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Journal of Natural Fibers

Journal of Natural Fibers

ISSN: 1544-0478 (Print) 1544-046X (Online) Journal homepage: http://www.tandfonline.com/loi/wjnf20

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To cite this article: Magdaleno Caballero-Caballero, Fernando Chinas-Castillo, José Luis Montes Bernabé, Rafael Alavéz-Ramirez & María Eugenia Silva Rivera (2018) Effect on compressive and flexural strength of agave fiber reinforced adobes, Journal of Natural Fibers, 15:4, 575-585, DOI: 10.1080/15440478.2017.1349709

To link to this article: https://doi.org/10.1080/15440478.2017.1349709

JOURNAL OF NATURAL FIBERS
2018, VOL. 15, NO. 4, 575–585
https://doi.org/10.1080/15440478.2017.1349709

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Effect on compressive and flexural strength of agave fiber reinforced adobes

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ABSTRACT

Adobe bricks, formed from raw clay, are used as construction materials since ancient times. Their main drawback is a low flexural and compressive strength. Agave bagasse is a waste material from the Mezcal production process. *Angustifolia haw* agave bagasse fiber was added to improve the properties of adobes. Adobe bricks were made with agave fibers ranging from 10 to 25 mm length and 0.25 to 1% concentration. At 1% concentration of agave, 25 mm long, the compressive and flexural strength are improved by 33% and 7.01%, fulfilling the requirements of Mexican construction regulation norm N-CMT-2-01-001/02 class C.

摘要

粘土砖是由原始粘土制成的，自古以来就被用作建筑材料。它们的要缺点是弯曲和抗压强度低。龙舌兰蔗渣从酒生产过程中废料。龙舌兰angustiolia山楂蔗渣纤维的加入改善砖坯的性能。土坯砖是用龙舌兰纤维从10到25毫米的长度和0.25至1%的浓度。在龙舌兰的浓度1%，25毫米长，抗压和抗折强度提高33%和7.01%，实现墨西哥建设管理规范N-CMT-2-01-001/02级的要求C。

KEYWORDS

Adobes; Agave *Angustifolia haw*; bagasse; fiber; flexural; compressive strength

关键词

砖坯; 龙舌兰angustifolia山楂; 甘蔗渣; 纤维; 弯曲，与抗压强度

Introduction

Adobes are one of the oldest and widely used building materials in construction (Degirmenci 2008). This building material has some advantages over traditional construction materials such as: a) its lower cost, b) reduced energy consumption by air conditioning, c) preserve environment from pollution (no baking process), and d) can be recycled or returned safely to the natural environment. However, adobes exhibit low flexural and compressive strength and poor behavior when subject to seismic loads (Sukuru, Çavdar, and Çavdar 2008) and deteriorate rapidly by humidity, erosion, shrinkage, and mechanical damage and thus, stabilization becomes necessary to modify their properties and meet the demands to be used as building construction materials.

In order to improve its strength properties, mechanically compacting procedures of soil are used. Other methods include stabilization by adding vegetable fiber reinforcement. Such fibers are used to form material composites with improved properties that include low cost, low density, low shrinkage, improved mechanical properties, low environmental contamination, etc. (Bos et al. 2006). Vegetable fibers, that provide support and strength to composites, are recyclable and unlike glass fiber are not brittle (Reddy and Yang 2005). Compacted adobe alone has not enough mechanical strength to be used safely as construction materials, therefore different natural fibers

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such as straw, coconut and sisal (Prabakara and Sridhar 2002) and polystyrene synthetic fibers have been employed to improve its mechanical properties (Binici, Aksogan, and Shah 2005). In general, fiber reinforced composite materials depend not only on fiber properties alone but also on how intense a load is transmitted to fibers through the matrix interface (Callister 2009). Natural fibers incorporated as a reinforcing material in a matrix face concerns over adhesion, low impact strength, hydrophilicity, humidity, and degradation problems. Previous studies had focused on testing additives such as cement, lime asphalt emulsions, and bituminous materials to improve the mechanical properties of compacted adobe bricks (Hossain and Mol 2011; Muntohar 2011). Dodecylamine and emulsified asphalt had been added to soil bricks resulting in enhancement of compressive strength and water resistance (Pineda-Piñon et al. 2007). Sugarcane bagasse ash and lime were added as chemical stabilizers in compacted soil blocks by Alavez-Ramirez et al. (2012) reporting that soil blocks with 10% lime+sugar cane bagasse ash showed higher strength than blocks fabricated with plain soil.

