Experimental study on self-healing effect of FRCC with PVA fibers and additives against freeze/thaw cycles

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ABSTRACT
It has been confirmed by some previous research that some types of fiber-reinforced cementitious composites (FRCCs) particularly using synthetic fibers (e.g. polyvinyl alcohol; PVA) has a great capability of self-healing of cracks. In this study, self-healing capability of FRCCs with the effects of additives such as silica fume and excess PVA dosage were tested. Experimental studies were carried out to evaluate the self-healing capability against freeze/thaw cycles, according to the JIS A 1148 (ASTM C 666-A) method. The damaged FRCC specimens were immersed in a water bath for up to 28 days to induce self-healing curing. For evaluating the self-healing capability, measurements of relative dynamic Young's-modulus (RDYM) and pore structures were carried out. The results confirmed recovery of the RDYM and densification of the microstructures due to $CaCO_3$ precipitation in the damaged FRCC specimens. In addition, an admixture of PVA could be expected to enhance the self-healing capability of cracks.

1. INTRODUCTION
Self-healing of cracks is a favorable phenomenon that facilitates the durability of concrete. Such self-healing phenomena can be expected to be more effective in the case of fiber reinforced cementitious composites (FRCC) than in the case of conventional concrete. FRCC has certain mechanical property that enable the control of crack width propagation in the cement matrix via bridging with randomly distributed short fibers. Since self-healing requires sufficiently small crack widths, FRCCs are expected to demonstrate significant self-healing capability. Homma et al. [1] confirmed that reinforcing fibers bridging the crack surface not only serve to the control crack width but also provide a core for the precipitation of chemical products. In our previous research [2], we confirmed that FRCC with synthetic fibers offers great potential for the self-healing of cracks. Different types of fibers were concluded to show different levels of self-healing performance. In particular, fibers based on a polar polymer (e.g., polyvinyl alcohol, PVA) promote the precipitation of crystallization products on the crack surface more effectively than do other types of fibers. However, the amount of reinforcing fiber that can be added to FRCC is limited, because large doses of the fiber may cause a decrease in the workability. In this study, experimental evaluations were carried out using an additional dose of PVA as an admixture. In order to evaluate the self-healing capability of damaged FRCC due to

freeze/thaw cycles, relative dynamic Young's-modulus (RDYM) measurements and mercury intrusion porosimetry (MIP) measurements were carried out.

2. MATERIALS AND METHODS

Table 1 shows the mix proportions of the specimens used in this study. PVA was employed not only as a reinforcing fiber but also as an admixture. PVAs with different degrees of saponification were employed: PVA with a higher degree of saponification (99%) was used as a short reinforcing fiber, and PVA with a lower degree of saponification (96%) was dissolved in the mixing water as an admixture. As a result, the PVA-II series contained a higher total volume content of PVA than the other series. The dissolved PVA could serve as a viscous agent to improve the workability and distribution of the reinforcing fibers. On the other hand, lower degrees of saponification could decrease durability because of the relatively high water solubility/absorbency.

The specimens had a prism (40 mm × 40 mm × 160 mm) geometry. Specimens were demolded 24 h after casting and then cured in a water bath at 20 °C up to 10 days. According to the JIS A 1148 "Method of Test for Resistance of Concrete to Freezing and Thawing" (similar to ASTM C 666-A), the specimens were subjected to 300 freeze/thaw cycles. Both freeze and thaw processes occurred under water. The dynamic Young's-modulus was measured every 30 cycles, and RDYM was calculated. After 300 cycles, the specimens were immersed in water bath at 20 °C for self-healing curing. Before and after this curing, MIP measurements were carried out according to the JIS R 1655 "Test Methods for Pore Size Distribution of Fine Ceramic Green Body by Mercury Porosimetry" in order to evaluate the micropore structure differences caused by self-healing.

Table 1: Mix proportions.

