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Effect of curing temperature on creep behavior of fly ash concrete

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HIGHLIGHTS

- We examined the creep of concretes cured under temperatures of 20 °C, 50 °C and 90 °C.
- The influence of temperature was analyzed by a variety of microscopic analysis.
- The main factor of effecting creep is quantity and microstructure of C–S–H gel.
- The hydration products have a trend of crystallize under curing temperature of 90 °C.

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ABSTRACT

To investigate the effect of curing temperature on creep behavior of fly ash concrete, the specific creep of concretes, with the water-binder ratio of 0.33 and different fly ash replacements of 20% and 40%, cured under temperatures of 20 °C, 50 °C and 90 °C was examined. All concrete specimens were loaded at 33% of their compressive strength to measure the creep, when they had an equivalent cubic strength of (48.0 ± 2.0) MPa. Based on the amount of non-evaporable water, the porosity and pore size distribution of hardened cement pastes, the scanning electron microscope (SEM) morphology of hydration products and X-ray diffraction (XRD) analysis, the influence of curing temperature on creep of fly ash concrete was analyzed. The results show that when concretes were loaded with the same stress level, the main factor influencing creep of fly ash concrete was the quantity and microstructure of C–S–H gel. Compared with the concrete with 20% fly ash dosage under the curing temperature of 20 °C, the concrete cured under the temperature of 50 °C produced more hydration products, with a slight decrease of $Ca(OH)_2$, and the specific creep of which is close to the reference concrete. At the curing temperature of 90 °C, concrete also produced more C–S–H gel, with a great decrease of $Ca(OH)_2$, and the total specific creep after 360 days is 87.1% of the reference concrete. The hydration products had a trend of crystallizing under temperature of 90 °C and fly ash concrete produced a few hydration products of Tobermorite which could reduce the creep evidently. The concrete with 40% fly ash dosage under the cuing temperature of 50 °C also produced more hydration products, but the specific creep of which increases significantly and is 119.5% of the reference concrete.

1. Introduction

Due to its design versatility, availability and cost efficiency, concrete continues to play a dominant role in the construction industry. However, the production of Portland cement, a primary component of typical concrete mixes, is known to have a serious impact on the environment [1]. Increasing the use of supplementary cementitious materials in concrete is an obvious and necessary step to reduce carbon emissions. Supplementary cementitious materials, such as ground granulated blast-furnace slag and fly ash, have been widely used in concrete due to the decrease of energy, the resources consumption and the protection of environment [2,3]. As a long-term deformation of concrete performance, creep can make the loss of prestress and the increase of deformation of the prestressed reinforced concrete structures. At the same time, the creep is a focal point that whether fly ash can be used widely in the prestressed reinforced concrete structures such as large bridges. In recent years, a lot of scholars have achieved some progress from many studies about the creep of fly ash concrete. Day et al. [4] studied the shrinkage and creep of different fly ash concretes (fly ash dosage of 30% and 50%, concrete strength of 25 MPa and 45 MPa, loaded with the same stress level at different ages), and found that the incorporation of fly ash can lower the

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shrinkage and creep as compared with the reference group without fly ash. Alexander et al. [5] researched the influence of fly ash on the creep of concrete with a load of 40 MPa and a slump of 75 mm. The results showed that creep of concrete with 25% high quality fly ash reduced about 30%. Hui et al. [6] studied the creep of fly ash concrete which was loaded after 7 days to keep 180 days. The creep of concrete with 20% fly ash and that of reference group basically unchanged, while the creep of concrete with 40% fly ash was higher than the reference group by 17%. In recent years, as a typical structural material, high performance concrete (HPC) is widely used in civil engineering because of its excellent performance, namely high workability, high strength, high durability and long-term performance [7]. Zhao et al. [8] observed the specific creep of HPC incorporated with 0, 12% and 30% fly ash under the stress-to-strength ratio of 33%, and concluded that the specific creep of HPCs with 12% and 30% fly ash after 1 year were 0.76 and 0.465 times that of HPC without fly ash, respectively.

Curing temperature not only affects the final hydration degree of Portland cement and the hydration reaction rate, but also the types, properties, stability and shape of hydration products [9–10]. Recently, some researchers have done a lot of studies about the hydration products of cement–fly ash pastes and fly ash concrete under high temperature. Hanehara et al. [11] studied the reaction of fly ash under different curing temperatures and found that a higher curing temperature would prompt the reaction of fly ash in cement paste. Curing temperature affects the inner and outer C–S–H gel structure, and Martinez-Ramirez [12] found that the C–S–H gel formed under the condition of 80 °C had a trend of fibrosis. Gallucci [13] found the similar trend, i.e. under the condition of high temperature C–S–H gel showed more fibrous. Jiang et al. [14] studied the effect of steam curing condition and composition of cementitious materials on hydration degree and hydration products of compound cementitious materials with high dosage of fly ash. Their results showed that the steam curing had no effect on the variety of hydration products but much effect on their amount and improved pozzolanic activity of mineral admixtures. Wu et al. [15] researched the variety and pattern of hydration products of fly ash concrete under different high pressure steam curing conditions by means of scanning electron microscope, X-ray diffraction analysis and EDS. They found a lot of hydration products of Tobermorite in stable crystalline phases under high pressure and high temperature steam curing and also found some hydration products of Tobermorite in poor crystalline phases under atmospheric steam curing.

