Committee Report : JCI- TC075B

Technical Committee on Autogenous Healing in Cementitious Materials

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Abstract

The Committee on Autogenous Healing in Cementitious Materials (chairman: Shin-ichi Igarashi, Kanazawa University) has carried out its activities to reorganize past studies on the self-healing/-repairing function of concrete over two years (2007-2008). A survey of the literature including the latest research trends of the committee members was conducted with a particular focus on the mechanism of self-healing/-repairing, in order to classify and define the phenomena. The Committee also held a workshop/panel discussion during the annual convention of JCI in 2008, at which valuable knowledge from researchers in various spheres was accumulated, with discussions made on the required direction of future study.

Keywords: activated repairing, autonomic healing, crack, natural healing, repair technique

1. Introduction

Self-healing of cracks in concrete is a generic term for phenomena including re-hydration of unhydrated cement, which has been recognized as a phenomenon for a long time, as mentioned by A. M. Neville[1)] as 'autogenous healing.' However, data accumulation and quantitative evaluation have not been sufficient for engineers to consider this phenomenon at the design stage. Therefore, it has not become available for design and use as a method of repair. JCI Technical Committee on Autogenous Healing in Cementitious Materials (JCI-TC075B, chairman: Shin-ichi Igarashi, Kanazawa University) has carried out activities to review past studies on self-healing/-repairing of concrete over the last two years (2007-2008). The committee members, who are listed in **Table 1**, conducted a literature survey including their latest research results and held discussions with the aim of achieving the quantification of self-healing on various scales. Specifically, these include a microscopic level (modeling using cement hydration models), mesoscopic level (evaluation on a level of constitutive models), and macroscopic level (utilization methods on a concrete member level). At a workshop/panel discussion held during the Annual Convention of JCI in 2008, valuable knowledge of researchers from various fields was accumulated, with discussions held regarding the required direction of future study.

Table 1: Members of the Committee

Chairman	Shin-ichi IGARASHI	Kanazawa University
Secretary	Minoru KUNIEDA	Nagoya University
	Tomoya NISHIWAKI	Yamagata University
Member	Yukio ASANO	Gifu University
	Tae-Ho AHN	The University of Tokyo
	Hiroshi INADA	Shimizu Corporation
	Tetsushi KANDA	Kajima Corporation
	Takahiro SAGAWA	Nittetsu Cement
	Tokuhiko SHIRASAKA	Taiheiyo Cement Corporation
	Hidenori HAMADA	Kyushu University
	Hiroshi HIRAO	Taiheiyo Cement Corporation
	Akira HOSODA	Yokohama National University
	Ippei MARUYAMA	Nagoya University

Table 2 gives the draft table of contents of the State-of-the-Art report. Chapter **2** defines the scopes and terms of self-healing/repairing phenomena dealt with in the report. These phenomena, which include the latent autogenous healing capability of cementitious materials, the use of supplementary cementitious materials for autogenous healing, and the addition of functional elements for activated repairing, were classified by the means (mechanisms) to achieve the self-healing/repairing effect. The terms were then defined for each phenomenon and technique. Chapter **3** introduces the latest trends of ongoing studies for each function-restoring phenomenon defined in Chapter **2**. Chapter **4** describes the possibility of modeling self-healing/-repairing, and Chapter **5** introduces an experimental investigation to evaluate the effect of self-healing/-repairing. Chapter **6** introduces the efforts to incorporate the self-healing/-repairing phenomena into the design stage, including application examples. Chapter **7** introduces the efforts related to self-healing/-repairing phenomena in sectors other than concrete and cementitious materials. Assoc. Prof. Kohji Takahashi of Yokohama National University, who works on cutting-edge research in the ceramics domain, contributes to Chapter **8** particularly regarding these phenomena in the ceramics field. Chapter **9** introduces the workshop "State-of-the-art self-healing/repairing of concrete" held by the Committee during the Annual Convention of JCI in 2008. The discussion with panelists, who are active in the frontlines of areas particularly related to cementitious materials, is described in detail.