Several experimental studies have found positive effects on mechanical and physical properties reinforcing soil with vegetable fibers such as sisal, coconut, wheat straws, jute, flax, bamboo, and others (Binici, Aksogan, and Shah 2005; Bouhicha, Aouissi, and Kenai 2005; Ghavami, Toledo Filho, and Barbosa 1999; Mesbah et al. 2004; Tolêdo Filho et al. 2003). Salehan and Yaacob (2011) found that the addition of 3% palm fibers improves the compressive strength of composite bricks. Ahmad, Bateni, and Azmi (2010) mixed palm fibers with silty sand soil to investigate the increase of shear strength during triaxial compression. The specimens were tested with 0.25 and 0.5% content of palm fibers of different lengths (i.e. 15, 30, and 45 mm). Reinforced silty sand containing 0.5% coated fibers of 30 mm length exhibited approximately 25% increase in friction angle and 35% in cohesion compared to those of unreinforced silty sand. In addition, palm fibers coated with acrylic butadiene styrene thermoplastic increased the shear strength of silty sand much more compared to uncoated fibers. Bouhicha, Aouissi, and Kenai (2005) reported the positive effects of adding straw, decreasing shrinkage, reducing the curing time, and enhancing the compressive strength at an optimum reinforcement ratio. Flexural and shear strengths increased and a ductile failure was obtained for the reinforced specimen. Abtahi et al. showed that 1% barley straw fibers are more effective than kenaf on the shear strength of the soil (Okhovat et al. 2010). Prabakara and Sridhar used 0.25, 0.5, 0.75, and 1% of sisal fibers by weight of raw soil with four different lengths of 10, 15, 20, and 25 mm to reinforce a local problematic soil. They concluded that the increase in fiber length and content also reduce the dry density of the soil. It was also found that the shear stress is non-linear with a length of fiber up to 20 mm, beyond that the shear stress is reduced. The percentage of fiber content also improves the shear strength, but beyond 0.75% of fiber content, the shear stress is reduced (Prabakara and Sridhar 2002). Millogo et al. (2014) carried out mechanical tests on pressed adobe blocks reinforced with Hibiscus cannabinus fibers to study the effect of fiber concentration and length. The authors reported that 0.2–0.6% fiber of 30 mm length reduced pore size, improving the mechanical properties of the material by non-propagating cracks, but using a higher concentration or longer fiber bring negative effects on compressive strength. The impact of palm fibers on tensile and compressive strength was also unfavorable (Taallah et al. 2014).

From the state of the art, it can be observed that performance of natural fiber reinforcement of adobes and soil blocks is strongly influenced by fiber type, pull out resistance, tensile strength and durability, as well as length and volume fraction of fibers in the matrix. The lignin content of fiber brings waterproofing to the matrix. Shrinkage cracks of soil matrix are also minimized by a higher tensile strength fiber reinforcement. However, high fiber mass fractions are detrimental since numerous fibers weaken the matrix (Ghavami, Toledo Filho, and Barbosa 1999).

In the present work, *Angustifolia haw* Agave bagasse fiber is used to reinforce adobe bricks and study the effect of fiber length and concentration on flexural and compressive strength to fulfill requirements of the Mexican construction regulation norm (N-CMT-2-01-001/02, 2005).

Experimental setup

Materials

The materials used in this study for adobe bricks was soil, coarse sand, *Angustifolia haw* agave bagasse fiber and water. The soil was collected from Cruz Blanca, Cuilapam de Guerrero, Oax., Mexico, a living area located at geographical coordinates 16°59′55″N latitude and 96°47′08″O longitude. This soil bank localization is shown in Figure 1. A soil sampling by quartering to get a representative sample from the collected soil zone was according to the Mexican Official Standard NOM-AA-61.

Granulometry

A granulometric analysis of sieved soil was carried out according to ASTM D422 standard to determine the percentage of sized particles in the soil, expressed as the quantity of particles which passed through the sieves down to mesh 200.

