the specimen. After curing for 28 days (at the end of the second curing step), specimens were split into 2 pieces, and the fractured surface (flanks of the crack) of the specimen was observed with a digital microscope in order to obtain information on the calcite precipitation area and the geometry of the crack surface. In order to calculate the precipitated area, phenolphthalein was sprayed onto the crack surface (its flank sides), and a photo of its surface was binarized (**Figure 3**). The white area ratio was calculated as the calcite precipitation area. The arithmetic mean roughness *Ra* was calculated according to JIS B 0601 (after ISO 4287). The surface profile was measured using microscope algorithm, based on where the obtained photographs are in focus, and out of focus (Nayar 1994).

**Table 1 Mix proportion of FRCC specimens**

| Series | W/B | S/B | SF/B | SP/B | Fiber (Vol. %) | Admixture* (Vol. %) |
|---|---|---|---|---|---|---|
| PVA-F | 0.45 | 0.45 | 0.15 | 0.009 | 2.0 | - |
| PVA-A | 0.35 | | | | | 1.5 |

B: binder (cement + silica fume), * Dissolved PVA that had a lower degree of saponification

**Table 2 Properties of employed materials**

| Material | Symbol | Properties |
|---|---|---|
| Cement | C | High early strength Portland cement, Density: 3.14 g/cm$^3$ |
| Silica fume | SF | Density: 2.20 g/cm$^3$ |
| Sand | S | Silica sand #5, Density: 2.61 g/cm$^3$, Diameter: ~500 μm |
| Super plasticizer | SP | Polycarboxylic acid ether system Density: 1.05 g/cm$^3$ |
| PVA fiber | PVA-F | Polyvinyl alcohol, Degree of saponification: 99 %, Density: 1.30 g/cm$^3$, Diameter: 37 μm, Length: 6 mm |
| PVA admixture | PVA-A | Polyvinyl alcohol, Degree of saponification: 96 %, Density: 1.30 g/cm$^3$ |

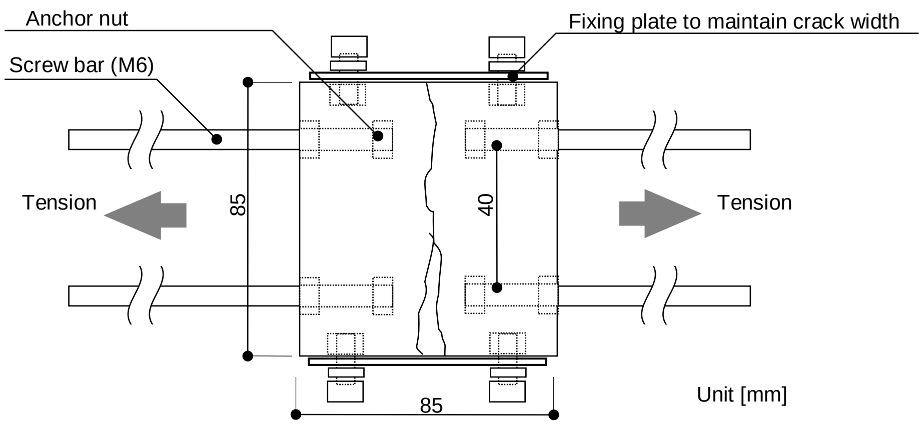



**Figure 1. Employed specimen**

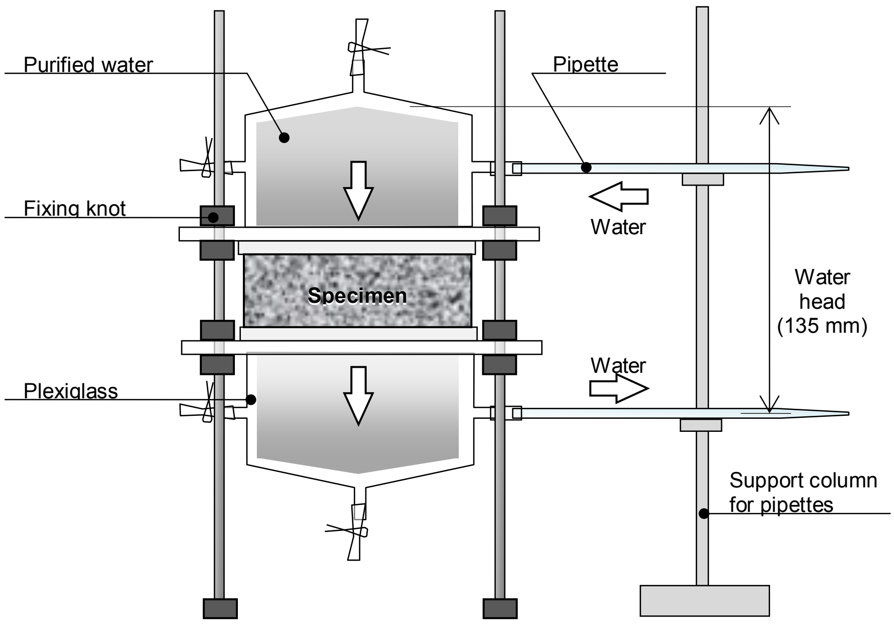
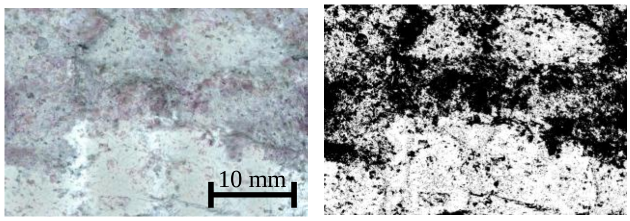



