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Study on compressive mechanical capabilities of concrete after high temperature exposure and thermo-damage constitutive model

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HIGHLIGHTS

- Thermo-physical properties of concrete at rising temperatures are investigated.
- The mechanical properties of concrete at rising temperatures are investigated.
- The failure modes of concrete at high temperature are investigated.
- The nonlinear elastic constitutive equation of concrete on thermo-damage is established.

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ABSTRACT

Deterioration of mechanical properties of concrete structure, caused by the high temperature of a fire, would seriously threaten people's lives and their properties. This paper aims to study the physical and mechanical properties such as strength, deformation, and elastic modulus and the changing regularity of the failure mode of concrete, with the uniaxial compression tests on C35 concrete being separately carried out under normal temperature and high temperature (300–1200 °C). A nonlinear elastic constitutive equation of concrete on thermo-damage is established on the basis of experiment. And its characteristic parameter is identified by the differential coefficient algorithm. Its reliability is testified by comparing and analyzing the calculated curve and testing curve.

1. Introduction

High temperature in a fire disaster can lead to the deterioration of mechanical properties of concrete, such as the decrease in the stiffness of a structure, the increase in its deflection, as well as surface crack, protective coating scaling, steel exposure, surface peeling, etc. Some practical problems after a fire like the safety degree evaluation of the concrete building and the possibility of the restoration are closely related to the study of mechanical properties of concrete after high temperature exposure [1–4].

Experimental studies and theoretical analyses of the physical and chemical properties of different types of concrete materials after exposure to high temperature have been made both at home and abroad [5–11]. Among which, the structural module study of concrete under high temperature is the key problem of the research of various mechanical properties under the thermal mechanical coupling, which has been attracting attentions from numerous scholars and experts in this field [12–16]. But due to the high demanding requirements for equipment and sensor in high temperature mechanics test, the studies of the effect of high temperature on concrete, at present, are mostly confined to 800 °C below. Unfortunately, the extreme temperature in a fire can amount up to 1100 °C and even higher. Furthermore, the majority of researchers focus on the study of the standard mix concrete. Since, in the practical construction, the concrete is mainly provided by commercial concrete mixing station, which contains large quantity of fly ash, slag, coal ash, and chemical admixture, the research result is a far cry from the practical application.

In this paper, the change of physical and chemical properties of C35 concrete, provided by a commercial concrete mixing station, are analyzed by testing it separately under normal temperature (20 °C)and high temperature (300 °C, 600 °C, 800 °C, 900 °C and 1200 °C respectively). Then, the uniaxial compression tests of the concrete specimens are carried out to study the influence of high temperature on the mechanical properties of concrete in its strength, deformation, failure mode, etc. Based on this experimental study, constitutive equations of the concrete material under

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high temperature are established with the consideration of damage under high temperature. The finite element numerical calculation is adopted to determine the required parameters in the constitutive equation. Then numerical calculation curves have been compared with test curves to demonstrate the reliability of the research method.

2. Experimental research on the physical and chemical properties of concrete under high temperature

2.1. Experimental preparation and operation

In the experiment this research is based on, the heating equipment is a box-type resistance furnace (MOD: SX30/13Q–YC), with a silicon carbide as heating element and high-performance fiber material as thermal insulation parts. The temperature control device is an intelligent temperature controller (MOD: KSY–16C), whose standard deviation of the temperature fluctuation is less than 1 °C. Through the contact of the central microspore between tungsten carbide block and corundum block with the specimen bottom, the actual temperature can be measured, and can also be shown on the temperature controller. The maximum temperature inside the heating equipment can reach up to 1300 °C.

The testing concrete comes from a large local commodity concrete mixing station and its strength grade is C35, widely used in practical construction. The material is put in a specially-made cylindrical steel module, 100 mm in diameter and 200 mm in height. In the concrete, $42.5^{\#}$ ordinary Portland cement is used with limestone pebble and gravel of 5–20 mm as its coarse aggregate and medium sized sand as its fine aggregate. Moreover, the pumping aid and a certain proportion of fly ash and mineral powder are mixed. The list of ingredients of the concrete specimen are shown in Table 1. Then the final composite will be kept in the standard curing room for 28 days at 20 °C and 95% humidity.

During the experiment, power regulation knob is used to control the percentage of load voltage (450 V) of three-phase alternating current so as to control the rate of temperature increase. The larger the percentage, the quicker it increases. To ensure the specimens are heated uniformly and avoid rock bursting, the equipment has to be preheated at the voltage of 75 V for 10 min. After that, the power can be increased to 100 V. Concrete specimens are separately heated at 300 °C, 600 °C, 800 °C, 900 °C and 1200 °C, and then heated at constant temperature for 2 h. The specimens, then, can be taken out after it gets cool by itself in the equipment.

