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

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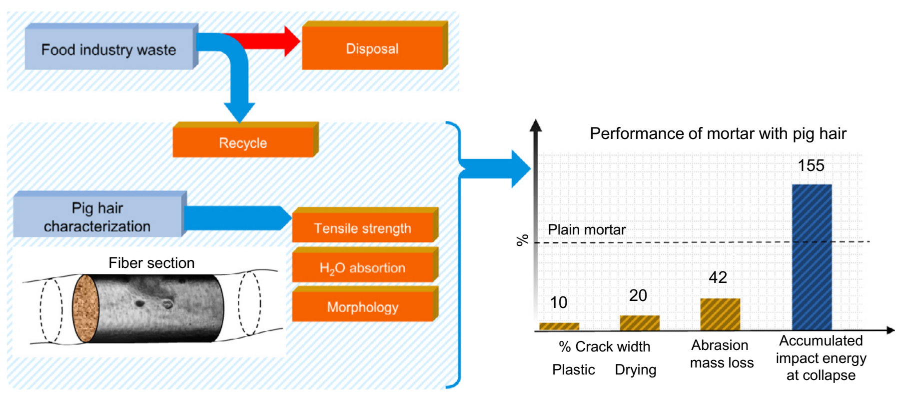
HIGHLIGHTS

- 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).

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

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).

$$\sigma_t = \frac{F_t}{A}, \tag{2}$$

where σ_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].

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

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

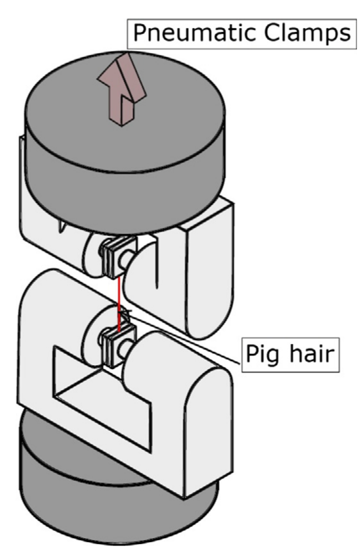

Fig. 1. Setup of pig hair tensile strength test.

approximately 2000 metric tons of pig hair per year in landfills. The clean condition of the pig hair was obtained after washing and immersing the hair in water at 60 °C for 24 h and then placing the hair in an oven at 60 °C for another 24 h.

2.3. Mortar specimens preparation

For each mortar mix defined in Section 2.2 of this study, twelve RILEM beam specimens (40 mm × 40 mm × 160 mm), one plastic shrinkage specimen, one restrained shrinkage ring specimens and three slab specimens (400 mm × 400 mm × 40 mm) for the impact test were cast. From the RILEM specimens of each mix, three were for flexural strength (the remaining six pieces, after the flexural test, were used for compression testing), two for density and porosity and one for abrasion testing. Pig hair reinforced mortar mixes were prepared by mixing cement, fine aggregates and pig hair in a mechanical mixer for 5 min prior to water and plasticizer addition to minimize the generation of clusters. RILEM beam and slab molds were oiled and placed on the consolidation table while mortar was poured. After each mold was properly filled, vibration proceeded to ensure good compaction. After consolidation, specimens were cured in sealed condition for 24 h. After that, specimens were demolded and cured in saturated conditions at 22 °C until testing at 28 days, with the exception of RILEM beams used for ultrasonic pulse velocity (UPV) measurements. The latter were extracted 5 min before each UPV measurement and then returned immediately to saturated condition.

2.4. Influence of animal fibers on physical properties of mortars

Previous works reported that adding fibers to cementitious materials could decrease surface density and, therefore increase porosity [6,30]. For this reason the porosity and surface density of plain mortar and fiber-reinforced mortar were measured for each mortar mix prepared for this work. Surface density, ρ, and porosity, n, at 28 days were determined according to the standard UNE-EN 1015 [31]. First, submerged weights of saturated samples were recorded. After that, samples were maintained in oven dried condition at 105 °C until no variation of weight was recorded. The results of n and ρ for each different mortar mix have been obtained as the average of two RILEM beam specimens as described in Eqs. (4) and (5), respectively.

$$n = \frac{m_{sat} - m_{dry}}{m_{sat} - m_{sub}}, \tag{4}$$

$$\rho = \rho_w \cdot \frac{m_{dry}}{m_{sat} - m_{sub}}, \tag{5}$$

where m_{sat} is the water-saturated mass of the specimen; m_{sub} is the water-submerged mass of the specimen; m_{dry} is the oven dried mass of the specimen and ρ_w is the water density at testing temperature.

2.5. Influence of animal fibers on mechanical properties of mortars

2.5.1. Flexural and compressive strength

Flexural and compressive strength of each mortar mix were assessed in accordance with the standard ASTM C348 [32] at an age of 28 days. Flexural strength was determined as the average of three RILEM beams, and compressive strength was determined as the average of the six specimens obtained from the RILEM beams (after flexural fracture, two pieces are obtained from each beam) for each mortar mix.

2.5.2. Dynamic modulus of elasticity

Addition of fibers in mortar typically improves toughness and tensile strength. Yet, in this work, fibers are expected to have low density and high absorption that might affect porosity and, therefore, the quasi-static elastic modulus, $E(t)$. To obtain sufficient experimental data using a limited number of specimens, the compressive-dynamic modulus of elasticity, $E_d(t)$, was determined at frequent intervals (one measurement per day) using UPV tests up to 28 days according to the standard ASTM C597 [33]. $E_d(t)$ is proportional to $E(t)$ and typically 20–30% lower than the former [6]. $E_d(t)$ has been estimated for 28 days combining UPV measurements (average of three RILEM beams at different ages) and ρ estimated as described in the previous section. According to this, a regression of $E_d(t)$ can be estimated using the maximum elastic modulus for a mixture, $E_{d-\infty}$, determined from the measured modulus at later ages as shown in Eq. (6) [34].

$$E_d(t) = E_{d-\infty}\frac{C_4(t-t_0)}{1+C_4(t-t_0)}, \tag{6}$$

where C_4, t and t_0 are the so-called rate constant, the time variable and time of final set of mortar respectively.

2.5.3. Abrasion resistance

It was reported previously that addition of fibers might improve surface abrasion resistance of mortar and concrete [9]. Addition of fibers might improve surface durability especially on those structures subjected to dynamic loading, such as pavements. For this reason, abrasion resistance was determined in this work according to the standard ASTM D968 [35]. This consists of striking a sample with 3 liters of sand, at a height of 0.92 m. Sand flows through a pipe of 914 mm diameter impacting the sample at a 45° angle. In each repetition, the time it takes to drop the sand is recorded. This is used as control parameter of the amount of sand dropped on each repetition. At the end of each repetition, the final mass of the sample is recorded, and the percentage of mass loss is estimated with respect to the initial mass of the sample. The percentage of mass loss was estimated as the average of three repetitions for each mortar with different fiber dosage. Analysis of the surface was performed visually using a high definition camera.

