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Effect of self-healing agents on inorganic crack repair materials for concrete infrastructures

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In this study, innovative repair methods based on crack self-healing technologies using cementitious materials were suggested in order to prevent water leakage in concrete infrastructures such as slab, tunnel and water-retaining structure. Especially, this study aims to develop new inorganic repair materials as needed to follow the crack and its repair methods. Crack repair methods such as Coating Method (CM), Drilling & Filling Method (DFM) and Coating and DF Method (CDFM) for the practical industrial application were examined in comparison with normal crack repair method without self-healing capability. From these results, it was confirmed that the sealing effects of water leakage through the penetrating cracks from field tests could be improved by cementitious composite materials with self-healing capability.

Key words: Crack, Water leakage, Repair, Self-healing capability.

Introduction

Crack in concrete is one of the biggest problems in terms of functionality, durability and aesthetics of infrastructures. Therefore, maintenance and repair of cracked concrete are also very important for civil engineering fields. So, various repair materials and techniques have been already suggested and many types of repair materials are currently being used.

In general, repair materials based on organic materials have properties such as high flexible capability and strongly adhesive against crack movement, however, until now they show the aged-related degradation and the UV-effected degradation after repairing. On the other hand, repair materials based on inorganic materials has the thermal expansion coefficient of cementitious materials and, it tends to be very similar to that of the substrate concrete. Therefore, they are widely used due to their efficient bonding with wet substrate concrete. However, they have also some demerits such as their low flexible capability and following cracks. In this study, innovative repair methods based on crack self-healing technologies using cementitious materials were suggested in order to prevent water leakage in concrete infrastructures such as slab, tunnel and water-retaining structure. Especially, this study aims to develop new inorganic repair materials as needed to follow the crack and its repair methods. Figure. 1 shows actual repair examples based on cementitious materials of concrete slab on viaducts in Japan.

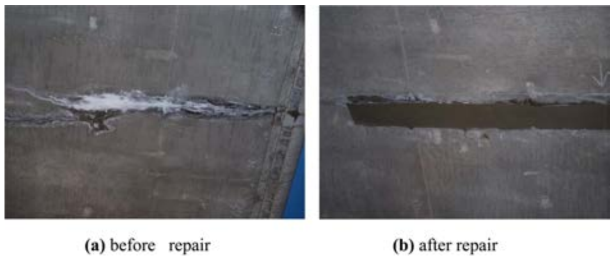

Fig. 1. Repair examples of concrete slab.

In previous researches [1-4], various repair materials were examined for new repair materials with self-healing capability applied to crack sealing method. Mineral admixtures such as expansive agent, geo-materials, and chemical agents were used in order to manufacture the self-healing agent based on previous research [1-2]. This study focused on two primary issues: (1) experimental and analytical design of new cementitious repair materials with self-healing capabilities, (2) development of crack repair materials, and their new repair methods.

Experimental Program

In this research, it was postulated that concrete slabs on viaducts of highway and rail road bridges have water leakage from coming through the cracks in the vertical direction. Therefore, concrete cylinders were prepared that they were split in the longitudinal section and were rebound in order to conduct the water leakage test through the cracks [5-7].

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Fabrication of Specimens

Table 1 shows the mix proportions of concrete cylinders (ϕ100 × 200 mm) in this research. After casting, the specimens were cured under sealed conditions (20 ºC, RH60%) for 14 days. And then, they were split with compressive strength testing machine. In order to remove sedimentation effects of concrete particles on the water leakage test, concrete surfaces were cleaned with the air compressor after splitting. Crack width was controlled between 0.1-0.3 mm in consideration of the maximum tolerable crack widths according to construction codes [8]. After rebinding, cylinder sides were sealed and polyvinyl chloride pipes ϕ100 × 200 mm in size on the top of cylinders were set in order to conduct on the experiment of water leakage as shown in Figure. 2.

Suggested new repair methods

Three repair methods with self-healing agents were suggested in this research as shown in Figure 3. There are new repair methods for water-leakage cracks of concrete slab on the railroad viaduct. Especially, repair works were postulated from bottom of cracks on concrete slabs

(1) Coating Method (CM)

The first method is called 'Coating Method'. The repair material was directly coated with 1mm thickness on the surface of cracks. As shown in Figure 3 (a), the water was supplied from the upper side through the cracks of concrete slabs and then repair materials were reacted with water. They were able to diffuse from the bottom side to the upper side.

