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Sustainable adobe bricks with seagrass fibres. Mechanical and thermal properties characterization

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Abstract

There is an incipient necessity and interest of generating sustainable materials for application in green buildings. In this study, the capability of *Posidonia Oceanica* seagrass, a biomass by-product from the Mediterranean coastlines, is analysed as a reinforcement material in adobe bricks. For this purpose, earthen specimens with these sea-plant fibres were compared with the most traditional additives for this purpose, i.e. straw-based adobes. Both biomass fibres were included with different lengths and quantities. First, to understand their behaviour, the fibres were evaluated; water absorption and tensile strength tests were performed. Test specimens themselves were subjected to mechanical and thermal tests as well as measuring dimensional changes. Tested as fibres, straw presented higher tensile resistance and water absorption than seagrass; but tested within adobe specimens, straw containing samples had worse mechanical behaviour than those containing seagrass. Specially, adobe with *Posidonia Ocenaica* seagrass fibres with their natural long length showed to be the most suitable in terms of mechanical behaviour. Furthermore, good thermal conductivity results were achieved with this level of biomass reinforcement, generating a sustainable and value-added construction product.

Keywords: earth construction; biomass by-products; seagrass fibres; mechanical and thermal properties; sustainable composite; building envelopes; energy efficiency in buildings

1. Introduction

Nowadays, energy efficiency in buildings is a fundamental necessity to take care in order to decrease the high effect that they produce to the atmosphere. The goal for all European Union towards 2020 wears to determinate a definition for nearly Zero Energy Buildings (nZEB), specifying minimum requirements and methodologies for energy certifications [1]. These

measures reside in the idea of higher level of insulation in envelopes and the installation of high efficiency systems [2]. Therefore, focusing on the building envelope, the choice of materials is a key point in the design process. The introduction of low environmental impact building materials is a good manner to reduce the CO₂ emissions, being the first part of the energy saving strategies in buildings life cycle [3]. Up to 30% of CO₂ emissions can be decreased with a bioclimatic design building that contains low environmental impact construction materials [4].

Earth as a construction material has been known for over thousands of years, where still today about 30% of the world population live in earthen structures [5]. It is an environmental friendly material that can be approached from local resources, conforming a great manner to build green architecture. Furthermore, several hydro-thermal comfort advantages are achieved. An earth wall balances air humidity, maintaining percentages nearly constant at 50% with little fluctuations around 5 to 10%, as well as storing heat [6]. Serrano et al. [7] experimented with cubicle-shape buildings the constant temperature that was achieved inside them against the wide range of exterior thermal amplitude during summer and winter.

A wide range of literature shows how natural bio-based materials and other fibrous materials are achieving attention with its inclusion in construction materials [8,9]. With this approach, energy demand and greenhouse gas emissions are improved during the production process of the material. At the same time, thermal and acoustic performance for indoor spaces can be enhanced [10,11]. A good example is the development of adobe bricks in Turkey, called *mud brick* by the authors, using fibrous additives to achieve an earthquake-resistant building material [12]; in this case straw, plastic fibres, and polystyrene fibres were used as additives to obtain good enough mechanical properties. Furthermore, the formulation was changed to also achieve good thermal [13] and acoustic [14] performance of the future building wall.

Several references experimented the implementation of seaweeds in earthen construction as a natural biopolymer by means of alginate, obtained from the cell walls of brown seagrass [15,16]. The effect that this biopolymer pretends to achieve is enhancing the particle binding as a stabilizer. Mechanically, the improved results of the construction pieces depended on the type of alginate used with its chemical distribution and the soil composition. Similar purposes were developed by [17], where the seaweed glue solution improved the compressive and flexural strength in a clayey sample. Fibrous components from biomass have highly included in this type of construction. The combination of biopolymers and natural fibres have been also a point of investigation. Achenza et al. [18] evaluated the use of seaweed fibres and agricultural biopolymers improving the mechanical resistance and water absorption, being the polymer a key factor for it, meanwhile other studies mixed natural fibres with alginate [19,20].

Posidonia Oceanica, a Mediterranean sea plant widely distributed in the coast of the sea, define a solid marine waste that causes economic and hygienic problems in the beach regions [21]. Therefore, a special effort in the conversion of these residues would be a good manner to close the recycling process.

Previous investigations have shown the feasibility to convert the seaweed leafs in bio-oil and bio-char as sustainable biofuels through a catalytic pyrolysis process [22,23]. From this point of view, enabling the use of this marine by-product as a part of a construction material generates a new opportunity to reduce this coast environmental impact.