**Figure 2. Apparatus for water permeability test**




(a) Original (b) Binarized

**Figure 3. Calculation of precipitated area**

## 4. RESULTS AND DISCUSSION

**Figure 4** shows the relationship between the elongation and the load during the uniaxial tension load test. As can be seen in the figure, the PVA-A series shows higher tensile strength and better ductility than the PVA-F series because of difference of water/binder ratio. In both cases, multiple cracking appeared. PVA admixture is normally applied to concrete in order to improve its workability and water tightness. In PVA-A series, additionally, to improve fiber distribution might be contributed to improve mechanical properties. **Figure 5** shows photographs of the surface of each specimen, including the maximum crack width, as obtained by microscopic observation. After the second curing step, remarkable self-healing was observed even after only 3 days of curing in both the PVA series. **Figure 6** shows the relationship between the number of curing days in the second curing step and the coefficient of water permeability ($k$). **Figure 7** shows the normalized coefficient of water permeability. This coefficient was estimated as the ratio of the value of $k$ on each curing day to the value of $k$ just after cracks were introduced. From these results, it can be seen that both PVA-F and PVA-A demonstrated self-healing such that they were able to recover the degree of water tightness that they displayed prior to the appearance of crack. In other words, the PVA admixture did not significantly affect the self-healing performance. However, **Table 3** presents the profile of the surface of the crack flanks, i.e., the area of calcite precipitation and the arithmetic mean roughness *Ra*. The capability of self-healing phenomena of FRCC was evaluated in terms of the degree of chemical precipitation and the complexity of crack surface (Nishiwaki 2012). Since the PVA-A series was able to improve both of these factors, an additional dose of PVA as an admixture is expected to enhance the self-healing capability.

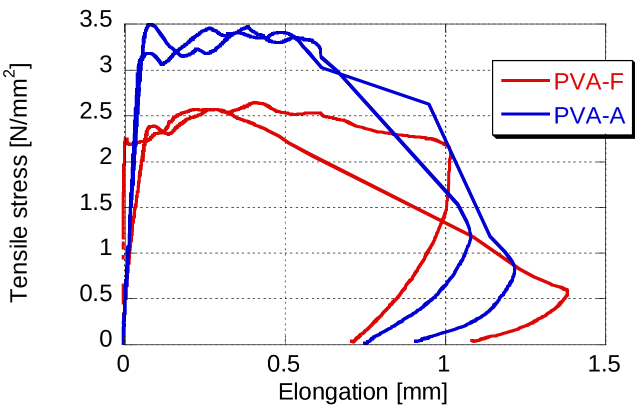
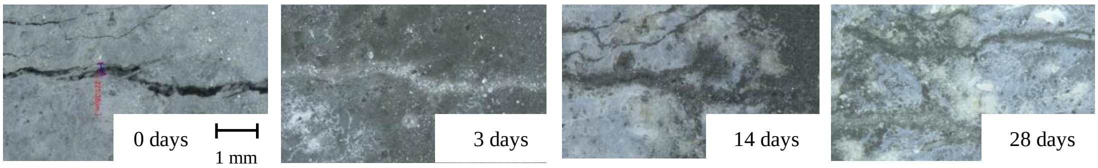
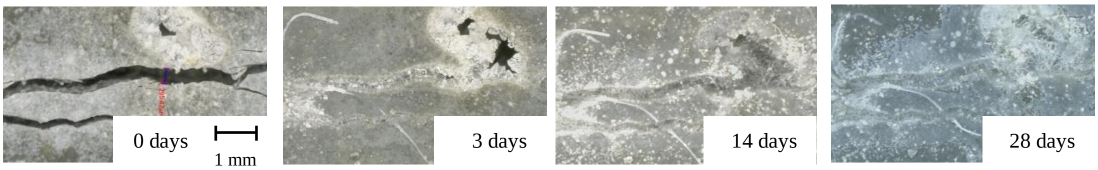