Table 2: Draft table of contents of the report

Chapter 1	Introduction
Chapter 2	Self-healing/repairing phenomena and definitions
Chapter 3	Self-healing/repairing mechanisms and current state of technology
Chapter 4	Material science models of self-healing/repairing
Chapter 5	Experimental evaluation of self-healing/repairing effects
Chapter 6	Application examples of self-healing/repairing functions
Chapter 7	Treatment of self-healing/repairing in other fields
Chapter 8	Self-healing phenomena of ceramic materials (Special contribution)
Chapter 9	JCI workshop in Fukuoka
Chapter 10	Conclusions
Appendix	

2. Classification of phenomena and definitions of terms

The Committee categorized the concept of self-healing/-repairing as shown in **Fig. 1** and **Table 3**, focusing on respective phenomena. **Table 4** gives examples of studies in each category. The categorization and differences of mechanisms between the categories are explained in the following paragraphs:

'Recovery,' which covers the entire area shown in **Fig. 1**, is defined as an event in general in which at least one function of concrete recovers by whatever means. Conventional repair/strengthening corresponds to this, while it is expected that self-healing/-repairing of concrete dealt with in this report will be regarded as a feasible means for recovery.

'Self-healing/-repairing' is defined as an event in general in which at least one function of concrete recovers by mechanisms inherently provided in concrete without the need for repair or strengthening. Note that 'healing' and 'repairing' are differentiated from each other as follows: the former refers to clogging of cracks by phenomena found in conventional concrete as well, such as re-hydration of cement and deposition of calcium carbonate, whereas the latter refers to means to clog cracking by the addition of an artificial device as a substitute for conventional repair/strengthening. In other words, 'healing' makes cracking of a cementitious material clogged by itself, utilizing its innate mechanisms. Addition of a supplementary cementitious material, for instance, at an appropriate proportion to accelerate such a crack-clogging mechanism is also included in 'healing.' On the other hand, 'repairing' adds devices, such as microcapsules and heat-generating devices, that are outside of the category of conventional supplementary cementitious materials to impart a crack-clogging capability as a new function.

Table 3: Mechanisms and classification of phenomena

Natural healing: A phenomenon in which cracks in concrete are naturally clogged in an environment involving moisture, for instance, without any special arrangement in the material design, etc.

Autonomic healing: A phenomenon in which cracks are clogged in concrete made with special material design, such as the use of an appropriate supplementary cementing material in expectation of its effect of clogging or accelerating the clogging of cracks in the concrete in an environment involving moisture, etc.

Activated repairing: A phenomenon in which cracks are clogged in concrete by a mechanism of devices embedded in the concrete beforehand for the purpose of autonomically repairing cracks.

Autogenous healing: A concept encompassing natural healing and autonomic healing; the whole phenomenon of cracks in concrete being clogged in an environment involving moisture, etc.

Engineered healing/repairing: A concept encompassing autonomic healing and activated repairing; a phenomenon in which cracks in concrete are clogged by the use of the concrete made with special material design to clog/repair cracks.

Self-healing/repairing: The whole phenomenon of clogging of cracks in concrete not by human hand.

