Journal of Ceramic Processing Research. Vol. 16, Special. 1, pp. s1~s13 (2015)

JOURNAL OF
Ceramic
Processing Research

Cementitiuous materials for crack self-healing concrete

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The serviceability and durability of concrete structures has been extensively studied by various researchers. Cementitious materials and concrete are the most widely used in construction site. However, cracking is a well-known phenomenon in concrete engineering. Concrete repairs are inevitable to enhance its service life which evokes additional expenditure separate to the building cost. Therefore, one of the most important issues is to seal cracks which occur due to drying shrinkage or exposed to external factors. Many researchers have already studied this topic with the intent to control cracking or develop a crack-free concrete. Two alternatives for crack control have been proposed; these include methodologies for either controlling residual stresses or developing ductile concrete. Recently, a lot of researchers are studied various crack control methods and concepts to achieve self-healing phenomenon in past decades. In this review paper, autogenous healing in cementitious materials is reported based on various articles, activity of JCI TC-075B (Japan Concrete Institute Technical Committee 075B), JCI TC-091A (Japan Concrete Institute Technical Committee 091A) and RILEM TC-SHC (Self-healing Phenomena in Cement Based Materials of (International Union of Laboratories and Experts in Construction Materials, Systems and Structures)).

Key words: Self-healing, Crack, Durability, Crack-free Concrete, Repair.

Introduction

The field of self-healing materials is considered a new area of materials research [1]. In 2001, S.R. White *et al*. [2, 3] from the University of Illinois published his results on self-healing in polymer-based systems by microencapsulated healing agents. His and related research in other fields of materials science were the result of an initiative by NASA launched amongst selected top institutes in the USA in 1996. Since then the field is developing rapidly. S.R. White et al. fabricated urea-formaldehyde microcapsules containing dicyclopentadiene (DCPD) liquid healing agent and paraffin wax microspheres contacting 10 wt% Grubbs' catalyst for the development of self-healing composites [3]. Fig. 1 schematically shows the autonomic healing concept. The healing mechanism proceeds as follows: healing is accomplished by incorporating a microencapsulated healing agent and a catalytic chemical trigger within an epoxy matrix; an approaching crack ruptures the embedded microcapsules, releasing the healing agent into the crack plane by capillary action as shown in Figs. 1 and 2.

In the case of cementitious materials, there is an inherent self-healing potential. This inherent self-healing mechanism has already been known for a long time, and can be explained simply as follows. In general, conventional concrete mixtures are made with a water/binder ratio between 0.40 and 0.55, but theoretically a water/cement ratio of 0.4 is enough for complete reaction of all cement. However, in reality, around 70% of cement will react at W/C = 0.4. The remaining 30% is left unreacted in the cement paste. Especially in the case of lower water/cement ratio and coarser cement, a lot of unreacted cement particles will remain in the system. Fig. 3 schematic clearly shows that full hydration cannot be achieved in a closed system, which is a system where there is neither loss nor gain of water from outside, unless the water/cement ratio is greater than or equal to 0.42 [4]. Therefore, in this system, if crack of concrete occurs under these conditions, unreacted cement particles may become exposed to moisture which penetrates the crack. In that case, it will be hydrated again and re-hydration products will fill up between the cracks. This means that if an inherent feature of cementitious materials can be controlled for the self-healing ability, a new cementitious composite with self-healing ability can be designed.

From a high-durability point of view, this mechanism can be also applied for the design of "crack-free" concrete. If it is assumed that the concrete contains more water than necessary to hydrate the cement, a

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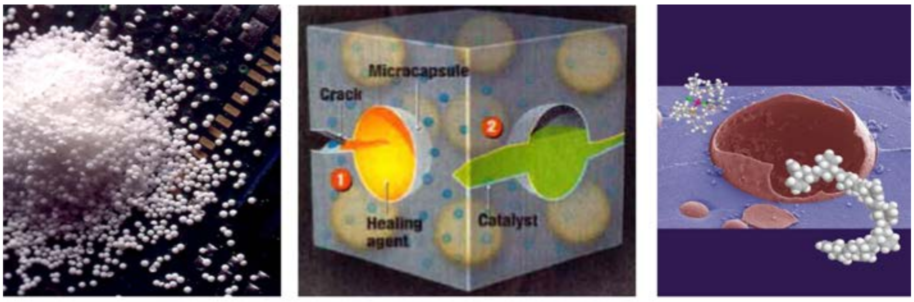

(a) Microcapsules (b) The autonomic healing concept (c) Self-healing Process

Fig. 1. Developed microcapsules and its self-healing process [adapted from S.R. White *et al*. 2001].

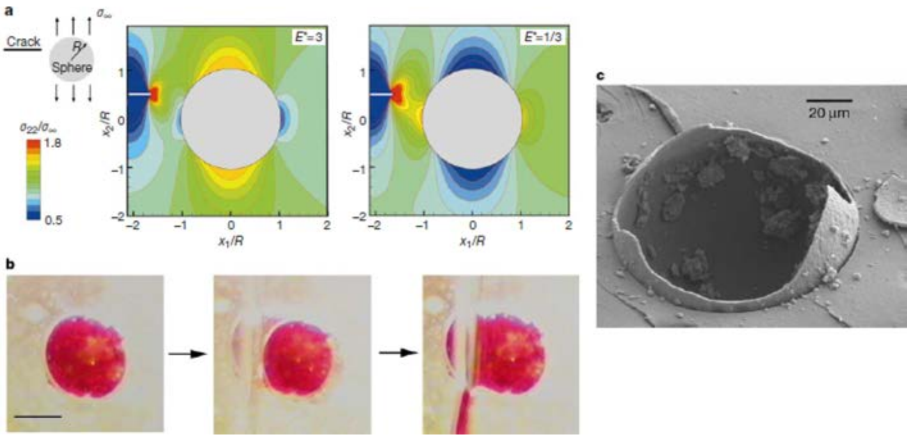

Fig. 2. Rupture and release of the microencapsulated healing agent (a) stress state in the vicinity of planar crack (b) the rupture of a microcapsule and the release of the healing agent (c) SEM images of self-healing material with a ruptured urea-formaldehyde microcapsule [adapted from S.R. White *et al*. 2001].

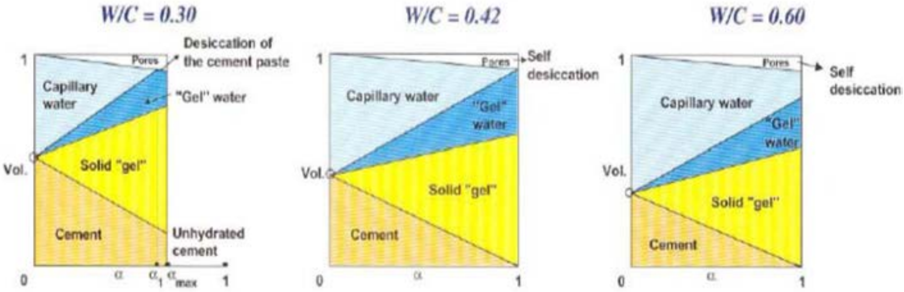

Fig. 3. Volume occupied by cement, water, and hydration products when portland cement hydrates in a closed system, where α is the volume fraction of cement hydrated [adapted from R. Morin *et al*. 2002].

certain gas-filled porosity is always present, whatever the degree of hydration. Jensen *et al*. reported that if an external source of water is available during the hydration period, it is possible to obtain hydrated cement paste with no empty pores (except for entrapped air bubbles) when the W/C is less than or equal to 0.36. (Fig. 4) [5].