(2) Drilling & Filling Method (DFM)

The second method is called 'Drilling & Filling Method'. At a certain distance within the cracks under water leakage, the hole (ϕ16 × 100 mm depth) was drilled through the concrete. And then they were filled with the cementitious repair materials incorporating self-healing agents as shown in Figure 3 (b).

(3) Coating and DF Method (CDFM)

The third method is called 'Coating & DF Method'. This method was combined as mentioned above two methods as shown in Figure 3 (c).

Materials

Table 2 shows mix-proportions of crack repair materials in this research. Total 18 samples based on each repair methods were prepared. Type I Portland cement and self-healing agents (A, B, C type) were used as repair materials compared to commercial products (powder and liquid type). Self-healing agents were prepared based on self-healing performance as reported in the previous research [1-3]. They were mainly composed of expansive agent, geo-materials and chemical agents. Microscopy and SEM-EDS were carried out to investigate morphology and shape and size of re-hydration products.

Re-cracking and water pass test

Concrete cylinders with 0.2 mm crack width were repaired by various repair materials. And then water pass test was investigated during 28 days. Re-crack was induced after water pass test as shown in Figure 4.

Finally, water pass test for concrete cylinders with 0.2 mm re-crack was conducted again in order to estimate self-healing performance of repair materials. The water flow through the crack was measured after filling water in the polyvinyl chloride pipes. The elapsed time was recorded for 5 mins, when the surface

Table 1. Mix-proportions of concrete specimens.

W/C (%)	Unit Weight (kg/m^3)				
	Water	Cement	Sand	Gravel	SP(AE)
58	168	290	826	1019	2.9

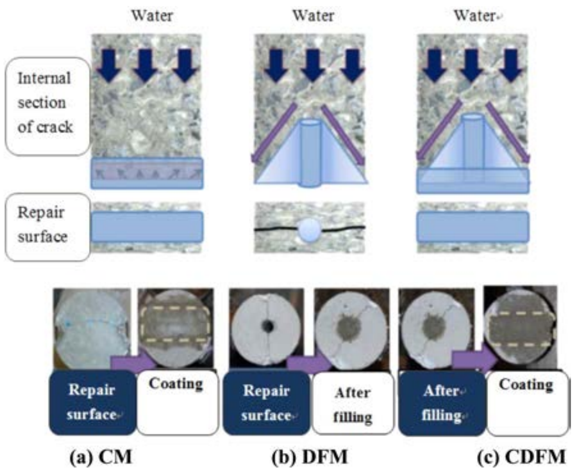

Fig. 3. Concepts of crack repair methods including the self-healing technique.

Fig. 2. Specimen preparations for water leakage test.

Table 2. Mix-proportions of crack repair materials.

Repair Methods	Samples	Bottom Coating Materials			Filling Materials		
		RCA*	Type	Materials	RCA*	Type	Materials
Coating Method (CM)	CM- N	–	–	No repair	–	–	–
	CM- A	–	Mortar (7 : 3)	Commercial A	–	–	–
	CM- B	–	Liquid	Commercial B	–	–	–
	CM- C	–	Mortar (7 : 3)	Cement	–	–	–
	CM- D(SH)	–	Mortar (7 : 3)	SH(A type)10%	–	–	–
	CM- E(SH)	○	Mortar (7 : 3)	SH(B type)	–	–	–
Drilling & Filling Method (DFM)	DFM- C	–	–	–	–	Paste	Cement
	DFM- A	–	–	–	○	Mortar (7 : 3)	Commercial A
	DFM- B(SH)	–	–	–	–	Paste	SH(A type)10%
	DFM- D(SH)	–	–	–	–	Paste	SH(A type)30%
	DFM- E(SH)	–	–	–	○	Paste	SH(C type)20%
	DFM- F(SH)	–	–	–	○	Mortar (7 : 3)	SH(C type)20%
Coating & DF Method (CDFM)	CDFM- C	–	Mortar (7 : 3)	Cement	–	Paste	Cement
	CDFM- A	○	Mortar (7 : 3)	Commercial A	○	Mortar (7 : 3)	Commercial A
	CDFM- B(SH)	○	Mortar (7 : 3)	SH(A type)10%	○	Paste	SH(A type)30%
	CDFM- D(SH)	○	Mortar (7 : 3)	SH(A type)10%	○	Mortar (7 : 3)	SH(A type)30%
	CDFM- E(SH)	○	Mortar (7 : 3)	SH(A type)10%	○	Paste	SH(C type)20%
	CDFM- F(SH)	○	Mortar (7 : 3)	SH(A type)10%	○	Mortar (7 : 3)	SH(C type)50%

RCA* : Reactive Control Agents (based on sodium silicate), SH (Self-healing agent).