The main aim of the present study is to measure the capability of *Posidonia Oceanica* seagrass as fibre reinforcement for adobes. To analyse its performance, prismatic earth specimens with seagrass fibres will be compared with the most typical additives for this purpose [7]; straw fibres. Both fibres are chopped at different lengths and implemented in different quantities according to the literature mix design of bio-based additions. Physical, mechanical and thermal properties are analysed in order to define the range of this new sustainable composite.

2. Materials and methods

2.1. Materials

Air-dried adobe bricks samples are composed by different soil particle size and water, which can be stabilized to improve their properties. In this study, clay, sand and gravel with small and large particle sizes, were the different components mixed with straw or seagrass fibres.

The clay used was commercialised by Ceràmica Almacelles S.A. It is described as a brick clay, suitable for current production of commercial fired bricks. The sand and gravel were supplied by Nordvert of Grup Sorigué, meanwhile straw came from Farratges La Noguera S.L. and seagrass fibres were produced by CNR-ITAE Institute for Advanced Energy Technologies “Nicola Giordano”.

Straw is an additive traditionally used in earthen construction. Its inclusion with earth is used in the experiment as a reference material. The Mediterranean sea-plant leafs of *Posidonia Oceanica* were collected from the southwest coast of Sicily region (Italy). All samples were washed before their use with running and distilled water to remove the sea salt that they content. After that, the leafs were dried in an oven at 80°C during 24 hours.

Both fibres act as a physical stabilizer, minimising the flexural tensions that generate shrinkage during the curing process, increasing the resistance to tension as well as reducing earth density of the construction element. Particularly in adobes, different from rammed earth or compressed earth blocks (CEB), the needed water quantity is relatively higher because of their high clay content and their drying process, therefore the presence of vegetal fibres helps to avoid retraction cracks [24]. Usually, about 5-10 kg/m³ of straw fibres is recommended to be added into adobes, a proportion that can be increased if the clay content increases [25]. The total organic origin of the composite makes them totally biodegradable, and therefore, returnable to the environment by closing the circular economy loop.

2.2. Sample preparation

Different compositions of adobe prismatic samples of 4x4x16 cm were prepared with varying the rate and length of the fibres. The inclusion of biomass fibres increased from 0wt.% to 0.5, 1.5, and 3wt.% (percentage in weight), allowing to compare non-fibrous to fibrous specimens, to have a blank to compare the results and following percentages used in previous studies [26]. Fundamentally, sample dimensions delimit the used length of the fibres. For this reason, both straw and seagrass fibres were cut at 1 and 3 cm of length, meanwhile the natural flexibility of the seagrass allowed to insert them with their original length (up to 19 cm) differently from the rigid appearance of the straw. Figure 1 shows the appearance of all of them.

Figure 1. From up to down, straw (1 cm, 3 cm) and seagrass (1 cm, 3 cm, long) fibres

In order to analyse the real effect that both type of fibres included in the earth material, a constant mixture of 60wt.% fine clay, 40wt.% sand-gravel, and 20wt.% water was taken into consideration.

The samples were produced by manually mixing and ensuring homogeneity by combining all the materials together with water until a paste-like texture was achieved. The mixtures were casted in standardized moulds and removed from them when they started to gain consistency. After that, all samples were left to dry in normal laboratory conditions (21-23 °C, 40-50% RH) during approximately 28 days until constant weight. Earth specimens were dried naturally for dissipating their moisture slowly and to reduce internal shrinkage cracks [27]. Three specimens of each samples were produced and tested.

2.3. Testing methods

In order to increase the knowledge and understand better the difference between traditional straw fibres and *Posidonia Oceanica* seagrass, both of them were evaluated in terms of tensile strength and water absorption.

The tensile strength of the straw and seagrass fibres was determined by Zwick Roell smart pro testing machine. The fibres were positioned straight within the equipment grips, with a maximum load capacity of 200 N and a displacement of 0.0833 mm/s that produced the fibre failure. Figure 2 presents the equipment for this purpose. The cross-section of fibres was determined with a Vernier scale device (accuracy 0.01 mm).

Figure 2. Traction machine and load cell of 200 N.

The water absorption of the fibres was also determined by following the specifications of DIN EN ISO 62 [28]. For this purpose, three replicates of each type of fibre were immersed in water in different containers at constant laboratory temperature conditions. The initial mass of the straw fibres was determined using the same analytical balance that in all cases. The amount of water absorbed by each specimen was determined by measuring its change in mass, after drying the fibres with filter paper. The difference between the initial mass and the one after the exposure to water was reflected as a percentage in weight. The water absorption capacity of the fibres was established through equation 1:

$$w = \frac{m_2 - m_1}{m_1} \cdot 100 \quad \text{Eq. 1}$$

where w is the percentage of the water absorption, and m_1 and m_2 correspond to the mass of the fibre before and after immersion in water respectively.

