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Effectiveness of new natural fibers on damage-mechanical performance of mortar

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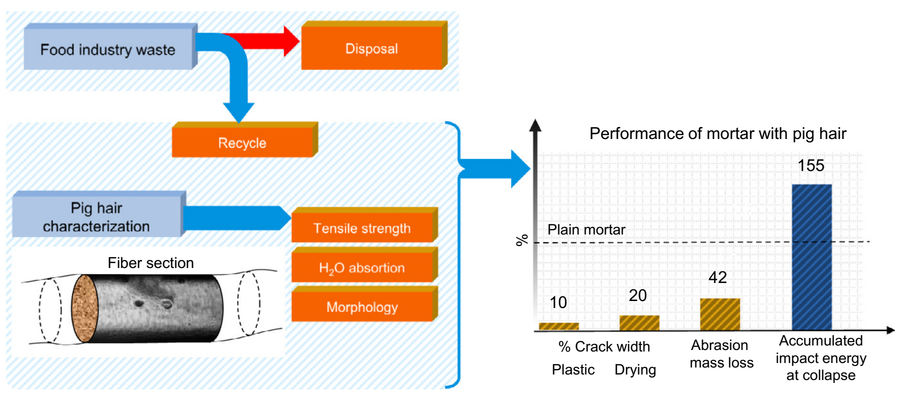
HIGHLIGHTS

- Pig hair is morphologically, physically and mechanically characterized.
- Addition of pig hair to mortar controlled plastic and drying shrinkage cracking.
- Impact strength increased with the incorporation of pig hair.
- Mass loss due to surface abrasion is reduced.
- Pig hair could work as potential replacement of polypropylene fibers.

GRAPHICAL ABSTRACT



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ABSTRACT

Addition of fibers to cement-based materials improve tensile and flexural strength, fracture toughness, abrasion resistance, delay cracking, and reduce crack widths. Natural fibers have recently become more popular in the construction materials community. This investigation addresses the characterization of a new animal fiber (pig hair), a massive food-industry waste worldwide, and its use in mortars. Morphological, physical and mechanical properties of pig hair are determined in order to be used as reinforcement in mortars. A sensitivity analysis on the volumes of fiber in mortars is developed. The results from this investigation showed that reinforced mortars significantly improve impact strength, abrasion resistance, plastic shrinkage cracking, age at cracking, and crack widths as fiber volume increases. Other properties such as compressive and flexural strength, density, porosity and modulus of elasticity of reinforced mortars are not significantly affected by the addition of pig hair.

1. Introduction

Recycled pig hair could be a cost-effective solution to improve mechanical properties and durability of cement-based materials (CBM), while at the same time be one step to mitigate the environmental issues from the pork industry worldwide. The use of waste to replace components and/or improve properties of CBM has been

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attracting research attention worldwide in the last decades, and significant progress has been achieved by incorporating wastes such as recycled aggregates, plastic bottles, rubber-tires, glass, or fly ash into cement-based materials [1–4].

CBM have a reduced mechanical and fracture capacity under tension due to their low tensile strength and fracture toughness, respectively [5,6]. Addition of fibers in CBM could provide cracking control at early ages and increase fracture toughness in a magnitude that depends on different factors such as matrix strength, fiber type, fiber modulus of elasticity, fiber aspect ratio, fiber orientation and aggregate size [6]. Industrialized fibers used as reinforcement of CBM are manufactured mainly from polypropylene, glass and steel, and their effectiveness at improving properties of CBM such as tensile and impact strength, fire and abrasion resistance, crack control, and shrinkage has been successfully proven [7–12]. In contrast, results from previous research on the addition of natural fibers (such as vegetable and animal) are promising but limited compared to industrialized fibers [13–16]. In particular, pig hair is currently a significant part of the waste produced by the food industry. The global pork production from 2008 to 2013 reached over 616 million of metric tons (measured in carcass weight) [17]. Approximately 890,000 metric tons of pig waste are produced each year in Europe, and related management costs have reached EUR 20.7 million per year [18]. Consequently, waste management of the pork industry is a major concern in many countries. To the best of the authors' knowledge, there have been only two studies addressing the incorporation of pig hair in CBM. Gagan and Lejano [19] addressed the effect of pig hair on the compressive strength of concrete. Araya-Letelier et al. [20] provided initial insights on the potential benefits of the use of pig hair in mortars, with a specific hair dosage, on flexural and impact strength as well as potential drawbacks on compressive strength, density and elastic modulus. Although these studies provide initial insight on the incorporation of pig hair in CBM, there are still questions about the characterization of the pig hair itself as well as cracking and abrasion performance of reinforced CBM with pig hair at early ages.

The novelty of this work resides on characterizing pig hair and addressing some of the most relevant benefits (e.g., cracking control) and potential drawbacks (e.g., compressive strength reduction) of adding this hair to mortars. In particular, the objectives of this study are: (i) to characterize the most relevant morphological, physical and mechanical properties of the pig hair; (ii) to assess the influence of the pig hair on relevant physical properties of mortars; (iii) to assess the influence of pig hair on the mechanical properties of mortars; and (iv) to assess the influence of pig hair on the fracture behavior of mortars.

