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Repair of Fire-Damaged Concrete: Improvement of Mechanical Property

Zhuguo Li[1], and Qingtao Li[2]

[1]*Department of Information and Design Engineering, Graduate School of Sciences and Engineering, Yamaguchi University, 2-16-1 Tokiwadai, Ube, Yamaguchi, 755-8611, Japan < li@yamaguchi-u.ac.jp>*
[2]*Department of Information and Design Engineering, Graduate School of Sciences and Engineering, Yamaguchi University, 2-16-1 Tokiwadai, Ube, Yamaguchi, 755-8611, Japan <k504we@yamaguchi-u.ac.jp>*

ABSTRACT

It is well known that the mechanical properties of concrete deteriorate after exposure to a fire. In this study, we first investigated the effects of heating temperature, cooling method, and re-curing time after heated on the strength recovery of fire-damaged concrete. Then, a method for improving the degree of strength recovery was discussed, using a kind of performance-modifying agent (CS). The experimental results indicate that the compressive strength of concrete decreased with raising the heating temperature for any cooling methods, and was smaller in case of cooling with water than in the air. Whether cooled by water or in the air, the application of the CS to the surface of fire-damaged concrete would raise the recovery degree of compressive strength. The compressive strength of concrete after exposure to less than 750^{o}C increased with elapsed time.

INTRODUCTION

The properties of concrete deteriorate when it is subjected to high temperature as in a fire due to the changes in the chemical composition and physical properties of cement paste and aggregate. The mechanical properties of concrete exposed to elevated temperatures have been widely studied. Most of the investigations have been focused on the effects of heating temperature, exposure time, cooling methods and loading conditions [Husem 2006; Sancak et al. 2008; Balogun 1986; Arioz 2007; Ichise et al. 2001; Yang et al. 2009; Chan et al 2000]. In spite of having a different opinion about the properties of concrete exposed to less than 300^{o}C, the compressive strength definitely decreases when the heating temperature is above 300^{o}C. The strengths decrease beyond 100 ^{o}C from a peak at 100^{o}C [Emre et al. 2008], and a rapid reduction of about 40% occurs at about 500^{o}C-600 ^{o}C [Ichise et al. 2001]. At 600^{o}C, the concrete's strength would be reduced 50% [Balogun 1986]. At 800^{o}C, a reduction is from 74% to 97% of normal concrete [Sancak et al. 2008]. The relative strengths of concrete after exposed to 1000^{o}C and

1200^{o}C were only 13% and 6% [Arioz 2007]. Hsuanchih Y et al. [Yang et al. 2009] investigated the effect of exposure time at the peak temperatures on the compressive strengths, and stated that the reduction in the compressive strength mainly is associated with the peak temperature, and the increase of exposure time lowers a little the residual strength. Metin Husem [Husem 2006] and Chan [Chan et al 2000] examined the influence of cooling methods on the compressive strength, and concluded that the decrease of compressive strength is greater when cooled in water, compared to in the air.

Some researches have studied the effect of the strength grade of concrete, cement and aggregate on the strength of concrete exposed to high temperature [Husem 2006; Sancak et al. 2008; Balogun 1986; Ichise et al. 2001; Savva 2005; Allen 1967]. The variation of compressive strengths of ordinary and high-performance concrete at high temperature was also investigated to show that the decrease in strength of ordinary concrete is more than that of high-performance concrete [Husem 2006]. Ichise [Ichise et al. 2001] discussed the mechanical properties of 6 kinds of high-strength concretes under high temperatures, and pointed that the compressive strength of concrete with 25-50% of water binder declined from 200 ^{o}C, and dropped to 30-40% of its normal strength at 600 ^{o}C.

The influence of elevate temperatures was investigated on mechanical properties of concrete prepared with blended cement (three types of pozzolans, one natural pozzolan, and two lignite fly ashes), and limestone and siliceous aggregates [Savva 2005]. The experimental results indicated that, up to 300 ^{o}C the concretes using pozzolanic materials showed a greater strength than the normal portland cement concretes, while they seemed to be more sensitive above 300 ^{o}C. The type of binder and aggregate does not affect the strength significantly below 300 ^{o}C. In temperature range of 300 ^{o}C and 750 ^{o}C, the greater the percentage of the replacement of normal portland cement, the greater the reduction in strength. When the concretes were exposed to the temperatures above 300 ^{o}C, the decrease in strength ranged from 66% to 47% for limestone concretes and from 68% to 51% for siliceous mixtures.

