PARAMETRIC ANALYSIS OF THE FRACTURE BEHAVIOUR OF POLYMERIC CONCRETE REINFORCED AND NOT REINFORCED WITH FIBBER UNDER DIFFERENT ENVIRONMENT CONDITIONS

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Abstract. *The polymeric concretes are agglomerated of fine aggregates, like as, silica sand, gravel, marble powder, etc, that are mixed with a polymeric bond that is usually a thermoset plastic.*
The polymeric concretes are materials with high mechanical properties and they are use in situations where the chemical strength is crucial. The nature polymeric of the matrix produces a material that confines the inert and the fibbers what originates a very little porous structure, that consequently it protects the interior of the pieces relative to the exterior, not needing external coverings as thick as if traditional cement concrete was used. It is possible at the same time reduce the section of the pieces that constitutes a great advantage, especially in architecture applications, because it allows to manufacture structural components that simultaneously reconciling two very important aspects, the high mechanical and chemical strength and the thinness or be the aesthetics of the component.
The study of the fracture behaviour of polymeric concretes still in our days at the initial phase, due to this reason, this research work intends to give a significant contribution in this matter facilitating their understanding.
For that purpose, in this paper will be presented and discussed the results of several static flexure tests in four points and fracture tests performed in concrete polymeric beams without notch and with notch with several depths, in order to study the effect of the geometry of the notch (rectangular, circular and "V") of the structure type (without fibber and with fibber) and of the environmental conditions (room temperature and after thermal fatigue cycles) on the fracture properties, namely, the notch sensibility, the fracture tenacity (K_{IC}) and the critical displacement of the opening of the crack tip ($CTOD_C$). Finally the properties of the polymer concrete were compared with the properties of the cement concrete.

Keywords: *Polymer concrete, Thermal fatigue, Fracture mechanics, Notch geometry*

1. Introduction

It is known that a good number of researchers has been used the knowledge of parameters of linear elastic fracture mechanics (LEFM) and elasto-plastic fracture mechanics (EPFM) to characterize the fracture strength of polymers, polymer composites, mortars of cement and concrete cement. Among several fracture parameters some of them play a crucial role namely, intensity factor of critic tension (K_{IC}), the critical integral J (J_{IC}), the critical displacement of the opening of the crack tip ($CTOD_C$), fracture energy (G_F) and the analysis of the strength curves, as the most popularly used to describe the fracture behaviour (Mindless, 1984, Young, 1979, Ziegeldorf, 1983, Velazco *et al*., 1980, Swartz *et al*., 1982, Yamini and Young, 1977, Vipulnandan and Dharmarajan, 1987, Vipulnandan and Dharmarajan, 1988, Wecharatna and Shah, 1982 and Garg and Trotman, 1980).

The methods based on the strength curves are only used when the growth of the crack is stable and slow. This is the case of mortars reinforced with fibbers used in the present study where the (K_{IC}) and ($CTOD_C$) were determined. This is justified because when the concrete has a fracture eminently fragile (as it happens in the case of the mortars with reinforcement). In this situation the fracture is simply characterized by a singular value of tenacity (K_{IC}). This value can be determined by using the (LEFM) and using the notch initial length and fracture load (Velazco *et al*., 1980). The direct measure of the extensions of the notches in mortars or concretes is possible without using expensive instrumentation and can be indirectly determined by using curves of load versus displacement and load versus crack mouth open displacement (CMOD) (Jenq and Shah, 1985a). The CMOD method is also used to evaluate the factor of intensity of critical tension (Tada *et al*., 1973), but if growth of crack is slow before reaching the load peak, the determination of these values based on (LEFM) are wrong and, therefore, the models of length with two or more parameters are used due to the slow non-linear growth of crack (Jenq and Shah, 1985a, Jenq and Shah, 1985b and Shah and Carpinteri, 1991).

In the present work flexural tests were performed, based in four points, and fracture tests with standard specimens were done too. These procedures were done in order to determine the strengths properties and to characterize the fracture behaviour of the concrete polymers and to compare the results obtained with those for the traditional concrete cements.

