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# Comparison of barley and lavender straws as bioaggregates in earth bricks

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## HIGHLIGHTS

- Physical differences between straws lead to distinct behaviour of the composites
- Barley straw improves thermal behaviour but reduces mechanical strength
- Lavender straw improves durability and resistance to fungal growth

## ABSTRACT

Nowadays, for environmental reasons, the demand for bio-based building materials is increasing. The number of studies focusing on earth building bricks with addition of plant aggregates is growing. In this study, barley and lavender straws were considered as bioaggregates in an earth matrix. Their characterization revealed distinct shape, size and porosity. Composites including 3% and 6% by mass of each bioaggregates were then elaborated. Their performances were investigated and compared in terms of mechanical and thermal properties, durability of the composite materials and resistance to fungal growth. The mixture with 3% of lavender straw showed satisfactory durability results while barley straw brought better thermal properties.

Keywords: durability, mechanical property, thermal property, fungal growth, earth bricks, barley straw, lavender straw.

## 1. INTRODUCTION

Earth is a natural material, known to have been used in construction for more than 10000 years as the Egyptian civilization used the raw earth for building since the 10<sup>th</sup> millennium BCE [1–3]. Nowadays, around 30% of the world's population still live in earth shelters [4], especially in developing countries. In France, earth constructions make up about 15% of the total architectural heritage, with a concentration of the adobe technique in the southwest [5]. After World War II, the need to rebuild quickly and in a more “modern” way justified the use of concrete, to the detriment of earth.

However, nowadays, the energy performance of buildings is a priority. Energy used for building is responsible for 40% of the EU's total energy consumption and 36% of its CO<sub>2</sub> emissions [6]. Recently, in the latest agreement, of 20<sup>th</sup> December 2017, the European Parliament, Council and Commission traced a clear path towards obtaining a low- and zero-emission building stock in the EU by 2050 [7]. To decrease the environmental impact of buildings and improve their energy efficiency, eco-friendly materials could be used. These materials would simultaneously enable good technical performances, waste reduction, low consumption of energy and low pollution during their whole life cycle, from the

extraction process to the end-of-life. As a building material, earth has many advantages, such as high availability, reduced impact on the environment and ability to regulate the indoor climate [4]. Moreover, it is a raw material that is available locally, requiring little transportation and processing, which makes it a building material with low grey energy. In this context, its use is experiencing a renewal in Europe, as part of a sustainable development approach. However, earth materials also have disadvantages, in particular their poor water resistance, but also shrinkage [4] and low ductility [8]. The use of plant aggregates as additions in the earth matrix can partially improve these aspects [9] and also allow add value to agricultural by-products while decreasing the storage of these wastes, which are available in huge amounts. It also leads to carbon storage in buildings. The use of these renewable resources is thus environmentally friendly.

Barley straw is the residual part of the grain harvest. In 2014, France produced more than 11.7 million tons of barley, generating large amounts of straw, mostly pressed in bales in order to be exported and reused as litter [10]. Among the 50 references reviewed by Laborel-Préneron et al. [11] concerning plant aggregates and fibres used in earth construction materials, only 3 concern barley straw incorporated in an earth matrix. Nevertheless, 17 references dealt with cereal straw and it is shown in studies by Ashour et al. [12,13] that wheat straw and barley straw exhibit similar behaviour. Thus, all studies about cereal straw are likely to provide information about barley, wheat or oat straws.

Lavender straw is a by-product widely available in France, where the production of lavender flower is up to 40 tons per year on 3500 ha in the southeast of the country [14]. Several other countries, like Bulgaria, the UK, or China produce lavender oil in large quantities [14]. Once distilled, the lavender straw becomes an agro-industrial waste that is stored near the distilleries. It can be used for heating, composting or greening but nearly half of this straw, i.e. more than 15 000 tons, has no commercial value in France [10]. No form of treatment exists for this waste to date, and this is a real hindrance to the development of the sector. Recycling lavender straw in the construction field would reduce waste production, use a locally produced aggregate and store carbon dioxide. It appears that adding lavender straw into unfired earth bricks has never been studied, although lavender straw has been investigated in another building application, as an aggregate of building materials with a pozzolanic mineral binder [15].

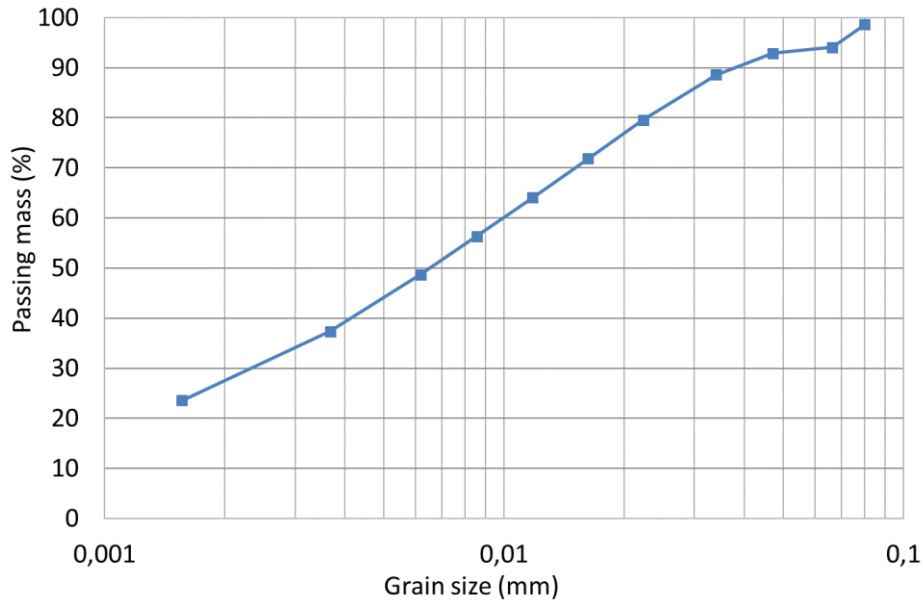
The objective of this study is to give an overview of the performances of composites made with two types of straw added to an earth matrix at rates of 3% and 6% by mass: barley straw, belonging to the group of cereal straws, which has been largely studied for these types of applications; and lavender straw, as a non-recovered by-product which has not been investigated for addition to earth bricks. The physical properties of the straws will be measured and compared, and the various mixtures will be investigated in terms of mechanical and thermal properties, durability and fungal growth resistance. This overview is intended to highlight the differences between the characteristics of these two straws and assess their potential for future applications in building materials.

## 2. MATERIALS AND METHODS

### 2.1 Raw materials

#### 2.1.1 Earth

The earth used as the main matrix in this study was FWAS (quarry fines from washing aggregate sludge), the waste obtained when sludge generated by the washing of limestone aggregates for the concrete industry is left to dry in sedimentation basins and is then reduced to powder. The particle size distribution of the FWAS is presented in Figure 1. It can be seen that the FWAS particles were extremely fine, smaller than 0.1 mm.

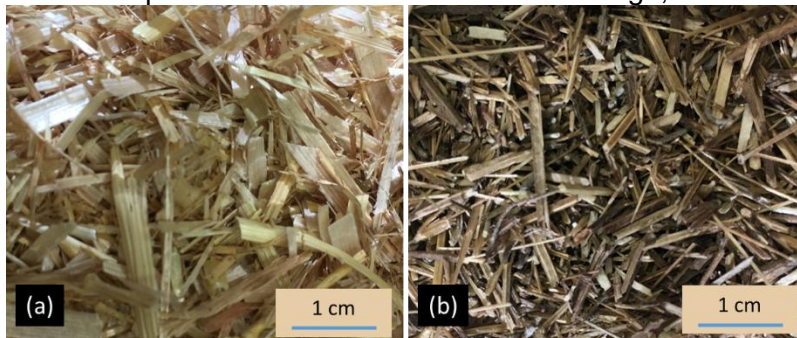


**Figure 1.** Grain size distribution curve of FWAS, adapted from Laborel-Préneron et al. [16]

#### 2.1.2 Straws

Two types of plant aggregates were used in this study (Figure 2): barley straw and lavender straw. Barley Straw (BS), the part of the cereal's stem rejected during the harvest, is a smooth, soft straw.

Lavender Straw (LS) is a by-product of the production of lavender essential oil and corresponds to the crushed stem. It is a rough, thin straw.



