- Technical Paper -

AUTOGENOUS HEALING PROPERTIES OF CONCRETE UNDER FLEXURAL LOADING

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ABSTRACT

Autogenous healing of concrete structure was studied as a part of measures for reduction of the total life cycle cost. This study presents the measurement for autogenous healing ability by using the stiffness through three-point bending test. It shows the relation between autogenous healing ability and the initial loading age for three kinds of concrete, such as normal concrete, fly ash concrete and fly ash concrete with fiber. Furthermore, the size effect of specimens on autogenous healing is examined.

Keywords: autogenous healing, crack, bending test, cement based material, initial loading age

1. INTRODUCTION

Concrete structure has crack due to live load, shrinkage, temperature, etc. Normally, cracks can be classified into two types; visible cracks and micro cracks. Regarding the micro cracks, detection is very difficult. Even if it is found, there is complicate problem how to repair. If autogenous healing of concrete is accepted for repair the micro cracks, it should be helpful for reduction of Mid- and Long-term life cycle cost.

This study clarifies the effect of autogenous healing ability intended for three kinds of concrete. Three-point bending test was conducted in this study, and also, the stiffness obtained from the test was used as a main index. The reason as follows; (1) three-point bending test is easier than uniaxial loading test to induce a uniaxial tensile stress. (2) Measured load-crack mouth opening displacement (CMOD) relations including a softening behavior has a sensitivity to crack propagation in the specimen, which is normally used in fracture mechanics approach. A micro crack in fracture process zone might be effective target for autogenous healing. (3) It is well known that recovery in strength is difficult in autogenous healing potentially. However, increased stiffness due to an autogenous healing can be used structurally. High sensitive index should be useful to evaluate the potential of autogenous healing.

In first part of this paper, effect of the initial loading age was investigated using normal concrete, fly ash concrete and fiber concrete. The second part of this paper presents the difference of specimen size on potential of autogenous healing by using fly ash concrete.

2. EFFECT OF THE INITIAL LOADING AGE ON HEALING (SERIES 1)

2.1 Test Program

Table 1 shows the mix proportions of concrete in this study. Three kinds of concrete that were a normal concrete (NC), a fly ash concrete (FC) and a fly ash concrete include fiber (FC+Fib) were used. It has been reported that a fly ash in concrete helps to improve the ability of autogenous healing [1][2]. In addition, included short fiber was adopted as nuclei for fixation of calcium carbonate during recuring refer to Homma et al [3].

An ordinary Portland cement with a density of 3.15g/cm^3, a coarse aggregate with surface-dry density of 2.58g/cm^3, and sand with surface-dry density of 2.51g/cm^3 was used. The maximum size of the coarse aggregate was 25mm and the water-cement ratio (W/C) was 45% in all mix, which refer the study of Hama et al [4]. A fly ash with a density of 2.38 g/cm^3, which can be classified into Type II of JIS A 6210, was used. And an air entraining agent and AE water reducing agent were admixed with the normal concrete in order to obtain better workability. A polyethyler fiber (with length of 3mm, diameter of 0.012mm, elastic modulus of 88GPa, tensile strength of 2700MPa and density of 0.97g/cm^3) was used and a volume fraction of the fiber was 0.2%.

Rectangular specimens with the size of 400x100x100mm were used to estimate an ability of autogenous healing of the difference of the initial loading age for three kinds of concrete. All specimens were casted into the rectangular mould after mixing by a mixer (capacity: 50ℓ). It was mixed for 30 seconds in dry condition firstly, and after adding water, 3 minutes mixing was adopted. The moulds were removed after

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Table 1 Mix Proportions of Concrete

Case	W/C (%)	Unit Content (kg/m^3)								
		Water	Cement	Sand	Gavel	Fly ash	AE	Fiber	AWR†	AEA‡
NC	0.45	175	389	780	879	-	-	-	1.22	0.0156
FC	0.45	175	389	624	879	137	0.97	-	-	-
FC+Fib	0.45	175	389	618	879	137	0.97	2.43	-	-