2.6. Influence of animal fibers on the fracture behaviour of mortars

2.6.1. Plastic shrinkage cracking

Effectiveness of incorporating pig hair as a reinforcement of mortar to reduce surface plastic shrinkage cracking was assessed following the standard ASTM C1579 [36]. Molds were fabricated with depths of 160 mm and rectangular areas of 570 mm by 360 mm. The molds were implemented with stress risers of 63 mm height (central raiser) and 32 mm height (the two lateral raisers). One mold was cast for each mortar mix as shown in Fig. 2a. During eight hours after casting, each mortar specimen was placed in an environmental chamber, keeping temperature and relative humidity at 36 ± 3 °C and 30 ± 10%, respectively.

Eight hours after casting, the specimens were removed from the controlled temperature and relative humidity chamber, and conserved at temperature of 23 ± 2 °C. During the following 16 h, average crack width sizes were measured using a crack width comparator tool at intervals of 60 min. A crack reduction ratio was calculated for each mortar mix using Eq. (7).

$$CRR = \left(1 - \frac{\overline{CWM_{ID\#i}}}{\overline{CWM_{ID\#0}}}\right) \cdot 100, \tag{7}$$

where CRR is the crack reduction ratio, $\overline{CCWM_{ID\#i}}$ is the average crack width of the mortar specimen ID#i, and $\overline{CWM_{ID\#0}}$ is the average crack width of the mortar specimen ID#0 (plain mortar).

2.6.2. Age at cracking under restrained shrinkage and resulting crack width

Likelihood of early cracking of mortar mixes, with and without fibers, under the restrained shrinkage condition was assessed using the restrained ring test in accordance with the standard ASTM C1581/C1581M [37]. One ring specimen was cast for each mortar mix, and mechanical consolidation was implemented. For each specimen, the inner ring consisted of a steel ring with strain gages that measure circumferential strain. The outer ring consisted of a plastic non-absorptive material that is removed 24 h after casting and strain measurements started to be recorded at that moment. Fig. 2b shows the test ring experimental setup for the four mortar mixes used in this study. Age at cracking is determined when mortar rings exhibited radial macroscopic cracks along their heights. This is consistent with a sudden drop of the circumferential strain measurement recorded during the test. Forty-eight hours after finishing the ring test, the resulting crack width of each mortar mix was measured using a crack width comparator tool at three different locations of the crack (top, middle and bottom of the crack along the height of the ring).

Table 1
Material properties.

Materials	Properties		
Cement	High strength Portland cement		
	Density: 3.1 (g/cm^3). Blaine fineness: 330 (m^2/kg)		
Fine aggregates		Type (a)	Type (b)
	Density (g/cm^3):	2.58	2.55
	Water absorption (%):	2.60	2.31
	Fineness modulus (dimensionless):	2.59	1.09
Water	Potable		
Plasticizer	Type: Lignosulphonate based. Density: 1.15 (g/cm^3)		

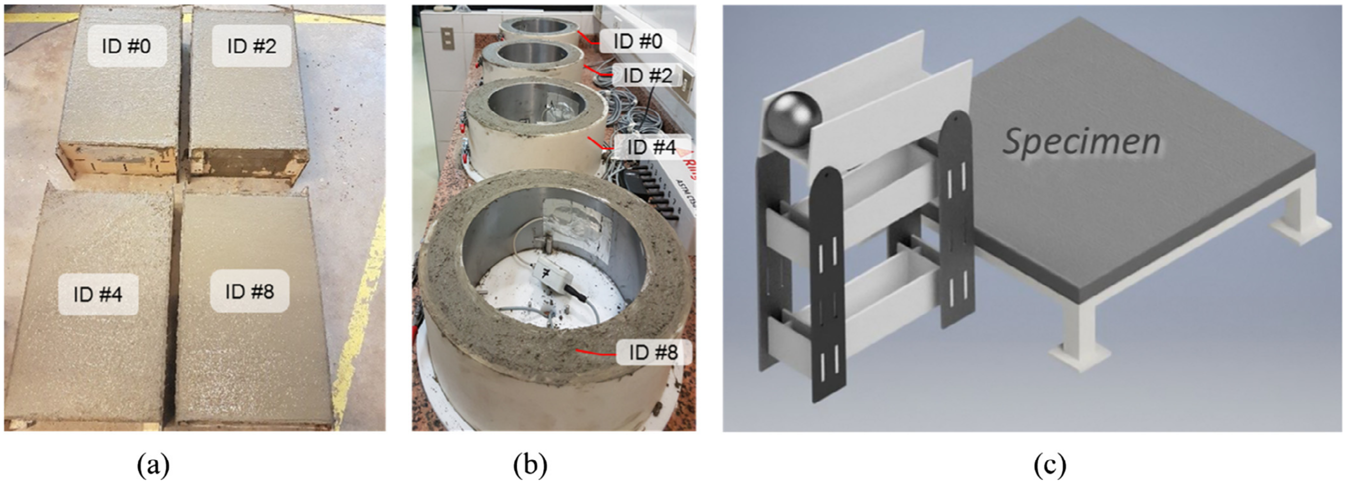

Fig. 2. Plastic shrinkage cracking test: (a) mortar specimens after casting; (b) age at cracking under restrained shrinkage setup for each mortar mix; and (c) impact test setup.

2.6.3. Impact strength

The impact resistance of the slab specimens was used as an indicator of toughness of the mortar mixes with and without pig hair fiber reinforcement according to ACI Committee Report 544.2R [38]. A projectile impact test assembly, shown in Fig. 2c, was specially fabricated for this test, using medium-density fiberboards and a steel frame to vertically support the slab specimens. The test setup was prepared such that the metallic ball fell at the center of the specimen. Three slab specimens for each mortar mix defined in Section 2.2 were tested. For each specimen, the number of blows required for the appearance of the first crack at the lower surface of the slab, and the number of blows required to propagate the crack through the entire slab's thickness, causing collapse, were recorded. The energy per blow is calculated using Eq. (8).

$$E_b = m \cdot g \cdot h, \tag{8}$$

where E_b is the energy per blow, m is the mass of the metallic ball (0.44 kg), g is the gravitational constant (9.8 m/s^2), and h is height of fall (160 mm). These values were maintained constant during the entire test and, consequently, each blow accounted for an impact energy of 0.69 J.

3. Results and discussion

3.1. Morphology, physical and mechanical properties of animal fibers

A 10 pig hair sample was studied in this work. Each hair was measured using optical microscopy at its mid-section and end-section (both end-sections were measured for each hair, but only the end-section with the largest difference from the mid-section was reported), and each measurement reported was the average of five measurements equally spaced (0.1 mm), at mid (top) and end (bottom) sections, as presented in Fig. 3a.