**Figure 2.** Macroscopic arrangement of (a) raw barley straw and (b) raw lavender straw

## 2.2 Manufacturing process

The proportion of plant aggregate was expressed by dry weight content, according to Equation (1):

$$St. \text{ content} = \frac{m_{St}}{m_{St} + m_{FWAS}} \times 100 \quad (1)$$

where St. content is the straw content in wt%,  $m_{St}$  is the dry mass of plant aggregates and  $m_{FWAS}$  is the dry mass of earth.

Five different mixtures were prepared: one mixture with the plant aggregates in a proportion of 3% by mass and another with 6%, for each type of straw, and a reference mixture composed only of FWAS. The water contents of the mixtures were determined by the Proctor test, and then rounded up. Table 1 recapitulates the different mixture proportions and dry densities of the specimens with straw. As expected, the water content needed to make the mixture increased when the plant aggregate content increased. It was slightly higher for barley straw than for lavender straw. It can be seen that the density decreased with increasing straw contents.

**Table 1.** Mixture proportions and Proctor density of specimens

Mixture name	Type of straw	Straw content (% of mass)	Water content (%)	Dry density (kg.m <sup>-3</sup> )
FWAS	-	0	14	1988 ± 9
3BS	Barley	3	19	1520 ± 1
6BS	Barley	6	21	1195 ± 169
3LS	Lavender	3	18	1772 ± 17
6LS	Lavender	6	20	1585 ± 11

To manufacture the specimens, the earth and plant aggregate fractions were first poured into a blender and briefly mixed by hand. Then, water was added and the materials were mixed mechanically until a homogeneous mix was obtained. The mixture was kept in a hermetically sealed plastic bag for 24 hours to allow the materials to become properly hydrated, and then moulded.

Three types of specimens were manufactured at the Proctor density for this study (Figure 3):

- Cylindrical specimens 5 cm in diameter and 5 cm high (Φ5H5), intended for compressive strength tests, were manufactured by double static compression.
- Specimens for microbial proliferation observations were manufactured from Φ5H5 cylinders, with 5 specimens per mould, separated by four PVC discs 5 cm in diameter.
- To carry out the durability tests, rectangular prismatic specimens 15x15x5cm<sup>3</sup> were manufactured by simple static compression.

All specimens were then put in an oven to be first dried at 40 °C for 24 hours, then the temperature was increased by 0.1 °C.min<sup>-1</sup> to 100 °C and kept at 100 °C until the weight became constant (weight variation less than 0.1% between two weighings 24 hours apart). Temperature of 100°C was set to be similar to the one used in brickworks before firing in order to accelerate the drying. The specimens were then stored in a room regulated at 20°C and 50% relative humidity (RH) and

were tested when they were in equilibrium with the environment (about one week later).



**Figure 3.** (a) Cylindrical specimens, (b) microbial proliferation specimens and (c) rectangular prismatic specimens

## 2.3 Physical properties of straws

### 2.3.1 Microscopic description

Porous structure and morphology were analysed visually with a JEOL - JSM-6380 LV Scanning Electron Microscope (SEM). The particles were glued onto a metallic support and then covered with a thin layer of evaporated carbon before observation. These microstructural investigations were carried out with a 15 kV accelerating voltage in high vacuum mode. The surface conditions were analysed visually using a Keyence - VHX-6000 numerical microscope.

### 2.3.2 Particle size analysis

A particle analysis was performed by image analysis using ImageJ software. According to several authors [17–19], this method seems to be more suitable than the sieving traditionally used for mineral aggregates. It yields accurate information such as size distribution, width and length whereas sieving would give a single dimension, unsuitable for non-spherical particles.

The protocol used was the one suggested by the RILEM TC 236-BBM group [20] and used by Picandet et al. [19], Nozahic et al. [18], Chabannes et al. [17] and Laborel-Préneron et al. [21]. It consists of homogenizing a large amount of plant aggregates and collecting samples of a few grams in boxes. These samples are sieved at 500  $\mu\text{m}$  to remove dust. Then, particles of each sample are scanned as an 8-bit grey scale image with 600 DPI (dots per inch). As the particles are light in colour, a black background is used in order to obtain better contrast for the ImageJ analysis. Particles are spread on the scanner glass in such a way that they do not touch or overlap one another.

The analysis gives the geometrical parameters of the particles:

- The major axis length (Major), which corresponds to the size of the longest line that can be drawn in the object
- The minor axis length (Minor), which corresponds to the size of the longest line that can be drawn in the object in a direction perpendicular to the major axis
- The Equivalent Area Diameter (EAD), which corresponds to the diameter of a disk having the same area as the object, calculated with Equation (2):

$$EAD = \sqrt{\frac{4 \times A}{\pi}} \quad (2)$$

with A the cross sectional area of the particle ( $\text{m}^2$ )

- The Aspect Ratio (AR), which is the length to width ratio, or Major to Minor ratio. This value is greater than 1. The shape of the particle rounds off when the ratio tends to 1 and lengthens as the ratio increases.

The RILEM TC 236-BBM group [20] recommends a sample mass between 3 and 6 g in order to obtain at least 2000 identified particles. In total, more than 5000 particles of barley straw and more than 6500 particles of lavender straw were analysed in this study.

#### 2.4 Compressive strength test

The compressive strength tests were performed on the  $\Phi 5H5$  specimens using a 100 kN capacity hydraulic press. Compressive strength tests were performed with the same protocol as in Laborel-Préneron et al. [16], using a constant deflection rate of  $3 \text{ mm}\cdot\text{min}^{-1}$ . For each mixture with lavender straw (3 and 6% by mass), three specimens were tested in order to be compared with the barley straw specimens of Laborel-Préneron et al. [16]. Displacements and loads were measured and the strain-stress curve was deduced from measurements of sample sizes. The Young's modulus of each mixture was then calculated from the linear part of the curve..

#### 2.5 Thermal conductivity

Thermal conductivity properties were measured on the  $15 \times 15 \times 5 \text{ cm}^3$  specimens using the protocol of Laborel-Préneron et al. [22]. The measurements were carried out with an EP500 guarded hot plate apparatus. Before testing, every specimen was dried at  $100^\circ\text{C}$  then cooled for about an hour at room temperature in a desiccator. As water content influences thermal conductivity [23,24], specimens were wrapped in a thin plastic film in order to avoid any humidity intake during the measurement. Data acquisition was performed with EP500 Multilingual software. The test temperature was chosen to be  $25^\circ\text{C}$ , close to room temperature in a building, with a difference of 10 K between the two plates. A measurement was assumed to be stable when the change in conductivity was less than 1% in 60 minutes. The conductivity assessment was based on Equation (3):

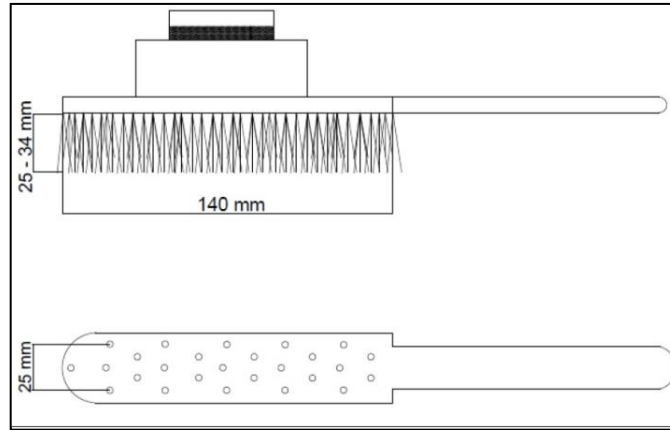
$$\lambda = \frac{Q \cdot e}{\Delta T \cdot S} \quad (3)$$

where Q is the heat input (W), e is the specimen thickness (m),  $\Delta T$  is the difference of temperature between the two plates and S is the cross-section of the specimen ( $\text{m}^2$ ).

#### 2.6 Durability properties

##### 2.6.1 Dry abrasion resistance

Dry abrasion was evaluated on the  $15 \times 15 \times 5 \text{ cm}^3$  specimens, according to the French standard XP P13-901 [25] intended for CEB (Compressed Earth Blocks) for walls and partitions, by measuring the quantity of material removed from the specimens after brushing back and forth 60 times ("roundtrips" hereafter) with a metallic brush. The total mass of the steel brush was 3,186 kg and its dimensions are detailed in Figure 4. The standard provides for a brush of  $28 \times 135$ - $140 \times 25 \text{ mm}$  and an additive charge of 3 kg.