AWR† : Water Reducing Agent
AEA‡ : Air Entraining Agent

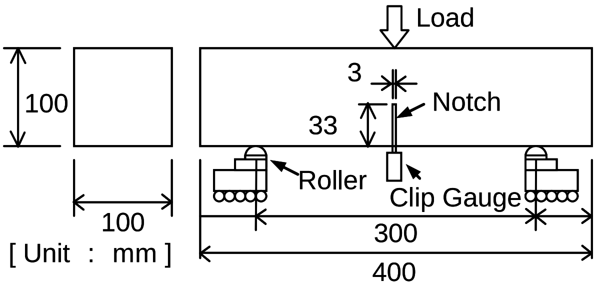


Fig.1 Shape of Specimen (Series 1)

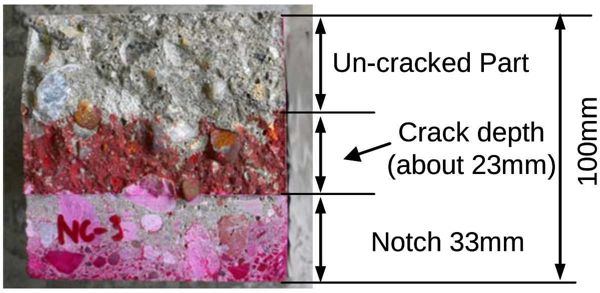


Fig.3 Crack Depth of CMOD 0.05mm
(Age 28 days)

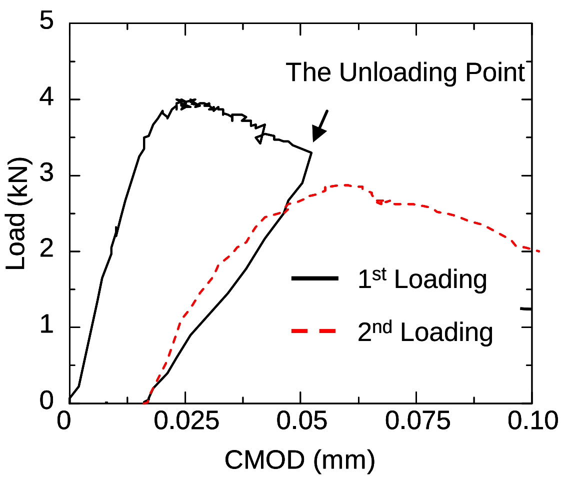


Fig.2 Example of Load-CMOD Curve
(NC 7-28W)

Table 2 Test Program

Case	Days after Casting									
	7		28		49		70	91		112
7-28	1st	⇒	2nd							
28-49			1st	⇒	2nd					
49-70					1st	⇒	2nd			
91-112								1st	⇒	2nd
Control			C		C		C			C

1st : 1st loading day (*m* days)
2nd: 2nd loading day after recuring (*n* days)
C : 1st and 2nd loading day without recuring (*n* days)
⇒: Recuring in air and water condition during 21days

24 hours, and all specimens cured under water of 20℃. Before the first loading, a notch having a depth of 33mm and a thickness of 3mm was induced at the midpoint of all specimens. The experimental setting is given in Fig.1.

The three-point bending test specified in JCI (JCI-S-001-2003) was performed to induce a crack in a specimen. A loading span was 300mm. The mechanical jack with load cell (capacity: 50kN) was used for the loading. A clip gauge (capacity: 5mm, sensitivity: 1/1000mm) at the notch was used to measure the Crack Mouth Opening Displacement (CMOD). For the estimating relationship between the initial loading age and the ability of autogenous healing, the unloading point at CMOD of 0.05mm was applied, which is different to previous study of Granger et al.[5] had set 60% of the peak load. This is feasibility study to apply the testing method and an index to the evaluation the potential of autogenous healing of concrete. Fig.2 shows the measured example of load-CMOD curve. The first loading was performed at the age of 7, 28, 49 and 91 days, and recuring was performed in water and in air condition for 21 days. After recuring, the second loading was performed by using same loading manner. A depth of crack by the first loading was about 23mm as shown in Fig.3. Every recuring series had five specimens depend on the initial loading age, and another five specimens were prepared for the control series. Table 2 shows test program. Two numbers of case names mean the first loading day and the second loading day, respectively. Fig.4 shows the change of the initial stiffness at each loading age. Slight increase can be observed and it should be potential of increment for autogenous healing.

