Influence of natural fiber dosage and length on adobe mixes damage-mechanical behavior

G. Araya-Letelier a,⇑, J. Concha-Riedel b, F.C. Antico c,⇑, C. Valdés d, G. Cáceres b

a Escuela de Construcción Civil, Facultad de Ingeniería, Pontificia Universidad Católica de Chile, Avenida Vicuña Mackenna 4860, Macul, Santiago 7820436, Chile
b Facultad de Ingeniería y Ciencias, Universidad Adolfo Ibáñez, Avenida Diagonal Las Torres 2640, Peñalolén, Santiago 7941169, Chile
c Facultad de Ingeniería y Ciencias, Universidad Adolfo Ibáñez, Avenida Padre Hurtado 750, Viña del Mar, Viña del Mar 2581907, Chile
d Escuela de Arquitectura, Facultad de Arquitectura, Diseño, y Estudios Urbanos, Pontificia Universidad Católica de Chile, El Comendador 1916, Providencia, Santiago 7520245, Chile

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Animal fiber
Mechanical properties
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Highlights
- Addition of pig hair to earthen materials controlled drying shrinkage cracking.
- Impact strength increased as fiber dosage and length increased.
- High dosage of long fibers formed clusters that reduced average flexural and compressive strength.

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Abstract
This study addresses the use of a natural fiber (pig hair), a massive food-industry waste, as reinforcement in adobe mixes (a specific type of earthen material). The relevance of this work resides in the fact that earthen materials are still widely used worldwide because of their low cost, availability, and low environmental impact. Results show that adobe mixes' mechanical-damage behavior is sensitive to both (i) fiber dosage and (ii) fiber length. Impact strength and flexural toughness are increased, whereas shrinkage distributed crack width is reduced. Average values of compressive and flexural strengths are reduced as fiber dosage and length increase, as a result of porosity generated by fiber clustering. Based on the results of this work a dosage of 0.5% by weight of dry soil using 7 mm fibers is optimal to improve crack control, flexural toughness and impact strength without statistically affecting flexural and compressive strengths.

1. Introduction

Earthen materials such as rammed earth, adobe, and cob have been used worldwide in the construction of houses for thousands of years, and currently approximately 30% of the global population and 50% of the population of developing countries live in earthen shelters [1]. The use of traditional earthen materials for construction has resurgen, and new earthen materials, such as earth bags [2], have emerged over the last decades. Earthen materials are sometimes preferred due to their availability [3], recyclability [4], good thermal and acoustic properties [5], fire resistance [3], and lower costs compared to other masonry materials [5]. In addition, the main process of manufacturing earthen materials does not generate CO2 emissions [6].

Since the beginning of the 1970s, interest in earthen construction materials has grown in Latin America, with a focus on rural, social, and heritage housing promoted by institutions such as UNESCO [7]. Earthen construction is even present in seismic coun-
tries in Latin America, as approximately 40% of houses in Peru [8] and 40% of the built heritage in Chile [9] are made of earthen mate-
rials. Despite the advantages and widespread use of earthen mate-
rials, their performance is worse than industrialized construction materials in terms of toughness, tensile and flexural strength, water erosion resistance, and volumetric instability [1,10–12]. The mitigation of some of the shortcomings of earthen materials, like toughness, tensile strength, permeability and drying shrinkage cracking, has been studied with the incorporation of natural fibers (e.g., straw, sisal, jute, banana, hemp, palm, wool and coconut fibers) [8,13–19] and industrialized fibers (e.g., polypropylene and glass fibers) [20–23]. Since earthen materials are natural, eco-
friendly materials, particular interest has been placed in reinforc-
ing them using natural fibers over industrialized fibers. Studies using natural fibers such as straw, coconut, and banana fibers, which are the result of a waste valorization process, show promising results. Ghabami et al. [14] studied the effect of sisal and cooco-
nut fibers on the behavior of different soils, concluding that the inclusion of 4% sisal or coconut fibers slightly increased the compres-
sive strength (from 1.5 MPa to 2.0 MPa) as well as the so-called “ductility” (i.e., in this work “toughness”) compared to plain soil. Yetgin et al. [6] addressed the incorporation of straw fibers on the performance of adobe, and results showed that as fiber content increased the shrinkage rates decreased, but both the compressive strength decreased (in some cases from 3.5 MPa to 1 MPa, approxi-
matel) and the tensile strength decreased (in some cases from 0.7 MPa to 0.2 MPa) compared to plain adobe. Millogo et al. [24] investigated the effect of Hibiscus cannabinus fibers (a vegetable fiber) on adobe blocks and results showed that in some cases the incorporation of these fibers increased the flexural strength (from 0.5 MPa to 1.1 MPa) and reduced the thermal conductivity (from 1.67 W/(m K) to 1.30 W/(m K)) compared to unreinforced adobe blocks.

