Influence of slag composition on cracking potential of slag-portland cement concrete

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HIGHLIGHTS

- Early-age cracking risk was evaluated for slags with variable Al_2O_3, MgO and fineness.
- All slags reduced temperature rise and improved cracking resistance.
- Cracking potential of slag concretes varied depending on slag properties.
- A linear relationship was observed between RCF indices and MgO/Al_2O_3 and fineness.
- A decrease in the MgO/Al_2O_3 ratio of the slag increased early-age reactivity.

ARTICLE INFO

ABSTRACT

Semi-adiabatic calorimetry and a rigid cracking frame were used to compare the effects of five different ground granulated blast-furnace slags with variable Al_2O_3 and MgO contents, but similar CaO/SiO_2 ratios on early-age cracking resistance. While cement replacement with slag significantly reduced concrete temperature rise and delayed the time of cracking compared to the plain concrete, it was observed that stress development varied with the MgO/Al_2O_3 ratio of the slag. Increasing this ratio reduced the cracking temperature and delayed the time of cracking. The worst performance of the low MgO/Al_2O_3 ratio slag was attributed to its higher early-age reactivity, which was confirmed by isothermal calorimetry in addition to its higher autogenous shrinkage assessed by free shrinkage measurements.

1. Introduction

Ground granulated blast furnace slag is extensively used in mass concrete to reduce concrete temperature rise and improve resistance to early-age cracking [1]. Although cement replacement with slag is expected to reduce concrete temperature rise, several studies have shown that heat evolution during slag hydration varies significantly with slag chemistry [2–7]. CaO, SiO_2, Al_2O_3 and MgO have been identified in the literature as having a major influence on slag reactivity [8–10]. It is generally accepted that slag reactivity increases with increasing CaO/SiO_2 (C/S) ratio [9], while the effect of Al_2O_3 and MgO has not been explored thoroughly. An increase in heat evolution, especially at early ages, has been observed with increasing Al_2O_3 content of the slag [2,3,6]. Ben

Haha et al. [7] also observed that at the same Al_2O_3 content, a decreasing MgO content increased the cumulative heat release during the first 2 days. Since heat evolution is indicative of reactivity, which affects the mechanical properties and stress development in restrained concrete elements, slags with higher reactivity might not be as effective in preventing early-age cracking as those with lower early-age reactivity. While the effect of slag composition has been studied with regard to heat evolution, there are currently no systematic studies that examine the effect of slag chemistry on the cracking potential of structural concrete elements.

The main causes of concrete cracking at early ages are restrained volume changes induced by temperature and/or moisture variation. Restrained strains generate tensile stresses that can exceed concrete tensile strength thus causing cracking. When considering cracking potential, creep and elastic modulus have to be taken into account, especially at early ages, since concrete

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elastic modulus is still developing and concrete is able to relax a portion of the induced stresses. Rigid cracking frames (RCF) have been used in a number of studies to compare the effect of concrete constituents, mix proportions and placement conditions on the early-age cracking potential of concrete [11–18]. RCF is able to assess uniaxial stress development in concrete under isothermal or non-isothermal conditions. The induced stresses reflect the effects of thermal volume changes and autogenous shrinkage as well as stress relaxation, elastic modulus and tensile strength development.

While a number of papers have been published on the effect of slag on concrete cracking, most of the research has focused on the effect of cement replacement level with slag on concrete cracking potential [15,19–21]. Byard et al. [15] compared the performance of a 50% slag concrete in the RCF to a plain concrete mixture. Cement replacement with slag reduced and delayed the maximum concrete temperature, thus reducing thermal stresses and significantly delaying the time of cracking. The slag used in that study had a low Al_2O_3 content of 9%, moderate MgO content (13%) and a CaO/SiO_2 (C/S) ratio of 0.9 indicating its relatively low reactivity. Slag fineness was not reported. Wei and Hansen [19] examined the effect of cement replacement level by slag (30% and 50%) on cracking. The chemical composition of the slag used in this study (8% Al_2O_3, 11% MgO, and C/S ratio of 1) was similar to that of the slag used by Byard et al. [15]. The Blaine fineness of slag was reported to be 602 m^2/kg, which may have accelerated slag hydration due to its high fineness. The authors reported that a slag content of 50% delayed cracking. They also concluded that cracking in the slag mixtures was predominantly due to their increased autogenous shrinkage, while in the plain OPC mixture, thermal stresses were deduced to be the main cause of cracking. On the other hand, Darquennes et al. [20] reported that cracking of slag concrete under drying conditions is not related to autogenous shrinkage. Slag composition was not presented in that study. Riding et al. [21] tested concretes prepared with 2 slags at 30% cement replacement level as part of a study on the cracking probability for mass concrete. Slag fineness and composition were very similar (Slag 1: Blaine fineness of 332 m^2/kg, 11.4% Al_2O_3, 7.3% MgO, and C/S of 1.2; Slag 2: Blaine fineness of 320 m^2/kg, 11.4% Al_2O_3, 8.3% MgO, and C/S of 1.2), and although the published work indicates that a number of slag mixes were tested in the RCF, the results were not presented.

While these studies show an improvement in cracking resistance with slag addition, they do not examine the effect of slag chemistry on early-age cracking. The variation in the C/S ratio (0.9–1.2) in these studies [15,19–21] covers mostly the range of this parameter (0.9–1.3) in slags available around the globe [9]. However, the variation in the Al_2O_3 and MgO contents is rather narrow, 8–11.4% and 7.3–13% respectively, compared to a possible range of 6–19% Al_2O_3 and 3–14% MgO reported in slags worldwide [9]. So the question remains: are all slags equally good at improving early-age cracking resistance of concrete? With a variety of slag compositions on the market, especially in terms of Al_2O_3 and MgO contents, the effect of different slags on concrete cracking potential needs to be evaluated. The objective of the current study was to compare the cracking potential of slags with a wide range of chemical compositions, in particular Al_2O_3 and MgO content, as well as slag fineness in slag-portland cement concrete through the use of RCF.