However, this does not mean that a fully-saturated hydrated paste is desirable, as aggressive ions can invade the concrete due to the development of osmotic pressures. Therefore, curing methodologies with proper water supplying are necessary. Morin et al. reported crack-free methodologies of high performance concrete structures by starting water curing at proper time, and using fog sprays and other evaporation-retarding methods when plastic shrinkage is a concern, as shown in Fig. 5 [5].

From these results, it can be summarized that pore control and the degree of hydration of cement by water are key factors for the design of cementitious composite materials with self-healing capability. Ideally, unreacted cement particles should be retained at normal or high water/binder ratio by the addition of special additives, without loss of designed concrete performance such as compressive strength, tensile strength, water permeability, etc. Furthermore, if these additives can react with

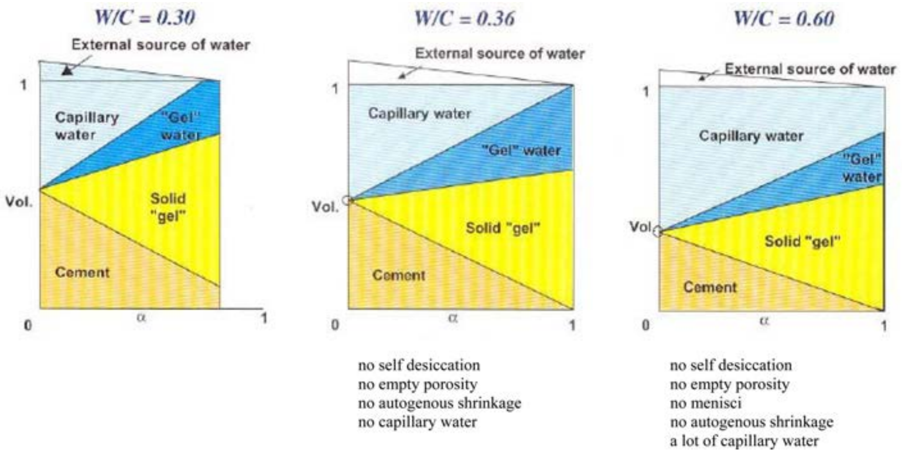

Fig. 4. Volume occupied by cement, water, and hydration products when portland cement hydrates while exposed to an external water source. [adapted from R. Morin *et al*. 2002].

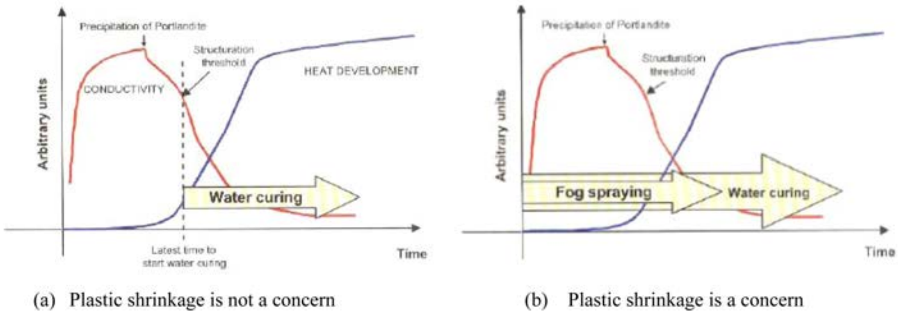

Fig. 5. The blue line shows that heat generation from the portland cement hydration reaction begins slowly. When the temperature starts to rise, water curing should begin. The red line shows electrical conductivity, which can be measured to help determine when water curing should start. When plastic shrinkage cracking is a concern, fog spraying is also needed. [adapted from Morin *et al*. 2002].

unreacted cement particles when cracking occurs, and if re-hydration products between cracks have good chemical stability, this is considered desirable for the design of self-healing cementitious materials.

Definition of Terms

Terms concerning self-healing are not yet fully defined. Many terms, such as recovery, self-healing, autogenous healing, autonomic healing, natural healing, activated healing and automatic healing, have been used in the construction material field with confusion. Therefore, to avoid disruption and minimize inconvenience concerning self-healing terms, RILEM TC-SHC committee (Self-healing Phenomena in Cement-Based Materials [International Union of Laboratories and Experts in Construction Materials, Systems and Structures]) was established in 2005. In Japan, JCI-TC075B (Technical Committee on Autogenous-healing in Cementitious Materials [Japan Concrete Institute]) began in June 2007.

Fig 6 schematically shows the summary of definition of terms concerning self-healing, as recommended by JCI-TC075B and JCI-TC091A [6]. Although not all terms are clearly defined yet, these definitions are more easily understood as compared to the previous state-terms such as recovery, self-healing, autogenous healing, autonomic healing, are now better understood. JCI-TC075B and JCI-TC091A reported that performance recovery meant the collection of all mechanisms to improve a performance of damaged concretes. However, it didn't mean the complete recovery of the damaged concretes. They reported that a certain property such as permeability was improved after a healing mechanism, but others were not as shown in Fig. 7 [6, 7]. They've

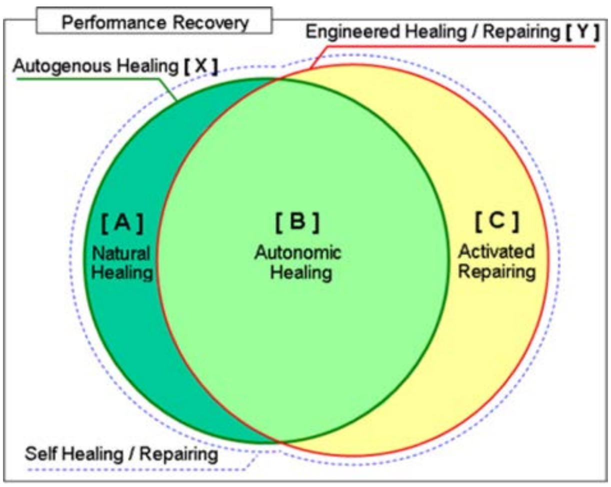

Fig. 6. Definition of self-healing terms [adapted from JCI-TC075B Committee, 2009].

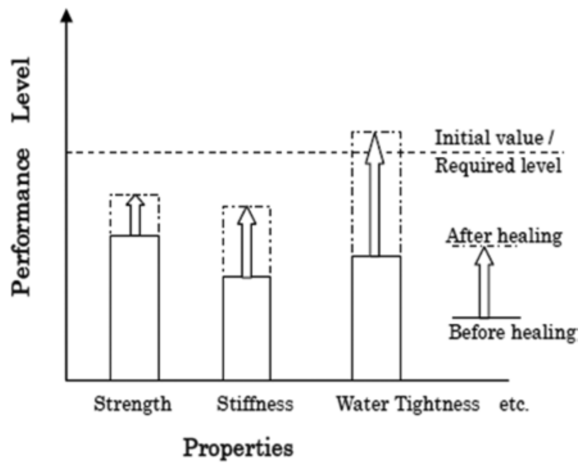

Fig. 7. The concept of performance recovery by self-healing function [adapted from S. Igarashi *et al*. 2009].

also suggested that the definition of these terms should be very useful for understanding research in this field as follows.