<table>
<tr><th rowspan="2">Notation</th><th colspan="2">B</th><th rowspan="2">W/B</th><th rowspan="2">S/B</th><th rowspan="2">SP/B</th><th rowspan="2">PVA-F (vol.%)</th><th rowspan="2">PVA-A (vol.%)</th></tr>
<tr><th>C</th><th>SF</th></tr>
<tr><td>Control</td><td rowspan="3">85</td><td rowspan="3">15</td><td rowspan="4">0.45</td><td rowspan="4">0.45</td><td rowspan="3">0.9</td><td>-</td><td rowspan="2">-</td></tr>
<tr><td>PVA-I</td><td rowspan="3">2</td></tr>
<tr><td>PVA-II</td><td>1.5</td></tr>
<tr><td>PVA-III</td><td>100</td><td>-</td><td>0.3</td><td>-</td></tr>
</table>

[Note] C: High early strength Portland cement (density: 3.14 g/cm^3), SF: Silica fume (density: 2.20 g/cm^3), B: Binder (=C+SF), W: Tap water, S: Silica sand #5 (density: 2.61 g/cm^3, diameter: ~500 μm), SP: Super plasticizer (polycarboxylic acid ether system, density: 1.05 g/cm^3), PVA-F: PVA fiber (degree of saponification: 99 %, density: 1.30 g/cm^3, diameter: 37 μm, length: 6 mm), PVA-A: PVA admixture (degree of saponification: 96 %, density: 1.30 g/cm^3)

3. RESULTS AND DISCUSSION

Figure 1 shows the relationship between the number of freeze/thaw cycles and the RDYM. Even after 300 cycles, the RDYM of all the series could be maintained at more than 90%. The PVA-III series without silica fume showed a relatively large degradation. The Control series without PVA fibers also showed continuous degradation of the RDYM. PVA-I and PVA-II showed a similar tendency and maintained a high RDYM of more than 98%. The PVA-II and I series showed a higher freeze–thaw resistance than did the Control series. Moreover, PVA additive with lower degree of saponification did not have any negative effect on the freeze–thaw resistance.

Figure 2 shows the difference in the RDYM values before curing (just after 300 freeze/thaw cycles) and after 28 days of curing in the water bath. Recovery of the

RDYM was confirmed in all the series during the curing period. This recovery was led to fill cracks due to precipitation of $CaCO_3$. In the case of PVA-I and PVA-II, the RDYMs were fully recovered up to 100%. In addition, the pozzolanic reaction of silica fume could enhance the filling up cracks in all specimens except for the PVA-III series.

Figure 3 shows the cumulative pore volume of all the series before and after 28 days of curing, in terms of the relationship between the pore diameter and the cumulative pore volume. Figure 4 shows the difference in the cumulative pore volume before curing (damaged by freeze/thaw cycles) and after 28 days of curing. According to Figure 4, in the case of the PVA-II series with both PVA fiber and additive, the cumulative pore volume decreased among the all range of pore size, and the difference was the largest among the other series. The PVA-I series also showed a decrease in the cumulative pore volume, however, no densification of pore structure was confirmed over the range 0.1 µm to 1 µm. This result demonstrates that the use of PVA as an additive could enhance the precipitation of $CaCO_3$ not only around the bridging fibers but also at the surface of the cracks. The Control series without PVA fiber also showed a decreasing trend in the cumulative pore volume. In the case of

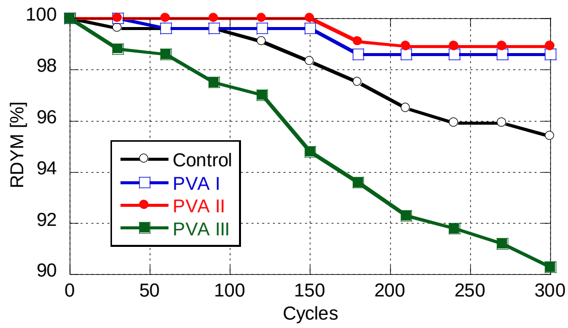


Figure 1: Relationship between freeze/thaw cycles and RDYM.

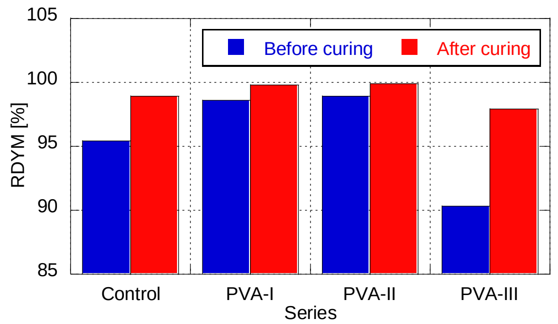
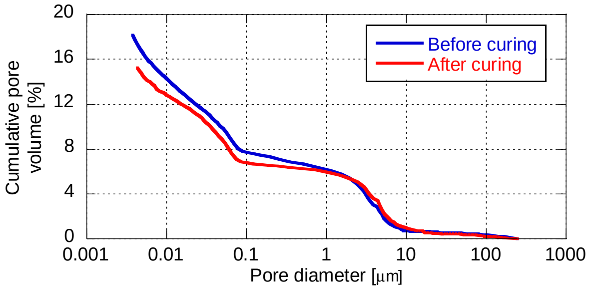
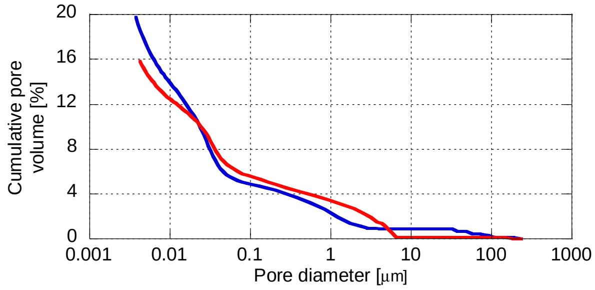


