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Development of Engineered Self-Healing and Self-Repairing Concrete

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Invited paper

Development of Engineered Self-Healing and Self-Repairing Concrete-State-of-the-Art Report

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Abstract

Challenging studies of engineered self-healing and self-repairing functions in concrete structures are briefly reviewed. While self-healing of concrete has been studied for a long time, it was only recently noticed that some engineered technologies are useful to stimulate the potential of concrete to be self-healed. For example, fiber reinforced cementitious composites (FRCC) have a much higher potential of self-healing than ordinary concrete because of their capability to keep cracks thinner and also because of the bridging network system in cracks; a specific bio-chemical approach, i.e. the application of mineral-precipitating bacteria, is now available; and various mineral admixtures are useful for practical application. Furthermore, the new concept of self-repairing concrete, which is based on the design concept of intelligent materials, is reported. Self-repairing concrete is concrete that incorporates devices for achieving the three key functions of an intelligent material, (1) sensing, (2) processing, and (3) actuating.

This paper is a state-of-the-art report on the recent development of engineered self-healing and self-repairing concrete.

1. Introduction

Concrete structures often suffer from cracking that leads to much earlier deterioration than designed service life. To prevent such deterioration, regular inspection of cracks in concrete structures and their repair are usually carried out by means of some kind of human intervention. On the other hand, for example, a small cut on our body can be healed by a simple treatment even though it takes a couple of days. In nature, animals and trees usually can heal small bodily damage by themselves.

Generally speaking, cracks in concrete can occur in any stage of the service life of concrete structures due to volume instabilities such as autogenous shrinkage and/or drying shrinkage since concrete is composed of aggregate of various sizes connected with the hydration products generated by mixing cement and water. Furthermore, the tensile strength of concrete is about 10% of the compressive strength, so that concrete is reinforced with steel bars at least in the parts subject to tensile stress. Once cracking occurs in reinforced concrete members, not only is the stiffness reduced but steel bars corrosion also occurs due to the permeation of rain and aggressive substances, reducing structural safety and serviceability. In order to avoid the dangerous situations caused by such deterioration, application of proper maintenance systems is required. For concrete structures to avoid most such damage, the initial performance of concrete needs to be set at a high level and comprehensive maintenance systems need to be applied. This presents the drawback of higher construction cost.

In the meantime, sustainability is now one of the top issues in the field of building and civil engineering from the viewpoint of global ecology. For this reason, extending the service life of structures has become a key objective. A full array of inspection and maintenance techniques for concrete structures has been developed. In some cases, however, it is difficult for engineers to access damaged sites for repair work because of their location and/or environmental conditions. Some examples are underground structural members, radioactive waste disposal facilities, and walls of tanks storing highly toxic waste.

The availability of self-healing and self-repairing systems would make structures more reliable. For example, if control and repair of early-stage cracks in concrete structures were possible, permeation of driving factors for deterioration could be prevented, thus extending the service life of the structures. For this reason, many papers have been published on self-healing and self-repairing concrete

Overcoming the apparent contradictory requirements of low cost and high performance is a challenging task. A major goal of concrete technologies might be to make concrete a functional material to meet a specific set of performance requirements. The adaptation of new technologies to structural engineering is expected to result in better, stronger, and more durable structures at lower life cycle costs. Meanwhile, the development of advanced concrete materials should be related to the cost-effective engineering means to achieve the desired structural properties.

In recent years, intelligent materials have been extensively developed in various research fields using a new material design approach based on the concept of in-

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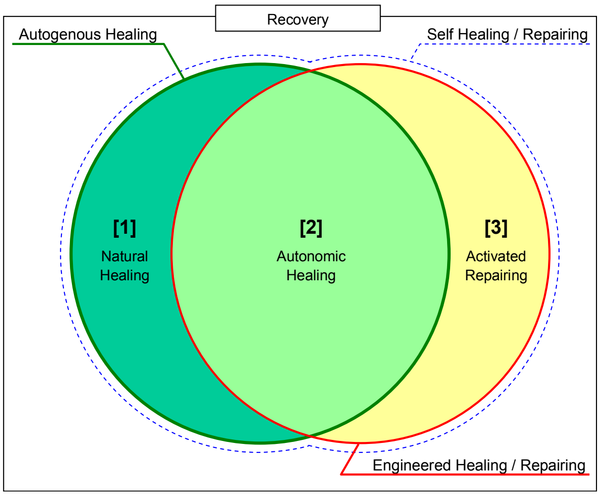
stalling smart functions such as sensing, processing and actuating in the material itself (Science and Technology Agency 1989). Shahinpoor (1997) reported that intelligent materials are currently defined as materials capable of automatically and inherently sensing or detecting changes in their environmental conditions and responding to those changes with some kind of actuation or action. Once the sensing function catches a change, the influence on the required performance of the structure is assessed. If the influence is not negligible, the change is repaired or improved automatically. In order to accomplish such functions, advanced apparatus such as optical fiber sensors, shape memory alloy and piezoelectric devices are usually employed. Generally speaking, the merging of such advanced devices results in a substantial escalation in costs. In specific fields such as aerospace and medical engineering, reliability and performance are the dominant factors in material design and cost is a secondary consideration. In the field of concrete used in civil and building engineering, however, solutions that involve a steep rise of the cost of materials are hard to justify in terms of the cost-benefit relation. Hence, the viability of new materials in the field of concrete engineering is highly controlled by their cost.

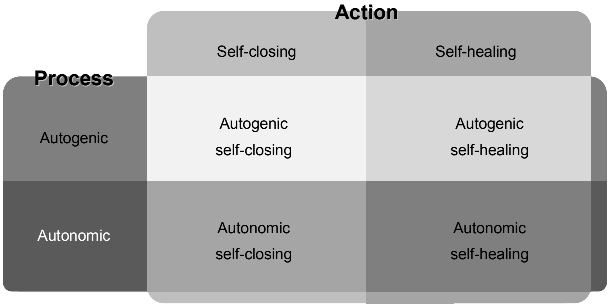
In this report, previous papers related to the self-healing and self-repairing concrete are briefly reviewed.

2. Definition of terms – self-healing and self-repairing

Self-healing, or autogenous healing, of concrete and reinforced concrete is a phenomenon that has been studied by various researchers. Reviews on healing of cracks can be found for example in Lauer & Slate (1956), Jacobsen *et al.* (1998) and de Rooij & Schlangen (2011). Many experimental results and practical experiences have demonstrated that cracks in concrete have the ability to heal themselves, reducing water flow through cracks over time. According to a review of the literature by Lauer & Slate (1956), the action of self-healing was first discovered by the French Academy of Science in 1836, which concluded that self-healing is the conversion of calcium hydroxide exuded from the hydrated cement and converted to calcium carbonate on exposure to the atmosphere. Many subsequent researchers, however, assumed that self-healing is an action of continued hydration and other actions. Summarizing previous studies, possible mechanisms of self-healing are cited as follows (Ramm and Biscoping 1998): (1) further reaction of the unhydrated cement; (2) expansion of the concrete in the crack flanks; (3) crystallization of calcium carbonate; (4) closing of the cracks by solid matter in the water; (5) closing of the cracks by spalling-off of loose concrete particles resulting from the cracking. Among these five mechanisms, however, Edvardsen (1999) clarified that crystallization of calcium carbonate within the crack is the main mechanism for self-healing of matured concrete.

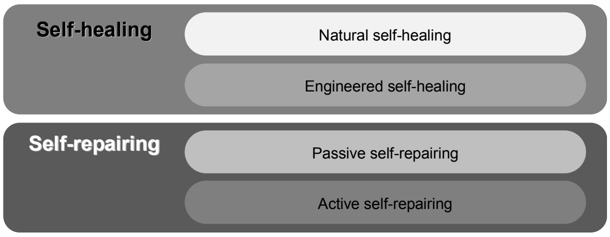


(a) Definition of self-healing/repairing concrete (JCI 2009, Igarashi et al. 2009).



	Self-closing	Self-healing
Autogenic	Autogenic self-closing	Autogenic self-healing
Autonomic	Autonomic self-closing	Autonomic self-healing

(b) Definition of self-healing concrete based on the action and the process by RILEM-TC221 (de Rooij & Schlangen 2011).



(c) Definition of self-healing/repairing concrete by the authors.

