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Barley residue reinforced polymer mortars: Fracture mechanics approach

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ABSTRACT

This research work aims to experimentally evaluate the fracture mechanics of polymer mortars reinforced with barley residue from the brewing industry. Barley reinforced polymer mortar samples were manufactured from 1% to 10% of barley residue, in weight, as aggregate substitute. Then, the resin content was varied from 12% to 20% in 5% of barley residue polymer mortars. Fracture tests were performed aiming to compare the fracture energy, G_f, fracture toughness, through the stress intensity factor K_{Ic}, and the modulus of elasticity (E). The results showed an improvement in the fracture properties of polymer mortars until 5% of barley residue were used. Also, resin content of 18% produced the best energy balance and resistance to crack propagation results. Ductility was improved with the use of barley residue in the manufacturing process of polymer mortars.

1. Introduction

In the past decades, researchers worldwide has focused their attention to sustainable development and residue elimination. Solid waste is a by-product of civilization and it is collected, some are recycled or composted, and most are landfilled or incinerated [1]. Thinking to contribute to reduce the amount that is landfilled or incinerated, waste management becomes more important. The waste hierarchy refers to "3Rs", reduce, reuse, recycle. If the actions concerning the R's increase lower solid waste will be discarded [2]. Reducing is a mandatory action, but increase the reuse and recycling is an excellent alternative.

Brewery industries produce a large amount of waste during the beer manufacturing process [3,4]. These include spent grain, hot trub, residual yeast and diatomaceous earth slurry. Throughout the manufacturing process, the spent grains are milled, mashed and clarified. Brazil is one of the major producers in brewery industry just after United Stated and China with a production of 12.4 billion L/year. These three world producers generate 16.9 million tons/year of spent grain, which is the largest waste generated from the brewing process [3]. Spent grains or malt bagasse are a fibrous material (70%) with high protein content with also high nutritional value [5]. Despite being recycled, especially for animal feed production, it may be used for other processes and in our case as fiber reinforcement.

Polymer mortar (PM) is a composite material mainly composed of fine aggregates mixed with a polymer binder. Regardless of being significantly stronger than ordinary cement concrete, lightweight, durable and fast-curing, PM presents brittle behavior that has limited its usefulness for load-bearing applications. Usually, PM's are manufactured as precast thin overlays for decks, bases and panels. Many studies have been made using different types of reinforcements to improve mechanical [6–10], chemical [11–13] and fracture properties [14–20] of polymer mortars but none with such type of residue.

The aim of this work is to investigate the fracture properties, energy and toughness, including elasticity modulus of polymer mortars with spent grains (Barley) from the brewing industry as fiber reinforcement.

2. Materials and methods

2.1. Materials

Specimens were prepared by following the specifications of RILEM TC113/PC-2 [21]. PM specimens were made by mixing first the barley residue from brewing process and the fine aggregates and then the polymer resin. Before mixed with the aggregates, the barley residue was dried to remove moisture and humidity. This is an important process since the brewing process generates

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large amounts of wastewater effluent and solid wastes. Drying was performed for 24 h at a temperature of 80 °C. After drying, barley residue (1%, 2%, 5% and 10% weight content) was used as partial replacement of natural aggregates. Previous studies by the authors indicate that more than 2% of natural fibers or other residues do not contribute to increase mechanical properties [16–19].

The aggregate used was foundry sand with a homogeneous grain size, uniform grains and a mean diameter of 300 μm, with finesses modulus between 3 and 5. The unreinforced PM had an aggregate content of 88% by weight. The specific gravity of the foundry sand was 2.63 g/cm^3. The aggregates were also dried before being added to the polymer binder to reduce moisture content, insuring a good bond between polymer, aggregate and residues.

The polymer system used was an epoxy resin MC109 based on a diglycidyl ether of bisphenol A and an aliphatic amine hardener FD 139 provided by EPOXYFIBER®. This system has low viscosity, and is processed with a maximum mix ratio to the hardener of 4:1. Resin content was initially set at 12%, in weight, and then increased to 14%, 16%, 18% and 20%. Barley residue content was fixed at 5%, in weight, as partial replacement of aggregates. Previous studies indicate that the resin quantity influences polymer mortar mechanical properties [22–25].

Barley reinforced polymer mortar fracture specimens have 30 mm depth (B), 60 mm width (W) and 250 mm length (L). The notch depth was 20 mm and the width 2 mm. The specimens were cured at room temperature for 7 days prior to testing.

2.2. Methods

The fracture 3 point bending tests was performed with 240 mm span (S) on a Shimadzu AG-X universal testing machine with 0.5 mm/min cross-head displacement at room temperature (23 °C). Three specimens have been used for each type of barley reinforced polymer mortar.

