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Effects of stress and high temperature on the carbonation resistance of fly ash concrete

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HIGHLIGHTS

- Bending tension was adopted in this paper to replace axial tension.
- Different stress states and levels were investigated.
- Concrete showed good carbonation resistance at 30% ultimate compressive strength.
- Concrete showed more defects and decreased anti-carbonization after exposure to 550 °C.

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ABSTRACT

In order to study the carbonation resistance of fly ash concrete under multi-factor coupling conditions and provide a suggestion for the design and analysis of actual projects, an experimental investigation was conducted on the effects of the compressive and tensile stress, the high exposure temperature, and the fly ash content, on the carbonation resistance of fly ash concrete. The process of carbonation was accelerated by using an accelerated carbonation chamber and the carbonation resistance of concrete were examined by measuring the carbonation depth of concrete specimens. Results from the tests indicate that the carbonation resistance of both types of concrete decreased with an increase in tensile stress level, while with an increase in compressive stress level, the carbonation resistance increased first and then decreased. Compressive strength and carbonation resistance of concrete was markedly affected by an increase in exposure temperature; the higher the temperature, the deeper was the carbonation depth. The combination of factors, namely, stress, high temperature and high fly ash content, will greatly reduce the carbonation resistance of concrete.

1. Introduction

Reducing carbon dioxide emissions and curbing global warming have become the global consensus in the 21st century and countries are seeking ways and methods for reducing carbon emission. One effective approach is to extend the useful life of projects. For instance, if the life of an engineering construction can be extended from 10 years to 20 years or 100 years, significant achievements can be made on energy saving and emission reduction. The level of emission reduction can be of several orders, unlike the incremental reduction achieved through conventional improvements. Service life is an important index of an engineering construction, and, for most structures, durability of concrete is a decisive factor for its service life. Therefore, durability of concrete has become a worldwide concern.

Concrete carbonation is one of the important factors that affect the durability of concrete. With the ever increasing consumption of natural resources, carbon dioxide concentration in the atmosphere has continuously increased. Carbon dioxide reacts with cement hydrates in a process called carbonation, which leads to corrosion of steel bars. Many concrete structures around the world have suffered from the loss of durability due to carbonation, so it is urgent to solve the carbonation problem of concrete [1,2].

Many researchers have investigated the carbonation resistance of concrete [3–9] and established several concrete carbonation

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models [2,10–13]. Talukdar et al. [12] developed a numerical model successfully involving the effects of variations in various properties such as porosity, humidity, temperature, atmospheric CO_2 concentrations and chemical reaction rates. Such models have helped to predict the life of buildings. Carbonation studies have been performed on a variety of concrete types including fly ash concrete [4,6–8] and recycled aggregate concrete [3,5].

However in practice, concrete structures are often under complex stress states, and the durability of concrete in the structures can be different from that of unrestrained concrete. In order to reflect the practical scenario, some investigations [14–20] have considered the load or stress in the study of carbonation properties of concrete. Ba et al. [15] reported that the carbonation rate of concrete with low water-binder ration increased exponentially with an increase in tensile stress level. Castel et al. [17] investigated the carbonation resistance of concrete under load and derived a relationship between the carbonation depth of concrete and its internal tensile stress. Jin et al. [18] reported that with an increase in bending load, the carbonation resistance of the tension face of concrete was significantly deteriorated. However, few studies report the effect of compressive stress and are often contradictory. For instance, Tu and Lv [19] concluded that 30%–50% ultimate compressive stress reduced the carbonation rate of concrete while Chen et al. [20] reported that 85% ultimate compressive load accelerated the process of concrete carbonation. Owing to the relatively fewer studies and contradictory findings, and considering that a lot of members in concrete structures are under compressive stress, it is essential to make further research and discussions on this subject, and consequently to improve the accuracy of service life prediction of buildings.

In recent years, frequent building fires have caused huge losses. Fire not only causes loss of life and property, but also causes some damage to concrete in the buildings. Under the action of high temperature in fire, the properties of building materials are deteriorated and the structures are weakened. After fires, in many buildings, concrete materials had different depths of carbonation, which seriously affected the service life of the buildings. However, the published materials [21–23] about the performance of concrete after fire mainly focuses on the strength, elastic modulus, constitutive relationship and other mechanical properties. The durability loss of concrete after fire is seldom studied [23], as are the economical, durable protection and restoration measures to the building. Therefore, it is necessary to investigate this issue and provide a reference for the restoration and reinforcement of fired structures.

In order to provide a suggestion for the design and analysis of actual projects, this paper reports an experimental investigation on the carbonation resistance of fly ash concrete by testing carbonation depth of concrete under multi-factor coupling (three stress states, fly ash content, and high temperature). The process of carbonation was accelerated by using an accelerated carbonation chamber. The effects of content of fly ash, high temperature, stress state, and stress level on carbonation resistance of concrete are discussed.

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 [24–26]. 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% absorption. 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 [27–28].

The mixture proportions of concrete 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 design and grouping

As shown in Fig.1, 2 and 3, specimens with three different stress states were used. The size of unstressed specimens and compression specimens were 100 × 100 × 300 mm and the size of tension specimens were 100 × 150 × 500 mm. During casting the compression specimens and tension specimens, 25 mm diameter ducts (one for compression and two for tension specimens) were constructed by embedding PVC (polyvinyl chloride) tubes into the specimens for inserting the bolt(s). Two steel reinforcing bars (rebars) were placed into the tension specimens with a concrete cover of 25 mm at the bottom. The properties of rebar are shown in Table 4. Since tensile stress in most concrete structures is through bending rather than axial tension, bending tension was adopted in this test to investigate the effect of tensile stress.

The study variables and their levels considered in the test included: fly ash content (0, 30%), temperature (20 ± 2 °C, 150 °C, 250 °C, 350 °C, 450 °C, 550 °C), stress states (unstressed, tensile stress, compressive stress) and stress levels (0, $0.3f_t$, $0.5f_t$, $0.7f_t$, $0.9f_t$; $0.3f_c$, $0.5f_c$, $0.7f_c$, $0.9f_c$). Here f_t is the flexural strength and f_c is the compressive strength of concrete in the specimens. According to the combinations of these factors, the specimens were divided into fourteen groups as shown in Tables 5, 6 and 7.

The high temperature specimens were applied with a stress of $0.7f'_t$, where f'_t is the ultimate flexural strength of the specimens after cooling from high temperature. After different high temperature, the value of f'_t is different.

2.3. Preparation and casting of specimens

The concrete mixtures were cast in wooden 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. Meanwhile, eighteen standard cube specimens (150 × 150 × 150 mm) for both mixtures were prepared for testing the compressive strength of concrete during the curing period.

2.4. High temperature conditioning

After taking the cured concrete specimens out of the curing room, the specimens were dried at 60 °C in an oven [29]. The specimens used for high temperature were put into a GWD-05 high-temperature energy-saving electric resistance furnace. According to the requirements of a Chinese Standard and the practical conditions of the test, the heating rate of the electric resistance furnace was set at 5 °C/min. When the temperature reached the predefined temperature, the specimens continued to be heated at the constant temperature for an hour to simulate the heating time of real fire. After heating, the specimens were taken out and cooled down to room temperature in the ambient room temperature.

2.5. Testing procedure and measurement

2.5.1. Testing of specimens

Before testing the specimens, as shown in Figs. 4 and 5, the compression and tension specimens were assembled by using 8.8