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Fracture Mechanics of Polymer Mortar Made with Recycled Raw Materials

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The aim of this work is to show that industrial residues could be used in construction applications so that production costs as well as environmental protection can be improved. The fracture properties of polymer mortar manufactured with recycled materials are investigated to evaluate the materials behaviour to crack propagation. The residues used in this work were spent sand from foundry industry as aggregate, unsaturated polyester resin from polyethylene terephthalate (PET) as matrix and polyester textile fibres from garment industry, producing an unique composite material fully from recycled components with low cost. The substitution of fresh by used foundry sand and the insertions of textile fibres contribute to a less brittle behaviour of polymer mortar.

Keywords: *fracture mechanics, polymer mortar, recycling*

1. Introduction

Nowadays, because of the more exigent legislation regarding the environment and the market demand for environmentally friendly products, manufacturers are concerned to develop studies aimed at reducing the environmental impact, through lowering the amount of residues or treating those that are inevitably generated during production processes[1]. High costs associated with raw material extraction, as well as the damage that the extraction causes to the environment, are also important reasons to motivate the use of industrial process residues. Depletion of reliable trustable raw material reserves and conservation of non-renewable sources also contribute to such reuse of waste materials.

The generation of residues is inherent to the casting process, mainly sand from moulds and cores. Therefore, there is growing interest in the re-utilization of this sand, since the amount of residual sand is quite significant. In general, these residues are classified as non-dangerous, class II, according to Brazilian laws. Therefore, recycled foundry sand presents high potential to be used as raw material. For this case, the foundry sand needs no pre-treatment to be used as inert in polymer mortar (PM).

Poly (ethylene terephthalate) (PET) is thermoplastic polyester widely used in applications as diverse as textile fibres, films and moulded products[2]. Among all plastics, PET has received particular attention in terms of post-consumer recycling, due to the relatively large availability of PET bottles from special collection schemes[4].

Numerous ways of recycling disposable beverage bottles have been reported[3], including methods for chemical recycling[3,5], such as methanolsis, glycolsis, hydrolysis, ammonolysis and aminolysis or physical recycling by re-melting[3,4,6-8]. In this case, the recycling of PET bottles was done by glycolysis producing unsaturated polyester resin.

Textiles are manufactured to perform a wide range of functions and are made up of different types of fibres mixed in varying proportions. While the textile industry has a long history of being thrifty with its resources, a large proportion of unnecessary waste is still produced each year, much of which is either incinerated or disposed of in landfill. Textile wastes take many forms and are often complex in nature due to the range of manufacturing specifications required. Complex mixtures of fibres make separation more difficult and more costly, and this have implications for the profitability of textile recycling.

Textile waste arising originates from both the household (consumer) sector and the industrial (manufacturing) sector. Consumer waste generally comprises binned waste or that separated for reuse or recycling, such as unwanted clothing and carpets. Manufacturing waste originates from the processing of raw materials and in the fabrication and production of finished textiles and garments, including cuttings and rejected materials.

The proposal of this work is to use, as inert, recycled foundry sand with organic pollutants in substitution of fresh foundry sand in the manufacturing process of unsaturated polyester resin based on recycled polyethylene terephthalate (PET) polymer mortar. Also, textile fibres from garment industry were used as reinforcement in order to reduce the brittleness of polymer mortar. The fracture characterization of the produced material enables the safe and appropriate use of the material in various precast applications.

2. Materials and Methods

2.1. Materials

Polymer mortar formulations were prepared by mixing fresh and recycled foundry sand as aggregates and unsaturated polyester resin recycled from PET as binder. Also textile fibres from garment industry were introduced to the mix proportion by 1 and 2% in weight as reinforcement. Resin content was 12% by weight and no filler was added in formulations. Previous studies carried out by the author[9], considering an extensive experimental program, allowed an optimization of mortar formulations that are now being used in the present work.

