PERFORMANCE OF GEOPOLYMERIC CONCRETE REINFORCED WITH STEEL FIBERS

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ABSTRACT

The purpose of this paper is to present the results of the development of fracture toughness to early ages of geopolymeric concrete (GEOCONCRETE) reinforced with steel fibers, based in a Colombian granulated blast furnace slag (GBFS) activated with waterglass ($Na_2SiO_3.nH_2O$ + NaOH). The concrete mixes with 400 kg of binder were prepared and fibers in proportions of 40 kg and 120 kg by m^3 of concrete were incorporated. The compressive and splitting tensile strength were determined; likewise fracture toughness parameters, pull-out curves and K_{IC} in samples after 7, 14 and 28 days of curing were calculated. Additionally, durability properties as porosity and capillary suction were reported. The mechanical testing results obtained indicate that the incorporation of steel fibers in Geo-Concretes reduces the compressive strength at early ages. On the contrary, the splitting tensile strength, the flexural strength and the toughness increase significantly. The strengths and the toughness of Ordinary Portland Cement Concretes (OPCC) with the same proportion of binder and fibers were lesser than the Geo-concretes reinforced with steel fibers. The results shown the elevated performance of the properties exhibited by the geopolymeric cements with and without reinforcement.

KEYWORDS: Alkali-Activated slag, geopolymeric concrete, steel fibers reinforced geopolymeric concrete**,** early ages toughness.

INTRODUCTION

Concrete is produced mainly from Portland cement clinker and it is the most widely-used material on the world after water. The annual production of cement is of the order of 1.8 billion tons and about 3 billion tons of natural resources per year (Sarkan, 2003) are needed for its production; at the same time, about one ton of carbon dioxide is released into the environment during the production of 1 ton of clinker besides SO_2 and NO_x emissions. The concrete industry is also the largest consumer of natural resources (8 billion tons per year of natural aggregates) and it is estimated that cement and concrete together consume 600 to 700 gallons of water per year (Sarkan, 2003). In order to protect the environment it is necessary that new materials with few durability problems be developed, which implies well-formulated cements, with less susceptibility to different types of internal and external chemical attack

The study of the microstructure and the chemistry of hydration of the Portland cement, main hydraulic binder since the 19th century, have led to the development of novel cements with environmental sustainability (Moranville-Regourd, 1999; Roy, 1994; Roy, 1991). Cement has been partially replaced by active nanopowders or supplementary cementing materials, such as ground granulated blast furnace slag (GBFS), silica fume (SF), rice husk ash (RHA), metakaolin (MK) or fly ash (FA). These are examples of those new binders and constitute a significant contribution to the eco-efficiency of the global economy (Moranville-Regourd, 1999; Roy, 2003; Tailing, 1997; Van Loo, 2003). Other materials are those called the chemically bonded ceramics (CBC) [4], the macrodefect free cements (MDF) and the densified systems which contain homogeneously arranged ultrafine particles (DSP) (Moranville-Regourd, 1999; Roy, 1991; Roy, 1994). These new binders, which are alternative materials to traditional and blended cements and concretes, are obtained by the alkaline activation or geopolymerization of different industrial by-products (blast furnace slag and/or fly ashes). The provision of new types of cements is an ongoing research topic for the scientific community (Glukhovsky, 1983; Puertas, 1995; Roy, 1992; Shi, 2000; Wang, 1995b).

The production of alkali-activated slag (AAS), which is a binder based on 100% of ground granulated blast furnace slag (GGBS) added with an alkaline activator, presents comparative ecological advantages with respect to that of Portland cement, such as the utilization of an industrial sub-product, low energy consumption and low greenhouse gas emissions (CO_2, SO_2, NO_x, etc.). These materials open new opportunities for development of high-performance structural materials. The basic principles of alkaline activation of slags have been known since the 1940's (Purdon, 1940), although its application as a binder in the construction industry started in Ukraine between 1960 and 1964 (Glukhovsky, 1978). These materials, alkali-activated slag and geopolymeric concretes are being investigated by numerous authors (Cheng, 2003; Fernandez, 2003a; Fernandez, 2003b; Mejía de Gutierrez, 2003; Mejía de Gutierrez, 2005).

