THEORETICAL AND EXPERIMENTAL INVESTIGATION ON THE FRACTURE OF MORTAR POLYMERIC REINFORCED WITH GLASS FIBBER

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Abstract. *Polymer mortar is a mixture of a polymer binder of epoxy, polyester, vinyl ester and a fine aggregate. In the recent years the polymeric mortars have increasingly been used in the construction and repairing of structures, pavements of highways, boards of bridges and residues pipes. The versatility in their formulation and processing associated to the fast application originated the use in large scale of polyester and epoxy mortars in many and several applications.*
The typical composition of these materials is based in fine aggregates and when employ in the repairing and construction of structures, their behaviour is invariably fragile, supporting however high tensions in extreme and adverse service conditions. Thus the knowledge of the fracture properties and their behaviour predict are essential for the efficient use of these new materials, concerns to the structures safety against flaws and collapses and to the service rehabilitee.
In this experimental research they were moulded normalized beams of polymeric epoxy mortars reinforced with glass fibbers, with several notch geometries and subsequently submitted to fracture tests in flexing in four points, at room temperature and after thermal fatigue cycles at high temperature.
In this paper will be presented and discussed an analytical model developed to explain the behaviour of the fracture in the performed different test conditions. From the results obtained it was possible concluded the existence of a very good correlation between the theoretical and experimental data for the several notch geometries and environmental conditions.

Keywords: *Polymer Mortar, Flexural tests, Theoretical model, Fracture mechanics*

1. Introduction

The evaluation of the importance of the defects requires the knowledgement of the material tenacity. This property characterizes the resistance to crack propagation. The intensity of tension factor plays a crucial role not only problems of unstable fissures propagation but also in stable fissures propagation problems, such as in fatigue problems. This observation motives the interest in study the possible techniques, analytical and experimental, to determine this factor. In fracture problems it is interesting to evaluate the fracture energy [Branco *et al*., 1986].

Similarly to what happiness in the generality of metal alloys of high resistance, usually with a behaviour not ductile, or with any fragile material, the concrete cements, especially the simple concretes without reinforce and polymeric concretes, have linear elastic behaviour, and hence the domain of validity application in fracture mechanic linear elastic [Barr and Sabir, 1985]. However, when the concrete is reinforced with fibber (see Fig. 1) a considerable ductility can occur, being not applicable the linear elastic mechanic fracture, after cracking has been occurred. Thus, it is convenient to determine beside the fracture tenacity, the critical displacement of the crack tip opening, since a plastic deformation exists and is not negligible at the crack tip, recurred to the two parameters model [RILEM, 1990]. Yet, the fracture behaviour depends on formulation, cure conditions, temperature of tests, load velocity, type and form of load, type and percentage of fibber used to reinforced the concrete. In addition if the concrete does suffer or not thermal fatigue at environment conditions, and when it was exposed to corrosive conditions, also influence fracture behaviour [Kesler *et al*., 1972]. The application to linear elastic fracture mechanics (LEFM) to the concrete was firstly proposed by Kaplan in 1963, and since that a good number of tests was performed with the intend to examine the validity of LEFM to concrete [Jenq and Shah, 1985a].

In this work, an extensive experimental work in fracture was performed, which consists in the realization of flexural tests in beams of square section of 50 mm of side and 300 mm of length according to standard ASTM E399. The specimens were made of polymer mortar of epoxy resin with and without reinforce of glass fiber. Different depths and geometries of notch were tested at room temperature and after being submitted to thermal fatigue cycles at high temperature. During the tests, the curves of load versus displacement and load versus crack mouth open displacement (CMOD) were constructed. From then curves it is possible to determine the fracture properties using the two parameters model. Furthermore, analytical expression that allows to anticipate the experimental results was deduced. In the process, the fundamental steps and mathematical methodology used are described. Finally a comparison between theoretical and experimental data was performed being the correlation quite good.