In the references [Chan et al. 1999, 2000; Lion et al. 2005; Rostasy et al. 1980], an attempt was made on the clarification of the pore structure of fire-damaged concrete, which helps to understand the mechanism of concrete deterioration. The changes in the amount and volume of the pores after high temperature exposure, proved by means of mercury porosimetry, would increase the concrete permeability, and thus worsen the permeability-related durability.

Some other studies have been performed to discuss the influence of post-fire-curing on the strength recovery of the concrete exposed to high temperature [Poon et al. 2001; Ichise et al. 2003; Matsudo et al. 2006; Chen et al. 2009]. Poon et al. [Poon et al. 2001] investigated the regain of fire-damaged concrete by exposed 20 kinds of normal and high-strength concrete mixes to elevated temperature till 800 ^{o}C. They found that all of the specimens gained a substantial compressive strength recovery after recurring in water or in air with 75% RH. The compressive strength recovery, which depends on the type of concrete, re-curing method and exposure temperature, is faster and more enhanced with water-recuring as compared to the air-recuring, and is greater after exposed to 600 ^{o}C than to 800 ^{o}C. Ichise et al. [Ichise et al. 2003] investigated the strength recovery of heated high-strength concrete. They observed that the compressive strength of high-strength concrete subjected to high temperature up to 500 ^{o}C recovered up to 80% of its normal strength if re-cured with water. Matsudo [Matsudo et al. 2006] studied the strength recovery of the ultra-high strength concrete of above $100N/mm^2$, and found that the recovery of compressive strength after two years is negligible, compared to normal concrete with greater water-binder ratio.

The fire-damaged concrete has to be strengthened and repaired in order to lessen the cost of rebuilding the concrete structure. The usual repairing methods of structural concrete include resin injection, and polymer wraps, etc. Mihashi developed the new method that crack repairing agents are installed as core materials in shell bodies embedded in concrete [Mihashi and Yoshio 2000]. Nishiwaki developed the concrete that has the self-healing function, attributed to embedded heating device and repair agent that is protected by heat-plasticity film and is hardened by heat [Nishiwaki et al. 2005].

In spite that the strength of fire-damaged concrete can regain naturally, the recovery extent of is little. There is a need to improve the strength recovery. The studies on self-repairing concrete were mostly about the adhesives, such as resin and repair agent, applied to crack repairing. It cannot be generalized to apply to fire-damaged concrete because the fire-damage not only includes cracks. We do not yet find an investigation in the technical literature on a feasible technology used for improving the strength of fire-damaged concrete.
Thus, in this study, we investigate the extent and influencing factors of the compressive strength recovery of concrete exposed to high temperature. The concrete specimens are exposed to high temperatures of 200^oC, 300^oC, 450^oC, 600^oC and 750^oC for 150min, and then cooled with different methods (in the air or by water). The compressive strength tests were carried out after the concrete specimens exposed to the high temperatures are cured in the air at room temperature for 0 day, 28 days, 60 days, and 90 days. We also examine the improvement in the strength recovery when applying the CS to the fire-damaged concrete for developing a new repairing technology.

EXPERIMENTAL INVESTIGATION

Materials used and preparation of specimens

The cement used in this study was ordinary portland cement, of which the specific gravity was 3.16 g/cm^3. Crushed stone with a maximum size of 20 mm was used, of which the density at saturated surface dry condition, and water absorption ratio were 2.73 g/cm^3, and 0.40%, respectively. Fine aggregate was sea sand with density of 2.59 g/cm^3 at saturated surface dry condition, water absorption ratio of 1.60%, and fineness modulus of 2.57. Water reducing admixture air-entraining agent was also used at a dosage of 1.1% by mass of cement. Also, polypropylene fiber with a length of 12 mm at 0.1% (in volume fraction) per cubic meter of concrete was mixed to prevent concrete from spalling during heating.

