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Drying shrinkage and cracking resistance of concrete made with ternary cementitious components

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HIGHLIGHTS

- Compressive strength of concrete cured under drying shrinkage is investigated.
- Slag and fly ash show different influences on drying shrinkage of concrete.
- The cracking resistance of concrete is more controlled by total drying shrinkage.
- Factorial design method is applicable for mixture proportion design.

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ABSTRACT

The compressive strength, free and restrained drying shrinkage and cracking resistance of concrete under drying condition were investigated for ternary cementitious systems containing Portland cement, slag and fly ash. The restrained shrinkage test (ring test) was carried out following ASTM C1581. The results showed that the increased replacement level of slag or fly ash from 0 to 50% led to a gradual decrease in 28d compressive strength of concrete. The free drying shrinkage increased with the increase of slag content, but reduced with the fly ash content. The cracking resistance was well related to the free drying shrinkage of concrete, other factors such as strength also showed certain effects on cracking resistance of concrete. The cracking resistance of concrete was enhanced with the addition of fly ash while weakened with the slag replacement level up to 50%.

1. Introduction

Higher shrinkage induced cracking increases the risk of penetration of aggressive substances into concrete. During the hydration or drying process of concrete, the decrease of absolute volume for the materials leads to the generation of inner stress. When this stress develops to an extent greater than the strength of concrete, cracking initiates. The cracking of concrete will accelerate the penetration of water and other aggressive substances, and thus exacerbate the deterioration of concrete [1,2].

Supplementary cementitious materials (SCMs), such as blast furnace slag and fly ash are widely used to partially replace Portland cement. The influences of these SCMs on shrinkage and subsequent cracking of concrete are significantly related to their physical properties, chemical and mineral component. Previous studies [3] showed that the use of fly ash and slag with fineness comparable to cement particles in concrete can efficiently restrain the cracking and show superior durability performance than concrete without SCMs. However, some studies [4,5] also found that fly ash only had small effects on reduction of drying shrinkage of concrete at late stage. Obla et al. [6] showed that the drying shrinkage were similar for concrete with and without fly ash, while the addition of fly ash slightly increased the restrained cracking resistance of concrete. For appropriately cured slag-blend concrete or when ultrafine ground-granulated blast-furnace slag (GGBS) is used, the amount of AFt ($Ca_6Al_2(SO_4)(OH)_{12}{\cdot}26H_2O$) and calcium silicate hydrate (C-S-H) and the density of hardened cement paste can be greatly increased, which makes concrete more resistant to shrinkage and cracking [7]. While a recent study [8] indicated that the expansive strain due to the formation of AFt at early stages for slag-blended concrete was cancelled by its higher creep. Low Blaine slag was considered to be inappropriate for improvement

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of cracking resistance of concrete. Based on the investigation on different factors contributing to early age shrinkage cracking in concrete, Aly and Sanjayan [9] found that the influence of the tensile elastic modulus is a major consideration for early age cracking of slag-blended concretes.

Free drying shrinkage and restrained cracking resistance is very important for mechanical properties and durability of concrete. Different SCMs such as slag, fly ash and silica fume have been used to decrease the drying shrinkage and enhance the cracking resistance of concrete [10,11]. The drying shrinkage of cement-fly ash-silica fume ternary mortars was measured in the study of Wongkeo et al. [12], the drying shrinkage of cement mortar with 100% Portland cement was higher than all of other groups. Hale et al. [13] investigated the drying shrinkage of concrete mixtures with ternary system cement-slag-fly ash and found that the shrinkage was decreased with slag addition while fly ash showed no effects on the shrinkage of concrete.

In 1958, Simplex-lattice Design was introduced by Scheffe [14], on which many design methods were developed, such as simplex centroid design and the extremeness vertex design. Factorial design method, a method to correlate the compositions of ternary composite cements with different performance of samples with only seven batches of experiments [15], has been applied in studying hydration properties [16], strength [17], ASR expansions [18] and chloride-ion permeability [19] for presenting the relationship between material properties and components in a global way and optimization of cementitious materials composition. In the study of Shi et al. [18], the efficiency of the factorial design method was verified by comparing the experimental and predicted results, and the results correlated very well.

Slag and fly ash are two kinds of SCMs commonly applied in civil engineering for partly replace Portland cement and improve the mechanical and durability performance of concrete structure [20,21]. The influences of slag or fly ash on shrinkage and cracking resistance have been widely studied, the reduction of compressive strength from fly ash [22] and increase of drying shrinkage from slag [23] were considered to increase the risk of concrete cracking when slag or fly ash was incorporated. The studies on how combination of slag and fly ash in cement concrete may affect the shrinkage and cracking resistance is of great interest for application of industrial waste and enhancement of concrete structure performance. By applying factorial design method, the synergetic effects of slag and fly ash on shrinkage and cracking resistance of concrete can be studied integratedly and provide some information about the determination and optimization of mixture proportion.