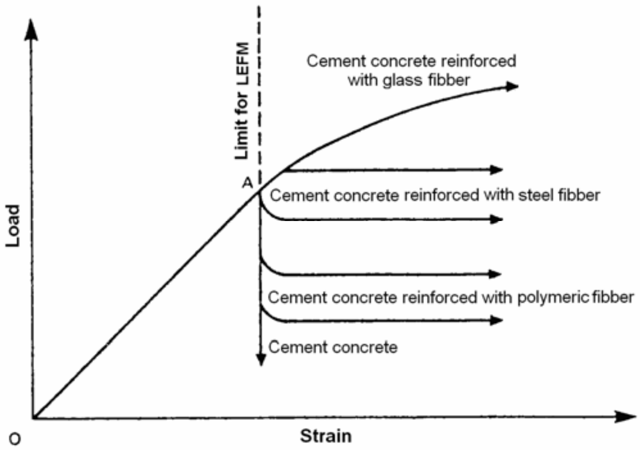

Figure 1. Typical curves load vs. strain obtained in fracture tests for several cement concretes.

2. Experimental program

2.1. Materials and properties

The polymer mortar of epoxy consists of a mixture of a resin of EPOSIL 551 with a hardener EPOSIL 551, in the following proportion 2/3 of resin and 1/3 of hardener. The mixture also includes fine foundry sand with average granulometry of 247 µm of type SP55 in proportions of 20% of resin and of hardener and 80% of sand. Beams with and without glass fibber reinforce were molded, being the fibber length equal to 25 mm, 0,25 mm of average diameter, traction elasticity modulus equal to 76 GPa and a flexural strength of 3,6 GPa [Marques, 1990]. The average value of resin viscosity is of 600 mPa.s, and 350 mPa.s for the hardener. Due to this structure the epoxy resin has groups of hydrogen and epoxy that permit a reticulation and gives high mechanical properties to polymer concretes of epoxy. This process results in a three-dimensional structure characterized by a dense net of crossings [Lombera, 1996].

2.2. Experimental procedure

The beams were submitted to a flexural fracture tests in four points in a Instron machine, which load cell has a capacity of 10 ton and includes displacement transducers. The distance between supports is of 220 mm, being this distance in 3 parts, which dimension is about 73,4 mm. In Fig. 2 the experimental setup is illustrated. The load velocity used was equal to 0,5 mm/min for the different condition tests. 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 and with a clip gauge that allows to measure the displacement values, loads and the crack mouth open displacement (CMOD). In Fig. 3 all the equipment involved in the experimental tests are illustrated.

Figure 2. Experimental setup.

Figure 3. Instron machine and the acquisition system.

3. Analytical model of the fracture behavior

Integrating the polynomial curves obtained by approximation with five order relative to load versus displacement obtained experimental, and considering the integration limits of strain zero and δ_0 (final strain), we can obtain the parameter W_0, which is the value of the area situated between the curves and strain axis (see Fig. 4).

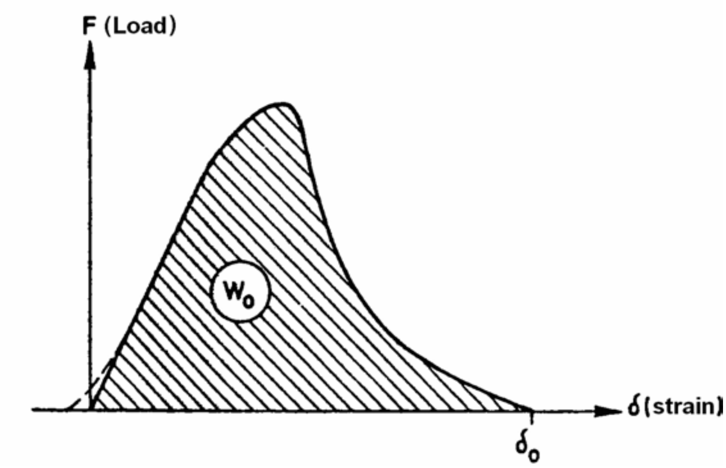

Figure 4. Curve load versus strain.