Several studies have shown that fiber addition is an efficient method to improve the mechanical performance of brittle matrices as mortars and concretes by cracking arresting, also it is well known the increase in fracture toughness provided by fiber bridging on the main crack plane prior to crack extension. Debonding, sliding and pulling-out of the fibers are the local mechanisms that control the bridging action (Silva, 2003a; Silva, 2003b; Penteado Dias, 2005). At the beginning of macrocracking, bridging action of fibers takes control of the opening and growth of cracks. This mechanism increases the demand of energy for the crack to propagate. The linear elastic behavior of the matrix could not be affected significantly for low volumetric fiber fractions. However, post-cracking behavior can be substantially modified, with increases of strength, toughness and durability of the material (Penteado Dias, 2005).

The purpose of this study is to contribute to the scientific literature that reports few publications referred to the fracture behavior of geoconcretes reinforced with inorganic fibers (Puertas, 2003; Silva, 2003a; Silva, 2003b; Penteado Dias, 2005; Savastano, 2005). In this research was evaluated the results of mechanical testing of GEOCONCRETE reinforced with steel fibers compared to control concrete specimens of Ordinary Portland Cement (OPC) in compressive, splitting tensile and flexural strengths, with the objective of research their performance and potential applications as building materials.

MATERIALS AND METHODS

Materials

A Colombian granulated blast furnace slag with a specific surface of 2.98 g/mL was employed. The activation was carried out used a *waterglass* solution based on a commercial mix of sodium silicate with a chemical composition of 31.70% de SiO_2, 12.32% de Na_2O and 56.9% of water, as alkali activator. The solution modulus (Ms= SiO_2/Na_2O) was 2.4. The reference material was a Portland cement type I (OPC) with a low contain of lime and a specific weight of 2.99 g/mL. 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 and its technical specifications are shown in Table 1.

Table 1- Technical Specification of the Steel Fibers (Dramix, 2006)

Diameter	d = 1 mm
Length	l =25 mm
Wavelength	λ =8mm
Traction strength of the wire	σ= 10.000 kg/cm^2

Mixes design and samples preparation

The Portland cement concretes (OPCC) and Geopolymeric concretes (AASC) with a 400 kg of binder per m^3 of concrete were designed based on the ACI standards. In the Geopolymeric concretes the alkali activator (*waterglass)* was incorporated in a concentration of 5% of Na_2O, expressed as percentage of slag weight. The steel fibers were added in amounts of 40 Kg/m^3 and 120 Kg/m^3 into OPCC and AASC concrete mixes, as it is seen in Table 2.

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

Table 2 – Mixes Codes

Hardened 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

Cylindrical concrete specimens with a diameter of 76.2 mm were made 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 samples with the following dimensions 7.6 X 7.6 X 27.9 cm to determine the flexural behavior (ASTM C293) were elaborated. The OPCC specimens were cured at 100% of relative humidity whilst the AASC samples were cured at 90 % of relative humidity to prevent the dissolution and lixiviation which could affect the reaction processes and the hydration products formation.

RESULTS AND DISSCUSION

Compressive Strength

The compressive strength losses due the incorporation of steel fibres on the concretes samples after 7, 14 and 28 days of curing were determined through the following Eqn. 1.

$$Compressive\,Strength\,Index = \frac{(\sigma_m - \sigma_f)}{\sigma_m} \times 100\% \qquad (1)$$

Where σ_m, is the compressive strength of the concrete without fibres and σ_f, the compressive strength of the concrete with fibres. The results are shown in Figure 1. Each data corresponds to an average of three specimens.

