| Fracture toughness of fiber reinforced polymer concrete

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Abstract

Fracture toughness of glass fiber reinforced polyester polymer concrete beams was investigated in loading conditions using three-point bending tests. Polymer Concrete is usually composed of natural aggregates such as silica sand, binded together with a thermoset resin. In this paper it is reported the use of a direct method to calculate, the critical stress intensity factor, K_{ic} and J integral from experimental results of unreinforced and glass fiber reinforced polymer concrete.

Keywords: fracture toughness, polymers, composite, fiber reinforcement

1 Introduction

During the last years polymer concrete become a good choice in civil engineering applications due its high strength, fast cure and durability when compared to ordinary cement concrete. Many of these are produced using epoxy and polyester resins. In South America, however, there is still limited knowledge of the properties and production methods of these materials and the market for these compounds is virtually non-existent, probably due to the elevated cost associated with polymer concrete if compared with conventional materials.

The enormous potential of high-performance fibers that is so successfully exploited in the conventional polymer composites has not been widely used in the polymer concretes. Nevertheless, the fiber reinforcement of the polymer concrete is not a new concept, the chopped strand glass fiber has been applied to the polymer composites for improving the strength and controlling the cracking [1, 2]. To characterize the failure behavior of the polymer composites in terms of the constituents, some attempts have been made for efficient use [3, 4].

Mode I fracture type according to loading condition is taken into consideration in most of the study performed in the fracture mechanics. However, there occur random cracks in general loading conditions.

In this paper, the fracture properties of epoxy polymer concrete and fiber-reinforced polymer concrete were tested by three-point bending tests after exposure to different weather conditions. Polymer concrete consists, in essence of an aggregate blend mixed with a polymer resin in convenient proportions which were previously studied [5, 6] and are used in repairing or in constructing layers or sections in reinforced concrete structures with high ductility [7].

To perform these tests, the TPFM is used to evaluate two independent-sized fracture parameters, the stress intensity factor, K_{Ic}; to RILEM recommendations [8, 9]. Another fracture parameter calculated from these tests was the J integral [10].

2 Experimental procedure

In the research study tests were performed on Polymer Concrete beams with in order to characterize the fracture behaviour of epoxy and polyester polymer concrete reinforced with glass fibers. Considering previous research [5, 6], in which the resin content and type of aggregate were studied, the best composition was 20% of resin and 80% of aggregate in mass, were the resin content is the biggest factor of influence on the behaviour. Analyzing the main effects and interactions an optimum formulation was obtained. The PC material components were foundry sand which consists of siliceous sand, designed by SP55, used in the foundry industry, with a uniform granulometry, and an average diameter of 245 μm. The polyester resin used to perform this investigation was S226E NESTE, an unsaturated orthophtalic polyester resin diluted in 44% styrene with a flexural strength of 119 MPa. The resin system is pre-accelerated by the manufacturer and the initiator used with this resin was methyl ethyl ketone peroxide MEKP (2% in mass). The epoxy resin system used was EPOSIL 551 SILICEM based on a diglycidyl ether bisphenol A and an aliphatic amine hardener, with a maximum mix ratio to hardener of 2:1, with low viscosity (500– 600 MPa s) and a flexural strength of 70$\pm$5 MPa, which cluster the sand, giving high strength and cohesion.

Chopped E-glass fibers were used as reinforcement of the PC system. The chopped glass fibers were provided by PPG with no sizing and soaked in a 2% Silane A174 solution. The Silane coupling agent (γ -methacryloxypropyltrimethoxysilane) was introduced into the PC by pretreatment of glass fibers. The trimethoxy group undergoes hydrolysis in aqueous solution and hydroxyl groups are then available to form oxane bands to the sand and glass fiber surface. The fibers were blended in the polymer concrete mix by 1% of glass fiber, of the total weight, and the fiber considered was 6 mm length.

All the different binder formulations and mix proportions were mixed and molded in prismatic specimens, according to RILEM TC-113/PC2 [11] specifications.