Among natural fibers, the use of animal fibers in earthen mate-
rials has limited research compared to vegetable fibers. Galan-
Marin and co-workers have studied the incorporation of wool fibers in earthen materials, reporting increments in flexural strength and toughness compared to plain earthen materials [25]. Yet, the results from their work showed that unfired bricks presented a lower compressive strength compared to traditional fired clayed bricks [26]. Aymerich et al. extended the research on incorporation of wool fibers in earthen materials, showing that wool fiber reinforcement improved the residual strength, tough-
ness, and energy absorption of unreinforced soil [18].

To extend the use of natural fibers (specifically animal fibers) in earthen materials this study proposes the use of pig hair, which is a worldwide waste produced by the food industry. In Europe 890,000 metric tons of pig waste are produced each year, and related management costs have reached EUR 20.7 million per year [27]. Therefore, the pork industry generates waste management prob-
lems worldwide, including Chile, and the use of pig hair as a natural fiber reinforcement in earthen materials could promote the waste valorization process of this fiber. To the best of the authors’ knowl-
edge, there have been only four studies addressing the waste valor-
zation of pig hair as fiber reinforcement, but their focus has been on characterizing the properties of pig hair and its incorpora-
tion into cement-based materials [28–31]. The novelty of this research resides in the incorporation of pig hair, a natural animal fiber obtained from the pork industry waste, into earthen materials, addressing some of the most relevant ben-
efits (e.g., shrinkage cracking control) and potential disadvantages (e.g., compressive strength reduction). As earthen material is a generic term, this study refers to the mix between clayey soil, water, and fibers as adobe mix since it might be used to produce adobe bricks. The objectives of this study are to assess the impacts of different dosages and lengths of pig hair on: (i) the mechanical properties of adobe mixes; and (ii) the fracture behavior of adobe mixes. The work is organized as follows: Section 2 presents the material characterization and experimental program. Section 3 presents the results and analysis of the experimental program. Finally, Section 4 presents the conclusions of this work.

Finally, it is worth mentioning that this study did not evaluate the long-term effects of the proposed natural fiber. Therefore, in future studies the long-term effects on adobe reinforced with pig hair should be explored knowing that protection methods were successfully applied to other natural fibers to increase their dura-
bility in earthen matrices [32].

2. Materials and methods

2.1. Materials

2.1.1. Clayey soil

This study used a clayey soil obtained from Peñalolén, a district located in southern Santiago (Chile). Fig. 1 shows the particle size distribution of the clayey soil, which was determined by hydrometer and sieving analyses in accordance with ASTM D7928 [33] and ASTM D6913 [34], respectively. The previous standards also provide a particle-size definition of clay (material finer than 2 μm), silt (material between 2 μm and 75 μm), and sand (material between 75 μm and 4.75 mm). Fig. 1 shows that the clay, silt, and sand contents are approximately 11%, 69%, and 20%, respectively. Since clayey soil is not an industrialized material, there are different recommendations regarding the clay content. Catalan et al. [35] suggested a 15–16% clay content to obtain good plasticity and workability of earthen materi-
als, whereas Quagliarini and Lenci [19] recommended a 12–16% clay content, and Kouakou and Morel [36] concluded that soils for construction materials are recom-
me red to have less than 20% of clay content. The 11% clay content of the clayey soil used in this study produced adobe mixes with good workability and cohesion to prepare laboratory samples. The liquid and plastic Atterberg limits as well as the plasticity index of the soil were obtained in accordance with ASTM D4318 [37]. Table 1 provides a summary of the most important physical properties of the soil.

Based on the results of particle size distribution and physical properties of the clayey soil as well as suggestions of previous studies [36,38], this material is consid-
ered appropriate for earthen construction.

2.1.2. Natural fibers

Pig hair is used as a natural reinforcing fiber for adobe mixes. Araya-Letelier et al. [30] developed an extensive study on the morphological, physical, and mechanical properties of pig hair obtained from a Chilean pork food company that disposes approximately 2000 metric tons of pig hair per year in landfills. Table 2 summarizes some of the results of that study.