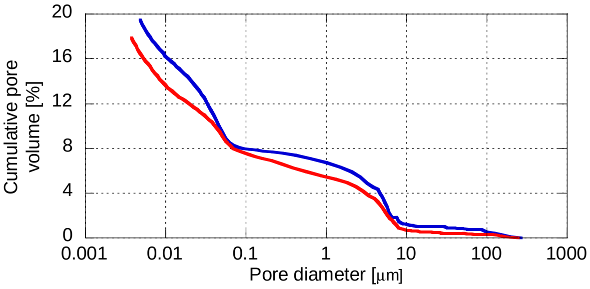
Figure 2: Comparison of RDYM before and after 28 days of curing



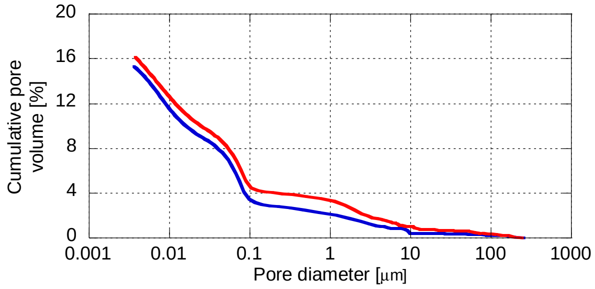
(a) Control



(b) PVA-I



(c) PVA-II



(d) PVA-III

Figure 3: Pore size distribution before curing (just after 300 freeze/thaw cycles) and after 28 days of curing

PVA-III without silica fume, the cumulative pore volume increased but the pore distribution was a slight change. Edvardsen reported that the chemical products formed in the pozzolanic reaction of silica fume can fill micropores with the size among 0.005 µm to 1µm [3]. The results for all the samples except PVA-III without silica fume agreed with the above mentioned trend, thus indicating that silica fume contributes to the densification of the microstructures.

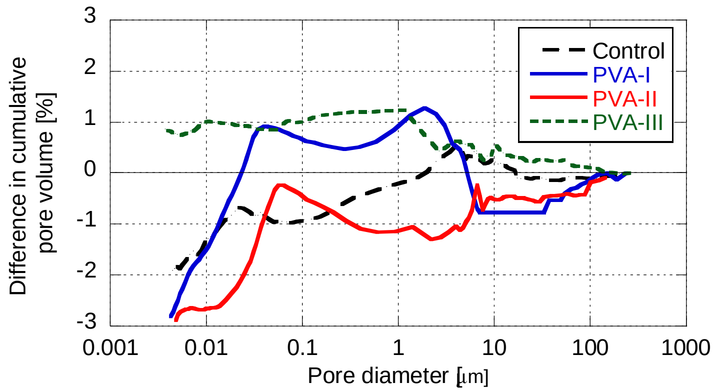


Figure 4: Difference of cumulative pore volume between before and after curing.

4. CONCLUSION

In this paper, experimental studies were carried out to evaluate the self-healing capability of FRCCs with additives, i.e., silica fume and excess PVA, against freeze/thaw cycles. The following conclusions could be drawn from the experimental results:

(1) FRCC with both PVA fiber and silica fume showed a high freeze–thaw resistance. PVA additive with lower degree of saponification did not have any negative effect on the freeze–thaw resistance.

(2) The RDYM of FRCCs degraded because of the freeze/thaw cycles but was recovered by the self-healing effect during water curing. The pozzolanic reaction of silica fume could help accelerate the filling up of cracks and pores.

(3) According to the results of MIP measurements, the cumulative pore volume decreased in the case of FRCCs with silica fume. Moreover, the combination of silica fume and PVA (fiber and/or additive) was preferable for enhancing the self-healing effect.

ACKNOWLEGDEMENTS

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