-Technical Paper-

EFFECT OF CRACK SELF-HEALING ON COMPRESSIVE STIFFNESS AND SHEAR TRANSFER OF CONCRETE SUBJECTED TO CYCLIC LOADING

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ABSTRACT

Self-healing concrete can heal itself from cracks and other minor imperfections and thus to prolong the life of the materials and structures. The critical width for crack healing is about 0.2 mm for concretes observed and proved by many researchers. After several generations, the self-healing additives are now stronger and more effective. To apply these products to real concrete structures, the fatigue behavior of self-healing concrete needs more investigation. Shear, compressive fatigue tests were conducted to exam the structural performance of new type of self-healing concrete.

Keywords: Self-healing concrete, fatigue, crack width.

1. INTRODUCTION

Cracks in concrete may accelerate the rate of chemical deterioration and reinforcement corrosion that affect the durability of infrastructures. Self-healing concrete is one of the modern smart concrete, which can heal the cracks by itself. The natural self-healing of concrete (autogenous healing) was found in many old concrete structures which have survived for long periods with only limited maintenance, the results of moisture interacts with un-hydrated cement clinker in the crack in some special situations [4].

The man-made self healing ability of concrete (autonomic healing) which replace a part of cement or sand by self-healing additives was introduced by many researches [1],[2]. From the water leakage tests of previous studies [3], the performance of new type self-healing additives showed remarkable decrease crack width (crack width is smaller than 0.2mm, water pass through the cracks all the time).

With the good results in blocking the water through cracks, now researchers pay more attention not only to increase the self-healed effect but also the strength itself of self-healing products.

There is report about the slightly self healing of high strength concrete from deterioration by freeze/thaw, after 3-4 months curing under water [5]. One objective of this study is to investigate the self-healing capability of concrete under compressive cyclic loading in new type SHC.

As the matter of fact, RC structures are associated with cracks from the onset of their service life. The stress transfer capability of these cracks may strongly influence the service life of some structures as bridge decks, girders, offshore structures. Especially, water is found to accelerate the damage of cracked concrete structures [6]. In the case of self-healing concrete, water on the other hand is needed for the self-healing process. Thus, another objective subjects to the contribution of self-healing products into the shear transfer performance of cracked concrete interfaces.

2. EXPERIMENTAL PROGRAM

2.1 Materials

The materials used in this study are shown in Table 1. Concrete is ready-mix from concrete plant and cast at the same time for all specimens. Self-healing additives developed by second authors and his research group. The mix proportions are shown in Table 2. Type A is the powder type self healing additives [2]. Type K is granulated type self healing additives and the main ingredient of type O contains low activated cement.

2.2 Compressive Tests

(1) Specimens details

Eight concrete cylinders with nominal dimensions D100×200mm were tested.

Table 1 Materials type

Material	Type (Density)
Cement	Ordinary Portland cement (3.15 g/cm^3) Low heat Portland cement (3.24 g/cm^3)
Aggregate	Fine aggregate S (2.57 g/cm^3) Course aggregate G (2.65 g/cm^3)
PVA-F	PVA Fiber (1.30 g/cm^3)
SH additives Type A,K	Expansive agent#20, low heat cement, geo-materials SiO_2, Al_2O_3 and other mineral (~2.6 g/cm^3)
AE	Super plasticizer SP8RV

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Table 2 Mix proportions of concrete

No.	Series	Type of SH additives	W/C (%)	W/P (%)	s/a (%)	Air (%)	Mix proportions（kg/m^3）						
							W	C	SH additives	S	G	PVA-F	AE (×%)
1	FRC	—	56.5	56.5	52.3	4.5	175	310	—	934	869	6.5	1.30
2	FRCA	Type A		50.0					40	894		6.5	2.75
3	FRCK	Type K		50.0					40	894		5.0	2.50
4	RCO	Type O		43.8					90	844		—	1.30