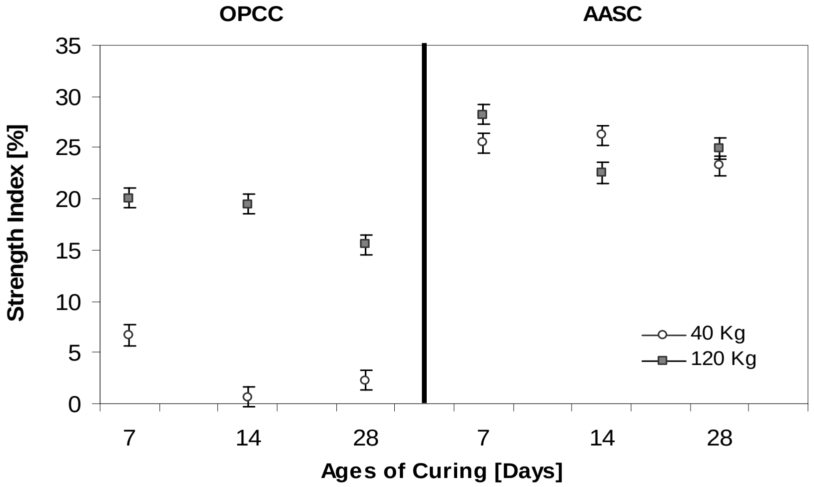

Figure 1 - Compressive Strength Index of Concrete

The addition of steel fiber generated a decrease in the compressive strengths in both the AASC and the OPC concretes, being this reduction superior with higher steel fiber volumes incorporated. The hardened mixtures of Geopolymeric concrete with addition of fibers reported more noticeable losses in compressive strengths that those exhibited by the equivalents OPC concretes. The fiber addition is unjustified for the OPCC and the AASC concretes to improve its resistant capacity in compression. The reduction of compressive strengths should be considerate for concrete design purposes when the addition of fibers has to be done to improve other properties.

Splitting Tensile Strength

Splitting tensile strengths at the ages of 7, 14 and 28 days of curing were determined. The results obtained are shown in Table 3, where it is possible to observe an increase in this property with the curing ages and the amounts of fiber added for all the AASC mixes until a 37.7 % at 7 curing days and 23.7 % at 28 curing days. One the other hand, the OPC concretes exhibited an decrease in this property with the incorporation of fibers, with the exception of the mixes at ages of 28 days where is shown a slight increase with the fiber content, however, it seems that the incorporation of amounts of fiber higher than 40 Kg/m^3 does not has sense for the OPC concretes reinforced with steel fibers. The Geoconcretes presented 32 % higher splitting tensile strengths than those reported by the control mix of OPC at 28 curing days.

The Geoconcretes reinforced with steel fibers displays a substantial enhancement in the splitting tensile strengths with the increment in the content of fiber embedded as it is observed in Table 3.

Table 3- Splitting Tensile Strength of Concrete

Hardened Mixes	Age of Curing [Days]					
	7		14		28	
	MPa	Variation wrt standard	MPa	Variation wrt standard	MPa	Variation wrt standard
OPCC 1	2,77	-	3,31	-	3,51	
OPCC 2	2,26	-18.4	3,17	-4.2	3,77	+7.4
OPCC 3	2,58	-11.6	2,85	-14.0	3,78	+7.7
AASC 1	2,84	-	3,30	-	3,75	
AASC 2	3,40	+19.7	3,52	+6.7	3,99	+6.4
AASC 3	3,91	+37.7	3,99	+37.7	4,64	+23.7

Flexural Strength

The flexural strength testing of the prismatic specimens at ages of 7, 14 and 28 days was evaluated. The load at the central point of the upper surface of the samples (three points loading) at a velocity of 3 mm/s was applied. The curves of load vs. mid-span deflexion are shown in Figure 2 and the Modulus of Rupture (MOR) results are exhibited in Figure 3.

