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Fracture toughness of geopolymeric concretes reinforced with basalt fibers

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Abstract

The purpose of this work was to investigate the influence of the volumetric fraction of the fibers on the fracture toughness of geopolymeric cement concretes reinforced with basalt fibers. The values of fracture toughness, critical stress intensity factor and critical crack mouth opening displacement were measured on 18 notched beams tested by three-point bending. The a_0/h (notch height/beam height) ratio was equal to 0.2 and the L_0/h (distance between the supports/beam height) ratio was equal to 3.

According to the experimental results, geopolymeric concretes have better fracture properties than conventional Portland cement. They are also less sensitive to the presence of cracks.

Keywords: Geopolymeric cement; Fracture toughness; Critical stress intensity factor; Critical crack mouth opening displacement; Notched beams; Basalt fibers

1. Introduction

The inorganic polymeric cement known as geopolymer [1] is being currently investigated by the composite materials group at the Instituto Militar de Engenharia (IME) as a cementitious material (as a partial or total replacement of Portland cement) in the production of mortars and concretes [2–7].

2. Objectives

The requirements imposed on construction materials are so demanding and diverse that no material is able to satisfy them completely. This has led to a resurgence of the ancient concept of combining different materials in a composite material to satisfy diverse user requirements [8].

Several studies have shown that fiber reinforced composites are more efficient than other types of composites. The essence of composite materials technology is the ability to put the fibers in the right places, at the right orientations and with an adequate volume fraction [9].

The main purpose of the fibers is to provide a control of cracking and to increase the fracture toughness of the brittle matrix through bridging action during both micro and macrocracking of the matrix. Debonding, sliding and pulling-out of the fibers are the local mechanisms that control the bridging action [10].

In the beginning of macrocracking, bridging action of fibers prevents and controls 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 is not 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 [11].

The purpose of this study was to evaluate the fracture toughness (critical stress intensity factor—K_{Ic}) and critical crack mouth opening displacement ($CMOD_c$) of geopolymeric concretes reinforced by different volumetric fractions of basalt fibers (0%, 0,5% and 1% by volume). The basalt fibers were chosen due to their chemical compatibility with alkaline environments [12].

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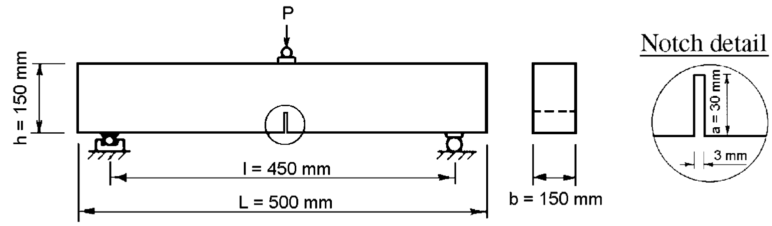

Fig. 1. Testing of notched beam specimens.

The experimental results were compared to those for high early strength Portland cement, since the main characteristic of the geopolymeric cement is an ultra-rapid strength gain.

3. General considerations

Three-point bending, single-edge, notched beam specimens, with a fixed span-to-depth ratio equal to 4 and a limited range of crack-to-depth ratios from 0.4 to 0.7, are the current standard [13–16] for the measurement of the critical stress intensity factor and of fracture toughness. Achieving reproducible results is easier with larger span-to-depth ratios (greater than 2.5) and deeper cracks [17,18].

The values of the critical crack mouth opening displacement ($CMOD_c$) and the critical stress intensity factor for mode I cracking (K_{Ic}), using a three-point bending single edge notched beam (Fig. 1), were calculated according to Ref. [17], because the dimensions of the specimens used in this work were not in accordance with the international standards.

4. Experimental procedure

4.1. Materials and sample preparation

In order to determine the fracture properties of the concretes reinforced by basalt fibers, 18 notched beams were tested by three-point loading. The dimensions of all specimens were 150 mm × 150 mm × 500 mm with a notch height to beam height (a_0/h) ratio equal to 0.2 and a free span to beam height (L_0/h) ratio equal to 3.

