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Intelligent Concrete with Self-healing Capability

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ABSTRACT: In this paper, a fundamental study is carried out to develop a kind of intelligent concrete with self-healing capability. Conceptual methodology with three functions of sensing, processing and executing is proposed. In the method, crack-repairing agent is installed as core materials within shell bodies embedded in concrete structures. The feasibility of the proposed methodology is clarified by making use of glass pipes as shell bodies containing crack repairing agent. The application of the proposed approach is demonstrated through the experimental examination for the case of both self-healing capabilities for strength and prevention of water leakage.

Key words: Intelligent concrete, Self-healing capability, Repair agent and High durability

1. INTRODUCTION

In recent years, the development of intelligent materials consisting of self-control function or self-healing function has been getting much attention in several research areas. This attempt is achieved by installing the intelligent functions with the notion of information in materials. In the system, materials themselves detect state function by sensory function, judge the information by processor function and execute active actions by actuator function. Based on this concept of intelligent materials, several research works on highly functional concrete have been conducted such as CFGFRP (Carbon Fiber Glass Fiber Reinforced Plastics) reinforced concrete[1), 2)] and self-repairing concrete that contains hollow porous fibers with a chemical[3)].

In this highly functional concrete, one function is specialized to actualize the intelligence. In other words, it is quite difficult to realize all intelligent functions within one concrete structure. In this paper, the feasibility on installation of self-healing capability in concrete is studied based on this background.

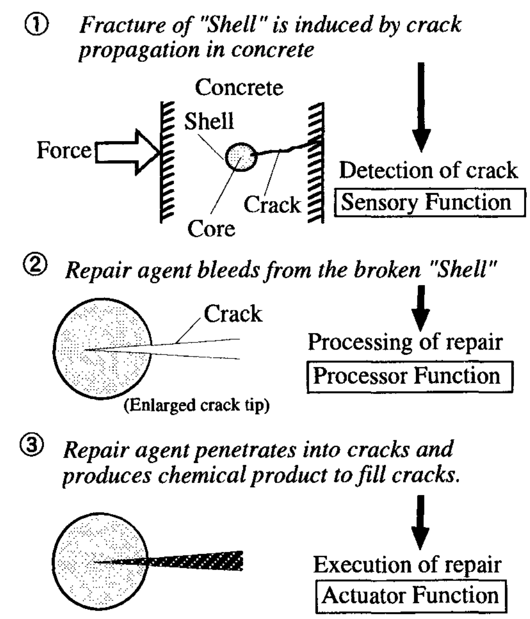

Fig. 1: Concept of Self-Healing System

2. SELF-HEALING SYSTEM

The conceptual methodology for intelligent concrete is shown in Fig. 1. This figure shows the self-healing system, in which the fracture of "Shell" is induced by the damage of concrete and "Core" of repair agent covered by "Shell" bleeds into the damaged zone in concrete from the fractured "Shell" and repairs it.

In the present study, glass pipes containing repair agent are used to realize intelligent concrete. Specifically, at the crack initiation and propagation in concrete, a glass pipe as "Shell" embedded in concrete is broken, which could be defined as the detection of fracture initiation by sensory function. Then, the repair agent as "Core" in the glass pipe bleeds from fractured area, which could be defined as the determination of the necessity to repair by processor function. Finally, the repair agent penetrates into cracks and produces a chemical product to fill cracks, which could be defined as the execution of repair by actuator function. By means of this mechanism, the active self-healing capability could be realized. The advantage in the employment of glass pipes could be specified such that glass pipes respond sensitively to cracks and relatively a large amount of repair agent can be preserved without response.

In the following sections, we demonstrate the application of the proposed methodology for the case of both self-healing capability for strength and the prevention of water leakage through the experimental examination.

3. SELF-HEALING FOR STRENGTH

3.1 Specimens and Testing Procedure

Three points bending test is carried out with a single-notched specimen shown in Fig. 2. In the specimens of c05-g series, a glass pipe is embedded. Here, in the use of epoxy resin of two liquors blend as repair agent, two glass pipes are embedded shown in Fig. 2c. In addition, two additional specimens are tested to compare with the intelligent concrete (c05-g series): specimens without glass pipe (a.g. series) which is not repaired at all and specimens without glass pipe (c-05 series) which is repaired by injecting the repair agent into cracks by hand. Here, three specimens for each test series are prepared.