ASSHTO test for optimum humidity of adobes

The optimum humidity of adobe samples was determined based on the Proctor compaction test ASSHTO T99 standard, preparing eight soil–water mixtures starting from a theoretical humidity of 10%, increasing stepwise in 1.5 up to 20.5%. All the samples were weighted and dried in an electric oven at 105°C for 72 h until a constant weight was attained. The graphical relationship of the specific weight to water content was then plotted to establish the compaction curve. Optimum humidity w_2 was calculated using Equation 1 where A is volume of water to add (ml), w_m weight of sample for initial moisture (gr) and w_1 is the initial moisture of the sample (%).

$$A = W_m \frac{W_2 - W_1}{100 + W_1} \quad (1)$$

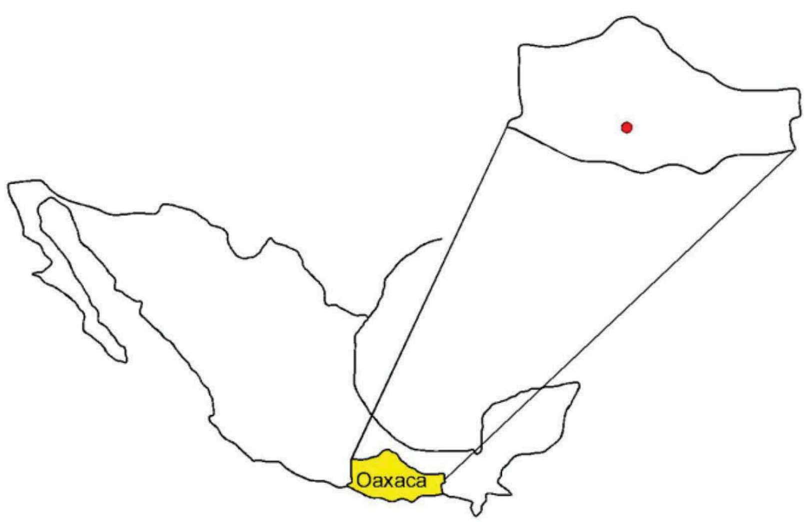

Figure 1. Geographical location of soil bank in Oaxaca, Mexico.

Experimental design

The experiments used a factorial design of 4 levels and 2 factors excluding the control. Each treatment had five replicates of samples with fiber concentrations of 0.25, 0.5, 0.75 and 1 wt. % and fiber lengths of 10, 15, 20, and 25 mm. This resulted in a total of 80 adobe brick specimens for flexural test and 80 adobe brick specimens for compressive test excluding the control.

Physical and mechanical characteristics of Angustifolia haw agave fiber

Agave *Angustifolia haw* fibers were collected from a palenque in the town of San Juan Guelavia in Tlacolula district, Oaxaca, México. Agave *Angustifolia haw* (Caribbean Agave) belongs to the *Asparagaceae* family, Agavoideae sub family, which is native to Mexico and Central America and it is mainly used to make mezcal. This agave is one of 140 species of the Agave genus and the leaf of angustifolia is about 3.8 cm wide with creamy yellow stripes along the spiny margins. These plants grow into a spherical clump of 0.9 to 1.2 m in diameter and can tolerate full sun, part shade, and reflected heat. It can also handle more water than most Agave species.

After the raw material was collected, it was manually and thoroughly washed, dried under the sun for 1.5 h and finally cut into lengths of 10, 15, 20, and 25 mm and stored separately in an air tight container. Fibers had the natural humidity of air-dried process. The fibers were assumed to be circular in shape, 0.33 mm average diameter.

The main properties of the agave fiber used in this study are given in Table 1. In Table 1, Agave *Angustifolia haw* tensile strength, Young modulus and humidity values for fiber lengths of 10, 15, 20 mm and diameter of 0.33 mm were taken from previous studies carried out at IPN unidad Oaxaca and reported in reference (Cortes-Martinez 2009). Fiber content of cellulose, hemicellulose, acid detergent lignin and humidity were taken from reference (Martinez-Gutiérrez et al. 2013).

For the scanning electron microscopy (SEM) study, the fiber specimens were mounted on cylindrical brass studs with carbon tape and a gold coating was applied using a Fine Coat Ion Sputter JFC 1100 metalizer (JEOL, USA). Fiber samples were observed with a SEM JSM 6390 (JEOL, Japan), equipped with an EDAX INCA X-ACT X-ray spectrometer (Oxford Instruments, UK), at 15 keV.

Adobe bricks mechanical properties and manufacturing

Once the soil was conditioned, what followed next was making adobe bricks with no fiber, as benchmark or control, considering the optimum water content that resulted from AASHTO test. Adobe bricks reinforced with agave fiber were prepared exactly in the same way. The adobe bricks were manufactured by mixing the clay and 15.9 wt/wt % water and manually pressed with a compaction pressure about 207

Table 1. Properties of *Angustifolia haw* Agave Fiber.

