- Technical Paper -

AUTOGENOUS HEALING PROPERTIES OF ULTRA HIGH PERFORMANCE STRAIN HARDENING CEMENTITIOUS COMPOSITES UNDER LOADING-RECURING CYCLES

Choonghyun KANG[*1], Minoru KUNIEDA[*2], Naoshi UEDA[*3] and Hikaru NAKAMURA[*4]

ABSTRACT

Ultra High Performance-Strain Hardening Cementitious Composites (UHP-SHCC) is a new strain hardening cementitious composite with a dense matrix. Silica fume and un-hydrated cement gave advantages for autogenous healing in UHP-SHCC, in addition to the controlled fine crack width. This paper evaluates autogenous healing effects of UHP-SHCC by using air and water permeability tests. Especially, permeability measurements were performed before and after loading-recuring cycles. Recovery of protective performance was observed under loading-recuring cycles (2 times).

Keywords: UHP-SHCC, autogenous healing, air permeability tests, water permeability tests

1. INTRODUCTION

A new strain hardening cementitious composite, Ultra High Performance Strain Hardening Cementitious Composite (UHP-SHCC), has a dense matrix, a significantly higher tensile strength and strain hardening at tensile strength [1]. Fig. 1 shows examples of tensile stress and strain response of UHP-SHCC. Low water to binder ratio that may provide the un-hydrated cement was used, and silica fume that causes pozzolanic reaction was also mixed in UHP-SHCC. These characteristic gave the advantages for autogenous healing.

As shown in Fig. 2, other aspect is that the multiple fine cracks of UHP-SHCC accelerate autogenous healing because it is easy to fill the crack (less than 30 micron) by generated products due to autogenous healing. As increasing the damage level represented by nominal tensile strain, crack width of each crack should be almost constant in SHCC type materials, and number of cracks should be increased. This paper is focusing on both material composition and controlled fine crack width of UHP-SHCC.

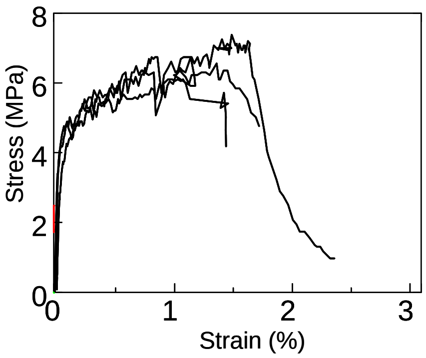


Fig.1 Examples of tensile stress-strain response of UHP-SHCC [1]

A sensitive index related to required performance should be selected for evaluating the ability of autogenous healing, and strength, stiffness, and water tightness were used in many report. For SHCC type materials with multiple fine cracks, a protective performance, such as a water permeability test, was usually used because of high sensitivity on durability issues [2][3]. Although the material has higher strength and higher strain capacity after cracking, the protective performance is decreased by cracking. If it can be recovered automatically, specific repair work is not needed. Therefore, this paper presents a recovery of protective performance, such as an air permeability test and a water permeability test due to autogenous healing of UHP-SHCC.

2. EXPERIMENTAL PROGRAM

2.1 Specimens

Fig.3 shows the shape of the specimen for this paper. A measured surface was 150x200mm to enough

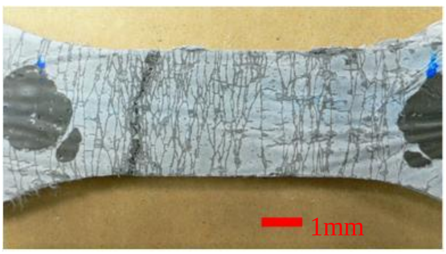


Fig.2 Fine cracks of UHP-SHCC [1]

*1 Doctoral Student, Dept. of Civil Engineering, Nagoya University, JCI member
*2 Associate Prof., Dept. of Civil Engineering, Nagoya University, JCI member
*3 Assistant Prof., Dept. of Civil Engineering, Nagoya University, JCI member
*4 Prof., Dept. of Civil Engineering, Nagoya University, JCI member

