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Development of Crack Self-healing Concrete by Cost Beneficial Semi-capsulation Technique

Toshiharu Kishi

Institute of Industrial Science, The University of Tokyo, Japan
Komaba 4-6-1, Meguro-ku, Tokyo 153-8505, kishi@iis.u-tokyo.ac.jp

ABSTRACT

Institute of Industrial Science (IIS), the University of Tokyo has been conducting a series of development of crack self-healing technologies for concrete since 1997 and a crack self-healing concrete containing expansive agent, geo-materials and chemical agents was developed as its third generation technology in 2008. Then, granulation technology accompanied by cost beneficial semi-capsulation effect for powder materials is being developed as the fourth technology from 2009. In this paper a fundamental study on whether improvements in performance of self-healing agent whose main component is geo-materials can be achieved by mixing it into granules instead of that in powder form, for the purpose of preventing leakage of water through cracks was conducted. It was found that even simple granulation of self-healing ingredients improved the slump retention capability and the water leakage prevention effect through cracks though further technical developments for satisfactory capsulation effect and cost performance are desired.

Keywords: *Concrete, Crack, Self-healing, Granule, capsulation*

INTRODUCTION

In this study, in order to apply materials with self-healing capability to the field application, the essential fresh properties of ready-mixed concrete with self-healing capability are examined and the recovery of water tightness to the leakage through penetrating cracks are examined in the laboratory. Cementitious composite materials with self-healing capability were prepared in order to develop autogenous healing concrete based on the basic design concept as reported in the previous paper (Ahn, 2010). Concretes including several self-healing ones and plain one for control were produced at a ready-mixed concrete plant for the other field test and the only experimental investigations conducted in the laboratory is reported in this paper. This study focused on the following issues, such as improvement of workability on self-healing concrete by granules and performance evaluation of crack self-healing concrete incorporating various granules.

EXPERIMENTAL PROGRAMS

Materials

The self-healing agents were prepared based on self-healing performance as reported in the previous research (Ahn, 2010). A crack with a width of 0.2 mm was induced in hardened self-healing cementitious paste with 45% W/C at the curing age of 120 days, and from the 3 days after water immersion, re-hydration products formed in the crack and crack healing was confirmed. This self-healing agent includes expansive agent, geo-materials and chemical agent and they are commercial products produced in Japan. These ingredients were selected to fabricate granules in this research.

Preparation of granules based on self-healing agents

Fig. 1 shows the concept of crack self-healing in hardened concrete incorporating granules. When a crack occurs in hardened concrete, granules break up, crystals precipitate through the reaction, dissolution, diffusion, etc., of components contributed to the self-healing agent through water supply in the cracked parts, and the crack closes. The two challenges of slump loss compensation and long-term preservation of the self-healing capability of ready mixed concrete are thought to be solvable through the use of such granules. An additional issue is that self-healing agent is traditionally incorporated in concrete through partial substitution of cement, so that mixing in large quantities of self-healing agent in powder form in ready mixed concrete causes reduced compressive strength besides slump loss. By contrast, in the case of granules, the self-healing agent is done through fine aggregate substitution, which is thought to improve compressive strength also.

The diameter of most of the granules manufactured with the mortar mixer was on the order of 300 μm or approximately 5 mm, greatly differing from the particle size distribution of fine aggregate used for concrete. This is thought to be due to the shape of the blades of the mortar mixer and other factors not being well suited for granulation. It was thus decided to use a granulator of the type used to produce pharmaceutical and food products (capacity: 25 l,

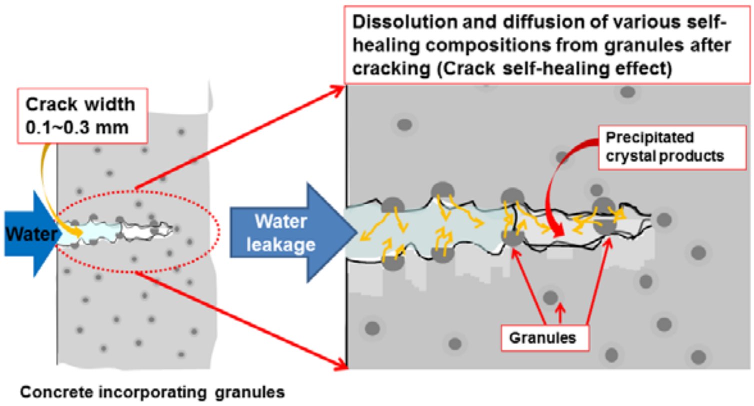

Figure 1. Concept of self-healing concrete for the water tightness

processing amount: 12 kg/batch, processing time: 10 minutes/batch) to produce granules as shown in Fig. 2.