The fracture energy G_f is evaluated using eq. (1), when m is the beam mass between two supports, g the gravity acceleration and A_{lig} the section of connection, being the area projected onto the fracture zone in an orthogonal plan to the beam axis [Jr Brown, 1966].

$$G_f = (W_0 + mg\delta_0) / A_{lig} \tag{1}$$

In Fig. 5, 6, 7 and 8 some of experimental curves for load versus displacement and load versus CMOD are presented, respectively, for the relations between the notch initial depth of the beam, d_i and the height of the beam, h, of 0,16, 0,36, 0,56 and 0,76, obtained with different environmental conditions and notch geometries.

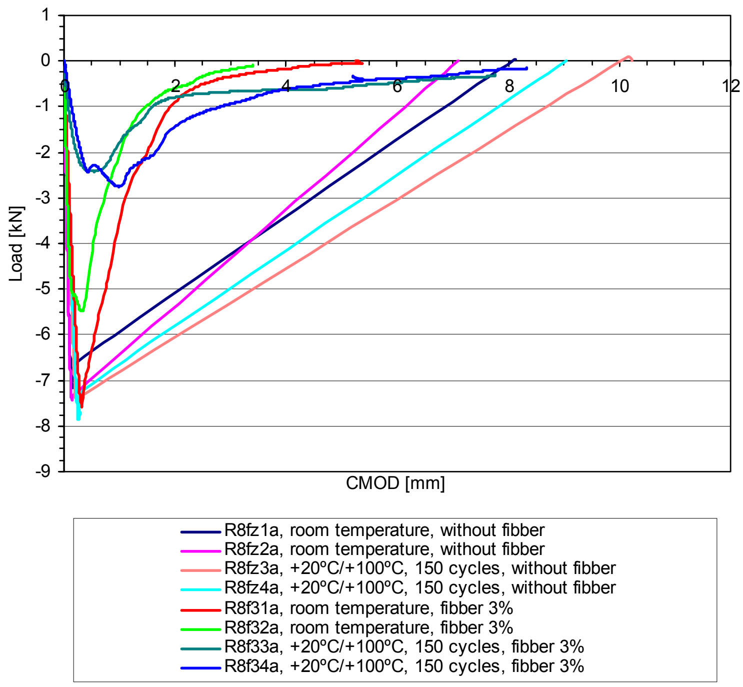

Figure 5. Curves load versus CMOD for the relation (d_i/h = 0,16) of the beams with rectangular notch, without fibber and with 3% of fibber, in the different environmental conditions.

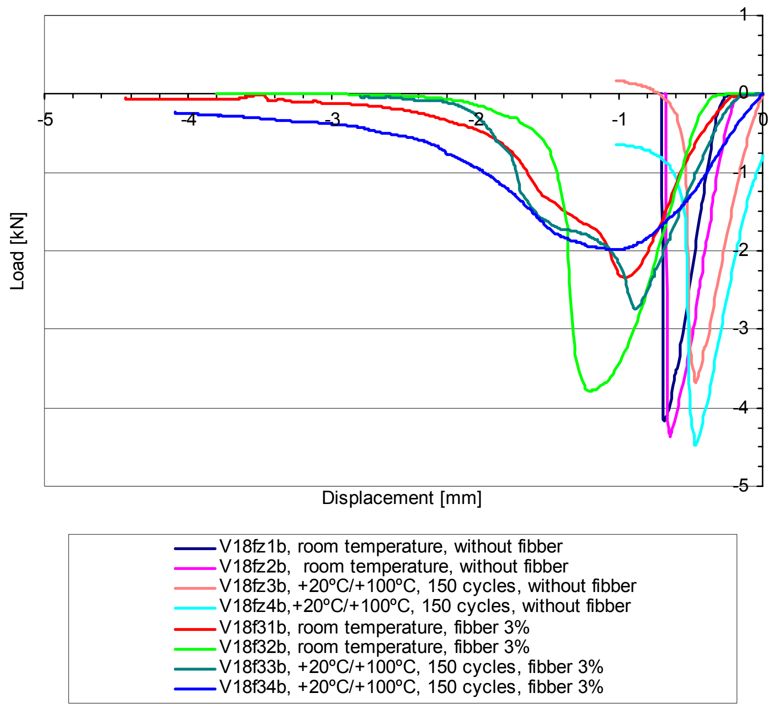

Figure 6. Curves load versus displacement for the relation (d_i/h = 0,36) of the beams with "V" notch, without fibber and with 3% of fibber, in the different environmental conditions.