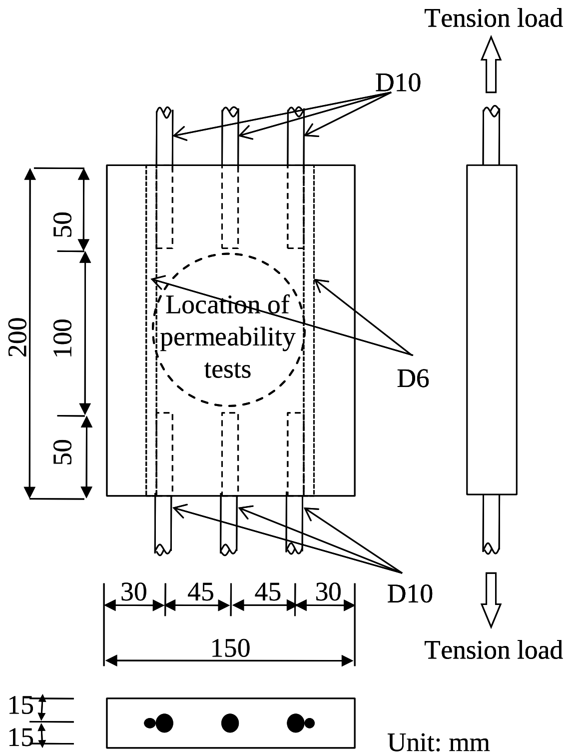


Fig.3 Shape of specimen

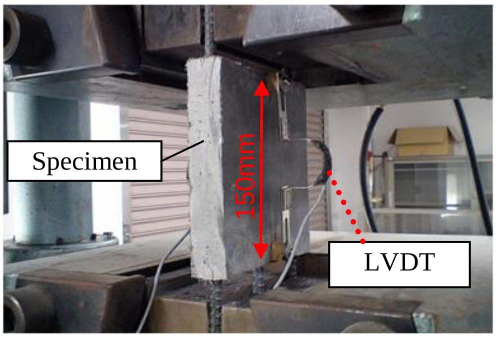


Fig.4 Uniaxial tensile test

for air and water permeability tests, and thickness was 30mm. There were two D6 re-bars (SD295, fy=407MPa) in the specimens to control the crack formation. Another three D10 re-bars (SD295A) were embedded in both of end sides to hold the specimen by a testing machine. All re-bars location was considered not to influence to the permeability test.

2.2 Loading Method

Cracks were induced to all specimens by uniaxial tensile test using Universal Testing Machine, as shown in Fig.4. Loading level was monitored by LVDT, which is fixed on both surfaces of specimens (measurement length : 150mm). Each specimen was loaded up to the tensile strain of either 0.1% or 0.2%, and then unloaded. Each residual strain was recorded. After recuring, the second loading test was conducted. The starting point of the second loading test was defined as the recorded residual strain point in the first loading test, and unloaded strain point was the same as the first loading test.