**Figure 4. Relationship between tensile stress and elongation**




**(a) PVA-F series (Maximum crack width: 225 µm)**




**(b) PVA-A series (Maximum crack width: 273 µm)**

**Figure 5. Microscopic observation of precipitation around crack**

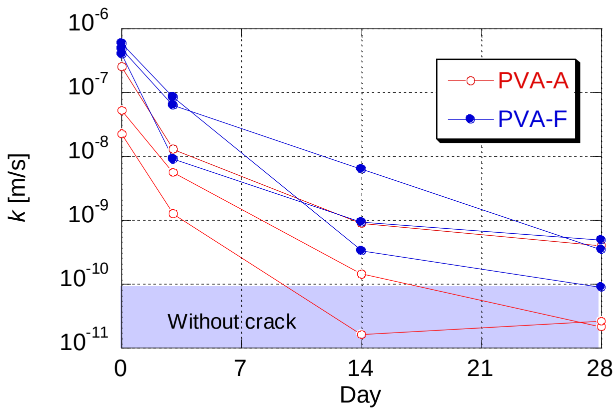



**Figure 6. Relationship between time and coefficient of water permeability (*k*)**

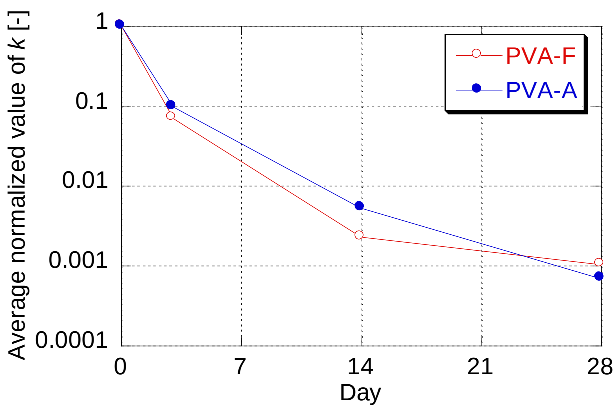



**Figure 7. Relationship between time and average normalized *k***

**Table 3. Profile of the surface of the crack flanks**

| Series | Calcite precipitation area (%) | Arithmetic mean roughness *Ra* (mm) |
|---|---|---|
| PVA-F | 32.0 | 1.14 |
| PVA-A | 46.3 | 1.74 |

## 5. CONCLUDING REMARKS

In this study, the self-healing capability of FRCC was investigated using PVA not only as reinforcing fibers but also as an admixture. As our results show, both PVA-F and PVA-A were able to fill up generated cracks with calcite precipitation and were also able to recover their coefficient of water permeability almost up to the level displayed when there was no crack. On the other hand, the PVA-A series exhibited a better profile of the crack flank surface where calcite precipitation had occurred, i.e., where there was the interaction of the chemical precipitation and the complexity of crack surface (flanks). Finally, an additional dose of PVA as an admixture is expected to enhance the self-healing capability of FRCC.

## ACKNOWLEDGEMENT

This research was partially supported by a Grant-in-Aid for Young Scientists (A) from the Ministry of Education, Culture, Sports, Science and Technology of Japan (#23686078, 2011-2014).

## REFERENCES

Edvardsen, C., (1999). “Water Permeability and Autogenous Healing of Cracks in Concrete.” *ACI Materials Journal*, 96 (96-M56), 448-454.

Homma, D., Mihashi, H. and Nishiwaki, T., (2009). “Self-Healing Capability of Fibre Reinforced Cementitious Composites.” *Journal of Advanced Concrete Technology*, 7 (2), 1-12.

Kan, L.L., Shi, H.S., Sakulich, A.R. and Li, V.C., (2010). “Self-Healing Characterization of Engineered Cementitious Composite Materials.” *ACI Materials Journal*, 107 (6), 617-624.

Kishimoto, Y. Hokoi, S., Harada, K. and Takada, S., (2007). “The Effect of Vertical Distribution of Water Permeability on the Modeled Neutralization Process in Concrete Walls.”, *Journal of ASTM International*, 4 (1), Paper ID JAI100323.

Koda, M., Mihashi, H., Nishiwaki, T., Kikuta, T. and Kwon, S.M., (2011). “Self-Healing Capability of Fiber Reinforced Cementitious Composites.” *Proceedings of the 3rd International Symposium on Advances in Concrete through Science and Engineering* (Hong Kong, China), RILEM, CD-ROM (abstract 119).

Li, V.C., Lim, Y.M. and Chan, Y.-W., (1998). “Feasibility study of a passive smart self-healing cementitious composite.” *Composites- Part B*, 29B, 819-827.

Mihashi, H., Ahmed, S.F.U. and Kobayakawa, A., (2011). “Corrosion of Reinforcing Steel in Fiber Reinforced Cementitious Composites.” *Journal of Advanced Concrete Technology*, 9 (2), 159-167.

Nayar, S.K. and Nakagawa, Y., (1994). "Shape from Focus." *IEEE Transactions on Pattern Analysis and Machine Intelligence*, 16(8), 824-831.

Nishiwaki, T., Koda, M., Yamada, M., Mihashi, H., and Kikuta, T., (2012). “Experimental Study on Self-Healing Capability of FRCC Using Different Types of Synthetic Fibers.” *Journal of Advanced Concrete Technology*, 10, 195-206.

Ramm, W. and Biscoping, M. (1998). “Autogenous healing and reinforcement corrosion of water-penetrated separation cracks in reinforced concrete.” *Nuclear Engineering and Design*, 179(2),191-200.