Scientific paper

Development of Self-healing System for Concrete with Selective Heating around Crack

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Received 13 February 2006, accepted 26 April 2006

Abstract

A fundamental study was carried out to develop a kind of smart concrete that has a self-healing system that incorporates a heating device. Self-diagnosis composite is employed as the heating device used to heat up cracked parts in the concrete. This heating device and a pipe made of heat-plasticity organic film containing a repair agent are embedded in the concrete. The film is melted through suitable heating. Selective heat around a crack can melt the film to allow the repair agent to fill up the crack and harden the repair agent in the crack. Three-dimensional thermal analysis and an experimental study were carried out to confirm the proposed method.

1. Introduction

Many concrete structures including infrastructures suffer from serious deterioration all over the world. The early deterioration of concrete structures in particular has grown into a social problem (e.g. AIJ 2004). Further, prolonging the service life of structures has become an important objective as “scrap and build” of structures is no longer acceptable from the viewpoint of global ecology. Inspection and maintenance techniques for concrete structures have therefore become the focus of increasing attention. However, the implementation of continuous inspection and maintenance is difficult, especially in the case of large-scale concrete structures such as infrastructures, owing to the considerable amount of labor and funds required. While all concrete structures do not require a semi-permanent service life, unexpected deterioration of structures before the end of their planned service life is always a problem. Once deteriorations occurred, proper repair and/or reinforcement are required to prevent the degradation of concrete from accelerating. **Figure 1** shows such a conceptual relationship between the performance and age of a concrete structure. Repairing becomes more difficult as the deterioration becomes more serious because of the technical and economical challenges involved. Cracks in particular allow the invasion of deterioration factors, such as water, into concrete, leading to more serious deterioration such as the corrosion of reinforcements. In

order to make concrete structures more durable, it is important to carry out proper repairs of cracks before they become harmful. For this purpose, much research on health-monitoring and/or repairing techniques for concrete structures has been carried out.

On the other hand, even if the diagnosis results dictate repair of the structure, repair may be difficult or impossible because of existing conditions such as the location of the damage in the affected structure. Many infrastructures such as highways and tunnels are also in continuous service and in such cases service cannot be discontinued for a long time. In the case of nuclear power generation facilities, which include many parts not accessible by humans, carrying out any proper repair work may be next to impossible. Moreover, even if such repair work were possible in principle, the cost and amount of labor required for diagnosis and repair work can be prohibitive in the case of large-scale infrastructures. In such cases, automatic repair of harmful cracks without onerous labor and capital requirements could be used to make structures more reliable.

A number of studies on self-healing concrete have

Fig. 1 Age versus building performance relationship.

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been carried out. They are divided into two types, namely studies on self-healing effect as an inherent function of concrete, and studies aimed at developing self-healing as a new function.

Regarding the former, Edvarsen (1999) investigated the autogenous healing effect whereby cracks in concrete gradually close up through water supply. Such autogenous healing is caused mainly by precipitation of calcium carbonate crystals (CaCO_3) on the crack surface. The growth rate of the CaCO_3 crystals depends on the crack width and water pressure. The narrower the crack width and the higher the water pressure, the higher the autogenous healing rate. Edvarsen's paper includes practical recommendations on permissible crack widths for various water pressures for autogenous healing.

Regarding the latter type of studies, Dry (2001) and Li (1995) proposed a self-healing function with adhesive containing a brittle pipe embedded in concrete. When cracks occur on the concrete, the embedded brittle pipe breaks and adhesive in this pipe is released into the cracks. The released adhesive fills up the cracks and hardens, producing self repair. The self-healing system proposed in this paper belongs to this latter type of studies. Our system is characterized by freedom from the constraints of having to handle very fragile pipes and also reliable self repair. In addition to the aforementioned two types of studies, a number of other approaches have been put forth, including Ramakrishnan *et al.* (2001), who proposes the use of micro organisms, and Sakai *et al.* (2003), who suggests shape memory alloy as reinforcement. However, none of these approaches have reached the practical application stage.