The high early strength Portland cement (CPV ARI PLUS), designated as PC, was provided by Holdercim Brasil S/A. The geopolymeric cement, designated as PSS—Poly(Siloxo-Sialate), was synthesized at the Instituto Militar de Engenharia (IME) [2]. PSS cements consist of chains and ring polymers with Si^{4+} and Al^{3+} in IV-fold co-ordination with oxygen and range from amorphous to semicrystalline. The PSS network consists of SiO_4 and AlO_4 tetrahedra linked alternately by sharing all the oxygen. Positive ions (Na^+, K^+ or Ca^{2+}) are present in the framework cavities to balance the negative charge of Al^{3+} in IV-fold co-ordination (Fig. 2). Metakaolin is a pozzolanic material used in this study to manufacture the PSS. The PSS empirical formula proposed is [1]

$$M_n[-(SiO_2)_z - AlO_2]_n,\ wH_2O$$

where M is a cation such as potassium, sodium or calcium, n is a degree of polycondensation and $z = 1$, 2 or 3.

The basalt fibers used in this work were manufactured by Albarrie Canada Inc. with an average length of 45 mm and an average diameter of 9 μm. The mechanical properties of the basalt fibers, as provided by the manufacturer, are summarized in Table 1. A semi-quantitative chemical analysis of the basalt fibers (Table 2) was obtained by Energy Dispersive Spectroscopy

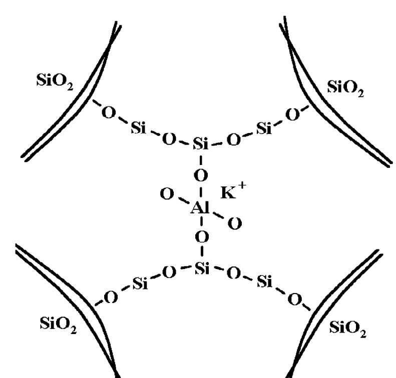

Fig. 2. Geopolymeric cement (PSS) network.

Table 1
Physical and mechanical properties of basalt fibers

Density (g/cm³)	Linear thermal expansion 0–300 °C (ppm/°C)	Tensile strength (MPa)	Modulus of elasticity (GPa)	Ultimate strain (%)
2.8	8.0	4.810	89	3.15

Table 2
Semi-quantitative chemical analysis of basalt fibers by EDS

Element	SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	Na_2O	K_2O	TiO_2	MnO
%	69.51	14.18	3.92	2.41	5.62	2.74	1.01	0.55	0.04

(EDS–NORAN) in a Scanning Electron Microscope (SEM—Jeol 5800LV).

In order to assure a good workability of the concretes without superplasticisers with 1% volume of fiber addition, a high water/binder ratio was used in this study. This volume was used because the compatibility of superplasticisers with geopolymer cement is not well understood. All test specimens were prepared with a binder:fine aggregate:coarse aggregate ratio equal to 1:2.25:3.25 and a water:binder ratio of 0.80. This water/binder ratio is very high for both concretes, especially for the PC concrete. However, for PSS concrete, the water works as a dispersal agent, as well as ionic conductor. Water catalyzes the polymerization and later may or may not leave the molecule. Once the polymerization is complete, the capillary water can be eliminated by heating, without any harmful effects on the final product.

The fine aggregate was washed river sand with a fineness modulus of 2.6 and the coarse aggregate used, gneiss, had a maximum size of 19 mm. Twenty four hours after casting, the specimens were removed from the molds and cured in tanks with lime and water for 27 days.

For each group of three beams with different V_f (0%, 0.5% and 1.0%), six 150 mm × 300 mm concrete cylinders were cast according to Ref. [17] to determine the 28-day average compressive and splitting tensile strength [19,20].

The geometry of specimens (beams) for establishing fracture properties followed the recommendations in Ref. [21]. Prismatic beams 150 mm × 150 mm × 500 mm were used, with a notch of a length of 30 mm a thickness of 3 mm, as shown in Fig. 1.