Properties	Value Reference
Cellulose (%)	*41.09 (dry basis) [*Martinez-Gutierrez et al. 2013*]*
Hemicelullose (%)	*28.32 (dry basis) [*Martínez-Gutiérrez et al. 2013*]*
Acid Detergent Lignin (%)	*10.68 (dry basis) [*Martínez-Gutiérrez et al. 2013*]*
Humidity (%)	*80.60 [*Martínez-Gutiérrez et al. 2013*]*
Density (kg m^{-3})	*106.50 [*Martínez-Gutiérrez et al. 2013*]*
Ultimate Tensile Strength (MPa)	*14.83 ± 6.33 [*Cortes-Martínez 2009*]*
10 mm long	*14.76 ± 6.12 [*Cortez-Martinez 2009*]*
15 mm long	*13.98 ± 4.94 [*Cortes-Martínez 2009*]*
20 mm long	
Young Modulus (GPa)	*0.20 ± 0.1 [*Cortes-Martínez 2009*]*
10 mm long	*0.25 ± 0.08 [*Cortes-Martínez 2009*]*
15 mm long	*0.24 ± 0.07 [*Cortes-Martínez 2009*]*
20 mm long	
Mean Diameter (mm)	*0.33 [*Cortes-Martínez 2009*]*

kN/m^2 to the mold form. Then the bricks were hardened by sun drying for nearly one day at a temperature of 30ºC approximately. Specimens used for this study were 29.2 × 15.4 × 8.4 cm.

Reinforced adobe bricks were made incorporating *Angustifolia haw* agave fiber in concentrations of 0.25, 0.50, 0.75, and 1.0 wt/wt %. Reinforced adobe bricks were prepared by adding fiber in lengths of 10, 15, 20, and 25 mm and the resulting mixture was compressed in the compacting machine. Once the bricks were made, mechanical testing was carried out to determine the flexural and compressive strength.

Compression test

The compression test was carried out in accordance to Mexican norm (NMX-C-036-ONNCCE, 2004) on five replicate samples for each test. Compression tests were set to allow uniform distribution of loads on samples. A layer of sulfur was put on both, lower and upper steel plate in order to lay samples flat, compensating for irregularity of the sample´s upper and lower faces. The apparatus used for compression tests on adobe bricks was ELVEC tester, Model 271103 with a 1% error, with an end scale of 400 kN. It has two transducers: for pressure and bottom plate vertical displacement.

The compressive strength of the adobe samples tested was calculated using Equation 2 where compressive strength (MPa), P maximum load (N), A mean area (mm^2):

$$\sigma_c = \frac{P}{A} \tag{2}$$

Flexural test

Three point bending test was performed in accordance with ASTM D1635 test method to measure flexural properties of the fiber reinforced adobe samples. The loading scheme was modified from third-point loading to center-point loading (less than 10 kN/min) (Millogo et al. 2014). In the test, the outer rollers were 180 mm apart and five specimens were prepared for each of the fiber lengths of 10, 15, 20, and 25mm. The equipment used for this test was a multi-load machine GEOTEST, Model 55830A, fitted with a 50 kN load cell and built-in digital display with peak hold feature and computer output for data acquisition (See Figure 2 for flexural strength test set up and specimen dimensions).

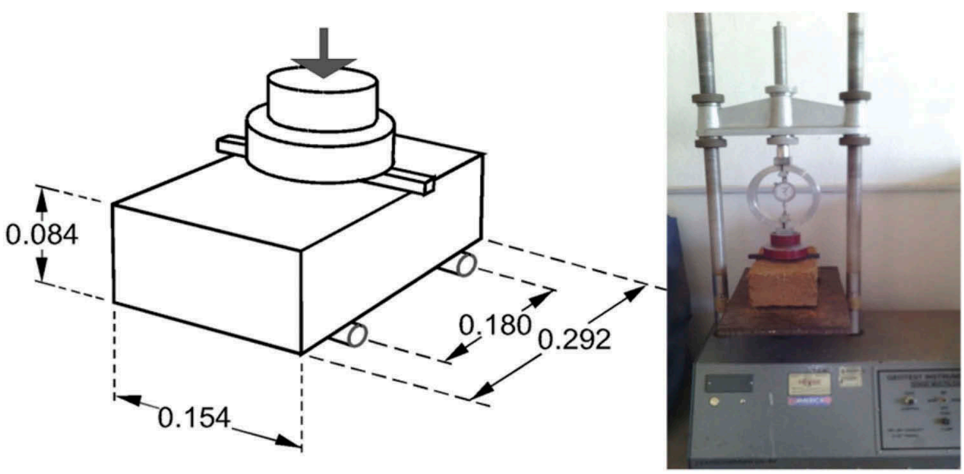

Figure 2. Flexural strength test set up and specimen dimensions (in meters).