Fig. 3b shows a typical pig hair with a 0.23 mm mid sections. Fig. 3c presents a 3D elevation of its surface at the mid-section. The average surface roughness of Fig. 3c reached 0.104 μm, which corresponds to roughness level N3 in accordance with the standard DIN4766 [39]. As transfer of load and displacement from fiber to matrix of composite materials could be controlled by chemical and mechanical bonding at the interface of these two [40], more work is expected to understand chemical and mechanical interaction between pig hair and mortar matrix.

Table 2 summarizes statistics of the dimensions of the 10 pig hair sample. All the measurements passed the recommended criterion for a single outlier detection with a significance level of 5% in accordance with the standard ASTM E178 [21]. It can be observed that the variability of these dimensions is significant (the smallest coefficient of variation is 26%), which is expected for a natural fiber. According to length and diameter, fibers can be classified into micro or macro fibers. Micro-fibers have a larger impact on material properties (e.g., delay the occurrence of micro cracks and block the widening of coalescence cracks), whereas macro-fibers have a larger impact on structural properties (e.g., they can carry loads across micro cracks, contributing to post-crack behavior of cement-based composites) [41]. According to Banthia et al. [42], macro-fibers have lengths of 25 mm or longer and transverse dimensions of 0.3–3 mm, whereas micro-fibers have lengths less than 20 mm and transverse dimensions less than 25 μm. From Table 2, the dimensions of the pig hair do not satisfy completely the definition of micro or macro fibers. Therefore, pig hair might be classified as a hybrid fiber. Hybrid fibers could have a positive double effect: (i) control nucleation and growth of cracks; and (ii) improve overall flexural strength [43].

Regarding water absorption of pig hair, the measured value reached 95%. In general, natural fibers present large water absorption values ranging from 40% (bamboo) to 180% (coconut) [16].

For the estimation of the tensile strength of the pig hair, since the maximum diameter of the pig hair sample was 0.23 mm, then standard ASTM C1557 [23] is applicable. Fig. 4a shows a result from a typical tensile test of a pig hair, reaching a maximum force of 3.4 N and a corresponding tensile strength of 135 MPa (diameter of 0.18 mm). 10 pig hairs were individually tested and all the test results passed the criterion for a single outlier detection (significance level of 5%) using the standard ASTM E178 [21]. Fig. 4b shows the experimental data of the 10 tensile strength tests and the fitted hypothesized Weibull cumulative distribution function with its estimated parameters obtained using the maximum likelihood method in accordance with the standard ASTM C1239 [24]. The tested sample is small ($n = 10$), and, consequently, the epistemic uncertainty on the parameter estimation is still significant. To quantify this uncertainty, 90% confidence intervals of the parameter estimators are obtained, in accordance with the standard ASTM C1239 [24], and these are (881.4 to 1,409.4) for σ_θ and (1.54 to 3.78) for m. These confidence intervals are relatively large and in order to reduce this epistemic uncertainty a more extensive experimental campaign is recommended to be done in a future study.

Table 3 presents the statistics of the tensile strength tests, with a mean of 99 MPa. Considering that the minimum tensile strength required for steel fibers by the standard ASTM A820/A820 M is 345 MPa [44], the resulting mean of 99 MPa might be considered low; nevertheless, this value is larger than the minimum tensile strength of other natural fibers such as water reed with 68 MPa [16], and much larger than the tensile strength of plain mortar.

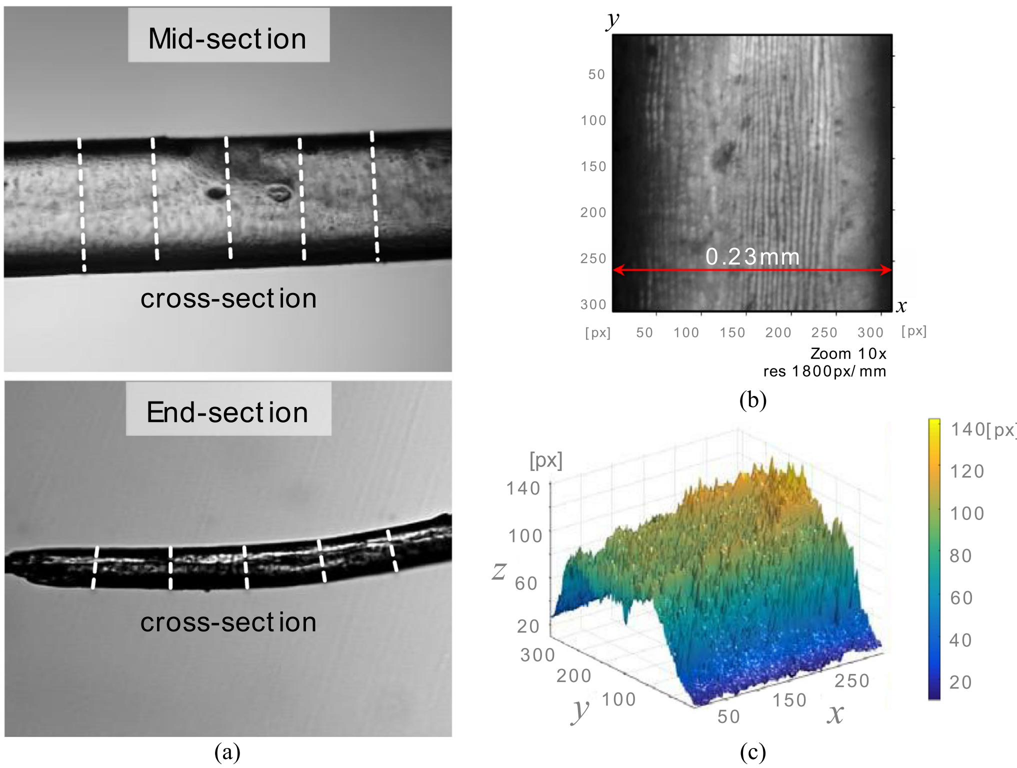

Fig. 3. Morphological analysis of pig hair for this work: (a) methodology to measure diameters at mid-section and end-sections; (b) 0.23 mm diameter pig hair: microscopy at mid-section; and (c) 3D elevation of its surface at mid-section.

Table 2
Statistics of the dimensions of 10 pig hairs.

	Mid-section diameter (mm)	End-section diameter (mm)	Length (mm)	Aspect ratio
Mean	0.16	0.13	35.7	249
Max	0.23	0.22	60.2	350
Min	0.07	0.06	22.1	150
SD[1]	0.05	0.05	11.4	65
COV[2]	31%	38%	32%	26%

[1] Standard deviation.
[2] Coefficient of variation.