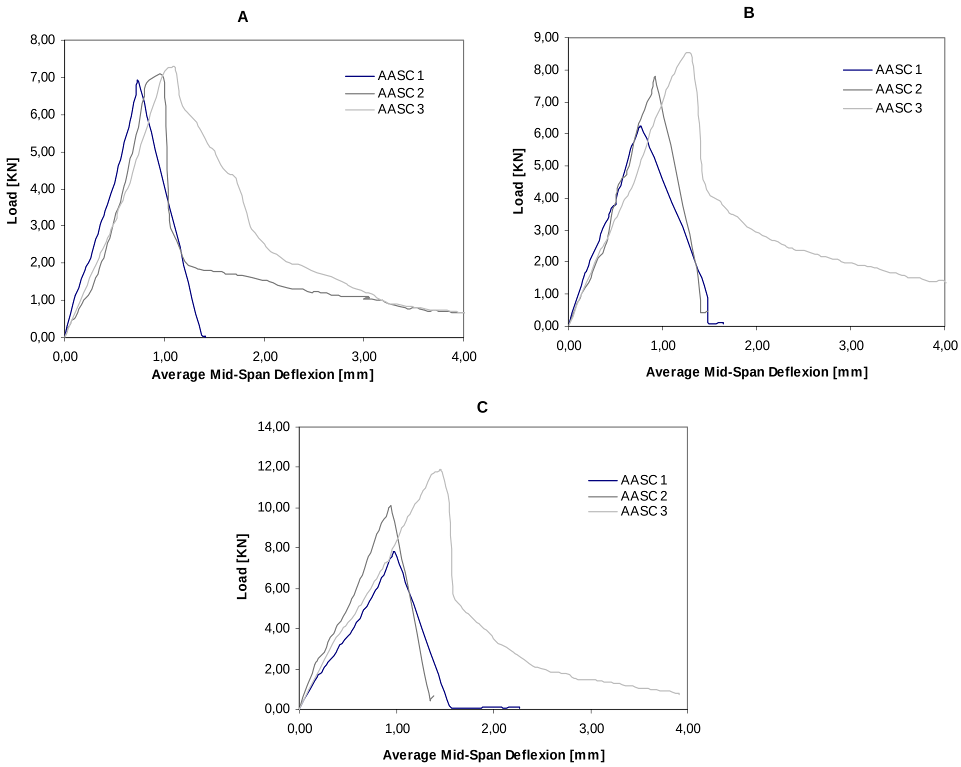

Figure 2- Flexural Behavior of Gepolymeric Concretes at (A) – 7 Days; (B) – 14 Days and (C) – 28 Days of curing, respectively.