Mix proportions of concrete used were 1 (cement): 0.50 (water): 2.01 (sand): 2.48 (coarse aggregate) by mass. Unit mass of cement was 370 kg/m^3. The concrete cylindrical specimens with diameter of 100 mm and length of 200 mm were produced.

The specimens were demolded 24 hours after cast, and cured in water at 20 ^oC for 28 days, and then moved to a room to cure at ambient temperature naturally for 12 months. The compressive strengths of the concretes at 28 days and 12 months were 40Mpa, and 51MPa, respectively.

Heating and cooling regimes

After 12 months curing, the concrete specimens were heated up to different high temperatures in an electric furnace, in which the temperature was controlled to follow the ISO834 standard fire temperature curve. The heating temperatures were monitored by a thermocouple set up in the electric furnace. At the same time, the inside temperatures of the concrete specimen were monitored by thermocouples to ensure the inside to be heated up to the desired temperature. After suffered to the desired high temperatures for 2.5 hours, the concrete specimens were taken out from the electric furnace and cooled down to the room temperature in the air or by a water jet for 15 minutes.

Applying performance-modifying agent (CS)

In order to develop a technology to improve the properties of heated concrete, after the heated specimens were cooled, some of them were embrocated with the CS on their surfaces, using brush. The CS, being viscous liquid, is usually used on the surface of concrete to strengthen it or repair cracks to lower the water permeability. The CS can react with $Ca(OH)_2$ and other cement-like ingredients in hardened concrete to form CSH when the water exists. The hydrate fills into the pores and cracks in the concrete. The reaction mechanism of CS is shown in Fig. 1.

The embrocation process is as follows: The surfaces of the specimens were firstly moistened with water before applying the CS. Then, the surfaces were sprinkled with water about 1 lit/m^2 after the applied CS on the surfaces became dry naturally. The total amount of embrocated CS was about 0.3 kg/m^2. The specimens with the application of CS were cured with sprinkling water about 1 lit/m^2 twice every day for 7 days.

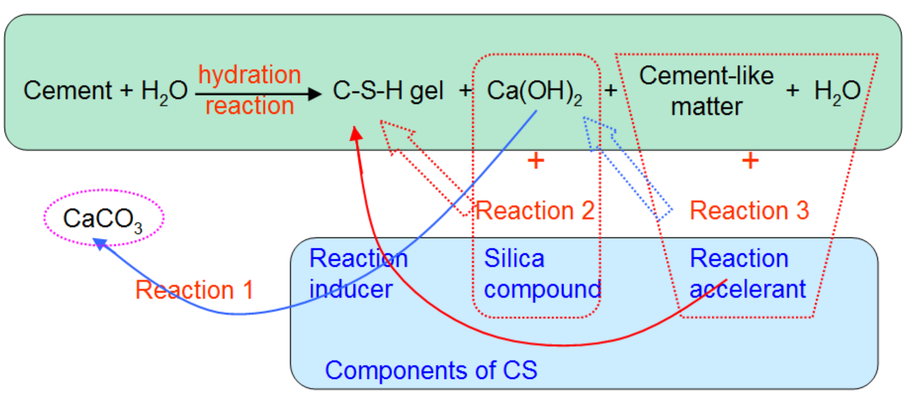


Fig.1. Reaction Mechanism of the CS

The reactions shown in Fig. 1 are as follows:

Reaction 1:

$$Ca(OH)_2 + H_2O + CO_2 \rightarrow Ca(OH)_2 + H^+ + HCO_3 \rightarrow CaCO_3 + 2H_2O \quad (1)$$

Reaction 2:

$$Na_2SiO_3 \cdot nH_2O + Ca(OH)_2 + nH_2O \rightarrow CaSiO_3 \cdot nH_2O + 2NaOH \quad (2)$$

Reaction 3:

$$2\{3CaO \cdot SiO_2\} + 6H_2O \rightarrow 3CaO \cdot 2SiO_2 \cdot 3H_2O + 3Ca(OH)_2 \quad (3)$$