**Figure 4.** Steel brush for dry abrasion test

The brick surface was brushed using the steel brush at the rate of one roundtrip per second for 60 seconds without applying additional vertical force on the brush during the test. The brushed width was kept as narrow as possible. Brushing was done along the entire length of the brick. At least half of the brush surface remained permanently in contact with the surface of the brick throughout the duration of the test, in order to avoid a cantilever that would stress the edges of the brick more.

A coefficient of abrasion in  $\text{cm}^2 \cdot \text{g}^{-1}$  was then calculated with Equation (4) according to the standard:

$$C_a = \frac{S}{m_0 - m_1} \quad (4)$$

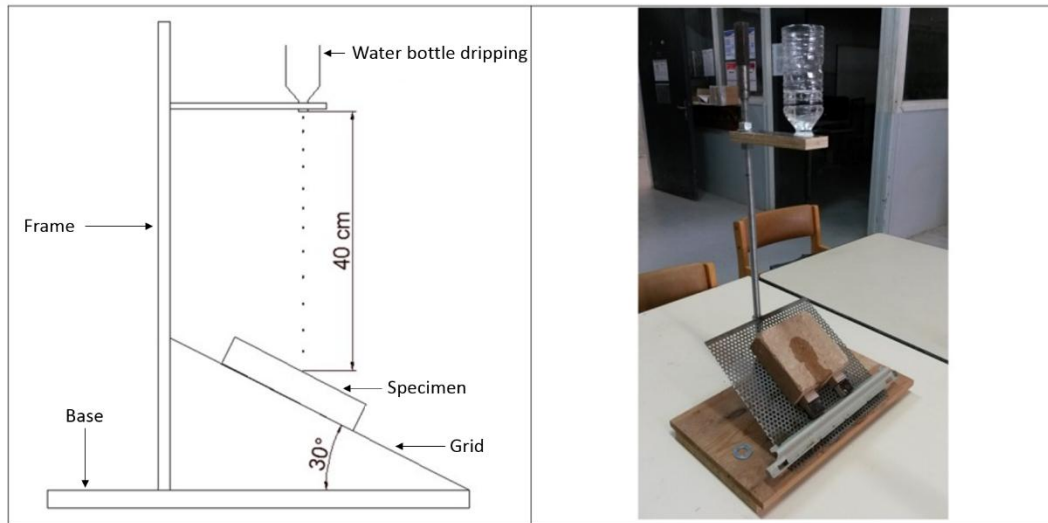
where  $m_0$  and  $m_1$  are the mass before and after brushing, in g, and  $S$  is the brushed area, in  $\text{cm}^2$ .

The higher the coefficient is, the more resistant the material is to abrasion.

### 2.6.2 Erosion resistance

The wet erosion test was performed on the  $15 \times 15 \times 5 \text{cm}^3$  specimens to simulate rain droplets. It was carried out according to the New-Zealand Standard NZS 4298 [26], intended for non-stabilized adobes and CEB, based on the Geelong method. The Geelong test is proposed especially for adobe possibly containing straw. As it is an aggressive test, it simulates accidental circumstances occurring mainly when the earth bricks are not rendered. 100 ml of water is allowed to drip from a height of 400 mm onto the sample, which is inclined at  $30^\circ$  (Figure 5). The duration of the test was between 20 and 30 minutes (adapted from the standard, from 20 to 60 min) and the pit depth was measured. An erodibility index, between 3 and 5 (fail), was deduced from this value according to the New Zealand Standard. With a pit depth between 5 and 10 mm, the erosion class was 3 and the material was considered as erosive. A pit depth between 10 and 15 mm corresponded to class 4 and the material was considered as very erosive. Finally, for a pit depth greater than 15 mm, the class was 5 and the material failed the test.





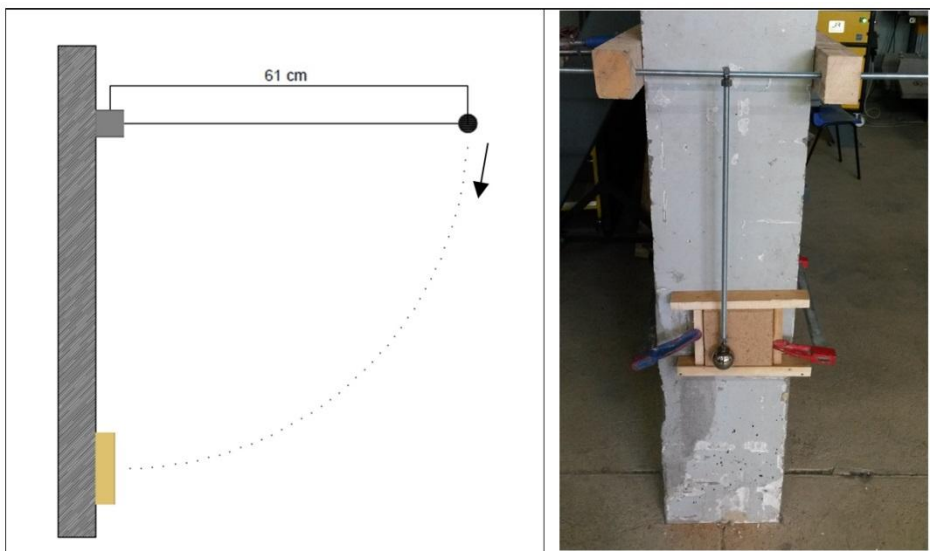
**Figure 5.** Wet erosion test

### 2.6.3 Sphere impact resistance

Vertical walls of buildings may be subjected to different kinds of impacts, such as a stone thrown at the wall or impacts from people or furniture. To evaluate the impact resistance, the Martinet-Baronnie impact apparatus was used and the test was carried out on the  $15 \times 15 \times 5 \text{ cm}^3$  specimens. The test was inspired by ISO 7892 [27] with a small, hard impact body.

The device consisted of a metallic mass of 508 g ( $500 \pm 5$  g in the ISO 7892 standard) linked to a rotation point by a rigid metal rod 61 cm long. It was dropped from the horizontal position onto the sample, which was located vertically below the rotation point and in contact with a rigid wall so that there was only one impact (Figure 6). The energy created was 3 joules.

The diameter of the impact point was measured, as was the cracking and general behaviour of the bricks.



**Figure 6.** Impact resistance test

### 2.7 Mould growth kinetics

The aim here was to compare the kinetics of mould development on specimens containing 3% of either barley or lavender straw in order to determine the

influence of the type of bioaggregate on the proliferation. According to Palumbo et al. [28], bio-based materials have very different mould resistance profiles depending on the plant used. The procedure used in this paper is the one developed by Laborel-Préneron et al. [29].

The samples were first decontaminated in order to set the initial state of the material in terms of fungal presence. Decontamination had to be achieved just before starting the study of mould growth in order to remove the fungi already present in the material. The method chosen was to expose the samples to the temperature of 100°C for 24 hours. This value was assumed to be high enough to eliminate most of the mould while avoiding modifying the material.

Artificial inoculation with a pipette was used so that the spore quantity deposited on each specimen was known exactly. A fungal suspension of *Aspergillus brasiliensis* (ATCC 16404 / CBS 733.88) was concentrated at  $3 \cdot 10^5$  conidia.mL<sup>-1</sup> and 5 µL was pipetted onto 5 different spots of the surface. Thus, each surface received 25 µL, or about 7500 conidia, i.e. more than 800 conidia.cm<sup>-2</sup>. Specimens were allowed to cool for 30 minutes after the decontamination before being inoculated. Five samples were inoculated, while two additional samples, serving as controls, were not.

To avoid cross-contamination, each sample was placed in a box where the relative humidity was maintained constant using a saturated saline solution [30]. Two different salts were used here to obtain 2 different RH conditions:

- 93% of relative humidity with a solution of potassium nitrate (KNO<sub>3</sub>)
- 84 % with potassium chloride (KCl)

According to Johansson et al. [31], such RH conditions are above the critical moisture level for this type of material and represent severe conditions.

The individual incubation set-up was composed of a plastic box in which the saturated saline solution was placed. Above this, the specimen was placed on a holder supported by rigid foam wedges to ensure good stability. The box was sealed with Parafilm® in order to increase the air-tightness of the assembly.

The materials were placed in a climatic chamber at 30°C to provide severe thermal conditions [32]. These stationary conditions do not correspond to the natural conditions in which humidity and temperature fluctuate. However, Johansson et al. [33] have shown that these simplified and accelerated conditions lead to results that give a good indication of mould growth within a building and, at least, serve to compare the sensitivity of two different materials to mould growth.

For microscopic observation, the plastic box was opened and the sample was removed with its holder in order to avoid touching it. The only possible contamination during the observations would have come from the air of the room, but exposure lasted for only a few minutes, once a week.