Figure 2. Outline of the granulator

Table 1. Mix-proportions of granules (Unit: %)

Sample	Self-healing agent			Binder		*PVA fiber (kg/m^3)
	Expansive agent	Geo-materials (A, B type)	Chemical additives	Low-heat portland cement	Water + Ethanol	
EG	O	O	O	42	18	0.08
	42					
NEG	-	O	O	49	18	0.08
	33					

*PVA fiber: ϕ27μm x length 6mm, density: 1.3g/m^3

Table 1 shows the mix-compositions of the granules. without expansive agent (EG and NEG) were fabricatec has self-healing capability, was used as the cement for t NEG mix, the reduction in expansive agent in the self-h heat portland cement. For the liquid binder, a mixture co ethanol, based on the above-mentioned previous results PVA short fibers (27 μm diameter × 6 mm length, 1 reported to contribute to self-healing of cracks in tl Composites), were added in the proportion of 0.08 kg/m^3

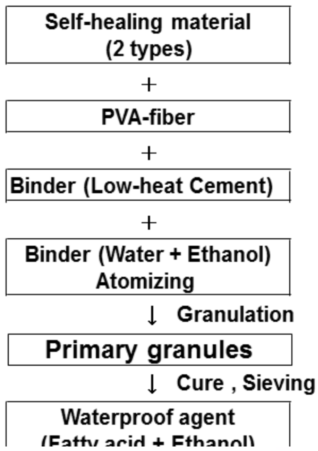

Fig. 3 shows the manufacturing process of granules. Following curing under sealed condition for 7 days, the manufactured granules were impregnated with a fatty underv ethano fatty a

Fig. 4 self-he analys

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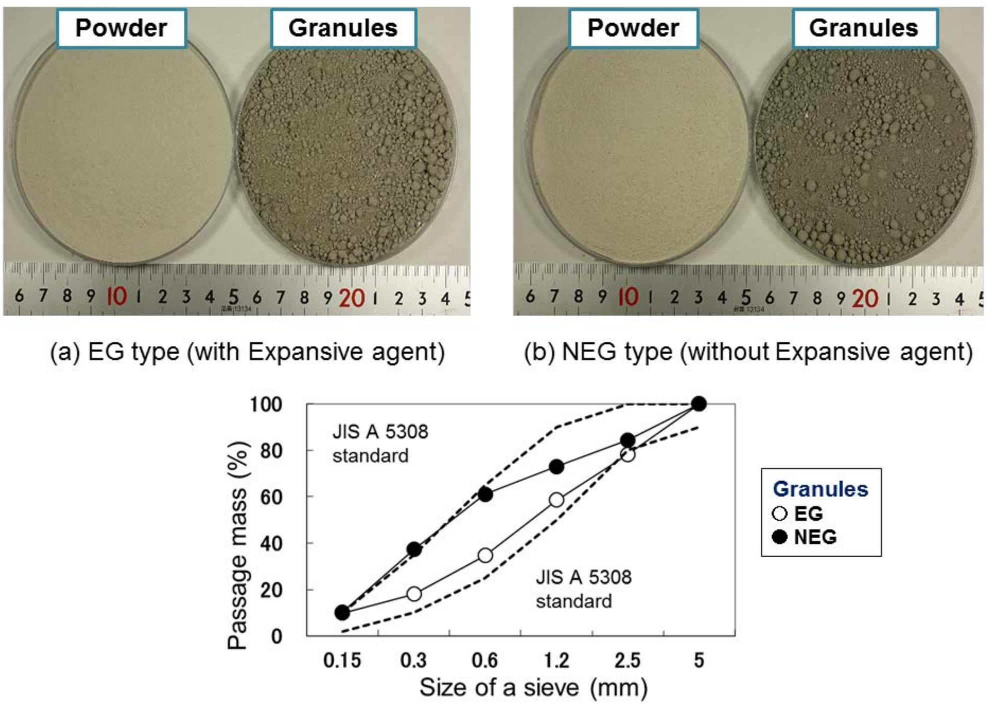

(a) EG type (with Expansive agent) (b) NEG type (without Expansive agent)

(c) Sieve analysis of granules

Figure 4. Fabrication of granules: (a) EG type (with expansive agent), (b) NEG type (without expansive agent), (c) Sieve analysis of granules

By measuring the slump and air content of concrete before and after discharge, the slump improvement effect obtained through the use/non-use of granules was investigated. Concrete 10Φ x 20 cm cylinders were prepared after conducting the concrete slump test for the compressive strength test and the water tightness test of cracked concrete in the laboratory. The compressive strength was measured by JIS 1108 after 7, 28, and 270 days.