2.2 Index of Autogenous healing

For evaluating the ability of autogenous healing, a sensitive index related to required performance of concrete structures should be needed. For example, the

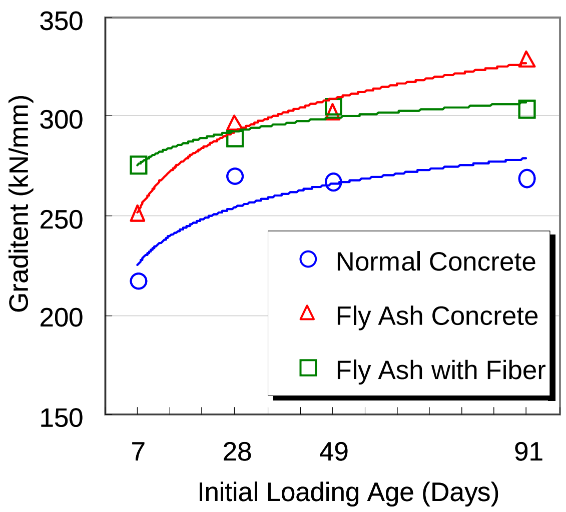
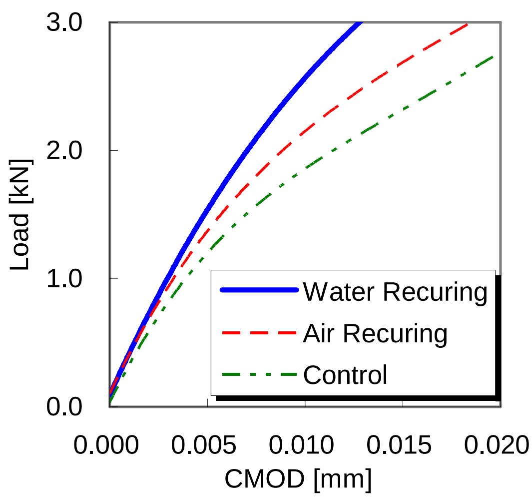
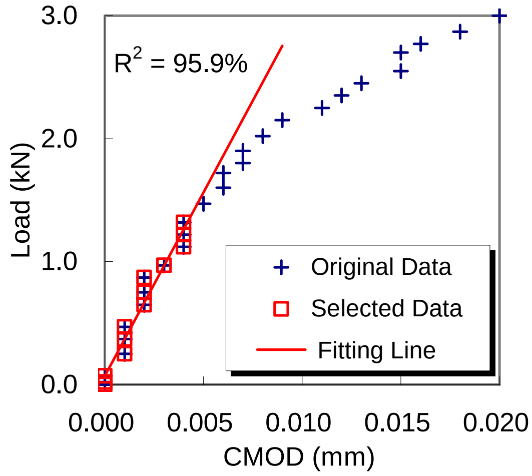


Fig.4 The Initial Stiffness at each Loading Age



(a) Difference of the initial stiffness at the second loading depending on recuring condition



(b) Example of the Initial stiffness at the second loading

Fig.5 Gradient at the second loading

permeability difference between before and after recuring [6], the strength recovery ratio between peak load at the first loading and at the second loading [7], and the location maps of micro-cracks used Acoustic Emission System [5] had been used. In this study, the stiffness of the second loading after recuring, which seems to be sensitive index to access the property of autogenous healing, was used for the index of autogenous healing ability. Fig.5-(a) shows an example of load-CMOD curves on the difference of the initial stiffness at the second loading depending on recuring condition. A material stiffness is usually determined by measuring a definite gradient, which is decided by two points in load-displacement curve. So this study used the initial tangent gradient of the second loading, which was secant stiffness between origin and CMOD of 0.004~0.006mm as shown Fig.5-(b).

