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Performance of an alkali-activated slag concrete reinforced with steel fibers

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ABSTRACT

This study investigated mechanical and permeability properties at early ages of an alkali-activated slag concrete (AASC) reinforced with steel fibers. The compressive, splitting tensile and flexural strengths, flexural notch sensitivity, pull-out and water absorption properties were evaluated. Test results reveal a reduction of AASC compressive strengths with fiber incorporations. However, splitting tensile and flexural strengths were largely improved with increasing fiber volume, varying from 3.75 to 4.64 MPa and from 6.40 to 8.86 MPa at 28 days of curing, respectively. The properties related to durability performance as water absorption, capillarity and water resistance penetration were enhanced with the steel fibers addition. The results show the enormous potential of AASC as building material with and without steel fiber reinforcement.

1. Introduction

The environmental impact associated with the production processes of Portland cements (OPC), the main hydraulic binder since the 19th century, includes: greenhouse gases emissions, high energy consumption and natural resource exploitation [1]. Also, the recognition of durability problems in older structures based in OPC [2] has acted as an impetus to transfer the microstructural and hydration chemistry studies of these conventional binders to develop a novel generation of cements with durability and environmental sustainability. The partial replacement of OPC by active nanopowders or supplementary cementing materials, such as ground granulated blast furnace slag (GGBS), silica fume (SF), rice husk ash (RHA), metakaolin (MK) or fly ash (FA), are examples of those new binders and constitute a significant contribution to the eco-efficiency of the global economy. Other modified systems such as the macrodefect free cements (MDF), the belitic cements (SAC-FAC) and the densified systems which contain homogeneously arranged ultrafine particles (DSP) have also been reported [3].

The complete substitution of OPC has been carried out using novel binders called alkaline-cements, which are alternative materials to traditional and blended cements, obtained through alkaline-activation and geopolymerization processes of different industrial by-products and natural minerals (blast furnace slag, fly ashes and metakaolin) [2,4–7]. Alkali-activated cements or alkaline-cements refer to any system that uses an alkali-activator to initiate a reaction or a series of reactions that will produce a material that possesses cementitious properties [8] such as the alkali-activated slag (AAS) cement, which is based on 100% GGBS added with an alkaline activator. The AAS presents comparative ecological advantages with respect to OPC, such as the utilization of an industrial by-product, low energy consumption and low greenhouse gas emissions (CO_2, SO_2, NO_x, etc.). The basic principles of alkaline-activation of slags have been known since the 1940s [9], and the application as a binder in the construction industry started in Ukraine since the 1960s [10]. In the past, it has been investigated by numerous authors [11–15].

In Colombia, research based on alkali-activation processes has been done on mortars [16] and concretes [17], involving an alkali-activated Colombian GBFS as unique binder. These particulate cementitious materials have exhibited excellent mechanical and durability properties [18], consistent with observations reported by other authors [19–22]. However, one of the main technological drawbacks identified in these new alkaline-cements is an increased susceptibility to suffer drying shrinkage, which is influenced principally by the slag microstructure and fineness, alkali-activator nature and concentration and curing conditions [23–27].

Several studies have shown that fiber addition is an efficient method to improve the mechanical performance and the shrinkage control of brittle matrices such as mortars and concretes based on alkaline-cements by crack arresting. Also, it is well known that the fracture toughness provided by fiber bridging on the main crack plane prior to crack extension increases. Debonding, sliding and pulling-out of the fibers are the local mechanisms that control the bridging action [28–30]. At the beginning of macrocracking, the opening and growth of cracks is controlled by the bridging ac-

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tion of fibers. This mechanism increases the demand of energy for the crack to propagate. The linear elastic behaviour of the matrix could not be affected significantly for low volumetric fiber fractions. However, post-cracking behaviour can be substantially modified, with increases of strength, toughness and durability of the material [30].

This paper reports the effects of incorporation of steel fibers on mechanical and fracture toughness properties of Colombian alkaline-concretes based on an alkali-activated GBFS at early ages of curing. The results are compared to the concrete specimens of Ordinary Portland Cement (OPC), with the view to identify their performances and potential applications as building materials, especially in those systems reinforced with inorganic fibers that require improved fracture behaviour and retraction stability.

2. Experimental

2.1. Materials used

A Colombian granulated blast furnace slag with a chemical composition shown in Table 1 and a basicity coefficient ($K_b = CaO + MgO/SiO_2 + Al_2O_3$) of 1.01 and a quality coefficient ($CaO + MgO + Al_2O_3/SiO_2 + TiO_2$) of 1.92, was used. Its specific gravity and Blaine fineness were 2980 kg/m^3 and 399 m^2/kg respectively. The alkali-activation was carried out with a *waterglass* solution of a commercial mix of sodium silicate with chemical composition of 32.4% SiO_2, 13.5% Na_2O and 54.1% of water and a solution modulus ($M_s = SiO_2/Na_2O$) of 2.4. Additionally, an ordinary Portland cement type I (OPC) with a specific weight of 2990 kg/m^3 was used as reference binder.