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|c|}
\hline
Liquid limit (%) & Plastic limit (%) & Plasticity index (%) & Density (kg/m$^3$) \\
\hline
29.1 & 17.4 & 11.7 & 2,507 \\
\hline
\end{tabular}
\caption{Physical properties of soil.}
\end{table}

Fig. 1. Particle size distribution of soil.
The pig hair used in this study was post processed to obtain three different average lengths (7 mm, 15 mm, and 30 mm) to perform a sensitivity analysis on the impact of different lengths and dosages of fibers on the performance of adobe mixes. Considering the average diameter of 0.16 mm reported by Araya-Letelier et al. [30] and the three different lengths used in this study, the average aspect ratios to be used are 43.8, 93.8, and 187.5 for fiber lengths of 7 mm, 15 mm, and 30 mm, respectively. Post processed fibers are shown in Fig. 2.

### Table 3
Adobe mix ID numbers and material proportions.

<table>
<thead>
<tr>
<th>Adobe mix ID</th>
<th>Soil (kg)</th>
<th>Base water (kg)</th>
<th>Fiber (%)</th>
<th>Fiber (kg)</th>
<th>Water to compensate fiber absorption (kg)</th>
<th>Fiber length (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0–0</td>
<td>1000</td>
<td>307</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0.5–7</td>
<td>1000</td>
<td>307</td>
<td>0.5</td>
<td>5</td>
<td>4.75</td>
<td>7</td>
</tr>
<tr>
<td>0.5–15</td>
<td>1000</td>
<td>307</td>
<td>0.5</td>
<td>5</td>
<td>4.75</td>
<td>15</td>
</tr>
<tr>
<td>0.5–30</td>
<td>1000</td>
<td>307</td>
<td>0.5</td>
<td>5</td>
<td>4.75</td>
<td>30</td>
</tr>
<tr>
<td>2.0–7</td>
<td>1000</td>
<td>307</td>
<td>2.0</td>
<td>20</td>
<td>19</td>
<td>7</td>
</tr>
<tr>
<td>2.0–15</td>
<td>1000</td>
<td>307</td>
<td>2.0</td>
<td>20</td>
<td>19</td>
<td>15</td>
</tr>
<tr>
<td>2.0–30</td>
<td>1000</td>
<td>307</td>
<td>2.0</td>
<td>20</td>
<td>19</td>
<td>30</td>
</tr>
</tbody>
</table>

1. In oven-dry condition.
2. Percentage of weight of oven-dry fibers to oven-dry clayey soil.
placement control testing protocol with a rate of 1 mm/minute to obtain a stable crack propagation and measurements of absorbed energy as suggested by Aymerich et al. [18]. The applied load and corresponding deflection were recorded continuously using the load cell of the testing machine as well as a linear variable differential transducer (LVDT) placed on the lower side of the beam specimen at the midspan. To obtain reliable displacement at the midspan of the beam, a steel frame was implemented as shown in Fig. 5, which is similar to the steel frame implemented by Aymerich et al. [18].

Flexural strength of each specimen was determined using Eq. (1), and average and standard deviation values for each adobe mix were obtained from the individual flexural strength results of six beam specimens.

\[
\sigma_f = \frac{3FL}{2bd^2} \tag{1}
\]

where \( \sigma_f \) is the flexural strength, \( F \) is the maximum applied load, \( L \) is the span between supports (270 mm), \( b \) is the average width of the specimen at the midsection (70 mm), and \( d \) is the average depth of the specimen at the fracture section (105 mm).

The flexural toughness of materials is an indicator of the energy absorption capability, which is expected to increase with the addition of fibers. This study calculated the flexural toughness indices as well as residual strength factors according to ASTM C1018 [40]. Generally, the flexural toughness indices are calculated as the area under the load-deflection curve up to a specific deflection value divided by the area under the load-deflection curve up to the deflection where the first crack occurs (\( \delta \)). Flexural toughness indices \( I_{5.5} \), \( I_{10} \), and \( I_{20} \) are the values obtained using deflections of 5.5\( \delta \), 10\( \delta \), and 20\( \delta \), respectively. The residual strength factors represent the average post-crack load retained over a deflection interval as a percentage of the load at first crack, and they were calculated directly from the flexural toughness indices using Eq. (2) and Eq. (3).

\[
R_{5.5} = \frac{I_{10}}{I_{5.5}} \tag{2}
\]

\[
R_{10.5} = \frac{I_{20}}{I_{10}} \tag{3}
\]

where \( R_{5.5} \) and \( R_{10.2} \) are the residual strength factors between the intervals of 5.5\( \delta \) and 3\( \delta \), and 10.5\( \delta \) and 5.5\( \delta \), respectively.

Average and standard deviation values of toughness indices and residual strength factors for each adobe mix were obtained from the individual flexural load-displacement curves of the six beam specimens.

