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The performance of high-strength flowable concrete made with binary, ternary, or quaternary binder in hot climate

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HIGHLIGHTS

- HSFC made with high contents of SCMs can be used in hot climates without a negative effect on the 28-day compressive strength.
- Using HSFC in hot climate slightly reduces the free shrinkage compared to control mixture under similar curing conditions.
- Using HSFC in hot climate slightly increases the compressive strength and reduces concrete permeability.
- The performance of HSFC made with high contents of SCMs in hot climates was better than that of concrete made with 100% cement.

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ABSTRACT

This paper investigates the performance of high-strength flowable concrete (HSFC) made with binary, ternary, or quaternary binder and with up to 70% of Portland cement replaced by supplementary cementitious materials (SCMs). Materials used as partial replacement of cement include class C and class F fly-ash, ground granulated blast furnace slag, and silica fume. A total of 16 concrete mixtures were prepared and tested. Two sets of concrete samples were prepared from each mixture. One set was cured under normal curing conditions (i.e. in a conventional curing room until the day of testing or in the curing room for the first 7 days and air cured for the remaining of the study) and the second set was cured in the curing room for the first 7 days and then exposed to a temperature of 46 °C (115 °F) in the oven on a 12-h based cycles until testing. Results showed that HSFC made with high volume of SCMs and exposed to hot climate condition performs similar, in some cases superior, to that of a similar concrete cured under normal condition.

1. Introduction

The use of high-strength flowable concrete (HSFC) in the recent construction of the tallest standing reinforced concrete structure in the world (Burj Khalifa), in one of the hottest region in the world (Dubai, UAE), has raised a question about the performance of such concrete in hot climate. In addition, HSFC has become the choice of most engineers in the design and construction of extremely tall reinforced concrete structures. The surrounding environment of such structure plays an important role in its long-term performance as well as the performance of such concrete during construction. Concrete compressive strength is usually considered one of the most important concrete properties, especially for the construction of high-rise buildings. Structural members built using high strength concrete are usually congested with reinforcing bars, which makes concrete placement more difficult and might leads to honeycombing and durability concerns. To alleviate this problem, HSFC is recommended.

The mechanical properties of concrete in general and concrete compressive strength in particular, are mainly affected by the composition of the mortar matrix, aggregate properties, and the aggregate–mortar interface. Nowadays, producing concrete with 28-day compressive strength as high as 70 MPa (10,000 psi) is an easy task and that can be achieved by using chemical and pozzolanic admixtures combined with a low water-to-binder ratio (w/b). To achieve a workable and stable concrete on the other hand, one can relatively increase the w/b ratio or use high range water reducing admixtures (HRWRAs). Increasing the w/b ratio alone might inflict destructive effect on concrete durability, especially in harsh environment and one should be careful in balancing between a required high compressive strength and a desired workability and durability. The addition of pozzolanic admixtures, such as fly ash (FA) and silica fume (SF) and cementitious materials, such as ground granulated blast furnace slag (SL) are often used to modify the microstructure of the mortar matrix and to enhance the transition zone surrounding coarse aggregate particles [1]. The

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effect of high temperature on the mechanical properties of typical HSFC is not well established and research on this subject is very limited.

The behavior of ordinary concrete in hot climate was studied [2], the study included the effect of elevated temperature, ambient and initial paste temperature, ambient relative humidity, solar radiation, and water/cement ratio on the rate of Portland cement hydration and hydration product structure. Berhane [2] concluded that the published works on the properties of concrete in hot climates are incomplete, uncoordinated and at times contradictory. Mustafa and Yusof [3] reported that the modulus of elasticity is reduced when concrete subjected to hot-humid climate and the target concrete strength in hot climate could be achieved. An experimental study on the performance of self-consolidating concrete (SCC) subjected to different temperatures (150, 300, 450 and 600 °C) and at ambient temperature is conducted [4]. The temperature was applied constantly at the target temperature for 1 h before cooling. Specimen mass was measured before and after heating in order to determine the loss of water during the test. The results allowed analyzing the degradation and mass loss of SCC due to heating. He compared the results of light weight self-consolidating concrete with those of normal weight concrete and concluded that the behavior of both concretes are similar under elevated temperature.

Laboratory investigations carried out [5] to study the effects of high temperatures ranging from room temperature to 800 °C on the compressive strength of different water-to-cement ratios high-strength SCC. It was found that the compressive strength at high temperatures decreases. Compared with normal-strength SCC, high-strength SCC possesses a higher compressive strength when exposed to high temperature. It was also found that the addition of polypropylene fibers decreased the compressive strength and increased the probability of explosive spalling.

Another experimental study on the strength retention and impermeability aspects of self-compacting, high-volume fly ash concrete mixes under elevated temperatures was reported [6]. In this study, [6] investigated the effect of elevated temperatures, in the range of 200–800 °C, on the properties of five SCC mixtures. The mixtures were prepared with more than 60% of cement replaced by fly-ash. The results were assessed in terms of weight loss, reduction in the compressive and tensile strengths, and concrete permeability measured using the rapid chloride permeability test. Results indicated that the weight loss of concrete specimens significantly increases by increasing temperature, with sharp variations beyond 600 °C. The study also shows lower permeability and better strength-retention for self-compacting high-volume fly-ash concretes at high temperatures.