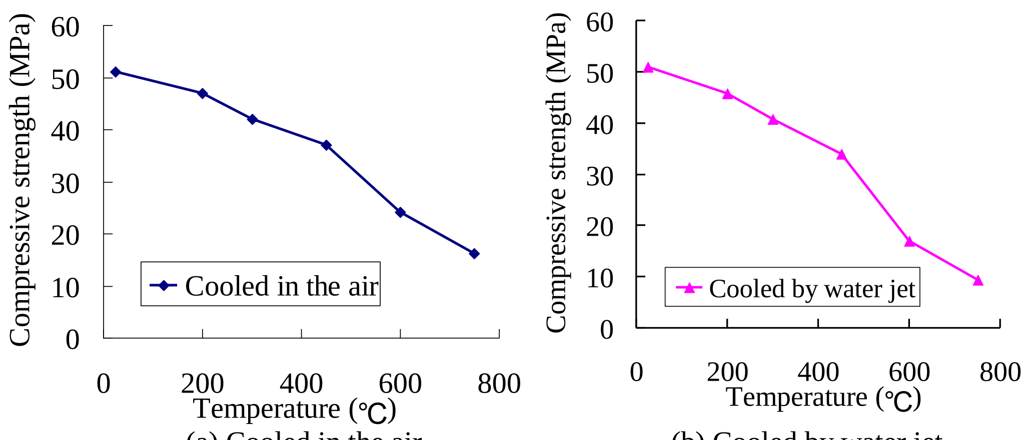
RESULTS AND DISCUSSIONS

Compressive strength of heated concrete

The test results of the compressive strength for the concrete specimens exposed to different temperatures are shown in Fig. 2. It is observed from this figure that the compressive strength decreased obviously with the increase of the heating temperature. As seen from the Fig.2, the decreasing rate of compressive strength varied from the temperature ranges. The temperature ranges are 25-200^{o}C, 200-450^{o}C, and 450-750^{o}C.

The compressive strength of concrete cooled in air or by water jet, after exposed to high temperature lower than 200^{o}C, decreased by only 8%, and 10% of its initial value, respectively.

In the temperature range of 200-450^{o}C, the compressive strength was rapidly reduced, compared to the temperature range of 25-200^{o}C. The strength loss of concrete heated to 300^{o}C and 450^{o}C cooled in air were 17.69% and 27.55%. The strength reduction of the concrete exposed to 300^{o}C and 450^{o}C cooled by water jet were 20% and 33%. High temperature of 300^{o}C and 450^{o}C leaded to a great decrease in the compressive strength. It may be considered that with increasing temperature, all of the bound water is removed up and the decomposition of hydrates and destruction of the gel structure occur, which lead to the change in the micro pore structure of concrete.



(a) Cooled in the air (b) Cooled by water jet

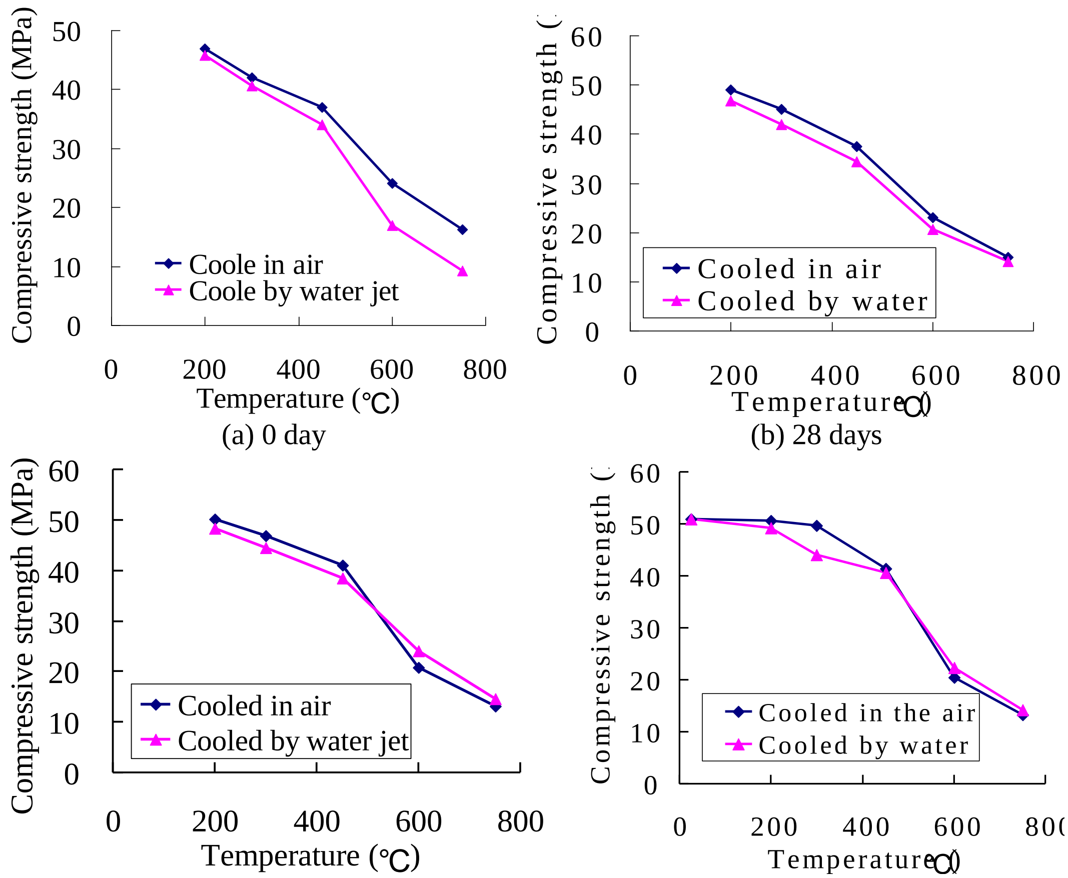
Fig.2. Effect of Heating Temperature on the Compressive Strength of Concrete Right After heated