2.4.1.2. Compressive strength. Compressive strength of each adobe mix was assessed using the prismatic pieces obtained after flexural fracture of six beam specimens and, therefore, 12 prismatic specimens for each adobe mix were tested in compression using a load control protocol with a rate of 200 N/s applied over a 75 mm × 75 mm section of the specimens (stress rate of 0.04 MPa/s). Compressive strength was determined using Eq. (4).

\[
\sigma_c = \frac{F}{A} \tag{4}
\]

where \( \sigma_c \) is the compressive strength, \( F \) is the maximum applied load, and \( A \) is the loaded section (5625 mm\(^2\)).

---

Table 4

<table>
<thead>
<tr>
<th>Specimen's type (Identification)</th>
<th>Dimensions (mm)</th>
<th>Test Purpose</th>
<th>Number of specimens per adobe mix</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam</td>
<td>310 × 105 × 70</td>
<td>Flexural strength; toughness indices, residual strength factors, ultrasonic pulse velocity (UPV) and compressive* strength at 28 days</td>
<td>6*</td>
</tr>
<tr>
<td>RILEM beam</td>
<td>160 × 40 × 40, with a 5 × 3 notch at midspan</td>
<td>Impact strength at 28 days</td>
<td>6</td>
</tr>
<tr>
<td>Flat</td>
<td>180 × 5 (diameter and height)</td>
<td>Restrained drying shrinkage distributed cracking at 7 days</td>
<td>2</td>
</tr>
</tbody>
</table>

Fig. 3. Batch of dry constituents of adobe mixes (clayey soil and pig hair) used for this study ready for mixing.
Average and standard deviation values of compressive strength of each adobe mix were obtained considering the individual compressive strength results of the 12 prismatic specimens tested.

2.4.1.3. Ultrasonic pulse velocity. Addition of fibers in construction materials typically improves toughness and tensile strength [18,30]. Yet, fibers with low density and high absorption might affect porosity and, therefore, strength. For this reason, UPV measurements were performed on adobe specimens at 28 days after casting in accordance with ASTM C597 [41] to address modifications to pore content that could affect macroscopic strength.

2.4.2. Influence of animal fibers on the fracture behavior of adobe mixes

2.4.2.1. Restrained drying shrinkage distributed cracking. Fibers are expected to control crack widths in adobe mixes due to restrained drying shrinkage. Experimental assessment of the drying shrinkage cracking behavior of earthen building materials is limited, and there are few studies addressing this phenomenon qualitatively [42–44]. To quantitatively study the cracking reduction effect of this animal fiber in adobe mixes, the two flat specimens prepared for each adobe mix were kept at controlled temperature and humidity (22 °C and 45%, respectively) for seven days. A grid with 20 mm × 20 mm cells put on top of the adobe flat specimens helped to identify and measure the lengths and widths of the distributed cracks that formed during this test. Specifically, widths and lengths were measured using a crack width comparator and a caliper. Fig. 6 presents a scheme of the grid, the measurement setup, and an example of the observed distributed cracking for this test.

For each adobe mix, the crack width average (CWA) was calculated using the formula defined in Eq. (5).

$$\text{CWA}_{IDx-y} = \frac{\sum l_{IDx-y} \cdot w_{IDx-y}}{\sum l_{IDx-y}} \quad (5)$$

where $\text{CWA}_{IDx-y}$ is the crack width average of adobe mix $IDx-y$, $l_{IDx-y}$ and $w_{IDx-y}$ are the length and width, respectively, of each visible crack in the two flat specimens of the adobe mix $IDx-y$.

Once $\text{CWA}_{IDx-y}$ values were obtained, the crack width reduction ratio (CWRR) for each fiber-reinforced adobe mix was calculated using Eq. (6).

$$\text{CWRR}_{IDx-y} = \frac{\text{CWA}_{IDx-y}}{\text{CWA}_{IDx-y}^{\text{baseline}}}$$

Fig. 4. Specimen preparation: (a) beam specimen, (b) RILEM beam specimen, (c) flat specimen, and total number of specimens prepared for adobe mix ID 2.0–30.

Fig. 5. Flexural test setup.
where \( CWRR_{x-y} \) is the crack width reduction ratio (expressed as a percentage) of the adobe mix \( ID_x-y \) with respect to the adobe mix \( ID_0-0 \), \( CWAID_{x-y} \) is the crack width average of the adobe mix \( ID_x-y \), and \( CWAID_{0-0} \) is the crack width average of the adobe mix \( ID_0-0 \) (plain adobe).

