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Effect of fiber reinforcement on mixed-mode fracture of polymer mortars

G.C. Moreira [a], J.M.L. Reis [a,*], U. Rohan [b], C.A.P. Soares [b], H.S. da Costa Mattos [a]

[a] Theoretical and Applied Mechanics Laboratory – LMTA, Mechanical Engineering Department – TEM, Universidade Federal Fluminense – UFF, Rua Passo da Pátria, 156, 24210-240 Niteroi, RJ, Brazil

[b] Civil Engineering Graduate Program, Universidade Federal Fluminense – UFF, Rua Passo da Pátria, 156, 24210-240 Niteroi, RJ, Brazil

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ABSTRACT

The present paper is concerned with the failure analysis of cracked polymer mortar reinforced with particles from waste Tetra Pak® aseptic carton packages, piassava lees and glass fiber in combined mode I and II. The Brazilian disk, a classic mixed mode fracture test specimen, was adopted for the experimental characterization of the crack initiation. A slight increase in critical stress intensity factors was observed with the addition of carton particles and piassava lees. Glass fiber reinforcement promotes the highest fracture resistance to crack propagation.

1. Introduction

In the past years different types of concrete appeared and continue to contribute to being the most widely used material in the world after water. High-performance concrete, self-consolidating concrete, shotcrete and polymer concrete are some of such material, which can be used in many applications [1–4]. Polymer concrete it is basically a composite material consisting of an aggregate held together by a polymer binder, instead of cement and water.

In addition to its use in precast cladding, polymer mortars (PM) it is used to produce a wide range of precast products, as a repair material in cement concrete, due to its fast curing and excellent bonding properties, in overlays or screeds, and may even replace metals, e.g. cast iron for machine bases. But due to its higher cost, its use in high volume applications is considered impractical except in very unusual cases [5].

The main disadvantage of PM is its brittleness, i.e. relatively poor resistance to crack opening and propagation. The use of dispersed fibers as reinforcement plays an important role in the development of concrete-like materials. Fibers perform as crack arrests, toughening effect by bridging effect decreasing crack opening [6].

Many types of fibers can be used as reinforcement in composite structures. Metallic fibers such as steel can greatly improve the tensile and flexural strength due to their ability to absorb energy and control cracks [7,8]. However, corrosion of steel fibers can be detrimental and lead to rapid deterioration of concrete structures [9]. Glass fiber has an excellent strengthening effect but poor alkali resistance [10]. Natural fibers, such as palm [11], sisal [12], coconut, sugarcane bagasse and banana fibers [13], are cheap and easily available, but they have poor durability [14]. Also, waste materials can be used as aggregate replacement not as reinforcement with good contribution to lowering density, improve flexural, compression and fracture properties [15–19].

The Brazilian disk test was first introduced by Carneiro and Barcellos [20] and Akazawa [21] as a substitute for the direct tension test. It consists of diametral compression of a center notched cylinder. Nowadays, it is an excellent tool to determine the mixed mode critical stress intensity factor, especially for brittle materials. The main advantage of this configuration (beyond the relatively simple experimental procedure) is that any combination of mode-I and mode-II loading types can be achieved by an appropriate choice of the crack inclination angle θ, (with respect to the loading direction) and the relative crack length. A widely used solution for the stress intensity factors (SIF) in a cracked Brazilian disk loaded under diametrical compression by concentrated forces was presented by Atkinson et al. [22] in the form of infinite series. Aliha and Ayatollahi [23] studied the mixed-mode fracture properties of cement mortar where a modified maximum tangent stress (MTS) criterion is proposed. Recently Dong et al. [24] also introduced a solution for a centrally cracked Brazilian disk under uniform radial pressure in the form of infinite series.

The goal of this study is to determine mode-I and mode-II critical stress intensity factors (SIFs) of epoxy PM by means of

* Corresponding author. Tel.: +55 2126295588.
E-mail address: jreis@mec.uff.br (J.M.L. Reis).

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the Brazilian disk test. The epoxy PM were manufactured with partial substitution of foundry sand aggregate for waste Tetra Pak® aseptic carton particles, piassava and glass fibers.

2. Materials and methods

2.1. Materials

In order to manufacture PM specimens, shredded Tetra Pak® aseptic cartons, piassava lees and glass fibers were mixed with foundry sand and an epoxy resin in an industrial mixer.

The cartons were obtained as post-consumer waste from a cooperative of waste pickers, using a paper shredder, they were cut up to 0.85 mm (25 mesh size). Recycling of these packages is predominantly done in paper mills, where fibers from the cardboard are separated from the polyethylene and aluminum (PEAL) by hydro-pulping and used in paper products; the remaining PEAL composite may also be reused in one of three ways: energy can be recovered through incineration of the composite, the aluminum may be recovered through pyrolysis, and the PEAL may be used to create new plastic products [25]. As an alternative to repulping for paper applications, Tetra Pak® developed a process that converts shredded cartons into thermally compressed panels to serve as alternatives to traditional wood-based panels, this product is produced in various countries under different brand names [26].

Aseptic carton recycling rate in Brazil was 29% in 2012, totalizing 61,000 tons, it is above the world average of 21.6% in 2011 [27], but lower than the European Union average, with a 40% recycling rate in 2012 [28].