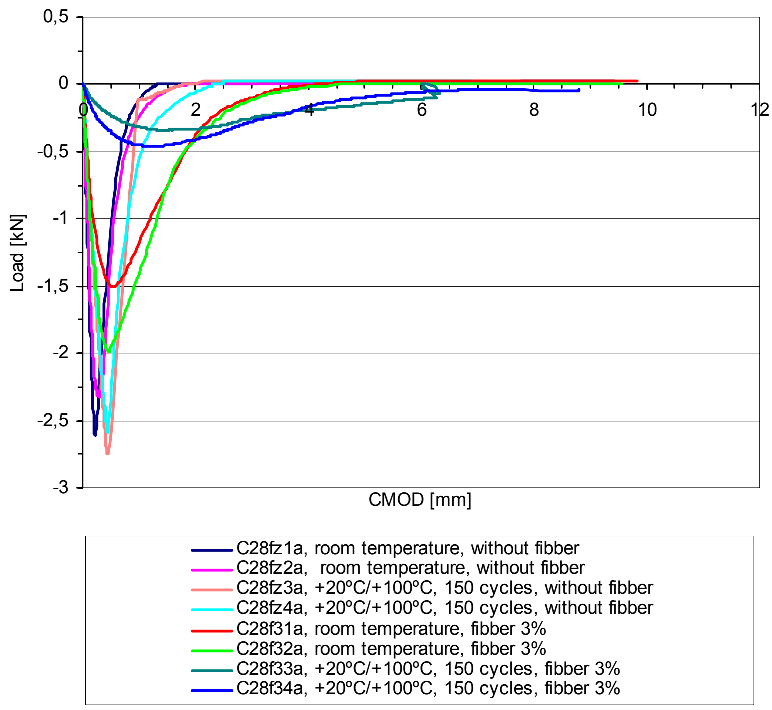

Figure 7. Curves load versus CMOD for the relation (d_i/h = 0,56) of the beams with circular notch, without fibber and with 3% of fibber, in the different environmental conditions.

Several ways should be followed to determine the intensity factors of tension in mode I of loading, K_I and, consequently K_{IC}, which is the critical tension intensity factor that corresponds to the fracture tenacity.

If the relation between load and CMOD is linear and there is no extension of the notch above the load peak, then that relation between the two variables is essentially linear elastic, denoting a fragile behaviour with suddenly fracture independently of environment conditions. Therefore, the determination of intensity factors of tension is done by using the method of initial depth of notch which admits only the knowledge of maximum load values obtained in fracture tests, $P_{máx}$, notch initial depth of the beams, d_i, flexure moment applied to the beams, M, relation $Y\ (d_i/h)$ being the beam of square section of side, h, and being the fracture tenacity, K_{IC}, the limit value of K_I when this is related with the variation of the depth notch [Jr Brown, 1966 and Ziegeldorf and Wittman, 1984].