Compaction (with and without fibers) was carried out during and immediately after the manual placement on a vibrating table for 30 s. The consistency of the concretes was measured using the VeBe time test.

4.2. Testing procedure

The mechanical properties of the cylindrical specimens were determined according to Ref. [22] using a 5000 kN testing machine.

All notched beams were loaded using three-point loading (in the plane perpendicular to the vibration direction to avoid aligned fibers planes) with the distance between the supports equal to 450 mm, using a 500 kN hydraulic testing machine, as shown in Fig. 1.

Crack Mouth Opening Displacement (CMOD) was measured using a clip gauge installed in the center of the notch. A Linear Variable Displacement Transducer (LVDT) was used to measure the deflection of the middle span.

5. Results and discussion

The 28-day average compressive strengths are given in Table 3. The splitting tensile strengths are shown in the same table. It can be seen that PSS concretes had higher strengths than the PC concretes.

Table 3
Results obtained or calculated from the experimental program

Matrix Type	V_f [a] (%)	F_{cm} [b] (MPa)	$F_{ctm,sp}$ [c] (MPa)	VB [d] (s)	P_m [e] (kN)	K_{Ic} [f] (MPa mm$^{1/2}$)	$CMOD_c$ [g] (mm)	$CTOD_c$ [h] (mm)
PC [i]	0	23.1	2.5	12	9.6	36.75	0.052	0.028
	0.5	22.2	2.7	13	12.5	50.08	0.062	0.033
	1.0	17.0	2.2	48	14.0	43.15	0.063	0.034
PSS [j]	0	39.5	3.2	56	16.0	45.65	0.045	0.024
	0.5	28.6	4.3	105	17.2	57.62	0.070	0.038
	1.0	36.9	4.0	389	21.0	90.99	0.152	0.078

[a] Volumetric fraction of fibers.
[b] Average compressive strength.
[c] Average splitting tensile strength.
[d] VeBe time.
[e] Average flexural strengths.
[f] Critical stress intensity factor for mode I cracking.
[g] Critical crack mouth opening displacement.
[h] Critical crack tip opening displacement.
[i] Portland cement concrete.
[j] Geopolymer cement concrete.

The addition of 1.0% basalt fibers resulted in 26.4% and 12% reductions in the compressive and splitting tensile strengths for the PC concrete, respectively. As the fiber percentage increased, the probability of these fibers balling together and leaving voids in the matrix was greater. In some situations, the constituents, particularly in the PC cement, were found in powder form. After mixing, the fibers had engaged too much water, denying the cement around them enough water for hydration. This can explain the decrease in the compressive and tensile strength values for V_f equal to 1%. PC concrete with V_f equal to 0.5% presented negligible changes in the compressive and splitting tensile strength relative to PC concrete without fibers.

The PSS concretes with fibers presented tensile strength gains compared to PSS concrete without fibers (34% for $V_f = 0.5\%$ and 25% for $V_f = 1.0\%$). A 28% reduction in compressive strength for PSS with V_f equal to 0.5 was observed, probably due to problems in the manufacturing process. No significant change in compressive strength was noted for PSS concrete with V_f equal to 1.0%.

The average values of the ultimate load of tested beams and of the VeBe time (VB) are shown in Table 3. All specimens with fibers had a larger flexural strength than specimens without fibers. Fora volume fraction of 1.0%, the failure load gains were about 46% and 31% for PC and PSS concretes, respectively.

As expected, the addition of fibers to all concretes tested caused increases in the VeBe time. This effect is characteristic of all fibers and partly results from the consumption of a fraction of mixing water and cement paste for coating the surface area of the fibers. It was observed that all PSS concretes exhibited lower workability than PC concretes (Table 3).

Typical load versus midspan deflection curves for prismatic specimens are shown in Figs. 3 and 4. It can be noticed that there are significant improvements in load capacity (P_m values in Table 3) as well as in fracture toughness (K_{Ic} values in Table 3). A superior load capacity and fracture toughness of PSS concretes over that of PC concretes can also be seen.