Verification methods for the recovery of water tightness on self-healing concrete

In case of the water tightness test, the specimens were split longitudinally using a compression tester. The fractured surfaces of the split specimens were cleared of fine particles through the use of high pressure air to suppress the occurrence of clogging favorable to self- healing (in order to make severe condition). Then, using two steel hose clamps to restrain each specimen, the crack width was adjusted between 0.2 mm and 0.3 mm under digital microscope observation. Crack width measurement was done at a total of six points, three at the top end face and three at the bottom end face of the specimen. A vinyl

Table 3. The effect of granules on the workability of self-healing concrete

Sample	Slump (cm)		Air content (%)		Temperature (℃)	
	Initial (5 min)	Final (30 min)	Initial (5 min)	Final (30 min)	Initial (5 min)	Final (30 min)
Plain	14.0	12.0	5.0	3.5	14	15
P-SHC	16.5	14.5	10.2	5.2	14	15
EG-SHC	23.5	SF40	3.8	3.4	14	15
NEG-SHC	19.0	19.0	2.0	3.4	14	15

SF: Slump Flow

chloride pipe measuring 100 mm in diameter and 100 mm in height was attached to the top end of the specimen to provide a water head of approximately 80 mm, and the space between

Table 2. Mix-proportions of concrete

<table>
<tr><th rowspan="2">Sample</th><th rowspan="2">W/C (%)</th><th rowspan="2">S/A (%)</th><th rowspan="2">Air (%)</th><th colspan="6">Unit (kg/m^3)</th></tr>
<tr><th>Water</th><th>Cement</th><th>Self-healing agent</th><th>Fine Aggregate</th><th>Coarse Aggregate</th><th>SP</th></tr>
<tr><td>Plain</td><td rowspan="4">57.9</td><td rowspan="4">45.2</td><td rowspan="4">4.5</td><td rowspan="4">168</td><td rowspan="4">290</td><td>-</td><td>826</td><td rowspan="4">1019</td><td>2.3</td></tr>
<tr><td>P-SHC</td><td rowspan="3">40</td><td rowspan="3">786</td><td>8.7</td></tr>
<tr><td>EG-SHC</td><td>8.7</td></tr>
<tr><td>NEG-SHC</td><td>8.7</td></tr>
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(P: powder type self-healing agent of EG, EG & NEG: granules type self-healing agent)

the specimen and vinyl chloride tube as well as the cracked areas along the side of the specimen were closed up with silicone resin. The laboratory water permeability test was done by pouring tap water into the vinyl chloride tube in a 20°C environment and comparing the degree of self-healing of the cracks yielded by the granules of self-healing material by recording water leakage over time.

(a) Water permeability test (b) Measurement of water leakage

Figure 5. Test setups: (a) Water permeability test, (b) Measurement of water

The water tightness test in the laboratory was conducted by maintaining a constant pressure, continuous flow state in the vinyl chloride pipe as shown in Fig. 5 (a), and measuring for five minutes the amount of water leaking from the bottom end face of the cracked specimens on days 0, 1, 3, 7, 14, 21, and 28, counting from the time the vinyl chloride pipe was filled with water. As shown in Fig. 5 (b), measurement was done by attaching a funnel to the bottom end face of the specimens and attaching this assembly over a graduated cylinder to allow measurement of the amount of water leaked from the cracked bottom end face only. The water pressure applied to the specimens when the vinyl chloride pipe was filled with water was calculated to be around 0.8 kPa. The relationship between changes in the water leakage amount and changes in pH was determined through measurement of the pH of the leaked water with pH test paper. The water leakage prevention effect of the granules and powder of self-healing agent was also investigated on a comparative basis before and after the permeability test by checking for the presence of precipitates in the cracks and cross-sections of the specimen with a digital microscope.