Table 3 Compressive strength of concrete

Series	7 days Concrete Plant MPa	28 days Concrete Plant MPa	100 days Experimental room MPa
FRC	20.0	25.2	24.0
FRCA	20.6	27.3	27.3
FRCK	25.3	32.1	32.7
RCO	31.2	40.7	38.2

Table 4 Loading patterns

Series	Loading level	Curing condition	Loading patterns	Duration
FRCwet	70% of ultimate Load	Water curing 6 days, dry 1 day	2 cycles each time.	1 month
FRCAwet				
FRCKwet				
RCOwet				
FRCdry		Dry 7 days		
FRCAdry				
FRCKdry				
RCOdry				

The cylinders are fully wrap curing in 7days and kept in normal environment until test day. The compressive strengths of concrete are shown in Table 3. Two 60mm strain gauges are attached to both sides of each cylinder.

(2) Loading patterns and curing condition

Loading patterns and curing condition are shown on Table 4. Age of cylinders at the first test is 100 days to make sure the increase of compressive strength are negligible. The compressive test is conducted in 2 cycles and curing again and test in next week, duration is one month.

2.3. Shear Fatigue Test

(1) Loading setup

In this study, four specimens with the dimensions 150 × 280 × 630 mm are considered. The experimental set-up is shown in Fig. 1a, b.

The specimens were cured in fully wrapped wet cloths and plastic sheets, and remove the cloths after 14days. The 5mm×5mm notches are adding in both sides of specimens to induce more regular crack. Before the specimens were subjected to shear fatigue loading, cracks

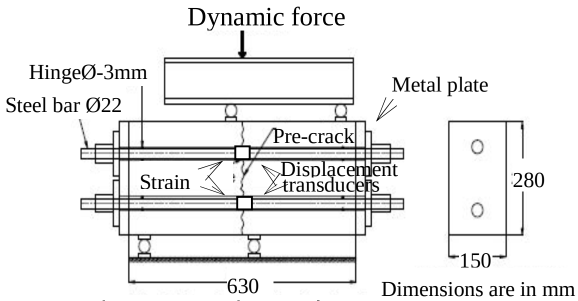

Fig.1a Experimental setup for dynamic loading

Fig. 1b Experimental set up

were introduced by splitting. The initial crack width for each specimen was maintained in the range of 0.2 mm. The two cracked halves were restrained by using un-bonded reinforcing steel bars passing through the longitudinal circular holes. The initial confining stress was kept very small, less than 0.1MPa. It is designed in such a way that the elements on the crack interface are in a pure shear state. All tests were load controlled and measurements of shear slip and crack opening were taken using two directional crack transducers, which are capable of measuring the shear slip and crack width simultaneously. The confining force was measured using strain gages attached to the steel bars. The D22-SD345 threaded steel bars are used in this study.

(2) Loading patterns and curing condition

Loading patterns and curing condition are shown on Table 5, after curing 1 month, shear test was applied to beams to detect the effect of self healing.

Table 5 Loading patterns of shear fatigue test

Series	Loading pattern	Curing condition	Shear load level
FRC	100003 cycles 1 side fatigue loading	1 month curing in water	50kN
FRCA			
FRCK			
RCO			

3. TESTS RESULTS AND DICUSSION

3.1 Self-healing Of Cracks

The effect of self healing is shown in Fig. 2. (Series RCO, FRCK after 1 month curing in water)

3.2 Compressive Test

The load-compressive strain relationship of specimens is shown in Fig. 3. At stress levels higher than about 70 percent of the ultimate strength, the stress concentrations at large voids in the mortar matrix become large enough to initiate cracking [8]. With repeating cyclic loading, the matrix cracks gradually spread until they join the cracks originating from the interfacial transition zone. In this study, the aim is to find out whether the self-healing product can partially repair the matrix cracks, delay the spread of matrix cracks. Therefore, the strain 0.75×10^{-3} will be adopted to compare the strength degradation of specimens. The first cycle's stress of concrete at the strain point 0.75×10^{-3} was determined as the initial value. Strength degradation of specimens is shown in Fig. 4.