This paper studies the strength, drying shrinkage and cracking resistance of concrete with cement-slag-fly ash ternary cementitious materials. The single and synergetic influences of slag and fly ash on shrinkage and cracking resistance of concrete are discussed. The effects of strength and drying shrinkage on cracking resistance of concrete are also discussed. In the aid of factorial designing method, optimal cementitious materials proportion for higher compressive strength and cracking resistance can be presented.

2. Experimental

2.1. Raw materials

A Portland cement (PO. 42.5) with the specific surface area of 336 m^2/kg was used. Grades II fly ash and S95 slag according to GB/T18046-2000 were used as SCMs. The chemical compositions of the Portland cement, fly ash and slag are shown in Table 1. In accordance with GB/T1596-2005, the residue fly ash on sieve with 45 μm square hole is 6.2%. The density and specific area of slag is 2900 kg/m^3 and 446 m^2/kg, respectively. The aggregates used in this study were river sand with fineness modulus of 2.8 and gravel with continuous gradation between 5 and 16 mm. In order to improve the workability, polycarboxylate based superplasticizer (water-reducing rate 30.6%, solid content 18.24%) was also applied.

2.2. Concrete mixture proportion and specimen preparation

Ternary binder materials comprising of Portland cement, fly ash and slag were designed using a factorial design method as previously used in Ref. [18]. The mix proportions of the binder materials are shown in Table 2 and projected in a ternary diagram as shown in Fig. 1. Concrete mixtures with three different water-to-binder (w/b) ratios, as shown in Table 3, were prepared.

In this study, three components x_1, x_2 and x_3 are defined as the percentage of Portland cement, fly ash and slag, and the sum of x_1, x_2 and x_3 is 100%. Then the value of responses Y, including any mechanical and durability characteristics of ternary cementitious materials can be obtained as:

$$Y = b_1x_1 + b_2x_2 + b_3x_3 + b_{12}x_1x_2 + b_{13}x_1x_3 + b_{23}x_2x_3 + b_{123}x_1x_2x_3$$

·b_i b_{ij} and b_{ijj} (i, j = 1, 2, 3) are coefficients to be estimated. Based on the equation shown above and experimental results of 7 mixtures, the values of 7 coefficients b can be calculated by data fitting. Then the contour lines in ternary diagrams with different characteristic parameters, such as compressive strength, drying shrinkage and cracking time were plotted. The software Surfer 8.0 was used for drawing.

Concrete samples were prepared according to the mixture shown in Tables 2 and 3. For compressive strength and drying shrinkage measurement, concrete was cast in molds with the size of 75 mm × 75 mm × 285 mm. In addition, pre-embedded probes were fixed at both ends of the specimen for drying shrinkage test. After casting, the specimens were covered with plastic films and stored in a standard curing room at 20 °C and relative humidity higher than 98% for 24 h. After demolding, samples were moved to a drying room at 23 ± 2 °C and relative humidity of 50 ± 4%.

For restrained cracking measurements, fresh concrete was filled into the space between two concentric steel rings. The concrete samples without demolding were cured at temperature of 20 ± 2 °C and relative humidity above 95% for one day. After that, the outer rings were removed and all samples with inner rings were moved to a dry room with constant temperature (23 ± 2 °C) and relative humidity of (50 ± 4%).

2.3. Testing methods

2.3.1. Compressive strength

The compressive strength was tested 28 days after mixing with one day curing in standard room and 27d of drying under condition of 23 ± 2 °C and relative humidity 50 ± 4%. The compressive strength was tested on two opposite lateral side of samples and area of 75 mm × 75 mm was pressed. Three samples were tested for each group and the average value was reported.

2.3.2. Free drying shrinkage

In this study, drying shrinkage of concrete was measured according to method described in ASTM C157-75. The length change of specimen was measured using vertical comparator. Three specimens were prepared for each mixture. The initial length of specimens (L_0) was measured two hours after the samples were demolded. The length (L_t) was measured at 1, 3, 7, 14, 21 and 28 days after the initial measurements. The drying shrinkage of the concrete at age of *t* days (ε_{st}) can be calculated as follows. The reported value for each mix is the average of three measurements.

$$\varepsilon_{st} = \frac{L_0 - L_t}{L_0} \times 100\% \tag{1}$$

2.3.3. Restrained shrinkage

The restrained shrinkage of concrete was measured according to ring test described in ASTM C1581. The mold for restrained cracking resistance measurement are shown in Fig. 2 [24]. The outer ring of the steel mold has an inner diameter of 406 mm, while the inner ring has an outside diameter of 330 mm. The inner steel ring has a thickness of 13 mm with four strain gages mounted for strain measurement. The cracking time to the nearest 0.25 day of each specimen was determined after the drying was initiated. The measurements were continued until the sharp change of the strain was observed.

3. Results and discussion

3.1. Compressive strength

The contour lines of compressive strength of samples for different batches at 28 days in ternary diagrams are plotted in Fig. 3. The compressive strength of concrete was gradually decreased with the increase of total SCMs content, which was more remarkable for samples with lower w/b ratio. The compressive strength of concrete in this study is more affected by fly ash than slag. It should be noted that the contour plots of the part with cement content