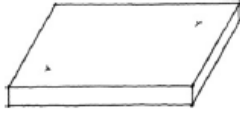
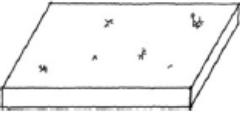
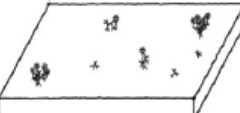
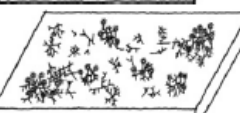
In order to create good conditions for microscopic observation, the two faces of the specimen were polished to limit their roughness, prior to sterilization. Then, specimens were coated with a polyester resin (Synolite® 0288), except over a square area of 3x3 cm<sup>2</sup>, which was the surface to be investigated.

The observation was made using a Zeiss optical microscope (magnification 10X), scanning the whole square area in order to detect mould growth.

Johansson et al. [33] rating scale for the assessment of mould (

Table 2) was used for the interpretation. The illustrations are intended to give an idea of how the mould might look for each rating.

**Table 2.** Rating scale for the assessment of mould. The analysis is performed with a microscope. [33]

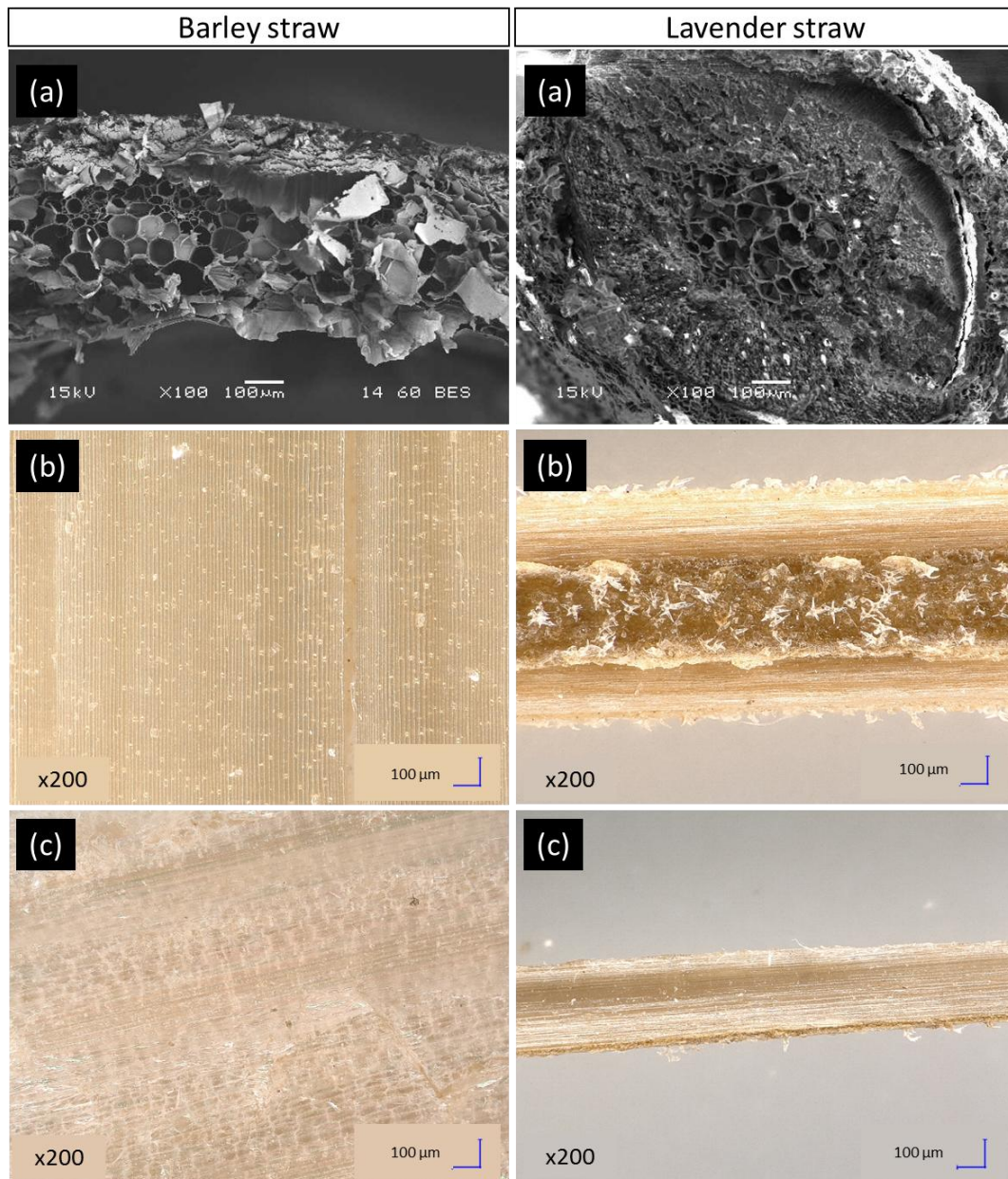
Rating	Description of extend of growth	
0		No mould growth
1		Initial growth, one or a few hyphae and no conidiophores
2		Sparse but clearly established growth; often conidiophores begin to develop
3		Patchy, heavy growth with many well-developed conidiophores
4		Heavy growth over more or less the entire surface

### 3 RESULTS AND DISCUSSION

#### 3.1 Physical properties of straws

##### 3.1.1 Microscopic description

The morphology and porous structures of the two straws were observed and analysed using SEM (Scanning Electron Microscopy) and numerical microscopy images. The structure of the inside of the strand as well as the surface is illustrated for each kind of straw in Figure 7.



**Figure 7.** (a) SEM images of a straw cross section, (b) numerical microscopy images of an external surface, and (c) numerical microscopy images of an internal surface for barley straw (first column) and lavender straw (second column)

The SEM images show the microstructure of the two straws, consisting of layers with a tubular structure, which are organized concentrically. Structural differences can be highlighted, however: in the barley straw, pores of different sizes from 2 to 100  $\mu\text{m}$  are observed everywhere, with a majority of large pores and thin cell walls up to 2  $\mu\text{m}$  [21] and a denser layer observed in the upper part. The porous network of the lavender straw seems to be more organized. The biggest pores (between 30  $\mu\text{m}$  and 60  $\mu\text{m}$  in diameter) have thin cell walls of about 2  $\mu\text{m}$  and are grouped in the centre of the strand, in a zone 400  $\mu\text{m}$  in diameter. This area is surrounded by a denser layer containing small square pores with a size range of 7 to 9  $\mu\text{m}$  and cell walls of about 1.5  $\mu\text{m}$ . A dense envelope surrounds the

straw, with pores of variable forms. Actually, on the SEM images, from the top to the bottom for the barley straw and from the periphery to the centre for the lavender straw, the structure is ordered as follows: an external denser envelope corresponding to the epidermis, a very lignified and therefore very rigid tissue called the sclerenchyma, and a cellular material mainly composed of cellulose named the parenchyma. In the case of barley straw, straws are hollow cylinders and the structure surrounds the empty part called the lumen [34].

The numerical microscopy images show the surface conditions of both straws. It can be observed on images (b) that the external surface of barley straw seems smooth and regular, without asperities. In contrast, lavender straw shows a very irregular external surface, with relief. This could be favourable for the adherence with earth, as highlighted by Millogo et al.[35]. Images (c) show the internal surface of a barley straw and the surface of a very thin strand of lavender straw, probably a fragment of a whole lavender straw strand. Internal surfaces are regular and show a linear arrangement, with a particularly streaked structure having grooves for the lavender straw, as observed in the case of kenaf [35].