In this paper, the authors propose a self-healing system for concrete that is composed of self-diagnosis composite and heat-plasticity organic film pipe. This system can diagnose and repair generated cracks. Self-diagnosis composite, which can detect the incidence of cracks, is functionalized as a heating device in such a way that this self-diagnosis composite can increase the electric resistance around cracks and heat the damaged parts selectively through electrifying. Then a heat-plasticity organic film pipe containing repair agent embedded in the concrete next to the heating device is melted only in the heated zone only. This self-healing system can be regarded as a proactive countermeasure, rather than a reactive countermeasure, against cracking in concrete structures. By means of this system, it may be possible to design concrete structures that provide a durable service life in a more reliable manner. This paper describes the proposed self-healing system and confirms the effectiveness of this system through three-dimensional thermal analysis and a fundamental experimental study on small-scale specimens.

2. Self-healing system

In this paper, self-healing system is defined as "a system whereby, when a crack occurs in the concrete, the in-

herent function of the concrete material can repair the crack without human intervention using the repair system including remote control (delivery system of repair agent and/or heating devices, etc.) embedded in the concrete beforehand." The concept of the proposed self-healing system based on this definition is schematically shown in Fig. 2. Both the heating device and the organic film pipe containing the repair agent are embedded in the concrete. A self-diagnosis composite made with ceramics fiber and a conductive matrix constitutes the heating device. The organic film pipe is made with a thermoplastic film, and the repair agent is supplied into this pipe. When a crack is generated, the self-diagnosis composite reduces the conductive path and increases its electric resistance around the crack, thus selectively heating the damaged part. This selective heating around the crack in turn melts the surface of the embedded heat-plasticity film pipe. Repair agent released from the melted surface of the pipe fills the crack and hardens in the crack. In this way, it is expected that the self-healing system will work against the generated crack.

Moreover, the generated crack information, which is measured as an electric resistance change of the self-diagnosis composite, indicates where repairs should be made. Consequently, the self-healing system will work more effectively by supplying repair agent to a limited area of the embedded pipe where crack generation is diagnosed.

In the following sections, the adopted materials and the required performance are described. The following three elements are required for the proposed self-healing system: A self-diagnosis composite that acts as the heating device, repair agent, and a heat-plasticity organic film pipe.

2.1 Self-diagnosis composite

A self-diagnosis composite is a kind of sensing materials that works not only as a strain gauge but also as a functional material, measuring damaged areas, recording damage-history, and so on. Generally, a

Fig. 2 Self-healing system.

self-diagnosis composite is made with fiber reinforced composites and electro-conductive materials. The self-diagnosis composite used in this research uses a conductive paste made with RuO_2 particles and $\text{PbO-SiO}_2\text{-B}_2\text{O}_3\text{-Al}_2\text{O}_3$ glass matrix co-mixed in an organic solvent. Al_2O_3 fibers 300 mm in length are dipped into these conductive pastes. Cylindrical green bodies containing 10vol% Al_2O_3 fibers embedded in a RuO_2 /glass matrix are thus formed. After drying at 130°C for 2 hours, the conductive green bodies are sintered at 850°C for 30 minutes in the atmosphere (Jang *et al.* 2004). **Figure 3** shows a schematic diagram of this self-diagnosis composite structure. The self-diagnosis composite free of any damage has an electric conductive path with distributed RuO_2 particles. Once the self-diagnosis composite is subjected to partial strain by a crack generated in the concrete, its electric resistance increases since a part of the electric conductive paths is cut off around the crack. The self-diagnosis composite can sensitively increase the resistance with very small strain due to the dispersive structure of conductive particles. By means of electrifying on this self-diagnosis composite, the partial increase in electric resistance can achieve selective heating around the crack.

On the other hand, concrete will deteriorate if overheated. Water in concrete is vaporized and diffused at temperatures over 100°C , and dehydration and collapse of the microstructure occur at temperatures over 180°C (Schneider 1982). Therefore, the maximum temperature of the heating device embedded in concrete should be controlled by the quantity of injection current and by the material properties of the self-diagnosis composite such as electric resistance and thermal conductivity.