2.4.2.2. Impact strength. The impact strength was used as an indicator of the variation of fracture toughness due to the incorporation of animal fibers in adobe mixes. The use of the impact test to assess impact strength was previously suggested for cement-based materials [45,46]. In particular, Araya-Letelier et al. reported improvements in impact strength caused by the addition of these fibers in mortars [29,30]. Similar to Araya-Letelier et al., the impact strength of adobe mixes in this work was calculated using a projectile thrown at the center of RILEM beam specimens, which were supported by a steel frame as shown in Fig. 7 [29,30]. For this test, RILEM beam specimens were used with a 5 mm (width) \( \times \) 3 mm (depth) notch at the center. Each RILEM beam specimen was placed on its support points on a layer of silicone attached to the frame to prevent rebounds (and possible damage of the sample at the support points) after each blow. Six RILEM beam specimens for each adobe mix were tested. For each specimen, the number of blows required to fracture and collapse the specimen was recorded. The total energy at collapse was calculated using Eq. (7):

\[
E_c = n \cdot m \cdot g \cdot h
\]

where \( E_c \) is the total energy at collapse, \( n \) is the total number of blows required to collapse the specimen, \( m \) is the mass of the projectile (0.047 kg), \( g \) is the gravitational constant (9.8 m/s\(^2\)) and \( h \) is the height of the fall (0.496 m). These values were kept constant during the tests and, consequently, each blow accounted for an impact energy of 0.22 J.

Average and standard deviation values of impact strengths for each adobe mix were obtained from the individual impact strength results of the six RILEM beam specimens tested.

3. Results and discussion

3.1. Influence of animal fibers on mechanical behavior of adobe mixes

3.1.1. Flexural strength, toughness indices and residual strength factors

Fig. 8 presents average values and error bars (one standard deviation above and below the average) of the flexural strength of each adobe mix tested 28 days after casting. The average values of flexural strength ranged from 0.34 MPa to 0.49 MPa, and these results correspond to a similar order of magnitude (0.47 MPa to 0.83 MPa) reported at 28 days for unreinforced earthen materials [47] and mechanically compressed earthen blocks (expected to have better performance than manually compacted specimens) reinforced with polypropylene fibers [23]. Overall, the average flexural strength of adobe mixes was reduced as pig hair dosage increased. These reductions range from 4% (ID 0.5-7) to 30% (ID 2.0-15). The standard deviation values varied from 0.06 MPa (ID 0-0) to 0.11 MPa (ID 2.0-30). These results are similar to those previously reported for compressed earthen blocks [23,47]. Results obtained in this work showed a reduction of 20% to 30% in average flexural strength for: (i) adobe mixes with 2% fiber dosages regardless of the fiber length, and (ii) adobe mixes with 0.5% fiber dosages.
with fiber lengths of 15 mm and 30 mm. If the error bars of Fig. 8 are analyzed, it can be observed that if one standard deviation is subtracted from the average flexural strength of adobe mix ID 0-0, the resulting value is: (i) still larger than the average flexural strength plus one standard deviation of adobe mixes ID 2.0-0, and ID 2.0-15, and (ii) smaller than the average flexural strength plus one standard deviation of adobe mixes ID 0.5-7, ID 0.5-15, ID 0.5-30, and ID 2.0-30.

Although the study from Aymerich et al. [18] and this present work differ in the type of soil, animal fiber (Aymerich et al. used wool), water to soil ratio, sample preparation and dimensions (Aymerich et al. tested beams with a transversal section at midspan of $b = 75$ mm and $d = 50$ mm), the results of flexural strength might be worthwhile to compare since the flexural test setups and animal fiber dosages were similar in both studies. Considering in both studies the specimens with 2% of fibers and fibers of 30 mm, the flexural peak load reported by Aymerich et al. increased from approximately 400 N (unreinforced specimens) to 700 N (reinforced specimens), whereas the average flexural peak load of the present paper reduced from 934 N (unreinforced specimens) to 648 N (reinforced specimens). On the other hand, studies evaluating macro polypropylene fiber-reinforced earthen materials using 1% (by weight of dry soil) fiber dosages have showed reductions (up to 31%) in average flexural strength compared to unreinforced earthen materials [23,48]. In the present work, the reduction in average flexural strength and the increment in dispersion as pig hair dosage increased is explained by the generation of fiber clusters, whose formation was more common in the largest dosage (2%) of fibers and mixes with longer fiber lengths (15 and 30 mm). The relative size of these clusters with respect to the fiber area that is in contact with the matrix caused low adhesion between the fibers in the clusters and the matrix. From a macroscopic point of view, fiber clusters worked as porosity in the matrix, affecting its average strength. The negative effects of fiber clustering on strength of reinforced materials has been previously reported [49]. It is worth mentioning that the average minimum flexural strength of earthen masonry materials in the State of New Mexico Earthen Building Materials Code is 0.35 MPa [50], and only one adobe mix exhibited an average flexural strength below this limit (i.e., ID 2.0-15, with an average flexural strength of 0.34 MPa).