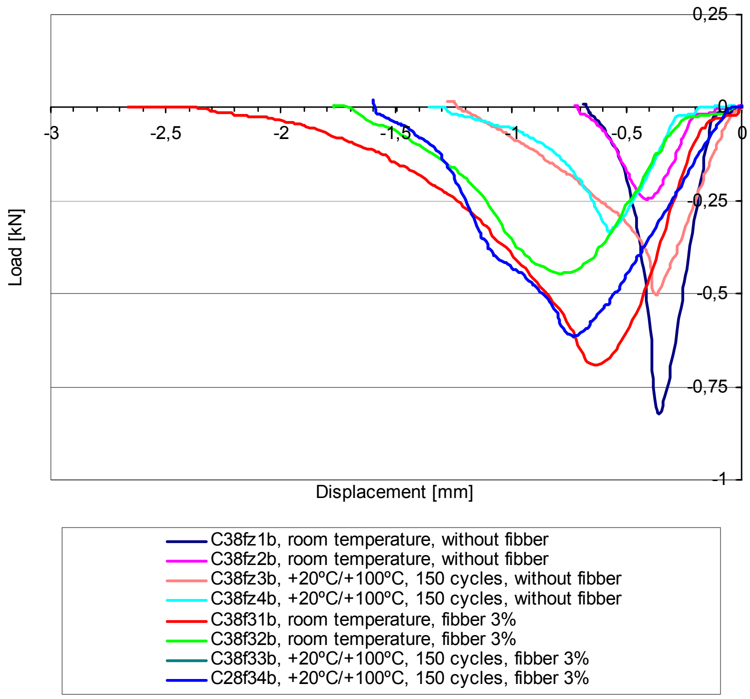

Figure 8. Curves load versus displacement for the relation (d_i/h = 0,76) of the beams with circular notch, without fibber and with 3% of fibber, in the different environmental conditions.

For the systems with 3% of fibber, independently of environmental conditions, the behaviour presents some ductility, being the curves load versus displacement non linear. This fact can be explained due to slow crack propagation, since the aggregate is fine being possible the friction phenomenon between the crack roughness and the aggregate. Thus, the fracture tenacity was determined using the method CMOD in flexural tests in four points [Jr Brown, 1966, Tada *et al.*, 1973, Jenq and Shah, 1985b and Vipulanandan and Dharmarajan, 1988]. In order to use the linear elastic fracture mechanics, the initial compliance, C_i, is equal to $CMOD_i/P_{máx}$. Since, due to experimental limitations, it was not possible in the flexural tests to done unload with accuracy at 95% of the maximum load [Jenq and Shah, 1985b and Vipulanandan and Dharmarajan, 1988], the inelastic component CMOD* was considered to be equal to zero. The final compliance, C_f is equal to $CMOD_T/P_{máx}$ considering the total displacement of the opening of the crack mouth, $CMOD_T$, equal to $CMOD_i$ plus $CMOD^e$, respectively, the initial and elastic crack mouth open displacement due to the slow growth of the crack mouth [Jenq and Shah, 1985a, Yamini and Young, 1977, Vipulanandan and Dharmarajan, 1987 and Vipulanandan and Dharmarajan, 1988]. The effective or final length of the crack d_f, is equal to the add the initial notch depth, d_i, with crack extension, Δd, i.e., $d_f = d_i + \Delta d$.

However, due to plastic deformation, it is convenient to determine an additional parameter $CTOD_C$, which is the critical displacement of the crack tip open. For flexion in 4 points this parameter is given by [Vipulanandan C. and Dharmarajan N., 1984]:

$$CTOD_c = Z(\alpha_i + \alpha_f).CMOD^e \tag{2}$$

Where $Z(\alpha_i + \alpha_f)$, with $\alpha_i = (d_i/h)$ and $\alpha_f = (d_f/h)$ is given by:

$$Z(\alpha_i + \alpha_f) = \left[1 - (\alpha_i/\alpha_f)^2\right]\left[(\alpha_i/\alpha_f).Y_{(\alpha)}/V_{(\alpha)} + 1 - (\alpha_i/\alpha_f)\right] \tag{3}$$

In which $CMOD^e$ is the elastic displacement of opening of the crack mouth due to the slow propagation and d_f, $V(\alpha)$ and $Y(\alpha)$ are parameters given by literature [Jr Brown, 1966, Tada et al., 1973, Jenq and Shah, 1985b and Vipulanandan and Dharmarajan, 1988].

In function of these two parameters K_{IC} and $CTOD_c$ is possible to determine a singular parameter Q that refers to the material length [Vipulanandan and Dharmarajan, 1984] and is an important design parameter, since an analytical model can be constructed to foresee the notch sensibility as strong indicator of structure collapse. In plane state of tension Q is given for:

$$Q = CTOD_c.E / K_{IC} \tag{4}$$

Where E is the flexure elasticity modulus.

