- Technical Paper -

INVESTIGATION ON THE RECOVERY OF COMPRESSIVE STRENGTH OF CONCRETE EXPOSED TO HIGH TEMPERATURE

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ABSTRACT

To develop a new repairing technology of fire-damaged concrete, the strength recovery of concrete after exposed to high temperature was investigated. The effects of temperature, cooling method, performance-modifying agent (PMA), and re-curing time on the compressive strength and its recovery were discussed. The test results indicate that the strength of heated concrete decreased with raising the heating temperature for any cooling method, and was smaller when the heated concrete was cooled by water than in the air. The embrocation of PMA on the heated concrete could accelerate the strength recovery.

Keywords: concrete, compressive strength, recovery, cooling method, high temperature, performance-modifying agent

1. INTRODUCTION

The compressive strength of concrete deteriorates when it is subjected to high temperature as in a fire because of the changes in the chemical composition of cement paste and in the physical properties of aggregates.

The mechanical properties of concrete exposed to elevated temperatures have been widely studied. Some investigations have been focused on the effects of heating temperature, exposure time, cooling methods and loading conditions [1-6]. In spite of differing in the properties of concrete below 300℃, there is a uniformity of opinion concerning a decrease in compressive strength above 300℃. Then a rapid reduction of about 40% at 500-600℃ [5]. At the temperature of 600℃, the compressive strength of concrete is reduced to 50% of its normal strength [3]. At 800℃, the reduction is from 74% to 97% [2]. The reduction is very sharp beyond 800℃. The relative strengths of concrete after exposure to 1000℃ and 1200℃ were measured as 13% and 6% [4]. Metin Husem [1] and Chan [6] studied the influence of cooling methods on the compressive strength, and presented that concrete strength decreases with increasing temperature and the type of cooling affects the residual compressive strength remarkably. The decrease of compressive strength is greater cooled in water than that cooled in the air.

Experimental studies have been performed to investigate the strength recovery of the concrete exposed to high temperature [7-9]. Ichise et al. [8] observed that the compressive strength of high-strength concrete subjected to temperatures of up to 500℃ recovered up to 80% at the room temperature with underwater curing. Matsudo [9] studied the recovery of the ultra-high strength concrete of which the strength is above 100N/mm^2, and found that the recovery of compressive strength after two years is negligible, compared to concrete with high 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, polymer wraps, and so on. Mihashi developed the new method that the crack repairing agents were installed as core materials in shell bodies and previously embedded in concrete [10]. 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 when heated [11].

In spite that the strength of the fire-damaged concrete can regain naturally, the recovery extent 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 can't 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 how to improve the strength of fire-damaged concrete.

In this study, we investigated the extent and influencing factors of the compressive strength recovery of concrete exposed to high temperature in succession of the research of carbonation resistance recovery [12]. The concrete specimens were exposed to different high temperatures for 150min, and then cooled in the air or by water jet. The compressive strength test was carried out after the heated concrete specimens were cured in the air at ambient temperature in the laboratory for 0 day, 28 days, 60 days, and 90 days. We also examined the improvement in the strength recovery when applying the PMA to the fire-damaged concrete for developing a new repairing technology.

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2. EXPERIMENTAL PROGRAM

2.1 Materials Used and Preparation of Specimens

The cement used in this study was ordinary portland cement, of which the specific gravity is 3160 kg/m^3. Coarse aggregate of crushed stone with a maximum size of 20mm was used. The density at saturated surface dry condition, and water absorption ratio of coarse aggregate were 2730 kg/m^3, and 0.40%, respectively. Fine aggregate was sea sand with density of 2590 kg/m^3 at saturated surface dry condition, water absorption ratio of 1.60%, and fineness modulus of 2.57. Water reducing admixture air-entraining (AE) agent was also used in a dosage of 1.1% by mass of cement. Polypropylene fiber with a length of 12 mm was used at 0.2% per 1m^3 concrete to improve the spalling resistance of concrete during heating.

Mix proportions of concrete were 1.0(cement) : 0.50 (water) : 2.42 (sand) : 2.78 (coarse aggregate) by mass (Table 1). Unit weight of cement is 346 kg/m^3. 216 cylindrical specimens with diameter of 100mm and length of 200mm were produced.