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The fresh aggregate was green foundry sand with very uniform grains and a mean diameter of 300 μm, produced by JUNDU, design as AG 40-50, meaning aggregate with finesses modulus between 4 and 5. The specific gravity of the fresh sand was 2.63 g/cm^3. The foundry sand was previously dried before added to the polymeric resins in an automatic mixer. The recycled sand, like the fresh one, consists primarily of silica sand, coated with a thin film of burnt carbon, residual binder (bentonite, sea coal, resins/chemicals) and dust with a specific gravity of 2.69 g/cm^3. It contains cured alkaline-phenolic resin whereas cross-linking is activated with very strong organic acids. The initiator used to promote the free radical to produce polymer mortar due to its high performance, resulting in a high strength and polymerization on the system was a carboxylic acid called Triacetin (glycerol triacetate), which determines the speed of cross-linking. Because of the presence of phenols in foundry sand, there is some concern that precipitation percolating through stockpiles could mobilize leachable fractions, resulting in phenol discharges into surface or ground water supplies.

The polyester resin used, as binder, was unsaturated polyester obtained from recycling PET. Polyester resin is the most used resin to produce polymer mortar due to its high performance, resulting in a high strength and durability against aggressive environments, with low permeability and lower cost when compared to epoxy resins. Polyester resin from PET showed similar results when used as binder to polymer mortar when compared to ordinary polyester resin, with the advantage of low manufacturing cost and processing energy and, of course contributing to reduce the plastic waste[10]. Resin properties are presented in Table 1.

The textile fibres consist of cotton, polyester, silk and rayon. A homogenous single type of textile usually consists of a combination of these materials in various percentages.

The textile cuttings may not be conceived as either an aggregate or reinforcement. It does however contribute to the increase in volume of the mixture (which is the major function of an aggregate) less the weight, and intent to contribute to the increase of polymer mortar ductility textile fibres reinforced polymer mortar were prepared in the same way as plain polymer mortar, with the incorporation of 1 and 2% in weight of chopped textile fibres. The textile waste cuttings are trimmed into average lengths between 2 and 6 cm.

Polymer mortar fracture specimens were compacted in a steel mould of dimensions of 30 × 60 × 250 mm^3 following the specifications of RILEM TC113/PC-2[11]. The specimens were initially cured at room temperature and then post-cured during 3 hours at 80 °C. The samples were notched using a 2 mm diamond saw to a 20 m depth.

2.2. Methods

To determine the fracture properties, three-point bending tests were conducted using a universal testing machine with a crosshead speed of 0.5 mm/min. The crack mouth opening displacement (CMOD) was measured using a COD gauge clipped to the bottom of the beam and held in position by two 1.5 mm steel knife edges glued to the specimen, as shown in Figure 1.

Fracture toughness, K_{Ic}, and fracture energy, G_f, are the main parameters determined to predict toughness and cumulative energy as crack propagates.

To identify fracture toughness of PC, which is a measurement of a material's resistance to crack extension when the stress state near the crack tip is predominantly plane strain, plastic deformation is limited, and opening mode monotonic load is applied, the Two Parameter Method (TPM)[12] was used. This method is a direct method to calculate fracture parameters and can be expressed as, in $(\mathrm{MPa}\sqrt{m})$[12]

Table 1. Properties of unsaturated polyester resin recycled from PET.

Property	Polyester
Viscosity at 250C μ (cP)	250-350
Density ρ (g/cm^3)	1.09
Heat distortion temperature HDT (°C)	85
Modulus of elasticity E (GPa)	3.3
Flexural strength (MPa)	45
Tensile strength (MPa)	40
Maximum elongation (%)	1