Fly ash is a weak pozzolanic material, and the pozzolanic reaction of fly ash does not start until sometime after mixing [16,17]. However, fly ash is active under the high temperature. Fly ash can react with $Ca(OH)_2$ easily under high temperature, and this reaction is sensitive to the temperature. The result of the reaction would influence the quantity and microstructure of hydration products, and then influence the shrinkage and creep of concrete. In general, high curing temperature increases the rate of development of autogenous shrinkage but reduces later age autogenous shrinkage, and vice versa for low curing temperature [18]. Some scholars have done a few studies about the shrinkage and creep of concrete under different curing temperature. The researchers [19] found that the autogenous shrinkage depends strongly on the imposed temperature regime, and that the amplitude of autogenous shrinkage was reduced in the cooling phase when subjected to variable temperature tests and that autogenous expansion occurred in some instances. Nagataki et al. [20] studied the concrete creep under high pressure steam curing and found that the creep of concrete with 40% of fly ash was the same as the reference group. Manh-Huyen et al. [21] did some uniaxial creep tests, which had been performed at ambient temperature on a saturated hardened class G cement paste hydrated at 60 °C and 90 °C and found that creep was enhanced at higher curing temperature. However, Sakata [22] found an opposite result by studying the creep of concrete cured at temperatures ranging from 5 °C to 35 °C. The curing temperature affected the microstructure because it influenced the kinetics of the chemical reactions which occurring during the hydration process.

The creep has a close relationship with the strength of the concrete [23], and the development law of strength of fly ash concrete cured under high temperature is obviously different from that under the room temperature. Researchers [24] thought the effect of curing temperature on strength development of concrete was that in the early age, compared with the condition of low temperature curing, a high temperature curing would increase the strength. The reason was that concrete produced more hydration products quickly under the condition of higher temperature, resulting in higher early strength.

Atmospheric steam curing is a heat treatment which has been used for many years to accelerate the strength development of concrete products and save curing time [25]. However, there is little research on the creep of fly ash concrete cured under atmospheric steam curing, based on a wide variety of the microscopic analysis, such as the porosity and pore size distribution of hardened cement pastes, SEM morphology of hydration products and XRD analysis. Through the past researches [26–28], there are a lot of factors influencing concrete creep. In order to avoid the influence of other factor on the creep of fly ash concrete, in the present study, the fly ash concretes are loaded with the same stress-to-strength ratio when they got similar compressive strength. The specific creep of concretes with the water-binder ratio of 0.33 and different fly ash replacements of 20% and 40%, which are cured under different temperatures of 20 °C, 50 °C and 90 °C, is examined at a stress-to-strength ratio of 33% in a controlled environment of 20 ± 2 °C and relative humidity of 60 ± 5%. To investigate the effect of curing temperature on creep of fly ash concrete, the amount of non-evaporable water of paste with same mixture proportion of concrete, the porosity and pore size distribution of hardened pastes, the SEM morphology of hydration products and XRD analysis are analyzed to provide evidence for the result of creep of fly ash concrete.

2. Experimental

2.1. Materials

The cementitious materials used in the experiment were Portland cement and fly ash, whose chemical components and specific surface area are shown in the Table 1. Fine aggregate was river sand with the fineness modulus of 2.7 and the apparent density of 2 650 kg/m^3. Coarse aggregate was crushed limestone with the size of 5–16 mm and the apparent density of 2 780 kg/m^3. A naphthalene water reducer with a water-reducing rate of 21% was employed to achieve a target workability.

2.2. Method

2.2.1. Preparations of concrete samples and creep test of concrete

According to ASTM C512 [29], the concrete shrinkage and creep were tested by electrometric method which is a way to measure the strain of components with resistance strain gauge as shown in Fig. 1.

Table 2 shows the mixture proportion of fly ash concrete with the water-binder ratio of 0.33 and different fly ash replacements of 20% and 40%. The slump of each mixture was controlled within (100 ± 10) mm by adjusting the dosage of superplasticizer. The samples whose original size was 40 mm × 40 mm × 160 mm were tested to measure creep and shrinkage of fly ash concrete. The samples whose original size was 100 mm × 100 mm × 300 mm were to verify the uniform degree of coarse aggregate of the specimens in different size. The samples whose original size was 100 mm × 100 mm × 100 mm were tested to measure the cubic strength. All concrete samples were cured in standard curing box of a controlled environment of 20 ± 2 °C and relative humidity ⩾95% and steam curing box for the reservation ages. In this paper, the first pre-cuing time of concrete curing under steam for temperature of 50 °C and 90 °C was 4 h. To avoid concrete producing larger temperature stress and temperature crack due to the large temperature difference between inside and