Polymer concrete specimens were compacted in a steel mold of dimensions of 30 mm x 60 mm x 600 mm, then cut to final size according to RILEM Report [9]. The specimens were initially cured at room temperature for 24 h. Epoxy specimens were then postcured during 7 hours at 60^o C while polyester specimens were post-cured during 4 hours at 80^o C. The samples were notched using a 2 mm diamond saw to a 20 mm depth. The PC samples were tested using an INSTRON machine with a cross head speed of 0.5 mm/min.

The crack mouth opening displacement (CMOD) was measured using a COD gauge clipped to the

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bottom of the beam and held in position by two 1.5 mm (H0) steel knife edges glued to the specimen. In this test, the relation a0=W ¼ 1=3 holds. This approach is the same as proposed in [9] (see Fig. 1).

3 Fracture mechanics tests

The tests were analyzed to evaluate K_{IC}, by the two parameter fracture method described in RILEMs reports [8, 9] and J integral.

To calculate K_{IC}, the effective critical crack length a_1, which is a_0 +stable crack growth at peak load, should be determined first. To obtain the value of a_1 the following equation has to be solved

$$E = \frac{6Sa_1V_1(\alpha_1)}{(C_uW^2B)} \tag{1}$$

where S is the specimen loading span, H_0 is the thickness of the clip gauge holder, W and B are the beam depth and width, respectively, Cu is the unloading compliance at peak load which is assumed to be the same as the unloading compliance at about 95% of the peak load in the postpeak stage V1(α) is

$$V_1(\alpha) = 0.76 - 2.28\alpha + 3.78\alpha^2 - 2.04\alpha^3 + \frac{0.66}{(1-\alpha)^2} \tag{2}$$

and α_1 is

$$\alpha_1 = \frac{(a_1 + H_0)}{(W + H_0)} \tag{3}$$

The value of the critical stress intensity factor, K_{IC}, is then calculated using

$$K_{IC} = \frac{3P_{\max}S}{2BW}\sqrt{\pi a_1}F(\alpha) \tag{4}$$

where P_{max} is the peak load, a_1 is the effective critical crack length and F(α) is given by

$$F(\alpha) = \frac{1}{\sqrt{\pi}}\frac{1.99 - \alpha(1-\alpha)(2.15 - 3.93\alpha + 2.7\alpha^2)}{(1+2\alpha)(1-\alpha)^{\frac{3}{2}}} \tag{5}$$

where

$$\alpha = \frac{a_1}{W} \tag{6}$$

4 Determination of J_{IC}

J-integral method can be applied to find fracture toughness of a nonlinear elastic material [10]. This method is based on determining the change of potential energy when a crack extends. That is,

$$J = -\frac{1}{B}\frac{dU}{da} \tag{7}$$

Where B is width of the specimen, U is the potential energy, and a is the length of the crack. If the polymer system is assumed to be a linear elastic material, the stress intensity factors can be converted into the strain energy release rate. For linear elastic materials, the strain energy release rate equals to J integral, which can be resolved approximately into J_I as follows,

$$J = \frac{(1-\nu^2)}{E} K_{\text{Ic}}^2 \tag{8}$$

Where ν is the Poisson ratio and E is the flexural modulus of the material. The resolved J-integral values were calculated using the above equation and the results are presented from table 1 to 4.

5 Results and discussion

Three-point tests results are presented in figure 1.

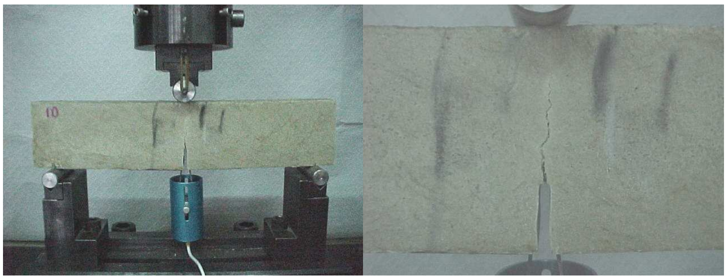

Figure 1: Glass fiber polymer concrete fracture test

Table 1: Polyester polymer concrete tests results

Specimens	K_{IC} (MPa$\sqrt{m}$)	J_{IC}(N/m)
POLY1	1.217	125.454
POLY2	1.241	130.451
POLY3	1.445	176.864
POLY4	1.186	119.144
POLY5	1.098	102.119
Average	1.237	130.806
St.Dev	0.12806366	27.794526
COV	10.3494146	21.35233
CI (95%)	0.13441643	29.624506

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Table 1 displays the tests results from unreinforced polyester polymer concrete. Glass fiber reinforced polyester polymer concrete is presented in table 2.