2. Materials and experimental procedures

2.1. Specimens preparation

The present work aims to study the fracture behaviour of epoxy concrete polymers with and without glass fibbers, which composition is summarized in Tab. 1.

Table 1. Polymer concrete formulations.

Composition	*Type of polymer concrete*	
	Without Fibber	With Fibber
Agglomerate [%]	82	79
Resin [%]	12	12
Hardener[%]	6	6
Fibber [%]	0	3
Charge [%]	0	0

The resin selected is an epoxy resin (EPOSIL 551) and a hardener of the same type (EPOSIL 551), which proportions are 12% and 6%, respectively, making a total of 18% of the mixture. The resin has low viscosity (500 to 700 mPa.s) and a flexural strength equal to 70 MPa. This aggregate is constituted by a sand foundry, which is a silicate sand named as SP55 with an average mesh of 342μm. The sand was dried before to mixture, being the sand agglomerate with the resin and hardener. In Tab. 2 the mixture characteristics are presented.

Table 2. Main characteristics of the mixture resin/hardener EPOSIL 551.

Mixture characteristics	*Resin*	*Hardener*
Viscosity [mPa.s]	500-700	300-400
Useful time of the mixture to 25°C [min]	27	
Hardening time [h]	6	

The reinforcement of the polymeric concrete was performed using glass fibbers that were imbibed in the mixture, being the sand agglomerate by the resin, provide highly stiff agglomerates. The glass fibber has 25 mm of length and 0,22 mm of average diameter, being listed in Tab. 3 some of its mechanical characteristics.

Table 3. Main mechanical characteristics of the fibber reinforcement used (RILEM, 1990).

Mechanical properties	*Glass fibber*
Tensile strength [GPa]	3,6
Tensile elasticity modulus [GPa]	76

The polymeric concrete beams were molded according to standard ASTM E399 in a mold especially fabricated for this purpose, which is illustrated in Fig. 1 and is used to produce beams notched and not notched. The beams/specimens were cured at room temperature during one day and then they were subjected to a post-cure at 70ºC during 7 hours. For this purpose the oven Venticell was used, as it is shown in Fig. 2.

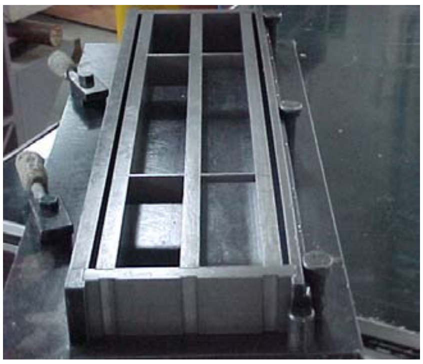


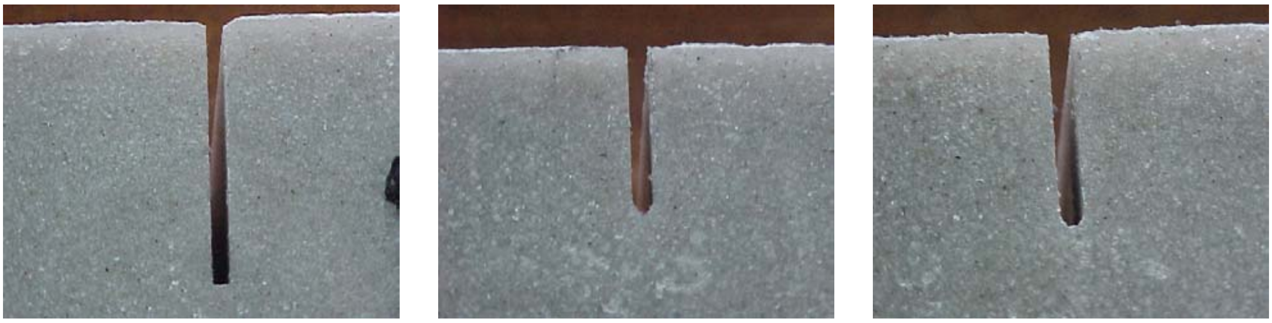
Figure 1. Mold used in the production of the polymer concrete beams.