All fracture parameters were determined through the single edge notched beams. The specific fracture energy G_f were measured according to the RILEM recommendation

[26]. It consists of the applied energy in a stable or quasi-stable fracture of a notched specimen averaged over the projected fracture area. Let P be the applied load, δ the displacement at the loading point, a the initial crack (or notch) length and $(W-a)\,B$ the projected fracture area. G_f is given by

$$G_f = \frac{1}{(W-a)B}\int^{P} d\delta \quad (1)$$

This definition relies on the assumption that all the energy required to break the specimen is transformed into surface energy by extension of a single macrocrack [26].

Also, the critical stress intensity factor (K_{Ic}), which is the ability of the material to prevent crack propagation, is characterized. It can be expressed by [27]

$$K_{Ic} = \sigma_n \sqrt{a_f}\,F(\alpha) \quad (2)$$

where $\bullet_n = 6M/(BW^2)$, $M = P_{max}\,S/4$, a_f is the fictitious notch whose stiffness remains unaltered and proportional to the modulus of elasticity (E) of the real beam, up to the maximum load [27] and $F(\alpha)$ is the finite depth correction

$$F(\alpha) = \frac{1.99-(1-\alpha)(2.15-3.93\alpha+2.7\alpha^2)}{(1+2\alpha)(1-\alpha)^{1.5}} \quad (3)$$

With the notch/depth relation $\alpha = (a_f\,/W)$

The modulus of elasticity (E) is calculated from the measured initial compliance C_i using

$$E = \frac{6SaV(\lambda)}{(C_i W^2 B)} \quad (4)$$

where S is the loading span, a is the initial notch depth, $V(\lambda)$ is the finite depth correction considering the thickness of the clip-gauge holder, C_i is the initial compliance, W is the depth of the beam and B is the beam width, in which

$$V(\lambda) = 0.76 - 2.28\lambda + 3.87\lambda^2 - 2.04\lambda^3 + \frac{0.66}{(1-\lambda)^2} \quad (5)$$

with $\lambda = (a + H_0)/(W + H_0)$, where H_0 the thickness of the clip-gauge holder

3. Results and discussion

Fig. 1 presents the fracture energy, G_f, Fig. 2 displays fracture toughness by means of the stress intensity factor, K_{Ic}, and Fig. 3 illustrates the modulus of elasticity, E. Specimens were coded by the resin quantity, then the letters of the materials used and finally with the amount of polymer resin used as a binder, 12BRPM0 represents 12% of resin content in Barley Reinforced Polymer Mortar with 0% of Barley residue.

It can be seen from Fig. 1 that Barley residue from brewing process increase the fracture energy of the reinforced polymer mortars. In terms of fracture energy, a 29 % increase was observed when 1% of Barley residue was used, 25% increment of 2% of barley reinforcement and 31.9% when 5% were used as reinforcement of polymer mortars. This behavior was not observed when polymer mortars were reinforced with 10% of barley reinforcement. A decrease of 28.4% was measured.

The elevation observed in the fracture energy was also observed when the resistance to crack propagation was calculated by means of the stress intensity factor. Quantities of 1% and 2% contribute to an increase of 21% and 12.6% respectively. Despite the higher fracture energy observed in 5% of barley residue in the polymer mortar mixture, this increase was not observed, in fact maintain the same level. Again, the use of 10% of barley residue contributes to decrease the fracture toughness of polymer mortars in 68.5%.

The stiffness of polymer mortars were affect by the used of barley residue as reinforcement. All quantities used in this study contributed to a decrease in the modulus of elasticity, E. Higher percentages of Barley residue lower the modulus of elasticity.

Since 5%, contributed to at least even the fracture properties and with the knowledge that the increase of resin content increase polymer mortar properties, the amount of polymer binder was elevated to evaluate the fracture properties of 5% Barley residue polymer mortars. Resin content, in weight, was elevated up to 20% in steps of 2% from 12%. An increase in the fracture energy of 7.8% was observed when 14% of resin content was used, but a slight decrease of 13.3% was measured in the fracture toughness. Then increasing resin quantity contribute to an increase in both fracture energy and fracture toughness of 5% Barley reinforced polymer mortars. The mixture which presented the best fracture results was 18BRPM5, with an elevation of 67.6% of the fracture energy and 20.3% increase in the fracture toughness. Overall, Barley residue quantities higher than 5% do not contribute to increase any studied properties. Despite elevating significantly the fracture energy, G_f, and stress intensity factor, K_{Ic}, polymer mortars became less stiff when barley residue was used as substitute to natural aggregate even when the amount of polymer binder were increased

Fig. 4 presents the typical load vs. mid-span displacement curves of polymer mortars with different barley residue content.

From Fig. 4 it can be seen that 1, 2 and 5% of Barley residue reinforcement produces higher work of fracture, which is the area