- Recovery: Phenomenon whereby the function of the concrete is recovered by all repair and reinforcement methods in general

- Self-Healing (Repairing): Concrete that can recover its function without any conventional repair or reinforcement works. A chemical reaction takes place connecting the two crack surfaces. The reaction can be continuing hydration of the cement or a chemical reaction that occurs after hydration (like the formation of calcium carbonate) [7]

- Self-Tightening: Crack is blocked with small particles from the crack faces or small parts present in fluids that flow through the crack [7]

- Automatic Healing: The concrete has the self-recovery effect as new function by usage of additional devices, admixtures, etc.

- Autogenous Healing: The concrete that is expected to have a healing effect by various admixtures. Most researchers used both self-healing and autogenous healing until now on. “Autogenous” emphasizes that the concrete heals without any help from outside.

- Activated Healing (Repairing): The concrete that has artificial healing functions as an automatic repair work, caused by a specific trigger:
  - Usage of healing device and capsule including repair agents
  - Usage of Bacteria

- Autonomic Healing: The concrete that has special elements for the objective of self-healing compare to the conventional concrete
  - Special admixtures such as optimized expansive agent, flyash and unhydrated epoxy for the self-healing
  - Fiber reinforced cementitious materials

- Natural Healing: Phenomenon that the crack in concrete is closed by self-healing on the special environmental condition like water existence, such as in the case of conventional concrete which doesn't expect any self-healing effect.
  - Rehydration or precipitated hydration products between cracks

Various self-healing mechanisms for cracked concrete

Autogenous or self-healing of fine cracks in concrete is often mentioned in literature but there is little quantitative data regarding its mechanism. In the literature up to now, the causes of self-healing are

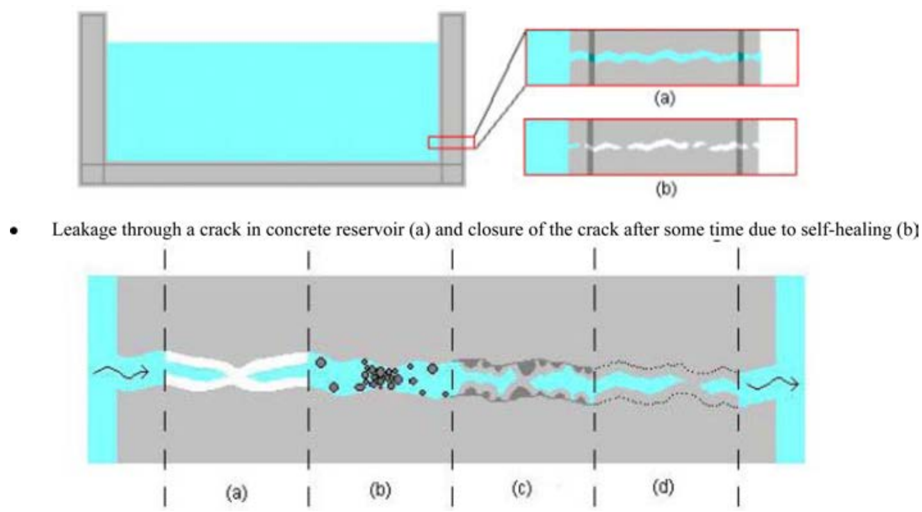

Fig. 8. Possible causes of self-healing: (a) formation of calcium carbonate or calcium hydroxide, (b) sedimentation of particles, (c) continued hydration, (d) swelling of the cement matrix [adapted from N. Heide 2005].

reported to be based on chemical, physical, and mechanical processes as follows: 1) swelling and hydration of cement pastes, 2) precipitation of calcium carbonate crystals and 3) blockage of flow path by water impurities or by concrete particles broken from the crack surface due to cracking. In particular, this phenomenon is generally attributed to the hydration of previously unhydrated cement grains and may be aided by carbonation since the bonding material so formed containing crystals of calcium carbonate and calcium hydroxide [8]. In the existing literature, the following four causes may be attributed to autogenous healing. These are also summarized by N. Heide (2005) as shown in Fig. 8 [9].

Fig. 8 schematically shows that water leakage through a crack in a water-retaining concrete structure might gradually reduce or even stop completely. From this consideration, there are four possible causes for self-healing of concrete structures, explained in the following sections.

(*a*) *Formation of calcium carbonate (calcite) or calcium hydroxide (portlandite)*

Calcium carbonate formation in the area of water-bearing cracks takes place in the material system $CaCO_3$-CO_2-H_2O according to the following reactions. Calcium hydroxide is a reaction product of the hydration of concrete. Calcium hydroxide in the area of the crack can dissolve in the water inside the crack and precipitate at the crack surface:

$$Ca(OH)_2 \leftrightarrow Ca^{2+} + 2OH^- \quad (1)$$

Then, in order to form calcium carbonate, the water in the crack has to contain dissolved carbon dioxide.

$$Ca^{2+} + CO_3^{2-} \leftrightarrow CaCO_3 \text{ (pH water > 8)} \quad (2)$$
$$Ca^{2+} + HCO_3^- \leftrightarrow CaCO_3 + H^+ \text{ (7.5 < pH water < 8)} \quad (3)$$

Fig. 9 shows the equilibrium concentration of $CaCO_3$ formation's participating components, CO_3^{2-} and HCO_3^-, as functions of pH value of the solution [10].

In case of precipitation of $CaCO_3$ between cracks, the water-insoluble $CaCO_3$ is evolved from a reaction between the calcium ions Ca^{2+}, derived from the concrete, and in-water available bicarbonates HCO_3^-, or carbonates CO_3^{2-} . Therefore, according to this, the solubility curve for the $CaCO_3$ passes through a minimum pH value of approximately 9.8 where there is the least Ca^{2+} requirement to trigger off a primary calcite precipitation. Crystal growth considerations of $CaCO_3$ have shown that the following circumstances favor a $CaCO_3$ precipitation in a cracks: 1) rising water temperature 2) rising pH value of the water 3) falling CO_2 partial pressure in the water. This is the most significant factor influencing autogenous healing.

(*b*) *Sedimentation of particles*

Various impurities such as water impurities, cement particles and concrete particles broken from the crack surface due to cracking can block the flow path,

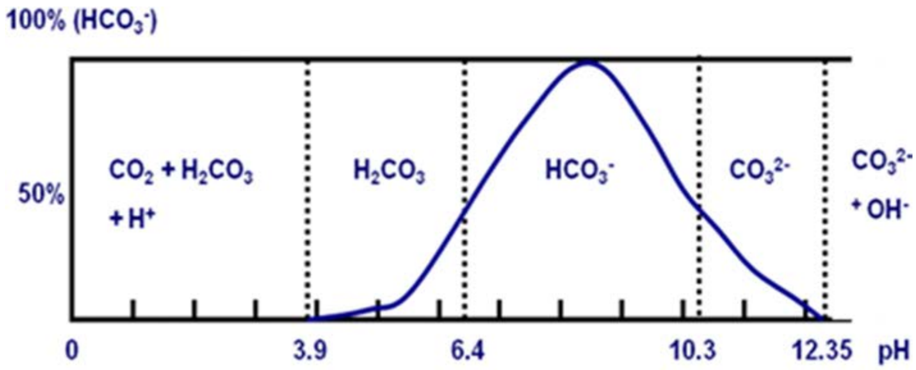

Fig. 9. Equilibrium concentrations at saturation of CO_3^{2-} and HCO_3^- as a function of pH [adapted from P. Barret *et al*. 1983].