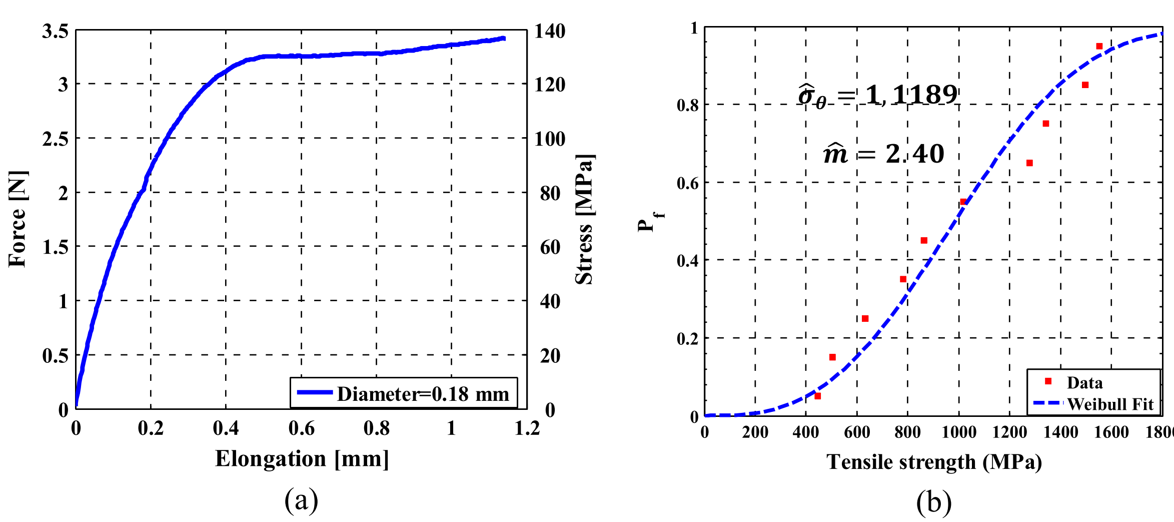

Fig. 4. (a) Tensile strength test of a pig hair; and (b) experimental data from the 10 pig hair sample tensile strength tests and Weibull cumulative distribution function obtained using the method of maximum likelihood.

In terms of variability, the coefficient of variation is 42%, showing again the significant dispersion of the physical and mechanical properties that natural fibers often present.

3.2. Influence of animal fibers on the physical properties of mortars

According to the results, no significant reduction of ρ and n is observed as the dosage of hair increases up to 8 kg/m^3 of mortar. The average value of ρ was 2,099.3 kg/m^3, with a standard deviation of 11.8 kg/m^3. Regarding n, the average value was 0.21, with a standard deviation of 0.0026. It is important to mention that values of ρ and n estimated with this method are sensitive to the period of time at which samples were saturated and the tortuosity of the mixtures' surface.

3.3. Influence of animal fibers on the mechanical properties of mortars

3.3.1. Dynamic modulus of elasticity

For adequately compacted specimens, the addition of fibers should have little effect on elastic modulus as previously reported [6]. The results obtained in this work showed that fiber-reinforced mortar has no significant reduction on E_d up to 8 kg/m^3 of pig hair. This is consistent with the small standard deviation of ρ and n reported in the previous section. Over 28 days of measurement, the maximum standard deviation of E_d was 8% at 19 days with respect to its average value at the same age. According to this, a unique regression was estimated to represent the age-dependent behavior of mortar in this work. The regression coefficients corresponding to Eq. (6) for the specific mortar design for this work are: $E_{d-\infty} = 46$ GPa, $C_4 = 1.0$ and $t_0 = 1.5$ days.

3.3.2. Flexural and compressive strength

Fig. 5a and b present the mean values and the error bars (one standard deviation above and below the mean) of the flexural and compressive strength of each mortar mix, respectively. There is an increment in the flexural strength of mortar mixes when pig hair is incorporated (compared to plain mortar ID#0), ranging from 10% (ID#4) to 16% (ID#8) in terms of the mean values. In general, increase of flexural strength is expected when adding high modulus fibers [6]. Therefore, the improvements on flexural strength of fiber reinforced mortar in this work might indicate that pig hair could have medium/high modulus of elasticity relative to mortar. However, if the error bars are analyzed, it can be observed that subtracting one standard deviation from the mean flexural strength of mortar ID#8 nearly equates the mean flexural strength of mortar ID#0 adding one standard deviation. This analysis might suggest that there is not strong evidence that supports that the incorporation of pig hair increases the flexural strength and that this difference between means could be as a result of aleatory variability and/or measurement errors.

On the other hand, there is a reduction in compressive strength values when pig hair is incorporated (compared to plain mortar ID#0). This reduction ranges from 7% (ID#2) to 12% (ID#8). This relatively small reduction is an indication that mortar samples were adequately compacted since typically compressive strength is not expected to be affected by the addition of fibers, and is consistent with the small variation of mortar density and porosity reported earlier [6]; however, reductions in compressive strength due to fiber incorporation have been previously reported [45]. If the error bars are analyzed, it can be observed that subtracting one standard deviation from the mean compressive strength of mortar ID#0 equates the mean compressive strength of mortar ID#8 adding one standard deviation. This analysis might suggest that there is not strong evidence that supports that the incorporation of pig hair reduces the compressive strength and that this difference between means could be as a result of aleatory variability and/or measurement errors.

Table 3
Statistics of tensile strength tests of 10 pig hairs.

	Mean (MPa)	Max (MPa)	Min (MPa)	SD[1] (MPa)	COV[2] (%)
Tensile strength	99.2	155.1	44.5	41.7	42.1

[1] Standard deviation.
[2] Coefficient of variation.

3.3.3. Abrasion resistance

In order to achieve significant changes of mass, 42 drops of sand (equivalent to 126 liters of sand) were performed on each face exposed to abrasion. The test was performed on the three confined faces, during casting, of each RILEM beam specimen. Fig. 6a shows the percentage of mass loss for RILEM beam specimens with different fiber dosages at different liters of dropped sand.

Abrasion removed the cement paste on the surface exposing the fine aggregate below, and eventually fibers. In general, it was observed that once a fiber was exposed on the surface, it was able to withstand direct abrasion for up to 3 repetitions (3–9 liters of sand). After that, the fiber was completely removed.