2.2 Heat-plasticity organic film pipe containing repair agent

The repair agent is contained in a pipe covered with heat-plasticity organic film. The organic film pipe should seal off the repair agent in concrete to prevent hardening in the pipe even without cracking. On the other hand, the pipe must melt easily as the result of heating around a crack once such a crack occurs, and release the repair agent into the crack. Therefore, the melting point of the organic film should be lower than the harmful high temperature for concrete. Moreover, the melting point should be higher than the range of temperature caused by normal conditions such as hydration heat and direct sunlight. In this paper, ethylene vinyl acetate (EVA) polymer film having a 93°C melting point and $40\text{ }\mu\text{m}$ thickness is employed. The pipe is made with this cover film and a core consisting of a spirally twisted wire. A diameter of this wire is 0.7 mm , and the outer and inner diameters of the formed EVA film pipe are 3.4 mm and 2.0 mm , respectively. When the temperature around the pipe rises higher than 93°C due to heating by the self-diagnosis composite around the crack, the EVA film on the surface of the pipe melts. Repair agent is then released into the crack from the

Fig. 3 Schematic diagram of self-diagnosis composite structure.

pipe. Moreover, the bonding strength between the EVA film and concrete is very low. Therefore the film-covered pipe can keep the repair agent inside without releasing it, even when a crack is generated in concrete, unless the self-diagnosis composite is electrified for heating. Thus this EVA film pipe can keep the repair agent inside until the crack expands to a certain width and the self-diagnosis composite heats up the concrete around the crack to the melting point of this pipe.

2.3 Repair agent

The repair agent for the proposed self-healing system should have a number of properties such as stability of reaction in the sealed containing pipe, low viscosity for penetration into narrow cracks and smooth hardening reaction under high temperature generated by the heating device. A kind of low viscous epoxy resin that can react without hardener is employed as the repair agent in order to satisfy these requirements. The viscosity of this epoxy resin is $156 \times 10^{-6}\text{ Pa}\cdot\text{s}$ at 23°C . This is much lower than the viscosity of normal epoxy resin, which is approximately 20 to $130\text{ Pa}\cdot\text{s}$ at 25°C . This epoxy resin penetrates mainly in the gravitative direction into cracks whose width is approximately 0.2 mm without pressure from the outside. Moreover, the repair agent also can penetrate against gravity through capillary action. Normally, this repair agent gently hardens with moisture in the air, but the hardening reaction is accelerated by heating. In a 60°C atmosphere, the repair agent hardens within 100 min.

3. Thermal analysis

The self-healing system proposed in this paper is implemented with a suitable arrangement of heating devices and thermal-plastic pipes containing repair agent in concrete. In this section, three-dimensional thermal analysis is carried out to simulate the temperature distribution in concrete with embedded heating devices, before examination by experiment. This analysis shows the required calorific value for the heating devices and

Fig. 4 Thermal analysis model.

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Table 1 Material properties.

Elements	Thermal Conductivity [W/mK]	Specific Heat [J/kgK]	Mass Density [kg/m³]
Mortar	1.8	921	2200
Heating device (Self-diagnosis composite)	1.2	750	2020
Repair agent (Epoxy resin)	0.19	1670	1600
Reinforcement	803	440	7800
Electric wire	398	380	8960

Table 2 Analysis conditions.

Heat Conditions	Normal Calorific Value	Cracked Calorific Value	Heat Transfer Coefficient (Top Surface)	Heat Transfer Coefficient (Bottom Surface)	Heat Transfer Coefficient (Side Surface)
1: Before loading (no crack) 69.6Ω, 33.6V	0.025 W/mm³	0.025 W/mm³	14.0 × 10⁻⁶ W/mm²K	8.90 × 10⁻⁶ W/mm²K	12.1 × 10⁻⁶ W/mm²K
2: After loading (crack generated) 76.7Ω(110%), 43.7V	0.035 W/mm³	0.323 W/mm³			

the proper arrangement of each element for this system.