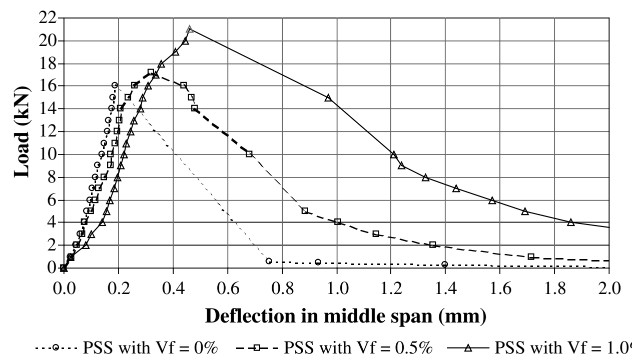

Fig. 4. Load versus deflection in middle span curves for PSS concretes.

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

Contrary to PC beams, with the addition of basalt fibers, PSS beams showed a smaller slope in the ascending part of the load-deflection curve, which means that the beams possess lower flexural rigidity. As V_f increased, PSS beams showed higher ultimate load and larger displacement before failure.

Fig. 5 shows the load versus CMOD curves used to calculate the initial and the critical compliances (C_i and C_c) and thus determine $CMOD_c$. The $CMOD_c$ values are presented in the Table 3. These values indicate a limit to stable crack growth (up to $CMOD_c$) and unstable crack growth (above $CMOD_c$). Here the term stable crack growth means that the major crack propagates only when the load increases. Thus, for values of CMOD values above $CMOD_c$, the major crack continues to propagate even though the load is decreasings. Contrary to PSS concrete without fibers, PSS concretes with fibers exhibited larger $CMOD_c$ values than PC

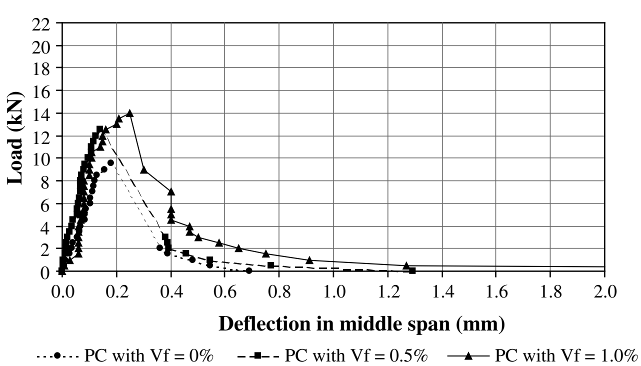

Fig. 3. Load versus deflection in middle span curves for PC concretes.

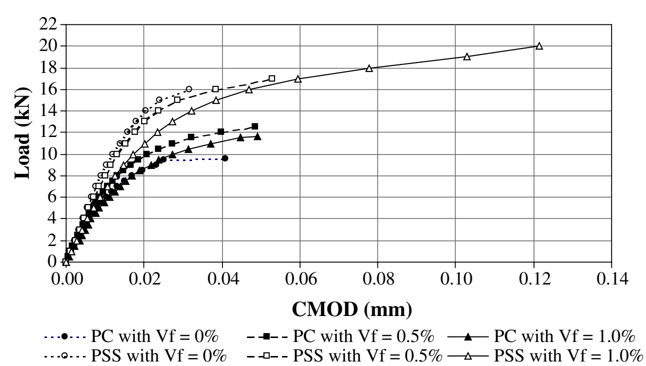

Fig. 5. Load versus CMOD curves.

concretes (Table 3); consequently, these concretes were less sensitive to the presence of sharp defects (cracks).