2. Materials and methods

2.1. Morphological, physical and mechanical properties of animal fibers

Initially, this study assesses some morphological (i.e., diameter, length, aspect ratio, and roughness), physical (i.e., water absorption) and mechanical (i.e., tensile strength) properties of pig hair. Optical microscopy was used to determine diameters, lengths, aspect ratios and roughness of 10 pig hairs, randomly selected after cleaning treatment. Diameter measurements were taken at mid-sections as well as end-sections of each pig hair. Since pig hair is a natural material and the removal process of the hair is not uniform, an outlying detection process was implemented for the latter in accordance with the standard ASTM E178 [21].

Water absorption was estimated using a 100 g oven-dry pig hair sample that was immersed in water for 24 h and then wiped with paper towels to remove surface water until the papers drying the sample returned completely dry, which was taken as evidence of an approximate saturated surface dry condition of the hair. This method was adapted from the paper towel method used to determine absorption and moisture content of lightweight aggregates [22]. The formula used for water absorption is shown in Eq. (1).

$$abs(\%) = \left(\frac{W_{ssd} - W_d}{W_d}\right), \quad (1)$$

where *abs(%)* is the estimated water absorption of the pig hair as a percentage of its dry weight, W_{ssd} is the weight of the saturated surface dry sample, and W_d is the weight of the dry sample.

To estimate the tensile strength of pig hair, 10 pig hairs randomly selected after cleaning treatment were tested in accordance with the standard ASTM C1557 [23], which is recommended to assess new fibers at research level, and fibers with diameters up to 0.25 mm. Fig. 1 shows the experimental setup for the tensile strength tests. The tensile strength of each hair is estimated using Eq. (2).

$$\sigma_t = \frac{F_t}{A}, \quad (2)$$

where $\sigma_t$is the tensile strength, F_t is the peak force of the tensile test, and A is the original fiber cross-sectional area at the rupture plane. A is assumed to be circular and perpendicular to the applied load.

Because of the natural origin of the pig hair, significant aleatory variability is expected to be found among the tensile strength of this fiber. Therefore, an outlying detection process for the tensile strength tests was implemented in accordance with the standard ASTM E178 [21]. An underlying Weibull probability function for the tensile strength of the pig hair is proposed to model the aleatory uncertainty, as suggested by the standard ASTM C1557 [23], whose formulation is shown in Eq. (3) in accordance with the standard ASTM C1239 [24].

$$P_f = 1 - exp\left[-\left(\frac{\sigma}{\sigma_\theta}\right)^m\right]; \sigma > 0, \quad (3)$$

where P_f is the probability of failure of the pig hair under tensile stress, σ_θ is the Weibull characteristic strength, and m is the Weibull modulus. The parameters σ_θ and m are estimated from the sample of 10 tests using the maximum likelihood method in accordance with the standard ASTM C1239 [24].

2.2. Mortar mix proportions

Table 1 presents the main properties of the materials used in the mortar mixes of this work. All the materials mentioned in Table 1 satisfy the following international standards: (i) ASTM C150/C150M [25]; (ii) ASTM C33/C33M [26]; (iii) ASTM C1602/C1602M [27]; and (iv) ASTM C494/C494M [28].

The experimental data presented in this work were obtained from a series of mortar mixes with the following mix proportions per m^3 of mortar: (i) 550 kg of cement; (ii) 247.5 kg of water (water-cement ratio of 0.45); (iii) 162.2 kg of fine aggregate type (a); (iv) 1,297.7 kg of fine aggregate type (b); and (v) 3.85 kg of plasticizer. The fine aggregates weights are reported in saturated surface dry conditions and all these material proportions were selected in accordance with the ACI 211 Committee [29]. This base mortar mix proportion was modified with the incorporation of pig hair as fiber reinforcement in dosages of 0 kg/m^3 (ID#0, which is plain mortar), 2 kg/m^3 (ID#2), 4 kg/m^3 (ID#4), and 8 kg/m^3 (ID#8). Before casting, water adjustment was performed to mortar mixes ID#2, ID#4 and ID#8 to compensate the water absorbed by the corresponding dosage of pig hair. The pig hair used as fiber reinforcement was obtained from a Chilean pork food company that disposes

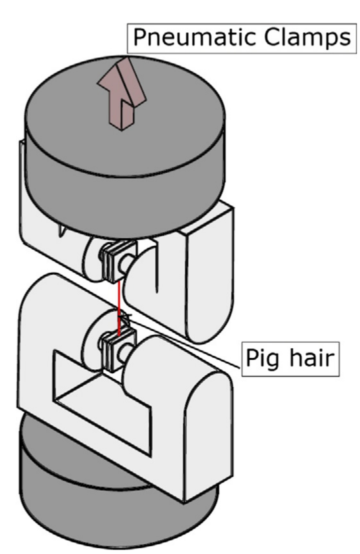

Fig. 1. Setup of pig hair tensile strength test.