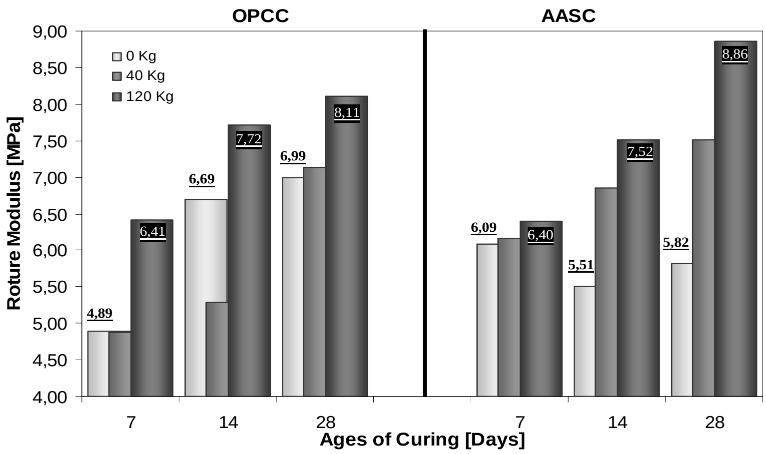

Figure 3- Modulus of Rupture (MOR) of the OPCC and the AASC

The concretes mixes in study exhibited an increase in the modulus of rupture with the age of curing, which is in accordance with the mechanical development due to the contribution of the high modulus of elasticity of the steel fibers and also because of the progressive dissolution and hydration reactions that occur at early ages in the geopolymeric matrix evaluated. The AASC 3 mix presented the highest modulus of rupture (8.86 MPa) at ages of 28 days. Besides of substantial improvements in load capacity with greater amounts of fibers added important increases in toughness with the incorporation of superior fiber quantities it was observed. The development of strength in flexion of AASC concretes can be explain for the effect of the volumetrical contraction that suffer the material as consequence of the reaction mechanisms that control the drying and hardened in the geopolymeric matrices, being they faster than the conventional hydration reactions in OPC concretes. Additionally, in agreement with Häkkinen et al (1993), the microcracks at early ages are generated due the presence of an elevated quantity of saturated water in type gel phases whilst at advanced ages of curing the CSH formed from silica gel in the AASC exhibited a elevated density permitting that these can act as porous plug, preventing the crack propagation at the same static loads due a cicatrisation effect (Bernal, 2004b).

Pull – Out Testing

Figure 4 shows the load-displacement curves reported by the pull-out testing. The pull-out was carried out in a Lloyds Instruments testing machine at a crosshead speed of 3 mm/min. The bond strength (t_{au}) was calculated from the maximum pull-out load by dividing it by the surface area of the embedded fiber.

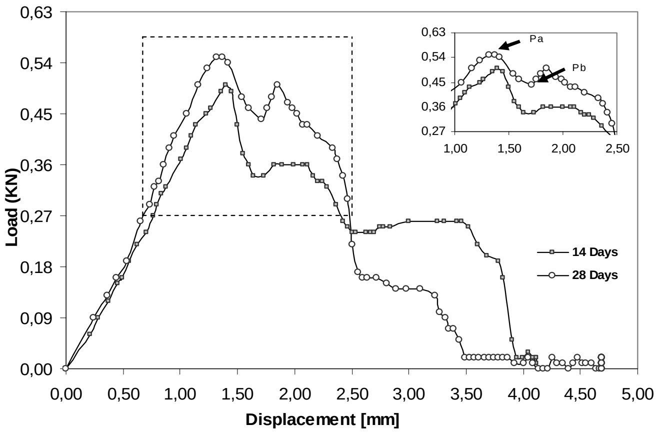

Figure 4 – Pullout Curves of Geopolymeric Matrix of Concrete

The pull-out test load-slip curves had shown a sudden drop at peak pull-out load. The interfacial shear friction strength (tfu) at the Pb load (Table 4) was evaluated. The t_{fu}/t_{au} ratio is augmented when the age of curing is increased. Indeed, the tried geopolymeric composites had shown a very marginal slip-hardening response under uniaxial tensile loading. Generally fiber pullout rather than rupture confers a larger ductility to the fiber reinforced composites it is desirable to have composites that exhibit strain-hardening behavior achieved through multiple cracking of the reinforced matrix (Redon, 2001)

Table 4 – Pullout Test in Geopolymeric Matrix of Concrete

Age of Curing [Days]	Linkage Strength (τ_{au}) [N/m^2 X 10^6]	Shear Strength (τ_{fu}) [N/mm^2 X 10^6]	τ_{fu}/τ_{au}
14	0,80	0,55	0,68
28	0,88	0,71	0,80

From the pull-out results is possible to conclude that the controlling mechanism after post-peak resistance is typically of the type high friction shear displacement which is responsible for high toughness generation.

