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Minoru Kunieda, Choonghy Kang, Naoshi Ueda, Hikaru Nakamura

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Scientific paper

Recovery of Protective Performance of Cracked Ultra High Performance-Strain Hardening Cementitious Composites (UHP-SHCC) Due to Autogenous Healing

Minoru Kunieda[1], Kang Choonghyun[2], Naoshi Ueda[3] and Hikaru Nakamura[4]

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Abstract

A new strain hardening cementitious composite with a dense matrix, Ultra High Performance-Strain Hardening Cementitious Composites (UHP-SHCC), has been developed. This material combines excellent protective performance with a significantly higher tensile strength and strain hardening at tensile strength. Further, the material has controlled fine cracks (less than 30 microns). A low water to binder ratio with silica fume that causes a pozzolanic reaction is used in UHP-SHCC. These characteristic may give advantages for autogenous healing after the cracking.

This paper presents autogenous healing behavior of cracked UHP-SHCC, and discusses about recovery of protective performance through air and water permeability test results. It was confirmed that UHP-SHCC has potentially autogenous healing properties. The air permeability coefficient and water permeation were dramatically decreased by increasing of re-curing period. Re-curing in water was more effective than re-curing in air for recovery. The effect of induced damage level on recovery of the used indices was not significant, because crack width was controlled and was almost the same among all the cracks. The repeatability of autogenous healing (twice in this study) was confirmed.

1. Introduction

Cracks are one of the causes of deterioration of concrete structures, and many efforts such as inspection and repair are being made in this area. Autogeneous healing of cementitious material may be helpful to reduce inspection and repair work within a maintenance framework, because the autogenous healing phenomena include crack sensing and crack closing. In recent years, state-of-the art reports have been compiled to accelerate the pace of research on autogeneous healing and its applications (Igarashi *et al*. 2009; de Rooij and Schlangen 2011), and work has been done in the areas of terminology definition and phenomena classification. The Japan Concrete Institute has defined autogenous healing that causes crack closure due to the original compositions of concrete (Igarashi *et al*. 2009). For instance, crystallization of calcium carbonate, which is a main mechanism reported by Edvardsen (1999), hydration of un-hydrated cement, and pozzolanic reaction are involved in autogenous healing.

Controlled crack width is also one of the key issues in autogeneous healing phenomena. Various kinds of recoveries due to autogenous healing are reported, such as recovery of strength, stiffness of members (Schlangen *et al*. 2006), and water tightness (Reinhardt and Jooss 2003), and most former research concluded that the capability of recovery due to healing depends on the induced crack width in concrete.

Adding short fiber is one of the effective methods to reduce (control) crack width in concrete. Regarding fiber reinforced cementitious materials including strain hardening type materials with multiple fine cracks, Li *et al*. (1998) reported experimental results on the self-healing of Engineered Cementitious Composite (ECC), describing the recovery of stiffness through resonance frequency. Yang *et al*. (2009) also reported on the recovery of stiffness in ECC under wet and dry cycles. Homma *et al*. (2009) investigated the self-healing phenomena of different types of FRCCs including a hybrid fiber system, and they confirmed the recovery of water tightness and tensile strength.

2. Autogenous healing of UHP-SHCC and its advantages

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 (Kunieda 2007, 2011; Kamal 2008). **Figure 1** shows examples of tensile stress and strain response of UHP-SHCC, for different fiber volumes (Kamal 2008). This material can also produce a multiple fine cracks in tension, as shown in **Fig. 2**.

UHP-SHCC was expected to have the following advantages for autogenous healing.

[1]Associate Professor, Dept. of Civil Engineering, Nagoya University, Japan.
E-mail: kunieda@nagoya-u.jp
[2]Graduate Student, Dept. of Civil Engineering, Nagoya University, Japan.
[3]Assistant Professor, Dept. of Civil Engineering, Nagoya University, Japan.
[4]Professor, Dept. of Civil Engineering, Nagoya University, Japan.

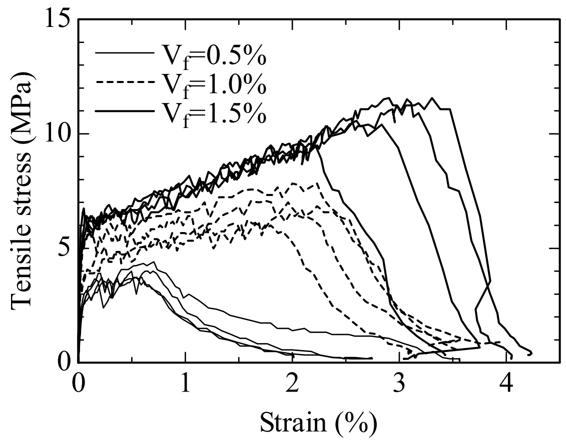


Fig. 1 Examples of tensile stress - strain response with different fiber content (Kamal 2008).

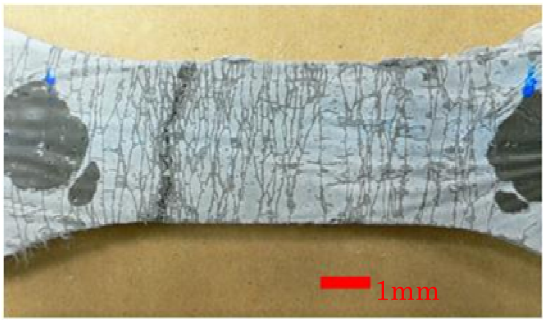


Fig. 2 Controlled fine cracks of UHP-SHCC.

