Development Toward Application of Crack Self-Healing Concrete to Actual Structures

Seiji Ikeno* Keisuke Yamada** Kaoru Kobayashi* Toru Masuda*

Crack self-healing concrete under development by the Frontier Service Development Laboratory is concrete that can fill cracks of approx. 0.2 mm width that have occurred after hardening by precipitating a compound. Upon completion of the development of concrete with this function, we can expect benefits such as a reduction of construction and maintenance costs by omitting underground structure waterproofing.

We checked durability and properties of fresh concrete such as liquidity at casting of that self-healing concrete, taking into account application to actual structures. Check results have clarified that there is no significant difference between self-healing concrete and concrete of normal mixture that it is compared to; thus, there will be no problem in application of self-healing concrete to actual structures.

● Keywords: Concrete, Crack, Healing, Durability, Properties of fresh concrete

1 Introduction

The Frontier Service Development Laboratory has undertaken development of self-healing concrete since 2002. We are now proceeding with it by joint research with Associate Professor Kishi of the Institute of Industrial Science at the University of Tokyo and Associate Professor Hosoda of Yokohama National University. Self-healing concrete is concrete that can fill cracks of approx. 0.2 mm width that have occurred after hardening by precipitating a compound.

When applying that concrete to railway structures after completion of development, we can expect the concrete to be able to prevent leaks beneath elevated structures. It could also allow omission of waterproofing underground because groundwater can be kept out with this concrete alone. Consequently, construction and maintenance costs can be reduced, and we can provide amenity-rich service spaces and build reliable structures (Fig. 1).

Taking into account application of that self-healing concrete to actual structures, we have checked durability and properties of fresh concrete such as liquidity at casting. This article will report on that checking.

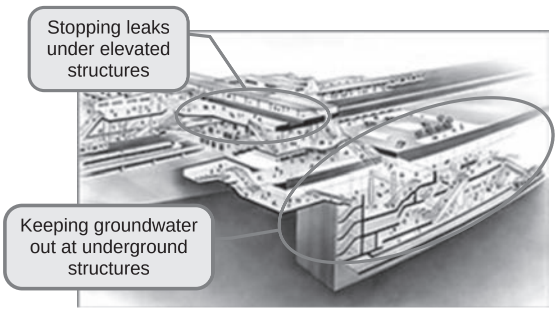

Fig. 1 Application of Self-Healing Concrete to Railway Structure

2 Overview of Self-healing Concrete

2.1 Mechanism of Self-Healing

Concrete originally has a nature of being able to self-heal cracks somewhat. Further bringing out that nature by applying a specific ingredient or mix proportion is the basic concept behind self-concrete.

In the self-healing mechanism, calcium carbonate precipitates out when water flows into cracks in concrete with mineral admixture, filling the cracks (Fig. 2). Calcium carbonate is a compound almost equal to stalactite and has high cutoff performance and great stability.

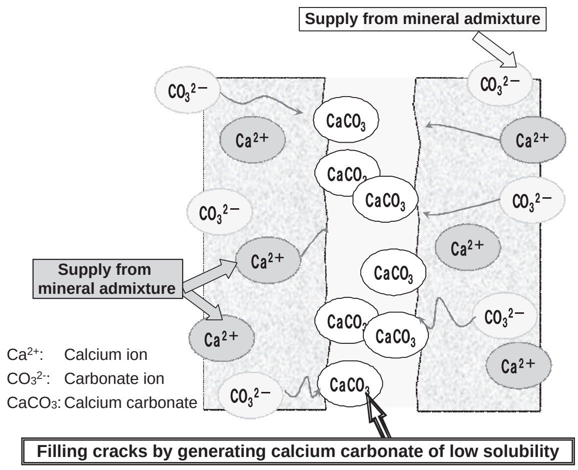

Fig. 2 Mechanism of Self-healing Concrete

2.2 Example of Self-Healing

Table 1 and Fig. 3 show a laboratory example of crack filling of self-healing concrete.

As the photos illustrate, we could confirm that precipitate filled the crack over time to completely fill the crack on the 46th day. As shown in the table, unit volume of cement and the water-powder ratio (W/P) are those for common concrete, and added mineral admixture is easily accessible inorganic material.

* Frontier Service Development Laboratory, Research and Development Center of JE East Group
** Tokyo Construction Office (Previously at Frontier Service Development Laboratory)

Table 1 Example of Mix Proportion of Self-Healing Concrete

Ingredient		Unit volume (kg/m^3)
Cement	Low-heat Portland	344
Water	W/P=45%	160
Mineral admixture A1		20
Mineral admixture B1		1

* Cracking produced and water penetration started after 14-day atmospheric curing.