RESULTS AND DISCUSSION

Effect of granules on the workability and compressive strength of self-healing concrete

Table 3 shows the effect of granules on the workability of self-healing concrete. Compared to P-SHC, which does not incorporate granules of self-healing agent, EG granules and NEG granules present improved slump values. In case of EG granules, material segregation was occurred partially, because of an excessive dosage of superplasticizer (SP). From these results, the addition of self-healing agent in the form of granules to concrete is considered to compensate slump loss. With regard to air content, while the incorporation of self-healing agent in powder form tends to cause excessive air content at the initial stage, the incorporation of granules keeps air content at a level comparable to that in plain concrete.

Fig. 6 shows the results of the compressive strength of the various concretes. No differences in compressive strength caused by the use or non-use of granules were observed at 7 days curing. Neither was a decline in compressive strength observed at 28 days and 270 days curing; on the contrary, a slight increase in strength compared to the plain concrete was seen. Based on these results, it was found that the substitution of self-healing agent for fine aggregate in the amount of 40 kg/m^3 does not have an adverse effect on compressive strength.

In the case of EG granules, compressive strength was lower than that of plain concrete, which is thought to be due to an excessive slump value (material segregation). However, at

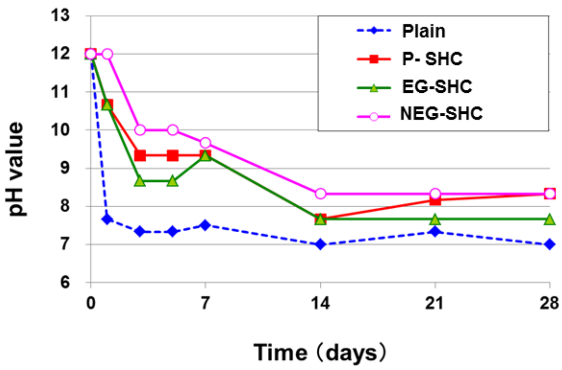

Figure 8. Effect of granules on the pH of water after permeability test

270 days curing, the compressive strength was somewhat higher than that of plain concrete, suggesting that the strength decrease is only in the initial stage.

Effect of granules on the recovery of water-tightness in cracked concrete

Fig. 7 shows the time-dependent changes in water leakage amount observed in the laboratory test and these date are the averages of three specimens for each mix proportion.

One can see in Fig. 7 that although the crack width of the specimens was adjusted between 0.2 mm and 0.3 mm, there is disparity among the initial leakage values. This is thought to be due to the differences not only in the topography of the crack surfaces (fracture surfaces resulting from splitting) but also in the chemical characteristics among the specimens.

Compared to plain concrete, SHC incorporating self-healing agent showed a tendency to have lower initial leakage values, whether or not granules of self-healing agent were included, and whether or not the granules contained expansive agent. This is considered to be due to the water cutoff effect obtained from the initial phase through the expansion and the swelling effects of the geo-materials included in the self-healing agent. Examination of the subsequent time-dependent changes in leakage reveals a large drop in leakage in the first day of permeation through the effect of water absorption, etc., even in the plain concrete, and the continuation of this effect until the fifth day, but no major change was seen after that and the leakage value never became nil. On the other hand, for SHC too, the leakage value greatly dropped in the first day of permeation, whether or not the concrete included granules, and the leakage value went on declining on the 14th and 21st day of permeation. The leakage value was finally observed to become almost nil on the 28th day after water permeability test.

Fig. 8 shows the time-dependent changes of the pH value of the leaked water immediately after leakage measurement and these data are the averages of three specimens for each mix proportion. In Fig. 8 plain concrete shows that the pH value of the leaked water dropped sharply from approximately 12 immediately after permeation to approximately 8 on the first day, and went on to decline to approximately 7. On the other hand, in the case of SHC, the changes in pH were less pronounced whether or not granules of self-healing agent and expansive agent were included. The pH value of the leaked water was approximately 11 on the first day of permeation, went on to decline to 8 on the 14th day, and remained level after that.