The specimens were cast, and demoulded after 24 hours of moist curing in mould. Afterwards, the specimens were cured in water of 20±3℃ for 28 days, and then moved to a room to cure at ambient temperature naturally for 12 months until they are heated. The compressive strength of the concrete at 28 days and 12 months were 40MPa, and 51MPa, respectively.

Table 1 Mix proportions of Concrete

Unit weight (kg/m^3)				
Cement	Water	Sand	Coarse aggregate	Admixture
346	173	837	962	3.8

2.2 Heating and Cooling Regimes

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

2.3 Embrocation of PMA

The PMA, being viscous liquid, is usually used to strengthen and repair cracks of concrete to lower its water permeability. The PMA which is a silicate system material would react with $Ca(OH)_2$ and other cement-like ingredients in hardened concrete to form calcium silicate hydrate when the water exists. The hydration product fills into the pores and cracks in the concrete.

In order to develop a technology to improve the properties of heated concrete, after the heated specimens were cooled to room temperature, some of them were embrocated with PMA on their surfaces, using a brush. The surfaces of the specimens were firstly moistened with water before embrocating the PMA, then were sprinkled with water about 1 lit/m^2 after the PMA was dried naturally. The totally used PMA was about 0.3 kg/m^2. The specimens with the application of the PMA were cured with sprinkling water about 1 lit/m^2 twice every day for 7 days.

3. RESULTS AND DISCUSSION

3.1 Compressive Strength of heated concrete

The test results of the compressive strength of the concrete specimens exposed to different temperatures are shown in Fig. 1. It is observed that the compressive strength decreased obviously with the increase of the heating temperature. The temperature ranges can be divided to two stages at 450℃.

The compressive strength of concrete cooled in the air and by water jet after exposed to high temperature of 200℃, decreased only 8% and 10% of its initial value, respectively.

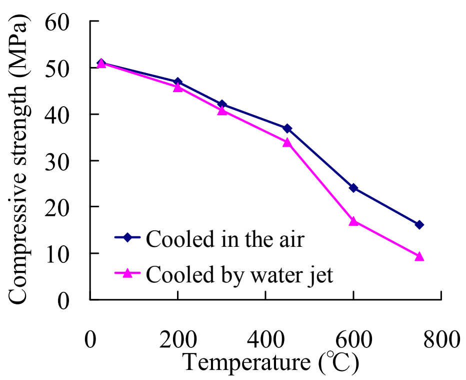


Fig.1 Variation of compressive strength with temperature (right after cooled)

Otherwise, at the temperatures of 300℃ and 450℃, the compressive strength reduced rapidly, compared to the temperature of 200℃. After heated at 300℃, the strength loss of concrete was 17.69% when the concrete were cooled in the air, and the strength loss was 20.0% when the concrete were cooled by water jet. Up to 450℃, the reduction of compressive strength was 27.55% when the concrete were cooled in the air, and the reduction was 33.0% when the concrete were cooled by water jet. High temperatures of 300℃ and 450℃ 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 the destruction of the gel structure occur, which result in a weak pore structure in the concrete.

With further increasing the heating temperature up to 600℃ and 750℃, the loss of compressive strength became more significant. For the concrete cooled in air, the reduction of compressive strength was 52.82% after heated at temperature of 600℃. When the concrete was cooled in air, the strength loss was 68.26% after heated at temperature of 750℃. The strength loss was 67.0% when the concrete was cooled by water jet after heated at 600℃. Up to 750℃, the reduction of compressive strength was 82.0% when the concrete was cooled by water jet. It is clearly that there was an extremely great decrease in the compressive strength, compared to the strength loss at temperature of 25℃, 200℃ , 300℃ and 450℃. This is probably because of an increase in the decomposition of calcite and connection of cracks and gas channels in large quantities. Therefore, we can conclude that the higher the heating temperature, the greater the strength reduction.