(a) Before re-cracking (After repair works) (b) Insert of steel plate for re-cracking (c) Re-cracking

Fig. 4. Re-cracking procedure for concrete cylinder after repair works.

of the water decreased. This measurement was conducted on the 0, 1, 3, 5, 7, 14, 21 and 28 days.

Results and Discussion

Self-healing behavior of repair materials after re-cracking

Figure 5 shows the result of water pass test in case of CM (Coating method). In this research, cement and commercial repair products (A type: powder, B type: liquid) were used as repair materials in order to compare to self-healing performance of repair materials.

In case of CM-A and CM-C, although water flow was decreased slightly at initial stage, they did not show self-healing behavior. However, CM-D and CM-E based on self-healing agents showed lower water flow than CM-A and CM-C at 1 day. Especially, crack of CM-D was almost self-healed after 21 days and its water flow value was almost 0. Moreover, re-hydration products between cracks after re-cracking were observed as shown in Figure 6. This means that re-hydration products greatly affected a decrease of water

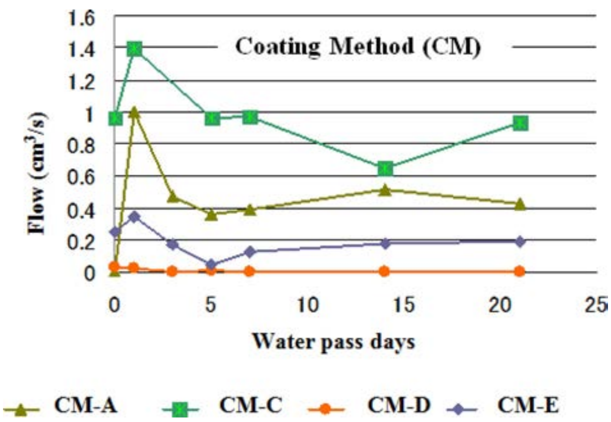

Fig. 5. Waterproof effects of repair materials after re-cracking.

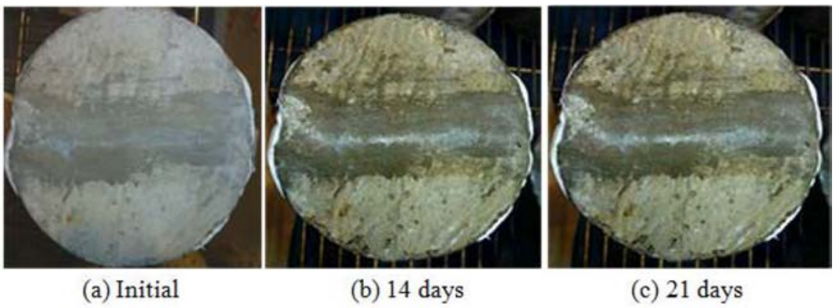

Fig. 6. Process of self-healing on repair materials after re-cracking.

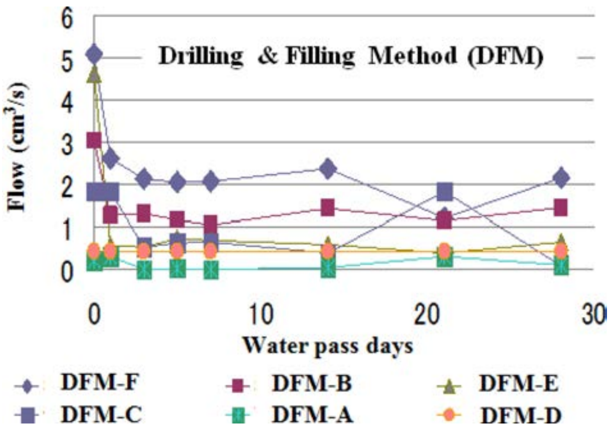

Fig. 7. Waterproof effects of repair materials after water pass tests.