From these results, it is thought that in the case of SHC, the movement of water inside the cracks was suppressed by the expansion of the swelling materials, leaving the other self-healing components, cement hydrates, etc., in place rather than flushing them out and thus

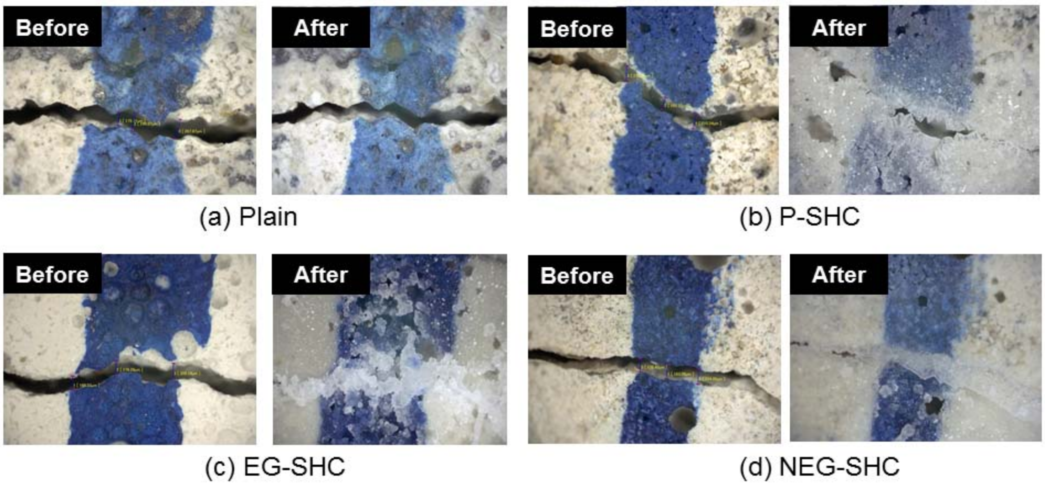

Figure 9. Self-healing behavior of concrete incorporating various self-healing agent

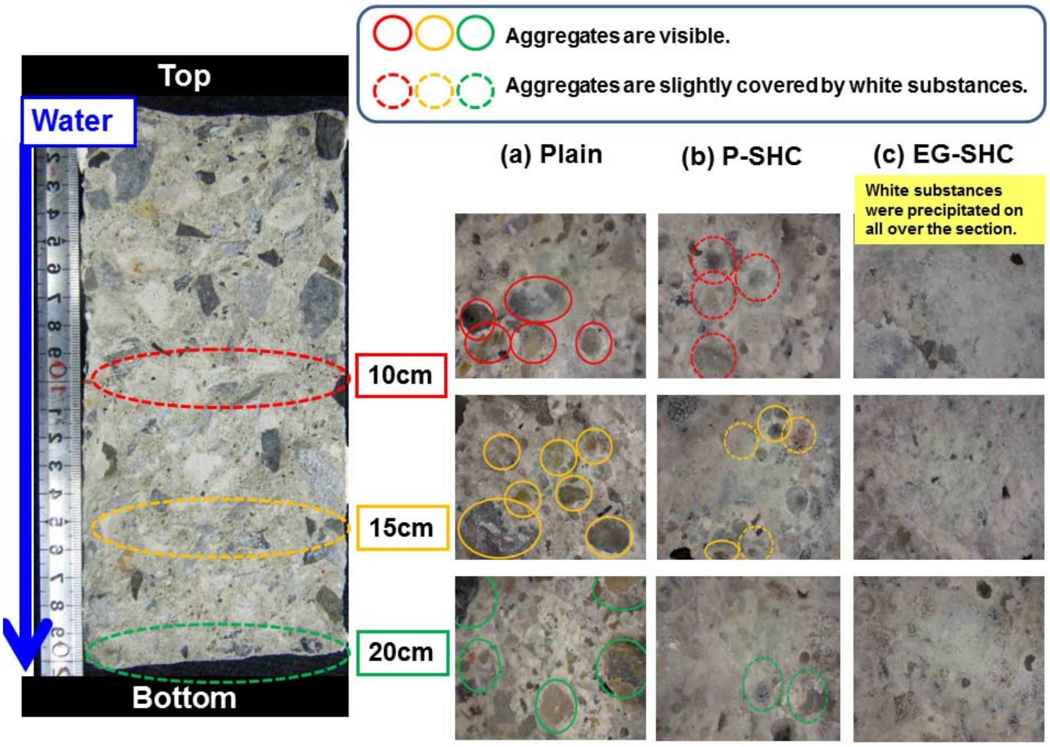

Figure 10. Cross section of specimen after water permeability test

allowing them to heal the cracks, thus demonstrating a high water cutoff effect.

Moreover, based on the fact that similar changes were observed for SHC up to the 14th and 21st day after water permeability test as shown in Fig. 7 and Fig. 8, it is considered possible to evaluate the retention of self-healing components and the water cutoff performance through measurement of the pH of the leaked water. In order to confer to SHC the full water cutoff effect, it is important to suppress leakage from the initial leakage phase through the use of swelling materials, etc. This allows the long-term retention of the self-healing components in order to obtain a strong water leakage prevention effect.