Flexural strength of adobe samples tested was calculated using Equation 3 where σ_f flexural strength (MPa), P maximum load (N), l distance between the two supports (mm), b wide (mm) y d thickness (mm).:

$$\sigma_f = \frac{3Pl}{2bd^2} \tag{3}$$

Results and discussion

Soil chemical composition and grain size distribution results

The collected soil was composed of gravel, silica sand and limo in an 18% clay–38% sand–35% gravel–09% limo weight ratio plus 15.9 wt% added water to prepare the adobe specimens. The chemical characterization of soil samples is essentially SiO_2 (62.33%), Al_2O_3 (13.86%), Fe_2O_3 (6.64%), Fe (5.27%), loss of ignition (4.71%), K_2O (3.78%), Na_2O (2.31%), Mg O (1.63%), CaO (1.42%), TiO_2 (1.05%), FeO (0.81%), P_2O_5 (0.21%), and MnO (0.08%). This chemical elemental and mineralogical analysis showed a high amount of silica and alumina, a low quantity of iron oxide, calcium oxide, and potassium oxide.

The grain size distribution and Atterberg limits of a soil are required for classification by AASHTO System. The soil used in this study can be classified as loamy–sandy soil type with liquid limit 40.40%, plastic limit 21.70%, plastic index 18.70%, linear contraction 6.10%, loose volume weight of 1,287 kg/m^3 and 23% goes through #200 sieve. Figure 3 a) shows a grading curve of the soil.

AASHTO optimum humidity results

From AASHTO test results it was concluded that the optimum amount of water needed was 15.90% and the maximum dry specific weight was 1,792.5 kg/m^3 as indicated in Figure 3 b).

Physical and chemical characteristics of fiber

Compared to other agave fibers *Angustifolia haw* are long, biodegradable fibers with low density and high toughness. These agave fibers are composed of a number of cells, known as ultimate cells, polygonal in shape, that overlap and hold together with a waxy film to form the filament and, as such, an individual fiber consist of a bundle of tissue vessels surrounded by lignified cells and are hard in comparison with soft fibers.

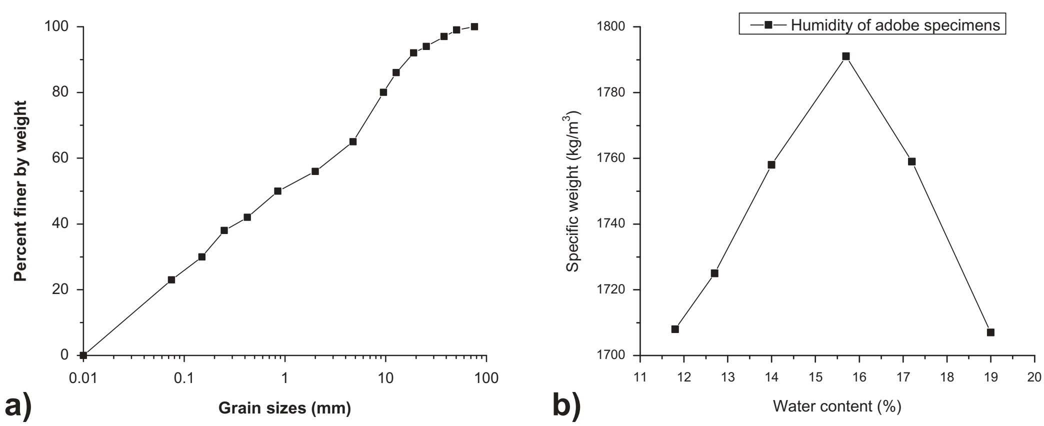

Figure 3. a) Grain size distribution, b) optimum amount of water needed for adobe specimens.

