Experimental assessment of bio-based earth bricks durability

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Abstract. Construction is one of the most polluting industrial sectors, that is the reason why developing sustainable building materials is a world-wide interest. Earth bricks have recently been more and more studied, mainly regarding their mechanical and hygrothermal properties. The interest in adding plant aggregates to an earth matrix, notably to improve the thermal behaviour, has also been shown. However, durability of the materials is a major concern to sustain performance levels, to limit maintenance and to ensure the comfort and safety of the occupants. Although earth construction seems to be durable, with the various examples of the vernacular heritage in France and all over the world, unstabilised earth is quite sensitive to environmental factors (weather, occupants, micro-organisms). The resistance of an earthen material to liquid water is particularly low, and the addition of plant fibres may decrease its resistance even more. Moreover, the incorporation of organic matter, containing cellulose, raises questions about the composite resistance to moulds. Investigations are thus needed to assess several durability properties. The present paper studies and compares durability of earth bricks containing 0% and 3% weight content of barley straw, lavender straw and rice husk. Some durability tests corresponding to weathering or occupants' actions are conducted: a wet erosion test is performed to simulate rain or accidental water droplets and the resistances to dry abrasion and to impact are also appraised. The resistance to fungal growth is also investigated. Results show a considerable interest in adding lavender straw in earth bricks. Indeed, a very good compromise has been found concerning properties of weathering durability and to microorganisms. The addition of lavender straw improves the dry abrasion resistance of earth bricks whereas rice husk and barley straw additions decrease it. The two types of straw greatly increase the resistance to wet erosion of earth bricks while rice husk only in a smaller extent. Concerning the brick resistance to impact, its behaviour is considerably improved by the addition of the three kinds of plant aggregates, particularly rice husk. Finally, as expected, the bricks made of earth alone are the more resistant to fungal growth. However, the addition of rice husk maintains a very high resistance with the first mould observed after only 10 weeks of incubation at 93% of relative humidity and 30°C.

1. Introduction

Earthen building materials are increasingly being recognized for their huge availability, their low environmental impact and their capacity to regulate indoor climate [1]. However, they can present major drawbacks, such as low resistance to liquid water or poor ductility and shrinkage. Some of these aspects can be partially improved by the addition of plant aggregates [2]. These resources are renewable, being

agro-industrial by-products, and are available in huge amounts. Their use is thus environmentally friendly. Several studies have dealt with bio-sourced earth bricks or plasters [3–6] but few of them focus on durability [7]. However, durability of the materials is a major concern to sustain performance levels, to limit maintenance and to ensure the comfort and safety of the occupants.

A huge amount of plant aggregate types has been tested in an earth matrix [6], such as cassava peels [8] or millet residues [9], but few of them were studied in several studies. It is the case of cereal straw, observed in 17 references of the 50 reviewed by Laborel-Préneron et al. [6], hemp hurds, observed in 5 references or wood shavings in 11 references. However, uncommon agricultural by-products, locally available, could be of interest for a use in sustainable earth materials.

Portugal and France are 2 of the 5 main rice producers in Europe. With this industry, they both produce rice husk, which is the protective coat of the grain. This agro-industrial by-product, often considered as waste, is known to be rot-proof and resistant to insects. It appears that adding unground rice husk into unfired earth bricks has never been studied, although rice husk has been investigated in several other building material applications, mainly to create lighter fired bricks that can improve thermal insulation [10–11] or lightweight concrete with a lime-based binder [12].

Lavender straw is a by-product widely available in France, where the production of lavender flower is up to 40 tons per year in the southeast of the country. Once distilled, the lavender straw becomes an agro-industrial waste that is stored near the distilleries. To the authors' knowledge, the addition of 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 [13], without showing a very high potential.

In this study, 0% and 3% weight content of barley straw, lavender straw and rice husk were incorporated into earth bricks and their effect on some durability properties were assessed. The influence of the type of plant aggregate on wet erosion, dry abrasion, impact and fungal growth resistances were thus analysed.

2. Materials and methods

2.1. Raw materials

Fines from limestone aggregate washing process (FWAS) were used for this investigation. These fines have a high proportion of limestone (around 60%) and only around 20% of clay. Barley straw, lavender straw and rice husk were also tested in the earth matrix in a proportion of 3% by dry mass. The rice husk was used directly and is about 1 cm long; barley and lavender straw were previously cut, at about 1 cm long. The manufacturing water content was determined with the Proctor test. Formulations of the different types of brick specimens are recapitulated in Table 1.