Siliceous gravel with a maximum size of 19 mm and river sand were utilized as aggregates. Wiremix® Dramix steel fibers with curly surface and high tensile strength were incorporated as reinforcement. The technical specifications are shown in Table 2.

2.2. Mixes design and samples preparation

Portland cement concretes (OPCC) and alkaline-concretes (AASC) with 400 kg of binder per cubic meter of concrete in accordance of ACI recommendations were designed. Alkali-activator (*waterglass*) with a concentration of 5% of Na_2O, expressed as percentage of slag weight, was incorporated. The steel fibers were added in amounts of 40 kg/m^3 and 120 kg/m^3 into OPCC and AASC concrete mixes, as shown in Table 3.

The water/binder and water/(slag and anhydrous activator) ratios were maintained at 0.45 for all the mixes studied. There were measured slumps of 100 mm and 75 mm in the mixes OPCC and AASC respectively. The coarse aggregate was incorporated in a proportion of 55%, whilst the fine aggregate was included in a proportion of 45% with respect to the total content of aggregate. A commercial superplasticizer with a concentration of 1.5% by weight of cement was included in OPCC mixes.

Cylindrical concrete specimens with a diameter of 7.62 cm and a height of 15.24 cm were cast to evaluate the mechanical properties, as follows: compressive strength, splitting tensile strength (ASTM C496), density, absorption and porosity in hardened concrete (ASTM C642). Additionally, prismatic concrete samples with the dimensions (7.6 × 7.6 × 27.9) cm were molded to determine the flexural behaviour (ASTM C293). The OPCC specimens were cured at 100% relative humidity whilst the AASC samples were cured at 90% relative humidity to prevent the activator dissolution and lixiviation which could affect the reaction processes and the hydration products formation.

Table 1
Chemical composition of the GBFS.

Chemical composition, %	
Loss on ignition	2.08
SiO_2	31.08
Al_2O_3	13.98
Fe_2O_3	3.09
CaO	43.92
MgO	1.79
SO_3	0.66

Table 2
Technical specification of the steel fibers [31].

Diameter	$d = 1$ mm
Length	$l = 25$ mm
Wavelength	$\lambda = 8$ mm
Traction strength of the wire	$\sigma = 10{,}000$ kg/cm^2

Table 3
Mixes codes.

Mixes	Incorporated steel fiber quantity (kg/m^3)
OPCC 1	0
OPCC 2	40
OPCC 3	120
AASC 1	0
AASC 2	40
AASC 3	120

3. Results and discussion

3.1. Compressive strength

The compressive strength losses due to the incorporation of steel fibers in the concrete samples after 7, 14 and 28 days of curing were determined through the following equation (Eq. (1)):

$$Compressive\,strength\,index = \frac{(\sigma_m - \sigma_f)}{\sigma_m} \times 100\% \tag{1}$$

where σ_m = Compressive strength of the concrete without fibers and σ_f = Compressive strength of the concrete with fibers. The results are shown in Fig. 1. Each data corresponds to an average of three specimens.

The addition of steel fibers generated a decrease in compressive strengths in both AASC and OPCC, suggesting that this reduction was greater with the incorporation of higher steel fiber volumes. The hardened mixtures of AASC with addition of fibers led to more noticeable losses in compressive strengths than the equivalents OPCC. The fiber addition did not improve the resistant capacity in compression in the OPCC and the AASC. The reduction of compressive strengths should be accounted for in concrete design purposes when the addition of fibers is included to improve other properties.

3.2. Splitting tensile strength

Splitting tensile strengths at the ages of 7, 14 and 28 days of curing were determined. The results are illustrated in Table 4 showing an increase with the curing ages and all the amounts of fibers added to AASC mixes, which was 37.7% after 7 curing days and the 23.7% after 28 curing days, respectively. In contrast, the OPCC exhibited a decrease in this property with the incorporation

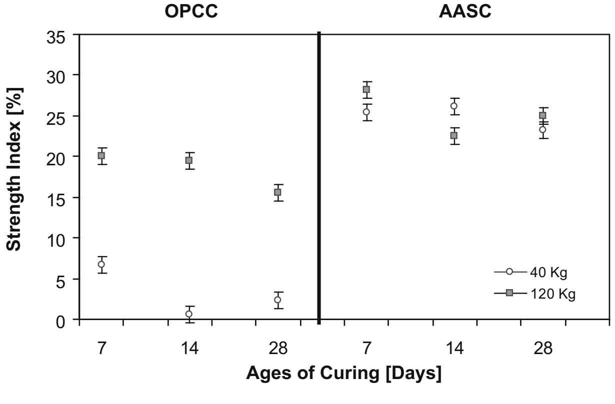

Fig. 1. Compressive strength index of concrete as function of age of curing.