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Design of high performance concrete with multiple performance requirements for #2 Dongting Lake Bridge

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HIGHLIGHTS

- A mixture design method with multiple performance requirements was used.
- A cementitious composition range meeting all requirements was obtained.
- The designed mixture was suitable for the construction of #2 Dongting Lake Bridge.

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ABSTRACT

Proper mixture design of concrete is of great significance for the quality of the concrete materials and structures. For #2 Dongting Lake Bridge in China, several performance requirements were required for designed concrete mixtures, including compressive strength, drying shrinkage, cracking resistance, alkali-aggregate reaction, permeability, and carbonation resistance. In this study, a mixture design method of concrete with multiple performance requirements was used to design C55 concrete for the project. The relationships between cement-fly ash-slag ternary cementitious composition and different properties were established based on the seven-batch factorial design method. Based on the requirements for different properties, a composition range meeting all requirements could be obtained. The verification tests showed that the designed mixture was suitable for the construction of #2 Dongting Lake Bridge.

1. Introduction

High performance concrete (HPC) is a type of concrete designed to meet the service requirements of structural applications. Except for the sufficient compressive strength, the workability, early-age properties, durability and even ecology requirements are also needed to be considered [1]. Typical applications of HPC include infrastructures in harsh environments, nuclear power project, hydroelectric structures, large-scale bridges, highway pavements, the marine engineering, tunnels, etc. [2,3]. In a word, HPC can be used to build a large number of durable structures at a comparable cost.

Over the last three decades, several methods have been proposed to design the HPC. Based on the ACI mix design procedure [4], Bharatkumar et al. [5] proposed a modified mixture proportion design method considering the efficiency factor of supplementary cementitious materials (SCMs). Results showed that an economical HPC mixture could be obtained when the superplasticizer and SCMs were simultaneously used by this modified method. Deficiently, only some limited durability properties containing the coefficient of absorption and sorptivity were considered. Chang et al. [6,7] and Zhang et al. [8] proved that the densified mixture design algorithm could produce HPC with good workability, required strength and durability. Raj et al. [9] combined the BIS and ACI methods and proposed a simplified mixture design procedure for high strength concrete, and the fresh and hardened properties of obtained concrete mixtures were acceptable. Based on the influences of water film thickness and excessive paste thickness on the performance of mortar [10], Li et al. [11] developed a mixture design chart for concrete, which could estimate the flowability and compressive strength of concrete according to the combination of water film thickness and excessive paste thickness. The nature of this method was based on the minimum paste theory. Coincidentally, Ji et al. [12] put forward a mixture design method for manufactured sand concrete according to the minimum paste theory.

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The stability and cracking resistance of concrete designed by this method was expected to be enhanced.

As mentioned before, durability is an essential property to be considered in the mixture design of concrete. Younsi et al. [13] stated that the designed concrete mixtures with high fly ash content obtained with the performance-based approach were suitable for the construction site with the requirements of the exposure classes XC1 and XC2 in EN 206-1 Standard. Based on the ideal grading curve, i.e. Fuller curve, Elrahman and Hillemeier [14] provided an experimental approach to optimize HPC with low cementitious materials content. The mechanical properties and some durability properties such as permeability, water adsorption and chloride diffusion were selected to assess the feasibility of this method. Recently, Amario et al. [15] proposed an optimal mixture design method for recycled aggregates concrete by using the Compressive Packing Model [16]. Afterwards, mechanical properties, water absorption, and permeability tests were employed to experimentally validate the proposed method. Interaction among the various materials is another crucial factor to be considered as it can cause wide variations in workability, mechanical properties and durability. Furthermore, the effects of SCMs on properties of concrete are hugely dependent on the physical and chemical properties of SCMs, mix proportions and compatibility with superplasticizers. Maintaining a simultaneous balance between strength and multiple durability properties at the same time is still a difficult technical issue.

In our previous studies [17,18], a method for mixture design of concrete with multiple performance requirements was proposed. The design procedure is as follows: (1) the sand to aggregate ratio is first determined according to the close packing theory; (2) the water to cementitious ratio is selected based on strength and durability requirements; (3) the dosage of chemical admixtures such as superplasticizer and viscosity modifying agent is added to reach desirable workability of fresh concrete; (4) the optimum paste content can be determined by the excess paste theory; (5) factorial design method is designed to establish the relationships between composition of cementitious materials and different properties of concrete; and (6) a mixture proportion of concrete with multiple performance requirements is determined based on the overlapped composition with desirable properties.