Figure 2. Illustration of the Venticell oven.

The beams have a square section of 50 mm of side and a length of 300 mm. Three beams are used for each composition and test condition, that is, 3 beams without fibber and 3 with fibber were tested after being submitted by thermal cycles (+20ºC/+100ºC). The thermal cycles duration was 8 hours for 1200 hours (150 cycles). This cycles is designated by cycle 1 as is defined as, 2h at + 20ºC/ 50% HR ⇒ 2h *Change* ⇒ 2h at +100ºC without humidity control ⇒ 2h *Change* ⇒ Cycle repetition.

Change denominates the passage from one to another isothermal level. This cycle was selected due to the necessity to study the structural components in concrete polymers subjected to situations of thermal fatigue such as in hot climate zones and due to viscoelastic matrix polymer nature which easily provoke fluency phenomena.

According to standard ASTM E399, 3 types of beams notched were produced for different test conditions making a total of 48 beams used to test the notch sensibility, fracture tenacity and critical displacement of the opening of the crack tip. The notches for the beams have a rectangular, V and circular geometry, as shown in Fig. 3. The notch depth were equal to 8, 18, 28 and 38 mm, resulting in following relations between notch depth (d) and beam height (h), 0,16, 0,36, 0,56 and 0,76, respectively.



a) Rectangular notch. b) "V" notch. c) Circular notch.

Figure 3. Types of beams notched used.

2.2. Test procedures

Static flexural tests

The specimens were subjected to static flexural strength tests in four points according the standard ASTM E399. The experimental setup for the beams without notch has the same configuration as the case for the fracture tests, as Fig. 4 illustrates.

The distance between support points is equal to 220 mm, being L/3 the distance between the load application points, which are applied at the mid point of the semi-cylinders. For this purpose, an Instron machine was used with a load cell of 10 ton of capacity, being the load velocity equal to 0,5 mm/min and the room temperature equal to 22ºC.

Fracture tests

The specimens notched were subjected to flexural tests supported in 4 points, being the conditions the same as presented previously. Figure 4 shows de experimental test rig. In this procedure, an acquisition system named Spider 8, was used together with a computer that uses the software Catman 3.1. These systems were associated with the Instron machine, which is equipped with a displacement transducer and a clip gauge that allows to measure the aperture of the notch (CMOD), which is rigidly attached between two plates in the direction of the notch. With this methodology the experimental tests can be performed. In Fig. 5 the Instron machine is illustrated as well as all equipment evolved in this process.

Figure 4. Experimental setup.

Figure 5. Instron machine and the acquisition system.

3. Results and discussion

3.1. Static tests

Basic on the average of 3 specimens tested for each composition and environment conditions, the curves for load versus displacement were obtained. Table 4 shows the results for flexural strength and the elasticity modulus for two systems, for the case of room temperature and after application of thermal fatigue cycles.

Analyzing Tab. 4 it can be observed that the concrete without fibber presents a high degradation of properties of strength with the application of thermal fatigue cycles (20 a 30%), but when 3% of fibber is added, then is a lightly increase of the flexure strength (1,4%) and a decrease of 11% of the flexural elasticity modulus.

Table 4. Average values of flexure strength and flexural elasticity modulus for the beams (without fibber and with 3% of fibber) obtained with different environmental conditions (room temperature and after cycle 1).

Mechanical strength properties	*Without Fibber*		*With Fibber*	
	Room temperature	Cycle 1	Room temperature	Cycle 1
Flexure strength [MPa]	26,6	19,6	26,9	27,3
Variation [%]	- 26,3		+ 1,4	
Flexural elasticity modulus [GPa]	24,70	17,48	22,90	20,43
Variation [%]	-29,0		- 10,7	

3.2. Fracture tests

<u>*Notch sensitivity*</u>

This property is evaluated by dividing the static flexural strength of the beams notched by the static flexural strength of the beams not notched. Thus, the diagrams of notch sensitivity versus d/h relation are presented in Fig. 6 and 7. The results are plotted for different conditions. For the cases in which the beam/specimen does not include fibbers, and tested at room temperature, geometry of the notch has almost no influence in the notch sensitivity, nevertheless small differences are visible, being the circular notch sensitive and stable to the variation of the notch sensitivity, when compared with other geometries. However, the application of thermal fatigue cycles at high temperatures increases substantially the values of the notch sensitivity with strong fluctuations in the cases of circular notch and in "V", especially in the last case. Thus, the values of the notch sensitivity in the cases with fibber are lesser than those in the cases without fibber, independently of the notch geometry and environment conditions.