(1) It is well known that autogenous healing works best for fine crack widths, as demonstrated in ECC (Li *et al*. 1998). The width of cracks in UHP-SHCC used in this study was smaller than that of ordinary Strain Hardening Cementitious Composites (SHCC) including ECC, because a high strength matrix and high stiffness polyethylene fiber (nominal elastic modulus: 88GPa) were used.
(2) Silica fume was used in UHP-SHCC under this study to allow activation of the pozzolanic reaction, contribution to autogenous healing. This is a similar mechanism to that in ordinary SHCC that includes fly ash.
(3) The low water to binder ratio (less than 0.22) of UHP-SHCC can be expected to yield much un-hydrated cement during the service period.

Based on the above material characteristics, autogenous healing of UHP-SHCC can readily expected.

On the other hand, the following aspects were identified as requiring clarification.
(1) UHP-SHCC has been used as a repair material in surface coating repair by using a low water to binder ratio. The protective performance of UHP-SHCC is much higher than that of ordinary SHCC. This indicates that the protective performance is dramatically decreased after cracking. Although recovery of permeability has been observed in former research on ordinary SHCC, recovery of higher protective performance caused by low water to binder ratio should be confirmed. Note that UHP-SHCC has higher strength and higher strain capacity in tension, and the recovery of stiffness and strength is not discussed in this study.
(2) In ordinary SHCC, PVA fiber which has a hydroxide on the surface of the fiber, is normally used. Nishiwaki (2012) reported that PVA fibers become nuclei of healing product. Polyethylene fiber, however, does not have hydroxide, and thus offers lesser autogenous healing capability compared with ordinary SHCC with PVA fiber.
(3) Existing research reports the recovery of damage that was induced once. The repeatability of autogenous healing of UHP-SHCC should be confirmed.

This paper presents the results of an investigation on recovery of protective performance of UHP-SHCC due to autogenous healing phenomena through air and water permeability tests, in order to clarify the above points. In particular, UHP-SHCC with different damage levels were tested, and recovered specimens were loaded and cured again to confirm the repeatability of autogenous healing.

3. Experimental program

3.1 Specimens

Table 1 lists the mix proportions of UHP-SHCC used in this study. The water to binder ratio (W/B) was 0.22. Low heat Portland cement (density: 3.14 g/cm^3) was used, and 15% of the cement was replaced by silica fume (density: 2.2g/cm^3). Quartz sand (less than 0.5mm in diameter, density: 2.68g/cm^3) was used as the fine aggregate. Fiber volume of 1.5% was used in this study. High strength polyethylene (PE) fiber (density: 0.97g/cm^3, tensile strength: 2700MPa, elastic modulus: 88GPa) was used for UHP-SHCC. The diameter and length of the PE fibers were 0.012mm and 6mm, re-

Table 1 Mix proportions of used UHP-SHCC.

Fiber volume V_f (%)	W/B	Unit content (kg/m^3)						
		Water	Cement	Silica fume	Sand	SP	ARA	Fiber
1.5	0.22	340	1313	232	155	15.4	0.062	14.6

SP: Superplasticizer
ARA: Air reducing agent

spectively. Superplasticizer (poly-carbon acid type) was used to enhance the workability of the material, and air reducing agent was used.

Uniaxial tensile tests were conducted by using dumbbell-shaped specimens (tested cross section: 10×30mm) for UHP-SHCC at the age of 28days. **Table 2** shows the averaged tensile strength and strain at the tensile strength.

Figure 3 shows the shape of the specimen used for the investigation on the autogenous healing properties of UHP-SHCC. Plate-shaped specimens having the cross section of 150mm×30mm were prepared. There were two re-bars of D6 (SD295, f_y=407MPa) in the specimen to impart stable crack formation. Re-bars of D10 (SD295A) were also embedded in both specimen ends to allow holding of the specimen by the testing machine.

3.2 Air permeability test

Air permeability tests were conducted using the Torrent Permeability Tester (TPT), proposed by Torrent (1992). This is an absolutely non-destructive method to check the denseness of the cover concrete and to evaluate the durability of concrete structures. The Torrent Permeability Tester device is shown in **Fig. 4**. The device consists of a chamber, a vacuum pump, a pressure sensor, and a logger. In the measurement, the chamber is put on the concrete surface. The chamber has two cells, an inner chamber and an outer chamber. Equalizing the pressure of both chambers, it is possible to make a unidirectional air flow. The air permeability coefficient is calculated according to the model of Torrent (1992). In this study, air permeability tests were performed on circular areas at the center of the specimens.

All specimens cured in water were taken out from water, and kept in air condition (20 degree C) for 2 days. After the pretreatment, the air permeability test was

Table 2 Tensile properties of used UHP-SHCC (28days).

Tensile strength (MPa)	Strain at tensile strength (%)
6.8	1.04

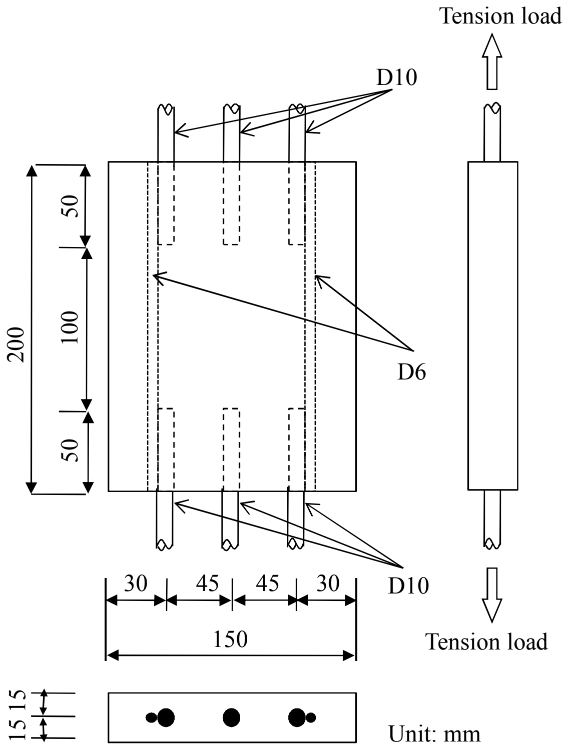


Fig. 3 Shape of specimen for accessing autogenous healing.