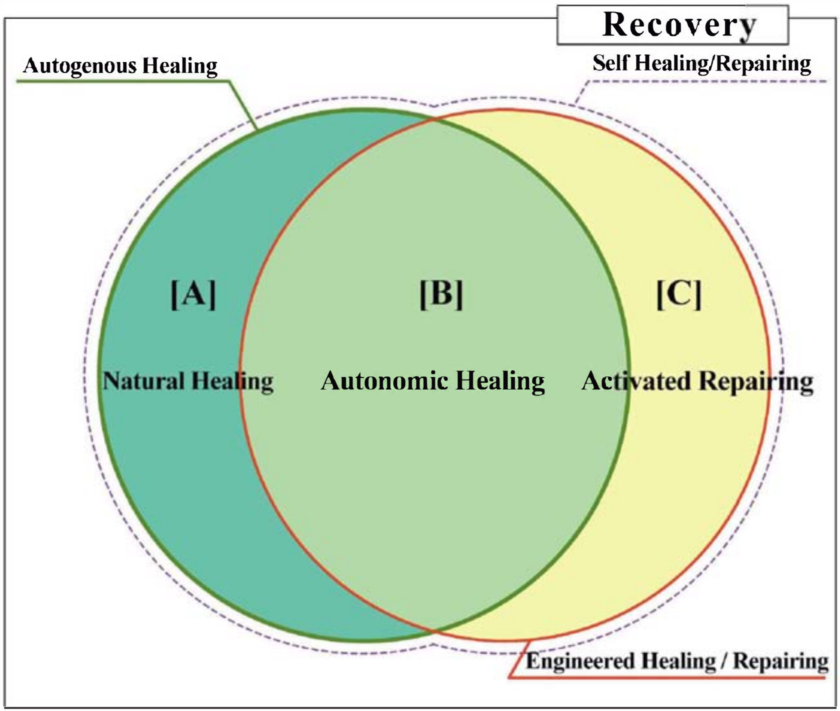


Figure 1: Classification and Venn diagram of self-healing/repairing of cracking

Table 4: Study cases corresponding to the classification of self-healing/repairing

	Type	Study case	Healing/ repairing	Inherent/ engineered
[A]	Natural healing	- Re-hydration of residual unhydrated cement in low W/C concrete - Re-hydration of cracks found in hydraulic structures	Healing	Inherent
[B]	Autonomic healing	- Use of fly ash - ECC containing fly ash - Use of special additive (expansive additive) - Use of bacteria		Engineered
[C]	Activated repairing	- Inclusion of microcapsules, etc. - Use of brittle pipe network - Use of heat-generating devices - Use of shape-memory alloys - Fusion with monitoring techniques	Repairing	

As stated above, the scope of 'healing' includes two directions. One is crack clogging by conventionally known phenomena, such as cement re-hydration and $CaCO_3$ deposition in hydraulic structures. The other is healing by adding chemical admixtures and/or supplementary cementitious materials, such as an expansive additive, fly ash, uncured epoxy, to concrete to extract its latent potential, or by including short fibers in concrete to suppress the widening of crack widths. The latter direction also includes a method that utilizes bacteria, living organisms, having them deposit $CaCO_3$ in cracks to clog them. The former direction is defined here as 'natural healing,' as

with no artificial means. This corresponds to area A in **Fig. 1**. The latter direction is defined here as 'autonomic healing,' in view of the fact that, though supplementary cementitious materials and/or reinforcing fibers are added to concrete, these have been conventionally added to concrete not for self-healing/-repairing but to be an integral part of the structure constituting concrete. The term 'autonomic' was adopted to express concrete's own healing effect, because the structure of concrete itself accelerates clogging of cracks. This corresponds to area B in **Fig. 1**. 'Autogenous healing' is defined as the concept encompassing areas A and B. It refers to a phenomenon in general in which cracking is clogged by mechanisms/capabilities possessed by the structure of concrete itself, regardless of whether or not any supplementary cementitious material/chemical admixture is added.

In the entire area of 'recover' shown in **Fig. 1**, the area outside of the category of 'healing' represents 'repairing.' Area C in the figure is defined as 'activated repairing,' emphasizing the point that the healing function is developed by a stimulus from outside. This area includes study cases attempting automatic clogging of cracks by incorporating something different from conventional concrete structure, such as concrete with an embedded device for automatic repairing by a specific trigger, including artificial ones, to actively imparting a self-repairing effect as a new function. Specifically, this includes the instances of embedding microcapsules or glass pipes containing the above-mentioned repair materials, as well as these combined with a heating device.

