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The use of surface coating in enhancing the mechanical properties and durability of concrete exposed to elevated temperature

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HIGHLIGHTS

- We studied the properties recovery of concrete exposed to elevated temperature.
- With SCC, the compressive strength of concrete exposed to 200–700 °C can recover.
- With SCC, the modulus of elasticity of concrete exposed to 200–700 °C was enhanced.
- With SCC, the carbonation resistance of concrete exposed to 200–600 °C was increased.

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ABSTRACT

An experimental investigation was conducted to evaluate the compressive strength, modulus of elasticity and carbonation resistance after heating of air-cooled concrete coated with surface coating of concrete (SCC). The concrete with water–cement ratios of 0.59, 0.50 and 0.36 were exposed to temperatures up to 700 °C and then they were naturally cooled in the air. Parts of the fire-damaged concrete specimens were coated with SCC and then they were recured in a controlled condition for a total duration of 90 days. After being exposed to elevated temperatures, compared with the uncoated concrete, the compressive strength of concrete with SCC was enhanced sizably. After exposure to temperatures above 500 °C, the compressive strength of air-cooled concrete without SCC could not recover. The modulus of elasticity of air-cooled concrete with SCC was enhanced. After being exposed to temperatures above 200 °C, the modulus of elasticity of air-cooled concrete without SCC decreased after recuring for 90 days. Without SCC, the carbonation depth of air-cooled concrete increased when the concrete was exposed to temperatures above 300 °C. SCC considerably increased the carbonation resistance of concrete exposed to temperatures below 600 °C.

1. Introduction

Numerous studies were carried out to investigate the variation of compressive strength and durability of concrete exposed to elevated temperature [1–6]. The deteriorations of physical properties, mechanical properties and durability of concrete were significantly affected by the exposure temperature. When the concrete was exposed to elevated temperature, the loss in compressive strength of concrete was attributed to the dehydration of concrete and related to the loss in weight of concrete [1]. It has been found that the compressive strength of concrete exposed to temperatures below 400 °C can be mostly maintained [2]. The compressive strength of concrete decreased significantly between 400 and 600 °C, and most of the compressive strength is lost from 600 to 800 °C [3]. On the other hand, the cooling method also affected the properties of concrete exposed to elevated temperature [3,4,7].

It is now realized that the fire-damaged concrete could regain part of the properties with post-fire-curing due to the rehydration of the C–S–H gel [8–15]. The heating temperature and the recuring conditions were considered as the main influence factors on the recovery of concrete exposed to elevated temperature [8,9]. Most researchers concluded that water played an important part in the rehydration of concrete exposed to elevated temperature [10,13,14,16].

The durability is one of the most important properties of concrete. Few researches were carried out on the recovery of the carbonation resistance of the concrete exposed to elevated temperature. Poon et al. measured the impermeability of

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air-cooled concrete exposed to 600 and 800 °C, the results showed that most of the concrete still had very high permeability although there was a significant recovery after post-fire-curing for 56 days in water [8]. They concluded that the residual compressive strength of concrete reduced for increasing values of exposure temperature, and that prolonging the air recuring period did not significantly help the recovery of compressive strength.

The surface coating has been studied to improve the durabilities of concrete at ordinary temperature in many literatures [17–21]. Moon et al. found that the penetration of chloride, freezing–thawing and carbonation resistance of concrete were improved significantly by surface coating [17]. Almusallam et al. reported that the durability of concrete could be improved by coating epoxy and polyurethane [18]. Moradllo et al. found that the surface coating appropriately decreased chloride diffusion coefficient in first stage of exposure [19]. Al-Zahrani et al. reported that the water absorption capacity of the specimens coated with the polyurethane elastomer-based waterproofing material performed better than concrete specimens coated with other waterproofing materials [20]. Swamy et al. examined the performance of concrete slabs coated with acrylic-based coating and pointed out that the coating prevented the penetration of carbon dioxide into concrete [21]. Li et al. investigated the effect of surface coating on the fire-damaged concrete cooled by water. The compressive strength and the durability of water-cooled concrete coated with coating performed better than that of the concrete without coating [22].

However, there are very few researches about the effect of surface coating on the property recovery of concrete exposed to elevated temperature. There is a need to conduct a comprehensive investigation to understand the effectiveness of surface coating on the mechanical properties and durability recovery of fire-damaged concretes cooled in the air. This study was conducted to evaluate the effectiveness of surface coating in improving the mechanical properties and carbonation resistance recovery of naturally cooled concrete.

2. Experimental details

The exposure temperature, surface coating of concrete are taken as the main variables in this study. Three kinds of concrete M1, M2, and M3 with different water–cement ratio were prepared. After heating and naturally cooling, the concrete specimens were divided into two groups which were recured with and without surface coating, respectively. The effect of surface coating on the compressive strength as well as carbonation depth of concrete was investigated.