Plain mortar showed higher loss of mass regardless of the number of liters of sand dropped (see Fig. 6a), which is consistent with previous results [9]. After 40 liters of sand dropped, percentage of mass loss evolves linearly (see Fig. 6a) and remains like that for higher volumes of sand beyond 126 liters, which is not reported graphically herein). After 126 liters of sand dropped, plain mortar mass loss was 13 and 42% higher than mortars with 8 and 2 kg/m^3 of fiber respectively. Mortars with 2 kg/m^3 of fibers showed consistently lower mass loss than the rest of the tested samples with fibers. At 126 liters of sand, mass loss of mortar with 2 kg/m^3 was 20% less than mortar with 8 kg/m^3 and 11% less than mortar with 4 kg/m^3 of fiber. Size and distribution of pores on the surface might be the reason why mortar ID#2 losses less mass than the rest (see Fig. 6b–e). The results presented in this section showed that the capacity of pig hair fibers to increase abrasion resistance is similar to commercial polypropylene fibers [9]. More work needs to be done to understand how fiber morphology and mechanical properties, aggregate gradation and cement paste can be combined effectively to improve mortar abrasion resistance using these fibers.

3.4. Influence of animal fibers on the fracture behaviour of mortars

3.4.1. Plastic shrinkage cracking

From the four mortar specimens placed during eight hours after casting (one per each dosage of fiber) in the controlled temperature and relative humidity chambers, the mortar specimen ID#2 is disregarded since its controlled environment did not work correctly and could not be fixed during the test execution. The remaining mortar specimen results are still valid since no problems occurred with these tests. Fig. 7 shows the mortar specimens with a crack width comparator tool 24 h after casting, and it can be seen the significant crack width reduction obtained with the incorporation of pig hair.

Fig. 8a shows the average crack width as a function of time after casting for each mortar mix. It can be seen that the incorporation of pig hair significantly reduces the average crack widths and is comparable with the performance of polypropylene fibers as reported previously [46]. Fig. 8b presents the evolution of *CRR*, calculated using Eq. (2), as a function of the time after casting for mortar mix ID#4, and mortar mix ID#8. It can be observed that *CRR* stays

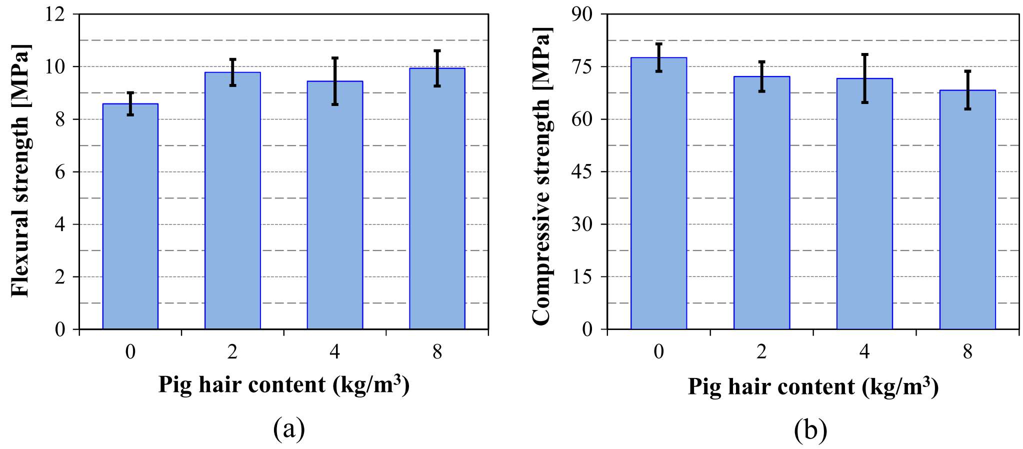

Fig. 5. (a) Flexural strength at 28 days versus pig hair dosage in kg/m^3; and (b) compressive strength at 28 days versus pig hair dosage in kg/m^3.

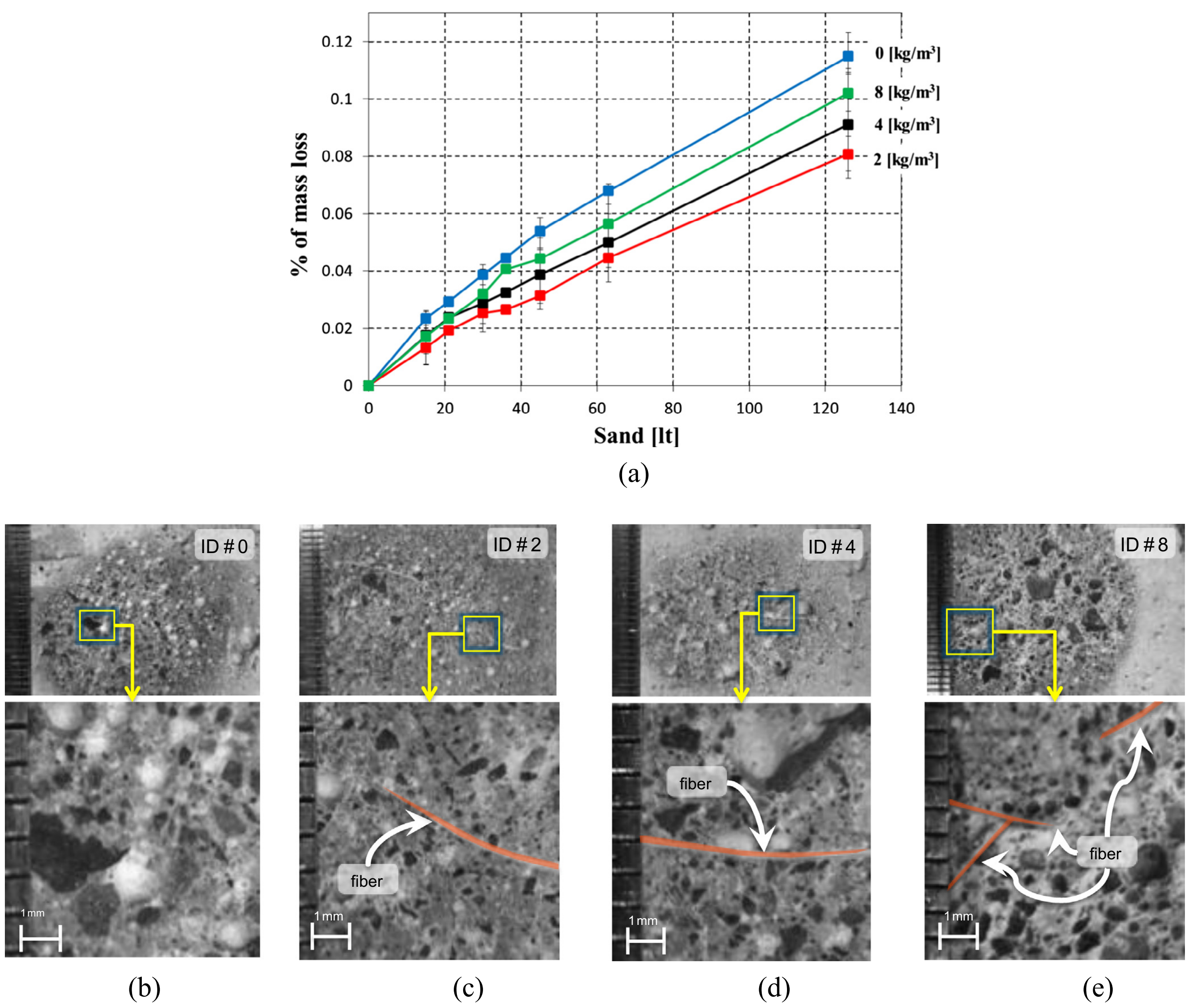

Fig. 6. (a) Percentage of mass loss at different volumes of sand versus dosage of fibers; and (b) to (e): abrasion surface of mortar with 0, 2, 4 and 8 kg/m^3 of fiber respectively at 126 liters of sand (fiber digital colored).