Piassava fibers were obtained from the broom industry of northeast state of Bahia and have been described as harder than others lignocellulosic fibers. Broom industry consumes almost the totality of piassava fibers but a significant amount of residue is produced and cannot be used. The piassava residue (lees) normally is disposed in landfills [29]. The piassava lees were shredded in 6 mm and used as partial replacement of natural aggregate. The density of piassava lees was determined using a pycnometer, and it was found 1.10 g/ml. To eliminate the impurities and humidity lees were washed and vacuum dried for 24 h.

Chopped glass fibers provided by PPG with no sizing were also used as reinforcement. Glass fiber lengths considered were 6 mm. The fiber ratio used in these mixtures was 1% in weight, substituting aggregates in the mixture. These amounts of fibers used were chosen according to previous study [30]. Large amount of recycling and replacing fibers, more than 2%, do not contribute to reinforce polymer mortars. It only contributes to increase porosity and decrease the mechanical properties.

The foundry sand is used in the foundry industry and is a quartz foundry sand with a rather uniform particle size; the particles have an average diameter of 245 μm. The sand specific gravity is 2.65 g cm^3 and fineness modulus of 2.5. The aggregate content was 87% in weight. Before being added to the polymeric resins to reduce moisture content, the foundry sand was dried, insuring a good bond between polymer and inorganic aggregate.

Table 1
Properties of the epoxy resin.

Property	Epoxy
Viscosity at 250C μ (cP)	12,000–13,000
Density ρ (g/cm^3)	1.16
Heat distortion temperature HDT (°C)	100
Modulus of elasticity E (GPa)	5.0
Flexural strength (MPa)	60
Tensile strength (MPa)	73
Maximum elongation (%)	4

The epoxy resin system was based on a diglycidyl ether of bisphenol A and an aliphatic amine hardener. The resin content was 12 wt.%. This system has low viscosity, and is processed with a maximum mix ratio to the hardener of 4:1. Epoxy polymer resin thermal and mechanical properties are provided in Table 1.

2.2. Methods

The PM configuration used in this work is called the Cracked Straight Through Brazilian Disk (CSTBD) where these cracks are created by inserting a thin metal shims with 25 mm width and 2 mm thickness in the metal mold shown in Fig. 1.

Noting that at the half length of the crack, R the disk radius and θ the angle of inclination of the crack relative to the line of loading, P the compression force and B the disk thickness, see Fig. 2.

The stress intensity factors are given by the following expressions [24]

$$K_I = \frac{P}{\pi BR}\sqrt{\pi a}\left[f_{11} + 2\sum_{i=1}^{n} A_{1i} f_{1i}\alpha^{2(i-1)}\right] \tag{1.1}$$

$$K_{II} = 2\frac{P}{\pi BR}\sqrt{\pi a}\sum_{i=1}^{n} A_{2i} f_{2i}\alpha^{2(i-1)} \tag{1.2}$$

where the coefficients A_{ji} (j = 1,2; i = 1,2,...,n) are given as

$$\begin{aligned} A_{1i}(\theta) &= i\cos(2i\theta) - i\cos(2(i-1)\theta) \\ A_{2i}(\theta) &= i\sin(2i\theta) - (i-1)\sin(2(i-1)\theta) \end{aligned} \tag{2}$$

The general expression of the coefficients f_{ji} (j = 1,2; i = 1,2,...n) is given by Eq. (2)

$$f_{ji} = \frac{(2i-3)!!}{(2i-2)!!}\left[1 + \frac{c_{j1}}{2i} + \frac{3c_{j2}}{4i(i+1)}\right] \tag{3}$$

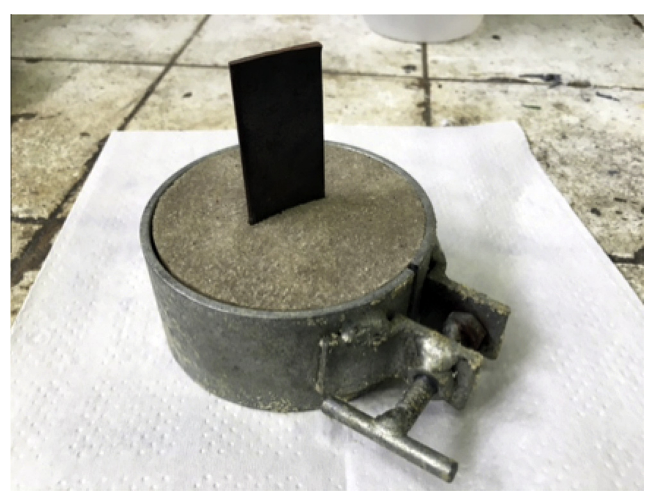

Fig. 1. Cracked Straight Through Brazilian Disk test polymer mortar.

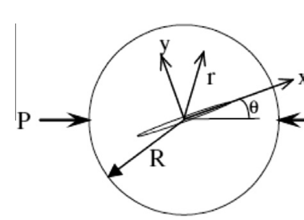

Fig. 2. Schematic diagram of the mixed-mode loading [24].