If α_i be substituted by $(\alpha_i + \Delta\alpha_i)$ and α_f by $(\alpha_f + \Delta\alpha_f)$, where $\Delta\alpha = \Delta d/h$, then the function $V(\alpha_f)$ it can be generalized using the series of Taylor, resulting the following expression:

$$V(\alpha_f) = V(\alpha_i) + \sum_{n+1}^{n} \left\{ \left[(d^n V(\alpha_i)) / d\alpha_i \right] . \left[(\Delta\alpha)^n / n! \right] \right\} \tag{5}$$

In which substituting n by 2 gives the equation:

$$V(\alpha_f) = V(\alpha_i) + \sum_{n+1}^{n} \left\{ \left[(d^n V(\alpha_i)) / d\alpha_i \right] . \left[(\Delta\alpha)^n / n! \right] \right\}$$

$$V(\alpha_f) = V(\alpha_i) . V^{'}(\alpha_i) + \left[(\Delta\alpha)^2 / 2 \right] . V^{''}(\alpha_i) \tag{6}$$

Substituting the eq. (5) in the following eq. (7)

$$d_f = d_i . (C_f / C_i) . \left[V(\alpha_i) / V(\alpha_f) \right] = g(\alpha_i, C_f / C_i, \alpha_f) \tag{7}$$

results in a two degree polynomial equation in $\Delta\alpha$, that it can be written:

$$\Delta\alpha / \alpha_i = \xi(\alpha_i) . \left\{ \left[1 + \lambda(\alpha_i) . (C_f / C_i) \right]^{\xi} - 1 \right\} \tag{8}$$

Where $\xi(\alpha_i)$ and $\lambda(\alpha_i)$ are given by eq. (9) and eq. (10), respectively:

$$\left\{ \left[V(\alpha_i) + \alpha_i \, V'(\alpha_i) \right] / \left[2\alpha_i V'(\alpha_i) + (\alpha_i)^2 V''(\alpha_i) \right] \right\} \tag{9}$$

$$\left\{ 2V(\alpha_i) . \left[2\alpha_i V^{'}(\alpha_i) + (\alpha_i)^2 V''(\alpha_i) \right] / \left[V(\alpha_i) + \alpha_i V'(\alpha_i)^2 \right] \right\} \tag{10}$$

By using the approach of the minimum quadratic approximation is possible to obtain the final expressions, given by the eq. (11) and eq. (12), respectively:

$$\xi(\alpha_i) = 1{,}8 / \alpha_i - 16 + 61{,}2\alpha_i - 111{,}2\alpha_i^2 + 95{,}3\alpha_i^3 - 31{,}1\alpha_i^4 \tag{11}$$

$$\lambda(\alpha_i) = 6{,}4\alpha_i - 3{,}4\alpha_i^2 \tag{12}$$

Equation (8) described an analytical model to foresee the behaviour to the fracture of polymeric concretes, and the medium values of the exponent ξ of this equation are variable for each situation and/or condition as it is indicated following:

- 3% of fibber at room temperature and rectangular notch ($\xi = 0{,}533$);
- 3% of fibber at room temperature and circular notch ($\xi = 0{,}333$);
- 3% of fibber at room temperature and "V" notch ($\xi = 0{,}423$);
- 3% of fibber at +20ºC/+100ºC – 150 cycles and rectangular notch ($\xi = 0{,}385$);
- 3% of fibber at +20ºC/+100ºC – 150 cycles and circular notch ($\xi = 0{,}423$);
- 3% of fibber at +20ºC/+100ºC – 150 cycles and "V" notch ($\xi = 0{,}510$).

In these conditions, the proposed model allows to construct the curves $\Delta\alpha/a_i$ versus Q/d_f that refers the foreseen solutions of the fracture behaviour, which are compared to the experimental solutions for the two systems and different notch geometries.