The typical load-midspan deflection curve for each adobe mix beam specimens is illustrated in Fig. 9. Similar behavior was exhibited by the remaining five beam specimens tested for each adobe mix. As shown in Fig. 9, the load initially increased at the same load-deflection rate until a visible crack was observed growing from the lower surface of the specimen (under tension), regardless of the fiber dosage and length of the fiber. The latter indicates that up to the peak load, the flexural response of the adobes mixes depended mainly on the brittle behavior of the matrix. The peak load of all the reinforced mixes was reduced by 20 to 30% with respect to ID 0-0, except for ID 2.0-30, which showed quasibrittle behavior. There are two possible mechanisms that explain the flexural peak load reduction: (i) length of natural fibers increased adobe mix tortuosity, and (ii) fiber content increased the density of discontinuities in the matrix. These two mechanisms are expected to affect the mechanical response of adobe mixes while still working as a brittle material, prior to the formation of a macroscopic crack.

Natural fibers are expected to have a positive impact on post-peak behavior [30]. Results from this work showed that flexural toughness was proportional to both fiber dosage and fiber length. Adobe mix ID 0-0 exhibited toughness indices ($I_{5}, I_{10},$ and $I_{20}$) values of 1.0, consistent with the brittle mode of failure where its maximum flexural load was followed by a sudden drop in load caused by the formation of an unstable macroscopic crack. On the contrary, all the fiber-reinforced adobe mixes exhibited a load recovery after the first crack, followed by an increment of the midspan deflection before collapse. Table 5 presents average and standard deviation values of $I_{5}, I_{10},$ and $I_{20}$ for each adobe mix and the average residual strength factor values. It can be seen that toughness indices increased proportional to both (i) fiber dosage and (ii) fiber length. In particular, the effect of the fiber length on toughness indices was greater than the effect of fiber dosage (e.g., $I_{20}$ increased 5.2 times, on average, as the fiber length increased from 7 mm to 30 mm, whereas $I_{20}$ only increased 2.4 times, on average, as dosage increased from 0.5% to 2%).

Results from this work showed that increments of both (i) fiber dosage and (ii) fiber length increased (i) load recovery after post-peak and (ii) toughness indices. Improvement of post-peak behavior by adding natural fibers to adobe mixes was consistent with what has been previously reported about the addition of animal fibers to mortar [29–31]. A possible explanation for the behavior described in this section can be related to the expected lower elastic modulus of the pig hair with respect to the matrix (e.g., adobe mix) [51]. Fibers with low elastic modulus are not expected to

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**Fig. 9.** Typical load-midspan deflection curves: (a) plain and 0.5% fiber-reinforced beam specimens, and (b) plain and 2.0% fiber-reinforced beam specimens.
increase the strength of the composite and may actually reduce it [51]. On the contrary, natural fibers are expected to improve impact strength and reduce crack width [30].

3.1.2. Compressive strength

Fig. 10 presents the average values and error bars (one standard deviation above and below the average) of the compressive strength of each adobe mix tested 28 days after casting. The average values of compressive strength ranged from 1.20 MPa to 2.02 MPa, which are similar to previous results reported for earthen materials with low compaction pressures and typical bulk densities for adobe [52,53]. There was a reduction in the average compressive strength when pig hair was incorporated (compared to adobe mix ID 0-0), with reductions ranging from 5% (ID 0.5-7) to 40% (ID 2.0-30). The standard deviations varied from 0.15 MPa (ID 0-0) to 0.33 MPa (ID 2.0-30), and this range is similar to others (0.12 MPa to 0.59 MPa) previously reported for compacted reinforced earthen materials [23]. From the average compressive strength results, it might be stated that there was a reduction of 26% to 40% in compressive strength when pig hair was incorporated into adobe mixes ID 0.5-30, ID 2.0-15, and ID 2.0-30. Porosity caused by formation of clusters, more common in the largest dosage (2%) of fibers and mixes with longer fiber length (15 and 30 mm), is most likely the cause of the compressive strength reduction described previously. If the error bars of Fig. 10 are analyzed, it can be observed that if one standard deviation is subtracted from the average compressive strength of adobe mix ID 0-0, the resulting value is: (i) still larger than the average compressive strength plus one standard deviation of adobe mixes ID 0.5-30, ID 2.0-15, and ID 2.0-30, and (ii) smaller than the average compressive strength plus one standard deviation of adobe mixes ID 0.5-7, ID 0.5-15, and ID 2.0-7. It is worth noting that the average minimum compressive strength of earthen masonry materials in the State of New Mexico Earthen Building Materials Code is 2.07 MPa [50] and, therefore, the reinforced adobe mixes of this study exhibited compressive strengths below this limit. Adobe mixes ID 0.5-7, ID 0.5-15, and ID 2.0-7 exhibited average compressive strengths of 1.92 MPa, 1.82 MPa, and 1.85 MPa, respectively, which are close to the minimum of 2.07 MPa stated in the previously mentioned code. Therefore, an enhanced manufacturing process (e.g., use of hydraulic press) could most likely increase the compressive strength of adobe mixes ID 0.5-7, ID 0.5-15, and ID 2.0-7 to the minimum value of 2.07 MPa.