Fig. 1 Definition of Self-Healing and Self-Repairing Concrete

While various techniques for engineered healing or repairing of cracks in concrete have been proposed so far, the targeted crack widths and adopted techniques greatly differ depending on the objective. For example, strength should be recovered for structural safety performance, but for durability performance, just filling cracks to prevent the permeation of water and aggressive substances is sufficient. Moreover, the key points are the materials and mechanisms used for filling up the cracks.

JCI Technical Committee on Autogenous Healing in

Cementitious Materials (JCI 2009) proposed the following definition of self-healing/repairing concrete: (1) Natural healing; (2) Autonomic healing; and (3) Activated repairing. Furthermore, (4) Autogenous healing covers natural healing and autonomic healing (i.e. 1+2), and (5) Engineered healing/repairing covers autonomic healing and activated repairing (i.e. 2+3). Finally Self-Healing/Repairing covers all the actions of closing and/or repairing cracks (**Fig. 1 (a)**).

On the other hand, in RILEM Technical Committee 221-SHC: Self-healing phenomena in cement-based materials, self-healing terms are defined based on the result of the action: “self-closing” or “self-healing”; and on the process of the action: ”autogenic” or “autonomic” (de Rooij & Schlangen 2011). Thus they are subdivided into the following four groups: (1) Autogenic self-closing: own generic material closes cracks; (2) Autogenic self-healing: own generic material restores properties; (3) Autonomic self-closing: engineered additions close cracks; and (4) Autonomic self-healing: engineered additions restore properties (**Fig. 1 (b)**).

Roughly speaking, previous studies on the subject can be divided into two groups: the first group focuses on the potential retaining capability in concrete (or cementitious composites) to fill cracks and some engineered technologies are installed to stimulate that capability; the second group opts to supplement a function to repair cracks, and some devices are embedded in advance for that purpose. In this report, the former approach is called “engineered self-healing” and the latter is called “self-repairing.” The latter can be further subdivided into two sub-groups: one is passive mode self-repairing in which functional elements such as hollow pipes are embedded in the designed position of the structural member similarly to reinforcing steel bars; the other is active mode self-repairing in which cracking is monitored by a sensor and cracks are repaired by actuation devices only when they become wider than a critical width (**Fig. 1 (c)**).

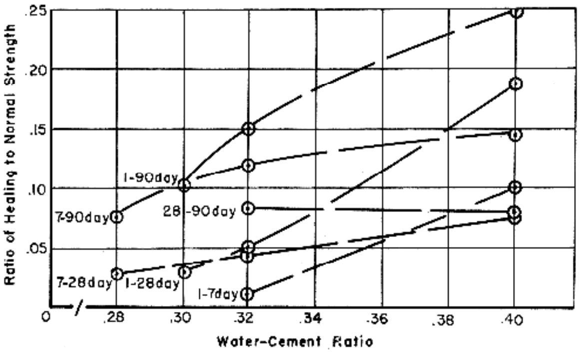


Fig. 2 Plot of ratio of healing to normal strength versus water-cement ratio (Lauer and Slate, 1956).

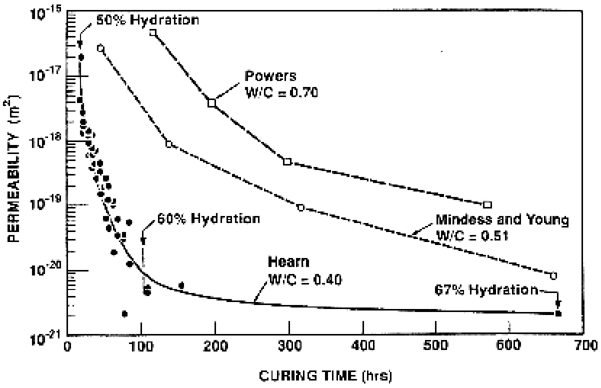


Fig. 3 Permeability vs. extent of hydration (Hearn and Morley 1997).

3. Natural self-healing

Lauer and Slate (1956) reported a study of the nature of the self-healing action and of the increases in tensile strength measured perpendicular to the plane of the crack. They studied the influence of age, conditions of curing, additions of lime and fly ash, and cycles of wetting and drying on healing. For example, **Fig. 2** shows an increase in healing with higher water-cement ratios, in which 1-90 days means the initial breaking age was 1 day and then curing was done for 90 days until the testing of the healing effect. On the basis of the results of microscopic examination, they concluded that the bonding materials formed during the action were 100% calcium carbonate $CaCO_3$ and calcium hydroxide $Ca(OH)_2$ crystals but that no amorphous hydrated products of cement were found, though the test samples were young (1 to 28 days). Their results indicated that the addition of lime and fly ash as mixtures had a slight detrimental effect on the subsequent healing strength in water curing but that no definite trend was found in an atmosphere of 95% relative humidity. They emphasized that the presence of water as the curing medium was essential to obtain the maximum healing strength.

Dhir *et al.* (1973) studied the influence of age and mix proportions on the self-healing of mortars. They concluded that the rate of healing decreased with age within the test range of 7-120 days and that the percentage of recovery in strength was greater for the mixes with higher cement contents. They also concluded that the ultimate strain of healed specimens was reduced.

Hearn and Marley (1997) carried out a permeability test with 26 years old concrete and confirmed that drying and re-saturation resulted in a substantial increase in the self-healing effect and that extensive microcracking due to drying stimulated the effect (**Fig. 3**) since most of the flow took place through cracks exposed to the atmosphere. Furthermore, he suggested that the reduction in permeability due to hydration had a minimal effect, as shown in **Fig. 4** (Hearn 1998).

Ramm and Biscoping (1998) performed an experimental study over a period of two years with respect to the self-healing and reinforcement corrosion of water-penetrated separation cracks in reinforced concrete in

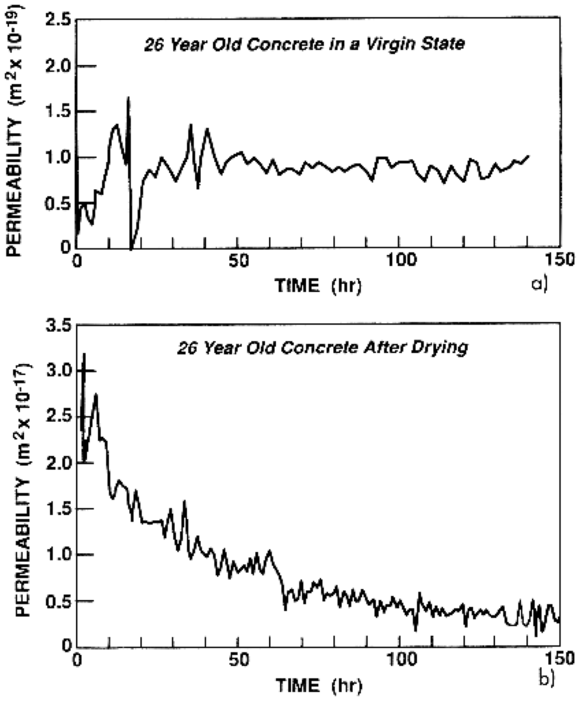


Fig. 4 Typical permeability vs. time data for virgin (a) and oven dry/resaturated (b) concrete (Hearn 1998).

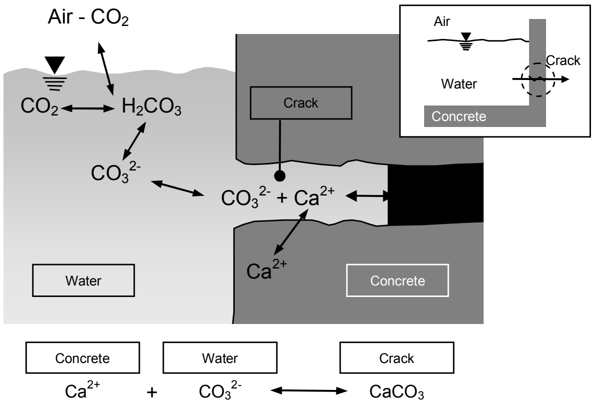


Fig. 5 Media, interfaces, and reactions in $CaCO_3$-CO_2-H_2O system (Edvardsen 1999).

which the influence of the crack width, the thickness of the structure, the water pressure, and the degree of acid of the water were studied. The following conclusions were obtained. With a crack width of 0.1 mm, corrosion was not observed in any case. For the test specimens with a crack width of 0.2 mm, corrosion was found to start depending on the pH value. At increasing crack widths, increasing corrosion development is to be expected for test specimens penetrated by acid water. At the crack width of 0.4 mm and pH value of 5.2, the highest corrosion development was observed. However, there was no weakening of the cross section worth mentioning even at the end of the 2-year test period.