4. Results and discussion

Figures 9 and 10 show the evaluation of fracture energy with relation to d_i/h, respectively, to systems without fibber and with 3% of fibber. It is visible that in the systems without fibber, for room temperature and for the effect of thermal fatigue cycle, the values of fracture energy is a sinusoidal form, being the curves very similar in both cases. Nevertheless, thermal fatigue cycle effect considerably increase the fracture energy relative to those obtained at room temperature reaching the minimum and the maximum value, respectively, at the relation d_i/h equal to 0,36 and 0,56. The effect of the notch geometry is not very relevant. For the systems with fibber, independently of the environmental conditions, the variation of the fracture energy values is quite diversified, in general, a little variable with geometry of the notch, being these values higher than those obtained in the systems without fibber, mainly at room temperature.

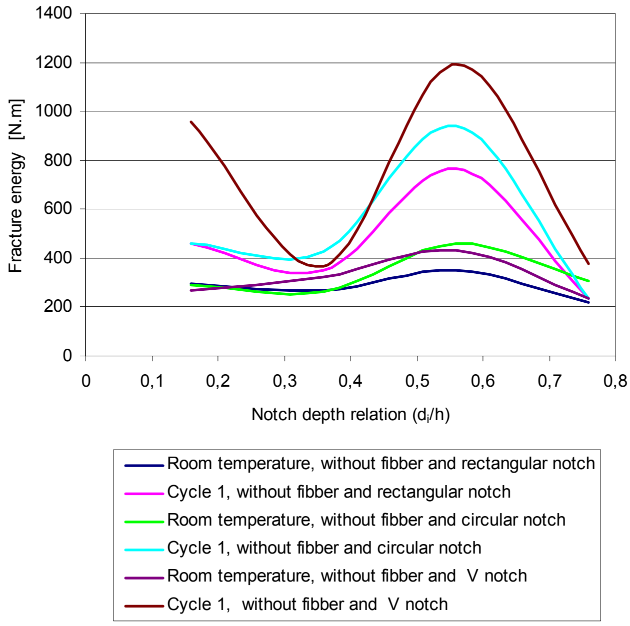

Figure 9. Fracture energy versus d_i/h for the beams without fibber.

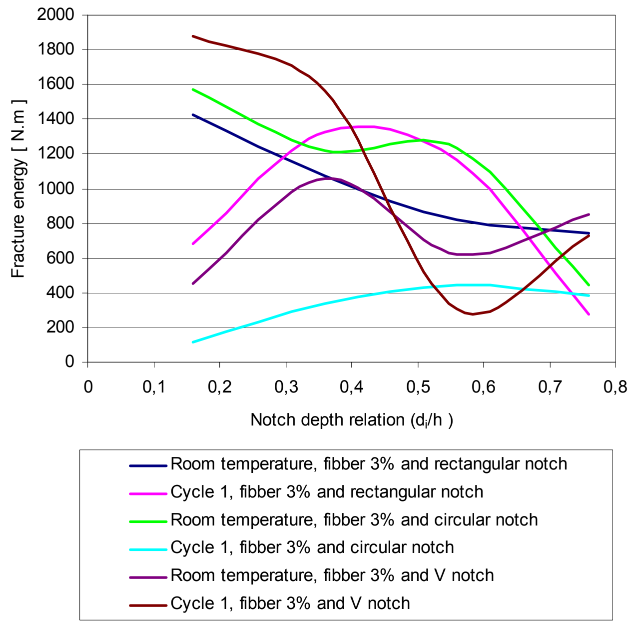

Figure 10. Fracture energy versus d_i/h for the beams with 3% of fibber.

Figures 11 and 12 show the experimental and analytical curves for $\Delta\alpha/\alpha_i$ versus Q/d_f, respectively, for the beams with 3% of fibber tested at room temperature and after being submitted to thermal fatigue cycles at high temperature (Cycle 1), for different geometries of the notch (rectangular, "V" and circular). Considering that, when Q increases, the fracture tenacity decrease, being the values of Q, in polymer concrete, much inferior to those for cement concrete [Mindless, 1984], the curves that more quickly reaches the structural collapse. It should be highlighted that the evolution of experimental and theoretical solutions is quite similar.