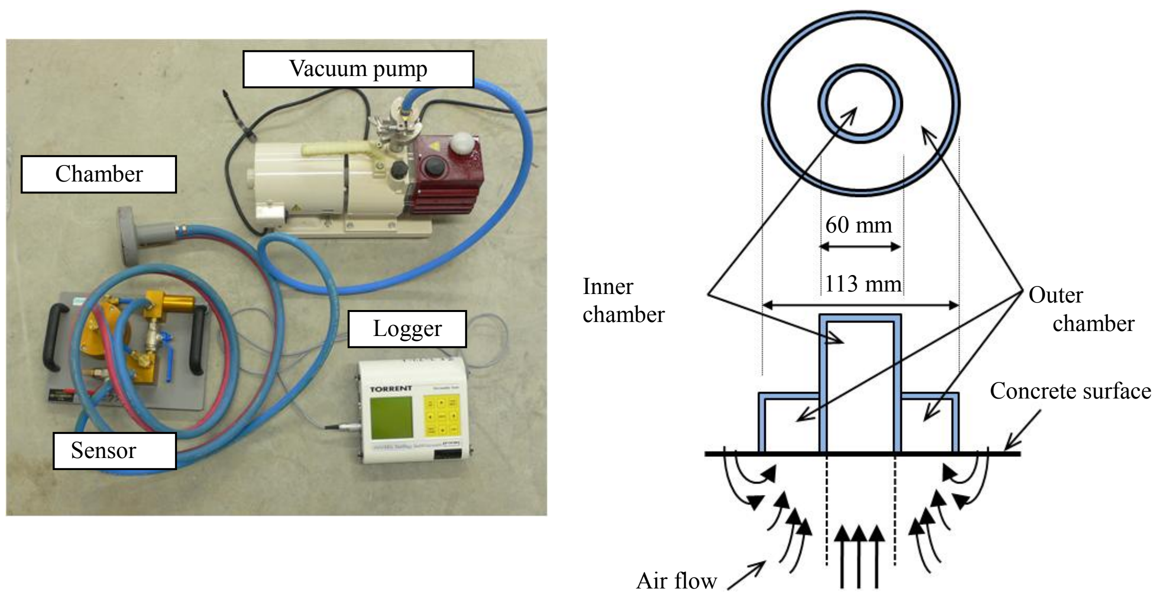


Fig. 4 Torrent permeability tester.

conducted. The specific water content of each specimen was not measured at the time of testing.

3.3 Water permeability test

In this study, the surface penetrant test method recommended by the Japan Society of Civil Engineers (JSCE 2004) was used. **Figure 5** shows the outline of the testing method. A caliber funnel 75 mm in diameter connected to a measuring pipette by a rubber tube was attached to the surface of the specimen and water was poured until the water head of 250 mm. Then, the change in water head was measured after about 20 hours. The amount of water per hour was calculated, and it was defined as water permeation in this study. The interface between the funnel and the surface of specimen was sealed with a silicone sealant. The tests were performed on circular areas at the center of the specimens, which was the same position used in the air permeability tests. Since the specimens after the air permeability tests were used for the water permeability tests, the specimens were exposed in dry condition (20 degree C) after having been taken out from water (water curing).

3.4 Induced cracks and re-curing method

The experimental procedures are summarized in **Fig. 6**. The specimens were demoulded at one day after casting and cured in water at constant temperature room (20 degree C). Then air permeability tests and water permeability tests were conducted at the age of 32 to 35 days. Then at the age of 36 to 37 days, cracks were induced by uniaxial tensile test, as shown in **Fig. 7**. Loading was monitored by LVDT fixed on both specimen surfaces (measurement length: 150mm). A schematic image of stress-strain curves of the loaded specimens is shown in **Fig. 8**. Each specimen was loaded until the tensile strain of either 0.1% or 0.2%, and then unloaded. Typical crack patterns are shown in **Fig. 9**. The averaged crack width $\bar{w}$ was calculated by Eq.1.

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

where,

$\bar{w}$: Averaged crack width

ε_{res} : Residual strain

$\Delta\ell$: Measurement length (150 mm)

n : Number of cracks in measurement length

After the tensile tests, air permeability tests and the water permeability tests were conducted again, and the specimens were cured in air or in water at a constant temperature (20 degree C) for 20 days, 90days and 360days.

Table 3 lists the specimen series, unloaded strain, re-curing conditions and re-curing periods. The number of specimens in each condition was 3 to 4. Three control specimens with no damage were also prepared. **Table 4** tabulates the obtained residual strain, number of cracks, and averaged crack width of each cracked specimen. Several cracks were observed in the measurement area.

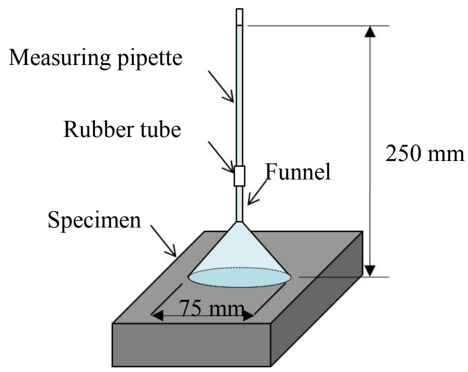


Fig. 5 Water permeability test setup.

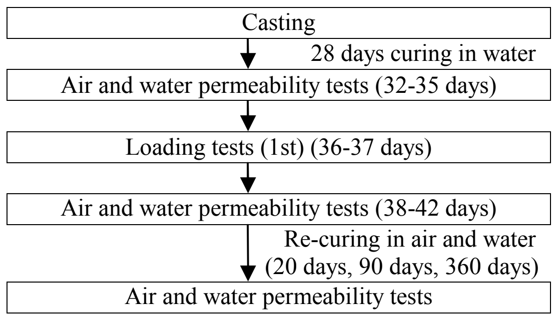


Fig. 6 Experimental procedures.