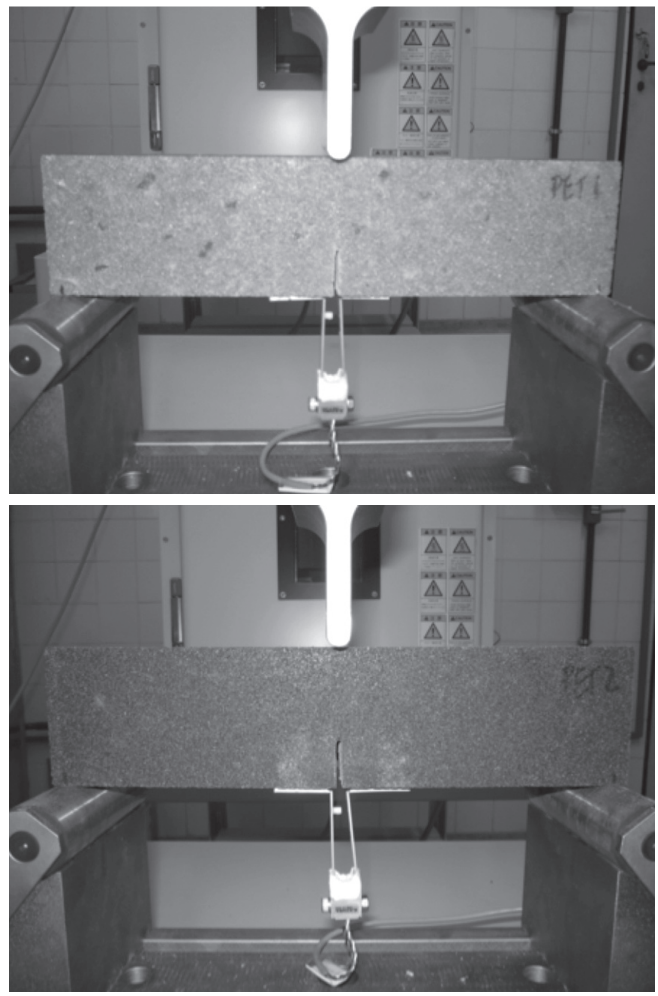

Figure 1. Three-point bending test set-up for polymer mortar with fresh and recycled aggregate.

$$K_{Ic} = \frac{3P_{\max}S}{2W^2B}\sqrt{\pi\underline{a}}F(\alpha) \quad (1)$$

in which a is the effective critical crack length, α is a/W, P_{max} is the measured maximum load [N], S, W and B are the span, depth and width, respectively. The results correspond to the mean values of five tests.

The fracture energy, G_f, was measured according to the RILEM Technical Committee[13], in single edge notched beams, when three-point bending tests are performed. It is the energy necessary to create a unit crack surface and it is also equal to the area defined by softening law. Crack propagation is essentially governed by the mechanical interaction of the aggregates with the polymer matrix.

$$G_f = \frac{W_0 - mg\delta_0}{A_{lig}} \quad (2)$$

where W_0 is the area under the load vs. deflection curve (N/m), m.g is the self-weight of the specimen between supports (kg), δ_0 is the maximum displacement (m), and A_{lig} is the fracture area [d(b-a)] (m^2); b and d are the height and width of the beam, respectively[13].

The Young Modulus (E) is calculated from the measured initial compliance C_i using equation

$$E = \frac{6Sa_0V_1(\alpha)}{(C_iW^2B)} \quad (3)$$

in which S is the specimen loading span, a_0 is the initial notch depth, H_0 is the thickness of clip gauge holder, W and B are the beam depth and width respectly according to RILEM[12].

3. Results and Discussion

Fracture tests results obtained from 3-point bending tests performed in polymer mortar manufactured with recycled raw materials are presented in Table 2. The specimens were organized in fresh and recycled sand, unreinforced, 1 and 2% textile fibres reinforcement. Polymer mortar manufactured with fresh sand has FS designation and PC formulation with recycled sand has RS designation. The numbers 0, 1 and 2 represent the fibres percentage in the formulations. Five specimens were tested for each formulation and the mean results were plotted.

It is known from previous studies[9] that textile fibres do not improve polymer mortar mechanical properties. From that knowledge the aim in this research is not improving fracture properties but retard crack propagation turning PM formulations less brittle. Increasing fibre content of fresh sand polymer mortar, the fracture toughness decrease 53.1 and 6% diminish is reported when fracture energy were measured. Also, the modulus of elasticity, E, lowered 33.1% with the increase of textile fibre content.

Figures 2 and 3 displays the average fracture behaviour, both toughness and energy, respectively, of plain and reinforced fresh sand polymer mortar. It is clear from Figures 2 and 3 that increasing fibre content, softer crack propagation is observed. Also, a decrease in the angle between the graph slope and the x-axis demonstrates lower stiffness of fresh sand textile fibre polymer mortar.

Following the behaviour reported by fresh sand textile fibre polymer mortar, recycled foundry sand textile fibre polymer mortar also displays decrease in measured parameters such as fracture toughness, energy and modulus elasticity. When textile fibres were added to the mixture, 2% in weight, the fracture toughness decreases 63.5% and fracture energy 34.8%. Substituting the fresh aggregate by a recycled one, the fracture properties of unsaturated polyester mortar are deeply affected. Fresh sand unreinforced polymer mortar is tougher and stiffer than recycled unreinforced polymer mortar but polymer mortar manufactured with recycled aggregate can retain more energy during crack propagation than fresh sand polymer mortar. When textile fibres are inserted in the mixture as fillers or reinforcement the fresh sand polymer mortar retains more energy than recycled ones.