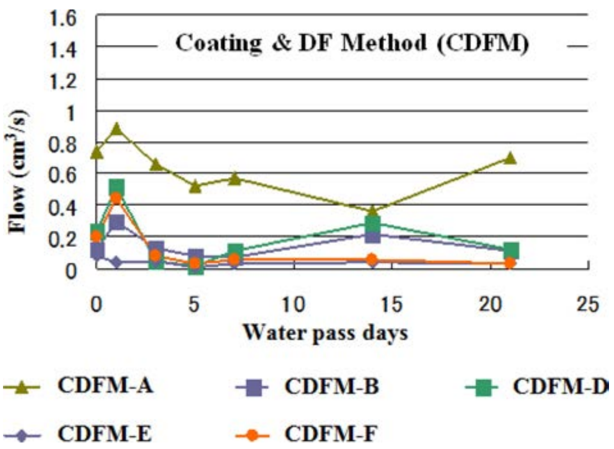

Fig. 8. Waterproof effects of repair materials after re-cracking.

flow, as compared to others. In case of DFM (Drilling & Filling Method), although all specimens showed a decrease of water flow, they couldn't be self-healed completely by themselves until 21 days as shown in Figure 7.

However, DFM-E(SH) showed the best performance for the water proof effect on the water pass tests in the DFM series. This indicates that this special mix-proportion has a high potential for applications of repair materials. Figure 8 shows the result of water pass test in case of CDFM (Coating & DF method). CDFM series except commercial product (CDFM-A), as filling materials, were observed a decrease of water flow in all specimens. In particular, CDFM-E(SH) was showed the best performance for waterproof. Water flow has fallen by around a tenth of initial value until 21 days.

From these results, it was found that the addition of self-healing agents to conventional inorganic repair materials contributes to increase in self-healing capability in the re-cracked specimens after repairs by the cementitious recrystallization and precipitated particles.

Diffusion effect of self-healing agents on repair materials

All specimens after water pass test were observed in order to clarify the self-healing capability after re-cracking. Microscopy and SEM-EDS-detector were carried out to investigate the morphology, shape, and size of re-hydration products and to clarify the mass transport process for recrystallization.

Figure 9 shows split sections of specimens after water pass test. Microscopy observations were conducted at every 5 cm in vertical direction from bottom side (0 cm) to top side. Concrete surface was examined the magnification of 100 times the actual size. In case of Coating Methods as shown in Figure 10, CM-C (Cement) didn't show re-crystallization and re-hydration products on the surface of split concrete.

However, CM-D (SH-A-10%: self-healing agent type A) showed the formation of crystallization on the surface of split concrete partially from bottom side to top side. Furthermore, in case of Coating & DF method, CDFM-E (SH-C-20%: self-healing agent type C) showed the formation of crystals on surface of concrete entirely as shown in Figure 11. CDFM-A(commercial product) without self-healing agent didn't show the formation of crystal as similar to results of water pass test.

Fig. 12 shows morphology of concrete surface and SEM-EDS analysis in case of CDFM-E. Gel phases were formed entirely from bottom side to top side as mentioned above. X-ray spectra obtained from these phases revealed a trend in their chemical compositions such as Ca, Mg, Si, and C. The microscopy image shows that most of cracks were fully filled by newly-formed hydration products. From these results, it was

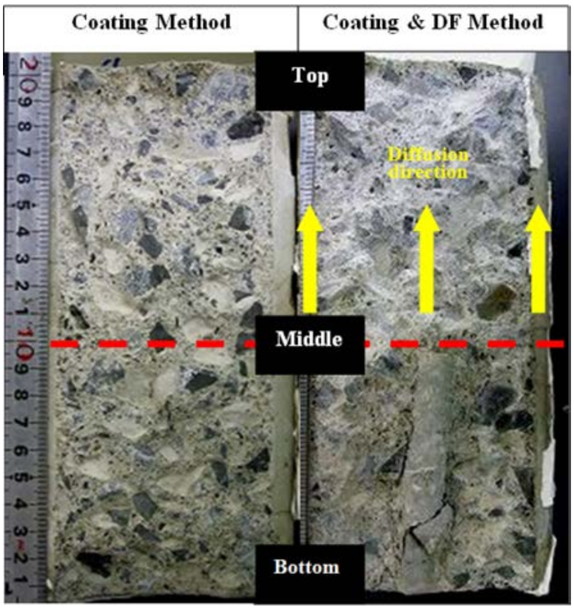

Fig. 9. Process of self-healing on repair materials after re-cracking.