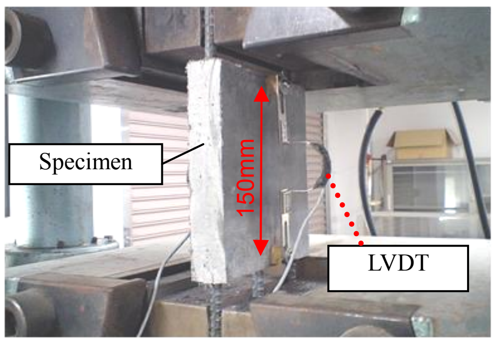


Fig. 7 Uniaxial tensile test.

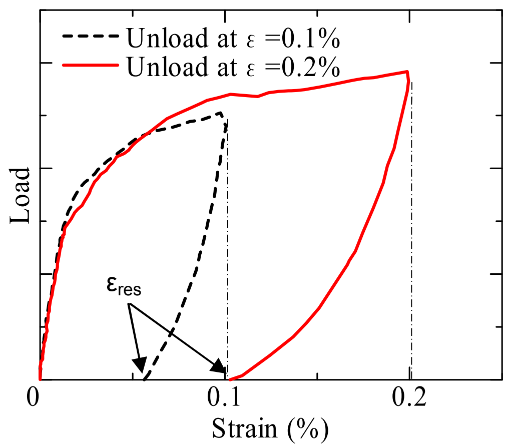
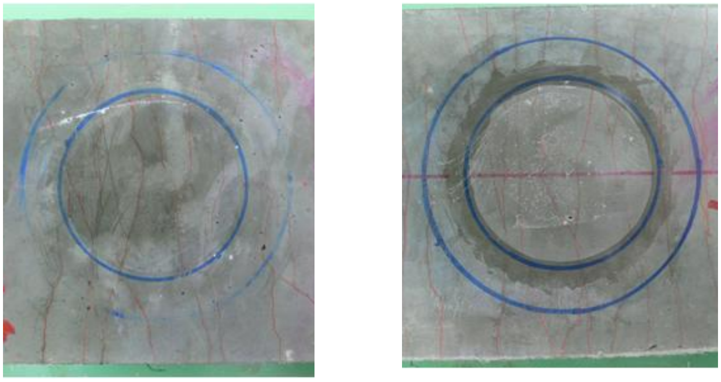


Fig. 8 Schematic image of loading manner.



(a) Unloaded at 0.1% strain (b) Unloaded at 0.2% strain

Fig. 9 Examples of induced cracks.

Table 3 Tested specimens.

Series	Unloaded strain (%)	Re-curing condition	Re-curing period
0W	(Without loading)	Water	20 days, 90 days, 360 days
0A		Air	
0.1W	0.1	Water	
0.1A		Air	
0.2W	0.2	Water	
0.2A		Air	

Table 4 Induced damage for each specimen.

Series	Residual strain after loading (%)	Number of cracks	Averaged crack width (micron)
0.1W-1	0.051	6	12.7
0.1W-2	0.051	5	15.2
0.1W-3	0.060	4	22.3
0.1W-4	0.052	5	15.5
0.1A-1	0.057	6	14.2
0.1A-2	0.052	6	12.9
0.1A-3	0.051	7	10.9
0.2W-1	0.091	9	15.1
0.2W-2	0.096	14	10.3
0.2W-3	0.114	16	10.7
0.2A-1	0.116	15	11.6
0.2A-2	0.108	15	10.8
0.2A-3	0.081	14	8.7

The averaged crack width was 8.7 to 22.3 microns. Although the unloaded strain differed, there was no significant difference in averaged crack width, which is the material nature of UHP-SHCC.

4. Experimental results

4.1 Results of air permeability tests

Figure 10 shows air permeability coefficients of each specimen before loading, just after the loading and after the re-curing for 20 days, 90days and 360days. In the figure, the averaged crack width calculated in Equation 1 is expressed as a dot. Note that the averaged crack width was measured and calculated based on the residual strain at the time of loading test. Crack widths of less than 30 microns were measured, and UHP-SHCC was found to produce fine crack widths, which is one of its advantages for autogenous healing.

In control specimens, air permeability coefficients became smaller with increasing of re-curing period. This decrease seems due to densification of the matrix of UHP-SHCC with increasing age.

The air permeability coefficients of cracked specimens just after loading were over $0.1x10^{-16}m^2$, and became dramatically larger than those of un-cracked specimens. After re-curing, however, the air permeability coefficients of all cracked specimens, especially those cured in water, became smaller. Some of the air-cured specimens showed decreasing air permeability coefficient, similar to the water-cured specimens. Regarding the difference in re-curing condition, water curing was more effective for autogenous healing, compared with air curing. The main cause for recovery of resistance against air permeability seems to be the formation of products due to re-hydration of cement, pozzolanic reaction and carbonation within induced cracks, with increases in the re-curing period.

Regarding differences in damage level, no significant trend could be identified, because the crack width, which is related to the autogenous healing capability, was almost the same across all cases, as shown in **Table 4**.

Torrent (1992) also proposed quality grading of concrete and a concrete quality index. In the proposal, an air permeability coefficient of less than $0.1x10^{-16}$ m^2 means good quality concrete, and a coefficient of less than $0.01x10^{-16}m^2$ indicates very good quality concrete. Note that resistivity of concrete should be used for the total evaluation in his proposal. Through this evaluation, UHP-SHCC recovered by autogeneous healing phenomena has sufficient quality in terms of protective performance.