Weight measurements were carried out at 24 h intervals during 18 days (when the mass loss was negligible) using an analytical balance (AG135 from Mettler Toledo, accuracy 0,0001 g). Before weighting, the water surface was removed from the fibres. This process did not exceed 1 minute, after the fibre was removed from the water recipient.

On the other hand, the first steps after the drying process of the consolidated adobe earthen pieces consisted in determining the average mass and density as well as the percentage of shrinkage. Dry density was calculated with the analytical balance. On the other hand, linear drying shrinkage was obtained calculating the decreased percentage of the dried sample lengths compared with the original 160 mm length of the mould.

Furthermore, flexural and compressive strength in the dried samples were tested according to the Standard EN 196-1 [29] by means of PROETISA Uniaxial testing machine equipment. The prismatic specimens were analysed in terms of flexural strength R_f , calculated by the Eq. 2. A load range of 2000 kg was applied with a velocity of 5 kg/s in order to perform the test.

$$R_f = \frac{1.5 \cdot F_f \cdot l_f}{b \cdot d^2} \quad \text{Eq. 2}$$

where R_f is the flexural strength (N/mm²), F_f is the maximum force at break point (N), b is the width of the specimen (mm), in the direction transversal to the applied force, d is the thickness of

the specimen (mm), in the direction parallel to the applied force and l_f is the distance between the holders (mm).

Compressive strength was calculated according to Eq. 3. The load cell of the equipment was 20000 kg with a velocity of 2.40 mm/min.

$$R_c = \frac{F_c}{S} \quad \text{Eq. 3}$$

where R_c is the compressive strength (N/mm²), F_c is the maximum breaking force (N), and S is the surface of the plates used in the test (1600 mm²).

Thermal conductivity (λ) of the prismatic samples was measured with a hot wire equipment based on single needle sensors. For this purpose, the model KD2 Pro from Decagon Devices was used. The RK-1 needle sensor of 6 cm long was accommodated in each sample after drilling by means of a rotary hammer, making sure that it was properly inserted into the material, being surrounded by a minimum of 1.5 cm of material in all directions. The hot wire technique can be applied to homogeneous, porous or dense samples with densities higher than 500 kg/m³ [30]. In order to be sure that the temperature of the samples was constant, the thermal measurements were carried out in a climatic chamber with constant temperature and humidity conditions.

3. Results and discussion

The measured physical properties of the biomass fibres are shown in Table 1. With a higher density, seagrass fibres have much lower break load when they are subjected to tension and therefore, according to their fibre section, they present lower tensile resistance. Regarding to the water absorption ability, straw has a general higher percentage of absorption.

Table 1. Physical properties of the biomass fibres

Type of fibre	Density (kg/m ³)*	Water absorption (%)*	Failure load (N)*	Average tensile strength (N/mm ²)
Straw	0.312 (0.092)	365.0 (0.305)	88.18 (13.26)	128.19
Seagrass	0.721 (0.0702)	293 (0.248)	23.59 (2.86)	56.01

*See in italics the standard deviation

Since the effect of increasing the fibre/soil ratio and the fibre length was decided to be investigated in adobe specimens, the shrinkage that the earthen pieces suffer was also analysed [32]. Figure 3 reflects dimension variations of the adobes in connection with both types of fibres. The linear variation depending on the type and quantity of fibre is presented. As expected, shrinkage decrease when increasing the fibre ratio and their length. Generally, shrinkage is stabilized earlier when the fibre ratio and length increases. Nevertheless, straw fibres generate significantly less dimension variation in specimens than all seagrass inclusions. From the point of view of the unreinforced adobe samples, the fact of introducing fibres reduced shrinkage from 4% up to 40% approximately.

Figure 3. Linear shrinkage (and its standard deviation) of the bio-based adobes. In black, straw results. Bars in green indicate the seagrass ones.

The shrinkage difference between both biomass fibres could be attributed to the higher water absorption of seagrass during the first 72 hours of the drying process, as shown in Figure 4. These fibres with high water absorption suffered a significant shrinkage in the interior of the earthen

piece, given that when the fibres lost their moisture, they shrank back to their initial size by generating little voids around them. On the other hand, a better bonding between the interface fibre-soil could cause less level of shrinkage according to the fibre length [31]. Since specimens with straw fibres cut at 3 cm presented the smallest level of shrinkage, that nature and determined length of the fibre could be that having the best bonding with the base material. In comparison to that, cut and long seagrass fibres produced worsen effects in shrinkage.