3.2 Effect of Cooling Method on Strength Recovery

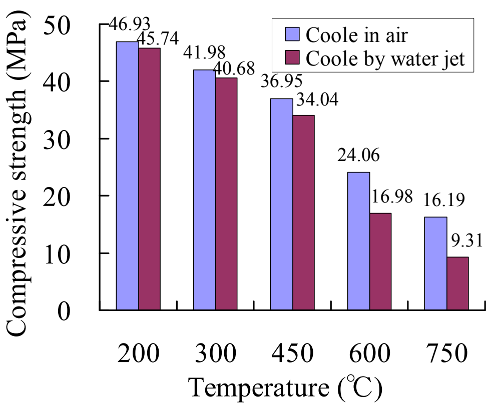
Fig. 2 shows the variation of the compressive strength of the concrete cooled by different methods after exposed to high temperatures.

As shown in Fig. 2(a), when the heating temperatures were 200℃, 300℃, and 450℃, the water-cooling reduced the compressive strength of concrete slightly, compared to the air-cooling. However, the effect of cooling method became remarkable if the concretes were exposed to 600℃ and 750℃, and the water-cooling caused a bit more deterioration in compressive strength of concrete than in the case of air cooling.

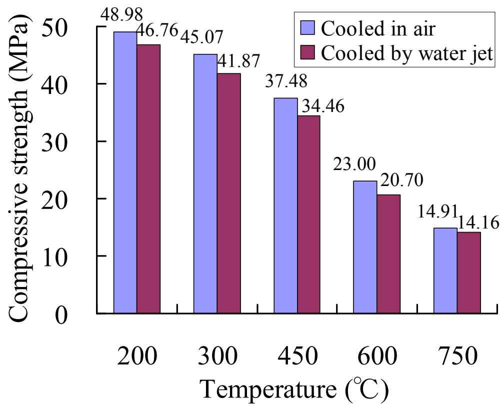
It is clear that the compressive strength of the heated concretes was not greatly affected by the cooling method when the temperature was not higher than 450℃. The recovery of compressive strength was not influenced clearly by cooling method when the re-curing time was 0 days or 28 days, and the strength of concrete cooled by water jet was smaller than that of the concrete cooled in air. However, the effect of cooling method was remarkable after the concrete were re-cured for 60 days and 90 days when the concrete were exposed to 600℃ and 750℃, the water-cooling caused a greater recovery 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 the concrete.

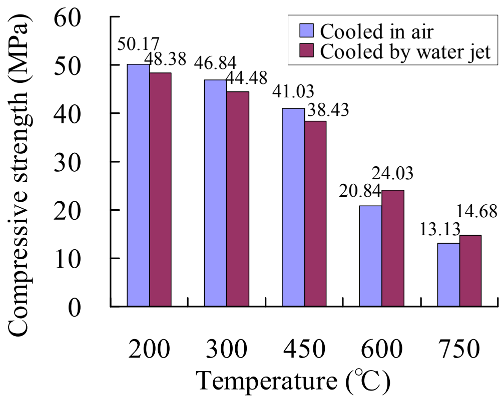
As shown in Fig. 2, with the increase in the re-curing time, the compressive strength of the heated concrete cooled by water was close to that of the concrete cooled in the air, when the temperatures were not over 450℃. At the temperature of 200℃ and 300℃, most of the free water and part of the bound water have escaped from the concrete in form of vapor exclusive of portlandite. At 450℃, part of the portlandite dehydrated and lost the dehydration water. However, the degree of compressive strength recovery in case of water-cooling was greater than in case of