### 3.1.2 Particle size analysis

In this study, some morphological characteristics of barley straw and lavender straw were compared. Dust content, determined by sieving at 500 µm, was about 14.3% for barley straw and 24.6% for lavender straw. The much higher dust content of lavender straw compared with barley straw could be explained by the thinner shape of lavender straw. Apparently, this allows more particles to pass through the sieve in the sense of their length and thus artificially increases the dust content. The grading curves are presented in Figure 8. Averages and standard deviations of the major and minor axes, EAD and aspect ratio were calculated from Equations 5 and 6 according to Picandet et al., [36] and are presented in Table 3.

$$E_{am}(x) = \frac{\sum A_i(x_i)}{\sum A_i} \quad (5)$$

$$Sd_{am}(x) = \sqrt{\frac{\sum A_i(x_i - E_{am}(x))^2}{\sum A_i}} \quad (6)$$

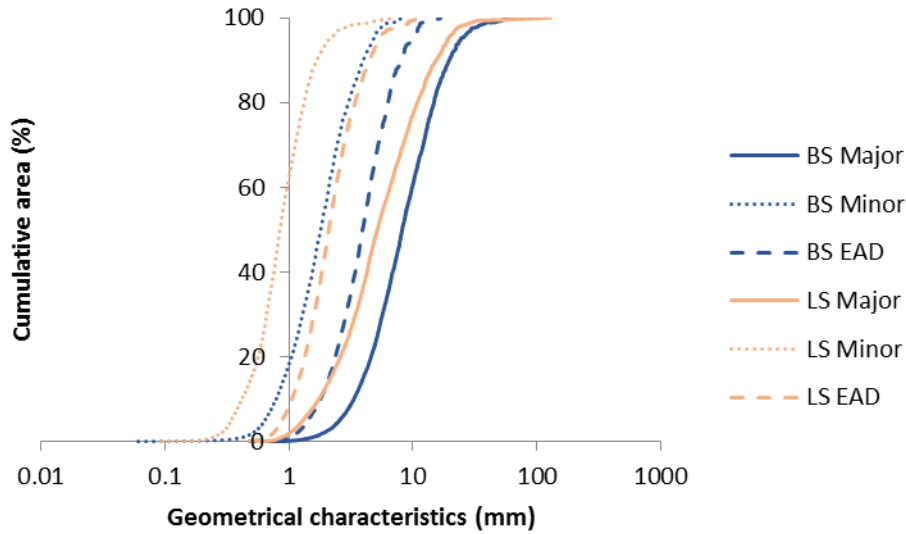
where  $E_{am}(x)$  is the arithmetic mean of the dimension  $x$  (Major, Minor, EAD or AR),  $A_i$  is the projected area of each particle detected (mm<sup>2</sup>),  $x_i$  is the dimension of each particle detected and  $Sd_{am}(x)$  is the associated standard deviation.

**Table 3.** Arithmetic means and dispersions of straw dimensions

Dimension	Barley Straw (BS)	Lavender Straw (LS)
Major (mm)	10.5 ± 8.5	7.7 ± 10.4
Minor (mm)	2.1 ± 1.4	1.0 ± 0.8
EAD (mm)	4.5 ± 2.6	2.5 ± 1.6
AR	6.2 ± 16.0	9.9 ± 17.3

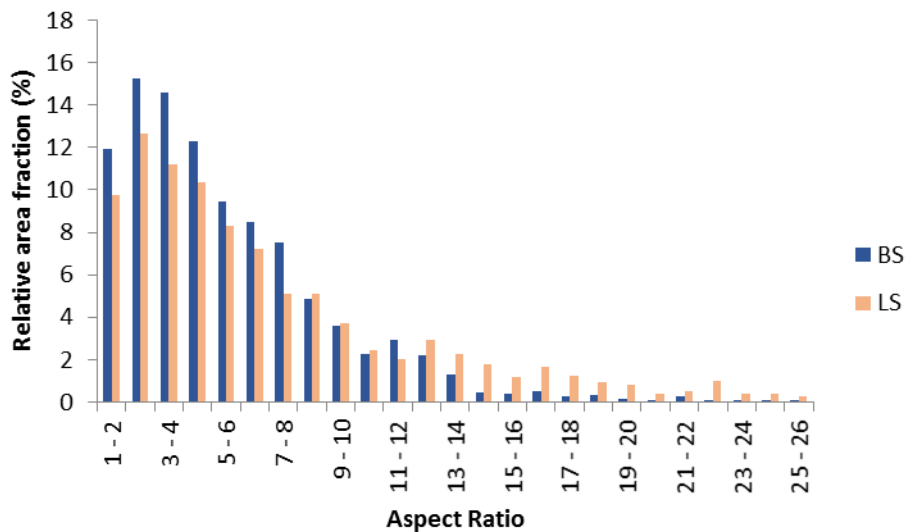
The standard deviations associated with the mean dimensions of both straws were high. This was due to the heterogeneity of these particles, which had not undergone any calibration process. The standard deviation associated with the major axis of lavender straw was higher than that of barley straw. So, it can be deduced that lavender straw always has an elongated (AR=9.9 ± 17.3), thin

shape (around 1 mm in diameter) with a variable length, whereas barley straw comes in more regular, short shapes.



**Figure 8.** Grading curves of barley straw (BS) and lavender straw (LS) as a function of the cumulative area

Figure 8 shows curves that are similar for both types of straw. The difference is that the particle size of barley straw is larger than that of lavender straw. The proportions of AR in cumulative area are presented in Figure 9.



**Figure 9.** Relative area distribution as a function of aspect ratio

It can be noted that both types of straw have a scattered AR, which means that they are composed of elongated particles. It can be seen that lavender straw contains more elongated particles than barley straw does.

### 3.2 Mechanical properties

The mean values of the dry density ( $\rho_{dry}$ ), the maximum compressive strength ( $\sigma_{max}$ ), the ultimate strain ( $\epsilon(\sigma_{max})$ ), the compressive strength corresponding to a strain of 1.5% ( $\sigma(1.5\%)$ ) and the experimental Young's modulus ( $E_c$ ) of each type

of specimen are reported in Table 4. Tests were performed on three specimens for each mixture.

**Table 4.** Mechanical properties of the five mixtures

	<b>FWAS</b>	<b>3BS</b>	<b>6BS</b>	<b>3LS</b>	<b>6LS</b>
$\rho_{\text{dry}}$ ( $\text{kg}\cdot\text{m}^{-3}$ )	2017 $\pm$ 35	1519 $\pm$ 1	1315 $\pm$ 27	1772 $\pm$ 17	1585 $\pm$ 11
$\sigma_{\text{max}}$ (MPa)	4.8 $\pm$ 0.9	3.3 $\pm$ 0.2	3.8 $\pm$ 0.3	3.7 $\pm$ 0.1	3.9 $\pm$ 0.3
$\epsilon(\sigma_{\text{max}})$ (%)	1.3 $\pm$ 0.7	7.8 $\pm$ 0.6	19.9 $\pm$ 1.1	4.2 $\pm$ 0.3	8.8 $\pm$ 0.6
$\sigma(1.5\%)$ (MPa)	3.7 $\pm$ 0.7	0.7 $\pm$ 0.1	0.4 $\pm$ 0.0	1.8 $\pm$ 0.4	0.6 $\pm$ 0.1
$E_c$ (MPa)	502 $\pm$ 171	62 $\pm$ 3	31 $\pm$ 1	134 $\pm$ 11	64 $\pm$ 3

All the results of compressive strength were above the minimum value of 2 MPa imposed by the New Mexico standards for adobe construction [37] and the value of 1.3 MPa specified by the New Zealand Earth Building standard NZS 4298 [26]. Although FWAS specimens were the strongest, for both straws, the ultimate compressive strength of specimens with 6% of straw was higher than with 3% of straw. This is in accordance with studies showing an increase of the compressive strength with the addition of plant aggregates: tea residue [38], sawdust, tobacco residue or grass in clay bricks [39] and cassava peel in compressed earth blocks [40]. However, Al Rim et al. [41] and Yetgin et al. [42] state that mechanical strength decreases with increasing plant aggregate content. Their results can be explained by a consolidation phenomenon due to the high compressibility of straw [16], evidenced by the high ultimate strains, of about 20% and 9% for barley and lavender straws respectively, or by the elongated shape of the particles. The mixtures also undergo very high ultimate strain before failure and such deformations cannot be tolerated for building structures. To limit these deformations and to compare the materials, the compressive strength corresponding to a strain of 1.5% was chosen as the reference, as used by Cerezo [43] for hemp concrete.