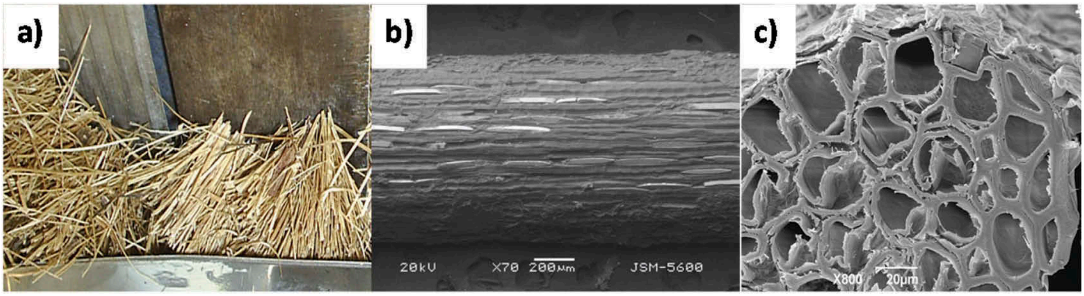

Figure 4. Micrographs of *Angustifolia haw* agave fiber a) Washed and cut fiber, (b) SEM longitudinal view of agave fiber, c) SEM cross section view of agave fiber.

Figure 4 a) shows images of agave fibers washed and cut. Figure 4 b) shows a SEM of an individual agave fiber in longitudinal view, taken at 70× magnification. A careful SEM observation of an individual fiber shows longitudinal streaks typical of long vegetable fibers. This fibrous material is a vascular strand with scarce tracheids observed. Remaining cells are fiber walls and, outside them, short cells seem to be cells of parenchyma. The outside longitudinal surface is knobby and rough, with longitudinal and transversal veins. Small wall fractures (coming from mezcal processing) and grating of irregular pattern are also noticed. The fiber has irregular sections and a composite structure, where the ultimate cells stick together by substances such as pectin and hemicellulose.

Figure 4 c) shows a cross-section SEM micrograph of the agave fiber. It has a type C slot along the center line and consists of around 200 microtubes. Microfibers are divided by a thin layer of binding material (~1.7 µm wide) that holds other microfibers closely linked together. These microfibers are oval and polygon shaped, with thick cellular walls, ~2.4 µm wide, that consist of a primary and secondary cellular walls bond together. Each microfiber has an irregular central opening of about ~28.6 µm in size, called lumen. Wall thickness between two microtubes is about ~6.5 µm.

Effect of fiber length on compressive strength

The effect of agave *Angustifolia haw* fiber length on compressive strength of adobes is illustrated in Figure 5a). From these results, it is observed that the best results were found for an agave fiber length inclusion of 25 mm and 1% concentration in the adobe bricks, increasing the compressive strength of the adobe control up to a strength value of 9.29 MPa with a standard deviation of 0.211 and

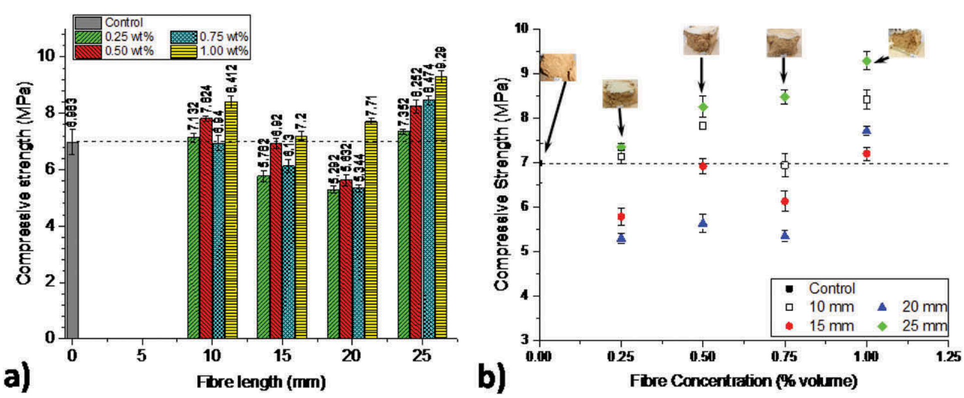

Figure 5. a) Compressive strength vs agave fiber length, b) Compressive strength vs agave fiber concentration. Error bars represent 95% standard deviations.

variance of 0.044, that is an enhancement of 33%. A similar trend on fiber length behavior (from 20 to 40 mm) of compressive strength enhancement was observed for palm (Marandi et al. 2008).