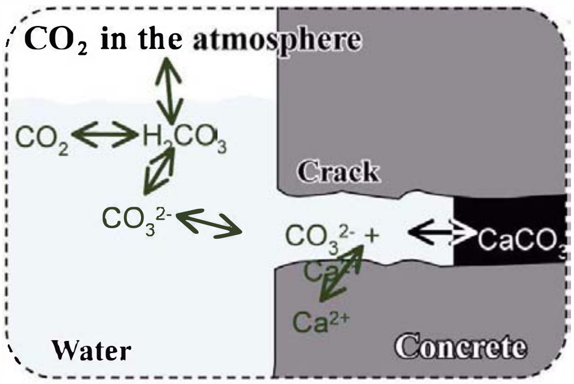
In addition, since 'autonomic healing' and 'activated repairing' are investigated in the same direction of adding a new function, the area including both is defined with a term 'engineered healing/repairing.'

3. Examples of self-healing/-repairing

3.1 Natural healing

Figure 2 shows an example of natural healing in concrete[2)]. This is a concrete specimen having artificial cracking induced and then exposed to a tidal zone enviromnent for 15 years. Most cracks with a small width (around 0.5 mm or less) have been naturally healed. The substances clogging the cracks are reported to be primarily ettringite with needle-like crystals and magnesium hydroxide.

(a) Ettringite and magnesium hydroxide depositing near cracking (courtesy of H. Hamada)



(b) Mechanism of natural healing[3)]

Figure 2: Example of natural healing in hydraulic structures

3.2 Autonomic healing

Concretes containing an expansive additive[3)] and fly ash[4)] are introduced in this section as typical examples of autonomic healing.

Figure 3 shows clogging of cracks in an autonomic-healing concrete containing an expansive additive at a slightly higher dosage than usual[4)]. It has been confirmed that a crack width of up to 0.4 mm can be sufficiently clogged by an age of 28 days. Active research is conducted on this type of concrete with the aim of reducing water leakage by crack clogging.

Figure 4 shows an example of autonomic-healing concrete utilizing the sustained hydration of fly ash. This study was conducted as a joint research by the Hokkaido Northern Regional Building Research Institute, Muroran Institute of Technology, and other institutions.

This type of healing is also characterized by the cracks to be healed – microcracks induced by frost damage, which are not as large as macroscopic cracks due to bending. Autonomic healing of cracks after undergoing deterioration due to freezing and thawing action has been evaluated based on compressive strength, relative dynamic modulus of elasticity, carbonation depth, pore volume, and visual cracking information. Re-curing for four weeks at 40°C has been carried out to enhance fly ash's potential capability of autonomic healing, proving a high autonomic healing effect of fly ash cement.

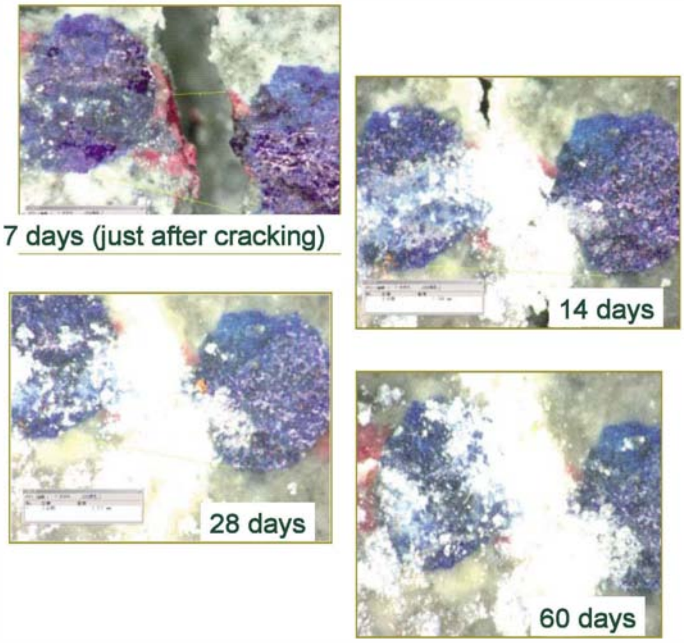
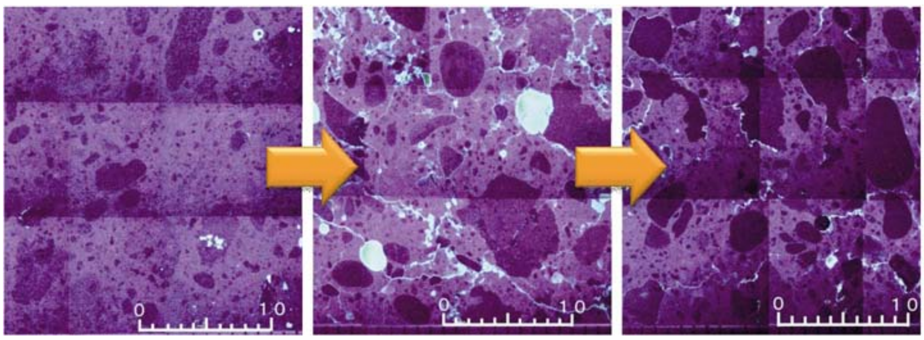