Edvardsen (1999) carried out a series of permeability tests on plain concrete and investigated the effects of self-healing upon the leakage of water through cracks in concrete. He found that the greatest self-healing effect occurred within the first 3 to 5 days of water exposure and that the precipitation of $CaCO_3$ crystals in the cracks was practically the sole cause for the self-healing of the cracks. The growth rate of the $CaCO_3$ crystals was dependent on crack width and water pressure, whereas the concrete composition and type of water had no influence on the self-healing rate. Edvardsen also concluded that the formation of $CaCO_3$ responded to two different crystal growth processes. In the initial phase of water exposure, the kinetics of crystal growth is a surface-controlled crystal growth but later this changes to a diffusion-controlled crystal growth (**Fig. 5**). A similar mechanism of healing was also suggested by Lauer and Slate (1956).

Reinhardt and Jooss (2003) reported a series of permeability tests with the constant temperature at 20, 50, and 80°C. They showed that the decrease of the flow rate depends on crack width and temperature and that a higher temperature favors a faster self-healing process.

Granger *et al.* (2007) carried out an experimental study on the mechanical properties of ultra high performance concrete and concluded that the self-healing of the pre-existing cracks was mainly due to hydration of anhydrous clinker on the crack surface and that the stiffness of newly formed crystals is close to that of primary C-S-H.

As for the recovery of material properties due to self-healing, Aldea *et al.* (2000) reported that the recovery in signal transmission with crack healing was not as spectacular as that in permeability.

The effect of self-healing on the properties of concrete subjected to cycles of freezing and thawing has been suggested as early as the middle of the 20th century (McHenry & Brewer 1945, Lauer & Slate 1956). Jacobsen *et al.* (1995, 1996) studied the microcracking of concrete due to freeze/thaw (1 to 10 micrometers) and self-healing of cracks after subsequent storage of deteriorated specimens in water for three months, using a scanning electron microscope (SEM). Two concrete types of W/B=0.4 and SF/B=0 or 0.05 were investigated. Deterioration/healing was measured by resonance frequency (dynamic modulus of elasticity) and compressive strength. While freezing/thawing led to substantial loss in both resonance frequency and compressive strength, subsequent self-healing gave a substantial recovery of the frequency but only a small recovery in the compressive strength. After self-healing, solid hydration products bridging cracks smaller than 5 micrometer were observed at several locations. Occurrence of the products was less apparent in the concrete with SF than in OPC concrete. Energy dispersive X-ray analysis revealed that the composition of the products was of the C-S-H type. Calcium hydroxide crystals and ettringite were observed, too.

4. Engineered self-healing of concrete

4.1 Engineering with fiber reinforcement

Compared with the rather large number of studies of self-healing of plain concrete, such studies on Fiber Reinforced Cementitious Composites (FRCC) are rather scarce. Hannant & Keer (1983) carried out an experimental study on the recovery of elastic modulus and tensile strength of thin FRCC sheets under tension. W/C was 0.34 using OPC mortar containing fine silica sand of 150 to 300 micrometers and reinforced with a polypropylene network. The specimens were 1.2 mm in thickness and 30 mm in width. The study concluded that specimens containing about 22 cracks of the average width of 7 micrometers showed almost complete recovery of elastic modulus but only about 50% recovery of tensile strength after curing of seven months to two years in natural weathering conditions.

Grey (1984) examined self-healing of the interfacial bond strength between steel fiber and mortar by means of a pulling-out test on single fibers embedded in water-cured specimens. The test results indicated that the extent of the interfacial bond healing was greater than that observed for the compressive strength of the plain mortar.

Li *et al.* (1998) carried out experimental studies on the self-healing capability of Engineered Cementitious Composites (ECC) and concluded that cementitious materials with inherently tight crack widths are conducive to self-healing and that self-healing can distinctly recover the stiffness of cracked ECC, a fact established through resonance frequency measurement.

Yang *et al.* (2005) investigated self-healing of ECC subjected to wetting and drying cycles. They used a mix proportion of water-binder ratio of 0.25 including a large amount of fly ash and 2% PVA fiber by volume fraction. The ECC material subjected to tensile load exhibited multiple cracking in which the crack width was between 60 and 80 micrometers on average. It was found that the resonance frequency could recover 76% to 100% of the initial value and that the tensile strain after self-healing could recover 1.8% to 3.1% for specimens pre-loaded to high levels of strain between 2% and 3%. Yang *et al.* (2009) also reported similar results and showed that the majority of the self-healed products were characteristic of calcium carbonate crystals (**Fig. 6**).

Herbert & Li (2011) reported the results of an experimental study on the self-healing behavior of ECC under natural environmental conditions. They concluded that self-healing was not as robust as that observed in some experimental results carried out under controlled laboratory conditions, though the self-healing in the natural environment was promising.

Homma *et al.* (2008, 2009) investigated the self-healing capability of FRCC by microscope observation, water permeability test, tension test and back-scattered electron image analysis. They prepared specimens with water/binder ratio of 0.45, containing three different types of fiber (i.e. steel cord 0.75 vol.%: SC, polyethylene fiber 1.5 vol.%: PE, and hybrid type including both of these two fibers: 0.75 vol.% & 0.75 vol.% for a total of 1.5 vol.%: PE+SC). It was found that lots of very fine PE fibers bridge over the crack and that crystallization products of calcium carbonate examined with Raman spectroscopy become easily attached to the PE fibers. As a result, in the case of PE, the mean thickness of the crystallization products attached to the crack surface increased much faster compared with the other fibers (**Fig. 7**). Water permeability reduced as a function of the crack width together with the curing time for the self-healing, though the reduction rate was not improved for crack widths greater than 100 micrometers even if 1.5 vol.% of PE was contained (**Fig. 8**). While specimens of PE+SC showed a significant improvement in tensile strength, the improvement in specimens of PE was only 10% to 60%, although the thickness of the attached crystallization products was the largest (**Figs. 9** & **10**). Furthermore, by means of backscattered electron

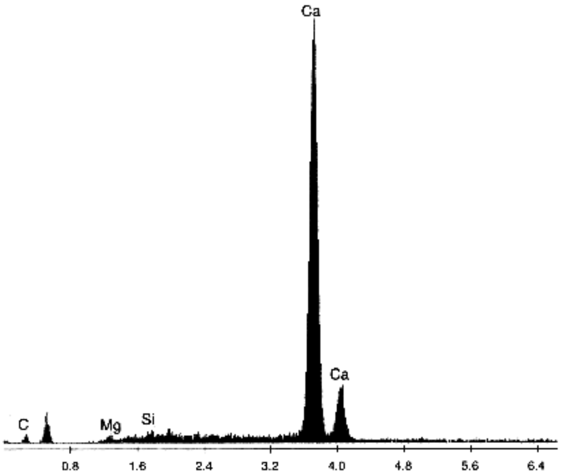


Fig. 6 Chemical composition of self-healed products (Yang *et al.* 2009).

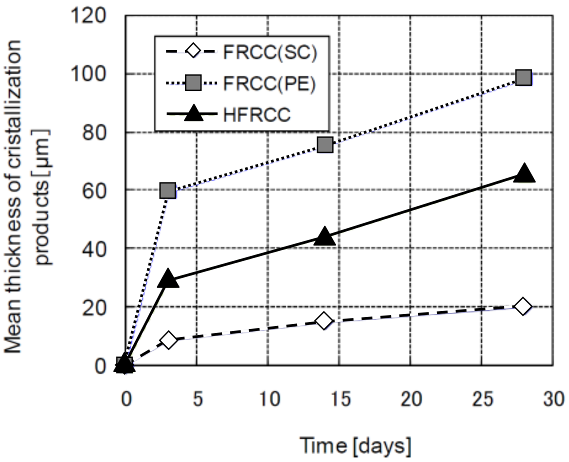


Fig. 7 Time dependence of mean thickness of crystallization products attached to the crack surface (Homma *et al.* 2009).