Notch Sensitivity

The relationship between the flexural strengths evaluated in notched samples and the equivalent in continuous samples is namely the notch sensitivity (NS). Prismatic specimens with a triangular notch of a height equal to half of thickness of the beams were used. All notched beams were loaded using three-point loading method (in the plane perpendicular to the vibration direction to avoid aligned fibers planes) with the distance between the supports equal to 260 mm, using a 500 kN hydraulic testing machine. The curves of Load vs. Mid-Span Deflexion are shown in figure 5.

The failure of the specimens without fibers was fast and almost without warning. In contrast, in the case of the specimens with fibers, after reached the ultimate load, the specimens still continued deforming and the rupture was more ductile, increasing with the ages of curing.

The notch sensitivity of the concretes in study were evaluated in terms of fracture properties, applied concepts of no lineal fracture mechanism which are indicated by the critical stress intensity factor (K_{IC}). Penteado Dias, 2005 purposed that the Reinforcing Efficiency (RE) of fibers can be defined as toughening factor (F_T) calculated from

$$F_T = \frac{K_{IC}\ fortheconcreteswithfibers}{K_{IC}\ fortheconcriteswithoutfibers}$$

Following a similar procedure, the F_T values for this study are shown in the table 5.

Table 5 – Reinforcing Efficiency Evaluated Through the Toughening Factor (F_T

Hardened Mixes	Toughening Factor (F_T)	
	14 Days	28 Days
OPCC 2	0,79	1,02
OPCC 3	1,16	1,16
AASC 2	1,24	1,29
AASC 3	1,37	1,52

It can be seen from Table 5 that steel fibers were more efficient in reinforcing Geopolymeric concretes than reinforcing the OPCC, since they had higher F_T values, which can be explained because of better fiber adhesion in geopolymer matrices.