Table 1. Mixture proportions and Proctor density of specimens

Specimen	Plant aggregate type	Plant aggregate content (weight %)	Water content (%)	Dry density (kg.m^{-3})
FWAS	-	0	14	1988 ± 9
3BS	Barley straw	3	19	1520 ± 1
3LS	Lavender straw	3	18	1772 ± 17
3RH	Rice husk	3	17	1813 ± 20

2.2. Manufacturing process

To manufacture the specimens, earth and plant aggregate fractions were poured into a blender and mixed by hand. Water was then added and the materials were mixed mechanically in the blender until a homogeneous mix was obtained. The raw materials were mixed the day before moulding.

For purposes of the different tests, the specimens were manufactured in different sizes: 15 x 15 x 5 cm^3 for wet erosion, dry abrasion and impact resistance tests and cylinders 5 cm in diameter and 1 cm

high for fungal growth test. The specimens were manufactured by static compression. They were then dried at 40°C for 24 hours followed by an increase in temperature until 100°C at a rate of 0.1°C.min^{-1}. This temperature was finally kept constant until the weight became constant (weight variation less than 0.1% between two weighings 24 hours apart).

2.3. Wet erosion

The wet erosion test was performed on the 15 x 15 x 5 cm^3 specimens to simulate rain droplets. It was carried out according to the New-Zealand Standard NZS 4298 [14], intended for non-stabilised adobes and Compressed Earth Blocks (CEB), based on the Geelong method. The Geelong test is proposed especially for adobe possibly containing straw. An amount of 100 ml of water is allowed to drip from a height of 400 mm onto the specimen, which is inclined at 30°. The duration of the test was between 20 and 30 minutes and the pit depth was measured. An erodibility index, between 3 and 5, 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.

2.4. Dry abrasion

Dry abrasion was evaluated on the 15 x 15 x 5 cm^3 specimens, according to the French standard XP P13-901 [15] intended for CEB 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 by Giroudon et al. [16].

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. 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 cm^2.g^{-1}, was then calculated as the ratio of the brushed area (in cm²) over the loss of mass (in g) after the brushing. The higher is the coefficient, the more resistant to abrasion is the material.

2.5. 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 x 15 x 5 cm^3 specimens. The test was inspired by ISO 7892 [17] with a small, hard impact body.

The device consisted of a spherical metallic mass of 500 g on a metallic stalk that is attached to the wall. It was dropped from the horizontal position onto the specimen located vertically underneath in contact with a very rigid wall. The energy created by the test was 3 joules. The diameter of the impact point was measured, and the cracking and general behavior of the bricks were assessed.

2.6. Fungal growth

The aim here was to compare the kinetics of mould development on specimens containing 0 or 3% of either barley straw, lavender straw or rice husk in order to determine the influence of the type of bioaggregate on the proliferation. According to Palumbo [18], 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. [19].

Fungal growth was assessed on the cylindrical specimens (5 cm in diameter and 1 cm high). In order to create good conditions for microscopic observation, the two faces of the specimen were polished to limit their roughness. They were then coated with a polyester resin, except over a square area of 3 x 3 cm², which was the surface to be investigated. A decontamination has been achieved just before starting

the study of mould growth by exposing the specimens to a temperature of 100°C for 24 hours. Specimens were allowed to cool for 30 minutes after the decontamination before being inoculated.

Artificial inoculation of a fungal suspension of *Aspergillus brasiliensis* spores was realized with a pipette so that the spore quantity deposited on each specimen was known exactly. This inoculum was concentrated at 3.10^5 conidia * mL^{-1} and 5 µl was pipetted onto each on 5 different spots of the surface, thus permitting rapid drying of each drop. Five specimens were inoculated, while two additional specimens, serving as controls, were not.

To avoid cross-contamination, each specimen was placed in a box where the relative humidity was maintained constant using a saturated saline solution [20]. Two different salts were used here to obtain 2 different RH conditions: a solution of potassium nitrate (KNO_3) to obtain 93 % RH and a solution of potassium chloride (KCl) to obtain 84 % RH. According to Johansson et al. [21], 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 sealed plastic box in which the saturated saline solution and the specimen on its holder were placed. The materials were placed in a climatic chamber at 30°C to provide severe thermal conditions [22].

For microscopic observation, the plastic box was opened once a week and the specimen was removed with its holder in order to avoid touching it. The observation was made using a Zeiss optical microscope (magnification 10X), scanning the whole square area in order to detect mould growth. The assessment of the fungal growth was made using the following rating scale, proposed by Johansson et al. [23]:
- 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. Wet erosion