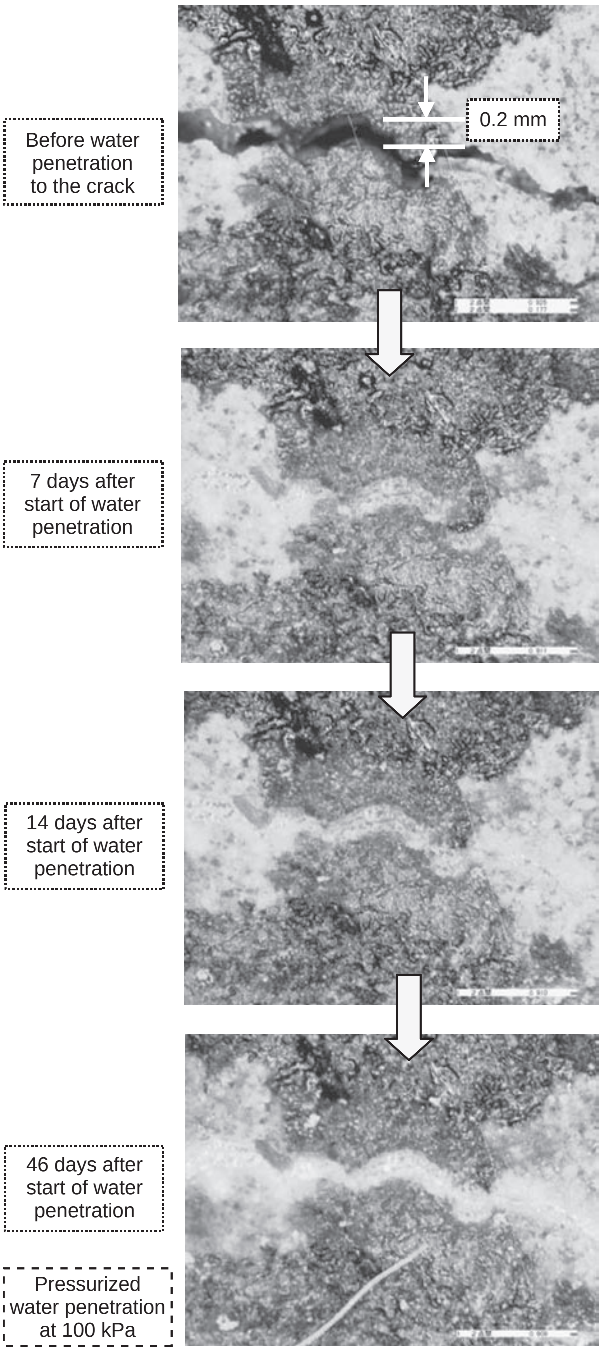

Fig. 3 Example of Crack Filling (With Mix Proportion Shown in Table 1)

For some mix proportions such as the example here, we could verify that cracks are filled by water penetration. Now we are further examining different mix proportion and environmental conditions.

3 Development for Application of Self-Healing Concrete to Actual Structures

3.1 Durability Test

3.1.1 Test Overview

We carried out different tests on durability of self-healing concrete to check the effect of different conditions. Test details are listed in Table 2 and mix proportion for test samples in Table 3 and 4. Mix proportions of Mix 2 and Mix 3 for self-healing concrete have less volume of cement with the same quantity of mineral admixture (self-healing concrete mineral admixture) mixed in to give self-healing performance, and total powder quantity is kept constant.

Table 2 Durability Test Details

Mix	Compressive strength	Freeze-thaw	Accelerated carbonization	Mortar-bar method
1	○	○	○	○
2	○	○	○	○
3	○		○	○

Table 3 Concrete Mix Proportion Condition (Common)

Mix	Type of cement	Max. size of coarse aggregate (mm)	Designed slump (cm)	Designed air content (%)	Water-powder ratio WP (%)	Fine aggregate ratio s/a (%)	Unit water quantity (kg)
1	Ordinary cement	20	8± 2.5	4.5 ± 1.5	55	46	160
2							
3							

Table 4 Mix Proportion of Self-Healing Concrete Mineral Admixture

Mix	Cement (kg/m^3)	Mineral admixture (kg/m^3)			Total powder quantity P (kg/m^3)
		Mineral admixture A1	Mineral admixture B1	Mineral admixture B2	
1	291	ī	ī	ī	291
2	270	20	1	ī	291
3	270	20	ī	0.88	291

3.1.2 Compressive Strength

We carried out compressive strength tests as specified in JIS A 1108:1999 "Method of test for compressive strength of concrete". We cured three test samples per set in water at a temperature of 20 ± 2°C until specified material age.