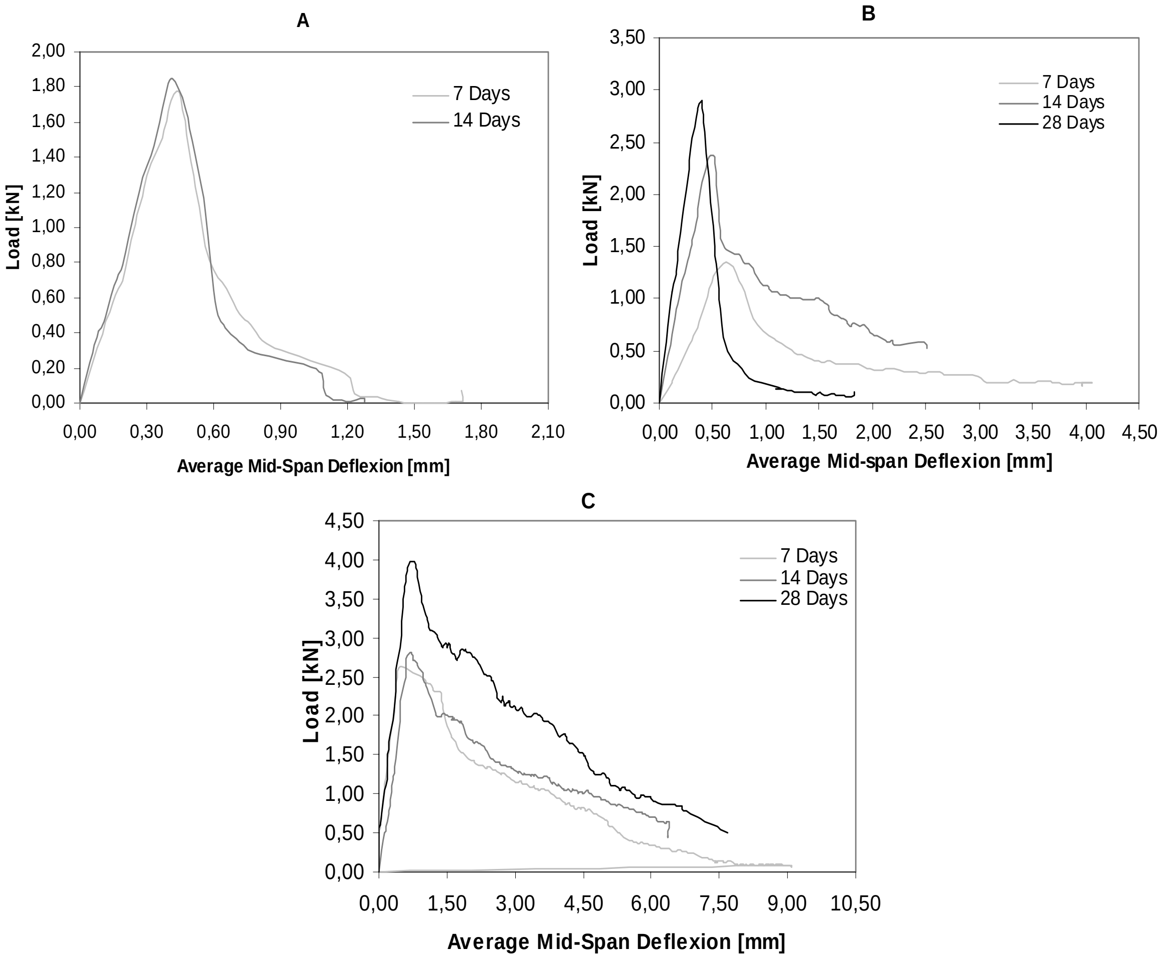

Figure 5- Flexion Strength of Gepolymeric Concretes in Notched Specimens with (A) – 0 Kg/m^3; (B) – 40 Kg/m^3 and (C) – 120 Kg/m^3 of fiber incorporated, respectly.

Water Absorption Tests

The ingress of various ions from the environment and its movement through building materials are responsible for the deterioration of structures. By this reason, the control of the permeability of concrete plays an important role in providing resistance to aggressive environments. The water absorption was evaluated by ASTM C642 “Standard Test Method for Density, Absorption, and Voids in Hardened Concrete” and by the test of capillarity. The results are showed in figures 6 and 7, respectly.

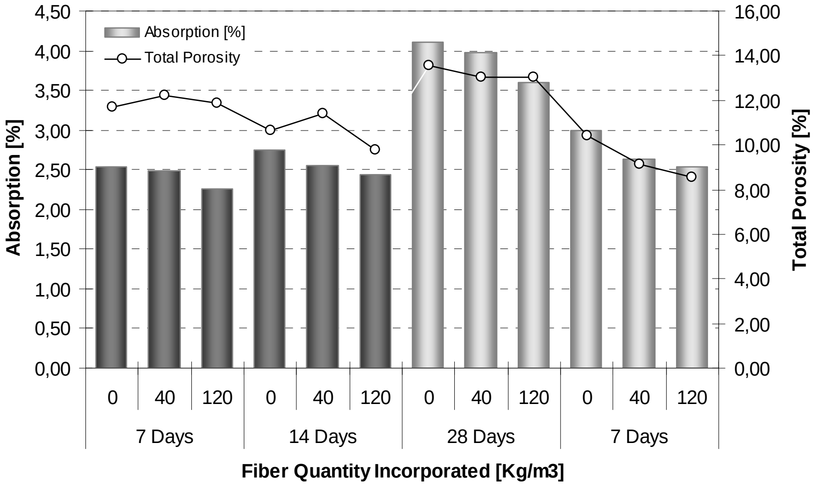

Figure 6 - Absorption and Total Porosity

In general the results obtained in the absorption test (Figure 6) shown that AASC concretes are more permeable than OPCC concrete, at all ages of curing and quantities of fiber studied; fact incoherent with the elevated mechanical properties exhibited by these materials when supporting compression, tension and flexion strains; in spite of these, the total absorption and porosity values, lower than 3 and 10% respectively, are considered acceptable as parameters of compaction and durability. These results permit to catalogue the AASC concretes as durable materials at ages higher of 14 days, due to comply with this criterion. Likewise, a reduction of 20% in the absorption and porosity in AASC concretes with steel fibres incorporation compared with the mixes without fibers is reported.