Table 2: Glass fiber reinforced polyester polymer concrete tests results

Specimens	K_{IC} (MPa$\sqrt{m}$)	J_{IC}(N/m)
FVP1	1.471	184.374
FVP2	1.538	201.552
FVP3	1.501	191.971
FVP4	1.423	172.538
FVP5	1.372	160.392
Average	1.461	182.165
St.Dev	0.06518052	16.1526758
COV	4.46136335	8.86703831
CI (95%)	0.06841389	16.9539512

Table 3 represents the tests results, Stress Intensity Factor (K_{IC} (MPa$\sqrt{m}$)) and J Integral from unreinforced epoxy polymer concrete. Glass fiber reinforced epoxy polymer concrete tests results are presented in table 4.

Table 3: Epoxy polymer concrete tests results

Specimens	K_{IC} (MPa$\sqrt{m}$)	J_{IC}(N/m)
EPOXY1	2.401	534.821
EPOXY2	2.039	385.708
EPOXY3	2.207	451.886
EPOXY4	2.214	454.757
EPOXY5	2.323	500.636
Average	2.237	465.562
St.Dev	0.13686197	56.3636338
COV	6.11865049	12.1065899
CI (95%)	0.1436512	59.1596282

Table 4: Glass fiber reinforced epoxy polymer concrete tests results

Specimens	K_{IC} (MPa$\sqrt{m}$)	J_{IC}(N/m)
FVE1	2.379	550.320
FVE2	2.576	645.236
FVE3	2.437	577.481
FVE4	2.340	532.425
FVE5	2.294	511.698
Average	2.405	566.710
St.Dev	0.10895733	59.116068
COV	4.53007364	10.4314496
CI (95%)	0.11436231	62.0486006

Figure 2 displays the load-unload tests results of unreinforced polyester polymer concrete