2.2. Experimental results

The pictures of the final specimens are shown in Fig. 1. Compared with the specimen at normal temperature, the baked specimen at 300 °C has black stripes; the baked specimen at 600 °C has red iron rust clearly on the surface; when the baked specimen is heated at 800 °C, its surface turns gray and has some tiny cracks.

When the temperature gets up to 900 °C, the pictures of the baked specimen are shown in Fig. 2. The specimen surface turns grey and white and has a large number of cross cracks. 1 day later, its surface has serious cracks; 2 days later, it spalls off greatly; 3 days later, most of it collapses, and the inside limestone aggregate is completely broken.

When the temperature gets up to 1200 °C, the pictures of the baked specimen are shown in Fig. 3. The moment being taken out, it has a complete form and its surface is melted and shows a layer of hard yellow enamel. But it starts to break after a while. 1 day later, it breaks more seriously; 3 days later, it breaks into small pieces by itself and its aggregate breaks into white porous blocks.

To sum up, when the temperature increases from room temperature 20 °C to 1200 °C, the physical state of the concrete specimen changes clearly. The higher the temperature is, the more damage there would be. Table 2 shows the details of the physical characters of the specimens at different temperature. It also shows both the average mass and volume of the specimen are slightly decreased after high temperature exposure. The former is reduced more, so the density of the specimen is reduced with the increase of temperature.

After analyzing the experimental results, it can be seen that the free water including the capillary water evaporates firstly when the specimens are heated at temperature of around 100 °C. With the increase of temperature, the colloidal hydrated calcium silicate (C–S–H) in cement gets dehydrated, thus causing structural deformation. When the temperature gets over 300 °C, $Ca(OH)_2$ begins to dehydrate and produces CaO, which causes further contraction.

At present, the majority of commercial concrete coarse aggregate in Xi'an is limestone. When the temperature gets over 800 °C, the limestone begins to decompose into quick lime and carbon dioxide. It tends to be fully decomposed at 1200 °C. In the cooling process by itself, the quick lime can absorb the moisture in the air and turns into hydrated lime, whose volume would get larger, which could break the balance of the pressures inside and outside the specimen and leads to expansion crack. We can come to a conclusion that the residual anti-deformation capacity of the concrete with limestone as its aggregate would be quite low when the temperature gets over 800 °C.

3. Experimental study on the compressive mechanical properties of concrete after exposure to high temperature

3.1. Compressive strength and failure mode of concrete after exposure to high temperature

Pressure testing device used in this test is automatic electro-hydraulic servo pressure machine, YA-300, with the maximum pressure strength 300 kN, whose standard deviation is ±1%. The ultimate compressive strength and failure mode of the concrete specimens under normal temperature and high temperature are tested respectively with the pressure testing device. The reached data are enlisted in Table 3. It can be easily found that the compressive strength of specimen baked at 300 °C is 60% of that of the specimen at the room temperature; when baked at 600 °C, its compressive strength is less than half of that of the original; once at 800 °C, it is less than 20% of that of the original. When the temperature rises to 900 °C and 1200 °C, the specimen will lose its compressive strength completely due to the serious damage of its structure.

3.2. Failure mode of concrete after high temperature exposure

As is shown in Fig. 4, after exposure to different temperature, the seriousness of the fracture of the concrete specimen is obviously different. When heated at 300 °C, the specimen will have vertical extension cracks and strip splitting fracture, which is the typical compressive splitting fracture. When heated at 600 °C, the specimen will have oblique cracks, which appear larger in the middle while smaller at both ends, presenting certain crisp cracks caused by the compressive damage. When heated at 800 °C, the middle part of the specimen will be directly destroyed and have bulging fractures. Its compressive strength will be greatly reduced. Both cement colloid and aggregate will crack quite badly, and finally breaks into loose blocks.

3.3. The stress–strain curve of concrete after high temperature exposure

The compression stress–strain curve of concrete is the macro reflection of its mechanical properties, which shows the mechanical properties of concrete under different pressures. Based on the testing data of uniaxial compression, concrete specimens after exposure to high temperature are treated by the average value of weighting via uniaxial compression tests, and then, the stress–strain testing curves are obtained and shown in Fig. 5.

As shown above, the stress strain curve of concrete specimen gradually becomes flat as the heating temperature rises. The peak stress decreases dramatically and is moving to the right, which indicates the compressive strength of the concrete declines after

Table 1
List of ingredients of the concrete specimen.

Item	Cement	Water	Coal ash	Mineral powder	Sand	Stone	Admixture
Ingredient/kg m^{-3}	250	155	90	60	670	1165	10.2
Scale	1	0.62	0.36	0.24	2.68	4.66	0.0408