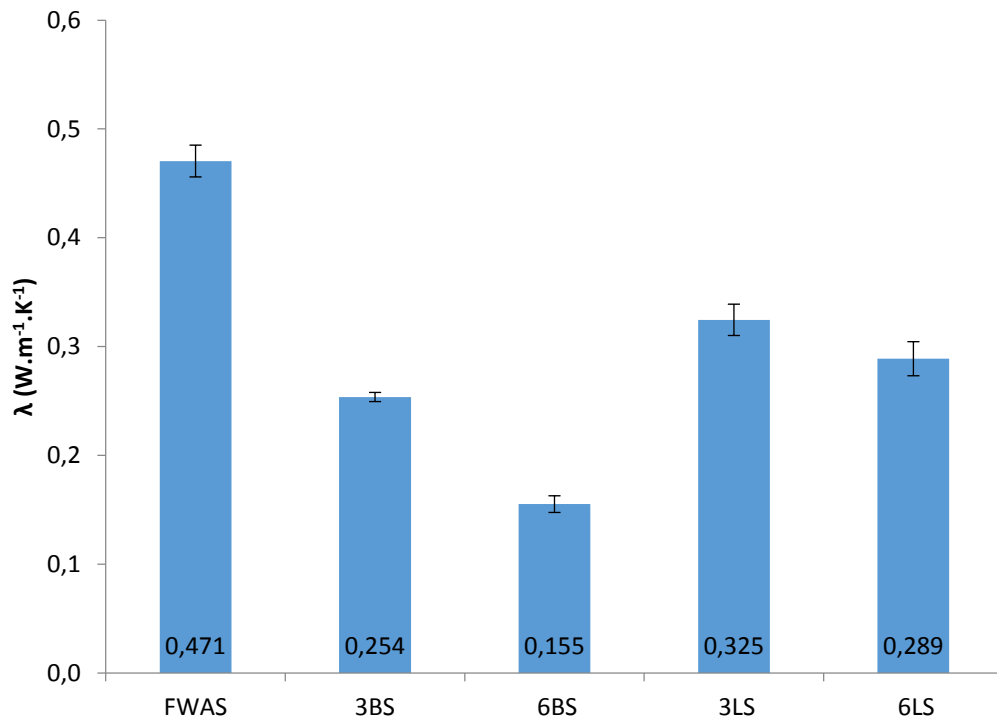
For a given strain of 1.5%, the compressive strength was higher for FWAS specimens and was about 1.85 MPa for the 3LS specimens. The value did not reach 1 MPa for the other specimens. Specimens with 3% of straw presented higher compressive strength for a strain of 1.5% than those with 6% of straw. Under these conditions, it can be said that straw additions decreased the compressive strength. The better results of lavender straw could be explained by its higher aspect ratio, since Danso et al. [44] showed that increasing the aspect ratio of several types of fibres (bagasse, oil palm, coconut) led to an increase in the compressive strength of the soil building blocks containing them. These results could also be linked to the difference of microstructure between the two straws. Whereas barley straw presents a homogeneous porous structure, lavender straw shows denser external layers, which lead to less compressibility. It can also be seen in Table 4 that the Young's modulus of the FWAS mixture (502  $\pm$  171 MPa) is higher than the moduli of the other mixtures, which are 62  $\pm$  3 MPa for 3BS, 31  $\pm$  1 MPa for 6BS [16], 134  $\pm$  10 MPa for the 3LS mixture and 64  $\pm$  3 MPa for 6LS. These results are in agreement with various references [41,42,45–47] in which it is observed that the increase in fibre ratio leads to an increase in deformation. The straw addition seems to control the plastic behaviour of the specimen and therefore implies a decrease in the Young's modulus. Chee-Ming [45] explains this by the soft, flexible, elastic nature of the fibres used. The difference of results between the two straws studied could be explained by the more flexible nature of barley straw (a large amount of porosity

with thin cell walls), while lavender straw is less ductile and more brittle (denser structure).

Even though mixtures with both straws have the same behaviour, it can be noted that the deformation for the 6BS mixture is very high and is more than 2.5 times that of the 3BS mixture, whereas the difference between 3LS and 6LS mixtures is lower with a ratio of approximately 2.1. The results also show that mixtures with barley straw are generally less resistant, deform more and have a lower Young's modulus than those with lavender straw. This is in accordance with the denser envelope of the lavender straw, which decreases the deformability of this straw compared to the very porous barley straw.

### 3.3 Thermal conductivity

Tests were performed on three specimens for each mixture.

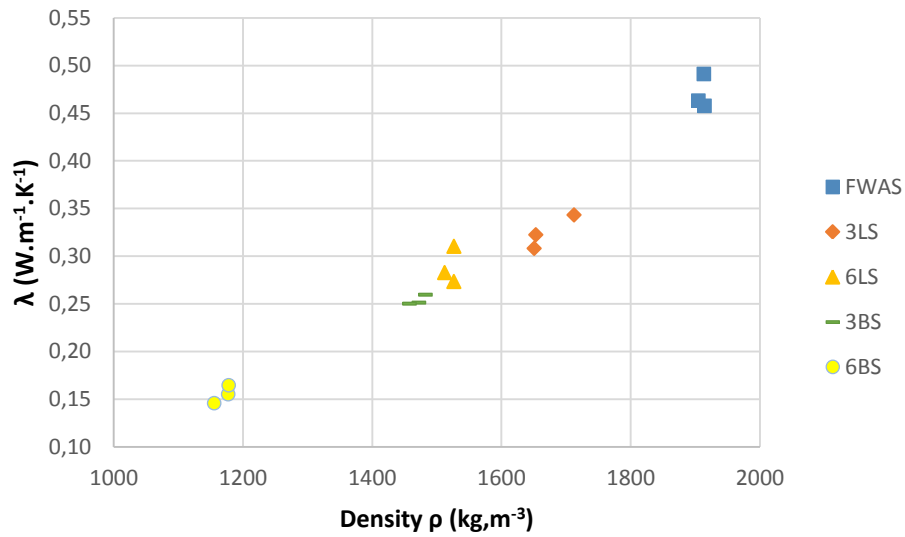


**Figure 10.** Thermal conductivity of the materials

The results on Figure 10 show that thermal conductivity decreases with the addition of straw, which means that the more straw it contains, the more thermally insulating is the material. Barley straw brings better thermal insulation than lavender straw, at a constant mass dosage. This could be explained by the microstructures of the two straws, where a denser structure has been observed for lavender straw, contrasting with the greater porosity of barley straw. This is in accordance with the specimens' dry densities, which are much higher for lavender straw specimens: about  $1672 \pm 35 \text{ kg}\cdot\text{m}^{-3}$  for the 3LS mixture and  $1522 \pm 08 \text{ kg}\cdot\text{m}^{-3}$  for the 6LS mixture, whereas the values are about  $1471 \pm 12 \text{ kg}\cdot\text{m}^{-3}$  for the 3BS mixture and  $1170 \pm 13 \text{ kg}\cdot\text{m}^{-3}$  for the 6BS mixture. The link between thermal conductivity and bulk density in raw earth matrix materials incorporating plant aggregates has been highlighted by Laborel-Préneron et al. [11]: the lighter the material is, the more insulating it is. Figure 11 shows the thermal conductivity of the specimens tested versus their dry density. An almost linear variation of the



thermal conductivity as a function of the density can be observed, whatever the aggregate nature.

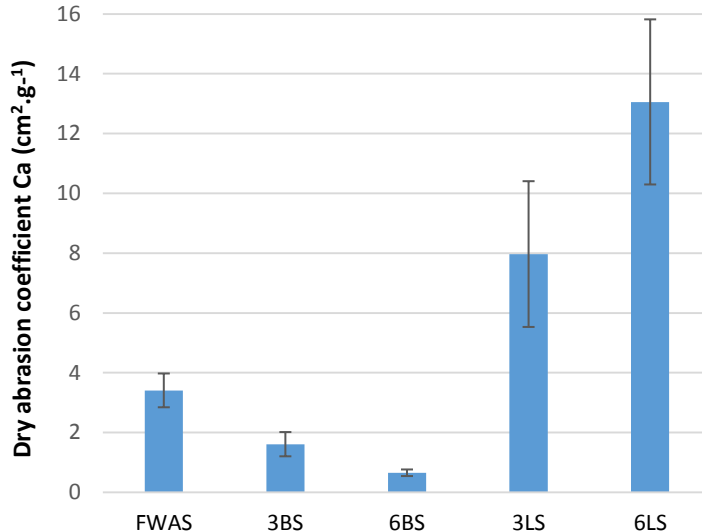


**Figure 11.** Thermal conductivity as a function of dry density

### 3.4 Durability properties

#### 3.4.1 Dry abrasion resistance

The results of dry abrasion tests are presented in Figure 12. The higher the coefficient of erosion is the better is the durability of the brick. Two samples were tested for each mixture, with two tests per sample.