3.1 Conditions for analysis

Three-dimensional thermal analysis was carried out with a commercial program using the non-linear finite element method (MSC. Marc). **Figure 4** shows the employed analysis model and the arrangement of the various functional elements in the model. **Table 1** lists the material properties of each element. The analysis model is 250 mm long, 80 mm wide and 10 mm thick. **Figure 5** shows the specimen geometry and the loading method for wedge splitting employed in the experiment. The self-diagnosis composite and the organic film pipe are

embedded in this specimen. The thin plate model is meant for practical application where the layer including the self-healing system is mounted on the surface of the concrete structure. The close arrangement of the heating device and the pipe in this model was determined based on recent research (2006) by the authors that showed that closer arrangement as one unit is more suitable than an alternating arrangement.

Figure 4 shows that the self-diagnosis composite is modeled as a prism that has a square section of 2 mm × 2 mm and has a heating length of 200 mm. The whole electric resistance of the self-diagnosis composite free of any damage is set to 69.6 ohms, and its calorific

value is set to 0.025 W/mm^3 as determined from the current value of 33.6 V.

Moreover, thermal analysis with a crack generated in the center of each specimen was carried out. Each crack caused a partial increase in electric resistance of the self-diagnosis composite around the crack. Modeling of this partial increase is represented with a 0.323 W/mm^3 calorific value of the composite elements in the crack part. This value is calculated so that the cracking increases the resistance up to 10% (the whole electric resistance amounts to 76.7 ohms). The initial condition of all the elements was set as a 20°C room temperature. Changes in temperature distribution were analyzed at 1 minute intervals for 30 min from the start of electrifying. Table 2 lists the analysis conditions adopted for the two

analysis cases of pre- and post- cracking.

3.2 Results and discussion

Figure 7(a) shows the temperature distribution at the surface of the specimen without any cracking, and Fig. 7(b) shows the temperature distribution at the vertical section of the center of the specimen, as obtained through thermal analysis after 20 min from the start of electrifying. Figure 7(c) is an experimental result corresponding to Fig. 7(a). Figure 7(d) is the temperature distribution at the A-A' cross section analyzed at the equilibrium state. These figures show that the highest temperature in the embedded organic film pipe rises up to 60°C to 80°C at the equilibrium state. This means that pipe will not melt and that it will keep the contained

Fig. 7 Temperature distribution before crack generation.

Fig. 8 Temperature distribution after crack generation. (20 min)

repair agent inside.

Figures 8(a) and 8(b) show the result of the thermal analysis on a specimen with cracking that leads to a partial increase in electric resistance. **Figure 8(a)** represents the temperature distribution at the surface of the specimen, and **Fig. 8(b)** shows the temperature distribution at the vertical section of the center of the specimen. **Figure 8(c)** is an experimental result corresponding to **Fig. 8(a)** that will be discussed later. **Figure 8(d)** shows the relationship between heating time and temperature at a reference point in the organic film pipe indicated by a white dot in **Fig. 8(b)**. **Figure 8(d)** shows that the temperature at the embedded pipe reaches 93°C, which is the melting point, after 11 min from the start of electrifying. These analysis results show that a partial increase in the electric resistance of the self-diagnosis composite can heat the concrete around the generated crack selectively, and that this selective heating can selectively melt the organic film pipe containing repair agent around the crack.

Figure 9(a) shows the analyzed temperature distribution at the surface of the specimen at 30 min from the start of electrifying. **Figure 9(b)** shows the analyzed temperature distribution at the B-B' cross section at the same time. **Figure 9(d)** is the relationship between heating time and temperature at the edge of the specimen shown as a white dot in **Fig. 9(a)**. These analysis results show that the entire cracked section is heated up a temperature higher than 62°C after 30 min heating by the electrified self-diagnosis composite. This heated condition causes the released repair agent to harden in the generated crack. Thus, the proposed self-healing system is expected to perform effectively. In the following section, experimental results using the same

conditions as this analysis are shown to prove the validity of the analysis and the effectiveness of the proposed self-healing system.