From the Fig. 4 after 1 week curing, almost no effect of self healing is found in 4 series. The decrease trend is still the same with the results of the first 2 cycles test. Fig. 4a shows the comparison between FRCwet and FRCdry. The slope of strength degradation is almost the same until week 3. The strength degradation of FRCwet is faster than FRCdry.

After 2 weeks curing, the recovery of strength at the cases FRCAwet and FRCKwet are remarkable. The strength recovery of RCO also was observed after 3 and 4 weeks curing (Fig. 4b, c, d). Even though the results show the changing and recovery of strength degradation,

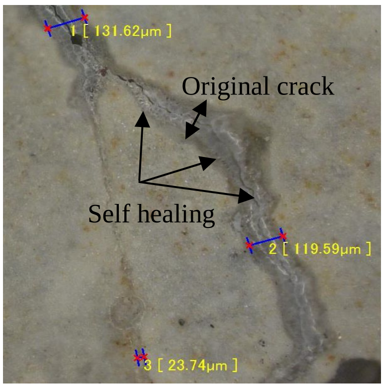

Fig. 2a Self healing of crack (RCO)

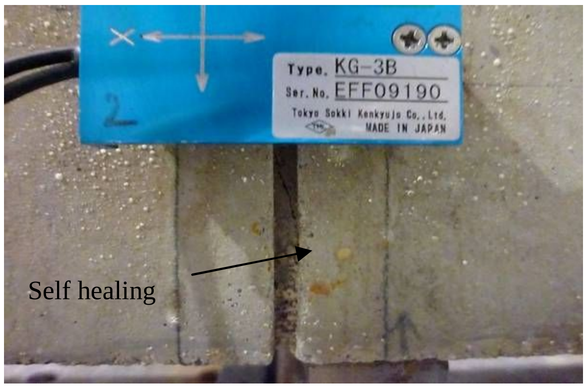

Fig. 2b Self healing of crack (FRCK)