Figure 3: Example of healing of a crack with a width of around 0.4 mm (courtesy of A. Hosoda)



Durability factor: 70%   Durability factor: 90%

Impart an effect of autonomically healing damage to concrete by long-lasting pozzolanic reaction of fly ash, positively utilizing its slow reaction.
Select a replacement ratio that keeps the freeze-thaw resistance high at later ages
(FA replacement ratio of 10 to 15% with a W/C of 50 to 55%).

Figure 4: Combination of freeze-thaw deterioration and autonomic healing[5)]

3.3 Activated repairing

Concrete in which a glass pipe encapsulating a repair material and a heat-generating device are embedded[6] as shown in **Fig. 5** is a representative example of activated repairing. The occurrence of a crack activates a mechanism that selectively heats the area near the crack, thereby automatically supplying the repair material from the pipe embedded in the concrete.

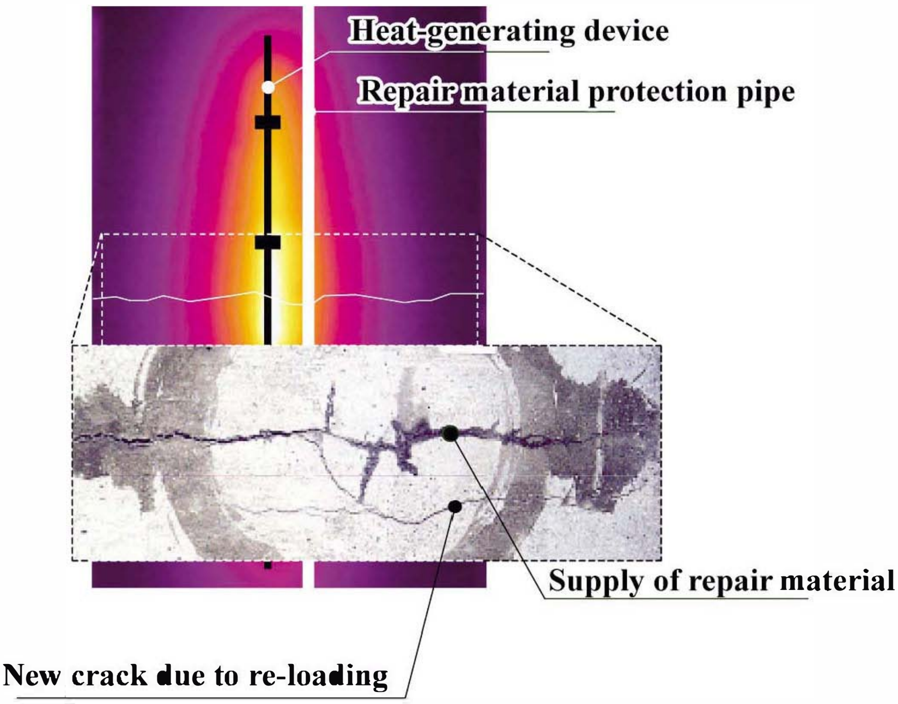


Figure 5: Activated repairing by supplying a repair material (courtesy of T. Nishiwaki)