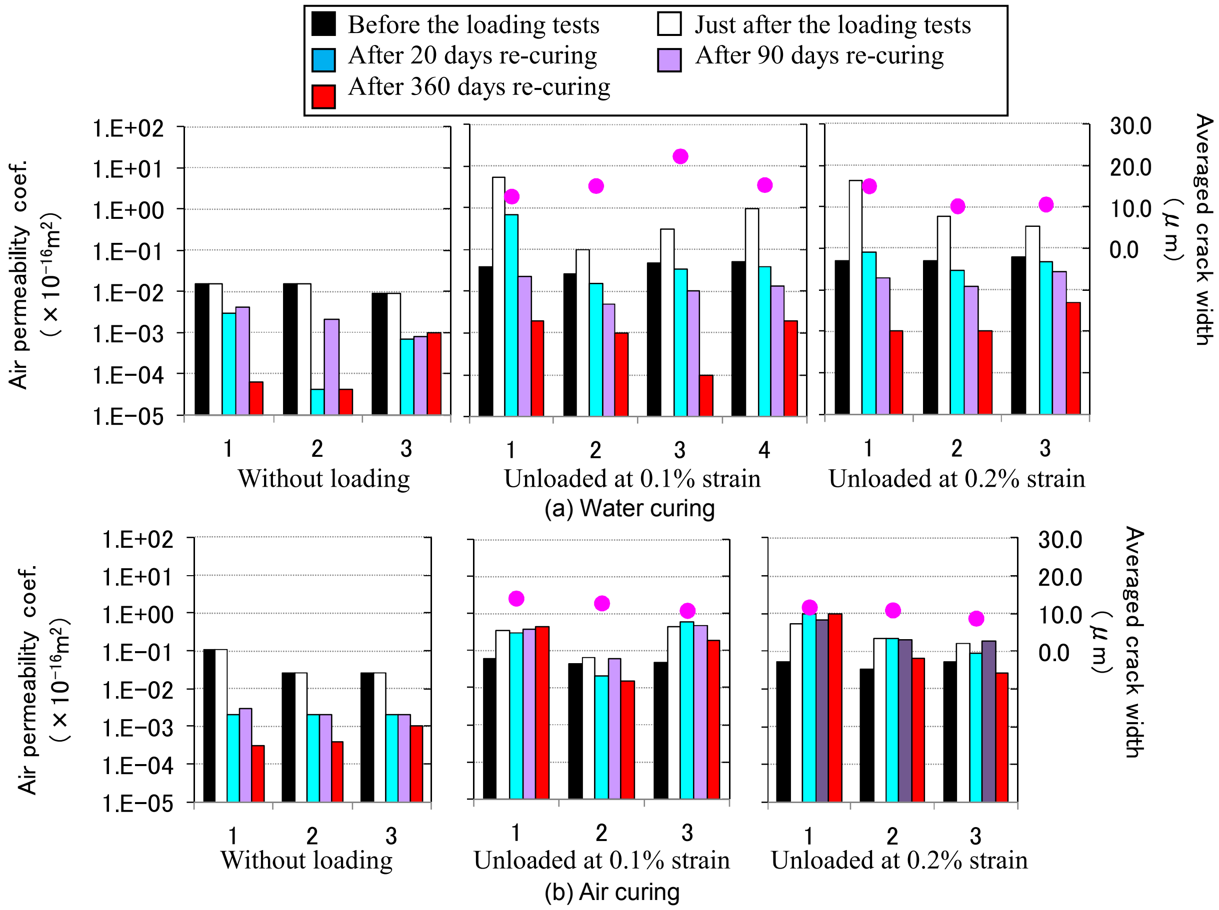


Fig. 10 Results of air permeability tests.

4.2 Results of water permeability tests

Figure 11 shows the water permeation of each specimen before loading, just after loading, and after re-curing for 20 days, 90days and 360days. Note that the averaged crack width is represented as a dot in this figure, and that fine cracks having a width of less than 30 microns were observed in UHP-SHCC.

In the control specimens, water permeation decreased with increases in the curing period. It seems that densification of the matrix in UHP-SHCC accelerates the decreases in water permeation with increases in the curing period.

Water permeation of cracked specimens increased dramatically compared with that before loading. After re-curing, however, water permeation decreased in most cracks.

Regarding the difference in re-curing condition, water curing was more effective than air curing for autogenous healing, and there was no significant effect of unloaded strain level on recovery of water permeation. In this study, a similar trend to that of air permeability coefficient was observed experimentally, and it can be concluded that these indices have a similar sensitivity to the recovery of protective performance on autogenous healing of UHP-SHCC. These indices were also affected by moisture content in the test. Further research is needed in this area.

4.3 Observation of cracked part and material itself

Figure 12 shows images of cracks observed with a microscope. **Figure 12a**) is the image of the cracks before re-curing (just after loading), and **Fig. 12b**) is the image of the cracks after re-curing. The induced cracks were filled with new product, which seems to be hydration products related to contained un-hydrated cement, products due to the pozzolanic reaction of silica fume, and carbonation producing $CaCO_3$.

Figure 13 shows the SEM image of a cracked part. The generated products filling the crack can be observed. The products have a slightly coarse appearance compared with the bulk matrix. **Figure 14** shows the results of EDX analysis, with Ca and Si detectable not only in the bulk matrix but also in the crack, indicating that the generated products contain Ca and Si. The products appear caused by crystallization of $Ca(OH)_2$ and pozzolanic reaction. **Figure 15** shows the back scattered image of UHP-SHCC at the age of 407 days. The light gray parts represent un-hydrated cement. In the image, half of the cement (about 49%) remains un-hydrated in the material after 407 days, and it seems that this un-hydrated cement helps the autogenous healing.