Employed materials are high-early-strength Portland cement (specific gravity ρ=3.13), silica fume (ρ=2.20), high range water reducing agent admixture composed from Naphthalene sulfonic acid system (ρ=1.20, no air entraining), river sand at Abukuma river in Miyagi prefecture (ρ=2.54, dried surface) and polypropylene fiber (ρ=0.91, diameter of 0.018 mm, length of 12 mm) to reinforce brittle fracture. Regarding mix proportion, water/binder of 40 % by weight, silica fume / binder of 10 % by weight, aggregate volume / matrix volume of 1.0 and fiber volume fraction of 0.5 % are adopted. In addition, glass pipes with the external diameter of 2 mm and the internal diameter of 0.8 mm, and three types of repair agent are used. Repair agent B is stereochromy with alkali-silica as major element (27%-diluted solution), repair agent B' is stereochromy with alkali-silica as major element (mother liquor) and repair agent C is epoxy resin (two-liquor blend, low viscosity type). Two types of curing duration after repair (7 days and 28 days) are adopted between the first test and the second one which will be discussed later. Here, mix proportion of mortar is fixed, and self-healing capability level regarding the type of the repair agent and duration after repair are examined.

Mixing is conducted with an omni-mixer. After dry mixing of the powder for one minute, water and water reducing agent are inputted and mixed for three minutes. Then, the paste is mixed with fibers for one minute and mixed with aggregates for 2 minutes. Mixed-up mortar is directly cast in the form in which glass pipes are allocated. The cast specimens are cured for 24 hours in the curing room with room temperature of 20 degrees of Celsius and 100 % of relative humidity. After that, forms are removed and specimens are cured up to 7 days of initial material age in the curing room under the wet air condition. After complete curing, the notch is inserted by a concrete cutter before the first test discussed next.

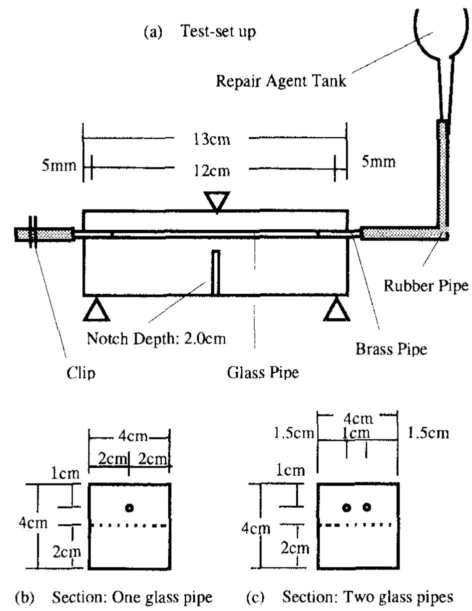

Fig. 2: Test Set-up and Specimen

By means of a universal testing machine, the loading is controlled by the displacement rate of 0.05 mm/min to observe the fractured state. Specifically, the specimen is unloaded at the crack width of a certain quantity after the maximum load and the first test is completed without extreme fracture. This unloading point is basically associated with the observation of penetration of repair agent. These cracked specimens are cured for 7 days or 28 days to penetrate the sufficient amount of repair agent. Here, specimens without glass pipes are also cured in the same manner. Then, the similar bending test (the second test) is again conducted to examine the recovered strength.

3.2 Test Results and Discussion

Fig. 3 shows schematically the relation between load and Crack Mouth Opening Displacement (CMOD). Here, P_r / P_1 is defined as "Strength Recovery Ratio" in the present study. In addition, the residual CMOD "δr" shown in the figure is considered as the parameter of damaged state.

Fig. 4 shows the comparison of strength recovery ratio between specimens with repair agent B' and ones without repair agent. The average value for each test is connected with each other by straight lines to clarify the comparison. Here, the number at the abbreviation of test series indicates the curing duration by week between the first test and the second one, such that c05-B'-4 implies 4 week curing after the first test.