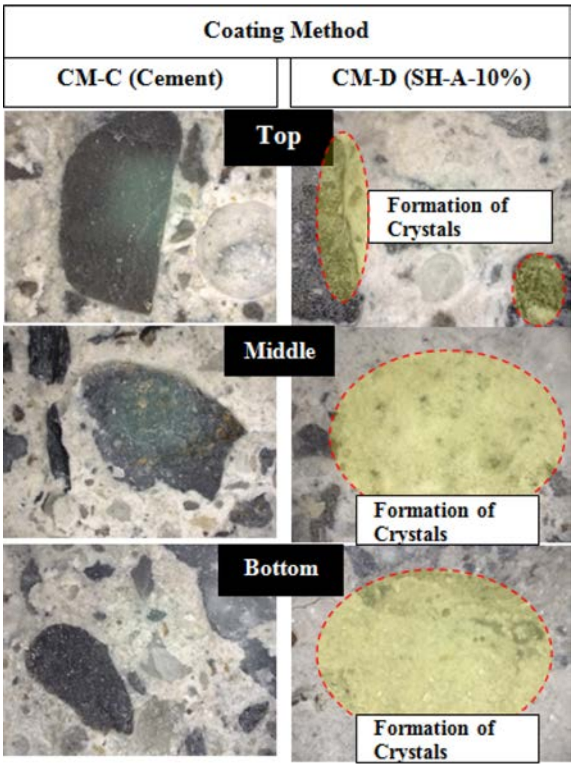

Fig. 10. Observation of concrete surface after split (Coating Method, Size: 2 cm × 2 cm).

found that self-healing agents were significantly affected by magnesium silicate materials and various modified calcium composite materials. Therefore, it is considered that the utilization of appropriate dosages of geo-materials has a high potential for one of new repair methods of cracked concrete. And some particular mix-proportions for new repair method with self-healing capability were suggested for actual applications.

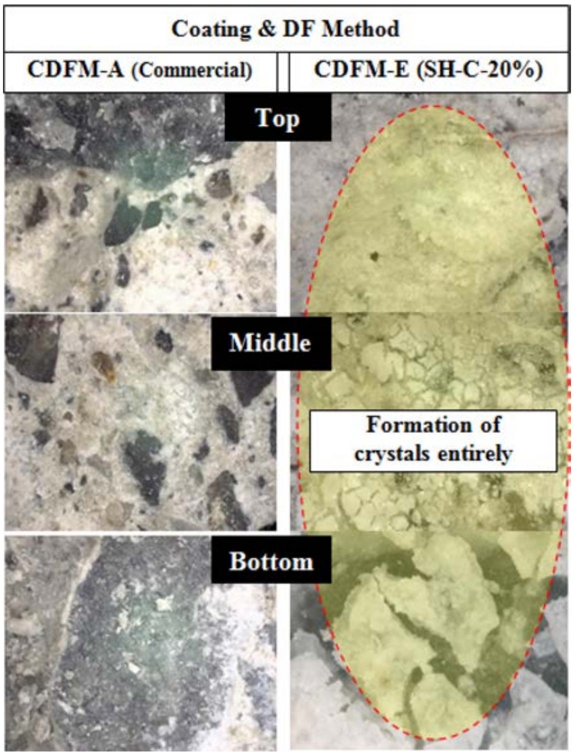

Fig. 11. Observation of concrete surface after split (Coating & DF Method, Size: 2 cm × 2 cm).

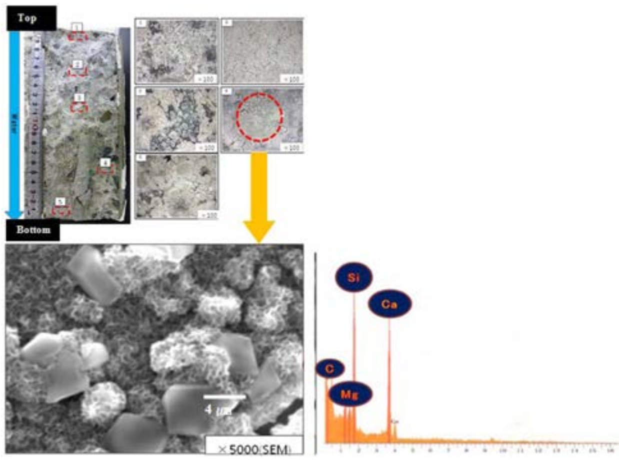

Fig. 12. Formation of gel phases on concrete surface between cracks (CDFM).