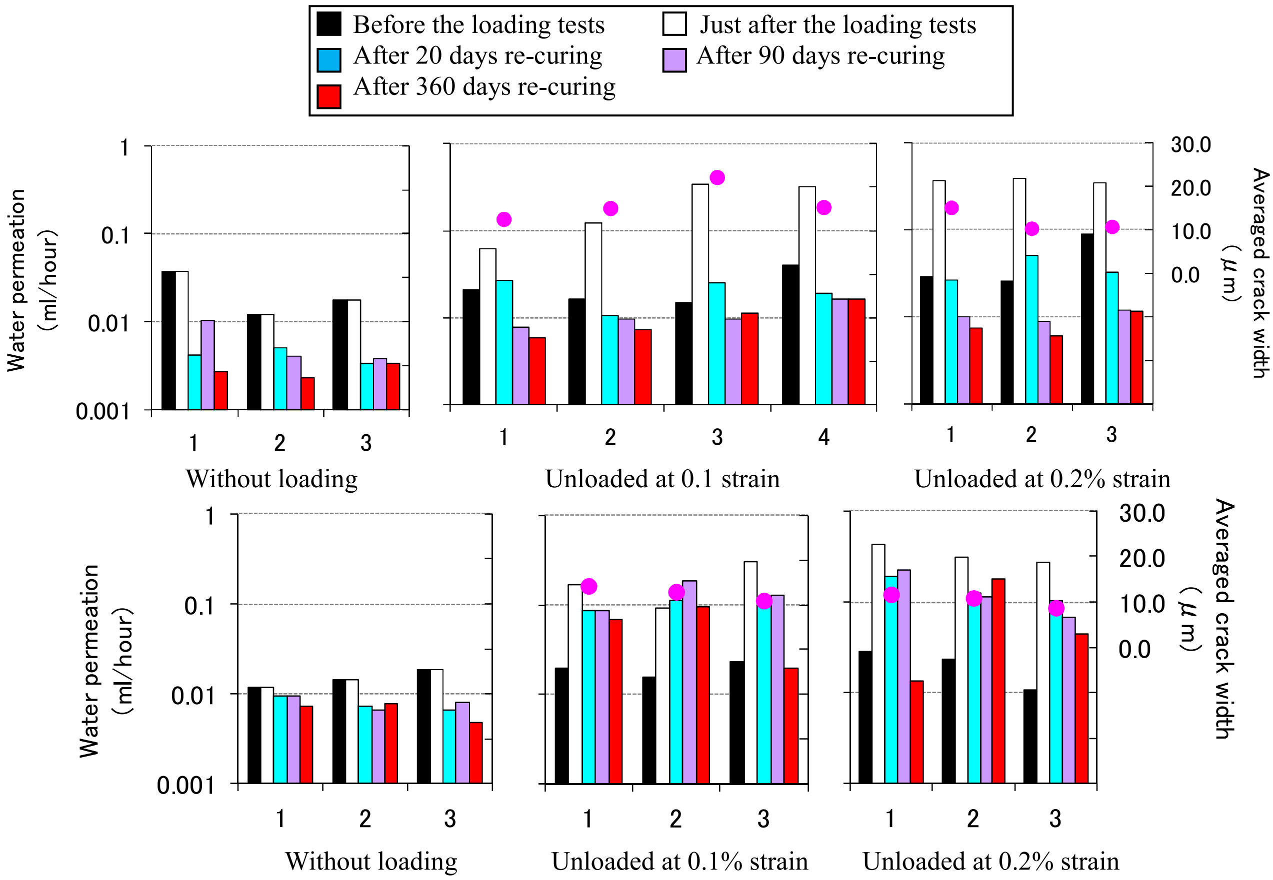
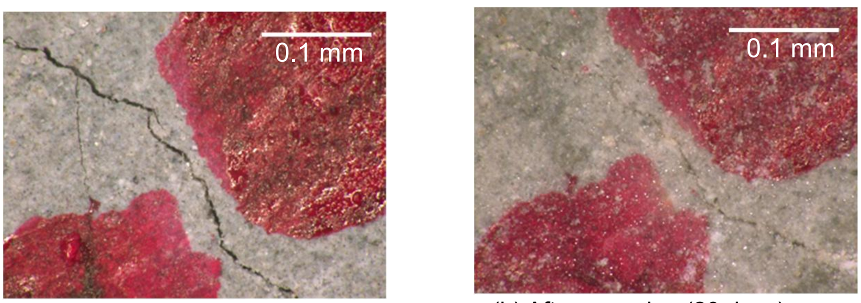
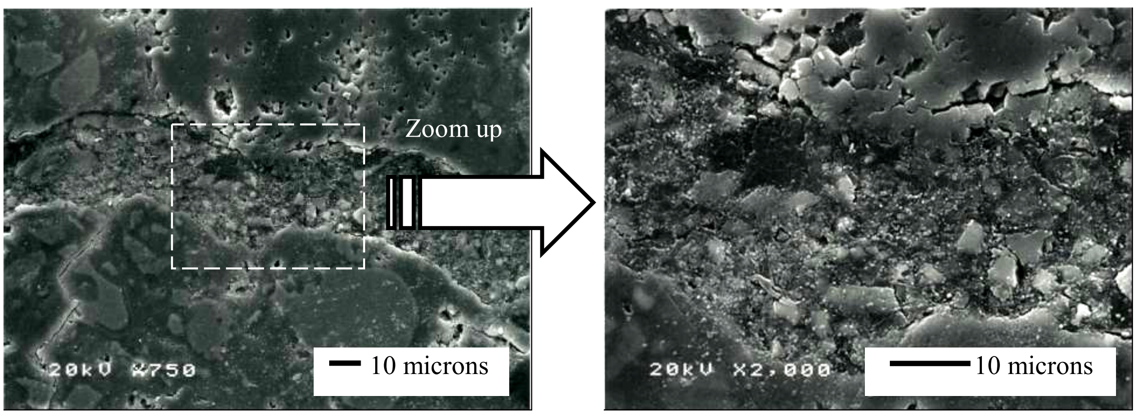


Fig. 11 Results of water permeability tests.