**Figure 12.** Dry abrasion coefficients of the bricks

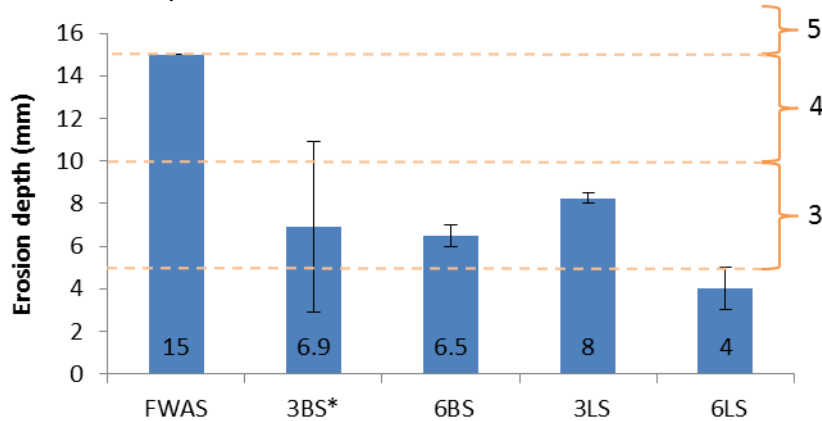
Differences of dry abrasion resistances between the formulations are particularly marked, especially between the two types of straw. 6BS bricks had the lowest abrasion coefficient ( $0.6 \pm 0.1 \text{ cm}^2 \cdot \text{g}^{-1}$ ), followed by 3BS with  $1.6 \pm 0.4 \text{ cm}^2 \cdot \text{g}^{-1}$ , FWAS with  $3.4 \pm 0.6 \text{ cm}^2 \cdot \text{g}^{-1}$ , 3LS with  $8.0 \pm 2.4 \text{ cm}^2 \cdot \text{g}^{-1}$  and then 6LS  $13.0 \pm 2.8 \text{ cm}^2 \cdot \text{g}^{-1}$ .

The results show that the addition of lavender straw to an earth brick increases its dry abrasion resistance whereas the addition of barley straw decreases it. This

can be explained by the different morphologies of the two straws (Table 3): the barley straw is wider (EAD = 4.5 mm), shorter (AR = 6.2) and smoother whereas lavender straw is thinner (Minor axis = 1.0 mm), more elongated (AR = 9.9 mm) and has a rougher external surface, allowing a larger specific surface in contact with the raw earth matrix. All these characteristics encourage higher bonding between lavender straw and earth.

### 3.4.2 Erosion resistance

Two tests were carried out on two different samples for each formulation. The greater the depth eroded, the lower was the erosion resistance of the material.



**Figure 13.** Erosion depth of the bricks after the erosion test. \* from Laborel-Préneron et al. [22]

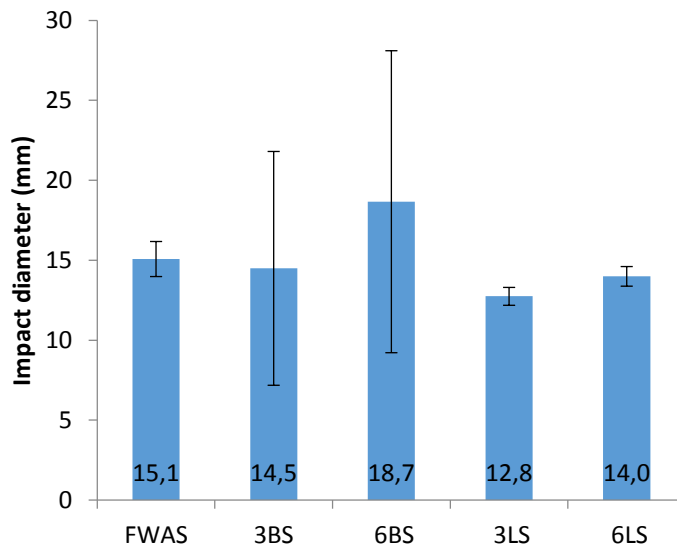
The erosion depth of each mixture is shown in Figure 13. The erodibility index has been added on the right of the graph. The least erosive brick was 6LS followed by 6BS, 3BS and FWAS. The 6LS mixture was lower than class 3 on the erodibility index, which corresponds to a little erosive material. 6BS, 3BS and 3LS specimens were class 3, which is erosive, and FWAS bricks were class 5, which corresponds to failing the test.

A difference of behaviour was noted between the various mixtures. For the FWAS and BS specimens, all the water dripped was absorbed by the bricks whereas it tended to trickle over the bricks containing lavender straw.

The results show that the addition of straw to an earth brick increases its erosion resistance and allows it to satisfy the New Zealand standard [26] for adobe for building purposes. Moreover, the higher the proportion of straw, the greater the increase in resistance. However, for the mixtures with 3% of straw, the least erosive mixture was the one with barley straw whereas, for the mixtures with 6% of straw, the best performance was obtained with the mixture with lavender straw. As 3BS results came from another study and in view of the large uncertainty of measurement for this mixture, it can be said that lavender straw brings better resistance to erosion. According to the visual observations during the tests, the good cohesion between lavender straw and earth seems to be the reason for the good performance of this straw, since lavender straw particles prevent the penetration of water into the sample. In contrast, the impacts of drops seem to dissociate barley straw from the earthen matrix.

### 3.4.3 Sphere impact resistance

The impact diameters on the bricks tested are presented in Figure 14.



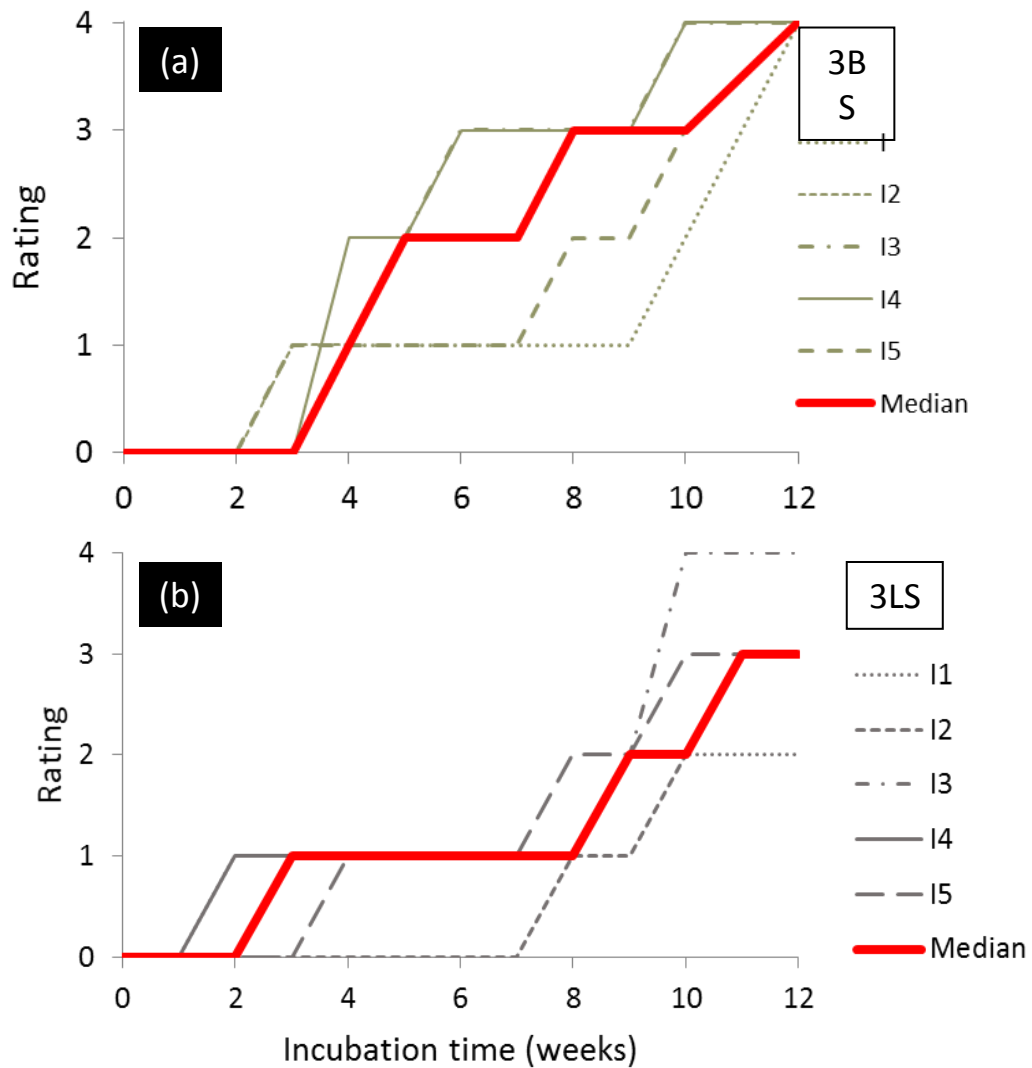
**Figure 14.** Impact diameter on the bricks

FWAS specimens presented cracks after the first impact and eventually broke. Other specimens did not show any cracks and the impact marks were not very visible. The resilience of these bricks leads to high measurement uncertainty for the BS mixtures and makes the result difficult to interpret as the only parameter taken into account is the diameter. Nevertheless, the general behaviour that emerges is that the addition of straw increases the ductility and decreases the depth of the impact.