Therefore, a higher percentage of water absorption generated a subsequent retraction of the fibre that produced voids around the fibre section, concerning the integral stability of the samples. This effect in natural biomass fibres was much higher than in synthetic ones, where it is typically decreased producing less empty spaces around them, independently of the type of soil [19].

Figure 4. Water absorption of natural straw and seagrass fibres (average values of three replicates)

Table 2. Results of the mechanical properties testing

Fibre content	Type	Length (cm)	Density (g/cm ³) *	Compressive strength (MPa)*	Flexural strength (MPa)*
0%	-	-	1.952 (0.007)	1.676 (0.012)	0.411(0.0005)
0.5%	Straw	1	1.947 (0.026)	1.573 (0.0381)	0.562 (0.0020)
		3	1.921 (0.012)	2.824 (0.0175)	0.472 (0)
	Seagrass	1	1.933 (0.007)	1.641 (0.0189)	0.492 (0.0025)
		3	1.927 (0.021)	2.640 (0.0233)	0.460 (0.0030)
		Long	1.906 (0.024)	2.662 (0.0431)	0.479 (0.0035)
1.5%	Straw	1	1.896 (0.013)	2.318 (0.0439)	0.413 (0.001)
		3	1.888 (0.025)	1.888 (0.0792)	0.450 (0.002)
	Seagrass	1	1.926 (0.011)	2.643 (0.0236)	0.455 (0.0037)
		3	1.919 (0.019)	2.631 (0.0346)	0.502 (0.0023)
		Long	1.918 (0.007)	2.672 (0.0368)	0.547 (0.0030)
3%	Straw	1	1.858 (0.014)	2.012 (0.0134)	0.401 (0.003)
		3	1.825 (0.016)	1.803 (0.0260)	0.388 (0.0032)
	Seagrass	1	1.903 (0.010)	2.237 (0.022)	0.429 (0.0028)
		3	1.913 (0.017)	2.496 (0.0987)	0.363 (0.0075)
		Long	1.898 (0.030)	2.346 (0.0294)	0.600 (0.002)

*See in italics the standard deviation

Generally, according to both mechanical results and as expected, flexural strength values present much less resistance than compression. This is due to the press that the material experiments when is being compacting, improving the adhesion of the soil particles. This is due to the pressure of the material that is experimented during the compression test, improving the adhesion of the soil particles.

Compressive and three-point bending test of the samples are represented in the following figures

(Figure 5,

Figure 6, and Figure 7). Flexural tests were developed in three prismatic specimens of each composition, meanwhile four halves from them were subjected to compression. In both mechanical tests, sample repetitions showed a good reproducibility, with an error lower than 0.1 N/mm².

Observing Figure 5 that shows the compressive strength of the specimens, the fact of increase the fibre fraction produces higher compressive resistance at 0.50% of content when the fibres are at 1 cm length. Nevertheless, when they are chopped at 3 cm or even the natural long seagrass, generally, the compressive resistance presents good values at 0.50% for both straw and seagrass, and at 1.5 % fibre content for only seagrass. After that, towards 3% fibre content, the resistance tends to decrease. This decreasing performance showed worse results in straw samples than seagrass fibres, where straw based adobe mechanical values are reduced by almost 50% compared to seagrass reinforcement. Therefore, the best values in terms of compressive resistance for straw-based specimens are reached when the fibres are cut at 3 cm with a 0.5% content. Meanwhile, adobes with seagrass presented almost similar values to straw, but these first allow the implementation of a higher fibre content of 1.50%. In practically all cases, the resistances are improved from the original state of the unreinforced specimens.

Figure 6 relates compressive mechanical properties of the specimens with their density. Density values correspond to the range found by most of the researchers in compressed stabilized earth samples, within 1.5 g/cm³ and 2 g/cm³ [32]. Looking at the trend of the density, adobes with straw fibres presented lower values than those that include seagrass. This density should be reflected in mechanical results, attending to higher compression strength when density is higher. Several studies confirm this trend with compression test carried out with earthen specimens [33,34]. In

almost all cases, straw fibre specimens presented minor compressive strength than the seagrass ones. Although, the higher strength value is reached by straw at 0.5%.

Figure 5. Compressive strength average values of the adobe specimens according to the fibre length (1 cm and 3 cm straw/seagrass, long seagrass) and fibre fraction (0, 0.5, 1.5 and 3%)

Figure 6. Compressive strength average results in connection with adobe specimen density (and its standard deviation). In black colour, straw adobe results. In green, the seagrass based ones.