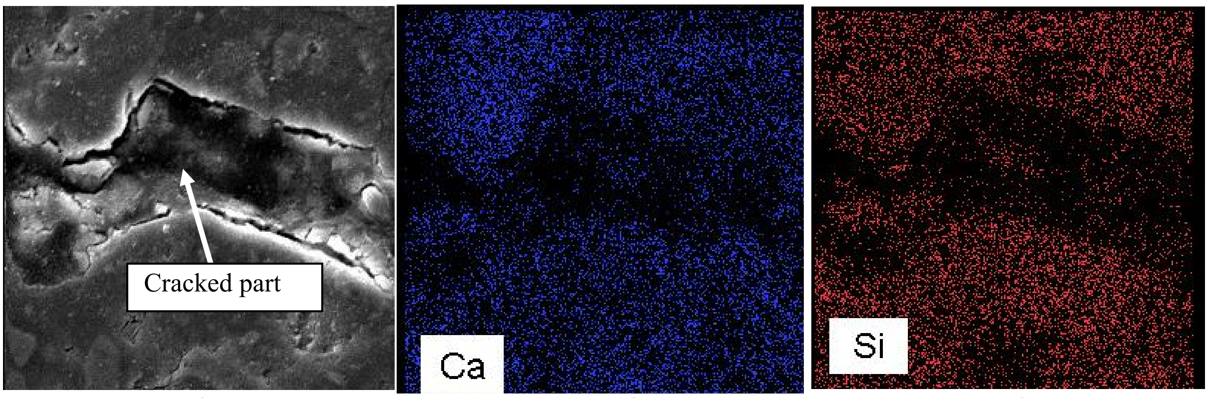
(a) Before re-curing (b) After re-curing (20 days)

Fig. 12 Details of cracks before and after re-curing observed by using microscope (cured in water).



(a) 750X (b) 2000X

Fig. 13 Image of cracked part by means of SEM (cured in water).



(a) Original image (b) Ca (c) Si

Fig. 14 Image of cracked part by means of energy dispersive X-ray spectrometry (cured in water).

5. Repeatability of autogenous healing

5.1 Outline of experiments

In this section, the repeatability of autogenous healing was confirmed. The mix proportions of the used UHP-SHCC with fiber volume of 1.5% are shown in **Table 1**. An outline of the experiments is given in **Fig. 16**. Loading tests were carried out twice. In the first loading, load was applied to the strain of 0.1% or 0.2%, and residual strain was given in each series. In the second loading, load was also provided up to the strain of 0.1% or 0.2% again. Here, the unloading point (strain) was the same as that in the first loading. In order to evaluate the recovery of protective performance, air permeability tests and water permeability tests were performed in accordance with the testing method described in the previous section. After each loading test and measurement of air and water permeability, only water curing was conducted. The test series are summarized in **Table 5**.

Table 6 tabulates the detailed data on residual strain and number of cracks after the first and second loading, respectively. As a result, the number of cracks in the 0.1% strain series was twice comparing that in the 0.2% strain series. Averaged crack width was, however, almost the same. After the second loading, a slight increase in the number of cracks was observed in some cases, and averaged crack width became a little larger than after the first loading.

5.2 Results of air permeability and water permeability tests

Figures 17 and **18** show the air permeability coefficients and water permeation of each specimen, respectively. Note that the plus and dot marks in the figure represent the averaged crack width after first loading and second loading, respectively. Significant change in crack width (less than 10 microns) was not observed.

Both air permeability coefficients and water permeation changed dramatically at each loading to induce cracks. The air permeability coefficient could not be measured in the 0.2% strain series. However, re-curing resulted the reduction of air permeability and water

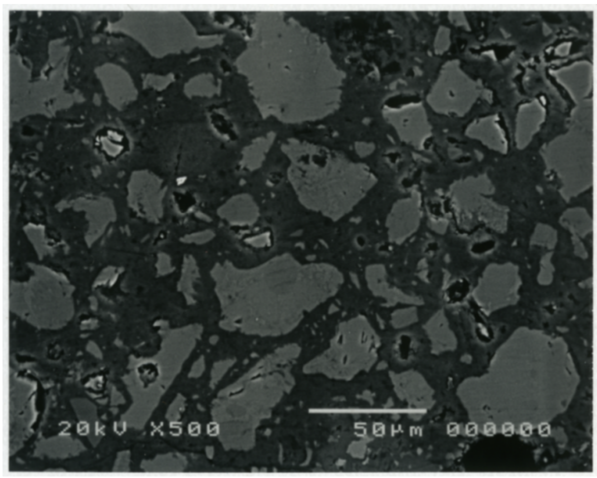


Fig. 15 Back scattered electron image of UHP-SHCC (407 days after casting, hydration ratio: 51.4 %).

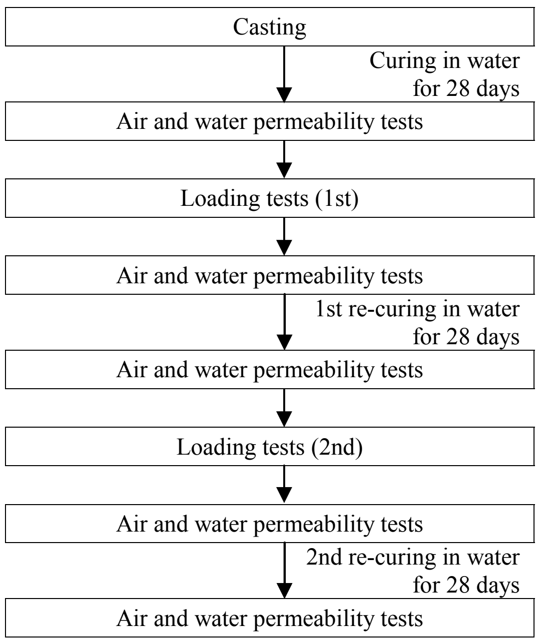


Fig. 16 Outline of the experiments concerning repeatability of autogenous healing.