3.1.3. Ultrasonic pulse velocity

For adequately compacted specimens, the addition of fibers should have little effect on the speed of elastic compressive waves [6]. Fig. 11 presents the average values and error bars (one standard deviation above and below the average) of the UPV measurements of each adobe mix. The results obtained in this work showed that addition of fibers to adobe mixes had no significant effect on the UPV measurements for all dosage (0.5% and 2%) and fiber length (7, 15 and 30 mm) combinations. These values are similar to those obtained by Slávka Andrejkovicová et al. [54] at late ages for earth-based materials with lime additions, where the sample with the largest percentage of lime had an UPV value of 1200 m/s. The previously discussed reduction in compressive strength and increment in dispersion of reinforced adobe mixes can be related to the quality of the mixes via ultrasonic pulse velocity (UPV) measurements [55]. Yet, the sensitivity of UPV measurements to microscopic changes, like fiber clusters, can be limited. For example, it has been reported that changes of 40% in the compressive strength of concrete cubes represent approximately a variation of 8% in UPV.

Table 5

<table>
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<td>1.21</td>
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<td>1.72</td>
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</table>

1 Average.
2 Standard deviation.

Fig. 10. Compressive strength test results.

Fig. 11. UPV test results.
3.2. Influence of animal fibers on the fracture behavior of adobe mixes

3.2.1. Restrained drying shrinkage distributed cracking

Fig. 12 shows one cracked specimen per type of adobe mix, seven days after casting. Crack width reduction was observed as both (i) fiber dosage and (ii) fiber length increased. Adobe mix ID 0-0 (plain adobe mix) exhibited crack widths up to 1.5 mm, whereas adobe mix ID 2.0-30 exhibited crack widths up to 0.2 mm.

Fig. 13 shows the crack width average (CWA), defined in Eq. (5), on the left axis as well as the crack width reduction ratio (CWRR), defined in Eq. (6), on the right axis for each adobe mix. It can be seen that both (i) fiber dosage and (ii) fiber length increment reduced the CWA. The CWA presented by adobe mix ID 0-0 (1.3 mm) was reduced to values that fluctuated between 0.46 mm (ID 0.5-7) and 0.15 mm (ID 2.0-30). These reductions corresponded to CWRR values oscillating between 63% (ID 0.5-7) and 91% (ID 2.0-30). In general, CWRR was larger for adobe mixes with 2% of fibers than dosages of 0.5%. Fig. 12 also shows that the cracking behavior was sensitive to the fiber length, where lengths of 30 mm showed larger CWRR than lengths of 7 mm. If the fiber dosage is increased, the characteristic length between the material matrix and the fiber would be statistically reduced. This would improve the chances to have crack width control after the matrix develops macroscopic distributed cracks. Additionally, increasing fiber length improves crack width control by preventing fiber pullout after macroscopic cracks occur [51, 56, 57].

3.2.2. Impact strength

There is little information about fracture behavior of manually compacted earthen materials. Similar to fiber-reinforced mortars, fiber-reinforced adobe mixes are expected to improve fracture toughness with respect to unreinforced materials [30, 58]. Different
types of tests have been developed to address the capacity of fiber-reinforced construction materials to absorb damage [46]. The impact strength is an effective test to measure the damage-absorbing capacity of fiber-reinforced quasi-brittle materials [30]. The increase of impact energy is related to an increase of fracture toughness due to the addition of fibers [59,60].