Three tests were carried out on three different brick specimens for each formulation. The results of the erosion test are shown in Figure 1. The erodibility index has been added on the right of the graph.
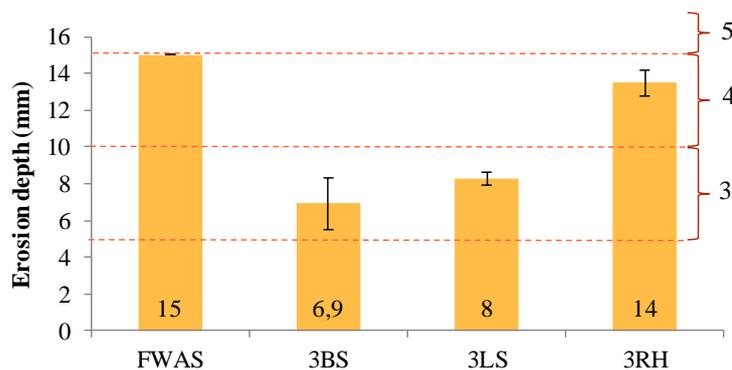

Figure 1. Erosion depth of the bricks after the wet erosion test

The least erosive formulation is 3BS followed by 3LS, 3RH and FWAS. According to the erodibility index, 3BS and 3LS specimens are class 3, which is erosive according to Frencham [24], 3RH specimens are class 4, very erosive, and FWAS specimens are borderline between class 4 and 5, which means, close to fail the test, according to the New Zealand standard [14].

A difference of behaviour has been noted between the various mixtures. For the FWAS, 3BS and 3RH 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 plant aggregate to an earth brick increases its erosion resistance and allows it to satisfy the New Zealand standard [14] for building purposes. This observation is particularly true in the case of the two types of straw.

3.2. Dry abrasion

The results of dry abrasion tests are presented in Figure 2. The higher the coefficient of erosion is, the better is the durability of the brick. Two brick specimens were tested for each mixture, with two tests per specimen.
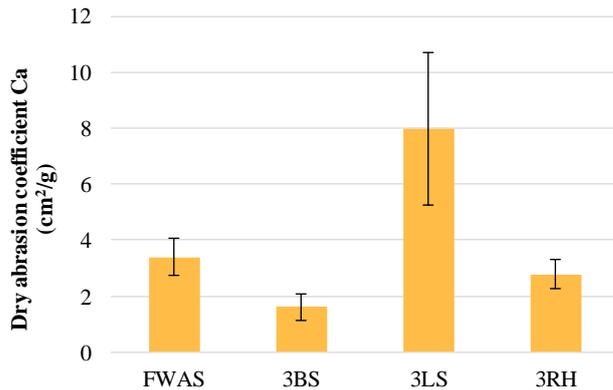

Figure 2. Dry abrasion coefficients of the bricks

Differences of dry abrasion resistances between the formulations are particularly marked, especially between the two types of straw. 3BS specimens have the lowest abrasion coefficient (1.6 ± 0.5 cm^2.g^{-1}), followed by 3RH with 2.8 ± 0.5 cm^2.g^{-1}, FWAS with 3.4 ± 0.7 cm^2.g^{-1} and 3LS with 8.0 ± 2.7 cm^2.g^{-1}.

The results show that the addition of lavender straw to an earth brick greatly increases its dry abrasion resistance whereas the addition of barley straw or rice husk decreases it. This can be explained by the different morphologies of the plant aggregates: according to Giroudon et al. [16], 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 the earth matrix.

3.3. Impact resistance

The impact diameters on the brick specimens tested are presented in Figure 3. Pictures of the bricks after the test are shown in Figure 4. The occurrence of cracking, observed visually, denotes a lower deformability, which is negative, while the capacity to recover shape indicates resilience, which in turn is interesting for a building material.
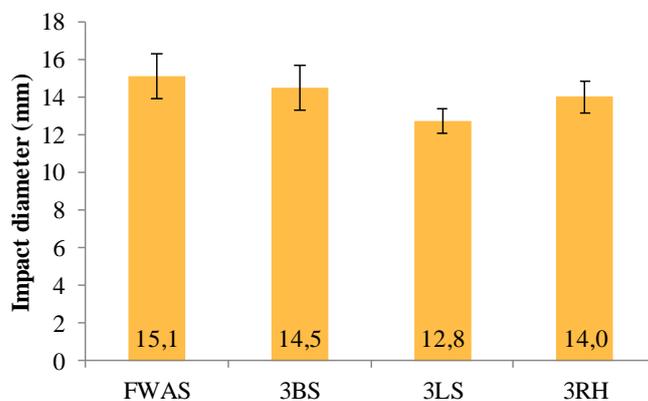

Figure 3. Impact diameter on the bricks

| FWAS | 3BS | 3LS | 3RH |

Figure 4. Specimens after sphere impact test

As can be seen in Figure 3, impact diameters are 15.1±1.2, 14.5±1.2, 12.8±0.7 and 14.0±0.8 mm respectively for FWAS, 3BS, 3LS and 3RH specimens. 3LS bricks presenting the lowest impact diameter may be considered as the most resistant formulation among the four mixtures tested.