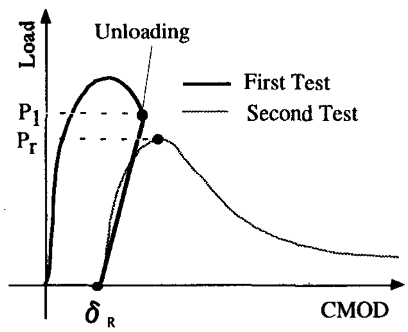

Fig. 3: Load vs. CMOD Relation

The obtained average recovery ratios are 1.15 and 1.56 for test series c05-g-B'-1 and c05-g-B'-4, respectively. These quantities are approximately identical to those in c05-B' test series that are repaired by injecting the agent into cracks by hand. Especially, c05-g-B'-4 series shows much higher recovery ratio than c05-B' series. This could be interpreted that the repair agent injected by hand did not penetrate sufficiently into cracks because of relatively high viscosity but the agent released from glass pipes instead penetrated into cracks soundly. Similar results are obtained in the case of repair agent B.

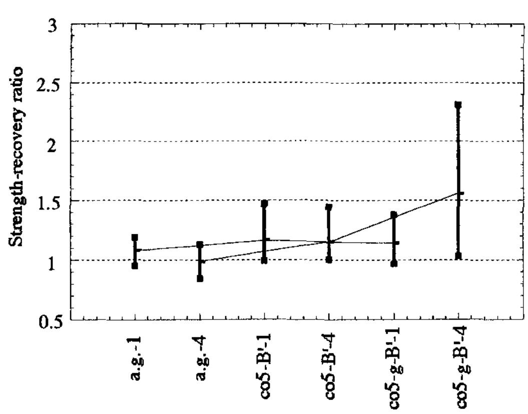

Fig. 4: Comparison of Strength Recovery

Fig. 5 shows the relation between the residual CMOD and the strength recovery ratio. It is clearly observed that the repaired specimens in the zone indicated by "*1" show the extremely high strength recovery ratio for the repair agent of both B and B'. Thus, the restraint of crack propagation could be effective for repair. On the other hands, the repaired specimens with larger residual CMOD than this zone give the relatively constant strength recovery. Namely, the strength recovery is not influenced by the crack propagation beyond a certain damage level. Furthermore, the specimens with the repair agent C do not show sufficient strength recovery. This is because the repair agent C can be activated by blending principal agent and hardening one, and two liquors released from each glass pipe are not mixed well. Therefore, the effective mixing mechanism for two liquors or one preservative liquor is necessary to obtain sufficient strength recovery.

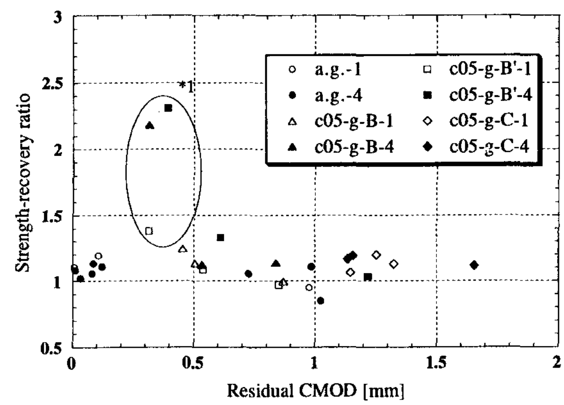

Fig. 5: Residual CMOD vs. Strength Recovery Ratio

4. SELF-HEALING FOR WATER LEAKAGE

4.1 Specimens and Testing Procedures

A splitting test is carried out with a double-notched specimen shown in Fig. 6. In the specimens of c05-g series, a glass pipe is embedded. In addition, two additional specimens are tested: specimens without glass pipes (c05 series) which are not repaired at all and specimens without glass pipes (c05-B series) which are repaired by anointing the repair agent on the surface by hand. In this test, repair agent B is used. The employed materials and mix proportion are identical to those in Section 3.1 except the embedded deformed steel reinforcement shown in Fig. 6.