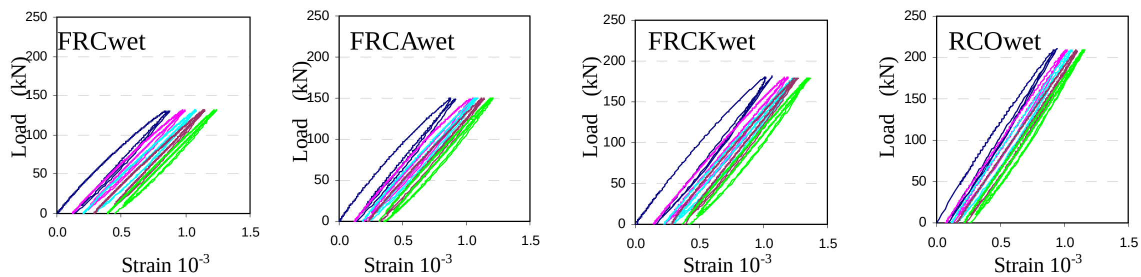

Fig. 3a Load – Compressive strain relationship of Wet series

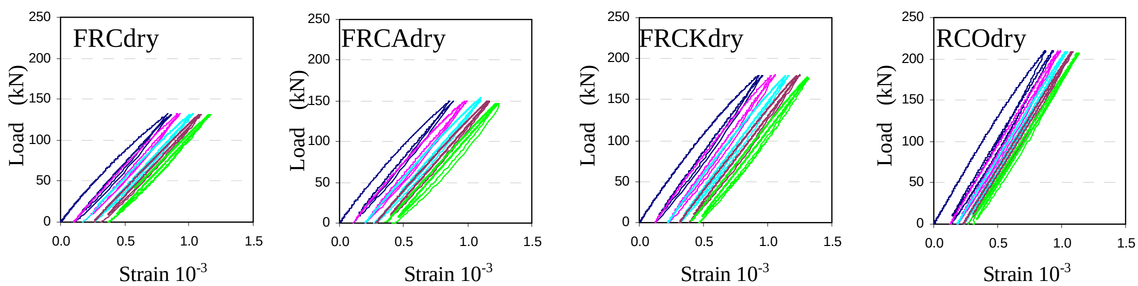

Fig. 3b Load – Compressive strain relationship of Dry series

Week 0 week 1 week 2 week 3 week 4

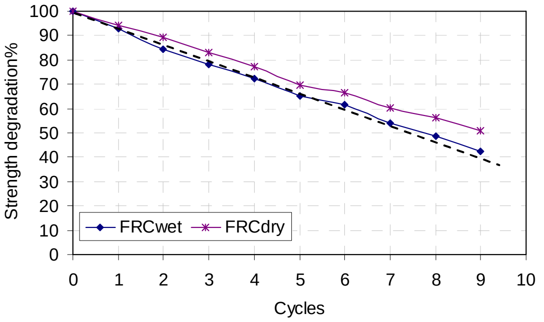

Fig. 4a Comparison of strength degradation (FRC)

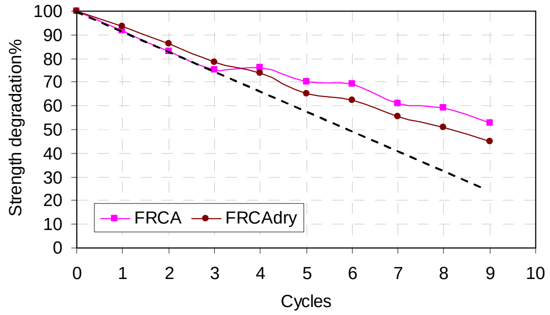

Fig. 4b Comparison of strength degradation (FRCA)

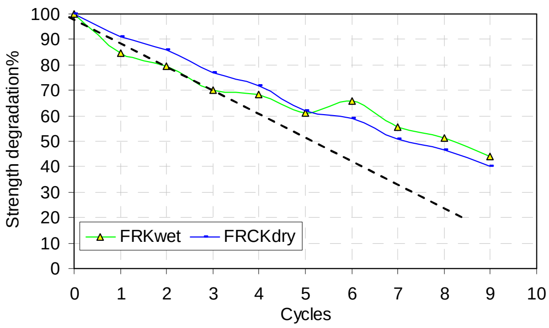

Fig. 4c Comparison of strength degradation (FRCK)

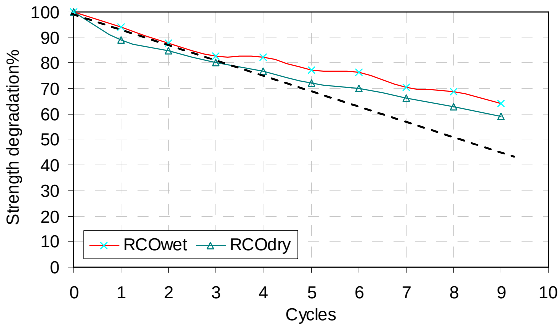

Fig. 4d Comparison of strength degradation (RCO)

Table 6 Crack width of specimens

Designation	Initial crack width (mm)	Crack width after 100003 cycles (mm)
FRC	0.23	0.21
FRCA	0.17	0.17
FRCK	0.19	0.15
RCO	0.362	0.5

but the assumption of the strain point in this study need to be proved and further investigation is considered to clarify the effect of self healing products on recover the deterioration of concrete caused by the fatigue, freeze/thaw etc. action.

3.3 Shear Fatigue Test

(1) Splitting

The crack width of four specimens after splitting and before curing is shown in Table 6. The main reason caused the larger crack width of RCO is the concrete without fiber, and the compressive strength of RCO is larger than the other case.