4. Summary of experimental investigation

Table 5 gives representative examples of existing methods of introducing damage and evaluating self-healing/-repairing, as well as evaluation indices. Since self-healing/-repairing is generally relevant to 'cracks,' most experiments induce tensile or bending cracks in concrete to a specified crack width. Then, the concrete is re-cured, and subjected to similar tests to confirm the restoration of the strength, rigidity, and absorbed energy (the area under the load-displacement curve)[7-9]. There are also many examples in which microcracks within concrete induced by freezing and thawing tests are clogged by autonomic healing, for instance, which is evaluated by relative ratios of dynamic modulus of elasticity[5, 10] and those in which changes in the water permeability according to changing crack width are measured[3, 11]. Examples of evaluating the resistance to mass transfer through clogged cracks other than water include those evaluating the resistance to chloride ion transfer[12]. However, most of these investigations currently remain on a research level. Furthermore, it is also hoped that self-healing of other types of damage will be investigated and that existing nondestructive test methods will be applied to the evaluation of self-healing.

Table 5: Types of damage, restoration mechanisms, and evaluation methods/indices relevant to self-healing (examples)

Method of inducing damage	- Loading test (tensile, flexural) - Freezing and thawing test
Restoration mechanism (shown above)	- Natural healing - Autonomic healing (Fly ash, expansive additive, fly ash + short fiber reinforcement, etc.) - Activated repairing (Resin capsule, glass pipe + repair material)
Evaluation method/index	- Microscope - Water permeability - Ultrasonic pulse velocity - Capillary absorption - Depth of chloride ion penetration - Flexural strength - Absorbed energy - Rigidity - Relative dynamic modulus

5. Outline of workshop

A workshop titled 'the Cutting-edge Techniques of Concrete Self-repairing,' which was held on the second day of the JCI Annual Convention at Fukuoka in 2008, was highly successful with 123 participants according to the executive committee (see **Fig. 6**).

At first, the committee chairman, Shin-ichi Igarashi of Kanazawa University introduced the purposes and background of the committee and the workshop. Then, the secretary, Minoru Kunieda of Nagoya University, summarized the discussions at the committee including the target scope and defmitions of terms. After that, other committee members introduced cutting-edge information related to self-healing/-repairing as follows:
Hidenori Hamada of Kyushu University reported natural healing found in marine structures; Takahiro Sagawa of Nittetsu Cement reported on autonomic healing utilizing the pozzolanic reaction of fly ash; Akira Hosoda of Yokohama National University and Tae-ho Ahn of the University of Tokyo reported on autonomic healing concrete using an expansive additive; and

Tomoya Nishiwaki of Yamagata University introduced study cases on self-repairing concrete designed to go through activated repairing using glass pipes and heat-generating devices. This briefing session was followed by a panel discussion coordinated by Prof. Hirozo Mihashi of Tohoku University, with the following panelists: Prof. Toyoaki Miyazawa of Kyoto University, Assoc. Prof. Toshiharu Kishi of the University of Tokyo, and Dr. Kazuo Yamada of the Central Research Institute, Taiheiyo Cement. In the discussion initiated by Prof. Mihashi, the panelists talked about the backgrounds to their study and new ideas, expectation for the establishment of guidelines based on quantitative evaluation, and the importance of control, actively exchanging views including questions from participants.

(a) Panelists

(b) Panelists

(c) The audience

Figure 6: JCI workshop in Fukuoka

6. Summary

As stated above, the review of the current state of self-healing/-repairing clarified matters necessary for putting this technology to practical use. JCI plans to organize a new committee on the systematization of self-healing technology for cementitious materials chaired by Prof. Shin-ichi Igarashi of Kanazawa University for 2009 and 2010 to developmentally take over the activities of the present committee. The new committee particularly intends to transmit research information and accumulate data on self-healing/-repairing technology.

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