With further increasing the heating temperature up to 750°C, the decrease of compressive strength became more significant. For the concrete cooled in air, the reduction was up to 68.26%. The strength reduction was 82% if cooled by water jet after heated at temperature of 750°C. It is clear that there was a greater decrease in the compressive strength, compared to that at temperature ranges 25-450°C. This is probably because that a very great increase in permeability would take place at 750°C, which is attributed to the decomposition of calcite and connection of pores and gas channels in large quantities. Therefore, we can conclude that the higher the heating temperature, the greater the strength reduction.

Effect of cooling method on strength recovery

Fig. 3 shows the variation of the compressive strength of the concretes with re-curing time, which were cooled by different methods after exposed to high temperatures. It is clear that the compressive strength of the heated concrete was greatly affected by the cooling method. When heating temperature was 200°C and 300°C, water-cooling reduced slightly the compressive strength, compared to the air-cooling. However, the effect of cooling method became remarkable when the concretes were exposed to 450°C, and the water-cooling caused a bit more deterioration in compressive strength than in the case of air-cooling. Also, the compressive strengths of all the specimens, no matter how to cool, were reduced greatly after they were exposed to 750°C, and water-cooling caused a greater reduction in the strength, compared to the air-cooling. The result mentioned above, which the reduction in the compressive strength right after cooled down to room temperature by water was greater than that cooled in the air, is attributed to that sudden cooling produces many cracks in concrete.

As shown in Fig.3, with the increase in the re-curing time, the degree of strength recovery in case of water-cooling was greater than in case of air-cooling, the compressive strength of the heated concrete cooled by water was close to that of the concrete cooled in the air. At the temperature of 200°C and 300°C, all the free water and part of the bound water have escaped from the concrete in form of vapor. At 450°C, the portlandite dehydrated and lost dehydration water. At 750°C, the calcite decomposes to generate CaO and CO_2 [Alonso and Fernandez 2004]. Thus, if cooled by water, the dehydrated cement paste in the specimens would rehydrate, and the CaO would participate in rehydration process with water to form new portlandites, which repair the cracks and improve the pore structure in the fire-damaged concrete.