In the present study, this method was applied to design the high-performance concrete for #2 Dongting Lake Bridge in China, with 100-year design service life required. The performances of designed mixtures were characterized by compressive strength, drying shrinkage, cracking resistance, alkali-aggregate reaction, permeability, and carbonation resistance. The effects of fly ash and slag on mechanical properties and durability were also discussed. At the same time, the factorial design method was used to provide a guide for predicting the performance of concrete with ternary cementitious components.

2. Materials, mix proportions and test procedures

2.1. Raw materials

In this study, the used cement was 42.5 moderate heat cement. Ground slag and fly ash were selected as SCMs to replace part of cement. The average particle size of cement, fly ash and ground slag were 16.49 μm, 5.54 μm and 11.03 μm, respectively. The chemical compositions of cementitious materials are presented in Table 1. The maximum particle size of gravel from Xiangjiang River was 25 mm. The apparent density and packing density of gravel were respectively 2630 kg/m^3 and 1590 kg/m^3. Fine aggregate was Xiangjiang River sand with fineness modulus of 2.81. The apparent density and packing density of river sand were 2660 kg/m^3 and 1570 kg/m^3, respectively. Sand and gravel grading curves are given in Fig. 1. A polycarboxylate-based superplasticizer with the solid content of 20% was used.

2.2. Mixes proportions

According to the proposed design method [17], the water-to-cementitious (w/c) ratio was determined at 0.33 and the dosage of superplasticizer was kept fixed at 0.9% by mass of cementitious materials for the desired concrete of C55. The proportions of water, total cementitious materials, sand and gravel were respectively 145.2 kg/m^3, 440 kg/m^3, 746 kg/m^3, and 1120 kg/m^3. The seven-batch factorial design method was selected to establish the relationships between cement-fly ash-slag ternary compositions and different properties of concrete. The composition design and proportions of concrete are shown in Table 2 and Fig. 2.

2.3. Testing procedures

2.3.1. Compressive strength

According to GB/T 50081 [19], which is similar to BS EN 12390-3 [20], the compressive strengths at 28 days were measured. The size of specimens was 150 mm × 150 mm × 150 mm, and the average value of three samples for each batch was taken as the compressive strength.

2.3.2. Drying shrinkage

According to ASTM C157 [21], the drying shrinkage was obtained using three 75 mm × 75 mm × 285 mm prisms for each group. After pouring into the mold, the molded specimens were immediately cured in a standard curing room for 24 hours, where the temperature was 20 ± 1 °C and relative humidity was 98%. Then, the concrete specimens were demolded and continued curing for another 48 hours. Before the specimens were transferred into a chamber with temperature of 20 ± 2 °C and relative humidity of 50 ± 5%, the original length of specimens was measured. The length of specimens at 3 days and 28 days were measured to assess the drying shrinkage of concrete.

2.3.3. Cracking resistance test

Cracking resistance of concrete was measured following ASTM C1581 [22]. The inner and outer diameters of steel rings are 330 mm and 405 mm, respectively. The wall thickness and height of the rings are 13 mm and 150 mm, respectively. The concrete ring specimens were cured for 24 hours in a room with the temperature of 23 ± 2 °C and relative humidity of 50 ± 4%. After demolded, the top surface of concrete specimens was coated with paraffin wax. Strains of the steel ring were obtained according to the four attached strain gauges in the inner steel ring. The strain gauges recorded strain every 15 min until a sharp change of the strain was observed.

2.3.4. Alkali-aggregate reaction

The alkali-aggregate reaction expansion of sand is determined by the accelerated mortar bar test according to ASTM C1260 [23]. The mass ratio of cementitious materials to sand was set as 1:2.25, and the w/c was kept fixed at 0.47. Prisms with the size of 25 mm × 25 mm × 275 mm were prepared. The initial length of specimens was measured after 24 hours of casting. Afterwards, all the specimens were immersed into water at 80 °C for 24 hours, followed by submerging in a sealed plastic container with 1 N NaOH solution of 80 °C. The average of three prisms is regarded as the final reported expansion.

2.3.5. Chloride migration

The non-steady state migration test following NT Build 492 [24] was selected to test the chloride migration coefficient. After curing