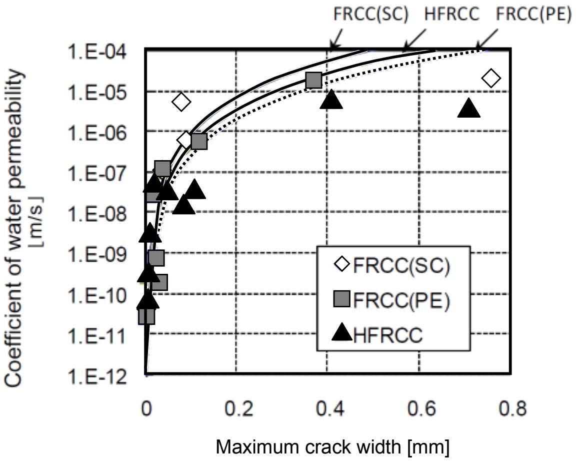


Fig. 8 Relationship between the coefficient of water permeability and the maximum crack width (Homma *et al.* 2009).

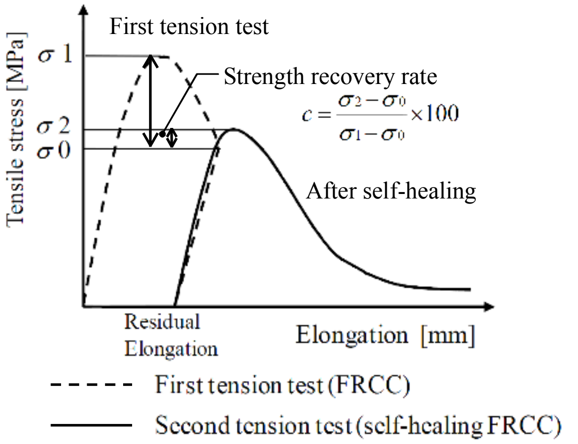


Fig. 9 Schematic description of the relationship between tensile stress and tensile elongation of FRCC (Homma *et al.* 2009).

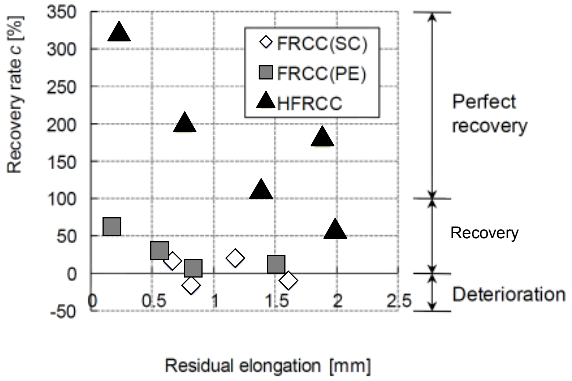
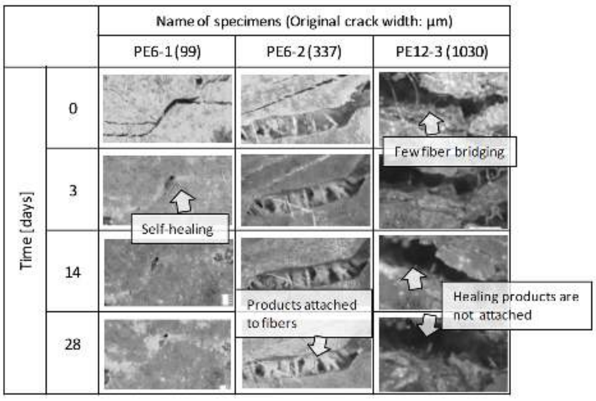
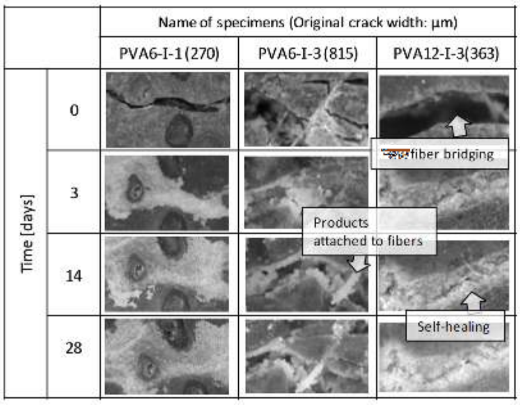


Fig. 10 Relationship between recovery rate and residual elongation (Homma *et al.* 2009).



(a) PE series



(b) PVA series

Fig. 11 Microscopic observation of crystallization products on crack surface (Koda *et al.* 2011).

image analysis, it was also verified that the difference of hydration degree had little influence on the self-healing capability.

Koda *et al.* (2011) carried out a similar permeability test to that of Homma *et al.* (2009) using PE and PVA fibers in which the volume content of both fibers was 1.5%. Fibers such as PVA fiber that possess chemical polarity had a significantly higher capability for self-healing of cracks caused by pre-loading (**Fig. 11**). It is noteworthy that the capability of self-healing of PE and PVA is almost the same for cracks thinner than 100 micrometers, but the difference becomes significant for cracks wider than 100 micrometers (**Fig. 12**).

Self-healing of FRCC has also been noticed as a key factor that contributes to the significant reduction of steel bar corrosion in RC members. Sanjuan *et al.* (1997) reported that FRCC containing only 0.5 vol.% of polypropylene with W/C=0.5 demonstrated an ability for self-healing of cracks under a corrosive environment.

Mihashi *et al.* (2011) reported the results of a series of long-term corrosion tests on FRCC containing PE alone and hybrid fiber (i.e. mix of steel cord and polyethylene: SC+PE). The results were also compared with ordinary mortar. While beam specimens were subjected to accelerated corrosion for one year by applying electrical potential of 3 volts across an internal anode (the steel bar) and an external cathode built with wire mesh and placed near the bottom face of the beams, the results showed that the hybrid FRCC exhibited excellent performance compared to mortar and another FRCC containing PE fiber (**Figs. 13 & 14**). Besides the narrow crack width due to bridging of fibers, the self-healing of cracks in these specimens might also contribute to the reduction of steel corrosion. As shown in Homma *et al.* (2009), cracks in specimens containing PE fibers are closed by the self-healing products and the steel bar embedded in the specimen was more obstructed against the access of chloride ions than that in the mortar specimen.

4.2 Engineering with admixtures

In order to stimulate the chemical reaction to produce hydration products for filling cracks in concrete, some admixtures can be used. For example, the application of mineral-producing bacteria and geo-materials has been proposed.

Recently, the precipitation of calcium carbonate due to biochemical action of bacteria has been noticed. According to Jonkers (2010), the principal mechanism of bacterial crack healing is that the bacteria themselves act largely as a catalyst and transform a precursor compound into a suitable filler material. Jonkers pointed out the following two requirements for applying this new technique to a self-healing concrete: (1) The lifetime of the bacteria needs to be long enough, that is equivalent to that of concrete structures; (2) The addition of bacteria or additionally necessary bio-cement precursor compounds should not cause the loss of other properties of the concrete itself. While alkali-resistant spore-forming bacteria existing in nature are viable over 50 years, the lifetime of bacteria in concrete is limited to only a few months when the bacteria spores are added directly to the concrete mixture. Furthermore, a drastic decrease of compressive strength was found because of various organic bio-cement precursor compounds, though a large number of bacteria spores hardly affected the strength.

A technique based on the application of mineral-producing bacteria has been developed in several laboratories. Ramachandran *et al.* (2001) published a paper describing an innovative biotechnology utilizing microbiologically induced mineral precipitation for concrete remediation. Cracks filled with bacteria and sand demonstrated a significant increase in compressive strength and stiffness when compared with crack without cells.

Van Tittelboom *et al.* (2010) investigated the use of a biological repair technique in which ureolytic bacteria are able to precipitate $CaCO_3$ in their micro-environment by conversion of urea into ammonium and carbonate. It was shown that cracks were filled completely by protecting bacteria in silica gel against the high pH in concrete, though pure bacteria cultures were not able to bridge the cracks.