above 90% over 24 h after casting on higher dosages of pig hair (ID#8), while ID#4 shows a continuous reduction during the first 24 h after casting, both compared to plain mortar (ID#0). Overall, it can be inferred that high dosages of pig hair tend to stabilize the evolution of crack widths during the first hours after casting, caused by plastic shrinkage, since mortar specimen ID#0 and mortar specimen ID#4 developed growing cracks along the time, whereas mortar ID#8 presented stable crack widths as a function of time. Previous works suggested that polypropylene fibers might reduce potential plastic shrinkage cracking partially because of the ability of fibers to redistribute water near the surface [47] regardless its reduced ability to retain water [9]. As previously reported, pig hair has high absorption and, therefore, it is expected that this feature contributes to redistribute water near the surface reducing the plastic shrinkage cracking of reinforced mortars.

3.4.2. Age at cracking under restrained shrinkage and resulting crack width

Fig. 9 presents the strain measurements at the inner ring of the ring test developed by each mortar mix as a function of time. The sudden drop in strain of the inner ring is an indication of the age at cracking (i.e., formation of a macroscopic radial crack along mortar radius) of each mortar mix. First, at approximately 2 days, the measured strain evolution of mortar ID#0 reduces from the strain response of mortars with fibers. This could be an indication of early microscopic damage initiation in ID#0 mortar as addressed previously by comparing mechanical response of restrained mortar rings and acoustic emission measurements [48]. Second, incorporation of pig hair consistently delays growth of macroscopic cracks. Specifically, mortar ID#0 presented an age of cracking of 6.5 days, whereas mortar ID#8 (with the largest amount of fibers) cracked at 8.25 days, which is a 27% increment compared to plain mortar. Similar delay behavior induced by fibers on the age at cracking during ring tests has been reported previously [49]. In addition, the incorporation of pig hair allowed the development of higher levels of strain without cracking. The age at cracking (AC) and the increment (compared to plain mortar) for each mortar mix is shown Table 4.

The resulting average crack width and the crack reduction ratio of each mortar mix, measured 48 h after the finalization of the ring test, are reported in Table 4, and Fig. 9b–e shows the procedure used to measure crack widths using a crack width comparator tool. It can be seen that the incorporation of pig hair consistently and significantly reduces crack widths. This is consistent with what was expected because of the particular morphology of the fibers (i.e., length and diameter) described in previous sections. In particular, mortar mix ID#0 (plain mortar) presents an average crack width of 0.80 mm, whereas mortar mix ID#8 exhibits an average crack width of 0.17 mm, which corresponds to a *CRR* of 79% using Eq. (7). Mortar mix ID#2 and ID#4 also present significant crack reduction ratios (16% and 51% respectively). These results are consistent with the *CRR* values obtained in Section 3.4.1 of this study.

The results of age at cracking of mortars under restrained drying shrinkage and resulting average crack width indicate a positive effect that incorporation of pig hair can have on crack control at early ages. Consequently, a positive impact on the durability of mortar mixes incorporating this animal fiber should be expected.

3.4.3. Impact strength

Addition of fibers is expected to significantly improve fracture toughness of mortars [50]. Different types of tests have been developed to address the capacity of fiber-reinforced cement-based materials to absorb damage [13]. The impact resistance is an effective test to measure the capacity of absorbing damage of fiber-reinforced mortar. Increment of impact energy is related to an increase of fracture toughness due to the addition of fibers [16,51]. Fig. 10a shows a pig hair slab specimen tested until collapse. The mean values and the error bars (one standard deviation above and below the mean) of the cumulative energy (0.69 J per each blow) for each mortar mix at the appearance of the first crack and at the collapse of the slab specimens is shown in Fig. 10b.

As seen in Fig. 10b, there is a consistent increment in the energy required to generate the first crack at the slab specimens when pig hair is added to mortar, and this increment ranges from 10% (ID#4) to 36% (ID#8). However, if the error bars are analyzed, it can be observed that subtracting one standard deviation from the mean first crack energy of mortar ID#8 equates the mean first crack energy of mortar ID#0. This analysis might suggest that there is not strong evidence that supports that the incorporation of pig hair increases the first crack energy and that this difference between means could be as a result of aleatory variability and/or measurement errors.

There is also a consistent increment in the energy required to collapse the slab specimens with pig hair, and this increment