The effect of extreme weather conditions on concrete properties was also studied [7]. He prepared, mixed, and cured concrete specimens at constant temperatures of 8 °C, 25 °C and 50 °C, for the first three days. After 3 days, all concrete samples were cured at room temperature. The study showed that high temperature slightly increases the compressive strength of concrete at early age but considerably reduces strength at a later date. Naus [8] also conducted a literature review on the effect of elevated temperature on concrete materials and structures. He concluded that loss in the compressive strength of concrete specimens at elevated temperatures is more noticeable if moisture is not permitted to escape during heating. He also noted that the decrease in concrete's modulus of elasticity due to exposure to elevated temperatures is more pronounced than that of the concrete compressive strength.

The performance of SCC and normal concrete subjected to elevated temperature up to 800 °C and for exposure duration up to 120 min was investigated [9]. They concluded that residual compressive and tensile strength of self-consolidating concrete were higher than those of normal concrete. Vasusmtha and Srinivasa [10] also studied the mechanical properties of high strength self-compacting concrete subjected to elevated temperature of 200, 400 and 600 °C with exposure duration of 4, 8 and 12 h. They stated that loss in compressive strength and split tensile strength was about 24% and 18% at 200 °C and 400 °C for 12 h, respectively. All specimens were totally powdered when exposed to 600 °C for 4, 8 and 12 h.

Khaliq and Kodur [11], investigated the effect of temperature on thermal and mechanical properties of self-consolidating concrete and fiber reinforced self-consolidating concrete (FRSCC). The properties like specific heat, thermal conductivity, and thermal expansion were conducted by [11]. The mechanical properties; compressive strength, tensile strength and elastic modulus were in a temperature range of 20–800 °C. The study showed that the presence of steel fibers improve high temperature splitting tensile strength and elastic modulus. The thermal expansion of FRSCC is slightly higher than that of SCC in 20–1000 °C range.

Mechanical characteristics of self-consolidating concretes subjected to elevated temperatures up to 700 °C were experimentally investigated by Sideris [12]. Different concretes of self-consolidating concretes of different strength classes were produced. Heat is applied at a rate of 5 °C/min at the age of 120 days using an electrical furnace to reach a maximum temperature of 100, 300, 500, and 700 °C for 1 h. Specimens were then allowed to cool in the furnace and tested for compressive strength, splitting tensile strength. The results were compared to specimens prepared and cured at room temperature. Residual strength of all concrete groups was reduced and explosive spalling occurred at temperatures greater than 380 °C. The residual compressive strength of self-consolidating mixtures was higher than the one of conventional concrete mixtures for the same strength group.

2. Experimental work

A total of 16 concrete mixtures, divided into two groups, were prepared and tested in this study. The first group (GI) consists of 9 mixtures made with water-to-binder ratio (w/b) of 0.3 and includes one control mixture and 8 mixtures made with high content of SCMs as partial replacement of cement. Mixtures in the second group (GII) however, were made with w/b ratio of 0.33 and also include a control mixture and 6 other mixtures made with high content of SCMs as partial cement replacement. All mixtures were prepared in accordance with ASTM C192-07 [13] "Standard Practice for Making and Curing Concrete test Specimens in the Laboratory" using an open-pan rotary mixer. They were proportioned to achieve an initial slump flow higher than 550 ± 10 mm and high filling capacity, and resistance to segregation and bleeding. The total content of cement and cementitious materials as well as the coarse aggregate/fine aggregate ratio (CA/FA) were kept constant in all mixtures. Table 1 shows the proportions of all concrete mixtures considered.

The properties of fresh concrete such as, flowing ability, filling capacity, and resistance to segregation as well as the compressive strength, unrestrained shrinkage and concrete permeability were evaluated for all prepared mixtures.

Duplicate concrete specimens were prepared from each mixture for each test. All specimens were cured in the curing room at room temperature and relative humidity (RH) higher than 95% for the first 7 days. One specimen was then cured in either open air at room temperature or left in the curing room until the day of testing whereas, the second specimen was exposed to a temperature of 46 °C (115 °F) in the oven during the day and placed in room temperature during the night until testing.

3. Materials

Type I Portland cement (C) confirms to the requirements of ASTM C150/C150M [14] and SCMs such as, ground granulated blast furnace slag (*SL*), class C fly-ash (*FAC*), class F fly-ash (*FAF*), and silica fume (*SF*) were used in this study. The specific gravity of cement, *FAC*, *FAF*, *SL*, and *SF* are 3.15, 2.6, 2.08, 2.94, and 2.16, respectively. A local well graded sand and a limestone based crushed stones with a maximum nominal aggregate size of 19 mm (3/4 in.) were used as fine and coarse aggregates, respectively. The relative specific gravity and absorption at saturated surface dry condition of the coarse aggregate (*CA*) were 2.68 and