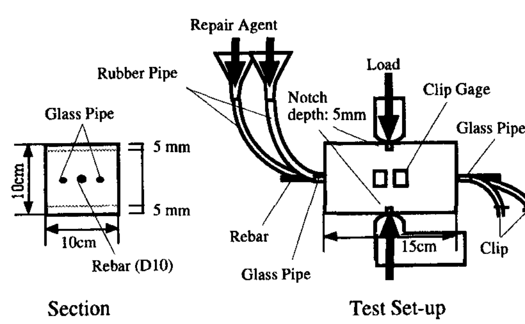

Fig. 6: Test Set-up and Specimen

Mixing procedures are also identical to those in Section 3.1. Forms are removed 24 hours later after cast and specimens are kept under steam curing with the condition such that the temperature increasing rate is 10 degrees of Celsius per hour and the specimens are kept under 80 degrees of Celsius for 5 hours and subsequently cooled naturally. After this treatment, the specimens are cured in the constant temperature room with the condition of room temperature of 20 degrees of Celsius and 50 % of relative humidity up to 3 days of material age. After every curing, the splitting test and repair treatment are conducted.

In the splitting test, the specimens are unloaded when CMOD measured by clip gages reaches a certain quantity of about 0.2 mm. Subsequently, the specimens are cured in the constant temperature room for 3 days with supplying the repair agent. During that, the specimens are kept as shown in Fig. 7a to prevent asymmetrical penetration of repair agent. After this curing, a funnel is placed on the surface orthogonal to the surface with notches shown in Fig. 7b and the consumed time to permeate a certain amount of water is measured.

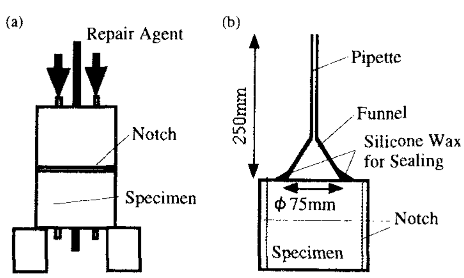

Fig. 7: (a) Repair condition and (b) Test Set-up

4.2 Test Results and Discussion

Fig. 8 shows the relation between the permeation time and the quantity of permeated water.

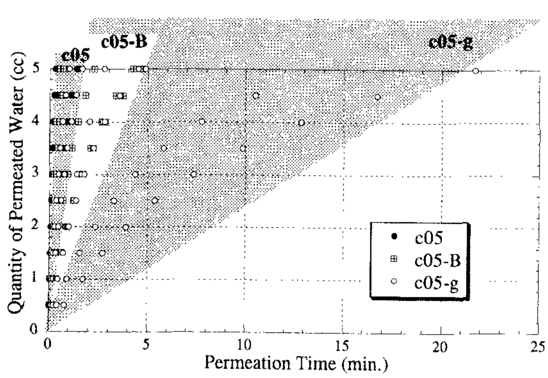

Fig. 8: Permeated Water vs. Permeation Time

In the figure, distributed plots for each test series are hatched to clarify the qualitative characteristics. It could be observed that the ratio of incremental quantity of permeated water to incremental permeation time is gradually reduced due to the capillary force in the poromeric medium, and asymptotically converges to a certain constant which is associated with a steady-state current. In addition, the hatched zone of c05-g test series extremely dominates the right-hand side in the graph, which indicates the smaller amount of permeated water for the identical time. It is thus clarified that the embedment of glass pipes is more effective than the repair by hands.

5. CONCLUSION

In this paper, conceptual methodology consisting of three functions of sensing, processing and executing is proposed to develop self-healing capability in concrete. The applicability of the proposed methodology is clarified experimentally by making use of glass pipes as shell bodies containing crack repairing agent for the self-healing capability for strength and prevention of water leakage. The following conclusions could be drawn.

(1) Glass pipes as both sensory function and processor function and the supplying system of repair agent as actuator function work effectively to achieve the self-healing capability for both strength and prevention of water leakage.
(2) The restraint of crack propagation is effective and important issue to achieve the self-healing capability.
(3) Recovery level of material performance by the self-healing system is higher than that repaired by hand if the repair agent works sufficiently.

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