Figure 7 presents the flexural behaviour of the samples. In this case, 1 cm straw fibres present a pick of resistance with 0.50% of content. At the same time, natural long seagrass fibres at 3% fibre content reached the same value or even better, almost doubling the values achieved by the

other samples. Therefore, in most cases, the flexural resistance showed to decrease when more fibre content is included in adobes.

Figure 7. Flexural strength average values of adobe specimens according to the fibre length and fibre fraction

Comparing both mechanical behaviours of the biomass fibre reinforcements, adobes with *Posidonia Oceanica* seagrass chopped at 3 cm and with its natural long length, have general better results with higher percentage of fibres than straw. The behaviour difference with those that include straw fibres could be imputable to the nature of the seagrass fibre itself. Straw has much more rigid appearance than seagrass, which is more flexible. This leads seagrass fibres to be more interlaced with the soil matrix than the others are, having less interactions fibre-soil over the piece. Moreover, the difference of fibre density makes that with the same weight percentage of inclusion; higher volume of straw is needed, since they are lighter than seagrass. Figure 8 represents two sample fibre sections where the fibre-soil intersection is higher in straw-based brick case. Therefore, these aspects in connection with fibre dispositions can highly contribute to improve the mechanical behaviour related to the contrast between specimens containing both fibres. Furthermore, as referred to the physical properties of the fibres themselves described in Table 1, the higher water absorption of straw and the subsequent loss of adhesion to the binder [34] can also be another reason to worsen their mechanical behaviour.

Figure 8. From left to right, seagrass and straw samples. Both present 3% content and 3 cm length of fibres.

In order to have some parameters to understand if an earthen material product would be suitable for construction, Vega et al. [36] enumerated several authors and institutions, which defined specific mechanical resistance values. These values were defined around 0.75 and 2.25 N/mm² for compressive strength whereas for flexural strength, the minimum values established were around 0.4 N/mm². Other studies located this compressive resistance suitable as bearing materials in a minimum of 1 N/mm² [34]. Table 3 includes several references from the literature where vegetal fibres have been introduced in earthen construction elements. Taken this into consideration, good mechanical properties are achieved in the adobe specimens tested with straw and seagrass fibres. Some other studies include also physicochemical stabilizers to the earth-fibre matrix in order to improve mechanical properties [37].

Table 3. Experimental results of fibre content and strengths in adobe specimens.

Type of fibre	Fibre content % (wt.)	Fibre length	Specimen dimensions	Best compression strength	Best flexural strength	Grain size distribution and water content	Ref.
Straw	0-0.78-1-1.3-1.5-2.4-3.2 %	5 cm	160 x 40 x 40 mm	1.6 MPa (1%)	1% (0.18 MPa tensile, 1% strain)	33% clay, 20% silt, 47% sand Water: 9-12%(without fibres), 20-50% (with fibres)	[35]
Straw	0-1-1.5-2-2.5-3 %	1-2, 2-4, 4-6 cm	250 x 120 x 100 mm	5.5 MPa (1-1.5%, 2-4cm)	-	28% clay, 29% silt, 23% fine	[36]

						sand, 20% coarse sand Water: 19%	
Straw	0.2-0.3-0.4- 0.5-0.6 -0.9 %	2-8 cm	160 x 40 x 40 mm	2.82 MPa (0.6%)	-	11.9% clay, 20.2 silt, 35% sand, 22.7% gravel Water: 8-10%	[37]
Straw	0-1-2-3-4-5 %	-	100 x 100 x 100 mm	0.9 MPa (4.2%)	-	58% clay, 15% silt, 24% fine sand, 3% coarse sand Water: -	[38]
Straw	0-0.5-1-3- 4-5%	1-4 cm	Compression: 220 x 107 x 60 mm Flexural: 280 x 70 x 70 mm	4.43 MPa (1%)	1.95 MPa (0.5%), 1.66 MPa (1%)	13% clay, 44% silt, 43% sand Water: 20-30%	[39]
Straw	1-2-3%	1-3 cm	230 x 150 x 130 mm	2.9 MPa (3%)	0.27 MPa (3%)	57% clay, 40% sand Water: 20%	[40]
Wool	0.25% fibres, 1% alginate	1 cm	n.a.	2.52-4. 42 MPa	0.66-0.99 MPa	Different clayey soil types Water: 19.25%	[41]
PP	0.25% fibres, 1% alginate	1 cm	n.a.	2.90-4.70 MPa	1.06-1.28 MPa	Different clayey soil types Water: 19.25%	[41]
Hemp	0.2-0.4- 0.8%	3 cm	Compression: 120 x 50 x 50 mm Flexural: 450 x 130 x 50 mm	2.7 (0.8%) - 2.85 (0.4%) MPa	0.85 (0.8%) - 1.15 (0.2%) MPa	25% clay, 30% silt, 45% sand Water: 20%	[42]