Figures 4 and 5 plot the average evolution of recycled sand textile polymer mortar during the three-point bending tests. Again, it is clear from the graphs that the increment of fibre content contributes to lowering brittleness and fracture properties polymer mortar, both fresh and recycled sand.

Table 2. Polymer mortar made with raw materials fracture test results (Avg. ± St.Dev.)

Specimens	K_{Ic} (MPa$\sqrt{m}$)	G_f (N/m)	E (GPa)
FS0	1.13 ± 0.09	173.24 ± 9.58	16.03 ± 1.68
FS1	0.86 ± 0.16	173.90 ± 6.01	12.39 ± 0.87
FS2	0.53 ± 0.08	162.77 ± 8.36	10.71 ± 0.63
RS0	0.85 ± 0.11	193.48 ± 9.89	10.96 ± 0.78
RS1	0.49 ± 0.04	170.91 ± 7.29	4.31 ± 0.67
RS2	0.31 ± 0.02	126.12 ± 2.29	4.12 ± 0.96

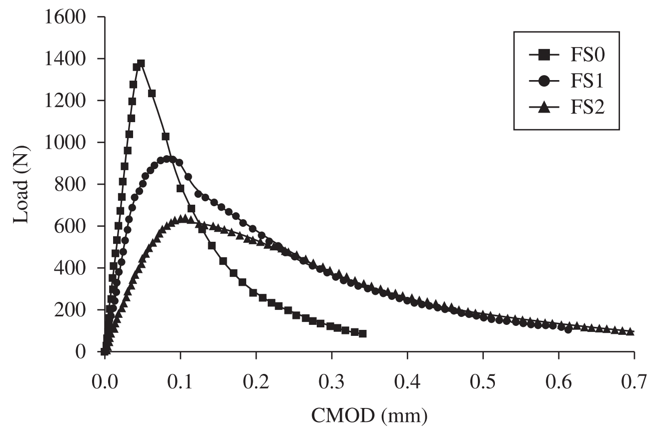

Figure 2. Load vs. CMOD test result of fresh sand textile reinforced polymer mortar.

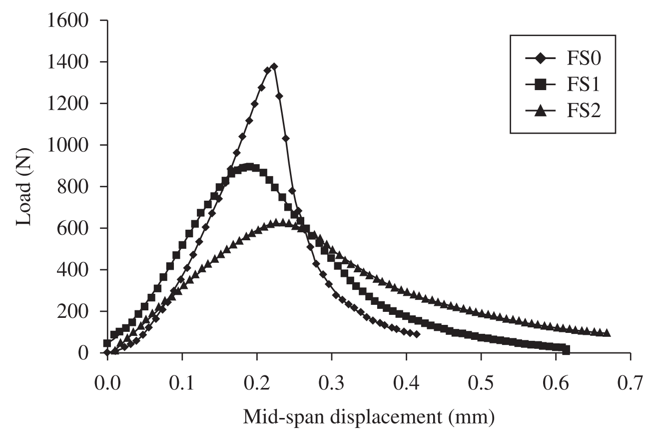

Figure 3. Load vs. Mid-span Displacement of fresh sand textile reinforced polymer mortar.

A comparative fracture toughness chart is presented in Figure 6. Fresh sand polymer mortar reinforced with 1% of textile fibres behaves similar to unreinforced recycled sand polymer mortar. Their resistance to crack propagation are at the same level. The same performance is observed for 2% textile fresh sand polymer mortar compared to 1% textile fibre recycled sand polymer mortar. The brittleness of both, fresh and recycled sand, polymer mortar decreases when textile fibres are added to the mixture.

According to Figure 7, instead of brittleness increase, the energy during the fracture process of all formulations is at the same level. The insertion of textile fibres in fresh polymer mortar does not prevent the initiation of crack, but when crack occurs the propagation is slower due to fibre bridging between textile fibres and the polymer matrix.