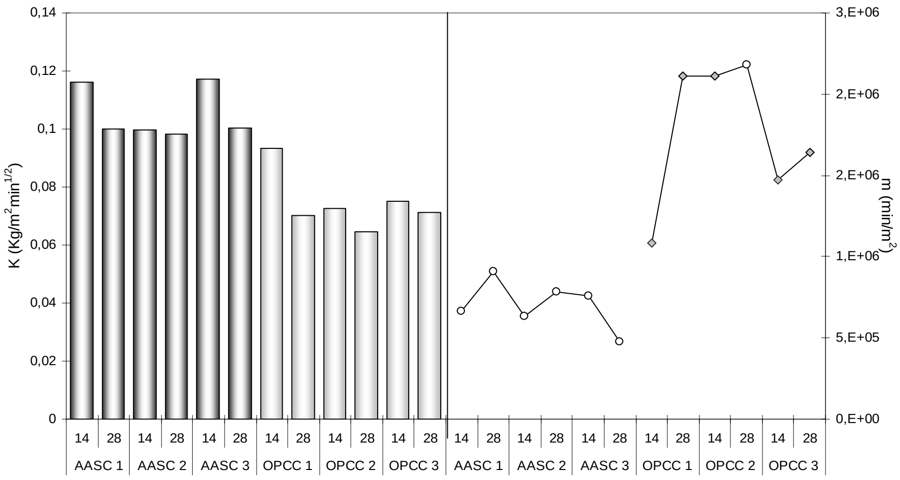

Figure 7- Capillary Coefficient and Water Resistance Penetration

The capillary suction technique was carried out using cylindrical concrete specimens with 76.2 mm in diameter and 50 mm in height. A polymeric coating was applied on the curved surface of the samples to make them impermeable. The samples were conditioned at 60°C for 48 hours before the test. It is observed (figure 7) an increment of the resistance to the water penetration (m) at advanced ages of curing, presenting an insignificant variation with low fiber quantities incorporated in the mixes in study. The AASC concrete present lower "m" values than reference concrete independently the fiber quantity used.

Likewise was showed a reduction of the capillary Index (k_C) in order up to 50% in AASC concretes when is compared to that of the reference concrete. The observed behaviour is comparable with that found in blended cement concretes including high reactivity pozzolans. These results agree with those reported by some researchers (Shi, 1996).

CONCLUSIONS

- The geopolymeric concretes based in AASC present higher compressive strength than OPC concretes, likewise, a higher susceptibility to reduction of the compression strength in OPC concretes with the addition of fibers could be identified, in spite of the AASC concrete exhibited superior decrease in this property.
- The splitting tensile strengths increase in both OPCC and the AASC concretes with the incorporation of fibers at advanced ages of curing, however, these augments were higher in AASC reinforced with steel fibers.
- The modules of rupture of the samples studied added with fibers were higher in AASC. A substantial improvements in load capacity as well as toughness (understood as absorption of energy until failure slip) with the addition of superior fiber quantities, was identified.
- The AASC concretes reinforced with steel fiber present a three times higher toughness than OPCC concretes to early ages of curing, both in continuous and in notched samples, behavior conserved to advanced ages more significantly in samples with notch.
- The notch sensitivity in the concretes studied increases with the addition of steel fibers, although the raise is higher when the fiber strengthened the AASC matrix.
- The properties related to durability performance as water absorption and permeable porous quantity were improved at advanced ages of curing with the addition of steel fibers, which is greatly notable when fibers quantities were increased.
- In generals terms the geopolymeric concretes reinforced with fibers exhibit a mechanical performance higher than control mixes of OPCC, which make of these new materials an optimal alternative to application in conditions where is required a raise toughness and crack strength.

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