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An investigation on thermal conductivity of fly ash concrete after elevated temperature exposure

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HIGHLIGHTS

- The effects of a range of micro-environment relative humidity were investigated.
- Fly ash improved the concrete properties after exposed to elevated temperature.
- Concrete showed quite a few defects after exposure to 550 °C.

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ABSTRACT

The influence of high temperature on concrete is closely related to the thermal conductivity of concrete. In this paper, the influence of high temperature and micro-environment relative humidity on the thermal conductivity of fly ash concrete were investigated. A high-temperature energy-saving electric resistance furnace and an artificial climate chamber were used to achieve different high temperature and micro-environment relative humidity in specimens, respectively, and the thermal conductivity of specimens were test by thermophysical properties analyzer. The results showed that after exposed to high temperature, the compressive strength and thermal conductivity of both ordinary concrete and fly ash concrete were markedly reduced, and when the specimens were subjected to 550 °C, the compressive strength reduced about 26%. With an increase in micro-environment relative humidity, the thermal conductivity of both ordinary concrete and fly ash concrete were increased and when the relative humidity reached 100%, the thermal conductivity increased about 22%. Under same conditions, the thermal conductivity of fly ash concrete with 30% fly ash replacement was lower than that of ordinary concrete.

1. Introduction

In recent years, with the development of economy and growth of urban population, buildings have been more and more intensive and led to the vast concentration of people and goods. Together with the extensive use of a large number of new materials and the popularity of gas, electrical appliances have greatly increased the possibility of building fires. In the event of a fire, not only causes loss of life and property, but also causes some damage to concrete in the buildings [1,2].

Under the high temperature in fire, the properties of building materials will be deteriorated rapidly and the structures bearing capacity will be weakened greatly, and buildings were seriously damaged or even collapsed [1]. Therefore, it is essential and helpful for the rescue work during a fire or the repair and reinforcement of buildings after a fire to investigate the performance of buildings after fires.

The performance of concrete after fires has attracted an increasing research interest and many researchers [1–6] reported that the damage of concrete after fires or high temperature was closely related to the temperature field in concrete, and the thermal conductivity of concrete was an important parameter to characterize its capacity of heat transmission and determine its internal temperature field. If the thermal conductivity of concrete at high temperature was determined, the effect of high temperature on concrete would be calculated. Therefore, in order to study the performance of concrete after fires, it is necessary to study the thermal conductivity of concrete after fires first.

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As one of the most widely used building materials, concrete is a kind of artificial composite material which is made up of a mixture of cement, water, coarse and fine aggregate, etc., and it is a complex structure composed of solid phase, liquid phase and gas phase. Due to the difference of the mineral composition and structure of various raw materials in the concrete, the thermal conductivity of these materials are also different [7]. After the concrete is cast, because of the difference of mix ratio, water content, age and construction technology, etc., the variation of thermal conductivity of concrete is greater [8].

Meanwhile, as an industrial waste, fly ash is a large amount of solid wastes produced from a power plant and its resource-oriented utilization has been a most concern of the government and experts concerned. Mixing it into concrete, not only saves a large amount of cement and fine aggregate and reduces water consumption, but also improve the workability, anti-permeability and modification of concrete and reduce the creep, hydration heat and thermal expansion of concrete [9,10]. Precisely because of these merit, fly ash concrete has been widely used in many projects, and it is also necessary and essential to investigate the performance of fly ash concrete after fires.