Effect of fiber concentration on compressive strength

Agave *Angustifolia haw* fiber concentration effect on compressive strength of adobes is illustrated in Figure 5b). In this figure, it is observed again that the best results were found for a fiber length of 25 mm and 1% concentration. There is a constant increase in the compressive strength with higher concentration of fiber from 0.25 to 1 wt. % at a fiber length of 25 mm. Under such conditions all the samples performed better than the control. It is observed that for a fiber length of 10 mm and 0.25% concentration, the compressive strength is just slightly higher (7.13 MPa) than the control (6.98 MPa). At 0.5% concentration, the compressive strength increases to 7.82 MPa (above the control value) but a further increase in concentration to 0.75% causes a drop to 6.94 MPa. This is attributed to the formation of lumps of fibers due to excessive adhesion and poor contact of fibers that result in a decrease in compressive strength. In previous studies, Cortés-Martinez 2009 studied the mechanical properties of agave *Angustifolia haw* fiber as a function of diameter and length, performing stress-deformation testing and found that as length increases, the ultimate tensile stress and unit deformation (simple strain) are reduced and Modulus of Young becomes higher. A further increase to 1% fiber concentration raises the compressive strength again to 8.41 MPa. Compressive strength results for fiber lengths of 15 and 20 mm did not outperform the control except at 1% concentration of fiber, registering values of 7.20 and 7.71 MPa, respectively.

Control samples showed a compressive strength of 6.98 MPa. For samples with a 0.25% agave fiber and 25 mm length, a compressive strength enhancement of 5.3% (7.35 MPa) against the control sample was observed. The applied load is transmitted from matrix to reinforcement fiber increasing its strength and tested sample showed damage in three sides as illustrated in Figure 6 b). When fiber concentration is increased to 0.5wt%, again, the compressive strength was enhanced to 19.7% (8.25 MPa). Figure 6 c) shows partial disintegration of tested sample in two sides. A further increase of 22.9% in compressive strength (8.47 MPa) against control was observed for samples with 0.75% fiber

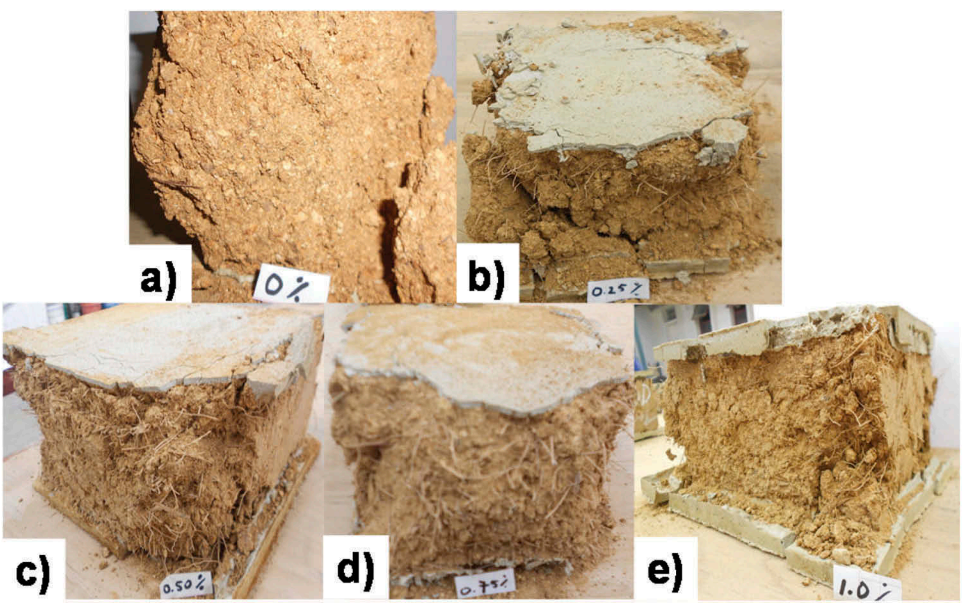

Figure 6. Photographs of compressive strength tested samples. a) control, b) 0.25% agave fiber, c) 0.5% agave fiber, d) 0.75% agave fiber and e) 1.0% agave fiber.

concentration. The tested sample showed damage in two sides and attached fibers to the matrix, as indicated in Figure 6 d). Finally, at 1.0% the compressive strength raised 33.09% (9.29MPa) respect to the fiber-free sample. No disintegration is observed in the tested sample, just small cracks and little damage in one corner, as shown in Figure 6 e). The short fibers provide resistance to crack propagation, cohesion to the soil matrix and retain load transfer. Mechanical interlocking and connecting effect of fibers is observed in Figure 6 e).

Compressive strength values of samples at concentrations lower than 1.0% and fiber length lower than 25 mm in most cases were lower than the control. That is probably related to a deficient adhesion at the interface fiber-matrix.