In order to substantially increase the lifetime and associated functionality of concrete incorporated bacteria, Jonkers (2010, 2011) immobilized both bacteria spores and a simultaneously needed organic bio-mineral precursor compound (calcium lactate) by applying a vacuum technique in porous expanded clay particles prior to addition to the concrete mixture. The particle size was 1

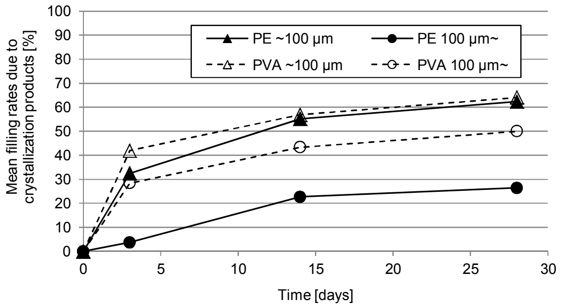


Fig. 12 Relationship between the mean filling rate of crack and the time (Koda *et al.* 2011).

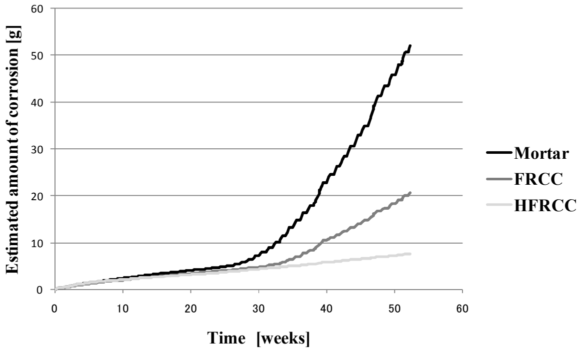


Fig. 13 Time-dependent change of the amount of estimated corrosion (Mihashi *et al.* 2011).

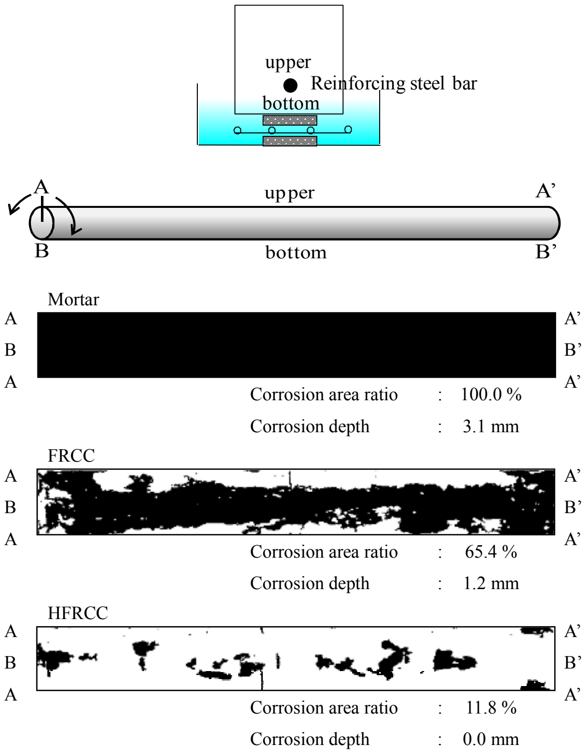


Fig. 14 Development charts of the reinforcing steel bar (Mihashi *et al.* 2011).

to 4 mm and the shape was spherical. Environmental SEM revealed that efficient healing of cracks occurred in the bacteria specimen in which large (50 to 100 micrometers) calcium-carbonate-based self-healing products were created. Tests also showed that bacterial spore viability increased from two to more than six months, though this duration is still much shorter than the usual lifetime of buildings and infrastructures.

Ahn and Kishi (2010) developed a self-healing concrete using geo-materials which was available for practical application. They concluded that self-healing capability was significantly affected by aluminosilicate materials and various modified calcium composite materials mainly due to the swelling effect, expansion effect and recrystallization. This approach requires the supply of water or at least moisture, but since most infrastructures are exposed to rain or underground water, usually this is an easily satisfiable requirement.

Taniguchi *et al.* (2011) studied self-healing of frost-damaged concrete in which sand was replaced with fly ash of 15% of cement by weight. The water-Portland cement ratio was 0.5. After undergoing accelerated freeze-thaw cycles until their relative dynamic modulus of elasticity was reduced to 80%, specimens were cured in water at 40°C for 28 days as a second curing. In addition to measuring the change in the relative dynamic modulus, carbonation tests were carried out. As a result, reduction of the carbonation rate after the second curing was found to be significant in the case of concrete containing fly ash and entrained air, although the recovery of the relative dynamic modulus of elasticity was comparatively not so good.

Sisomphon *et al.* (2011) proposed a self-healing system for carbonated blast furnace slag mixtures subjected to carbonation and frost salt scaling attack. They used expanded clay lightweight aggregates (LWA) impregnated with a sodium-monofluorophosphate (referred to as Na-MFP) solution and subsequently coated with a cement paste layer as a healing medium. Na-MFP is one of the corrosion inhibition agents for reinforced concrete. The experimental results revealed that the mortar specimens containing encapsulated LWA had better resistance against frost salt attack and that the capillary water absorption was obviously decreased in comparison with mortar with normal fine aggregates. The conclusion was that the healing mechanism could be due to the reaction of Na-MFP compound and portlandite crystals supplied from the coating layer of Portland cement paste.

5. Self-repairing

5.1 Intelligent materials

Self-repairing concrete is involved in a category of intelligent materials which is popular definition in various material research communities other than concrete. Intelligent materials possess the following three functions (**Fig. 15**) (Science and Technology Agency 1989, Mihashi *et al.* 2000, Mihashi *et al.* 2002).

(1) Sensing function – for locating or detecting the presence of targeted changes such as cracks.
(2) Processing function – for judging which action should be taken and/or when it should be taken.
(3) Actuating function – for putting the planned repair operations into action.

That is to say, an intelligent material can treat stimuli from the changing external environment as information to process the condition of the material itself. Such functions can be incorporated into cementitious materials not necessarily in the form of the natural healing process and/or ordinary admixtures as mentioned above, but also through the supply of specialized devices to repair cracks. The choice of such devices includes sensing devices, tubular network-like vessels, and synthetic resins that harden without the presence of water. Functions are given by different substances from the original constitutions of concrete. This concept was defined as "Activated Repairing" by the JCI Technical Committee on Autogeneous-Healing in Cementitious Materials as shown above (**Fig. 1(a)**).

5.2 Passive self-repairing

The Science and Technology Agency (1989) suggested the basic concept of intelligent materials composed of distributed functional capsules and matrices (**Fig. 15**). This concept was widely recognized as a practical research topic for research on polymeric materials using encapsulated chemicals (White *et al.* 2001). **Figure 16** shows a conceptual diagram of self-healing. In the field of concrete engineering, there were some researchers who adopted a similar concept, i.e. mixing brittle capsules containing healing agent in concrete. One of the earliest studies in the field of concrete engineering was carried out by Dry (1994). In this study, an adhesive agent contained in hollow brittle glass fibers served as the repairing chemicals. A crack in a brittle cementitious

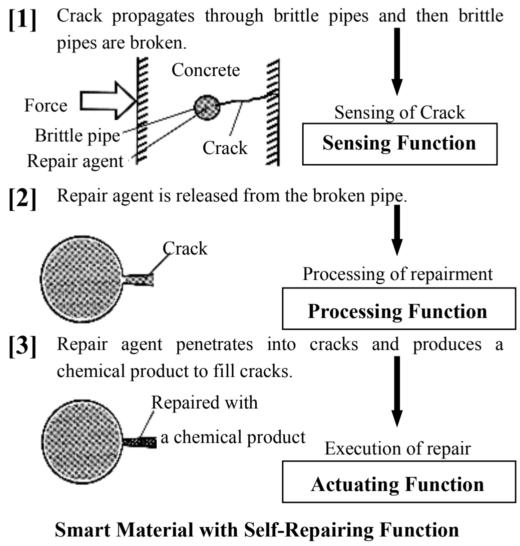


Fig. 15 Schematic description of the self-healing system (Science and Technology Agency 1989, Mihashi *et al.* 2000, Mihashi *et al.* 2002).