Fig. 14 shows the average values and the error bars (one standard deviation above and below the average) of the cumulative energy at collapse for each adobe mix tested 28 days after casting. A consistent increment in the energy required to generate collapse of specimens can be observed when pig hair was added into adobe mixes, and this increment was sensitive to both length and dosage of pig hair. For adobe mixes ID 0.5-30 and ID 2.0-30, the impact energy at collapse was eight and 47 times, respectively, the impact energy that collapsed adobe mix ID 0-0 (plain adobe). Even the smallest increment in impact energy at collapse, exhibited by adobe mix ID 0.5-7, was approximately five times the impact energy required to collapse adobe mix ID 0-0. The different levels of sensitivity of impact strength to fiber length and fiber dosage were in agreement with the sensitivity of reinforced adobe mixes with respect to toughness indices and CWRR previously reported in this work. Overall, higher fiber dosages exhibited a higher increment of impact strength with respect to plain adobe specimens, regardless of the fiber length. Additionally, as fiber length increased, impact strength increased exponentially, especially for 2% fiber adobe mixes. Unlike the mechanical results of flexural and compression strengths, the variability of impact strength was small compared to its exponential increment on the average values as pig hair dosages increased. This might be explained by the fact that the impact strength at collapse depends mainly on the post-peak behavior of the materials, where fibers are expected to contribute to the transfer of loads, while flexural and compressive strength testing are ruled mainly by the behavior of the matrix and the fibers acting as discontinuities.

The results presented in this section proved that addition of pig hair was effective on manually compacted earthen materials in terms of impact strength, as they controlled the formation and propagation of a single macroscopic crack subjected to localized external loading. Consequently, the incorporation of pig hair could enhance the durability of the material.

4. Conclusions

This study assessed the effectiveness of incorporating pig hair as an animal fiber reinforcement in adobe mixes. In this work, the experimental damage-mechanical behavior of plain adobe mixes was compared to pig hair reinforced adobe mix specimens using two different dosages (0.5% and 2.0% of weight of oven-dry fibers to oven-dry clayey soil) and three different fiber lengths (7 mm, 15 mm, and 30 mm). The experimental evaluation included flexural toughness, flexural and compressive strength, ultrasonic pulse velocity, drying shrinkage distributed cracking, and impact strength tests. The main conclusions obtained by this study may be summarized as follows:

Flexural and compressive strengths were reduced when pig hair was incorporated into adobe mixes, and these reductions occurred mainly for adobe mixes with high fiber dosage (2%) and long fiber lengths (15 mm and 30 mm). The authors understand that the reduction of strength in fiber-reinforced adobe mixes was mainly related to two microscopic features: (i) porosity caused by cluster formation and (ii) tortuosity (expected to be larger as fiber length increased). Other features, such as pull out strength of fibers, should be analyzed to understand in more detail the reduction of flexural and compressive strengths.

Flexural toughness increased when incorporating pig hair in adobe mixes, and this increment was sensitive to both fiber dosage and fiber length. Unreinforced adobe mixes behaved as brittle materials under flexural loading.

The restrained drying shrinkage distributed cracking was reduced by the addition of pig hair, especially for high dosages of fiber (i.e., 2%) and long fiber lengths (i.e., 30 mm). In other words, the longer the fibers, the larger the expected maximum pullout loads. As for the fiber dosage increment, more fibers are located in the cross sections, increasing chances of reducing the crack density and/or crack widths. In particular, plain adobe exhibited a 1.3 mm CWA, whereas adobe mix ID 2.0-30 had a CWA of 0.15 mm that corresponded to a CWRR of 91% compared to plain adobe. The CWRR values ranged from 63% (ID 0.5-7) to 91% (ID 2.0-30) for fiber-reinforced adobe mixes, which shows that even small dosages of pig hair had a significant impact in mitigating the drying shrinkage distributed cracking of adobe mixes.

The impact strength was highly sensitive to both length and dosage of pig hair. For adobe mixes ID 0.5-30 and ID 2.0-30, the impact energy at collapse was eight and 47 times, respectively, the impact energy that collapsed plain adobe. Even the smallest increment in impact energy at collapse, exhibited by adobe mix ID 0.5-7, was approximately five times the impact energy required to collapse plain adobe. Even the smallest increment in impact energy at collapse, exhibited by adobe mix ID 0.5-7, was approximately five times the impact energy required to collapse plain adobe.

Fiber-reinforced adobe mix ID 0.5-7 (0.5% fiber dosage and 7 mm fiber length) is recommended for adobe brick manufacturing since it exhibited enhanced flexural toughness, drying shrinkage cracking and impact strength performance without statistically reducing the flexural and compressive strength compared to plain adobe.

Conflict of interest

None.

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References