2. Materials and methods

2.1. Materials

Two ordinary portland cements (OPC) designated as Cement A and Cement B and five slag cements labeled S1-S5 were selected for this study. The cements were selected to have similar C_3S, equivalent-alkali (Na_2O_{eq}), and Blaine fineness, but variable C_3A content. The C_3A content of cement and the Al_2O_3 content of slag were selected as variables in this study because both of these parameters have been identified by ASTM C989 [22] to have a significant effect on durability performance of slag. The Al_2O_3 content of the slags used in the current study ranged from approximately 8% to 16%. The chemical oxide composition of cements and slags was determined using X-ray fluorescence spectroscopy (XRF) in accordance with ASTM C114 [23] (Table 1).

The mineralogical composition of the as-received cements and slags was determined using X-ray diffraction (XRD), which was performed using a Phillips X'Pert PW3040 Pro diffractometer equipped with an X'Celerator Scientific detector and a Cu-Kα X-ray source. Tension and current were set to 45 kV and 40 mA respectively; and 5 mm divergence and anti-scatter slits were used in the automatic mode. Scans were collected for the 7–70° 2θ angular range, and samples were rotated at 30 rpm during data collection to improve counting statistics [24]. Phase quantification was performed using the Rietveld refinement functionality of the Panalytical HighScore Plus 4.5 software (Table 2). Corundum (Standard Reference Material 676a) obtained from the National Institute of Standards and Technology was used as an external standard to calculate the amorphous content of the as-received cements and slags [25–28]. Mass absorption coefficient (MAC) values for cements and slags were calculated based on their respective chemical oxide compositions, with any loss on ignition attributed to CO_2.

Blaine fineness of cements and slags was measured following ASTM C204 [29]. A b-value of 0.9 was used in calculating the Blaine fineness of slags. Arvaniti et al. [30,31] stated that the Blaine test is less reliable when applied to supplementary cementitious materials; therefore, particle size distribution (PSD) of all cements and slags was also determined. PSD was measured using LA-950 laser scattering particle size analyzer manufactured by HORIBA Instruments, wet method, with ethanol as a dispersant. Additionally, slag S4 was ground using the Micronizer jet mill manufactured by Sturtevant to a mean particle size (MPS) of approximately 5 μm to examine the effect of fineness. The ground slag S4 was named S4G. The physical properties of cements and slags are listed in Table 3.

2.2. Experimental methods

Isothermal calorimetry was performed at 30 °C following ASTM C1702, Method A, internal mixing [32]. Since Wu et al. [4] reported that slag reaction contributes to early-age heat flow at temperatures of 27 °C and above and since concrete mixes, in this study, were heated and concrete was placed into the RCF at the temperature of approximately 30 °C, this temperature was selected for isothermal calorimetry measurements. Additionally, a concrete temperature of 30 °C is quite typical for concrete placement during the summer. A TAM Air isothermal calorimeter manufactured by TA Instruments was used to measure the heat flow and the total heat of the OPC-slag pastes for 7 d.

Control and slag concrete mixtures were prepared at a constant water-to-binder (w/b) ratio of 0.385 by mass and a total cementitious content of 395 kg/m^3. In the OPC-slag mixes, slag content was fixed at 60% replacement level on a mass basis (Table 4). Due to the limited quantity of slag S5, it was only tested in combination with Cement A. Plain cement mixes were also prepared with each cement and were designated Control A and Control B. In order to maintain adequate workability, the dosage of the high-range water-reducing admixture (HRWR) was varied. The following dosages of HRWR per 100 kg of cementitious material were used: 196 ml (mixes 60S1-A, 60S4-A, 60S5-A, 60S4-B), 280 ml (mixes 60S2-A, 60S3-A, 60S1-B, 60S3-B) and 365 ml in mix 60S2-B due to the higher slag fineness. In order to maintain a constant w/b ratio, mixing water was adjusted to account for the water contributed by the HRWR.

Concrete mixes were prepared in the laboratory following ASTM C192 [33]. In order to simulate fresh concrete temperatures in the field, mixing water and aggregates were preheated prior to mixing. Coarse and fine aggregates were heated to approximately 55 °C, and the mixing water was heated to approximately 40 °C.

Semi-adiabatic calorimetry measurements were conducted to generate concrete temperature profiles for each mix that were then imposed in the rigid cracking frame (RCF) and free shrinkage frame (FSF). For semi-adiabatic calorimetry, which was performed following the guidelines provided by RILEM [34], a 150 mm × 300 mm fresh concrete cylinder was placed inside the calorimeter immediately after mixing. The concrete temperature at the beginning of the test was approximately 34.5 °C.

RCF measures uniaxial stress development in concrete under restrained conditions. This test was originally described by Springenschmid et al. [11] in 1994. Fresh concrete is placed into a dove-tailed frame, where the cross-heads are connected by two invar steel bars providing a high degree of restraint. Strain gauges are attached to the invar bars, and strain measurements are used to calculate the stress development in concrete [16]. Detailed information on the RCF used in this study, which is shown in Fig. 1, has been previously published in [13,35]. A programmable water bath was connected to the RCF, allowing active temperature control of the concrete specimens.

The measured concrete temperature at the start of data collection in the RCF was approximately 31 °C due to the longer placement time required. Prior to starting the test, the RCF was heated by circulating water at 45 °C through the pipes for approximately 1 h. After the start of data collection, the actual concrete temperature matched the imposed temperature profile typically within 30–45 min. The longer induction period observed for the slag mixtures was also helpful in ensuring