Fig. 9 shows the changes in the cracks before and after water permeability test of specimens.

In the case of plain concrete any product was not observed as shown in Fig. 9 (a). On the other hand, in the case of P-SHC, EG-SHC and NEG-SHC the precipitation of self-healing products were clearly observed in cracks as shown in Fig. 9 (b), (c) and (d), respectively.

Fig.10 shows a cross-section of samples after water permeability test. Surfaces of the cross section 10 cm, 15 cm, and 20 cm from the water inflow site (from top and bottom) were investigated by the digital microscopy.

From these results, it was found that in the case of P-SHC, which has high water leakage prevention capacity, ample crystals precipitated so as to cover the surface of the fine aggregate exposed at the split surfaces. The amount of crystal precipitation tended to be particularly pronounced for SHC-granules, compared to SHC-powder. This suggests that the use of self-healing agent in the form of granules makes it possible to reduce the amount of self-healing agent for obtaining the requisite water leakage prevention performance, compared with the use of self-healing agent in powder form.

Based on the laboratory test results, specimens for 8 months demonstrated ample water leakage prevention effect whether or not they included granules of self-healing agent and expansive agent. Therefore, at the approximately 8 months curing, the long-term retention effect of the self-healing component in the form of granules could not be confirmed.

However, the fact that the concrete specimens that incorporated the self-healing agent whose principal component was geo-materials used in this study processed in the form of granules rather than powder exhibited a larger amount of crystalline precipitate on their cross-sections even though the amount of self-healing agent was lesser, indicates that the performance of SHC can be improved by processing self-healing agent into granules.

DIRECTION OF DEVEOPMENT FOR COST BENEFICIAL TECHNOLOGY

It was found in the beginning of fourth generation development in the University of Tokyo that even simple granulation of self-healing ingredients improved the slump retention capability and the water leakage prevention effect through cracks. Its effect, however, was not satisfactory enough to apply the real construction in both functional and cost aspects. Thus, further technical development for much advanced semi-capsulation effect with cost beneficial performance is strongly desired.

The reason why a simple granulation is not sufficient seems to be water absorption by granule which would bring the strength development of granule due to hydration of self-healing binders and then result in the lost of self-healing capability since they have trade-off relationship. Granules getting strong due to water absorption would be hardly broken when crack occur. Similar scenario maybe happens in the case where coarse crashed cement clinker is used as self-healing agent since it is very strong. Capsule can play roll as it is by breaking when crack occurs. Thus, granules have to be breakable at cracking but not be ruptured during mixing and casting. One of key technology maybe water proofing treatment for granules, but it is relatively expensive if chemical water-proofing agent is applied.

For further development to seek much cost beneficial technology it is ideal that semi-capsulation effect is directly given during mixing process of concrete without dosage of pre-manufactured granules even though its effect is limited. It is regarded as the fifth generation technology in the development of self-healing concrete in the University of Tokyo.

CONCLUSIONS

In this study, the new method of self-healing design to improve water tightness in cracked concrete was suggested, and the self-healing properties of cracked concrete using various self-healing agent (powder and granules) were investigated. The following conclusions can be drawn from the experimental study.

(1) Binder such as low-heat cement, water, and ethanol was added to powder of self-healing agent consisting principally of geo-materials that have high reactivity with water to achieve granulation, yielding granules with a size distribution comparable to that of fine aggregate used for concrete.
(2) The 40 kg/m^3 admixture of self-healing agent in granule form as a fine aggregate replacement was found to improve the workability of ready mixed concrete without lowering compressive strength, compared with using self-healing agent in powder form.
(3) Investigation of performance of the self-healing agent in terms of preventing water leakage from cracks through laboratory tests found that the use of granules of self-healing agent as a fine aggregate replacement improved the slump of ready mixed concrete and produced a high water leakage prevention effect through self-healing of cracks even at the 8 months curing.

Drastic improvement in self-healing technology would be achieved by developing advanced granulation technique accompanied by semi-capsulation effect for ingredients instead of that in powder form, for the purpose of preventing leakage of water through cracks as the fourth generation technology among a series of them conducted in the University of Tokyo so far from year 2000. It can be emphasized that the key of the fourth generation technology is brought by not chemical effect but physical one and the fifth generation technology should be much cost beneficial technology which can provide arbitrary self-healing performances according to the request of client based on the tailor-made concept.

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