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

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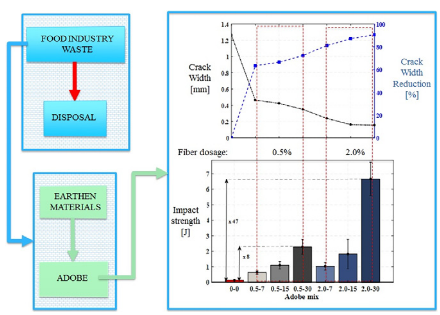
HIGHLIGHTS

- 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.

GRAPHICAL ABSTRACT



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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 resurged, 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 CO_2 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-

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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 materials. Despite the advantages and widespread use of earthen materials, 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 reinforcing 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. Ghavami et al. [14] studied the effect of sisal and coconut fibers on the behavior of different soils, concluding that the inclusion of 4% sisal or coconut fibers slightly increased the compressive 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, approximately) 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 materials 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, toughness, 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 problems 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' knowledge, there have been only four studies addressing the waste valorization of pig hair as fiber reinforcement, but their focus has been on characterizing the properties of pig hair and its incorporation 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 benefits (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 durability 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 materials, whereas Quagliarini and Lenci [19] recommended a 12–16% clay content, and Kouakou and Morel [36] concluded that soils for construction materials are recommended 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 considered 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.

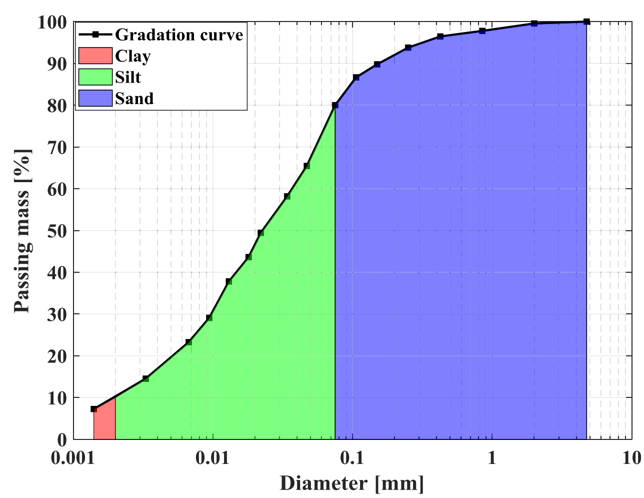

Fig. 1. Particle size distribution of soil.

Table 1
Physical properties of soil.

Liquid limit (%)	Plastic limit (%)	Plasticity index (%)	Density (kg/m^3)
29.1	17.4	11.7	2,507