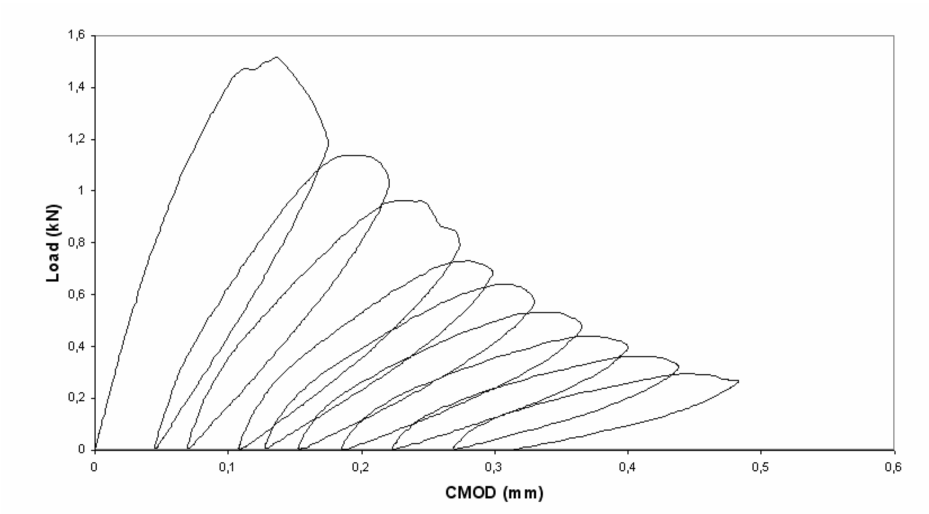

Figure 2: Unreinforced polyester polymer concrete test result

Figure 3 shows the cyclic test of glass fiber reinforced polymer concrete

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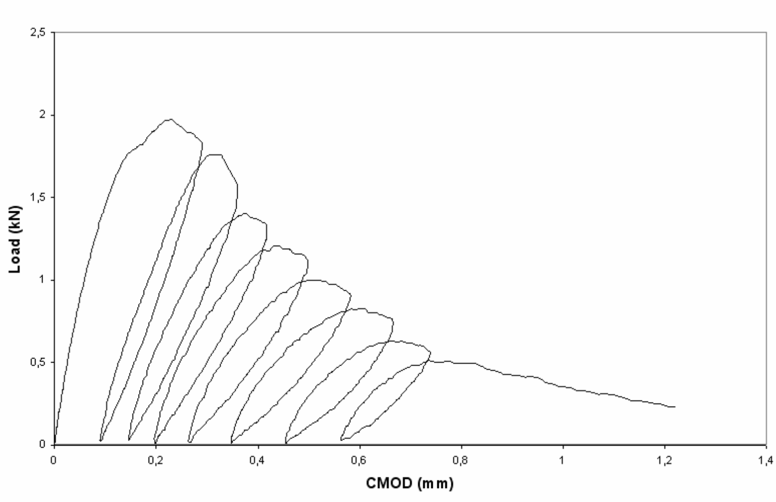

Figure 3: Glass fiber polyester polymer concrete test result

Figure 4 displays the load vs. CMOD tests results of unreinforced epoxy polymer concrete

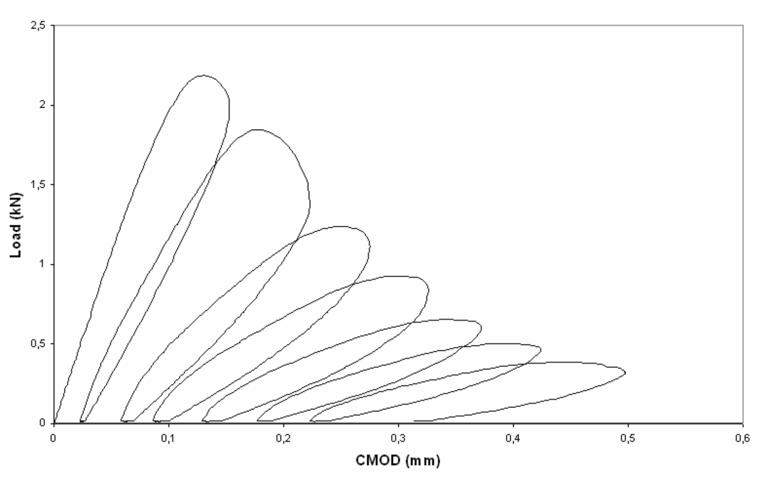

Figure 4: Unreinforced epoxy polymer concrete test result

Figure 5 shows the cyclic test of glass fiber epoxy polymer concrete

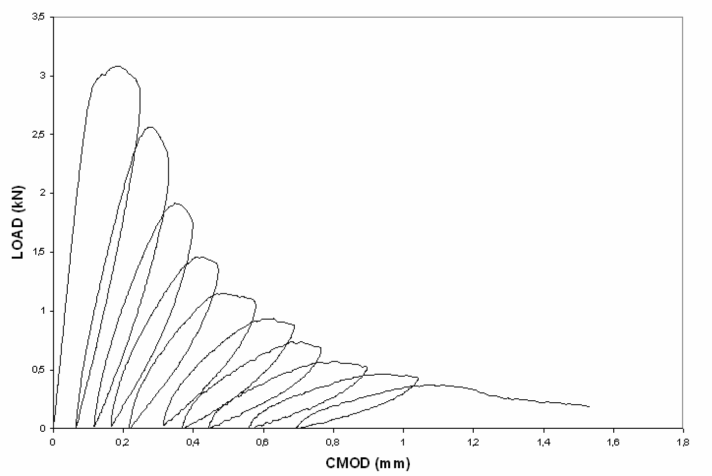

Figure 5: Glass fiber epoxy polymer concrete test result

It is clear, analysing the tests results, that fiber reinforcement improves fracture toughness of polymer concrete. The stress intensity factor of glass fiber reinforced system is 18,1% and the J integral increases 39,3% when polyester system is used as binder

Applying the same analogy, when glass fiber reinforces epoxy resin system the increase in the fracture toughness is 7,5% and a 21,7% increasement is observed for J integral.