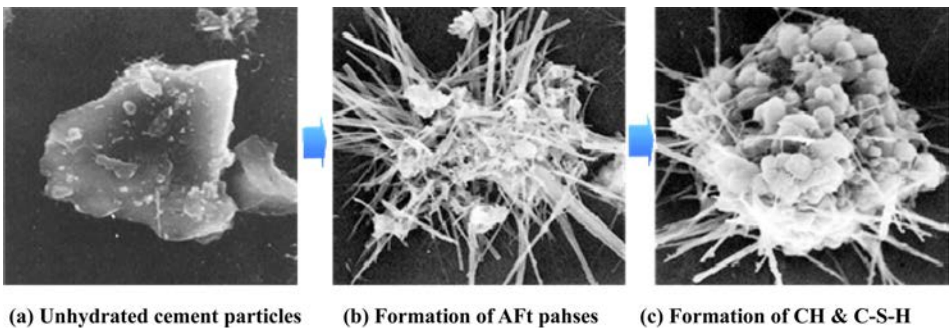

Fig. 10. Hydration process of unhydrated cement particles [adapted from Cement, Geotech Co., Ltd. 2005].

resulting in a possible source of self-healing.

(*c*) *Continued hydration*

When cracking of concrete occurs, unreacted cement particles may become exposed to moisture that penetrates the crack. In that case, it will be hydrated again and re-hydration products will be filled up between cracks. However, it is reported that this is only true for very young concrete. Fig. 10 schematically shows hydration process of unhydrated cement particles after water supply [11].

(*d*) *Expansion and swelling of the cement matrix*

As water moving through a crack causes saturation, the crack surfaces may swell, making the crack smaller. This can close small cracks or stimulate the other causes for self-healing in wider cracks. However, when the crack dries up again it will return to its wider shape. Unfortunately, some researchers neglect this mechanism when compared to the formation of calcite and sedimentation of particles. However, this is also a very important factor for the development of a new cementitious composite material with self-healing ability. If the swelling capability can be increased through the addition of artificial materials, it may lead to self-healing capability similar to cementitious recrystallization between cracks. Especially, in case of mineral admixtures, various materials such as $C_4A_3\overline{S}$, CaO and bentonite are potentially useful for expansive and swelling materials. Chemical reaction of $C_4A_3\overline{S}$, and CaO for expansion as well as change of volume after chemical reaction are presented in Table 1. Fig. 11 schematically shows the structure of AFt phase and its substitution mechanism of various ions. This also means that these hydration products can be formed easily in the cracks by usage of various ions through water impurities.

Table 1. Volume change of solid by hydration ($C_4A_3\overline{S}$ and CaO) [12].

	$C_4A_3\overline{S}$	+	$8C\overline{S}H_2$	+	6CH	=>	$3C_3A\cdot 3C\overline{S}\cdot H_{32}$
Density	2.61		2.31		2.24		1.78
M. Wt.	610.3		172.2		74.1		1255.1
M. Vol.	233.8		74.5		33.1		705.1
Change of Vol.			341.4				705.1
			(1		:		2)

	CaO	=>	$Ca(OH)_2$
Density	3.37		2.24
M. Wt.	56.1		74.1
M. Vol.	16.6		33.1
Change of Vol.	16.6		33.1
	(1	:	2)

In the case of sodium bentonite, such as in geo-materials, it can swell 15-18 times its dry size when wetted by water, as shown in Figs. 12 and 13 [14]. Therefore, it has a natural swelling ability and will maintain its swelling ability throughout its lifetime.

Bentonite is a natural sealant and is used for sealing stock and recreational ponds, dairy and sewage lagoons, and city landfills. It is also effective as a hole plug for controlling dust on highways. This means that it has high potential to be useful for the self-healing materials, when utilizing it in appropriate dosages.

Various conditions of crack self-healing

From literature survey, possible conditions of self-healing are summarized and presented in Table 2 [9]. In case of crack width, the maximum allowable crack width is often mentioned in the literatures, and is given in Table 3 [15].

But it is true that its healing depends on conditions of water pressure, therefore fixation of maximum

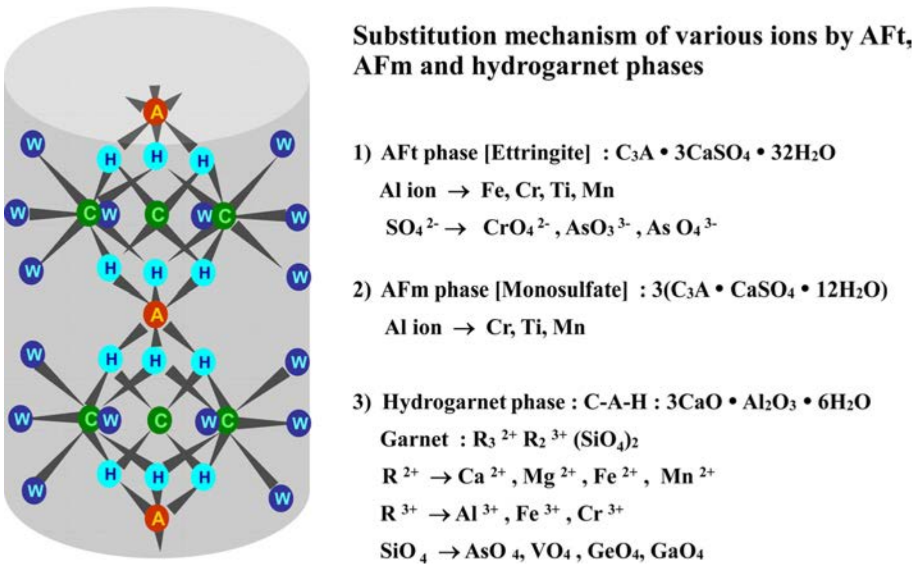

Fig. 11. Representative substitution mechanism of various ions on AFt , AFm and Hydroganet phases. (Crystal structure of ettringite: A=Al C = Ca, H = O of an OH group, W = O of an H_2O molecule) [13] [adapted from T. H. Ahn *et al*. 2014].

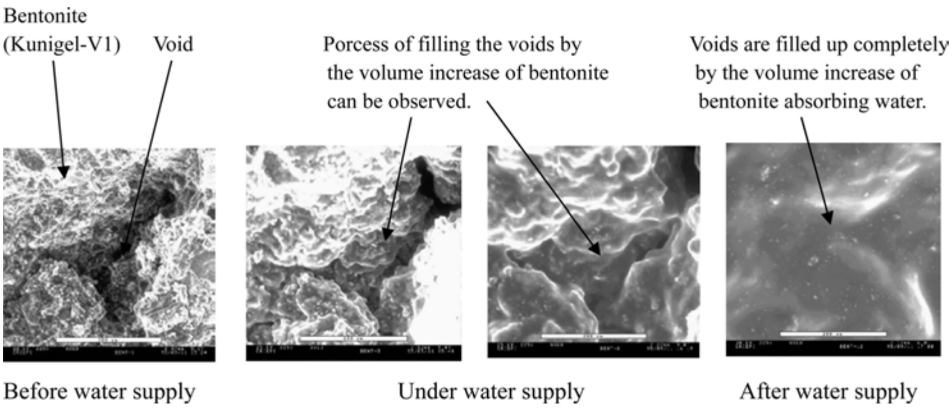

Fig. 12. Swelling behavior of bentonite [adapted from H. Komine 2004].