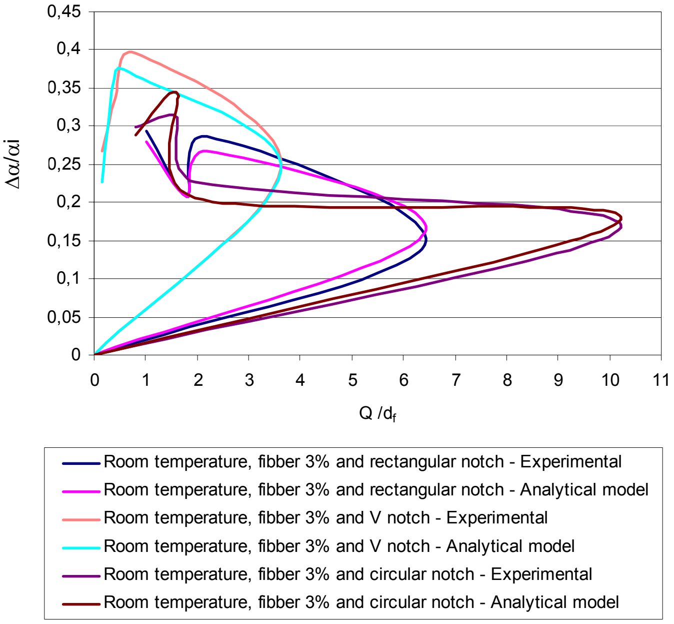

Figure 11. Experimental and analytical curves $\Delta\alpha/\alpha_i$ versus Q/d_f for the beams with 3% of fibber tested at room temperature for different notch geometries.

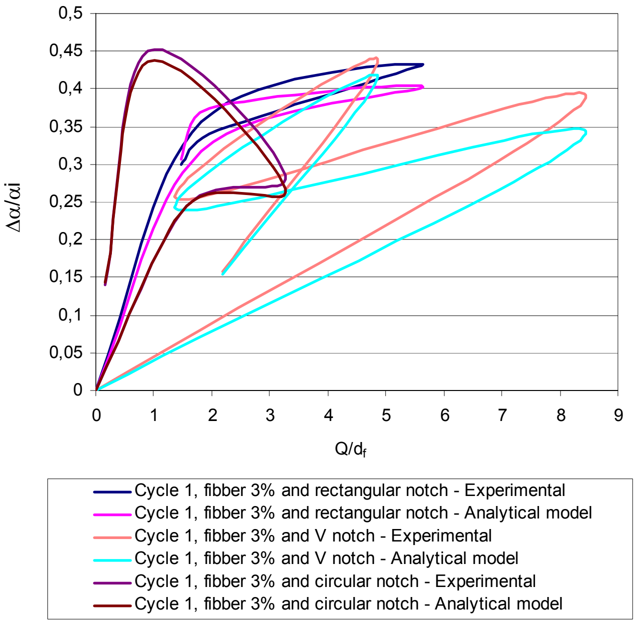

Figure 12. Experimental and analytical curves $\Delta\alpha/\alpha_i$ versus Q/d_f for the beams with 3% of fibber subject to high thermal fatigue cycles (Cycle 1) for different notch geometries.

5. Conclusions

In what follows, the main conclusions resulted from this research work are listed and discussed:

(i) the values of fracture energy in the systems with fibber are higher than the systems without fibber, and the geometry of the notch, in both cases, independently of the environmental conditions not very influence those values;
(ii) the fracture tenacity does not depend on the depth of the notch varies inversely with *Q*;
(iii) the values of Q are smaller in the systems in polymeric concrete than those in systems of cement concrete;
(iv) the application of not linear analytical model proposed is only logical in reinforced polymer concrete with fibber;
(v) the analytical model proposed to represent and foreseen the fracture behaviour of system with fibber presents a very good correlation.

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