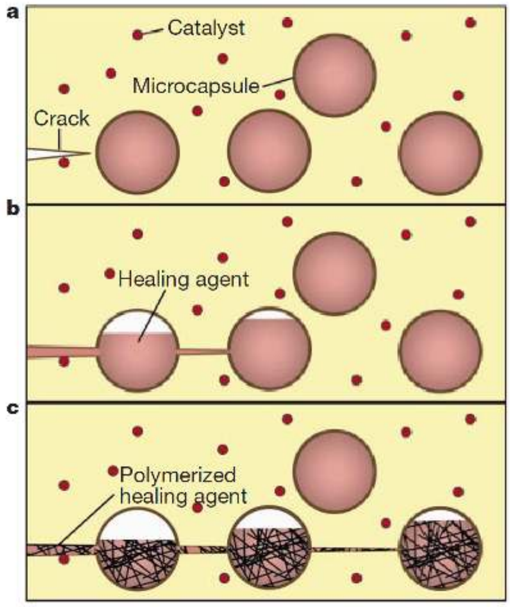


Fig. 16 The autonomic healing concept (White *et al.* 2001).

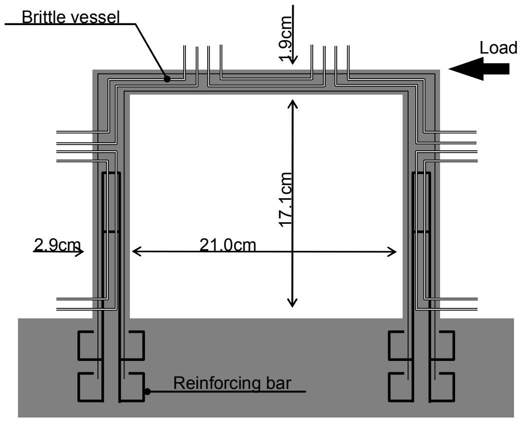


Fig. 17 Sample test frame (Dry 2001).

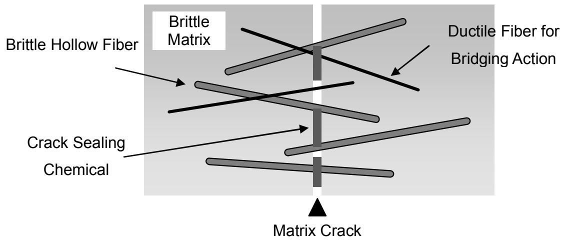


Fig. 18 PSS-ECC proposed by Li (drawn based on Li 1995).

material caused by overloading was detected by breaking the fibers. The resulting tensile cracking of the matrix and breaking of the glass fibers stimulate the actuating mechanisms to repair the crack in this totally passive smart material system. The adhesive agent can be released into and fill up the crack. Thereafter, Dry investigated some applications of this idea to concrete structures (Dry 1998 and Dry 2001). **Figure 17** shows the employed specimen, a plane, one-story, rigid portal frame cast monolithically with a concrete base. The chemically inert tubing was cast within the cross section of the member and then filled with adhesive agents. As adhesive agents with different characteristics could be applied, a series of experimental investigations was carried out to evaluate the ability of three different adhesive agents, i.e. cyanoacrylate, two-part epoxy resin, and silicon based adhesive agent. In order to evaluate the efficiency of each adhesive agent for self-repairing, changes in the stiffness and frequency of cracking were monitored during loading. Both of these parameters showed that cyanoacrylate adhesive agent was the most effective for recovering stiffness and preventing crack reopening.

Li *et al.* (1998) studied a Passive Smart Self-healing Engineered Cementitious Composite (PSS-ECC). The PSS-ECC in that study consisted of brittle glass tubes containing superglue (ethyl cyanoacrylate) embedded in ECC (**Fig. 18**). The authors emphasized that controlling the crack width within tens of micrometers is essential for PSS-ECC because wider crack widths rapidly exhaust the amount of adhesive agent available for healing the cracks. Otherwise, very thick hollow glass tubes are necessary, which in turn reduces the mechanical properties of the FRCC. Moreover, the maximum allowable crack width should be also limited by the actuation mechanism because the release of adhesive agents into the crack is dependent on the capillarity of the thin channels created by the crack surfaces against the capillary force inside the hollow glass fibers. Thus, the crack width of the matrix should be limited to less than the inner diameter of the glass fiber for effective actuation.

Nishiwaki *et al.* (2004) investigated a passive self-repairing system composed of embedded brittle glass tubes and an HPFRCC matrix. The repair agent was selected to recover not mechanical properties but water tightness, and a water permeability test was carried out on the pre- and post-cracked specimens. **Figure 19** shows the relation between the maximum crack width (wR) and the calculated coefficient of water permeability (K). The results showed that the self-healing system was effective in FRCC specimens with maximum crack widths larger than 0.2 mm, but also that it was often ineffective when the maximum crack width was below this value because of the viscosity of the repair agent.

5.3 Active self-repairing

Since cementitious materials including concrete are brittle, all passive repairing systems such as those mentioned above require brittle containers for preserving self-repairing agents, and these container need to break as soon as critical cracks occur in order to release the agents. However, handling of such fragile devices is quite difficult at construction sites. Allowing the introduction of minimum inputs such as electrification or heating could greatly increase the selection of devices that can be used.

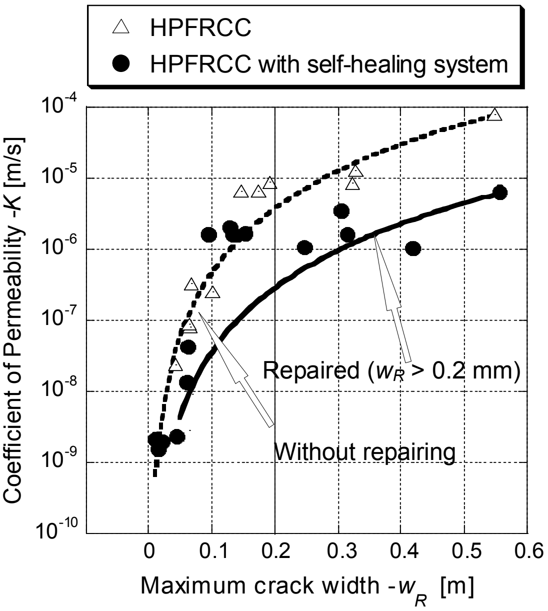


Fig. 19 Relationship K–w_R (Nishiwaki *et al*. 2004).

A crack-closure system using Shape Memory Alloy (SMA) was proposed by Sakai *et al*. (2003). They used SMA as main reinforcing bars for concrete beams in order for large cracks under loading to be mechanically closed after unloading, although total crack closure was elusive.

Jefferson *et al*. (2010) developed a similar crack-closure system for cementitious materials using shrinkable polymer tendons. The system involved the incorporation of unbonded pre-oriented polymer tendons in cementitious beams. Cracks can be closed through thermal activation of the shrinkage mechanism of the restrained polymer tendons (**Fig. 20**). However, if external human intervention is required for heating the structure to close cracks, the material does not qualify as an intelligent material as defined above. Moreover, too much energy would be required to activate the system if the whole structure needs to be heated.

Nishiwaki *et al*. (2006a) developed a new approach to achieve a self-repairing function in a totally different way from the previous technologies including passive ones. That approach could be called an “active self-repairing system.” This system automatically starts in response to electrical signals triggered by cracking in concrete. The system consists of a conductive composite for self-diagnosis of cracking and pipes made with heat-plasticity film that contains a low viscosity epoxy resin as a repairing agent. The self-diagnosis composite is a kind of crack monitoring sensor and at the same time it has the function of a heating device for a specific location through electrification. The self-diagnosis composite is fabricated using fiber-reinforced composites and conductive particles (**Fig. 21**). In the absence of any damage, the sensor can monitor the strain due to the electrical conduction path with dispersed conductive particles. When the sensor detects a localized large strain due to the formation of a crack in the concrete, its electrical resistance increases since part of the electrical conduction path is cut off around the crack. The sensor

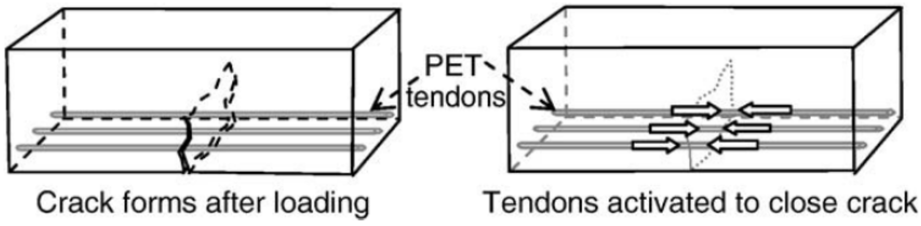


Fig. 20 Schematic illustration of concept for new composite material system (Jefferson *et al*. 2010).