Test results are shown in Fig. 4.

Compared to Mix. No. 1 (the basic mix proportion), strength of No. 2 was slightly lower, and that of No. 3 was a little higher. The difference, however, was small.

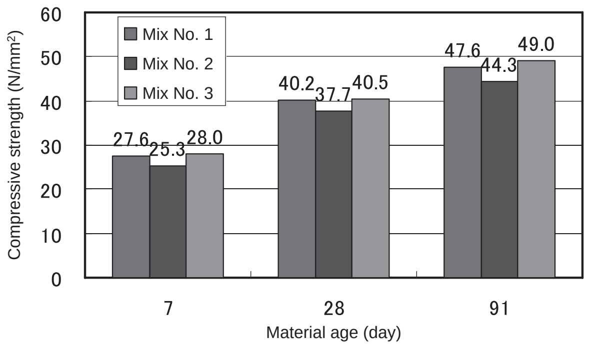

Fig. 4 Compressive Strength Test Results

3.1.3 Freezing-Thawing

We carried out freezing-thawing tests as specified in Method A (In-water freeze-thaw test method) of JIS A 1148:2001 "Method of test for resistance of concrete to freezing and thawing". We cured three test samples per set in water at 20 ± 2°C temperature until 28-day material age.

In the tests, we measured primary resonant frequency of flexural oscillation and mass at every 30 cycles while repeating freezing and thawing. We also evaluated deterioration of internal texture as durability based on the relative decrease rate of dynamic elastic modulus (relative dynamic elastic modulus) that can be calculated from resonant frequency. The tests were repeated up to 300 cycles. Test sample 2 was tested in bonds with bonding endplates as the sample includes expansive components in the mineral admixture. Fig. 5 shows relative dynamic elastic modulus test results.

Dynamic elastic modulus of Mix 2 that includes mineral admixture for self-healing is slightly lower than that of Mix 1 that does not include such mineral admixture. However, the value of dynamic elastic modulus of Mix 2 is greater than 80%. That value was demonstrated to be greater than 70%, the minimum limit for common cross sections specified in Standard Specifications for Concrete Structures (Japan Society of Civil Engineers, established in 2007).[1]

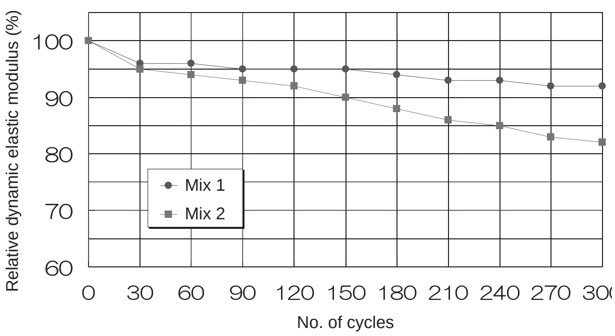

Fig. 5 Freezing-Thawing Test Results
(Relative Dynamic Elastic Modulus)

3.1.4 Accelerated Carbonation Tests

We carried out accelerated carbonation tests as specified in JIS A 1153:2003 "Method of accelerated carbonation test for concrete". We pre-cured three test samples per set in water for four weeks and in air for four weeks, then set samples in the accelerated carbonation test chamber. Tests were carried out for 26 weeks after setting in the test chamber.

Fig. 6 shows test results.

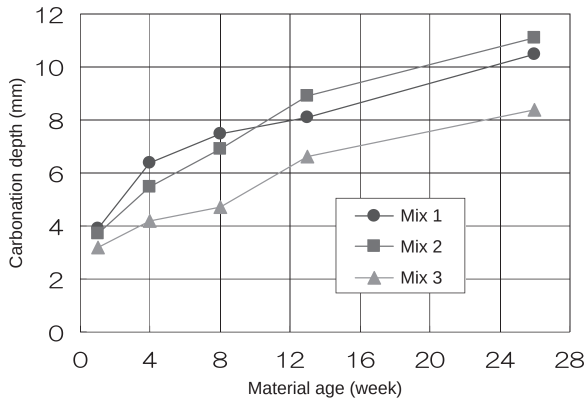

Fig. 6 Accelerated Carbonation Test Results

At 26-week material age, carbonation depth was 8–11 mm, with no significant difference between samples.

3.1.5 Mortar-Bar Method

We carried out alkali-silica reactivity tests (mortar-bar method) as specified in JIS A 1146:2001 "Method of test for alkali-silica reactivity of aggregates by mortar-bar method".