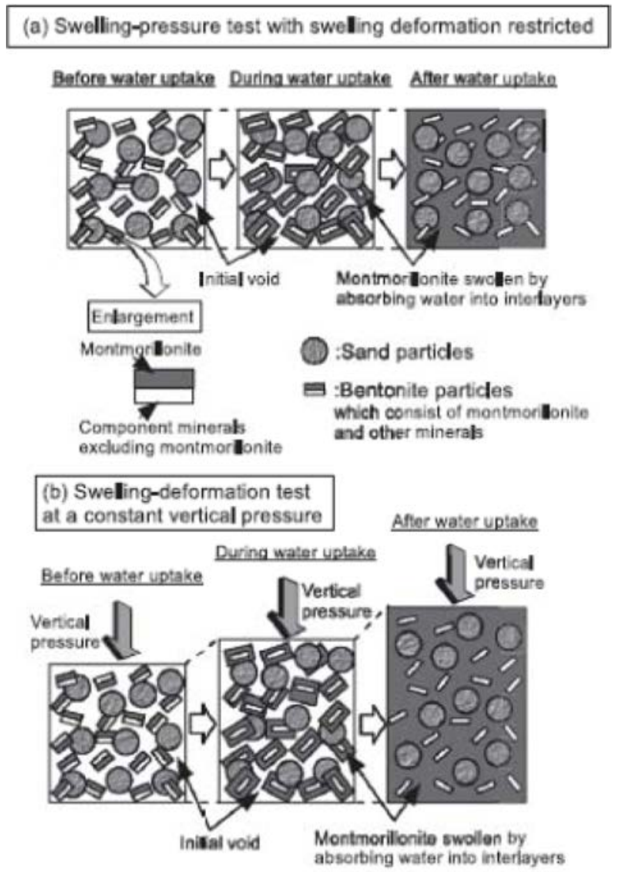

Fig. 13. Image of processes of the swelling behavior of buffer and backfill materials [adapted from H. Komine 2004].

allowable crack width is very difficult. Crack stability is also an important factor for self-healing because it will take a longer time for self-healing of dynamic cracks.

There are limits concerning maximum crack width as a function of the water pressure and the required stability of cracks. Fig. 14 schematically shows the possibility of crack healing of young concrete. N. Heide [9] reported that, in case of crack healing at an early age, if the conditions shown in Table 4 are fulfilled, complete recovery of strength is also possible.

Table 2. Various conditions for self-healing [9].

Presence of water	• The presence of water is essential for all mentioned mechanisms. • Lauer reported that healing ability was much lower when the relative humidity was 95%
Crack width	• Self-healing can only close small cracks. • Longer healing times allow larger cracks to heal, but above a certain time limit healing will no longer take place.
Water pressure	• When the liquid flows too fast through the crack, self-healing will not occur. • This condition is often expressed as a maximum ratio between water height and thickness of the structure for a certain crack width.
The liquid may not lead to a leaching or dissolution reaction	• A liquid that leads to a leaching or dissolution reaction can affect the healed crack.
Stability of the crack	• The crack has to be stable. • When the crack is dynamic, meaning a varying crack width over time, the healed crack is ruined again.

Autonomic healing in cementitious materials

T. Kishi et al. [16] reported that re-expansion of expansive concrete with a low water to binder ratio (0.35) under restrained conditions were examined in comparison to conventional concrete without expansive agent. Type I Japan Portland cement and expansive agent were used as binding materials in all specimens. For the concrete beam test, two concretes with water/binder ratio of 0.35 were investigated. One used only OPC and the other used OPC incorporating 10 wt% expansive agent. Polycarboxylate-based superplasticizer was also used in the preparation of both mixtures. Concrete beams 15 by 15 by 88 cm were prepared for this research. D10 rebar was also used to reinforce the concrete in each specimen. Fig.15 schematically shows the method for inducing cracks in concrete beams. The specimens were pre-cracked by straining this tool in tension at 28 days after manufacture, in order to clarify the

Table 3. Typical values of maximum allowable crack width [15].

Source	Exposure Condition	Maximum allowable crack width			
		in	mm	in	Mm
ACI Committee 224	- Interior exposure (dry air, protective membrane)	0.016	0.40		
	- Exterior exposure (moist air, soil)	0.013	0.33		
	- Seawater, wetting and drying	0.006	0.15		
	- Water-retaining structures	0.004	0.10		
	- Deicing chemicals	0.007	0.18		
CP-110 (England)	Two limits are recommended depending on the tensile stress in the concrete and the pre-stressing method	0.0078 0.0039	0.20 0.10		
Abeles		Cracking not permitted under dead load		Cracking permitted under dead load	
	- Air or protective membrane	0.012	0.30	0.010	0.25
	- Salt air, water and soil	0.010	0.25	0.008	0.20
	- Deicing chemicals, humid tropical climate, sea water, wetting and drying	0.008	0.20	0.006	0.15

Nation	Standard	Environmental conditions	Maximum allowable crack width
Japan	JSEC Concrete standard (2002) Investigation of concrete performance	General environment	c: cover concrete (mm) deformed rebar : 0.005c (PC steel bar : 0.004c)
		Corrosive environment	0.004c
		Sever corrosive environment	0.0035c
	AIJ Concrete standard (Architectural Institute of Japan) (2002)	General environment	0.3 mm
America	ACI Building Code 318-95	Outdoor	0.33 mm
		Indoor	0.41 mm
New Zealand	New Zealand Standard	In case of protection against tempera-ture between land and part	RC part : 0.4 mm PC part : 0.3 mm
		Outdoor	RC part : 0.3 mm PC part : 0.2 mm
		Sever corrosive environment	RC part : 0.2 mm PC part : 0.1 mm
Europe	Eurocode 2	Dry air environment	RC part : 0.3 mm PC part : (post-tension) 0.2 mm PC part : (Pre-tension) 0.2 mm
		Hot air environment	RC part : 03. mm PC part : (post-tension) 0.2 mm PC part : (Pre-tension) 0.2 mm
		Hot air environment Cold area, Anti-freezing agent	RC part : 03.mm PC part : (post-tension) 0.2 mm PC part : (Pre-tension) 0.2 mm
		Marin environment	RC part : 03. mm PC part : Both case 0.2 mm
Norway	DET NORSKE VERITAS (1991)	Sever environment	0.2 mm
		Etc.	0.4 mm
		Short period	The above 1.5 times
England	British Standard Institution (1985)		0.3 mm

self-healing process of load-induced cracks at low water to binder ratio. Crack width was controlled between 0.1 mm and 0.3 mm in consideration of the maximum tolerable crack widths according to construction codes. The specimens were then, once more, water cured for one month after cracking.