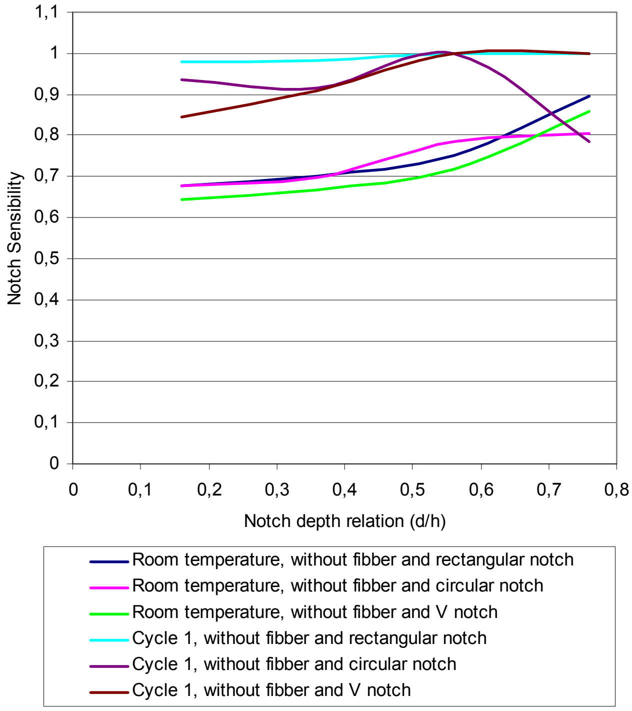


Figure 6. Notch sensibility versus d/h for the beams without fibber.

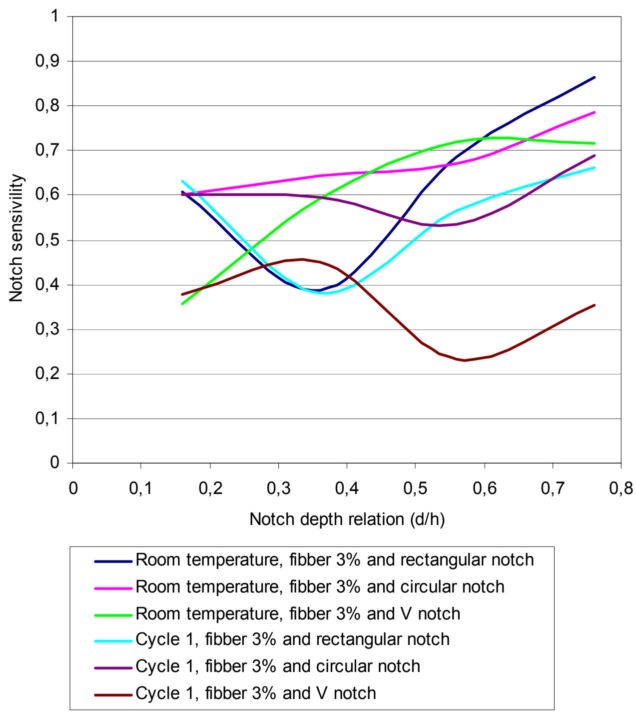


Figure 7. Notch sensibility versus d/h for the beams with 3% of fibber.

Fracture tenacity and critical displacement of the opening of the crack tip

From the results obtained in the fracture tests, it was possible to build the curves load versus displacement and load versus CMOD (crack mouth open displacement), and the stress intensity factor K_I. These factors were obtained by using two methods: the method of initial depth of crack and the method CMOD that allows the determination of critical displacement of the crack tip opening, $CTOD_C$.