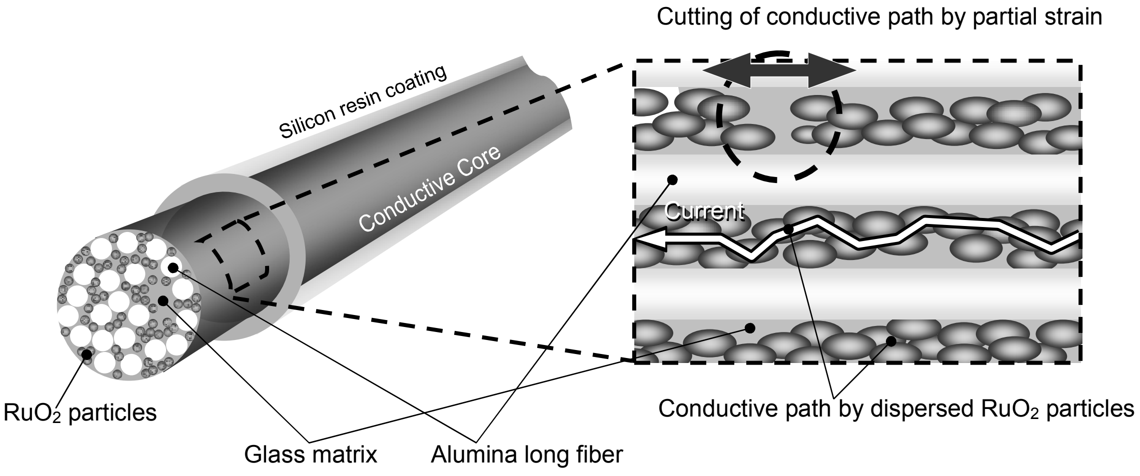


Fig. 21 Schematic diagram of self-diagnosis composite structure (Nishiwaki *et al*. 2006a).

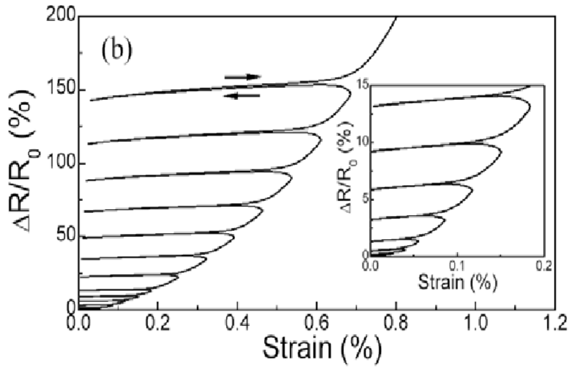


Fig.22 Strain vs. resistance change ratio relationship of strain monitoring sensor under tensile cyclic load (Mihashi *et al.* 2008).

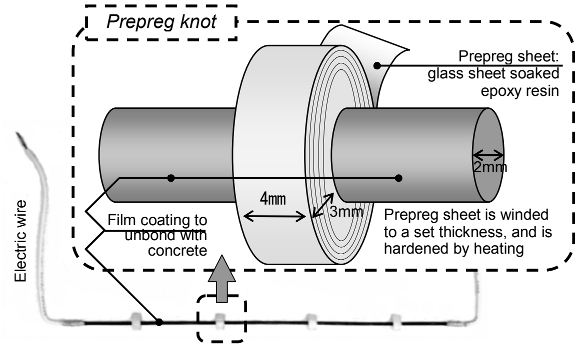


Fig. 23 Schematic diagram of prepreg knot and the self-diagnosis composite. (Nishiwaki *et al.* 2007).

can then delicately increase the resistance even in the case of a very small strain due to the dispersive structure of the conductive particles (**Fig. 22**). By means of electrification in this sensor, a partial increase in electrical resistance can achieve selective heating around the crack. In these sensors, different conductive particles such as RuO_2 and carbon black particles can be used for different monitoring targets. Moreover, different types of conductive particles yield various calorific values under the same electrification condition because of the different resistance ratios of the sensors (Nishiwaki *et al.* 2006b).

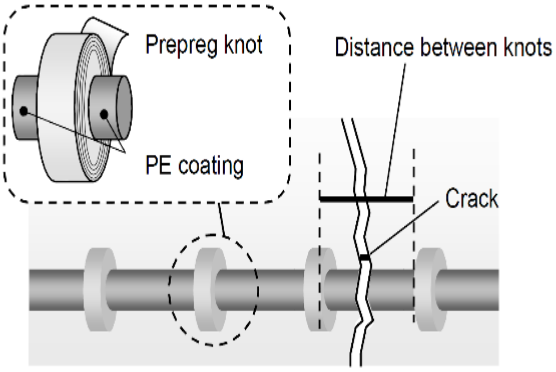


Fig. 24 Schematic diagram of crack monitoring sensor (Mihashi *et al.* 2008).

In order to investigate the quantitative relation between the strain of the diagnosis and the crack width, Nishiwaki *et al.* (2007) installed nodes on the surface of the self-diagnosis composite as shown in **Fig. 23**. Between these nodes, the self-diagnosis composite was coated with polyethylene film to eliminate the bond between the concrete and the self-diagnosis composite (**Fig. 24**). Thus the crack width was directly related to the measured strain with some accuracy.

A schematic diagram of this self-repairing system is shown in **Fig. 25** (Nishiwaki *et al.* 2010). In this system, copper plates were employed to connect the heating device and the melting pipe for smooth thermal transfer. Once selective heating at the location of the crack starts, the plastic pipe at the crack is melted to supply the epoxy resin to the crack. The heat-plasticity pipe seals off the repair agent inside the concrete in order to prevent its hardening reaction and the melting point of the film should be low enough to allow easy melting of the film by heating around the crack. For that purpose, an ethylene vinyl acetate polymer film with a melting point of 93°C was employed.

Figure 26 (Mihashi *et al.* 2008) shows a schematic description of a specimen and the test setup that was used for confirming the function of the self-diagnosis composite. The effectiveness of the heating function was proved by means of direct observation with an infrared

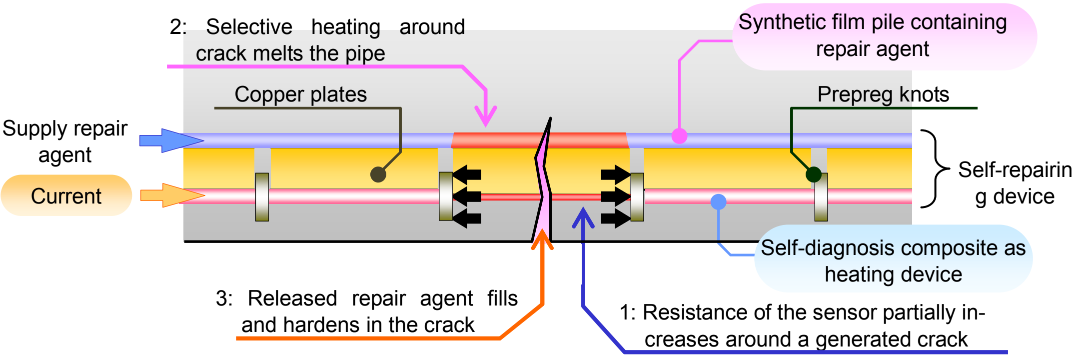
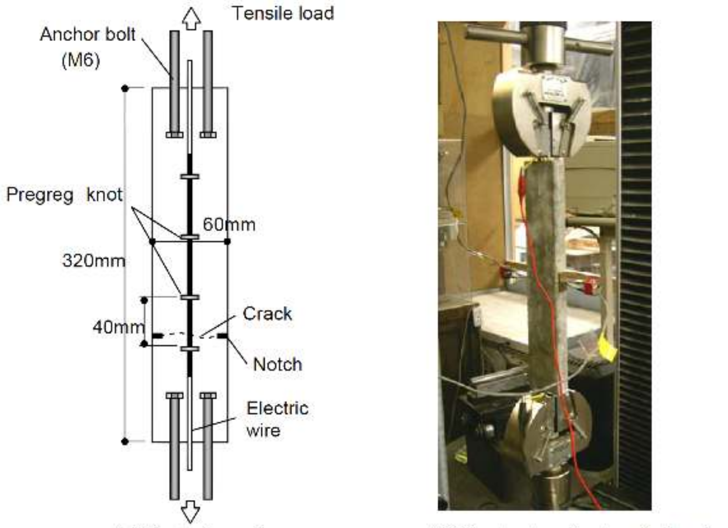
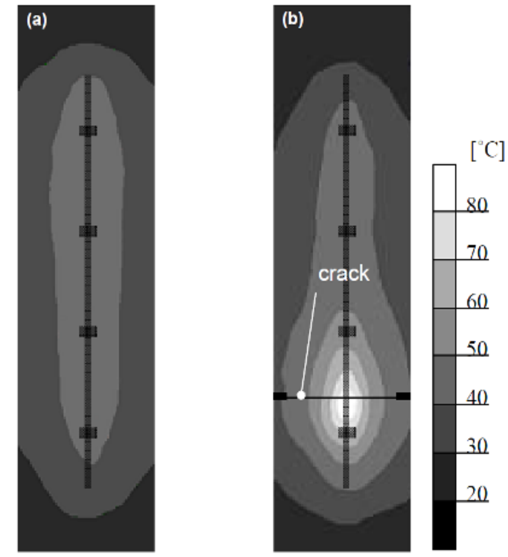