(2) Response under static loading

When an incremental shear stress is applied to the interface of crack, a shear slip δ will be mobilized with a corresponding dilation ω (Fig. 5). Thus, it results in the increase of the confining stress σ. Depending on the boundary conditions provided; the shear response is different [7].

The shear stiffness of specimens will be gradually decreasing when the shear load is applying. At low stress level the shear slip can recover as the result of reduced friction but residual shear slip still remaining and irrecoverable. The load – shear slip relationship under low stress level are shown in Fig. 6.

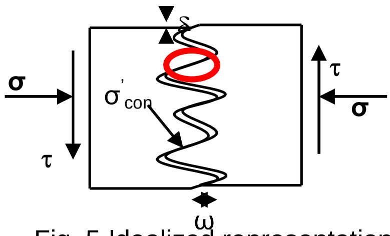

Fig. 5 Idealized representation of asperities in a crack plane

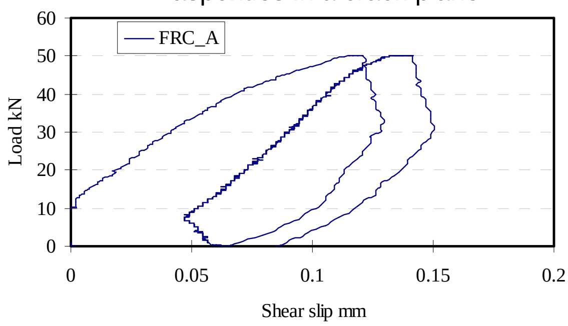

Fig.6 Response under static shear loading

(3) Response under one side fatigue loading

During the increasing of shear slip, the crack width and confinement force are also rising. At the same time with the gradually decreasing of the increment of shear slip, crack opening is also reducing due to the loss of

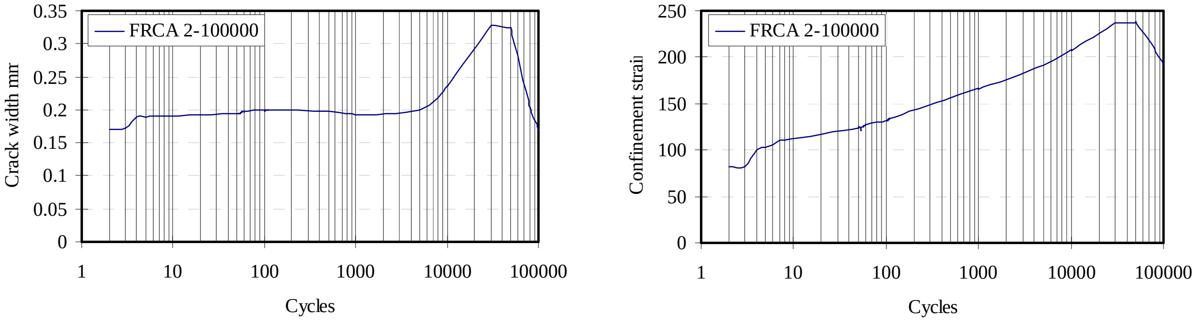

Fig. 7a Responses of Crack width and Confinement force under one side fatigue loading