Thus, for the beams without reinforcement, where the relation between load and CMOD is linear, and there is no crack extension over the load peak. The stress intensity factor is calculated based on maximum load values obtained in fracture tests for different notch depths (Young, 1979) and using the theory presented by (Brown and Srawley, 1966).

For reinforced beams the relation between load and CMOD is non linear, a certain plasticity exists and a slow crack growth over the load peak. Thus, the calculation of the tension intensity factor and critical displacement of the crack tip open is done using the curves load versus CMOD, initial compliance and unloading diagrams, and two model parameters, being neglected the inelastic component (RILEM, 1990) in beams with square section of 50 mm side. The values of fracture tenacity are the average values of the tension intensity factors for the 4 notch depths and different situations and conditions.

Figure 8 shows the values of fracture tenacity as function of environment conditions for both systems (without and with fibber) and different notch geometries and methodologies of determination of fracture properties. In the systems without fibber at room temperature, the fracture tenacity is reduced lightly when the rectangular notch is substituted for circular notch, and decreases more intensely when the notch is change from circular to "V". The application of cycle 1 increases these values. However, in the systems with fibbers and at room temperature higher values of fracture tenacity were observed, and vary in a similar way as previously according to the notch geometry. The effect of thermal cycles degrades the fracture properties, mainly for the systems with rectangular notch compared to the circular notch, and this observation is more evident in the case of the notch "V".

Figure 9 shows the values of critical displacement of the crack tip opening, $CTOD_C$ as function of environmental conditions for the systems with fibbers and using the method of two parameters. The variation of $CTOD_C$ with the environmental conditions for the systems with fibbers is very similar to the variation of the tenacity fracture, yet for different values, excepted for the case of circular notch and in "V" at room temperature, which sense of variation is inverse to that shown in relation to fracture tenacity, using as referential the rectangular notch.

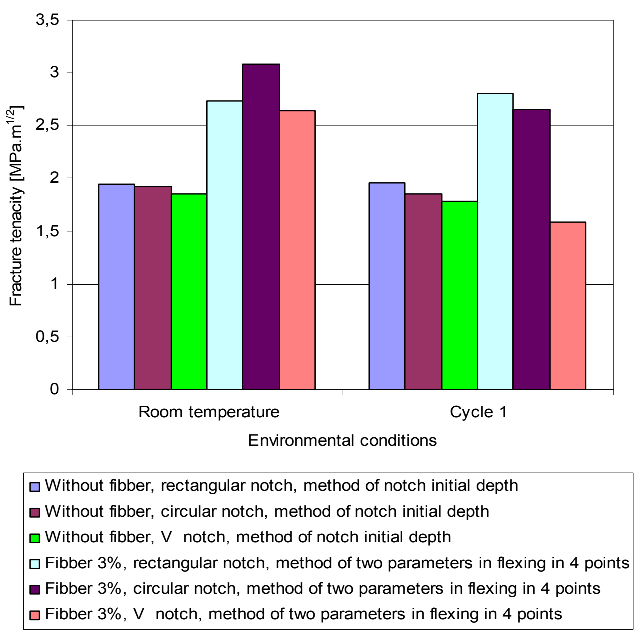


Figure 8. Fracture tenacity for different environmental conditions and notch geometries in agreement with several methodologies of determination of fracture properties.