First, the re-expansion of expansive concrete with a low water to binder ratio under restrained conditions was examined in comparison with normal concrete without expansive agent in order to clarify the self-healing mechanism. Fig. 16 and Fig. 17 show the difference in healing process of cracked concrete under water supply in each case. For concrete beams incorporating expansive agent, a crack with an initial width of 0.22 mm was almost healed after one month. Re-hydration products between cracks were observed. However, for the normal concrete beam, the cracks still remained and were only partly closed after the same

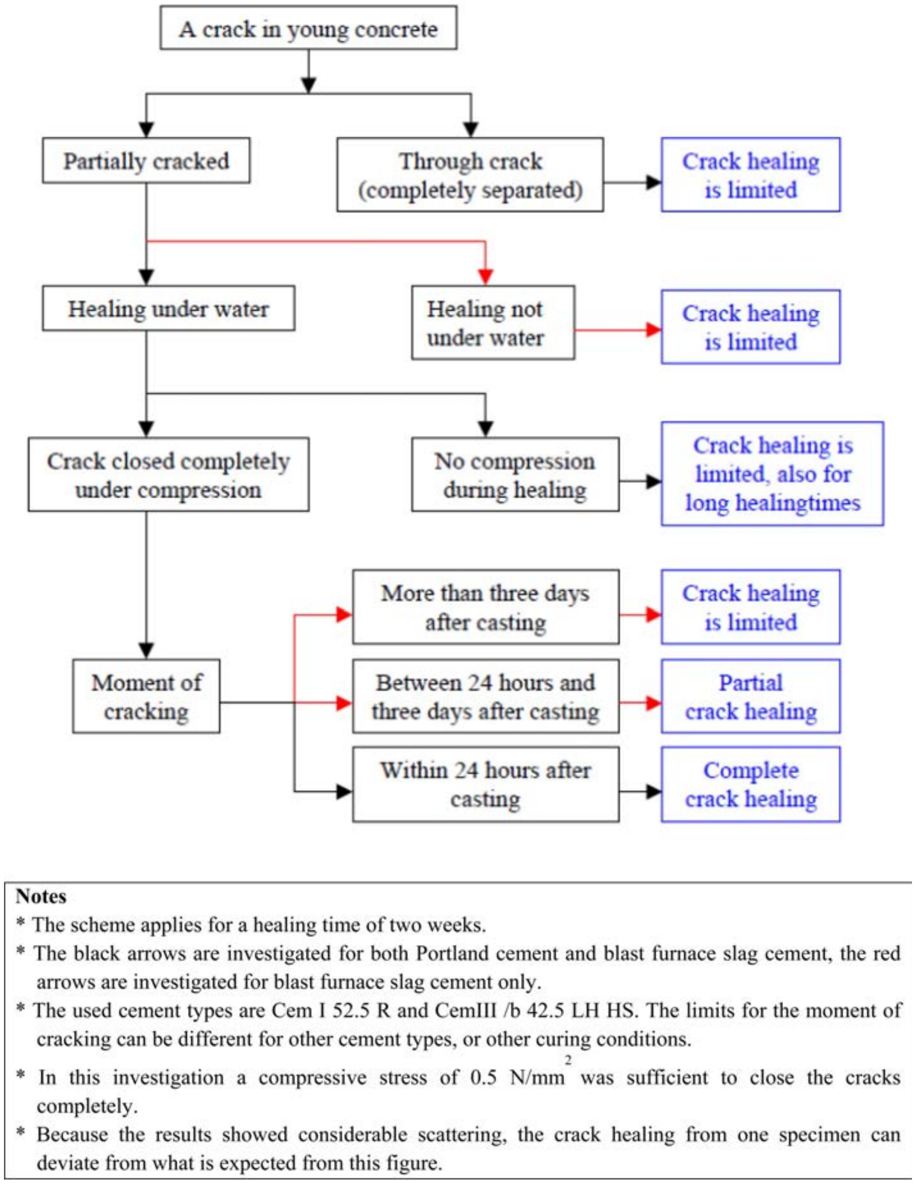

Fig. 14. The scheme of crack healing in young concrete [adapted from N. Heide 2005].

Table 4. Crack healing conditions of early age cracks.

Early formation of the crack	Cracking within the first 24 hours (strength = 0.2 f_{28days}) is necessary for complete strength recovery. After that time, the later the crack is formed the more limited the strength recovery will be.
Compressive stress during healing	The crack must be closed completely under compressive stress, and the compressive force must be maintained during healing. To guarantee a good closure, the crack must be closed soon after the formation of the crack.
Moisture	Good crack healing was only observed when the specimens were stored under water.
Partially cracked cross-section	The two crack faces must be placed accurately to each other for a good crack healing. To guarantee a good fit between the two crack faces it is necessary that a part of the cross-section is still connected. Only a small part of the cross-section is already sufficient to provide a good fit.

amount of time. This showed that recrystallization of expansive agent in air voids for self-healing was more effective than that of normal concrete at low water/binder ratio.

T.H. Ahn *et al*. [17] reported that the self-healing phenomenon of autogenous healing concrete using geo-materials for practical industrial application was investigated. And then, they reported that a self-healing concrete was fabricated by ready-mixed car in a ready-mixed concrete factory then used for the construction of artificial water-retaining structures and actual tunnel structures. Their results show that the crack of concrete was significantly self-healed up to 28 days re-curing. Crack-width of 0.15 mm was self-healed after re-curing for 3 days and the crack width decreased from 0.22 mm to 0.16 mm after re-curing for 7 days. Furthermore, it was almost completely self-healed at 33 days as shown in Fig. 18.

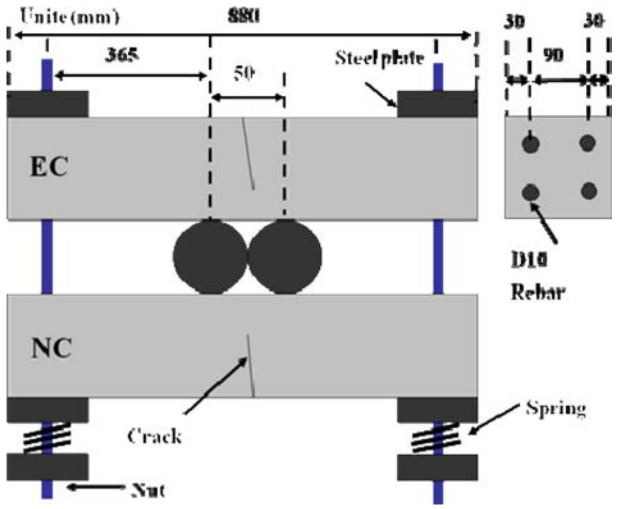

Fig. 15. Dimensions of the test specimens in order to induce crack in concrete beam [adapted from T.Kishi *et al*. 2007].

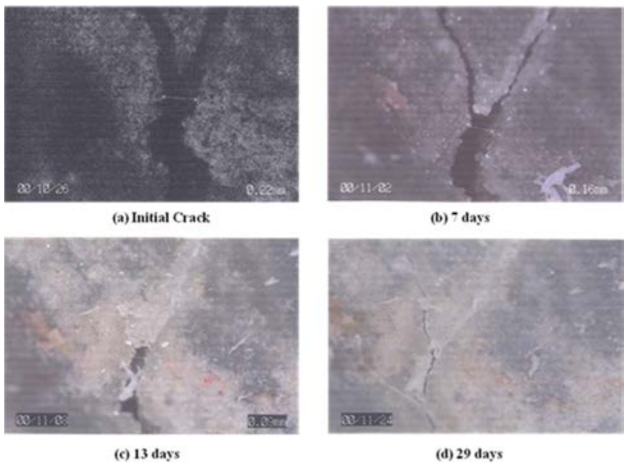

Fig. 16. Process of self-healing on expansive concrete beam at low water/binder ratio [adapted from T. Kishi *et al*. 2007].