4. Testing of self-healing system

Experimental studies were carried out to prove the effectiveness of the proposed self-healing system. We prepared specimens in which a self-diagnosis composite as the heating device and a heat-plasticity organic film pipe containing repair agent were embedded. Loading was carried out to generate a crack in each specimen. Then the damaged self-diagnosis composite was electrified to repair the crack automatically.

Test 1 demonstrated the effectiveness of the proposed self-healing system, including a partial increase in the electrical resistance of the self-diagnosis composite around the crack, selective melting of the organic film pipe, and release and filling of the repair agent into the crack. Test 2, a water leakage test, demonstrated recovery of watertightness of a cracked mortar plate using the proposed self-healing system.

4.1 Test 1

Mortar (W/C=0.45, S/C=2.0) was employed for making specimens. Early-strength portland cement (density = 3,140 kg/m³) was used for cement, and river sand (density = 2,470 kg/m³) was used for fine aggregate. Both the self-diagnosis composite and the organic film pipe were embedded in each of the specimens. **Figure 5** shows the geometry of the employed specimen, which is the same as the analysis model, i.e. a plate 250 mm long, 80 mm wide, and 10 mm thick. Notches 5 mm deep at both edges at the center of the specimen were sawn us-

Fig. 9 Temperature distribution after crack generation. (30 min)

ing a concrete cutter to limit the generated crack part. A loading test was carried out as shown in **Fig. 6** using a universal testing machine. The speed of the cross head of the loading machine was adjusted to 0.1 mm/min. The loading caused the resistance of the self-diagnosis composite to rise significantly. After confirming the increased electric resistance, the specimen was unloaded until the loading value reached zero using the same loading speed.

Before this loading test, the electrifying test was carried out for each specimen. The resistance of the embedded self-diagnosis composite was 69.6 ohms. Then the temperature distribution at the surface of the specimen was observed using thermography. A 33.6 V potential obtained from a 100 V power supply voltage through a transformer was applied for 20 minutes. **Figure 7(c)** shows the temperature distribution through thermography after 20 minutes from the start of electrifying. The self-diagnosis composites show some unavoidable dispersion of electric resistance because of the manufacturing procedure. As shown in **Fig. 7(c)**, there is a dispersion of temperature distribution along the embedded self-diagnosis composite, but the figure shows that the observed temperature distribution is generally acceptable for the required performance. Based on the results of the experiment and the analysis, it is concluded that heating by the self-diagnosis composite under a given condition without cracks will not melt the embedded organic film pipe.

The loading test generated a 2.5 mm crack in each specimen. This crack increased the electric resistance of the embedded self-diagnosis composite up to 76.7 ohms which is 10% higher than the initial resistance. During the loading test, repair agent was supplied to fill in the organic film pipe from an external reservoir through a pressure gradient. No leakage of the repair agent from the generated crack was observed before the self-diagnosis composite was heated.

An electrifying test was carried out on the self-diagnosis composite, which maintained a resistance 10% higher than of the resistance under the initial condition. The applied voltage was 43.7 V, the same level used for the analysis. **Figure 8(c)** shows the temperature distribution observed by thermography after 20 min from the start of the electrification test. In this photograph, the high temperature part is clearly concentrated around the generated crack where the resistance partially increases. As compared with **Fig. 8(a)**, which is the result of analysis under the same condition, the temperature distribution obtained by the experiment (shown in **Fig. 8(c)**) is similar to the analytical result. Therefore, it is concluded that the analysis model, which includes the selective increase of the resistance of the self-diagnosis composite around the crack, is appropriate. Moreover, even without repair agent pipes, the thermography observation of selective heating by the embedded self-diagnosis composite showed that it may be applicable as a monitoring tool that can detect cracks

in concrete.