Using two types of fine aggregate, one with no reactivity (determined to be "harmless" in advance tests) and one with reactivity (determined to be "not harmless", similarly), we tested each mix proportion. Amount of sodium hydroxide added to adjust alkali content is the same as among all mix proportion types, with that of Mix 1 as the standard.

Fig. 7 shows test results. In order to exclude the effect of expansive ingredient of mineral admixture for self-healing concrete, expansion rate at the second week was regarded here as 0. When using "harmless" aggregate, we found no difference between mix proportion types. The expansive rate was high with Mix 2 and low with Mix 3. This could be because mineral admixture B1 of Mix 2 includes some alkali metal. Thus, when using reactive aggregate in Mix 2, we must check total alkali content, taking alkali content in mineral admixture into account (standard value: Na_2Oeq ≤ 3.0 kg/m^3).[2]

As to the reason of low expansion ratio of Mix 3, we presume that alkali content of mineral admixture that was replaced with cement was less volume than the cement.

3.1.6 Summary of Durability Tests

The results of four types of tests explained in the previous paragraphs demonstrate that there was no significant difference between two mix proportion types of self-healing concrete.

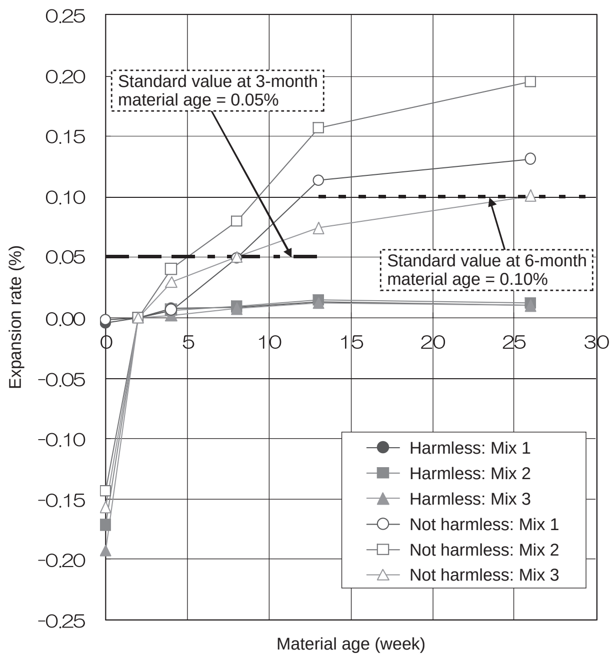

Fig. 7 Mortar-Bar Method Test Result

3.2 Workability Test

3.2.1 Test Overview

For the purpose of looking into property changes of fresh self-healing concrete over time, we checked change of slump over time after mixing concrete and carried out casting tests using concrete actual mixers.

3.2.2 Slump Test

To check change of slump of self-healing concrete, we checked change of slump over time based on the mix proportion shown in Table 5, using mixes applied to actual structures as reference.

We mixed concrete using a 50-liter mixer, and measured slump height at 30 min. and 60 min after lightly stirred using a shovel.

Fig. 8 shows the test results.

In Mix 2, we found no effect on slump from adding mineral admixture. In Mix 3, we could confirm that slump can be maintained equal to the slump of standard concrete compared to Mix 1 by adding 10 kg to the water unit volume.

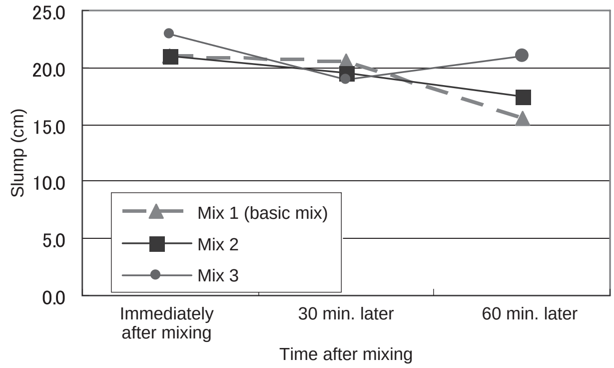

Fig. 8 Slump Change Over Time

3.2.3 Workability Check by Actual Mixer

In order to determine workability of self-healing concrete when placed for actual structures, we checked properties of fresh concrete in mixing by an actual mixer and transporting and mixing by an agitator truck. Fig. 9 illustrates the test flow and Fig. 10 shows discharging from the agitator truck.

The check results proved that properties of fresh concrete (slump height) did not change at 30 min. and 60 min. after mixing and at test sample placing (90 min. later), just as in the results in 3.2.2.