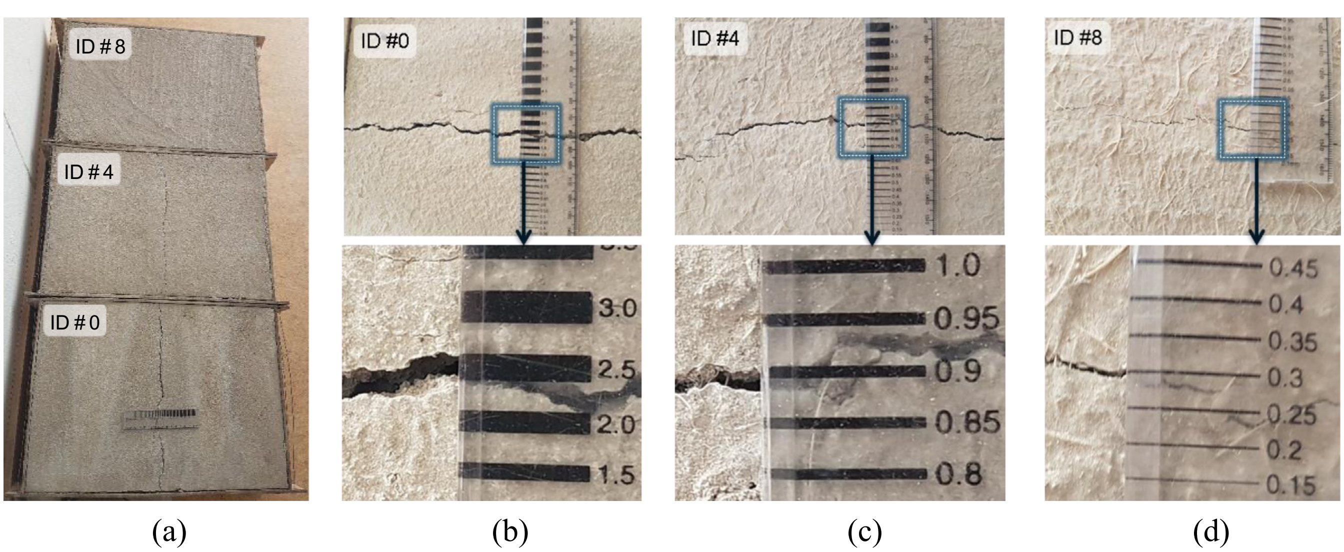

Fig. 7. Plastic shrinkage cracking test: (a) samples after-testing from bottom to top mortar specimens ID#0, ID#4, and ID#8 are showed; (b) mortar specimen ID#0 with crack width of 2.5 mm; (c) mortar specimen ID#4 with crack width of 0.9 mm; and (d) mortar specimen ID#8 with crack width of 0.3 mm.

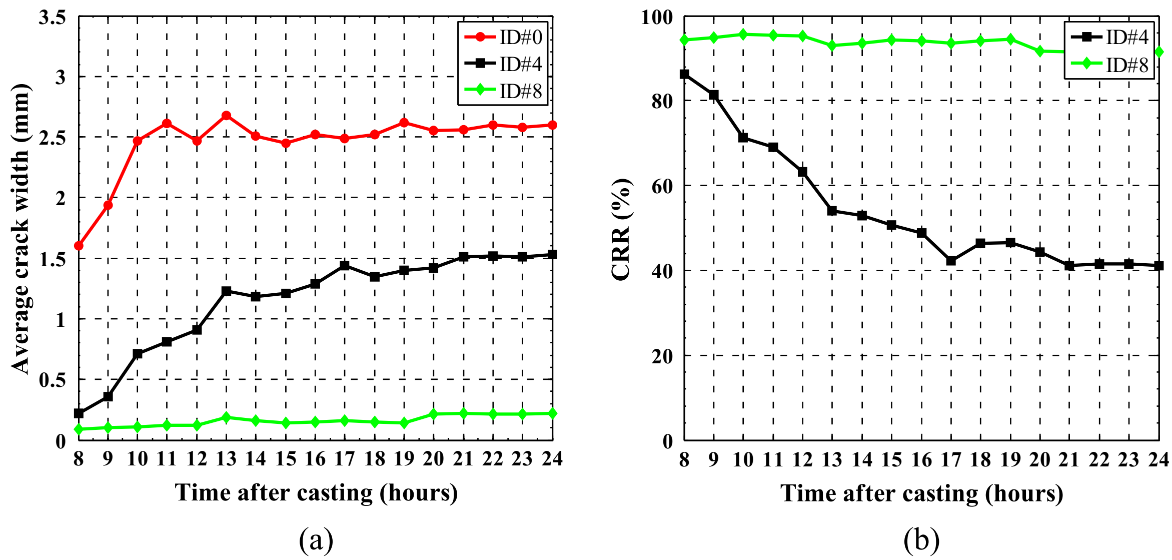

Fig. 8. Plastic shrinkage cracking tests for each mortar mix: (a) average crack width as a function of time after casting; and (b) crack reduction ratio as a function of time after casting.

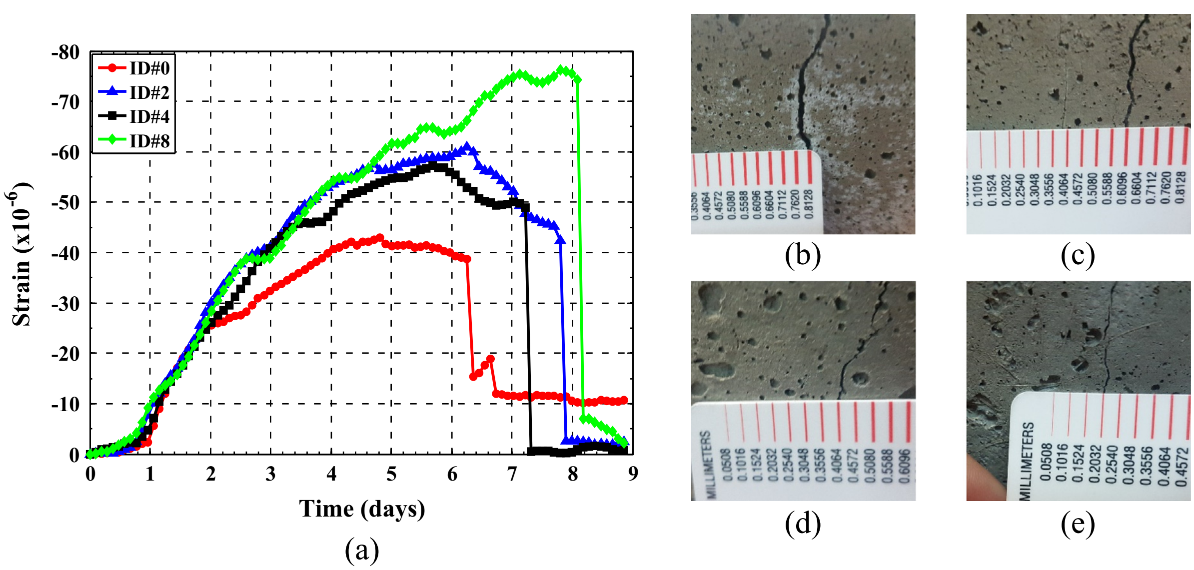

Fig. 9. (a) Strain measurements of the steel ring for each mortar mix. Measurements of crack width after ring test for mortar mix: (b) ID#0; (c) ID#2; (d) ID#4; and (e) ID#8.

Table 4
Age at cracking for each mortar mix.

	Mortar mix ID#			
	0	2	4	8
Age at cracking (days)	6.50	7.75	7.25	8.25
Increment AC[1] (%)	0	19	12	27
Average crack width (mm)	0.80	0.67	0.39	0.17
Crack reduction ratio (%)[2]	0	16	51	79

[1] Compared to mortar ID#1 (plain mortar).
[2] Calculated using Eq. (7).

ranges from 31% (ID#2) to 55% (ID#8). Similar to the mechanical results of flexural and compression strength, the variability of these results is larger for mortar mixes with pig hair, which might be explained by an uneven distribution of the fibers into the mortar matrix. If the error bars are analyzed, it can be observed that even subtracting one standard deviation from the mean collapse energy of mortar ID#8, this value is still larger than the mean collapse energy plus one standard deviation of mortar ID#0. This analysis suggests that there is evidence that supports that the incorporation of pig hair increases the collapse energy in mortars.