Verification of self-healing effect from field test

The verification of inorganic crack repair materials with self-healing capability in an actual concrete slab was also investigated. Two repair methods such as CM and CDFM were applied to actual concrete slabs of railroad viaduct with water-leakage cracks as shown in Figure 13. Length of cracks on the concrete slab was around 3 m. In case of CM, the width of coating repair materials was 100 mm, and the thickness was around 1 ~ 2 mm. In case of CDFM, the depth of drill holes was 40 mm. the holes with 50 mm intervals were prepared for repair work of cracks under water leakage

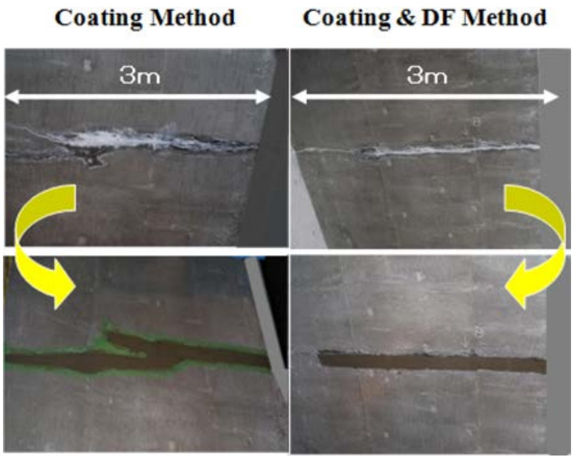

Fig. 13. Water-leakage cracks of actual concrete slab and application of new repair methods**.**

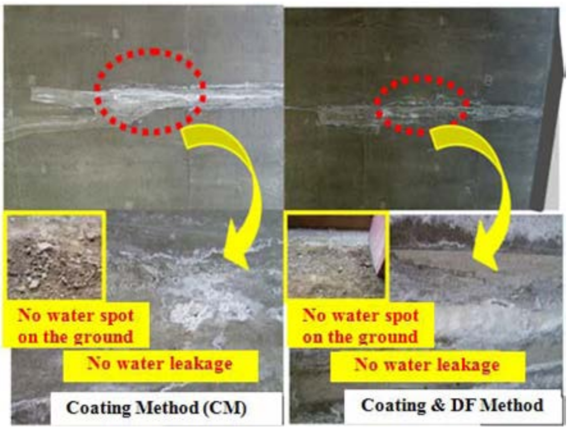

Fig. 14. Repair results after 3 months later (Formation of crystallization on the surface of coating repair materials).

and they were filled with the cementitious repair materials incorporating self-healing agents. CDFM-E(SH-C-20%) was selected as filling materials. Finally, CM-D (SH-A-10%) was coated on the crack surface after filling of repair materials. This project was conducted over 1 year including the visual inspection after repair from October 2010 to September 2011.

After 3 months later, it was found that crystallization was formed on the surface of coating repair materials in both cases as shown in Figure 14.

Furthermore, it was confirmed that the sealing effects of water leakage through the penetrating cracks from field tests could be improved by cementitious composite materials with self-healing capability.

Conclusions

In this research, the new method based on self-healing technique to repair cracks in cracked concrete structures was suggested, and various repair materials and methods were investigated.

(1) Various repair materials were examined for new repair materials with self-healing capability applied to crack sealing method.

(2) Crack repair methods such as Coating Method (CM), Drilling & Filling Method (DFM) and Coating and DF Method (CDFM) for practical industrial application were examined in comparison with normal crack repair method without self-healing capability.

(3) The results of self-healing after re-cracking of repaired area show Coating and DF method (CDFM) incorporating self-healing agents exhibit much higher self-healing behavior than other methods. And re-cracks with width of 0.2 mm in the case of some mix-proportions were almost healed after water pasting tests.

(4) Verifications of new crack repair materials and methods with self-healing capability in an actual concrete slab were investigated. It was confirmed that the sealing effects of water leakage through the penetrating cracks from field tests could be improved by self-healing capability.

(5) It is considered that the utilization of self-healing agents with appropriate dosage has a possibility as new repairing methods for cracked concrete under the water leaking situation, which is common among concrete structures.

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