n.a. – not available

Figure 9 presents the evolution of samples thermal conductivities (λ). The fact of including more biomass fibre ratio and increasing the length makes that the density decreases. Thanks to this, the thermal performance of the studied materials improves [26]. Since straw fibres are lighter than seagrass, the density of the adobe specimen itself tends to be lower and therefore, characterized by better thermal insulated properties. Results show thermal conductivity improvements regarding to unreinforced specimens from 2% to 24% when higher ratio of fibres are included in straw-based samples. In case of seagrass reinforced specimens, from 3% to 19% of improvement is reached. Regarding to the comparison of fibre lengths and inclusion rations, generally, the thermal conductivity improves when higher fibre length and percentage of fibres are included in adobe samples.

Figure 9. Thermal conductivity (and its standard deviation) and density of the samples. Black bars indicate straw, meanwhile green ones indicate seagrass,

Other studies with earthen materials and biomass fibres obtain their thermal conductivities around 0.35-0.55 W/m·K when cork is included in a clay material [44]. Brzyski et al. [34] incorporate hemp shives and flax straw in a mixture which also included lime and cement, reaching values around 0.112 W/m·K with lower densities than 0.5 g/cm³. Millogo et al. [45] investigated the fabrication of pressed adobe blocks with hemp fibres, with thermal conductivity values from 1.30 up to 1.67 W/m·K. In this context, the obtained thermal values from straw and Posidonia Oceanica reinforced adobes, are positioned among other research studies done in the earthen construction-manufacturing field.

Therefore, from the thermal behaviour point of view, adobes with 3% straw content and 3 cm length are the best results. Nevertheless, their mechanical behaviour was relatively weak, being seagrass-based adobes the most suitable. Taking this into consideration, 3% seagrass inclusion with its long natural length seems to meet the best conditions in terms of mechanical and thermal outlook.

4. Conclusions

The main objective of this study was focused on analysing *Posidonia Oceanica* seagrass as a fibre reinforcement in adobe specimens, conforming a sustainable building material for green building envelopes. Since straw fibres are the most typical additive included in earthen construction, they were taken as a reference. Therefore, adobe specimens based on both types of biomass fibres with different contents and lengths were manufactured in order to create a direct comparison.

First, key physical properties of the fibres themselves were analysed to increase the knowledge about them separately. Density, water absorption, and tensile strength were examined, concluding that both types of fibres present large differences.

Focusing on the evaluation of the adobe specimens, the shrinkage indicated to have a direct correlation to the existence of fibres in the bricks and their level of water absorption. Straw-based adobes presented less level of shrinkage compared with seagrass ones since the fibres absorbed less water during the first drying hours. The inclusion of both biomass fibres and determined lengths generated a positive aspect in this sense, opposing sample deformations and promoting their flatness.

From a mechanical point of view, seagrass additives on adobes seem to be more suitable. Concerning compressive strength, straw-based specimens reached the best result when the fibre ratio was 0.50%. Nevertheless, this value is practically ranged by seagrass reinforced adobes when they are included in a rate of 1.50%. In terms of flexural resistance, when higher ratio of *Posidonia Oceanica* seagrass is included with its natural length, better flexural performance is achieved, different from the other cases. Thus, by observing both compressive and flexural behaviours of the bricks, they are generally improved with higher contents of reinforcement when seagrass leaflets are included. Specially, when they are disposed with their natural long length. Comparing to the un-reinforced origin specimens, an improvement of around 30% is reached when this sea-plant in this natural disposition is included at 1.50% or 3% content.

According to the thermal performance of the earthen pieces, the fact of including more fibre content with higher lengths makes the density decrease and therefore, generally improving the thermal conductivity. Since straw fibres are relatively lighter than seagrass, straw-based adobes have better thermal insulation capacities than the other reinforced with seagrass. From this context and taking in consideration the good mechanical performance of *Posidonia Oceanica* based specimens, with a 3% of their reinforcement and their long natural length, suitable results are also reached.

Therefore, it can be concluded that adobe specimens with *Posidonia Oceanica* seagrass as a reinforcement with their natural length present very interesting results in terms of mechanical and thermal behaviours, in some cases even better than straw-based specimens. The fact of including such novel fibres into the mixture without any cutting process, makes that the manufacturing of the pieces be much cheaper and easier, generating an overall more sustainable cycle in the production of this renewable, low cost and value-added product.

