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Influence of added water and fly ash content on the characteristics, properties and early-age cracking sensitivity of alkali-activated slag/fly ash concrete cured at ambient temperature

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HIGHLIGHTS

- Increasing added water dosages from 48 to 64 kg/m³ resulted in increasing both values of absorption after immersion values and volume of permeable voids in the tested alkali-activated concretes.
- Increasing fly ash content from 20 to 30% of total precursor content resulted in a significant increase of absorption after immersion and volume of permeable voids, no significant effect was observed when increasing further the fly ash content to 40% of total precursor content.
- Increasing added water dosages from 48 to 64 kg/m³ did not affect significantly the air void system whereas increasing the fly ash content resulted in increasing air volumes and larger air voids on average, yet overall similar spacing factors.
- Increasing the added water dosage from 48 to 56 kg/m³ did not affect significantly the elastic modulus; however, increasing it further to 64 kg/m³ resulted in a reduction of the order of 10%.
- Increasing either the added water dosage or fly ash content resulted in lower amounts of cracks in the tested alkali-activated concrete mixtures, and, at the same time, in reduced autogenous volume changes in the corresponding alkali-activated paste mixtures; this strongly suggests that shrinkage is an important contributing factor in the early cracking occurring in the investigated alkali-activated systems.

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ABSTRACT

For an appropriate air void system, good mechanical properties and low porosity/microcracking in alkali-activated binder systems, appropriate slag/fly ash proportioning, water and admixture contents are needed. Air entraining admixture dosages of up to 10 times the recommended dosage were necessary to obtain minimal air void properties similar to what is needed for normal portland cement concretes subjected to freezing conditions. Increasing added water resulted in increasing absorption and decreasing crack counts in concrete. Increasing fly ash contents resulted in increasing absorption and decreasing early-age crack counts. Increasing both added water and fly ash content resulted in less autogenous shrinkage.

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1. Introduction

The urge to reduce global CO₂ emissions has triggered many studies on alternative cementitious materials to replace partially or completely portland cement in concrete. Recent studies have shown that CO₂ levels in the atmosphere have reached a concen-

tration of 406.8 ppm in average for the year 2017 [1] and it is now well documented that the production of portland cement is responsible for 5–8% of annual anthropogenic CO₂ emissions around the world [2]. Research has shown that blast furnace slag and fly ash are two industrial by-products that offer good potential to replace portland cement in concrete if an alkaline solution is used as an activator along with water (i.e. materials often referred to as geopolymer or alkali-activated binders).

In the case of ordinary portland cement (OPC) concrete designed to withstand the deleterious effect of freezing and thaw-

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ing cycles, there are essentially two different types/levels of porosity to consider, i.e. the capillary pores and air-entrained voids. The capillary pore system represents the volume that is not occupied by the hydration products in the paste/binder. The size and connectivity of capillary pores influence the permeability of the paste and, therefore, the ability of fluids to flow through the paste and potentially damage (cracking) the concrete in multiple ways (e.g. build-up of hydraulic/osmotic pressure) [3]. In the case of air-entrained voids in OPC concrete, it is established that three essential characteristics determine the effectiveness of an air void system in frost-resistant concrete, namely the air content (A), the spacing factor (\bar{L}) and the specific surface (α) [4]. The function of the air void system in concrete is essentially that of expansion chambers (between 10 and 100 μm) which can take up without harm, when sufficient and closely spaced, the volume increase resulting from the freezing of the water contained in the interstitial solution of the concrete [5].

Regarding the permeability of alkali-activated pastes, concerns arise from the detection of early age microcracking, even in concrete specimens moist cured at ambient temperatures [6]. Such microcracking could potentially promote the penetration of aggressive agents and lead to premature deterioration to concrete subjected, especially in cold weather conditions. Early-age shrinkage in OPC concrete can lead to important cracking and thus, deleteriously affect the durability of the affected element. It is already well known that high alkali contents in portland cement concretes result in the formation of gelatinous hydration products, thereby increasing drying shrinkage and the cracking sensitivity [7]. Skalný [8] demonstrated that higher alkali contents increased reaction rates in the early hydration process which had an effect on the morphology of the hydration products.

Alkali content also seems to have a strong effect on shrinkage and early-age cracking of alkali-activated pastes and mortars. In fact, Lee and al. [9] showed that fly ash/slag pastes are prone to greater self-desiccation shrinkage but less chemical shrinkage than OPC pastes. Moreover, the observed self-desiccation shrinkage of mortars increased while the drying shrinkage decreased with a decreasing water-to-binder ratio. Ma and Ye [10] reported that higher Na_2O and SiO_2 contents led to higher autogenous and drying shrinkage on alkali-activated fly ash pastes using a sodium silicate solution for activation and cured at 40 °C for 7 days. Gao and al. [11] showed higher bound water contents associated with higher slag contents and low activator moduli for slag/fly ash mortars but also lower self-desiccation shrinkage with lower slag contents. Sodium silicate content in the activator also seems to play an important role with respect to total shrinkage. For instance, an increase in sodium silicate content leads to higher self-desiccation shrinkage in slag mortars, as a result of a higher degree of hydration [12]. An increase in sodium concentration increases the drying shrinkage of slag mortars. For a Na concentration increasing from 4 to 8%, drying shrinkage was found to increase by 3–3.6 times when compared to OPC mortars [13].