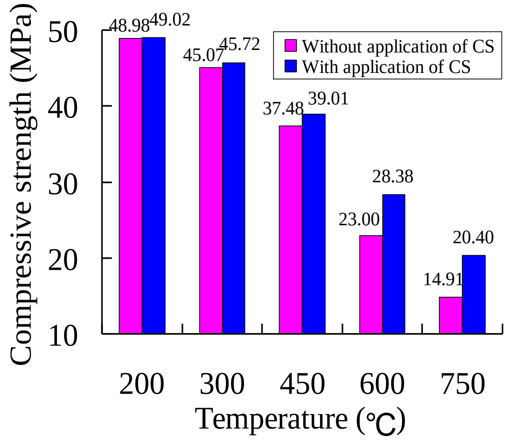
(a) 0 day (b) 28 days

(c) 60 days (d) 90 days

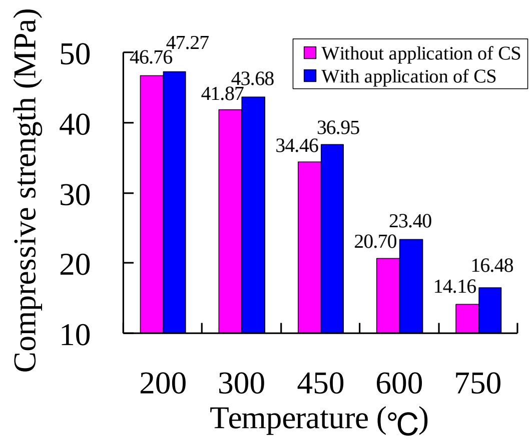
Fig.3. Effect of Cooling Method on Strength Recovery

Effect of CS embrocation on strength recovery

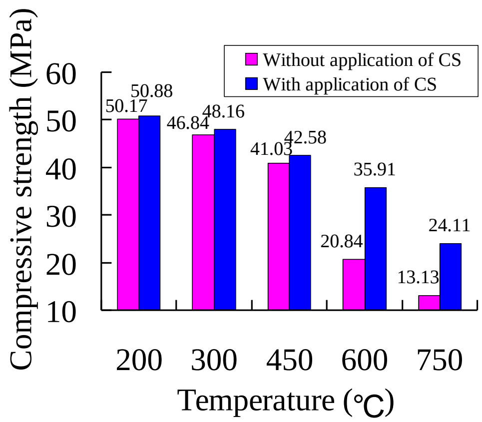
Fig.4 shows the effect of the CS embrocation on the strength recovery of heated concrete. As shown in this figure, the use of the CS improved significantly the compressive strength of the concrete subjected to high temperatures. When the concrete were exposed to the temperature in a range of 200-750^{o}C, the compressive strength of the specimens embrocated the CS was substantially larger than that of those without using the CS. The recovery of compressive strength of concrete became more and more evident when increasing the heating temperature. In other words, when the concrete was heated below the temperature of 750^{o}C, the effect of CS embrocation on the strength recovery of hard-damaged concrete was higher than that of the concrete damaged slightly. The application of the CS significantly increased the compressive strengths of the concrete specimens subjected to high temperatures. This is due to the reactions shown in Fig.1.



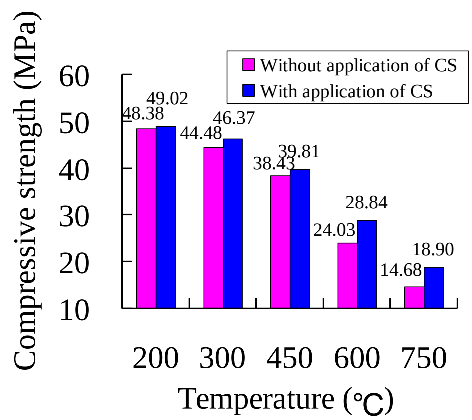
(a) Cooled in the air, 28 days after heated



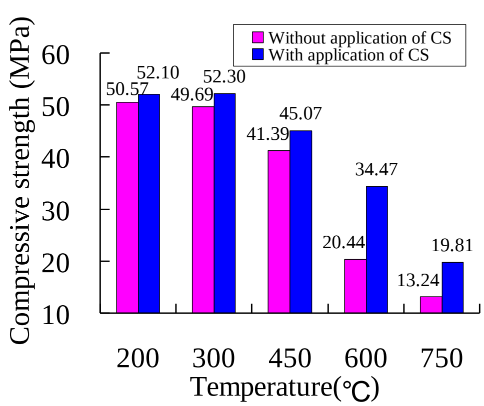
(b) Cooled by water, 28 days after heated