3.2.4 Production of a Square Tank Test Sample with Actual Mixer-Mixed Concrete

We made a square tank-form test sample of self-healing concrete checked in 3.2.3. In that, we caused cracks on the sample at young material age using a jack, and stored water in the sample at a specific water level by constantly supplying water to the interior to check leakage from the cracks.

Fig. 11 shows the results of Mix 2. While leakage remained the same from cracks of 5–6 mm width, leakage was reduced from slight cracks (around 0.2 mm width) for which we expect self-healing and at the separator. We could thus verify the self-healing effect. A similar leak cutoff effect could be found in Mix 3 too.

Table 5 Specified Mix for Actual Mixer Mixing (kg/m^3)

Target slump = 21cm

	Cement	Mineral admixture				Water	Fine aggregate		Coarse aggregate	Chemical admixture
	N	1) Mineral admixture A1	2) Mineral admixture A2	3) Mineral admixture B1	4) Mineral admixture B2		I. Pit sand	II. Inland sand	i	High-performance AE water-reducing chemical admixture
① Basic mix	370.0	0.0	0.0	0.0	0.0	175	324	485	920	4.26
② Self-healing concrete	343.0	20.0	5.0	0.0	2.0					
③ Self-healing concrete	344.0	20.0	5.0	1.0	0.0	175+10	319	479	906	

Step	Details and notes
Ingredient measurement	
Mixing by an actual mixer (3m^3)	Mineral admixture addition control (Normal 45 sec. mixing changed to 60 sec. mixing after adding mineral admixture)
Loading to agitator truck	Testing properties of fresh concrete just after charging (mixing). (Slump test, slump flow, air content)
Continued mixing in the agitator truck	Testing properties of fresh concrete at around 30 min. after mixing.
Continued mixing in the agitator truck	Testing properties of fresh concrete at around 60 min. after mixing.
Adding short synthetic fibers at 60 minutes after starting mixing	Add fibers at 0.05% ratio to total concrete capacity. Check properties of fresh concrete after addition.
Transport to casting location	Time from departing to starting to cast = approx. 30 min.
Placing sample concrete	Directly placed concrete from the chute of the agitator truck. Use two vibrators.

* On-site measurement (in the plant): Temperature, humidity (every hour)

Fig. 9 Test Flow of Actual Mixer-Mixed Self-Healing Concrete

Fig. 10 Discharging from the Agitator Truck (Test Concrete)

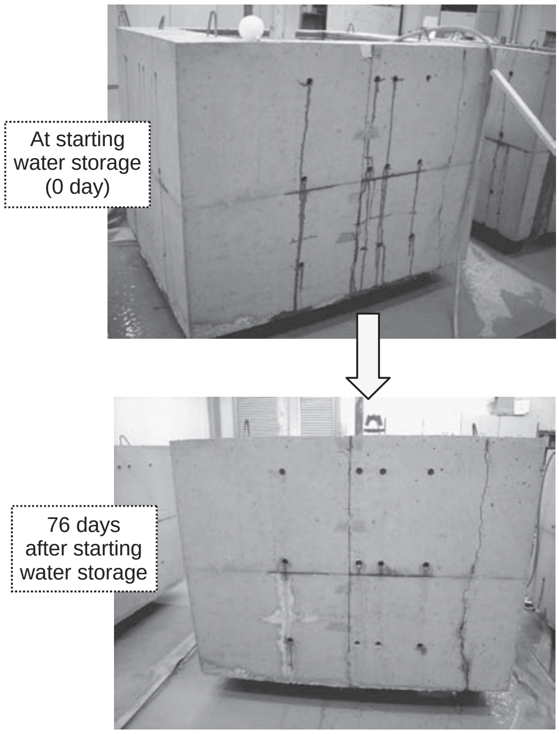

Fig. 11 Change of Leakage from Square Tank Test Sample (Mix 2)

4 Conclusion

Shrinkage cracking in concrete is an age-old technical issue. Inflow of water from cracks corrodes reinforcement in concrete, deteriorating structure durability. Thus, conventional countermeasures have been to prevent harmful cracks. To do that, we have used mineral admixtures such as expansive agents and contraction reducing agents, and determined acceptable crack width in structural design. In this context, water has been detrimental to concrete. In this study, however, we have instead aimed at bringing out the original nature of concrete with the help of water to improve durability of concrete structures.

Development of this concrete is still underway, however. We will thus further study costs and more reliable healing properties with an aim of early practical introduction.

Reference:

1) "2007 Standard Specifications for Concrete Structures (Design)", Japan Society of Civil Engineers, 8.4.1

2) JIS A 5308:2003 "Ready-mixed concrete", Appendix 2 (Provisions) "Alkali-silica reactivity control method"