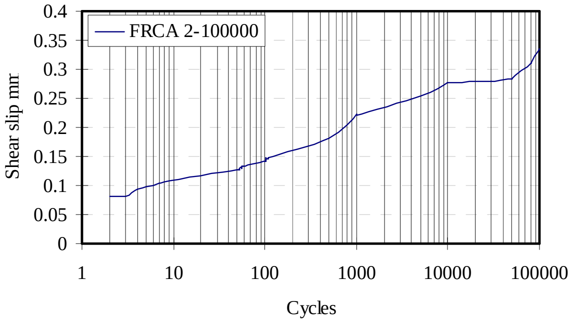

Fig. 7b Low amplitude fatigue response

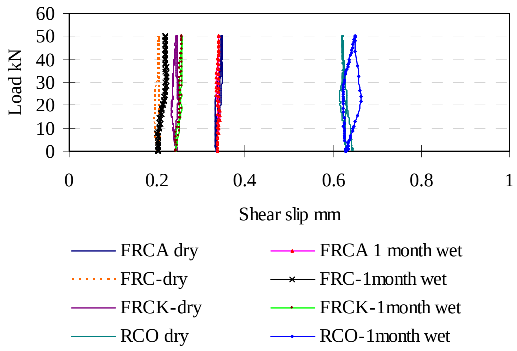

Fig. 8 Response of shear slip before and after curing

particles on the crack surface. This result also reflects to the reducing of confinement stress (Fig. 7a).

Fig. 7b shows the typical shear fatigue response at relatively low stress level. The increment of shear slip at the beginning is larger, results of damage within the crack interface. After 10000 cycles the increment is gradually decreased due to the developing of contact units.

(4) Effect of self healing

From the response of shear slip, crack width and confinement force mentioned above, after 100000 cycles one side fatigue loading, the increment of shear slip, crack width and confinement are almost zero. That means in few cycles loading, all three variables return to original value. Fig. 8 shows the changing of shear slip during 1 cycle before and 1 cycle after curing.

Fig. 9a~d shows the relationship between shear load and confinement force. In case of FRCA, the increase of confinement at the very low shear load (3 kN