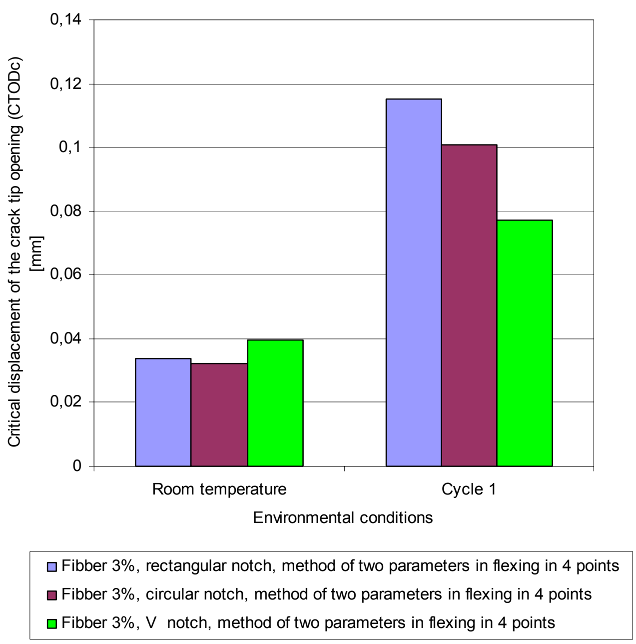


Figure 9. Critical displacement of the crack tip opening for different environmental conditions and notch geometries for the beams with 3% of fibber.

In Tab. 5 is shown the comparison between the values of fracture properties (K_{IC} and $CTOD_C$) for several authors for different systems, for cement and polymer concretes, which are similar to those presented in this investigation. Thus, it is visible that at room temperature the values of tenacity are, in general, greater than for the upper limits presented for cement concrete, being these values even greater for the cases in which polymer concrete is reinforced with fibber, mainly when it is substituted by thermal fatigue cycles at high temperature, as in the present work (referred in the table by an *). The plastic deformations in the tip of the crack are lesser in the concrete cements in relation to polymer concretes, being the values of $CTOD_C$ much higher when compared to those of this investigation (referred in the table by an *).

Table 5. Comparative table of the fracture properties between the polymeric and cement concretes (values obtained in the present work are referred in the table by an *).

Concrete formulations	*Type of fracture test and/or method of determination of the fracture properties*	*Fracture tenacity* K_{IC} [$MPa.m^{1/2}$]	*CTODc* [mm]
Without reinforcement			
Cement	Flexure – Load mode I	0,20 [Barr and Sabir, 1985]	
Traditional cement concrete	Flexure – Load mode I	0,3 to 2,0 [RILEM, 1990]	
	Compact compression eccentrically loaded	0,84 to 1,03 [Ziegeldorf, 1983]	
	Axial splitting test	1,23 to 1,57 [Sabir, 1994]	
	Flexure in 3 points - Load mode I	0,42 to 0,61 [Jenq and Shah, 1985a]	
High strength concrete cement without reinforcement	Flexing in 3 points - Load mode I - Method of two parameters	1,06 [Mindless, 1984]	0,010 [Mindless, 1984]
Epoxy polymeric concrete without reinforcement	Flexure – Load mode I	0,80 to 2,20 [RILEM, 1990]	
	Flexing in 4 points - Load mode I - Method of notch initial depth	1,96 *	
With reinforcement			
Epoxy polymeric concrete reinforced with short glass fibbers	Flexing in 3 points - Load mode I - Method of two parameters	2,27 to 3,07 [Reis and Ferreira, 2002]	
Epoxy polymeric concrete reinforced with short carbon fibbers	Flexing in 3 points - Load mode I - Method of two parameters	2,29 to 2,58 [Reis and Ferreira, 2002]	
Epoxy polymeric concrete reinforced with 3% of glass fibbers with 25 mm length	Flexing in 4 points - Load mode I - Method of two parameters	2,74 *	0,0338 *
Epoxy polymeric concrete reinforced with 3% of glass fibbers with 25 mm length and submitted to the Cycle 1 of high thermal fatigue	Flexing in 4 points - Load mode I - Method of two parameters	2,80 *	0,115 *

4. Conclusions

The main conclusions observed throughout this work are listed in what follows:

(i) at room temperature, the concrete non reinforced has a static flexural strength lesser those concrete reinforced; and after application of cycle 1 of thermal fatigue at high temperature, the strength is reduced about 25% for first case, while in the second case the strength increase lightly;

(ii) the notch sensitivity varies from 0 to 1, being greater for the system without fibber, and independently of environmental conditions;

(iii) the notch "V" is more sensitive to fracture;

(iv) the fracture tenacity does not depend on the depth of notch and the levels of confidence obtained in statistical treatment of the experimental results in what concerns to fracture properties are greater when the model on two parameters is used when compared to the method of notch initial depth;

(v) the concrete polymers haves higher fracture properties than those for concrete cements.

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