Table 5 Tested specimens.

Series	Unloaded strain (%)	Re-curing condition	Re-curing period
0.1W	0.1	Water	1st re-curing: 28 days 2nd re-curing: 28 days
0.2W	0.2		

Table 6 Residual strain and averaged crack width.

Series	After 1st loading			After 2nd loading		
	Residual strain (%)	Number of cracks	Averaged crack width (micron)	Residual strain (%)	Number of cracks	Averaged crack width (micron)
0.1W-1	0.058	3	28.9	0.065	4	24.4
0.1W-2	0.049	3	24.7	0.061	4	22.9
0.1W-3	0.027	2	20.4	0.069	4	25.9
0.2W-1	0.088	8	16.5	0.153	8	28.7
0.2W-2	0.100	8	18.8	0.154	8	28.9
0.2W-3	0.124	7	26.6	0.144	7	30.9

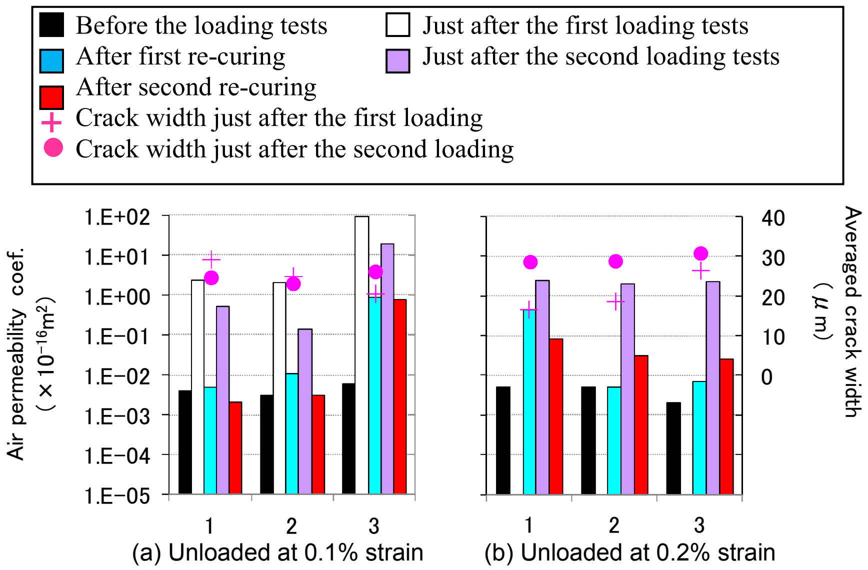


Fig. 17 Results of air permeability tests (*In the series of 0.2% strain, air permeability coef. at first loading tests cannot be measured.).

permeation after first re-curing and second one. Consequently, the used re-curing period (28 days) seems to be sufficient to recover up to the same level as the control specimen (without loading) under water curing conditions. In this study, the reduction of air and water permeability was observed twice, and the repeatability of the autogenous healing was confirmed.

6. Conclusions

The autogenous healing phenomena for protective performance were experimentally investigated, and the following conclusions were obtained.

(1) It was confirmed that the UHP-SHCC has potentially autogenous healing properties. The air permeability coefficient and water permeation were dramatically decreased with increases in the re-curing period. Re-curing in water was particularly effective for recovery, compared with re-curing in air. Eventually, recovery of protective performance was possible under water curing conditions, even if a higher protective performance level is associated with a low water to binder ratio.

(2) The effect of induced damage level on recovery of the used indices (air permeability coefficient and water permeation) was not significant because crack width was almost constant throughout the material, although the number of crack differed.

(3) In this study, recovery of protective performance, which was represented by reduction of air and water permeability, was observed twice, and the repeatability of the autogenous healing was confirmed..

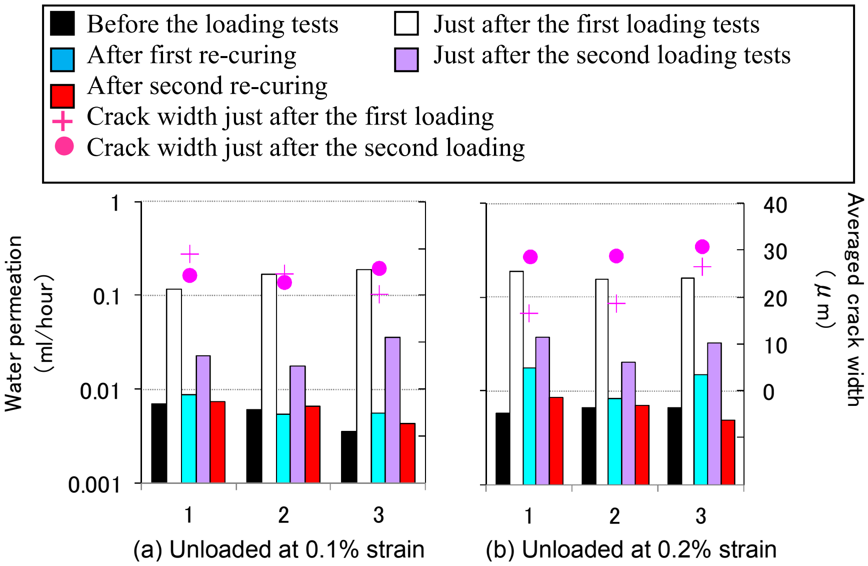


Fig. 18 Results of water permeability tests.

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