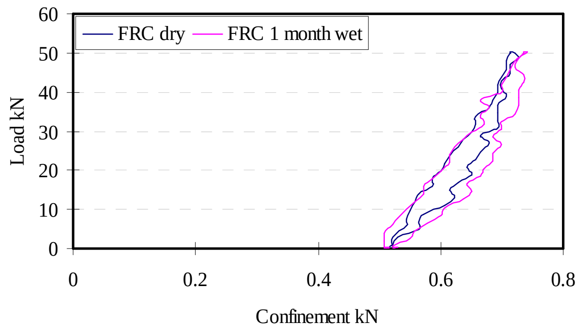

Fig. 9a FRC increase of confinement

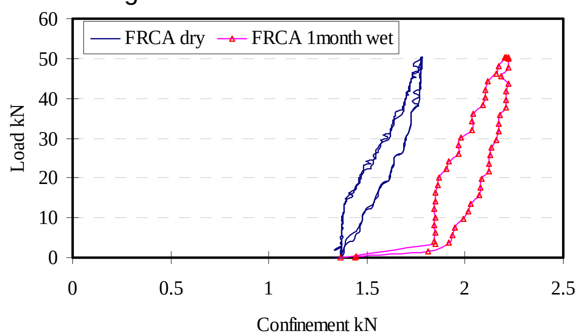

Fig. 9b FRCA increase of confinement

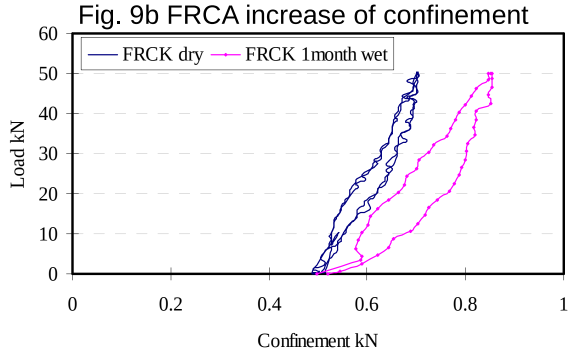

Fig. 9c FRCK increase of confinement

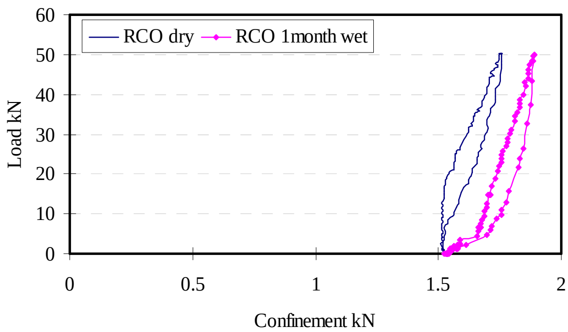

Fig. 9d FRCA increase of confinement

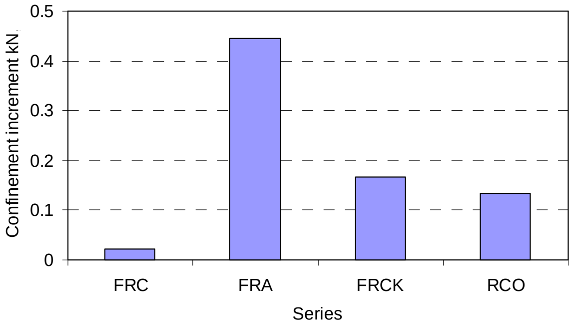

Fig. 10 The increment of Confinement force after curing

shear load correspond to 0.45 kN of confinement increase). This phenomena can be explained by the fill of self heal products into crack surface. In the case of normal concrete (FRC), no changing of confinement was observed. In other cases: FRCK and RCO the enhancement of confinement force at low shear load are observed. The increment of confinement after 1 month curing is shown on Fig. 10.

With the large crack width (0.5 mm), that is not ideal environment for progress of self healing, but still some good performances be obtained in RCO case. Further investigation and modification are considered to study the structural performance of new type of self-healing concrete.

4. CONCLUSIONS

With significance in healing the crack, reducing the crack width, new type of self healing concretes is expected to prolong the service life of concrete structures. Several testing methods are adopted to detect the contributions of self healing additives in concrete members, especially the performance of self healing products under fatigue loading. The following conclusions are derived from this study:

(1) By the direct and microscopic observation, the self-healing effects of new type of self-healing concrete are significant. Case RCO shows the capability to heal the crack width even smaller than 0.1mm.
(2) Deterioration of concrete and the degradation of compressive strength can be partially recovered after two weeks curing.
(3) Self-healing products are found on the crack interface, and the contributions of them to shear transfer are observed.

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REFERENCES

[1] Kishi, T., Ahn, T., Hosoda, A., Suzuki, S., and Takaoka, H.: Self healing behaviour by cementitious recrystallization of cracked concrete incorpotrating expansive agent, First International Conference on Self Healing Materials, Noordwijk, The Netherlands. 2007

[2] Tae-Ho Ahn and Toshiharu Kishi: Crack Self-healing Behavior of Cementitious Composites Incorporating Various Mineral Admixtures. Journal of Advanced Concrete Technology Vol. 8, No. 26, June 2010, pp.171-18

[3] A. Hosoda, S. Komatsu, T. Ahn, T. Kishi, S. Ikeno and K. Kobayashi: Self healing properties with various crack widths under continuous water leakage. Concrete Repair, Rehabilitation And Retrofitting Ii. 2009

[4] Edvardsen, C.: Water Permeability and Autogenous Healing of Cracks in Concrete. *ACI Materials Journal*/ July-August, 1999, pp.448– 454

[5] Stefan Jacobsen and Erik J. Sellevold.: Self healing of high strength concrete after deterioration by freeze/thaw. Cement and Concrete Research Volume 26, Issue 1, January 1996, pp. 55-62.

[6] Esayas Gebreyouhannes, Toshiharu Kishi, Koichi Maekawa: Shear Fatigue Response of Cracked Concrete Interface. Journal of Advanced Concrete Technology Vol. 6, No. 2, June 2008, pp. 365-376.

[7] Mattock, A.H., and Hawkins, N.: Shear Transfer in Reinforced Concrete – Recent Research, *Journal of Prestressed Concrete Institute*, V. 17, No. 2, 1972

[8] P. Kumar Mehta, Paulo J. M. Monteiro: Concrete Microstructure, Properties and Materials, McGraw-Hill, Third Edition 2006.