Twenty-one minutes from the start of electrifying, it was confirmed that the repair agent seeped from the embedded pipe and filled the crack. This means that the organic film pipe was melted by the selective heating of the self-diagnosis composite and released the contained repair agent into the crack. The temperature distribution obtained by the analysis (see **Fig. 8(b)**) shows that the area of 93°C, which is the melting point of the organic film, reached the position of the embedded organic film pipe. Therefore, both the experiment results and the thermal analysis results indicate that the proposed self-healing system does work effectively. According to **Fig. 8(d)**, however, the temperature of the embedded pipe reached the melting point of 93°C 11 min from the start of electrifying and there was a time lag of 10 minutes between the analytical prediction and the experimental observation.

To harden the repair agent released into the crack, further electrifying test was carried out, for up to 30 minutes from the start of electrifying. Hardening of the released repair agent in the crack was confirmed through visual observation (**Fig. 10**).

4.2 Test 2

In Test 2, recovery of watertightness was experimentally studied to prove the effectiveness of the proposed system. Two types of specimens having the same geometry as those employed in Test 1 were prepared: The first type of specimen consisted of specimens repaired with the self-healing system (3 specimens), and the second type consisted of specimens without the system (2 specimens). To prove the effectiveness of the self-healing system, a permeability test was carried out for each specimen. A testing method for water permeability through coating materials for the textured finishing of building (JIS A 6909) was adapted and employed. The testing method is outlined in **Fig. 11**. The interface gap between the pipette funnel and the testing plate was sealed with a silicone gel material. The test was carried out until penetration of a water volume of 5 cc through the surface.

Figure 12 shows the relationship between the generated crack width and the quantity of water leakage through the crack. Generally, the amount of water leaked quantity through a crack is proportional to the

Fig. 10 Visual observation of repair agent leakage from the generated crack.

Fig. 11 Water leakage test setup.

fourth power of the crack width (Tsukamono *et al.* 1991). However, this graph shows that cracks in the specimen repaired with the self-healing system let in a much smaller amount of water than cracks in specimens without repair. That is to say, the self-healing system automatically repaired the generated crack and restored the watertightness of the concrete specimen.

5. Conclusive remarks

This paper proposes a self-healing system with self-diagnosis composite as a heating device and heat-plasticity organic film pipe containing repair agent. The proposed self-healing system, involving selective heating around the generated crack, melting the embedded pipe, and filling and hardening the repair agent in the generated crack, was studied through three-dimensional thermal analysis and was proved by experiments using small specimens. The results of thermal analysis were confirmed by comparison with the experimental results.

In the case of the non-cracked specimens, the organic film pipe was not melted by the uniform heating from the embedded self-diagnosis composite. On the other hand, in the case of the specimens with a generated crack, a partial increase in the electric resistance of the self-diagnosis composite around the crack was confirmed. The rise in calorific value caused by this change in resistance gives the self-healing system its effectiveness. Namely, selective melting of the embedded organic film pipe, releasing of repair agent into the crack, and hardening of the agent in the crack are effectively carried out.

Further studies need to be done for practical applications, addressing a number of issues including the following: for the self-diagnosis composite, the relationship between the generated crack width and the increasing ratio of electric resistance or calorific value; for the repair agent, improvement of the shelf-life and the

Fig. 12 Relationship between generated maximum crack width versus quantity of water leakage.

proper viscosity for repair agent to penetrate into and stay in narrow cracks; for the organic film pipe, development on an automatic repair agent supplying system and a pipe network system for simultaneous and repeatable crack healing actions. As our next step, we will study the improvement of the self-diagnosis composite and the development of the pipe network system.

Acknowledgments

This research was carried out as a part of the Research Project on Development of Self-Diagnosis and Self-Repair Materials for Maintaining Safety and Serviceability of Infrastructures supported by the New Energy and Industrial Technology Development Organization (NEDO) in collaboration with Osaki Research Institute Inc. (Managing director: Mr. Minoru Sugita). The authors would like to express their thanks to Dr. Hideaki Matsubara of the Japan Ceramics Center for valuable input.

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