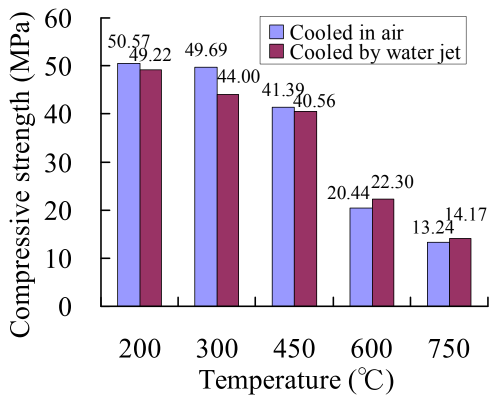
(a) Elapsed time after cooled: 0 day



(b) Elapsed time after cooled: 28 days



(c) Elapsed time after cooled: 60 days



(d) Elapsed time after cooled: 90 days

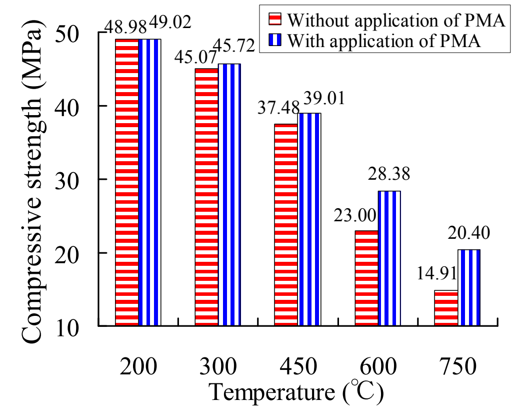
Fig.2 Effect of cooling method on the strength recovery air-cooling, when the concrete were heated at temperatures of 600℃ and 750℃.

At 600℃the portlandite dehydrated to CaO and water, and lost the dehydration water. At 750℃, the calcite decomposes to generate CaO and CO_2[13]. Thus, if cooled by water, the dehydrated cement paste would rehydrate, and the CaO would participate in rehydration process with water to form new portlandite, which repair the cracks and improve the pore structure in fire-damaged concrete.

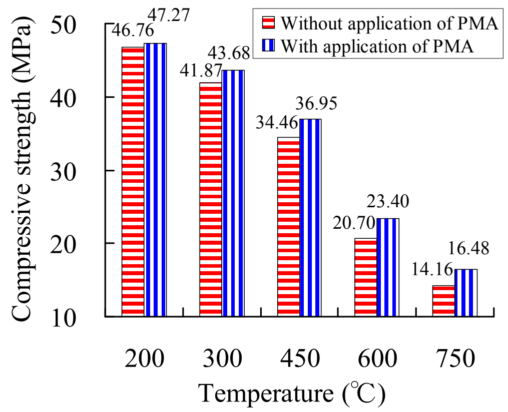
3.3 Effect of PMA Embrocation on Strength Recovery

Fig. 3 shows the effect of PMA embrocation on the strength recovery of heated concrete. As shown in this figure, the use of the PMA improved significantly the compressive strength of the concrete subjected to high temperature. When the concrete were exposed to the temperature in a range of 200-750 ℃ , the compressive strengths of the specimens embrocated the PMA were substantially larger than those without using the PMA. The higher the heating temperature, the greater the recovery degree of compressive strength of concrete using the PMA. In other words, when the concrete was heated below the temperature of 750℃, the PMA embrocation speeds up more greatly the strength recovery of hard-damaged concrete than that of slight-damaged concrete. The application of the PMA significantly increased the compressive strength of the concrete specimens subjected to high temperature.

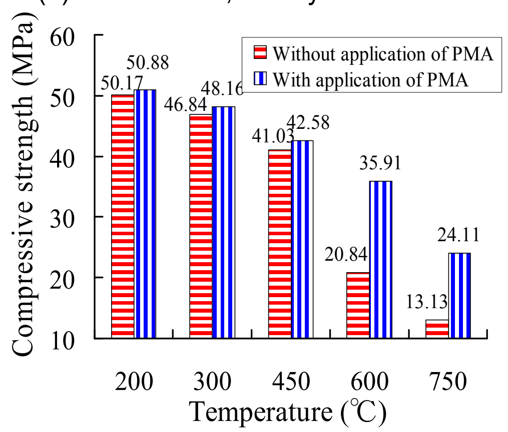
As observed from Fig.3 (e), Fig.3 (f), when the