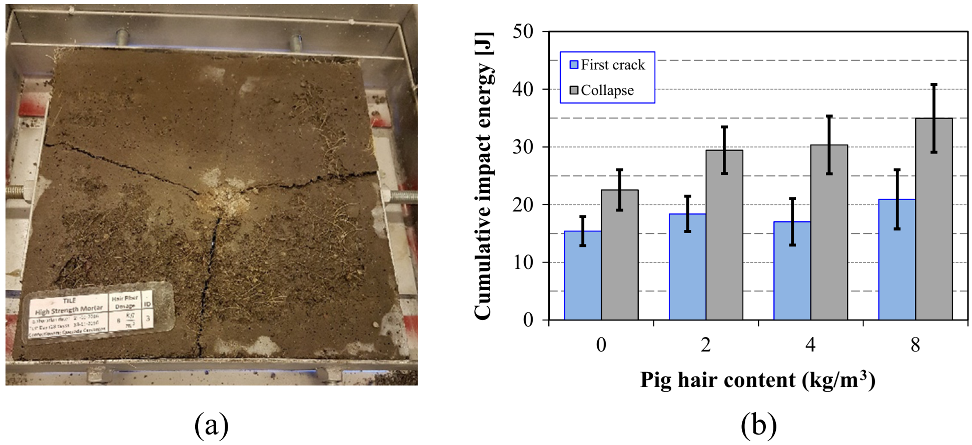

Fig. 10. Impact strength: (a) mortar mix ID#8 slab specimen tested; and (b) mortar mixes cumulative impact energy at occurrence of first crack and at collapse.

Additionally, under impact testing, mortars with addition of polypropylene fibers have been reported to have a fracture mode (fracture of fibers) similar to mortars with pig hair in this work [51]. Commercial-type polypropylene fibers tested previously under impact testing with an addition of up to 1.0% by volume of fibers, showed increment of 10 (first crack) and 40% (collapse) of impact strength compared with plain mortar [52], which is similar to the results of impact strength presented in this study.

The results presented in this section proved that addition of pig hair is effective on hardened mortar (at 28 days) in delaying macroscopic crack formation and propagation subject to localized external loading. Consequently, durability of the material could be extended by the incorporation of pig hair.

4. Final comments and conclusions

In this experimental study, pig hair, a waste from the food industry, was processed and characterized morphologically, physically and mechanically to be used as a natural fiber reinforcement in mortar mixes. The effectiveness of the incorporation of pig hair in mortar mixes was assessed experimentally comparing the performance of plain mortar specimens to mortar specimens incorporating pig hair (dosages of 2, 4, and 8 kg of pig hair per m^3 of mortar) under strength, abrasion resistance, and fracture tests.

Pig hair morphological properties (e.g., diameter, length and aspect ratio) showed COV as large as 38%. Although this is a large variability compared to industrialized fibers, even larger variabilities can be found in other natural fibers that are being used in cement-based materials. In particular, the results show mean values of length, diameter and aspect ratios of 36 mm, 0.16 mm and 249, respectively. These results do not completely satisfy the definitions of micro or macro fibers, which suggests that this fiber might have a hybrid-fiber effect at different length scales of mortar. Mechanical properties such as tensile strength of pig hair also showed significant variability (COV of 42%), and its mean value reached 99 MPa. This mean value is low compared to industrialized fibers such as steel fibers, but it is larger than the tensile strength of other natural fibers already used in concrete (e.g., water reed) and much larger than the tensile strength of plain mortar.

Although mean flexural strength was increased by up to 16% and mean compressive strength was reduced by up to 12% when pig hair is incorporated to mortars, these difference might be result of aleatory variability and/or measurement errors; when these means were analyzed along with its standard deviations, there was not strong evidence that supports that the incorporation of pig hair modifies the flexural and compressive strength.

Physical and mechanical properties of mortars such as density, and porosity, and dynamic elastic modulus were measured and confirmed that addition of these new fibers to mortar does not affect its behavior up to 8 kg/m^3.

Experimental evaluation of abrasion resistance and damage control in fiber reinforced mortar presented promising results. Based on these the following conclusions can be mentioned:

1. Addition of pig hair proved to be effective on abrasion resistance, reducing up to 42% mass loss (ID#2) with respect to plain mortar. Fibers were broken as a result of the impact of sand during the test. This confirms that fibers present good adhesion to mortar matrix. It is possible that natural fibers near the surface of mortar have two opposite effects on abrasion resistance: (i) above 4 kg/m^3 of fibers, the paste near the surface might be weakened due to the low mechanical properties of the fibers; and (ii) provide an effective locking effect of the unreinforced paste on low fiber dosages (2 kg/m^3). More work needs to be done to understand how tensile strength, surface energy and morphology of pig fibers interact with mortar micro/meso-structure.
2. This work presents important evidence that pig hair could be an effective crack control mechanism on mortars at early ages: (i) when mortar is subject to volumetric changes due to drying while setting (plastic shrinkage test); (ii) while hardened mortar is subject to drying under restrained conditions (restrained shrinkage test); and (iii) when hardened mortar at 28 days is subjected to localized-dynamic loading (impact resistance tests).
3. Particularly, addition of pig hair effectively controlled plastic shrinkage cracking, especially on high doses of fibers (8 kg/m^3), since more fibers are located in the cross section above the stress raiser during the test; CRR on mortar ID#8 samples remained above 90% over 24 h after casting. Meanwhile, CRR on mortar ID#4 samples stabilizes around 40% 16 h after casting. Addition of fibers increase mortar stiffness at early ages and redistribute water near the surface. These mechanisms are expected to be responsible for reducing plastic shrinkage cracking. In terms of age at cracking and resulting crack widths, the incorporation of pig hair consistently delays the occurrence of macroscopic cracks. Moreover, the incorporation of pig hair consistently and significantly reduces the widths of cracks as pig hair dosage increases up to 8 kg/m^3 of mortar. Overall, as fiber content increases it is expected that pig hair shortens the length of unreinforced paste subjected to volumetric changes, controlling its strain caused by external (i.e., stress raisers, ring) and internal (heterogeneities) restraints that cause cracking.

4. Impact strength, as an indicator of fracture toughness, consistently increased with the incorporation of pig hair, reaching an increment as large as 36% to generate the first macroscopic crack. Additionally, the post-cracking behavior of the fiber-reinforced mortar with pig hair significantly improved its capacity to withstand damage beyond initial crack formation (up to 55% of more energy absorbed at collapse). Mortars with pig hair fibers showed a similar impact strength improvement compared to fiber-reinforced polypropylene mortars, proving that the former have potential to be used as a replacement of some commercial fibers.

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