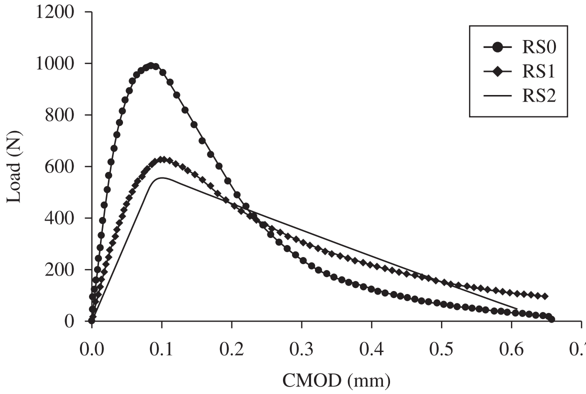

Figure 4. Load vs. CMOD test result of recycled sand textile reinforced polymer mortar.

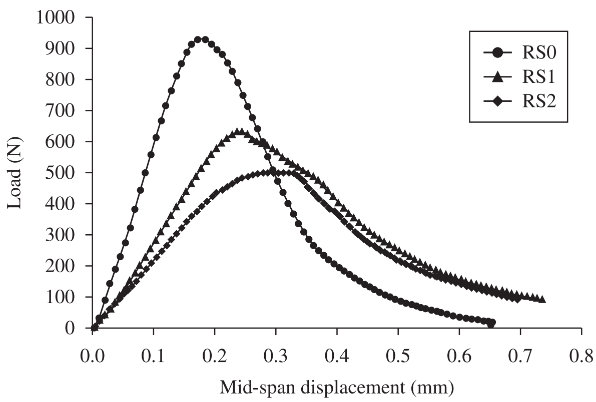

Figure 5. Load vs. Mid-span Displacement of recycled sand textile reinforced polymer mortar.

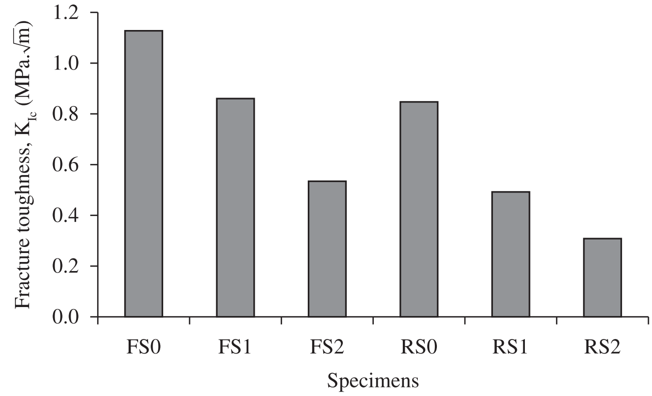

Figure 6. Polymer mortar fracture toughness comparison.

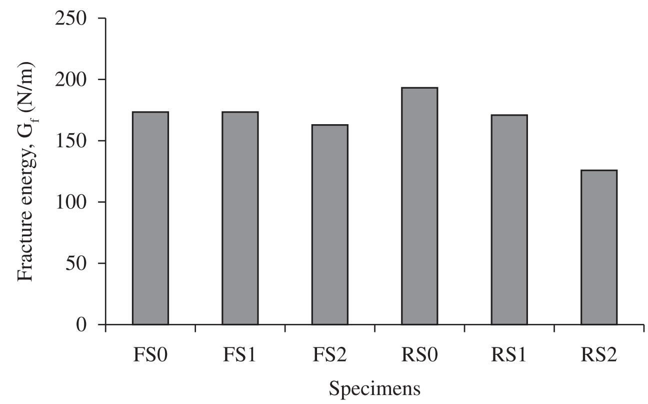

Figure 7. Polymer mortar fracture energy comparison.

4. Conclusion

The fracture properties of fresh and recycled sand polymer mortar with unsaturated polyester resin from recycled PET, as binder, were investigated in this research work. Also, textile fibres from garment industry were added to the mixture producing a unique material complete manufactured with waste as raw materials, recycled sand, textile fibres and recycled unsaturated polyester resin from PET.

The substitution of fresh by used foundry sand contributes to decrease crack resistance and propagation. Again, the insertions of textile fibres diminish the fracture toughness becoming polymer mortar less resistant to crack propagation and also changes in the post-peak status are reported. Recycled foundry sand and waste textile fibres from garment industry could be very conveniently used in making good quality polymer mortar and construction materials.

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