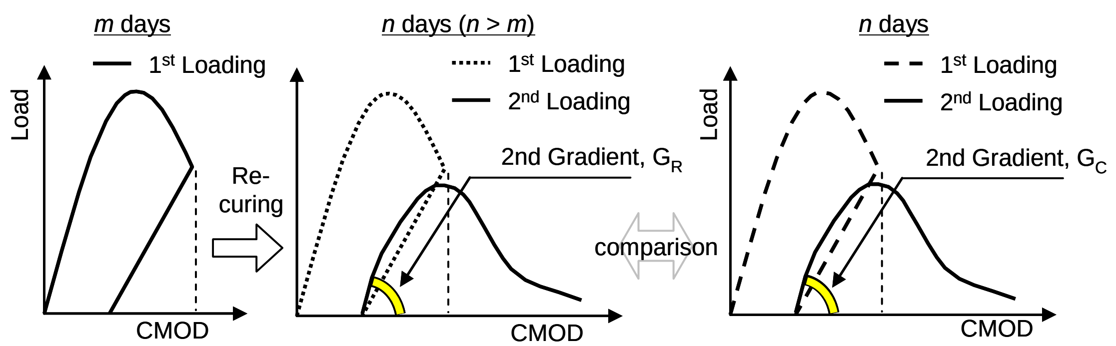
The gradient difference between specimens with and without recuring was the index of autogenous healing in this study. Fig.6 shows the image of gradient as an index. The control series has the first loading and the second loading at same day. Note that there was no recuring process. If the gradient of recuring series is larger than that of control series, it means pre-crack recovered during recuring process by autogenous healing effect. This study used the gradient ratio to estimate the degree of autogenous healing, as shown in the following equation.

$$\text{Gradient Ratio} = G_R / G_C \quad (1)$$

where,

G_R : The gradient at the second loading of recuring series. (*m* days)

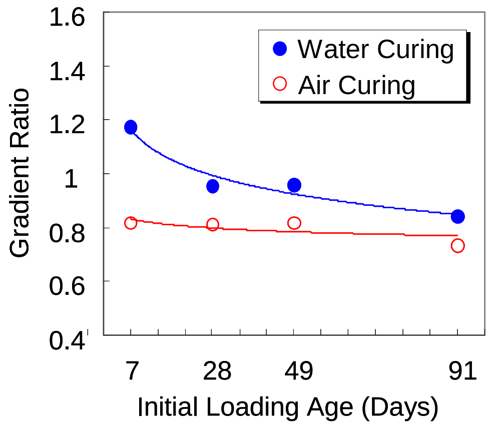
G_C : The gradient at the second loading of control series. (*n* days)



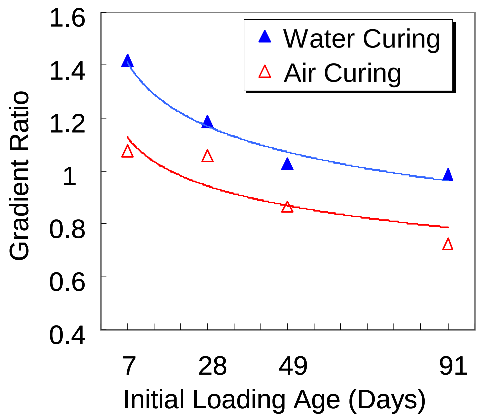
(a) Recuring Series

(b) Control Series

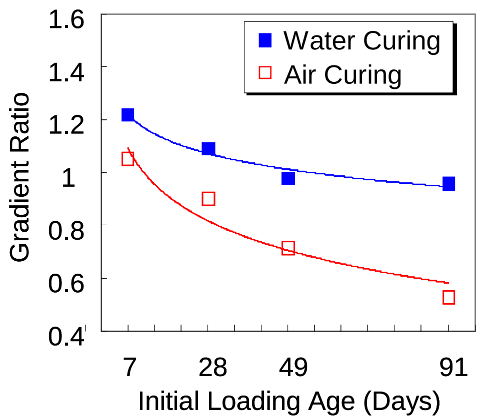
Fig.6 Image of Gradient as an Index



(a) Normal Concrete (NC)



(b) Fly Ash Concrete (FC)



(c) Fly Ash Concrete with Fiber (FC+Fib)

Fig.7 Relation between the Initial Loading Age and the Gradient Ratio

The gradient ratio was able to use for estimating how autogenous healing was occurred, i.e., the larger value of the gradient ratio means the more effective in autogenous healing.

2.3 Results and Discussions

Fig.7 shows the relationship between the initial loading age and the gradient ratio in each series.