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References

1. Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings.
2. P. Chastas, T. Theodosiou, D. Bikas. Embodied energy in residential buildings-towards the nearly zero energy building: A literature review. *Building and Environment* 105 (2016) 267-282.
3. F. Asdrubali, A.L. Pisello, F. D'Alessandro, F. Bianchi, C. Fabiani, M Cornicchia, A. Rotili. Experimental and numerical characterization of innovative cardboard based panels: Thermal and acoustic performance analysis and life cycle assessment. *Building and Environment* 95 (2016) 145-159

4. M.J. González, J.G. Navarro. Assessment of the decrease of CO₂ emissions in the construction field through the selection of materials: Practical case study of three houses of low environmental impact. *Building and Environment* 41 (2006) 902–909.
5. H. Niroumanda, M.F.M. Zain, M. Jamil, S. Niroumand. Earth Architecture from Ancient until Today. *Procedia - Social and Behavioral Sciences* 89 (2013) 222–225.
6. G. Minke. *Building with Earth. Design and Technology of a Sustainable Architecture*, ed. Birkhaeuser, 2006.
7. S. Serrano, L. Rincón, B. González, A. Navarro, M. Bosch, L.F. Cabeza. Rammed earth walls in Mediterranean climate: material characterization and thermal behaviour. *International Journal of Low-Carbon Technologies* 12 (2017) 281–288.
8. V.L. Castaldo, V. Coccia, F. Cotana, G. Pignatta, A.L. Pisello, F. Rossi. Thermal-energy analysis of natural "cool" stone aggregates as passive cooling and global warming mitigation technique. *Urban Climate* 14 (2015) 301-314.
9. A.L. Pisello, F. Rosso. Natural Materials for Thermal Insulation and Passive Cooling Application. *Key Engineering Materials* 666 (2016) 1-16.
10. S. Secchi, F. Asdrubali, G. Cellai, E. Nannipieri, A. Rotili, I. Vannucchi. Experimental and environmental analysis of new sound-absorbing and insulating elements in recycled cardboard. *Journal of Building Engineering* 5 (2016) 1–12.
11. F. Hernández-Olivares, M.R. Bollati, M. del Rio, B. Parga-Landa. Development of cork–gypsum composites for building applications. *Construction and Building Materials* 13 (1999) 179-186.
12. H. Binici, O. Aksogan, T. Shah. Investigation of fibre reinforced mud brick as a building material. *Construction and Building Materials* 19 (2005) 313-318.
13. H. Binici, O. Aksogan, M.N. Bodur, E. Akca, S. Kapur. Thermal isolation and mechanical properties of fibre reinforced mud bricks as wall materials. *Construction and Building Materials* 21 (2007) 901-906.
14. H. Binici, O. Aksogan, D. Bakbak, H. Kaplan, B. Isik. Sound insulation of fibre reinforced mud brick walls. *Construction and Building Materials* 23 (2009) 1035-1041.
15. C. Dove. The development of unfired earth bricks using seaweed biopolymers. *Eco-Architecture V* 219. *WIT Transactions on Ecology on The Built Environment* 142 (2014).
16. C. Galán-Marín, C. Rivera-Gómez, J. Petric. Clay-based composite stabilized with natural polymer and fibre. *Construction and Building Materials* 24 (2010) 1462–1468.
17. Ki-Chang Lee, Jai-Hyuk Her, Soon-Ki Kwon. Red clay composites reinforced with polymeric binders. *Construction and Building Materials* 22 (2008) 2292–2298.
18. M. Achenza, L., Fenu. On earth stabilization with natural polymers for earth masonry construction. *Materials and Structures* 39 (2006) 21–27.