Effect of fiber length on flexural strength

The effect of agave *Angustifolia haw* fiber length on flexural strength is shown in Figure 7a). Agave fiber reinforced adobe samples with concentration of 1.0% and length of 25 mm gave the highest flexural strength (0.61 MPa). This value of 0.61 MPa was slightly higher than the control sample value of 0.57 MPa. At a fiber concentration of 0.75% and fiber length of 25 mm was observed a smaller increase in flexural strength (0.59 MPa) just above the control sample. The samples at different concentration than 1% and 0.75% and fiber length of 25 mm were unable to increase the flexural strength above the control sample.

Effect of fiber concentration on flexural strength

Flexural strength behavior vs concentration of adobe bricks reinforced with agave fiber is illustrated in Figure 7b). The reinforced adobe samples reach their maximum flexural strength at 1.0% concentration and 25 mm length, increasing the flexural strength from 0.57 MPa up to a strength value of 0.61 MPa that represents an enhancement of about 7.01%.

Based on the above results, the increase of compressive strength can be attributed to the dominance of agave fiber effect on the adobe matrix. The voids created by fiber in adobes under an important compaction pressure will render the mix adobe-fiber rigid forming a large number of connecting points between adobe soil particles and fiber after unloading, that in turn, produces a reduced pore network of adobe bricks, giving a higher compressive strength. The compressive strength of reinforced adobe bricks was about 1.33 times higher than that of fiber free adobe bricks. The compressive strength in agave fiber reinforced adobe bricks tested in the present study at a fiber length of 25 mm vary from 7.35 to 9.29 MPa for concentrations ranging from 0.25 to 1% and these values are higher than the compressive strength values observed for the control adobe bricks (6.98 MPa).

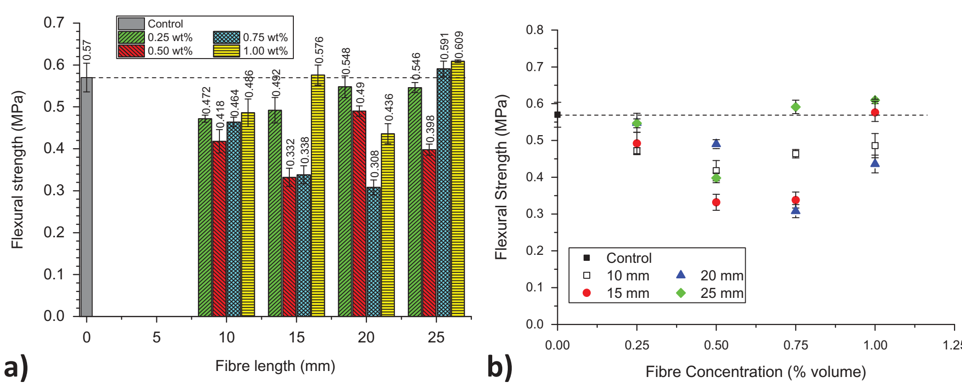

Figure 7. a) Flexural strength vs agave fiber length. b) Flexural strength vs agave fiber concentration. Error bars represent 95% standard deviations.

The Mexican construction regulation norm (N-CMT-2-01-001/02, 2005) indicates a minimum compressive strength of 20 MPa for class A, 12 MPa for class B, 8 MPa for class C, and 4 MPa for class D for masonry use. The norm does not indicate any minimum limit for flexural strength. Adobe control bricks (0% fiber) prepared in this study exhibit an average compressive strength of 6.98 MPa, that only fulfills class D requirements at the most. However, adding agave bagasse fiber (1% fiber of 25 mm length) as reinforcement, adobe bricks reach a compressive strength of 9.29 MPa that represents an improvement of about 33% compared to fiber-free control and also fulfills class C requirements.

Conclusions

In this study, adobe brick samples reinforced with *Angustifolia haw* agave bagasse fiber were prepared. The effect of fiber length and concentration was studied. Compressive strength of adobe reinforced samples is enhanced as agave fiber concentration is increased. Adobe bricks reinforced with 1.0% fiber, 25 mm long, provide a compressive strength enhancement of 33%, fulfilling requirements of compressive strength from class D to class C of the Mexican construction regulation norm N-CMT-2-01-001/02. This concentration and 25 mm length of agave fiber improves also their flexural strength but this enhancement is only by 7.01%. The results obtained are positive and at present, authors are working on improving further the fiber-matrix interface adhesion to increase the flexural strength incorporating a natural pozzolana, but these results will be the subject of another paper.

Funding

The author(s) disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: This study received the financial support from Instituto Politecnico Nacional (Project No. IPN/SIP: 20090624), National Council for Science and Technology (CONACyT), Secretary of Public Education (SEP), Instituto Tecnologico de Oaxaca/TECNM.

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