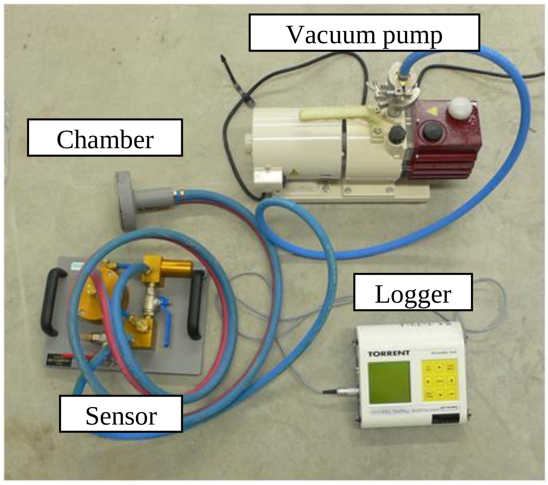


Fig.5 Torrent permeability tester

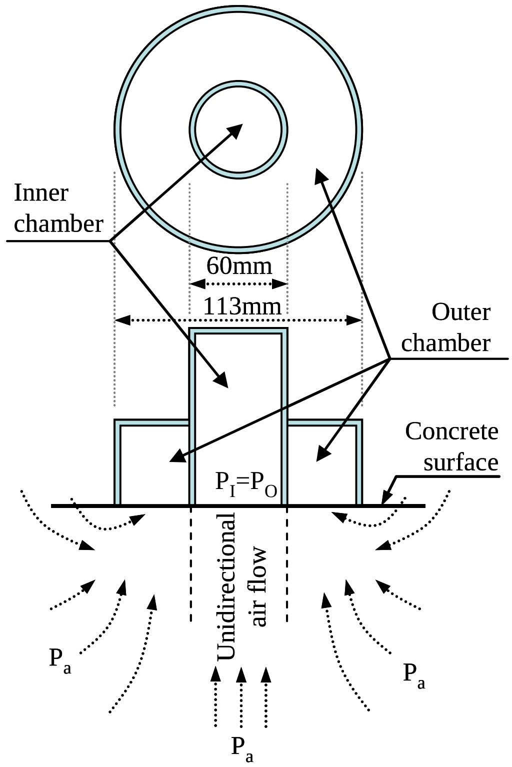


Fig.6 Conceptual diagram of the chamber

2.3 Air Permeability Tests

Air permeability test was conducted using the Torrent Permeability Tester (TPT), proposed by Torrent [4]. Fig.5 shows the Torrent Permeability Tester device. The device consists of a chamber, a vacuum pump, a pressure sensor, and a logger. It is possible to measure the denseness of the cover concrete and to evaluate durability of concrete. There is a two-chamber cell, consisting inner chamber I and outer chamber O, which is put to concrete surface, as shown in Fig.6. Equalizing the pressure of the both chamber, it is possible to make unidirectional air flow. An air permeability coefficient can be calculated based on the theoretical model [4]. The measuring was performed on circular areas at the center of each specimen during 12 minutes.

Table 1 Mix proportions of UHP-SHCC

Fiber content	W/B	Unit content (kg/m^3)						
		Water	Cement	Silica fume	Sand	Super-plasticizer	Air reducing agent	Fiber
V_f=1.5%	0.22	340	1313	232	155	15.4	0.062	14.6

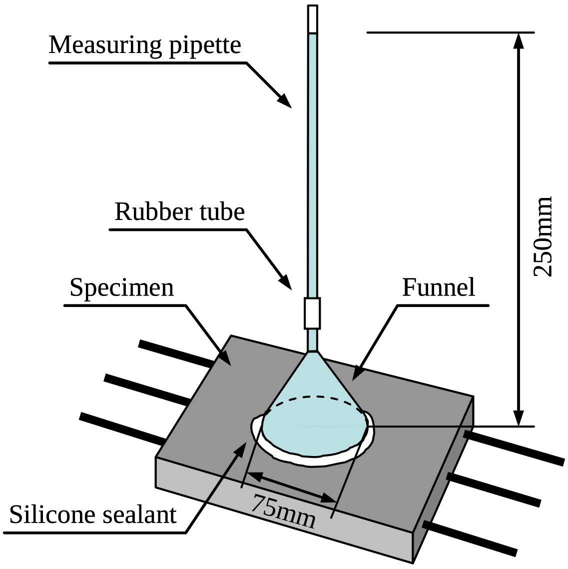


Fig.7 Water permeability test set-up

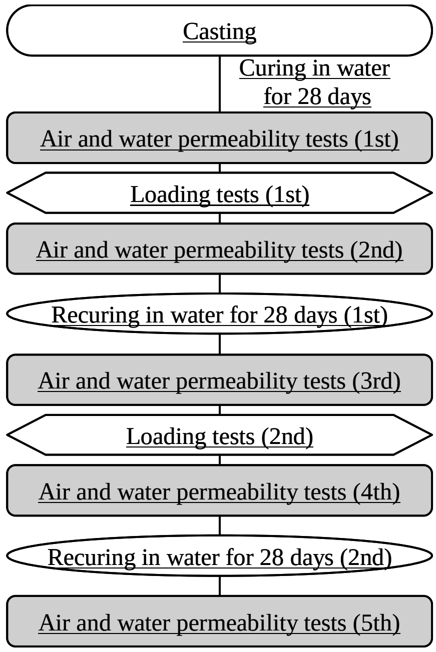


Fig.8 Experimental procedures

2.4 Water Permeability Tests

Water Permeability Test was used in this study according to a testing method of surface penetrant (JSCE-K571-2004) [5], as shown in Fig.7. A caliber funnel having the size of 75mm in diameter was attached to the surface of the specimen. The measuring section was located at the center of each specimen, which was the same position used in the air permeability tests. An interface between the funnel and the surface of specimen was sealed with a silicone sealant. A measuring pipette was connected with funnel by a rubber tube. At start, water was poured until 250mm water head, and change of water head was measured after about 50 hours. Averaged water permeation rates were calculated in water per an hour.