The Reinforcing Efficiency (RE) of the basalt fibers can be defined as follows [22]:

$$(\mathrm{RE}) = f(F_\mathrm{S}, F_\mathrm{T})$$

where F_S is a strengthening factor and F_T is a toughening factor calculated from

$$F_\mathrm{S} = \frac{\mathrm{CTOD_c}\ \text{for the concretes with fibers}}{\mathrm{CTOD_c}\ \text{for the concretes without fibers}}$$

$$F_T = \frac{K_\mathrm{Ic}\ \text{for the concretes with fibers}}{K_\mathrm{Ic}\ \text{for the concretes without fibers}}$$

where $\mathrm{CTOD_c}$ is the Critical Tip Opening Displacement, which can be obtained according to [23].

The $\mathrm{CTOD_c}$ values can be seen in the Table 3 and the RE values are shown in Table 4. It can be seen from Table 4 that basalt fibers were more efficient in reinforcing PSS concretes than PC ones, since they had higher F_s values. The reason is better fiber adhesion of the geopolymer matrix. Contrary to concretes with $V_\mathrm{f} = 1.0\%$, in the case of concrete with $V_\mathrm{f} = 0.5\%$ the F_T value was higher for the PC concrete.

Fig. 6 shows the toughening mechanisms in the PSS concrete. Debonding, sliding and pulling-out of the fibers are the local mechanisms that control bridging action. The *bridging action* is shown in the Fig. 6a and *fiber pullout*, the main toughening mechanism in PSS concretes, is show in the Fig. 6b.

Table 4
Reinforcing efficiency array

Material type	V_f (%)	(RE)	
		F_S	F_T
PC	0.5	1.18	1.36
	1.0	1.21	1.17
PSS	0.5	1.58	1.26
	1.0	3.25	1.99

6. Conclusions

From this study the following results were obtained:

PSS concretes exhibited higher strengths than PC concretes. The addition of 1.0% of basalt fibers resulted in 26.4% and 12% reductions in the compressive and splitting tensile strengths for PC concretes. All PSS concretes with fibers presented splitting tensile strength gains in relation to PSS concrete without fibers. Increases in the flexural strength for all PSS specimens with fibers relative to PSS specimens without fibers were observed. As expected, the addition of fibers to all concretes tested caused increases in the VeBe time. PSS concretes exhibited lower workability than PC ones. A superior load capacity and fracture toughness of PSS concretes over that of PC concretes were noted. The load-deflection relationship is linear for all test specimens up to the maximum load. As V_f increased, PSS beams presented higher ultimate load and larger displacement before failure. Contrary to concretes without fibers, PSS concretes with fibers exhibited larger values of $\mathrm{CMOD_c}$ than PC concretes; consequently, these concretes were less sensitive to the presence of cracks. The basalt fibers were more efficient in strengthening PSS concretes than PC concretes and they were more efficient in toughening PSS concretes than PC concretes only for higher fiber concentrations ($V_\mathrm{f} = 1.0\%$). This difference in behavior is probably related to the nature of the bond between fiber and matrix.

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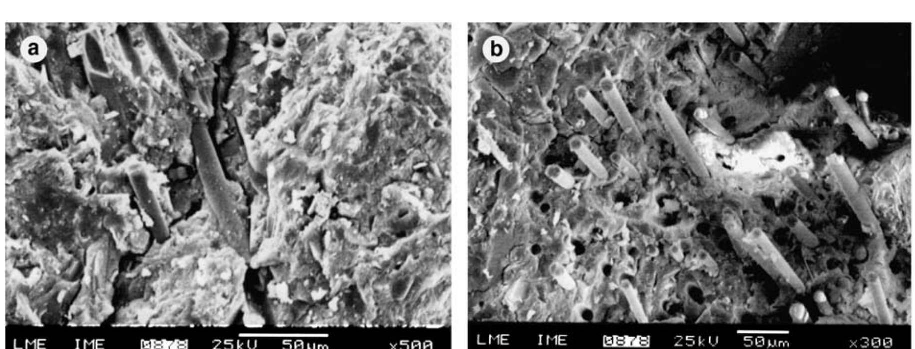

Fig. 6. Toughening mechanisms in the PSS concrete with $V_\mathrm{f} = 1\%$: (a) bridging action and (b) pullout of the fibers.

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