Unreinforced epoxy polymer concrete has higher fracture toughness than polyester ones 80% and the glass fibers are applied to the mixture 64,6% increasement is observed. The J integral results are even higher, 255,9% for unreinforced polymer concrete and 211,1% for glass fiber reinforced epoxy polymer concrete when compared to glass fiber polyester polymer concrete.

Fiber reinforcement is been used by construction industry during the last decades reinforcing concrete structures. Polymer concrete is a recent material and is proving that is a good choice over ordinary cement concrete for certain applications. As it happens with ordinary cement concrete glass fiber reinforcement improves facture toughness of polymer concrete.

6 Conclusions

Factors such as material variability (polymer, aggregates, promoter, initiator), degree of compaction and curing conditions will affect the PC properties.

Different fracture parameters are calculated to evaluate the application of the method proposed by RILEM [8] and Shah and Carpinteri [9], and in plain and reinforced polymer concrete.

As expected the use of glass fiber reinforcement increases fracture parameters such as stress intensity factor, K_{Ic}. The increasement observed in this research is higher in the polyester polymer concrete when compared to epoxy polymer concrete.

As observed in the fracture toughness, the J integral results are higher in the polyester PC than in the epoxy ones. Glass fiber increases fracture toughness of polymer concrete with both binders producing better reinforcement in polyester resin systems than in epoxy resin.

According to previous studies and as expected due to better performed of the epoxy resin, the results that polymer concrete has when epoxy resin is used as binder is clearly high.

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References

[1] Avci, A., Akdemir, A. & Arikan, H., Fracture behaviour of glass fiber reinforced polymer composites. *Cement and Concrete Research*, **34**, pp. 429–434, 2004.

[2] Vipulanandan, C. & Mebarkia, S., Flexural and fracture properties of glass fiber reinforced polyester polymer concrete. *ACI SP*, **166(1)**, pp. 1–16, 1996.

[3] Ramana, V.P.V., Kant, T., Morton, S.E., Dutta, P.K., Mukherjee, A. & Desai, Y.M., Behaviour of cfrpc strengthened reinforced concrete beams with varying degrees of strengthening. *Compos Eng*, **Part B 31**, pp. 461–470, 2000.

[4] Vipulanandan, C. & Dharmarajan, N., Critical stress intensity factors of epoxy mortar. *Polym Eng Sci*, **28(18)**, pp. 1182–1191, 1988.

[5] Reis, J.M.L. & Ferreira, A.J.M., The influence of notch depth on the fracture mechanics properties of polymer concrete. *International Journal of Fracture*, **124(1-2)**, pp. 33–42, 2003.

[6] Ferreira, A.J.M., Tavares, C.M. & Ribeiro, M.C., Flexural properties of polyester resin concretes. *Journal of Polymer Engineering*, **20(6)**, pp. 459–468, 2000.

[7] El-Hawary, M., Al-Khaiat, H. & Fereig, S., Effect of seawater on epoxy-repaired concrete. *Cement and Concrete Composites*, **41-52(20)**, 1998.

[8] Rilem, Tc 50-fm. determination of the fracture parameters (k_{IC} and $ctod_C$) of plain concrete using three-point bend tests on notched beams. *Materials and Structures*, **23(138)**, pp. 457–460.

[9] Shah, S.P. & Carpinteri, A., *Fracture Mechanics Test Methods for Concrete*. Chapman and Hall: London, 1991.

[10] Rice, J.R., A path independent integral and the approximate analysis of strain concentration by notches and cracks. *J Appl Mech Trans*, **375-386**, 1968.

[11] RILEMPC2, Technical Comittee TC-113, Method of making polymer concrete and mortar specimens. *Symposium on Properties and Test Methods for Concrete - Polymer Composites*, Oostende, pp. 129–132, 1995.