2.5 Experimental Procedures

The outline of the experiments is schematically illustrated in Fig.8. At the first step, the casting of UHP-SHCC with the mix proportion shown in Table 1 was performed. An ordinary Portland cement was used, and properties of the used other material are summarized in Table 2.

All specimens were cured for 28 days in water of 20˚C. Before the first loading tests, air and water permeability tests (1st test) were performed to evaluate the permeability of specimens without damage. To exclude the effect of water in the specimens, all specimens were kept in constant temperature curing room (20˚C, RH 70~80%) for 24 hours before permeability tests. After that, air permeability tests were performed before water permeability tests.

After air and water permeability tests, the first loading tests were conducted. There were two kinds of series depend on load levels, as shown in Table 3, and four specimens were prepared for each series. Each specimen was loaded until tensile strain of 0.1% and 0.2%, and residual strains were given in each series. Fig.9 showed the example of load-strain curve. After the first loading, air and water permeability tests (2nd test) were performed.

The damaged specimens were recured after the

Table 2 Properties of used materials

Content	Property	
Cement	Density	3.14g/cm^3
Silica fume	Density	2.20g/cm^3
Quartz sand	Diameter	less 0.5mm
	Density	2.68g/cm^3
High strength polyethylene fiber (PE fiber)	Density	0.97g/cm^3
	Tensile strength	2700MPa
	Elastic modulus	88GPa
	Diameter	0.012mm
	Length	6mm

Table 3 Types of specimens

Series	Unloading strain (%)	Recuring condition	Recuring period
0.1W	0.1	Water	1st : 28 days 2nd : 28 days
0.2W	0.2		

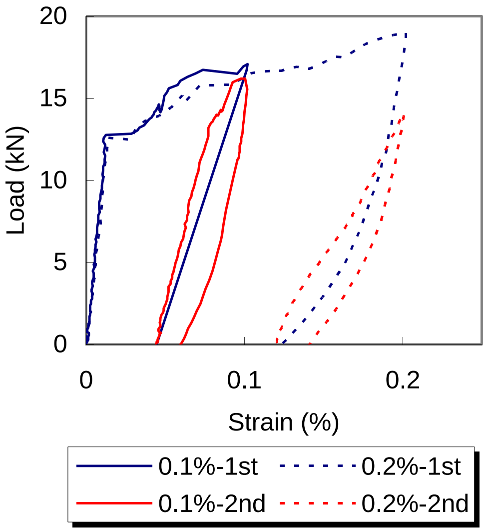
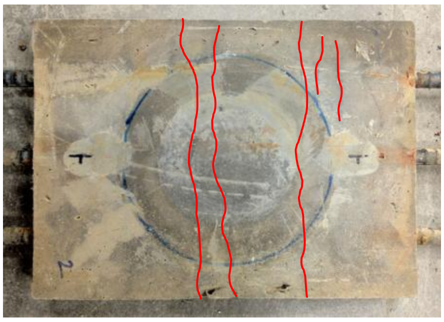
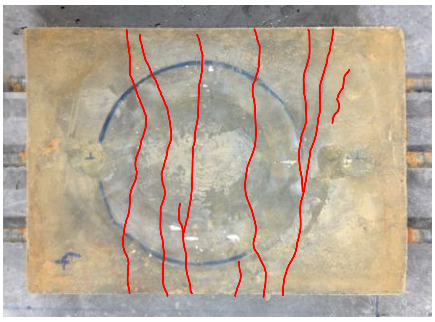


Fig.9 Example of load-strain curve in uniaxial tensile test



(a) Unloading at 0.1% strain



(b) Unloading at 0.2% strain

Fig.10 Examples of induced cracks

2nd permeability tests. Recuring was performed in water of 20˚C.