In addition to the quantitative result of the impact diameters, Figure 4 gives qualitative result about the bricks' behaviour after impact. FWAS specimens presented cracks after the first impact and eventually broke. The other formulations did not show any crack and the impact marks were not very visible due to the high resilience of these materials. To conclude with both parameters considered, the general behaviour that emerges is that the addition of plant aggregates, decreasing dry density (Table 1), increases the earthen material ductility and decreases the depth of the impact.

3.4. Fungal growth

After 12 weeks of monitoring, no proliferation was observed for an incubation at 84% RH for any material. Mould growth was not found on non-inoculated specimens except on one 3LS specimen, until rate 1 only. Results are thus shown only for inoculated specimens, incubated at 93% RH and 30°C (Figure 5). The growth was described as a function of time and was analysed using the rating attributed each week (median value of the 5 specimens) for FWAS, 3BS, 3LS and 3RH specimens. A critical threshold is drawn at a rating of 2, which corresponds to a specimen with conidiophore. Conidiophore is indeed the part of the mould that can affect the health of the occupant.
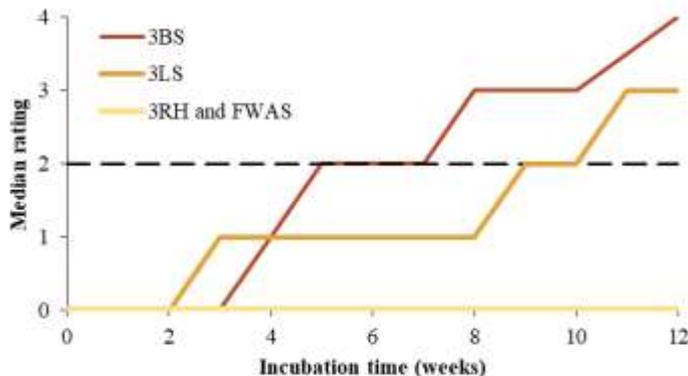

Figure 5. Median rating for inoculated specimens at 93% RH and 30 °C

Figure 5 shows a median rate for fungal growth of FWAS and 3RH specimens equal to zero. For the 3RH specimens, mould was detected on a rice spot only on one inoculated specimen after 10 weeks of exposure at 93% RH and 30°C. In the case of FWAS specimens, a proliferation rate of 1 was observed on two specimens from week 8 until the end of the test. It appears that mould growth started earlier for the 3LS specimens compared to the 3BS ones, but the colonization of the 3BS specimens was faster and the mould reached more advanced stages, until rate 4 after 12 weeks of incubation, with a large variation of rating between the five specimens. The critical rate of 2 was reached after 5 weeks in the case of the 3BS specimens whereas it was reached after 9 weeks of exposure in the case of 3LS specimens.

The earthen bricks made with rice husk (3RH) and the ones of earth alone (FWAS) present the highest microbial resistance, followed by the bricks made with lavender straw and finally the one

containing barley straw. In the case of the FWAS specimens, the very high resistance to microbial proliferation is due to the lack of carbon source necessary for the microbial growth. The difference of fungal growth resistance between the bio-based bricks can be explained by the differences of chemical compositions between the plant aggregates. According to Harper and Lynch [25], lignin is resistant to most microbial attacks. Rice husk chemical composition is made of 26 to 31% of lignin [26], while lavender straw contains 23 to 25% of lignin [27 cited in 28] and barley straw contains 5 to 16% of lignin [29]. It is most probable that the higher lignin content of rice husk makes the 3RH specimens more resistant to fungal growth than the 2 other materials.

4. Conclusion

This work allowed the addition of three plant aggregates in earth bricks to be compared in terms of durability. Earth bricks without any plant aggregates and earthen bricks containing 3% weight content of barley straw, lavender straw and rice husk were studied. Four durability tests corresponding to weathering, occupants use or microorganisms' actions were conducted.

Overall, the experimental tests have shown that the addition of plant aggregates in an earth matrix enhanced the durability properties of earth bricks. More specifically, the wet erosion resistance was improved by the addition of plant aggregates, particularly in the case of the two types of straw (lavender and barley). Dry abrasion resistance was greatly increased by the addition of lavender straw, but the two other plant aggregates decreased it in comparison to bricks of earth alone. The three types of plant aggregates allowed the material to resist to an impact without any crack. Finally, fungal growth resistance was the highest for earth alone bricks and with the rice husk addition. Lavender straw still gave good fungal resistance compared to barley straw.

Because of their distinct morphologies and chemical compositions, plant aggregates do not affect the earth matrix in the same way. According to the various results, lavender straw and rice husk seem to have a very high potential of use in earth bricks.

Although this study needs to be completed with some mechanical and hygrothermal tests to validate the use of such plant aggregates, these results highlight the importance of considering various agro-industrial 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 [13, 30]. In contrast, its incorporation into a raw earth matrix, in which curing takes place by the evaporation of water, seems to be promising.

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