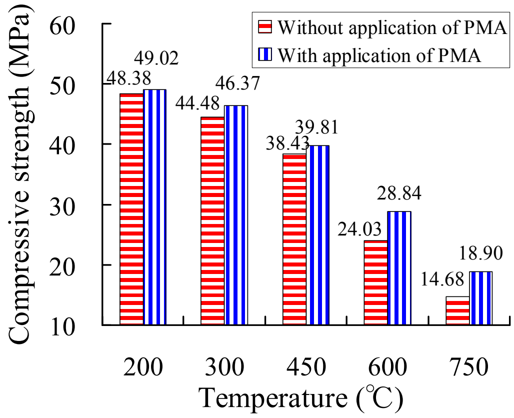
(a) Cooled in air, 28 days after cooled



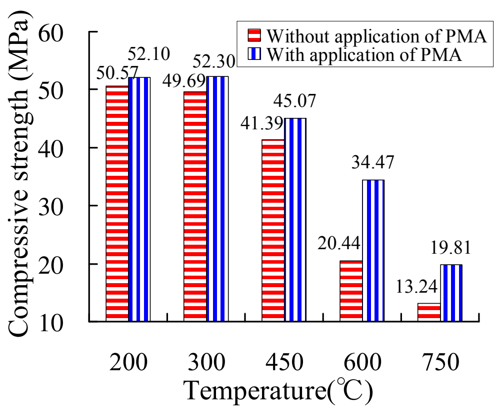
(b) Cooled by water jet, 28 days after cooled



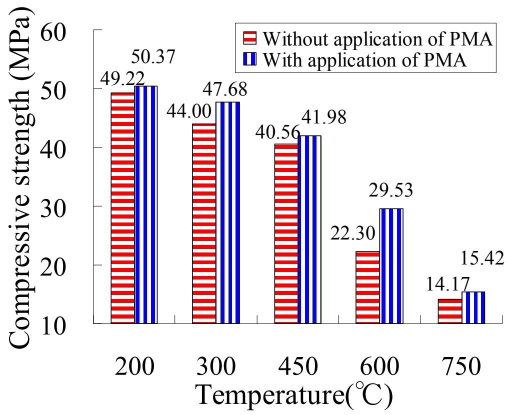
(c) Cooled in the air, 60 days after cooled



(d) Cooled by water jet, 60 days after cooled



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



(f) Cooled by water jet, 90 days after cooled

Fig.3 Effects of PMA embrocation on the strength recovery concrete was exposed to high temperatures of 200℃, 300℃, 450℃, 600℃ and 750℃, the recoveries in the compressive strength of the concretes embrocated the PMA after cooled in air, being 1.53MPa, 2.61MPa, 3.68MPa, 14.03MPa and 6.57MPa, respectively, were higher than those of the concretes without using the PMA. Moreover, if exposed to 600℃, the strengths of the air-cooled and the water-cooled concrete applied with PMA, which recovered to 67.59% and 57.90% of the initial strength respectively, were much greater than that of the concrete without applying PMA only recovered to 40.07% and 43.73% of the initial value.

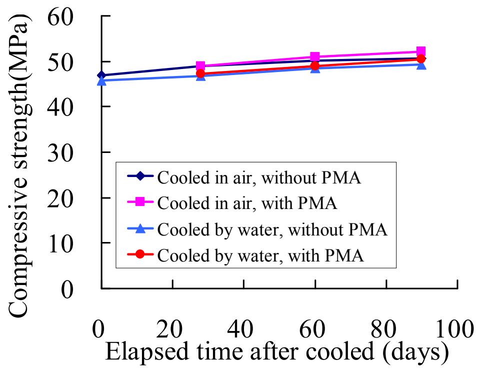
The effect of PMA on the recovery of compressive strength of concrete exposed to 600℃ is more obviously than that the case of 200℃. This result may be attributed to the permeation of the PMA and the rehydration. The cracks of the concrete exposed to 200℃ were fewer than that of the concrete heated up to 600℃, at which the decomposition of portlandite and calcite is in a greater degree. Much the PMA permeated into the damaged concrete through much the cracks and pores, thus greatly improved the compressive strength through much rehydration of the decomposed portlandite and calcite.

3.4 Time-dependent of the Strength Recovery

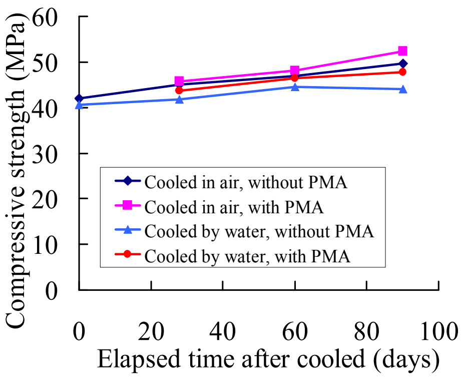
The strength recovery of heated concrete with elapsed re-curing time is demonstrated in Fig. 4. It can be seen that the increase of the compressive strength with the elapsed time was dependent on the extent of high temperature-damage. The compressive strength of concrete exposed to high temperatures below 600℃ 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℃.