All specimens were taken out from water and dried for 24 hours in curing room (20˚C) again, and the air and water permeability tests (3rd test) were conducted. After that, the second loading tests were carried out, in which load was also provided up to the strain of 0.1% or 0.2%. Here, unloaded point in strain was the same with that in the first loading tests. After the second loading tests, the air and water permeability tests (4th test) to evaluate protective performance were performed.

All specimens had one more recuring, and the air and water permeability tests (5th test) were conducted lastly.

Table 4 Residual strain and averaged crack width after the first loading tests

Series	After first loading		
	Residual strain (%)	Number of cracks	Averaged crack width (㎛)
0.1W-1	0.058	3	28.9
0.1W-2	0.049	3	24.7
0.1W-3	0.027	2	20.4
0.1W-4	0.039	2	29.4
0.2W-1	0.088	8	16.5
0.2W-2	0.100	8	18.8
0.2W-3	0.124	7	26.6
0.2W-4	0.127	8	23.8

Table 5 Residual strain and averaged crack width after the second loading tests

Series	After second oading		
	Residual strain (%)	Number of cracks	Averaged crack width (㎛)
0.1W-1	0.065	4	24.4
0.1W-2	0.061	4	22.9
0.1W-3	0.069	4	25.9
0.1W-4	0.075	3	37.5
0.2W-1	0.153	8	28.7
0.2W-2	0.154	8	28.9
0.2W-3	0.144	7	30.9
0.2W-4	0.148	8	27.8

3. EXPERIMENTAL RESULTS

3.1 Crack Width

Fig.10 shows examples of crack patterns after the first loading tests. Cracks propagated cross section of the specimen. Residual strain after the loading was measured, and an averaged crack width $\overline{w}$ was calculated by Eq.1.

$$\overline{w} = \frac{\varepsilon_{res} \times \Delta\ell}{n} \qquad (1)$$

where,

$\overline{w}$: averaged crack width

ε_{res} : residual strain

$\Delta\ell$: measurement length

n : number of cracks in measurement length

Table 4 tabulates the detailed data after the first loading tests. Residual strains of 0.2% strain series were about two times larger than those of 0.1% strain series, and number of cracks was also same trend. As a result, averaged crack widths of both 0.1% strain and 0.2% strain series were almost same, because UHP-SHCC associated total displacement to multiple fine cracks. This is one of the characteristic of UHP-SHCC.

After the second loading tests, slight increasing of number of cracks was observed in some cases. And pre-cracks, which were opened by the first loading tests and recovered by recuring, were re-opened by the

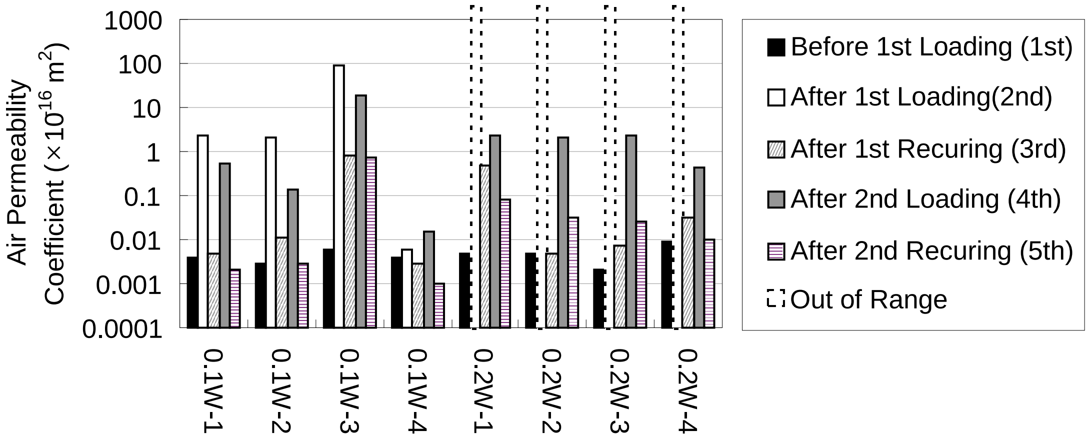


Fig.11 Results of air permeability tests (*In the 0.2% strain series, air permeability coef. at first loading tests cannot be measured)