The gels formed by alkali activation of slag or fly ash are different in terms of composition and water binding potential. An alkali activated fly ash forms an amorphous hydrated alkali-aluminosilicate (N-A-S-H) gel [14,15] while activated slag will form a C-S-H like gel that incorporates aluminium in its structure (C-A-S-H gel) [16–18]. In addition, C-A-S-H gels offer a lower alkalis binding capacity [19] and a higher water binding capacity compared to the N-A-S-H gels [20] that are formed when fly ash is used. Therefore, higher slag contents (higher C-A-S-H contents) result in higher self-desiccation because there is less free water present and thus, higher capillary tensions in the forming paste. Provis and al. [18] showed, using synchrotron X-ray microtomography, that high fly ash content pastes (<25% slag) are dominated

by N-A-S-H gels which contain less chemically bound water in their structure and thus, lead to higher porosity and lower tortuosity. Replacement levels of slag greater than 50% by wt. result in higher alkalis efflorescence and are associated with higher shrinkage values [21]. The same authors point out that lower humidity curing also favour efflorescence and thus, shrinkage, cracking and strength loss. Other work performed by Sarathi and al. [22] points out that for alkali-activated fly ash/slag concretes shrinkage tends to decrease with increasing slag content (from 10 to 20% of binder content).

C-A-S-H gels contain chemically bound water similar to C-S-H gels of normal portland cement pastes. This bound water content is highly influenced by the type of activator; for instance, sodium silicate activated systems show a slower hydration time, which results in a lower porosity and higher strength compared to similar systems activated with NaOH only [23]. However, C-A-S-H gels tend to form a denser and less porous hardened matrix [24] than N-A-S-H gels but alkali-activated slag/fly ash pastes still show a higher porosity than OPC specimens when tested with ASTM C642 [25]. Moreover, an increasing fly ash content (over 50% by wt.) results in an increasing volume of permeable voids [26].

The research work presented in this paper is an attempt to understand the cause(s) for the presence of early-age cracking and to evaluate the consequences on the mechanical properties, absorption, volume of permeable voids and damage level of alkali-activated slag/fly ash concretes designed to resist freezing and thawing conditions as well as de-icing salts scaling. The effects of air entraining admixture (AEA) dosage, added water dosage and fly ash/slag proportioning are also investigated.

2. Objectives and scope of work

The main objective of this research was to develop an alkali-activated concrete mixture design able to withstand severe winter conditions involving freeze and thaw cycling and de-icing salts. To achieve this objective, adequate air void system and low permeability of the hardened concrete are needed, along with good mechanical properties.

A number of concrete mixtures were first made using blast furnace slag as the only binder. While performing the ASTM C457 for the evaluation of the air-void system in the hardened concrete specimens, it was noticed that significant cracking was present in the paste. Therefore, fly ash was incorporated to all the subsequent mixtures in order to prevent/reduce the development of cracking. Different replacement levels of fly ash and water dosages were investigated with regards to their effect upon cracking, porosity, mechanical properties and autogenous shrinkage.

3. Experimental program

3.1. Materials

The raw materials used for this study were a grade 80 blast furnace slag from Stoney Creek, Canada and a class F fly ash (Sundance fly ash). The Blaine fineness are of 479 and 334 m^2/kg and the percentages of retained particles on the 45 μm sieve are of 1.2 and 26% for the blast furnace slag and class F fly ash respectively. The chemical composition of these two precursors is presented in Table 1.

A 20-mm crushed granitic gneiss (Quebec, Canada) and natural granitic sand were used as coarse and fine aggregates, respectively. Table 2 shows the bulk density and absorption values for these aggregates.

The alkaline activator used was a mixture of an 8 M sodium hydroxide solution with a sodium silicate solution. These two solutions were combined at a sodium silicate to sodium hydroxide weight ratio (Ss/NaOH) of 0.5. The activator to binder ratio was fixed at 0.35. All activators were prepared at least 24 h before mixing. The total Na_2O content of the activator (NaOH and sodium silicate) is amounted to 18.7%. Table 3 gives the chemical composition of the grade N sodium silicate used.

Two different air entraining admixtures (AEA1 and AEA2) were used.

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