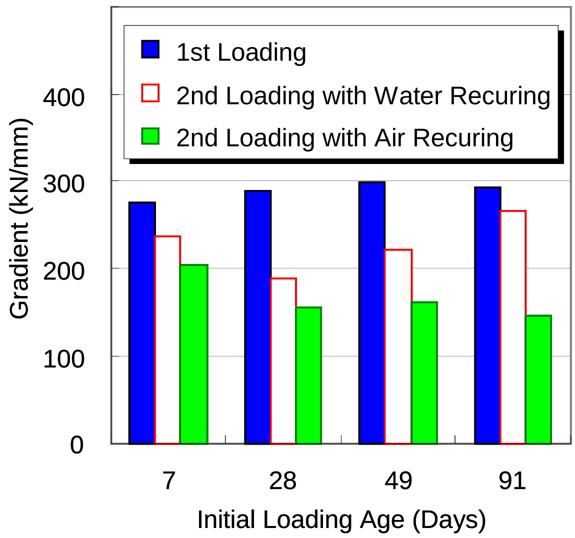


Fig.8 Difference of Gradient by Loading Process (Fly Ash Concrete)

Regardless of material difference, the gradient ratio decreased with increasing of the initial loading age. Same trend has been reported by Schlangen et al [8]. The gradient ratio with water recuring condition was higher than that with air recuring condition, and it means recuring in water condition is more effective in autogenous healing than in air condition. These results show that the ability of autogenous healing depends on hydration of concrete material, which means hydration of cement material influence on the ability of autogenous healing.

Comparing to concrete with and without fly ash, the gradient ratio of fly ash concrete and fly ash concrete with fiber provided larger value than that of normal concrete regardless of the initial loading age, and convergent value of the gradient ratio with fly ash also higher than that of normal concrete, especially in the case of water recuring.

The gradient ratio of fly ash concrete with fiber was also larger than that of normal concrete, but smaller than that of fly ash concrete without fiber. Especially, rapid change of the gradient in air recuring condition was also significant comparing to other case. It was reported that ECC specimens with PVA fiber in water curing showed the recovery of stiffness[8]. However, recovery of stiffness after recurring was not significant in the case of PE fiber[3]. One of the reasons seems to be that PE fiber does not have hydroxide (OH^-) and it does not become to be nuclei for recovery of stiffness during recuring. Further study and discussion should be needed.

The gradient at the second loading with water recuring condition recovered over 70~80% of that of the first loading regardless of the initial loading age, but recovery of air recuring condition was only 50~60%. Fig.8 shows gradients at the first loading and at the second loading with air and water recuring in fly ash concrete. The comparison of the gradient value at the first loading and that at the second loading had advantage in comparing values of same specimens directly.

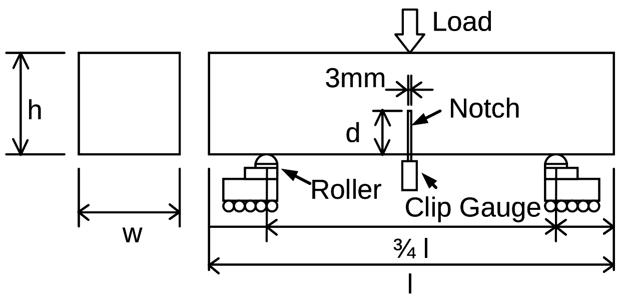


Fig.9 Shape of Specimen (Series 2)

Table 3 Size of Each Case (unit: mm)

Case	Length l	Height h	Width w	Notch Depth d
S100	400	100	100	33
S200	800	200	200	66
S300	1200	300	300	100