19. C. Rivera-Gómez, C. Galán-Marín, F. Bradley. Analysis of the Influence of the Fiber Type in Polymer Matrix/Fiber Bond Using Natural Organic Polymer Stabilizer. *Polymers* 6 (2014) 977-994.
20. Galán-Marín, C.; Rivera-Gómez, C; Petric, J. Clay-based composite stabilized with natural polymer and fibre. *Construction and Building Materials* 24 (2010) 1462–1468.
21. G. Balata; A. Tola. Cost-opportunity analysis of the use of *Posidonia oceanica* as a source of bio-energy in tourism-oriented territories. The case of Alghero. *Journal of Cleaner Production* 172 (2018) 4085-4098.
22. S. Maisano, F. Urbani, N. Mondello, V. Chiodo. Catalytic pyrolysis of Mediterranean sea plant for bio-oil production. *International Journal of Hydrogen Energy* 42 (2017) 28082-28092.
23. V. Chiodo, G. Zafarana, S. Maisano, S. Freni, F. Urbani. Pyrolysis of different biomass: Direct comparison among *Posidonia Oceanica*, *Lacustrine Alga* and *White-Pine*. *Fuel* 164 (2016) 220–227.
24. S. Bestraten, E. Hormías, A. Altemir. Earthen construction in the 21st century. *Informes de la Construcción* 63,523 (2011) 5-20.
25. S. Yetgin, O. Çavdar, A. Çavdar. The effects of the fiber contents on the mechanic properties of the adobes. *Construction and Building Materials* 22 (2008) 222–227.
26. S. Serrano, C. Barreneche, L.F. Cabeza. Use of by-products as additives in adobe bricks: Mechanical properties characterisation. *Construction and Building Materials* 108 (2016) 105-111.
27. H. Schroeder. Moisture transfer and change in strength during the construction of earthen buildings. *Informes de la Construcción*, 63, 523 (2011) 107-116.
28. DIN EN ISO 62:1999-05. Plastics – Determination of water absorption
29. EN 196-1:2005. Métodos de ensayos de cementos. Parte 1, Determinación de resistencias mecánicas.
30. A. Sales, F. R. de Souza, W. N. dos Santos, A. M.s Zimer, F. C. R. Almeida. Lightweight composite concrete produced with water treatment sludge and sawdust: Thermal properties and potential application. *Construction and Building Materials* 24 (2010) 2446–2453.
31. K. Ghavami, R. D. Toledo Filho, N. P. Barbosac. Behaviour of composite soil reinforced with natural fibres. *Cement and Concrete Composites* 21 (1999) 39-48.
32. M. Bouhicha, F. Aouissi, S. Kenai. Performance of composite soil reinforced with barley straw. *Cement & Concrete Composites* 27 (2005) 617-621.
33. F. V. Riza, I. A. Rahman, and A. M. A. Zaidi, “A Brief Review of Compressed Stabilized Earth Brick (CSEB),” presented at the Science and Social Research (CSSR), 2010 International Conference on, (2010) 999–1004.

34. P. Brzyski, D. Barnat-Hunek, Z. Suchorab, G. Łagód. Composite Materials Based on Hemp and Flax for Low-Energy Buildings. *Materials* 10 (2017) 510.
35. P. Zak, T. Ashour, A. Korjenic, S. Korjenic, W. Wu. The influence of natural reinforcement fibers, gypsum and cement on compressive strength of earth bricks materials. *Construction and Building Materials* 106 (2016) 179–188.
36. P. Vega, A. Juan, M. I. Guerra, J. M. Morán, P. J. Aguado, B. Llamas. Mechanical characterisation of traditional adobes from the north of Spain. *Construction and Building Materials* 25 (2011) 3020–3023.
37. S. Serrano, C. Barreneche, L. Rincón, D. Boer, L. F. Cabeza. Optimization of three new compositions of stabilized rammed earth incorporating PCM: Thermal properties characterization and LCA. *Construction and Building Materials* 47 (2013) 872–878.
38. S. Yetgin, Ö. Çavdar, A. Çavdar. The effects of the fibre contents on the mechanic properties of the adobes. *Construction and Building Materials* 22 (2008) 222–227.
39. M. Bouhicha, F. Aouissi, S. Kenai. Performance of composite soil reinforced with barley straw. *Cement & Concrete Composites* 27 (2005) 617–621.
40. E. Quagliarini, S. Lenci. The influence of natural stabilizers and natural fibres on the mechanical properties of ancient Roman adobe bricks. *Journal of Cultural Heritage* 11 (2010) 309–314.
41. D. Sow, M. Ahmat, S. Gaye, M. Adj, I.K. Cisse. Integration of Agricultural Waste in Local Building Materials for their Exploitation: Application with Rice Straw. *Research Journal of Applied Sciences, Engineering and Technology* 7(15): 3030-3035, 2014.
42. R. Illampas, V. G. Loizou, L. Loannou. Effect of straw fiber reinforcement on the mechanical properties of adobe bricks. *Sixth Biot Conference on Poromechanics*, 2015.
43. C. Rivera-Gómez, C. Galán-Marín, F. Bradley. Analysis of the Influence of the Fiber Type in Polymer Matrix/Fiber Bond Using Natural Organic Polymer Stabilizer. *Polymers* 6 (2014) 977-994.
44. Y. Millogo, J. Morel, J. Aubert, K. Ghavami. Experimental analysis of Pressed Adobe Blocks reinforced with Hibiscus cannabinus fibers. *Construction and Building Materials* 52 (2014) 71–78.