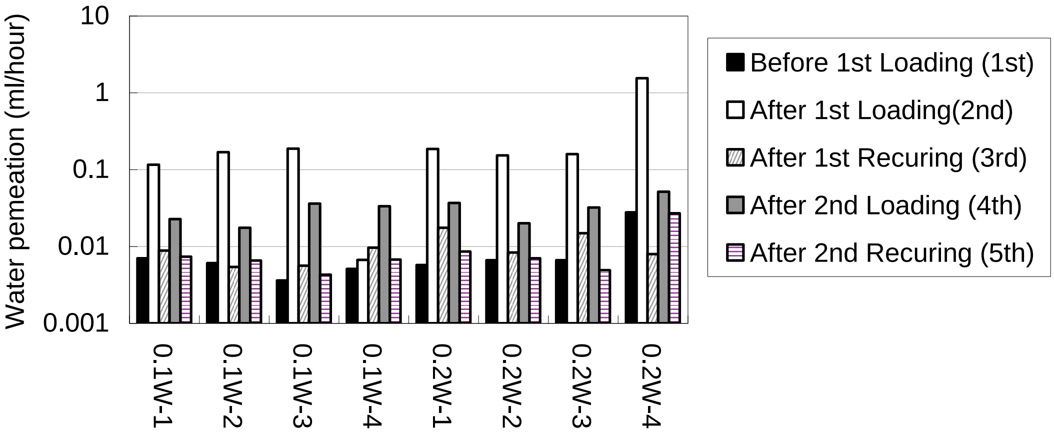


Fig.12 Results of water permeability tests

second loading tests. Averaged crack widths became a little larger than those after the first loading tests. Table 5 is detailed data after the second loading tests.

3.2 Results of Air Permeability Test

Fig.11 shows air permeability coefficients in each specimen of each step. Before the first loading tests (1st test), the values in all specimens were almost same level. However, the values were increased dramatically just after the first loading tests (2nd test). In the 0.2% strain series, blanks in the graph (Fig. 11) mean that air permeability coefficient was too large to measure by the measuring device.

Air permeability coefficients of all series after the first recuring (3rd test) had trend of recovery similar to those before the first loading tests. Especially, measuring of 0.2% strain series was also possible due to autogenous healing. In this study, 28 days was enough period to recovery up to almost same level comparing to without damage series.

Air permeability coefficients after the second loading tests became larger than those after the first recuring (3rd test), but it was smaller than those of after the first loading tests (2nd test). The reason seems to be that the second loading tests were performed up to the same load level with the first loading tests, and there was not significant increase of number of cracks and increase of averaged crack widths.

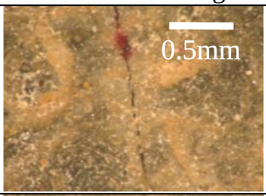
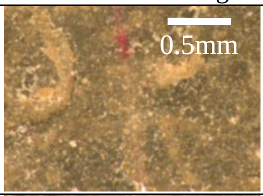
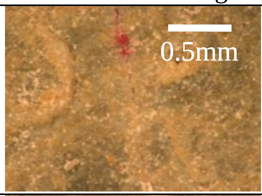
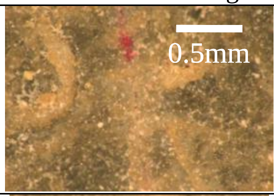
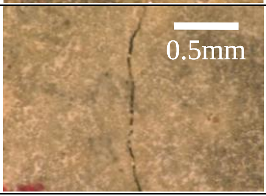
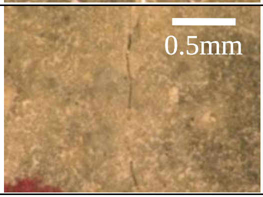
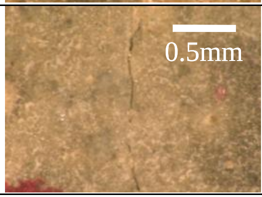
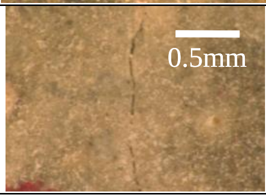
After the second recuring, air permeability coefficients (5th test) were similar to those after the first recuring (3rd test). It means that the second recuring was also effective to specimens, and re-opened crack by the second loading tests may be recovered again.