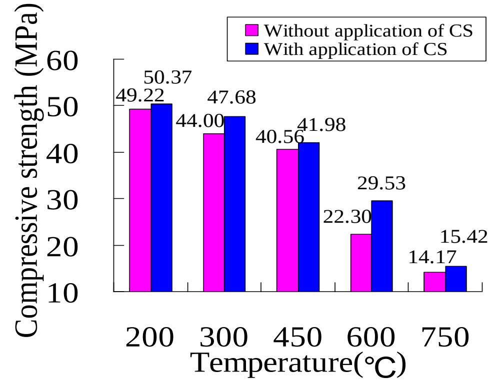
(c) Cooled in the air, 60days after heated



(d) Cooled by water, 60days after heated



(e) Cooled in the air, 90 days after heated



(f) Cooled by water, 90 days after heated

Fig.4. Effect of the CS Embrocation on the Strength Recovery

As observed from Fig.4 (a), when the concrete was exposed to high temperature of 200°C, the recoveries in the compressive strength of the concrete embrocated the CS after cooled in air and by water, being 0.04MPa and 0.51MPa, respectively, were higher than those of the concretes without using the CS. However, if exposed to 750°C, the recovered strength in case of water-cooling, being 5.49 MPa, was much higher than in case of air-cooling. This result may be attributed to the cracks and pore structure of fire-damaged concrete. The cracks of the concrete exposed to 200°C were fewer than that of the concrete heated up to 750°C, at which the decomposition of portlandite and calcite should be in a greater degree. Much the CS permeated into the damaged concrete through much the cracks and pores, thus greatly improved the compressive strength.

Time-dependent of the strength recovery

The strength recovery of heated concrete with elapsed time is demonstrated in Fig. 5. It can be seen that the increase of the compressive strength with the elapsed time was dependent on the extent of high temperature-damage. The compressive strength of concrete exposed to high temperatures below 750 °C increased gradually with re-curing time. However, the concrete almost did not show an increase in the strength after suffered to high temperature of 750 °C.

The concrete, which was subjected to the temperature of 200°C, then cooled in the air, had 92% of the initial compressive strength, then became to be 96.04%, 98.37%, and 99.15% after re-cured for 28 days, 60 days, and 90 days, respectively. Also, the compressive strengths of the heated concrete, which was embrocated with the CS after air-cooled, were 96.12%, 99.76% and 102.15% of the initial value after placing 28 days, 60 days, and 90 days, respectively.

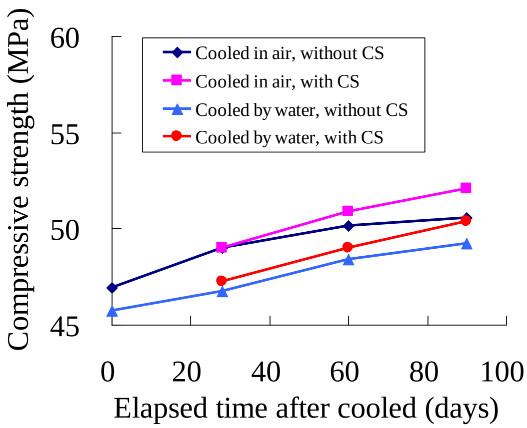
However, it can be seen from Fig. 5 that the compressive strength of concrete after exposed to the temperature of 750°C, and then cooled in air reduced with the elapsed time. Moreover, the compressive strengths of the specimens heated at 750°C then cooled by water almost did not increate with re-curing time.
The strength recovery of the heated concrete, which was embrocated with the CS after cooled by water or in the air, was more rapid than that of the concrete without using the CS with the re-curing time. That is, the CS would be used to improve the recovery of the compressive strength of fire-damaged concrete.