The concrete, which was subjected to the temperature of 200℃, 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 were embrocated with PMA after air-cooled, were 96.12%, 99.76%, and 102.15% of its initial value, after placing 28 days, 60 days, and 90 days, respectively.

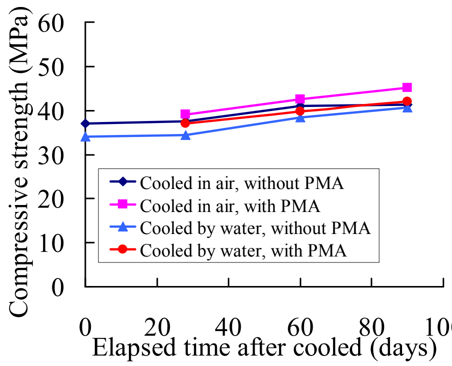
However, it can be seen from Fig. 4 that the strength of concrete, cooled in the air and without using the PMA, decreased with the elapsed time after exposing to temperatures of 600℃ or 750℃. Moreover, the compressive strengths of the specimens heated at



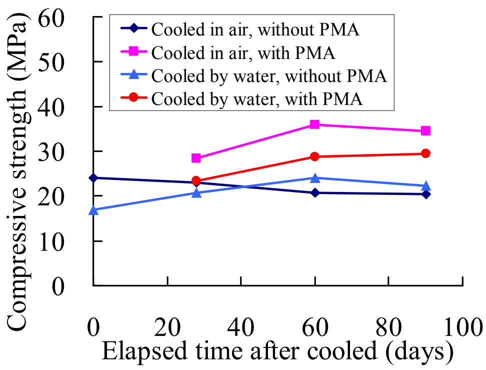
(a) 200℃



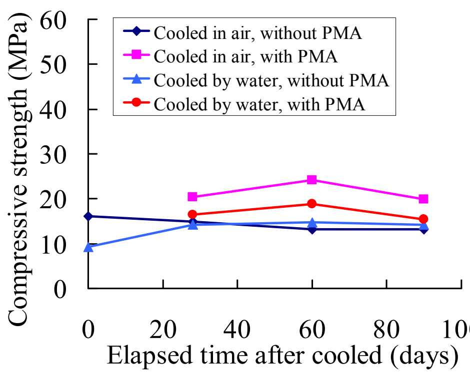
(b) 300℃



(c) 450℃



(d) 600℃



(e) 750℃

Fig.4 Effect of re-curing time after heated on the strength recovery

750℃ and then cooled by water jet were lower than at 600℃, and they can't recover naturally as the case of 600℃ though the water was supplied outside.

The strength recovery of the heated concrete with the re-curing time, which was embrocated with PMA after cooled by water or in the air, was more rapid than that of the concrete without using the PMA. That is, the PMA would be used to improve the recovery of the compressive strength of fire-damaged concrete.

3. 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 exposed to 750℃ and cooled by water jet, it was only 18% of its initial strength.

(2) The reduction in the compressive strength of concrete, which was heated and then cooled in air, was smaller than that of the concrete cooled by water when the concrete was re-cured for 0 days and 28 days. When the concrete were re-cured for 60 days and 90 days after the concrete were exposed to 600℃ and 750℃, the water-cooling caused a greater recovery in the strength, compared to the air-cooling.

(3) The PMA embrocation can greatly improve the strength recovery of the fire-damaged concrete exposed to temperatures below 750℃. If exposed to 600℃, the strengths of the air-cooled and the water-cooled concrete applied with PMA, which recovered to 67.59% and 57.90% of the initial strength respectively, were much greater than that of the concrete without applying PMA only recovered to 40.07% and 43.73% of the initial value.

(4) The recovery degree of the compressive strength varies with re-curing time after heated at the temperature below 450℃. The compressive strength increased obviously with the re-curing time. However, the compressive strength of the concrete heated at 600℃ and 750℃ decreased with the elapsed time after air-cooled.

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

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