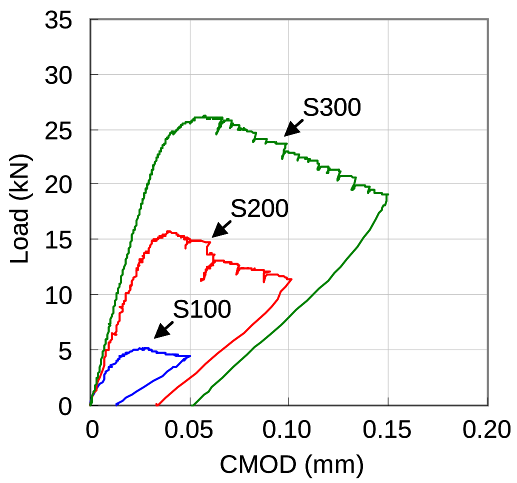
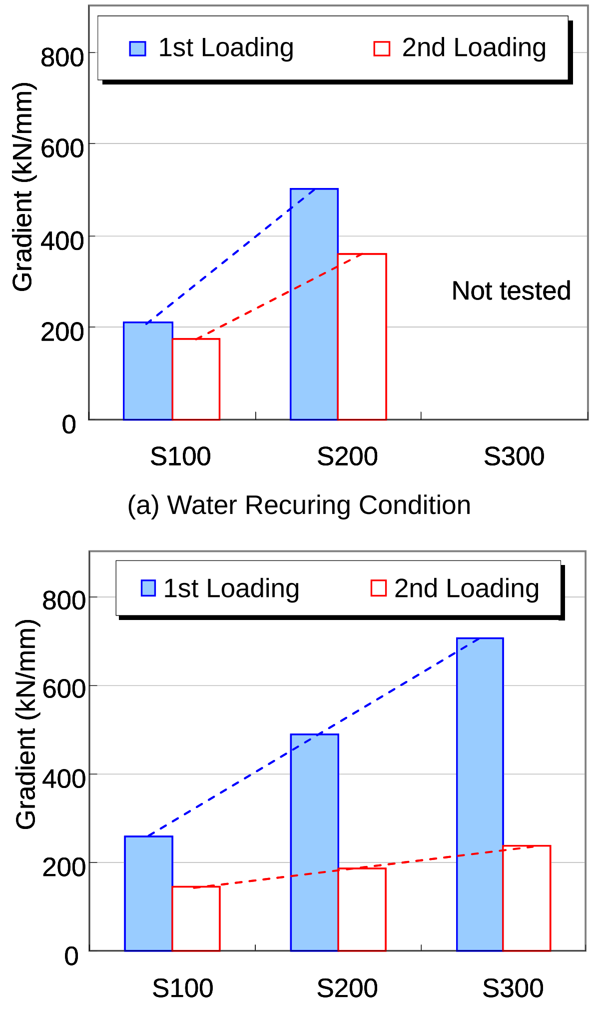


Fig.10 Load-CMOD Curve of S100, S200 and S300



(b) Air Recuring Condition

Fig.11 Gradient after Recuring of S100, S200, and S300 (Fly Ash Concrete)

3. SIZE EFFECT ON HEALING (SERIES 2)

3.1 Test Program

Fly ash concrete was used to observe the size effect of specimens, because autogenous healing ability of fly ash series was observed more clearly than that of other series in Series 1 in this paper. Material and the mix proportions was the same as fly ash concrete as shown in Table 1. A casting and a demoulding was the same as Series 1. Fig.9 and Table 3 show the size of each series. Three kinds of specimen size were used for observing the size effect of specimens, such as S100, S200 and S300. In addition, depth of notch was one third of the specimen depth (value of 33mm in S100, 66mm in S200, and 100mm in S300, respectively). The loading machine and used the clip gage was also same with Series 1, but the unloading points were 0.05mm in the case of S100, 0.10mm in the case of S200(two times of S100), and 0.15mm in the case S300(three times of S100). Note that the damage level in terms of crack propagation was corresponding to each other. The initial loading age was 28 days after casting, and recuring conditions was in water and in air condition, except S300, which is just in air condition. Fig.10 shows the measured example of load-CMOD curve of S100, S200 and S300 series. The second loading was conducted after 56 days from the first loading to consider the characteristic of slow hydration of fly ash concrete.

3.2 Results and Discussions

Fig.11 shows the gradient at the first loading and that of the second loading with recuring in air condition and in water condition. The gradient at the first loading increases by increasing specimen size, and the gradient at the second loading was also affected by that. In the case of water recuring, the ratio of the gradient at the second loading to that at the first loading was decreased with increasing of specimen size. In the case of air recuring, however, the gradient at the second loading was significantly smaller comparing to that in water recuring. This trend indicates crack width possible to recovery depends on recuring condition, although crack depth was relatively the same each other. However, crack width was completely different in each series.

4. CONCLUSION

This study presented an experimental study on the autogenous healing ability regarding concrete type and specimen size. The following conclusions were obtained;

(1) Autogenous healing ability of fly ash concrete was higher than that of normal concrete. Especially, water curing is essential to obtain effective autogenous healing of concrete (e.g. fly ash concrete and normal concrete).

(2) In this study, effect of short fiber (PE fiber) was not significant.

(3) The stiffness of three-point bending test was one of the effective indices to represent autogenous healing properties.

(4) Autogenous healing of large specimen having relatively wider crack under air recuring was not significant.

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