CONCLUSIONS

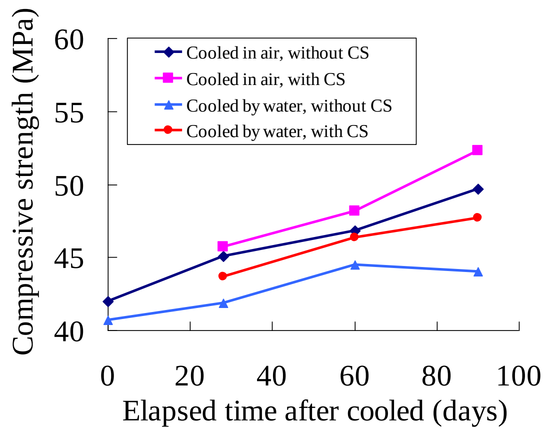
In this study, in order to develop a repairing technology for fire-damaged concrete, the compressive strength and its recovery of heated concrete were investigated under different heating temperatures, cooling methods, and re-curing time. And the effect of embrocating the performance-modifying agent on the strength recovery was examined in detail. The obtained conclusions are as follows.

(1) The compressive strength of concrete decreased with raising the heating temperature, when the air-cooled concrete was exposed to 750°C, it was only 31.74% of its initial strength.

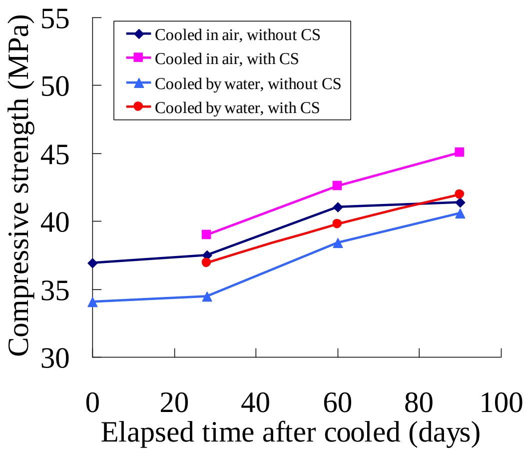
(2) The reduction in the compressive strength of concrete, which was heated and then cooled in the air, was smaller than that of the concrete cooled by water, when re-curing was within 28 days. But after 28 days, the compressive strength of the heated concrete cooled by water was close to that of the concrete cooled in the air.
(3) The CS embrocation can greatly improve the strength recovery of the fire-damaged concrete.



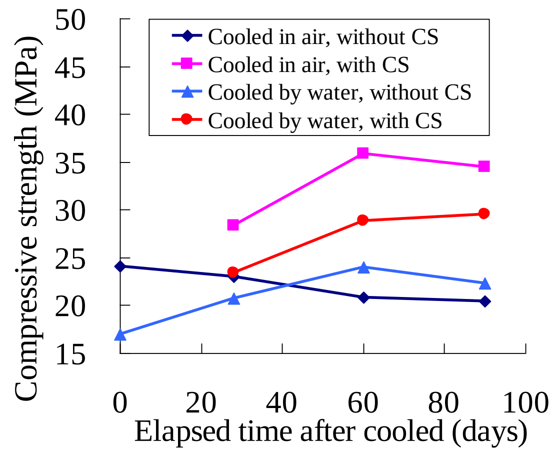
(a) 200 °C



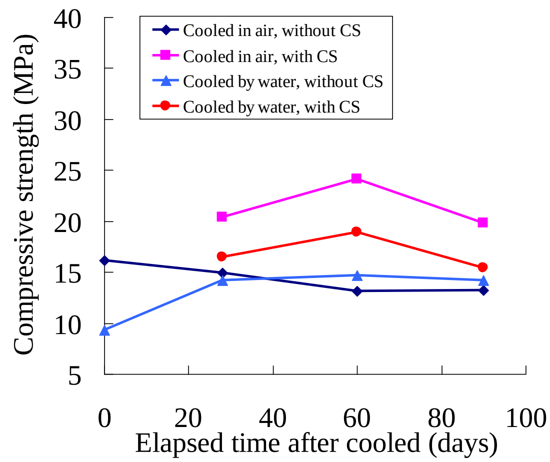
(b) 300 °C



(c) 450 °C



(d) 600 °C



(e) 750 °C

Fig.5. Effect of Re-curing Time After Heated on the Strength Recovery

(4) The recovery degree of the compressive strength varies with the re-curing time after heated at the temperature below 450°C. The compressive strength increased obviously with the elapsed time after cooled. However, the compressive strength of the 750°C-heated concrete decreased with the elapsed time after air-cooled.

As a further research work, we would like to change the embrocating method of the CS to improve more greatly the strength recovery of fire-damaged concrete.

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