2.1. Materials

The cement used in this study was ordinary Portland cement 42.5 grade, of which the specific gravity is 3.16. The chemical composition and physical properties of cement used in this study are given in Table 1. Crushed stone with a maximum size of 25 mm was used as coarse aggregate. Sea sand with specific gravity of 2.60 was used as fine aggregate. The physical properties of the fine aggregate and coarse aggregate are presented in Table 2. The potable water which is free from injurious amount of deleterious materials was used. To obtain workable concrete mixtures, the superplasticizer was used in the concrete. To improve the spalling resistance of concrete during heating, polypropylene fiber with a length of 12 mm was used at 0.1% per cubic meter.

The surface coating was utilized in the surface treatment of concrete exposed to elevated temperature. The SCC is a surface coating with silicate system material. It is a viscous liquid of which the specific gravity is 1.23. It is usually used on the surface of concrete to strengthen concrete or repair cracks to lower the water permeability. The surface coating reacts with $Ca(OH)_2$ in concrete to form C–S–H when the water exists. The reaction product fills into the pores and cracks in the concrete. The physical properties and main components of the surface coating are listed in Table 3.

Table 1
Chemical composition and physical properties of cement.

Characteristics	Value
SiO_2	23.06
Al_2O_3	7.14
Fe_2O_3	3.24
CaO	56.64
Na_2O	0.15
MgO	1.94
K_2O	0.93
SO_3	2.02
TiO_2	0.38
MnO	0.07
P_2O_5	0.06
Cl	0.029
Ignition loss (%)	4.14
Specific gravity	3.15
Specific surface (cm^2/g)	3280

2.2. Preparation and casting of specimens

Details of the mixture proportions of concrete are given in Table 4. Three kinds of concrete were prepared with water–cement ratios of 0.59, 0.50 and 0.36, respectively. The cubic specimens (100 × 100 × 100 mm) were prepared to determine the compressive strength of concrete. The prismatic specimens (100 × 100 × 300 mm) were used to determine the modulus of elasticity of concrete. The dimensions of the concrete specimen for carbonation test were 100 × 100 × 400 mm. The concrete specimens were cast in steel molds and compacted by a vibrating table. The specimens were cured in water at 20 ± 2 °C for 28 days after being demoulded. All of the concrete specimens were placed in a room maintained at 20 ± 2 °C and 60 ± 5% R.H. for 90 days until they were heated. The compressive strength and modulus of elasticity of the concrete before heating at elevated temperatures are shown in Table 5.

2.3. Heating and cooling rates

With an electric furnace, the specimens of concrete were heated up to 200, 300, 400, 500, 600, and 700 °C. The average heating rate of the electric furnace was 5 °C/min. The concrete specimens were heated to the chosen temperatures and the peak temperatures were maintained for 150 min. Then the concrete specimens were taken out from the electric furnace and naturally cooled down to room temperature in air. No explosive spalling was observed during the heating test on concrete specimens with temperature ranging from 200 to 700 °C.

2.4. Coating process

In order to improve the mechanical properties and carbonation resistance recovery of concrete exposed to elevated temperature, the surface of some concrete specimens was coated via SCC. Before coating SCC on the concrete specimens, the surface of concrete should be moistened with water. The amount of SCC coated on the surface of concrete specimen for the first time was about 0.15 kg/m^2. Then the surface was sprinkled with water about 1 L/m^2 after the coated SCC on the surface became dry naturally. The amount of SCC coated on the surface of concrete for the second time was also about 0.15 kg/m^2. The total amount of SCC was about 0.3 kg/m^2. About 1 L/m^2 water was sprinkled on the concrete twice every day for 1 week. In order to expedite rehydration of concrete without SCC as concrete with SCC, the concrete specimens without SCC were also sprinkled with water about 1 L/m^2 twice every day for 7 days. Afterwards, the concrete specimens were stored in a curing room (20 ± 2 °C and 60 ± 5%) and tested after recuring for 90 days.

2.5. Testing procedures

After the concrete specimens were cooled down to room temperature, the loss in mass, the compressive strength and static modulus of elasticity of concrete were tested. The mass of the concrete specimen before heating and after being exposed to different temperature was measured, respectively. Then the loss in mass was calculated and analyzed.

Table 2
Physical properties of coarse aggregate and fine aggregate.

Aggregates Type	D_{max} (mm)	Solid volume percentage (%)	FM	Specific gravity	W_b (%)
Coarse aggregate	25	59.0	6.65	2.72	0.41
Fine aggregate	5	65.2	2.55	2.60	1.63

D_{max}: maximum aggregate size; FM: fineness modulus; W_b: water absorption.