### 3.5 Mould growth kinetics

The following results concern only the inoculated samples. The tests were limited to the 3LS mixtures in order to be compared to the study of 3BS by Laborel-Préneron et al. [29]. As for the bioaggregates studied by Laborel-Préneron et al. [29], no growth was reported for the 84% RH condition on the 3LS samples. Fungal growth was observed for the relative humidity of 93%.

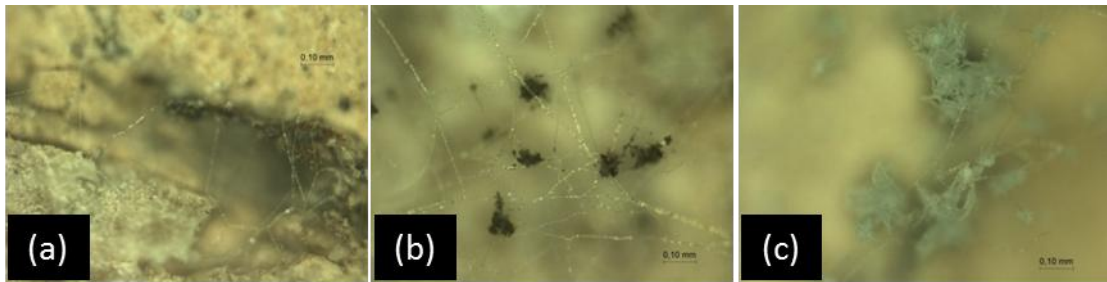
The growth was described as a function of time and was analysed using the rating attributed each week (to each sample and the median value) for 3BS and 3LS specimens (Figure 15).



**Figure 15.** Rating for (a) 3BS [29] and (b) 3LS samples (93% RH, 30 °C)

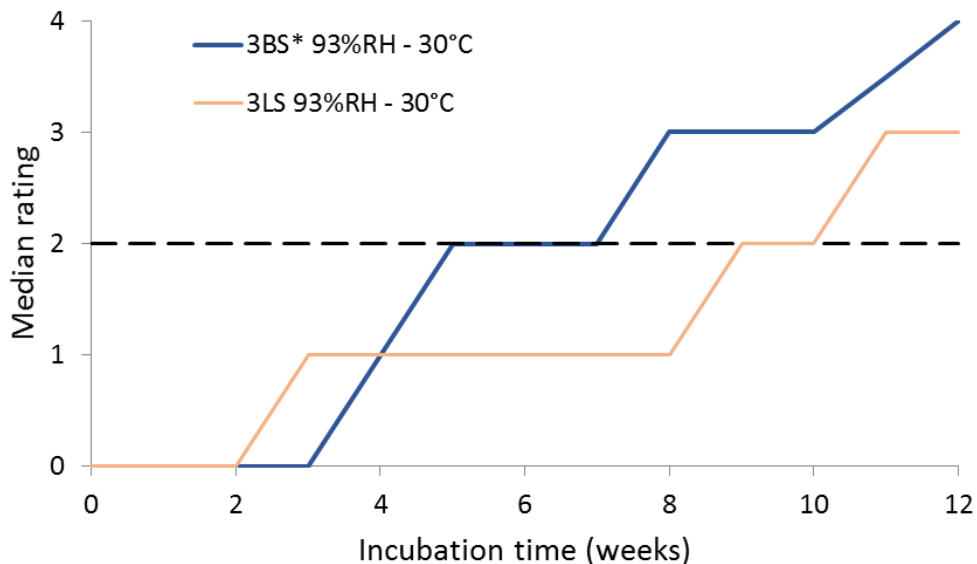
It appears that mould growth started earlier for the 3LS specimen but the colonization of the 3BS specimens was faster and the mould reached more advanced stages, with a large variation of rating between the five specimens and marked fungal diversity.

For the 3LS samples, the first observation of proliferation started with a growth of hyphae (rated 1) 2 weeks after the inoculation. The time when the median rating reached the critical threshold (rated 2) coincided with the occurrence of conidiophores after 9 weeks of incubation (Figure 16). All the 3LS specimens followed approximately the same development.



**Figure 16.** Mould observed with the microscope on 3LS samples for the 30 °C and 93% RH condition: (a) hyphae at the 7<sup>th</sup> week, (b) black conidia at the 9<sup>th</sup> week and (c) green conidia at the 10<sup>th</sup> week

It was observed that the samples least affected by mould had a particularly smooth surface. This is in accordance with the study of 3BS specimens [29], where first growth was often observed to occur on wisps of straw. For the 3LS samples with the most mould, it was noted that growth often started at a point in contact with the site of inoculation and at the interface with a straw particle, whereas Laborel-Préneron et al. [29] state that the first occurrence of growth for 3BS specimens was not exclusively on inoculation sites.



**Figure 17.** Median rating for 3BS\* [29] and 3LS specimens.

The threshold is represented as a dotted line in Figure 17. The figure shows that, under these severe conditions (93%RH – 30°C), the 3LS specimens reach the critical threshold (when mould becomes unacceptable) much later than 3BS specimens. Thus, lavender straw mixture gives better results than barley straw in terms of fungal growth resistance. This behaviour could be explained by the particular chemical composition of lavender, which is mainly composed of polyphenols and aroma substances [48]. According to several authors, polyphenols have beneficial antioxidant activities [49–51], and also antimicrobial and insecticidal properties [52,53]. The aromatic compounds have antibacterial, anti-fungal and insecticidal properties [54,55]. These compounds are probably found in the lavender straw, explaining the better performance of this straw against mould growth.

#### 4. CONCLUSION

Two straws have been studied and tested in proportions of 3% and 6% by mass in an earth matrix: barley straw and lavender straw. Their influence on compressive strength, thermal conductivity, durability properties and mould growth have been studied. Both earth-with-straw mixes show good resistance to impact. Whereas barley straw mixtures have the best thermal conductivity, lavender straw mixtures show the best performances in terms of compressive strength, dry abrasion resistance, erosion resistance, and resistance to mould growth. The addition of lavender straw also improves the thermal insulation. According to the various results, lavender straw seems to be the most suitable straw to use in earth bricks but should rather be added in a proportion of 3% to keep a satisfactory compressive strength, associated with good performance and regular results in the other tests. The better results of lavender straw could be linked not only to its denser microstructure and its rougher surface, which favour good adhesion at the straw / earth interface, but also to its particular chemical composition.

These results highlight the importance of considering several ways of recycling agricultural by-products in building materials. These materials show particular intrinsic properties which can be very beneficial for some applications but problematic for others. This is the case of lavender straw, whose high concentration of water-soluble substances induces setting delays and greatly disrupts the curing mechanisms of mineral binders, making its use in plant concretes very difficult [15,56]. In contrast, its incorporation into a raw earth matrix, in which curing takes place by the evaporation of water, seems to be promising.

Whereas cereal straws are widely used as litter in the agricultural sector in France, nearly half of the straw produced after lavender distillation is currently unused and becomes an agroindustrial residue stored near the distilleries, constituting an obstacle to the development of the essential oils industry. It is estimated that 15 000 tons of lavender and lavandin straws are non-recycled in France each year. Thus, the use of lavender straw as a bioaggregate in earth bricks could lead to a decrease in the waste accumulated. Moreover, its use seems to improve the durability and the thermal insulation of earth bricks, while providing acceptable mechanical and mould growth resistances, thus making lavender straw an interesting bioaggregate for use in buildings.

Nevertheless, the hygrothermal characterization should be completed with measurements of hygroscopic properties (such as water vapour permeability, sorption and desorption isotherms and Moisture Buffer Value (MBV)). In addition, if they are to be marketable, it will be necessary to manufacture bricks with lavender straw in local brickyards of the south-east of France, where the straw is available. Two techniques could be used for the manufacture of earth bricks containing lavender straw: compaction or extrusion. Further real-scale experiments are thus needed to transfer the results obtained in this study to the industrial production of earth bricks and to study the feasibility of manufacturing these bricks using the standard extrusion process.

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