The main mechanism for the recovery of resistance against air permeability seems to be both carbonation of $Ca(OH)_2$ and formation of re-hydration products in addition to pozzolanic reaction along the induced cracks. As a result, these mechanisms seem to be worked during the first and second recuring.

3.3 Results of Water Permeability Test

Fig.12 shows water permeations of each specimen of each step. It has a similar trend with results of air permeability tests. The water permeations before the first loading tests (1st test) were almost same level each other. After the first loading, the water permeations became larger (2nd test). A significant difference with 0.1% strain series and 0.2% strain series was not observed. It was possible to measure water permeations even if 0.2% strain series.

Table 6 Details of cracks of each step

	After 1st Loading	After 1st Recuring	After 2nd Loading	After 2nd Recuring
0.1W				
0.2W				

The water permeations after the first recuring (3rd test) became smaller than those after the first loading tests (2nd test), and this phenomena is caused by autogenous healing.

The water permeations after the second loading tests (4th test) also had same trend with those of the air permeability tests. However, the increase was not significant.

Lastly, the water permeations of both 0.1% strain series and 0.2% strain series decreased again after the second recuring (5th test). Water permeations seem to be also affected by the autogenous healing phenomena, which also impart decrease of air permeability coefficients to the cracked specimen.

Consequently, the results of water permeability tests had similar trend with those of air permeability tests. This can be concluded that both indices indicated similar trend on the recovery of protective performance due to autogenous healing of UHP-SHCC, but air permeability tests may have higher sensitivity against the recovery, comparing to the water permeability tests.

3.4 Observation by Microscope

Table 6 shows examples of the cracks of each step. Crack in 0.1% strain series was closed by first recuring. Although crack width of 0.2% strain series also became smaller due to the first recuring, a perfect crack closure could not be observed clearly.

After the second loading tests, the averaged crack widths became larger, as shown in Table 5. But it could not be confirmed through the visual observations. The closed crack in 0.1% strain series was re-opened by the second loading tests.

For the second recuring, re-opened cracks of 0.1% strain series were re-closed. In the case of 0.2% strain, it was difficult to observe the change of crack width by naked eyes.

As described, it was difficult to certify the change of permeability of all series by observation using microscope. However, closing of crack after the first recuring and re-closing of re-opened crack after the second recuring were confirmed. It showed the autogenous healing phenomena of UHP-SHCC under loading-recuring cycles visually.

4. CONCLUSIONS

This paper described the autogenous healing effects of UHP-SHCC under loading-recuring cycles, by using air and water permeability tests experimentally. Following conclusions were obtained:

(1) It was confirmed that the UHP-SHCC had potentially autogenous properties under loading-recuring cycles through air and water permeability tests.
(2) Air permeability coefficients and water permeations were increased by the first loading, and recovered by recuring. After the two cycles, the recovery in terms of air and water permeability was also observed experimentally.
(3) Both indices indicated similar trend on the recovery, but air permeability tests may have higher sensitivity against the recovery in this study, comparing to the water permeability tests.

REFERENCES

[1] Kunieda, M., Denarie, E. Bruehwiler, E. and Nakamura, H., “Challenges for strain hardening cementitious composites-deformability versus matrix density”, Proceedings of HPFRCC 5, pp. 31-38, 2007
[2] Reinhardt, H. and Jooss, M., “Permeability and self-healing of cracked concrete as a function of temperature and crack width”, Cement and Concrete Research No. 33, pp. 981-985, 2003
[3] Yingzi, Y., Michael, D. L., En-Hua, Y., and Victor C. L., “Autogenous healing of engineered cementitous composites under wet-dry cycles’, Cement and Concrete Research No. 39, pp. 382-390, 2009
[4] Torrent, R., “A two-chamber vacuum cell for measuring the coefficient of permeability to air of the concrete cover on site”, Material and Structures, vol.25, pp. 358-365, 1992
[5] Japan Society of Civil Engineers, “Test methods of surface penetrant (draft), Concrete Library of JSCE, 119”, Recommendations for design and construction about method of surface protection, pp. 58-59, 2005
[6] Research activity report of JCI technical committee TC-075B, “Autogenous healing in cementitious materials”, Vol. 1, pp. 89-96, 2009