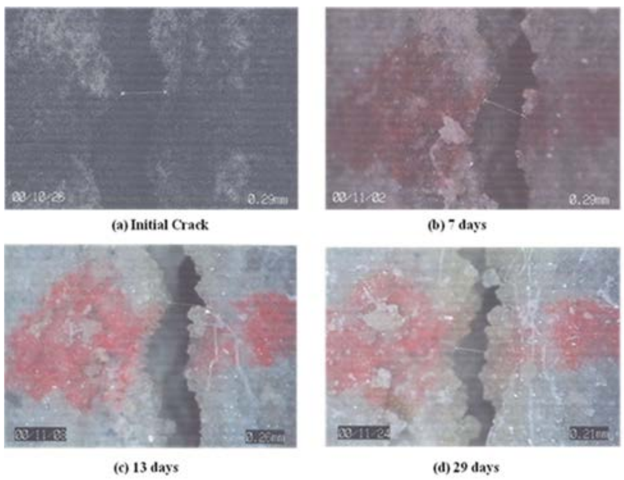

Fig. 17. Process of self-healing on normal concrete beam at low water/binder ratio [adapted from T. Kishi *et al*. 2007].

Jonkers *et al*. [18-20] reported that bacteria can potentially act as a self-healing agent in concrete. The goal of this research was to incorporate dormant but

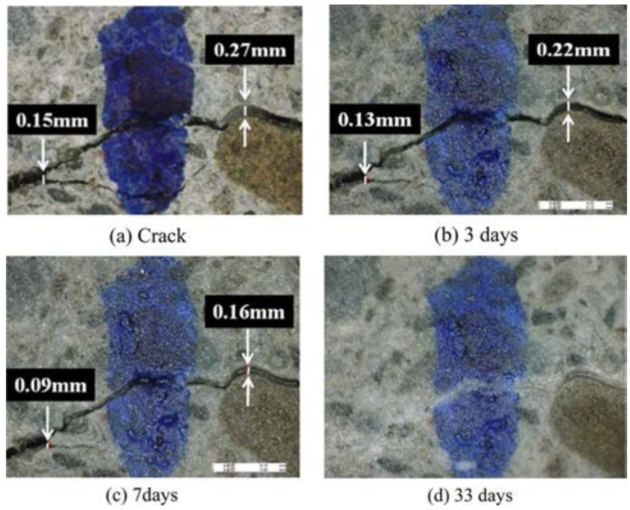

Fig. 18. Process of self-healing on self-healing concrete at water/binder ratio of 0.47 [adapted from T.H. Ahn et al. 2010]

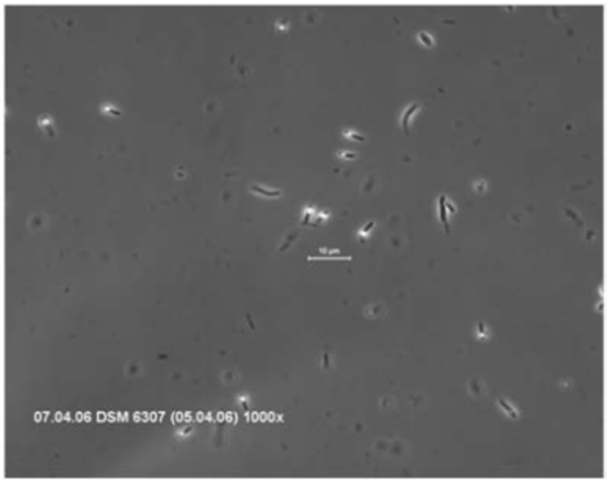

Fig. 19. Spore formation by *Bacillus cohnii* grown in mineral medium with sodium citrate as growth substrate. Bright dots are spores formed by the vegetative cells (dark rods) [adapted from H.M. Jonkers *et al*. 2007].

viable bacteria in the concrete matrix which would contribute to the concrete's self-healing potential. Fig 19 shows spore formation by *Bacillus cohnii* grown in mineral medium with sodium citrate as growth substrate.

They tested the applicability of alkaliphilic spore-forming bacteria of the genus *Bacillus* as a self-healing agent in concrete. They found that incorporation of high numbers of bacteria ($10^9\ cm^{-3}$) as well as some suitable organic growth substrates in concrete did not negatively affect compressive and flexural tensile strength. ESEM analysis furthermore revealed the self-healing potential of immobilized cells, as bacterial, but not control cement stone samples, were found to deposit a new layer of calcium carbonate minerals on its surface as shown in Fig. 20. Finally, they concluded that these specific bacteria were promising candidates to act as a self-healing agent in concrete structures.

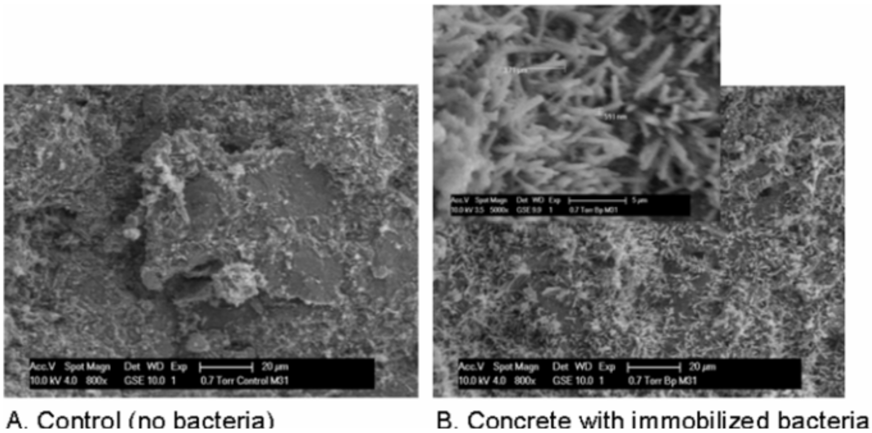

Fig. 20. Copious formation of minerals on the surface of cement stone with *B. pseudofirmus*-immobilized spores [adapted from H.M. Jonkers *et al*. 2007].

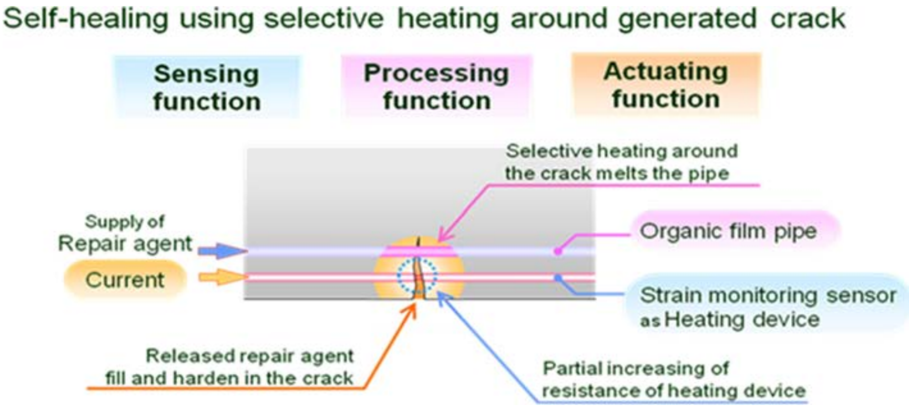

Fig. 21. Schematic illustration of activated repairing systems [adapted from T. Nishiwaki *et al* 2007].