Fig. 25 Schematic illustration of activated repairing system (Nishiwaki *et al.* 2010).



(a) Tested specimen (b) Test set-up for tensile loading

Fig. 26 Schematic description of the specimen and the test setup (Mihashi *et al.* 2008).



(a) Before cracking (b) After cracking

Fig. 27 Temperature distribution measured by thermography (Mihashi *et al.* 2008).

radiation thermography technique as shown in **Fig. 27**. **Figure 28** shows an example of the experimental results of the permeability test to prove the effectiveness of the self-repairing system (Nishiwaki *et al.* 2010). **Figure 29** shows an example of load-displacement curves of specimens with and without the self-repairing system. The whole results are shown in **Fig. 30**, in which the recovery of strength and stiffness by the system is obvious (Nishiwaki *et al.* 2009).

6. Concluding remarks

This paper has reviewed previous studies on self-healing and self-repairing of concrete. The following concluding remarks can be made.

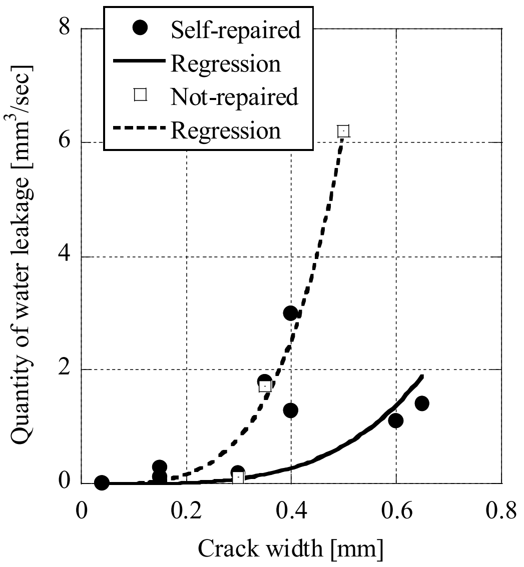
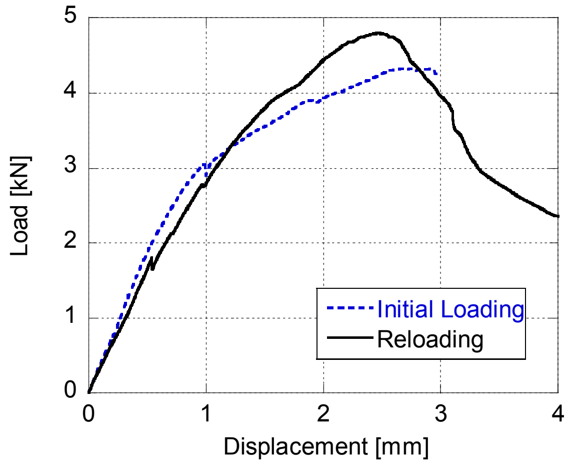


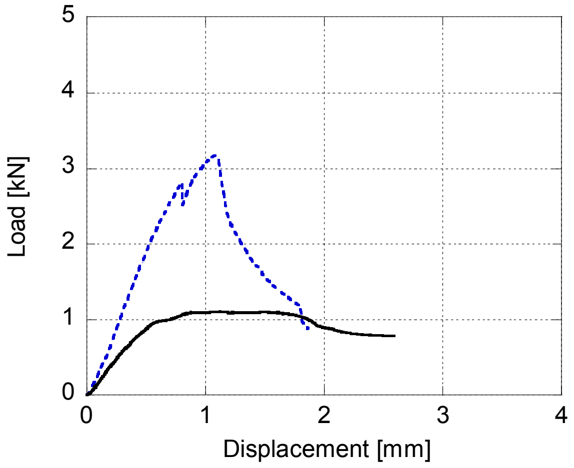
Fig. 28 Relationship between the generated maximum crack width versus the quantity of water leakage (Nishiwaki *et al.* 2010).

(1) Fiber reinforced cementitious composites (FRCC) have higher self-healing potential than ordinary plain concrete. Fibers bridging the crack can reduce the crack width and furthermore they can work as cores for the precipitation of calcium carbonate in the crack. However, the latter mechanism can function only when water or at least moisture is supplied.

(2) Precipitation of calcium carbonate due to biochemical action of bacteria has been expected to be one of the new technologies for self-healing of concrete, though there are still problems, such as the fact that the lifetime of bacteria in concrete is much shorter than the service life of buildings and infrastructures.

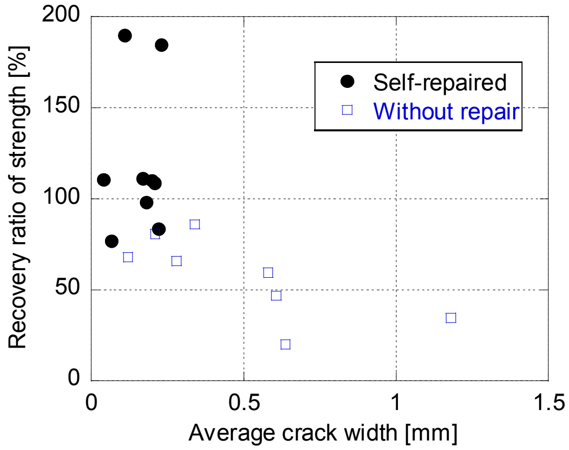


(a) Self-repaired

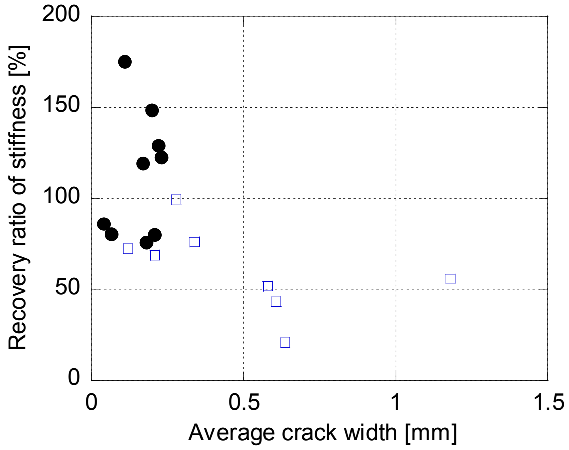


(b) Without repair

Fig. 29 Examples of load-displacement curve (Nishiwaki *et al.* 2009).



(a) Strength



(b) Stiffness

Fig. 30 Relationship between average crack width and recovery ratio of strength and stiffness (Nishiwaki *et al.* 2009).

(3) At present, the geomaterial approach using mineral admixtures seems to be more practical in the field of civil engineering than other self-healing technologies. While this approach requires the supply of water or at least moisture, most infrastructures are exposed to rain or underground water.

(4) Self-repairing concrete has the potential to be an intelligent material and it can be applied to specific concrete structures for which ordinary means of repairing cracks are not available owing to engineer safety considerations or inaccessible location.

In closing, engineered self-healing and self-repairing concrete hold promise for longer lasting concrete structures and we expect significant development of this field in the future.

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