Many researchers [7,8,11–14] have investigated the thermal conductivity of concrete and established some models. Nematollahi et al. [11] investigated the thermal properties of lightweight concrete and reported that the thermal conductivity of the lightweight concrete was significantly (38–49%) lower than that of the normal weight concrete. Li et al. [13] reported the thermal conductivity of early age concrete was mainly influenced by free water content. Kim et al. reported that the main affecting factors on the thermal conductivity of concrete were aggregate volume fraction and moisture condition, and proposed a prediction equation. Zhang et al. [14] established mesoscale models for thermal conductivity of undamaged concrete and damaged concrete, respectively. These models helped to predict the thermal conductivity of concrete and the predicted values were consistent with the experimental results. However, these investigations mainly performed in the ordinary concrete at room temperature, and since the moisture content in concrete is different to concrete, the influence of moisture content was just investigated in the dry or fully saturated conditions rather than a range of humidity conditions (Null to 100%). Under high temperature, a series of physical and chemical changes would occur in concrete and the thermal conductivity also changed. Few studies [15–17] reported the effect of high temperature on the thermal conductivity of concrete. Kizilkanat et al. [16] reported that the thermal conductivity and moisture resistance factor of concrete decreased with an increase in exposure temperature. Owing to the relatively fewer studies and the considering that, it is essential to make further research and discussions on this subject, and consequently to improve the accuracy of damage prediction of concrete after fires.

The present study investigates the influence of high temperature and micro-environment relative humidity on the thermal conductivity of fly ash concrete. The specimens were put into a GWD-05 high-temperature energy-saving electric resistance furnace to simulate the real fire. Then, the specimens were put into an artificial climate chamber whose temperature and humidity were preset to achieve different micro-environment relative humidity in concrete. Last, the thermal conductivity of specimens were test by QuicklineTM-30 thermophysical properties analyzer.

Table 2
Physical properties of cement and fly ash.

Properties	Cement	Fly ash
Specific gravity	3.15	2.4
Fineness (% retain in 45 μm)	–	7%
Specific surface area (m^2/kg)	328	308
Water demanded (%)	–	84
Loss on ignition (%)	4.14	6.2

2. Experimental details

2.1. Materials and mixture proportions of concrete

The cementitious materials used were ordinary Portland cement 42.5 (P.O.42.5) and class F fly ash based on Chinese Standards [18–20]. Tables 1 and 2, respectively, present the chemical composition and physical properties of cement and fly ash.

Crushed stone with a maximum size of 16 mm was used as coarse aggregate. It had a specific gravity of 2.70 and absorption of 0.21%. Fine aggregate was natural river sand with water absorption of 1.22%, specific gravity of 2.65, and fineness modulus of 2.42 (medium sand). The sand and stone both complied with the requirements of the Chinese Standards [21,22].

The mixture proportions of concrete used in this study are summarized in Table 3. Polycarboxylic superplasticizer, which is suitable for fly ash concrete, was used to achieve a target slump of 90 ± 5 mm.

2.2. Specimens grouping and preparation

The variables and their levels considered in the test included: fly ash replacement (0, 30%), temperature (20 ± 2 °C, 150, 250, 350, 450, 550 °C), micro-environment relative humidity (20%, 45%, 75%, 100%). According to the combinations of these factors, the specimens (150 × 150 × 150 mm) were divided into forty-eight groups (2 × 6 × 4). Each group consisted of eight cube specimens (three for compressive strength testing, three for thermal conductivity testing, one for controlling the high temperature and one for controlling the micro-environment relative humidity).

The concrete mixtures were cast in plastic moulds and compacted with a vibrating table. After 24 h, the specimens were demolded and cured in a standard curing room whose temperature and relative humidity were controlled at 20 ± 2 °C and 90 ± 5%, respectively, until their compressive strength was almost stabilized [23].

2.3. High temperature conditioning

After taking the cured concrete specimens out of the curing room, the specimens were dried at 60 °C in an oven [24]. The specimens which were prepared for controlling the high temperature were used to control the furnace by monitoring the temperature in concrete. By making a hole, thermocouples were embedded at the center of the control specimens. Then, the test specimens and control specimens were put into a GWD-05 high-temperature energy-saving electric resistance furnace, as shown in Fig. 1. According to the requirements of a Chinese Standard and the practical conditions of the test, the heating rate of the electric

Table 1
Chemical composition of cement and fly ash.

Oxide	Na_2O	MgO	Al_2O_3	SiO_2	K_2O	CaO	Fe_2O_3	MnO	TiO_2	P_2O_5	SO_3
Fly ash	0.51	0.75	32.8	54.5	1.4	2.7	4.1	0.02	1.3	0.15	0.4
Cement	0.17	2.5	7.0	22.5	0.78	59	3.3	0.03	0.31	0.1	1.8