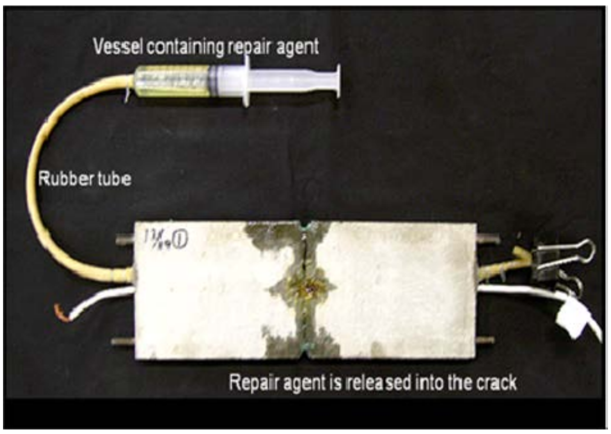

Fig. 22. Crack healing through activated repairing systems [adapted from T. Nishiwaki 2007].

Activated repairing system for self-healing

Nishiwaki *et al*. [21] reported the development of smart concrete with a self-healing system with heating devices as shown in Fig. 21. They explained that the self-diagnosis composite employed the heating device, which can heat up the cracked part of concrete. This heating device and a pipe made with heat-plasticity organic film containing a repair agent are embedded in concrete. Fig. 22 schematically shows the healing process of the activated repairing system when crack occurs. The embedded film is melted by proper heat. Selective heat around a crack can melt the film to let the repair agent fill up the crack and harden the repair agent in the crack as shown in Fig. 22. A three-dimensional thermal analysis and an experimental study were carried out to confirm the proposed method as shown in Fig. 23.

New repairing method using self-healing technologies

T.H. Ahn *et al*. [22-25] reported the new surface treatment repair method using crack repair stick and putty for micro-crack (less than 0.3 mm) of concrete. It was commercialized by some companies in Korea and Japan. Fig. 24 schematically shows repair process of crack repair stick with self-healing agents. Fig. 25 also shows the self-healing phenomenon of these repair materials on the re-cracking case (below 0.1 mm) under the water supply after repair works. The self-healing phenomenon was investigated various experiments such as relative dynamic modulus of elasticity, water permeability test, observation of microscope and SEM analysis, before and after repair works. And then, it has founded that durability was enhanced significantly by self-healing effects. From these results, it was

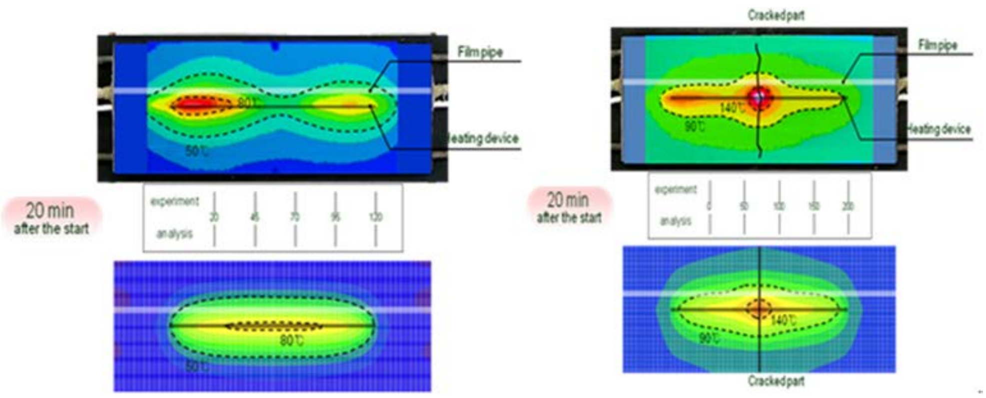

Fig. 23. Thermal analysis of activated repairing systems [adapted from T. Nishiwaki 2007].

Fig. 24. New repairing method for micro-crack of concrete [adapted from T.H Ahn *et al*. 2014, 2015].

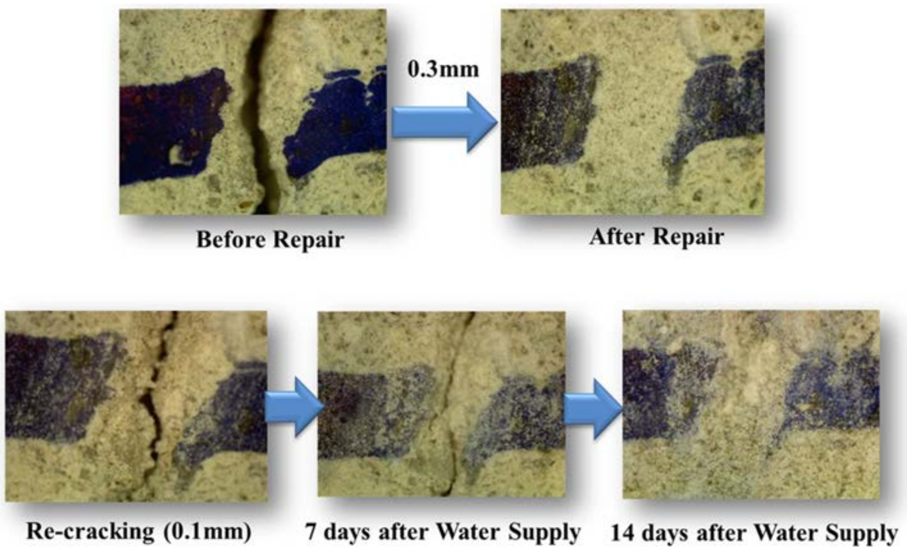

Fig. 25. Process of self-healing on repair materials with self-healing agents [adapted from T.H Ahn *et al*. 2014, 2015].

concluded that crack repair stick incorporating self-healing agents has a high potential for one of new repairing methods of cracked concrete.

Conclusions

In this review paper, various previous research results were surveyed in order to understand the self-healing concept for the cracked concrete. The definition of terms concerning self-healing, as recommended by JCI-TC075B (Technical Committee on Autogenous-healing in Cementitious Materials of Japan Concrete Institute0, JCI-TC091A (Japan Concrete Institute Technical Committee 091A) and RILEM TC-SHC [Self-healing Phenomena in Cement-Based Materials of (International Union of Laboratories and Experts in Construction Materials, Systems and Structures)] were introduced. The mechanism of self-healing phenomenon and type of self-healing were summarized for the establishment of the self-healing concept. It is considered that these definitions and summary are useful for researchers studying in this new field.

Acknowledgments

This work (Grants No. C0193581) was supported by Business for Academic-industrial Cooperative establishments funded Korea Small and Medium Business Administration in 2014.

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