INFLUENCE OF STRAW CONTENT ON THE MECHANICAL AND THERMAL PROPERTIES OF BIO-BASED EARTH COMPOSITES

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Abstract

Construction is one of the most polluting sectors of industry, which is the reason why developing sustainable building materials is of world-wide interest. Earth is being increasingly studied as a building material because of its low environmental impact and its abilities to regulate indoor moisture and to improve building users' comfort. However, very few studies deal with unfired earth bricks with plant aggregates incorporated into the earth matrix to lighten the material and improve some properties of the composite. In response to such issues, the Bioterra ANR project aims to develop and characterize bio-based earth composites. In this paper, the mechanical and thermal properties of earthen bricks with barley straw are investigated. The proportions of straw used in the present study were 3% and 6% by weight of the earth, which was made of fines from aggregate washing sludge (FWAS). The results showed that the addition of 3% and 6% of straw decreased the compressive strength by 20% and 5% respectively. Concerning thermal insulation, the thermal conductivity of the specimens with 6% of straw decreased by 75%.

Keywords:

Unfired earth blocks, barley straw, compressive strength, thermal conductivity

1 INTRODUCTION

Earth has been used as a building material for thousands of years, as have wood and stone. Nowadays, around 30% of the population still live in earth shelters [Minke 2000], especially in developing countries.

One of the main advantages of building with earth is the availability of the material and its low cost. Moreover, it is ecofriendly because it is abundantly available, recyclable and requires little energy for the transformation process [Minke 2000]. Construction is indeed one of the most polluting industrial sectors and developing sustainable building materials is therefore of world-wide interest. Earth is thus increasingly being studied because of its low environmental impact and its abilities to regulate indoor moisture and to improve the comfort of the building's users.

Nevertheless, earth material has some weaknesses, such as hygroscopic shrinkage, limited durability to water and poor ductility [Aymerich 2012]. Stabilizers are generally used to reduce the disadvantages of these characteristics [Danso 2015]. Stabilizers may be hydraulic binder such as cement or lime, or plant fiber such as straw, hemp or wood shavings, which are renewable and generally locally available. Fibers and excrement have always been used to improve earth properties [Chazelles 2011] but their use was based only on empirical knowledge and not on scientific investigation.

To date, only around twenty studies have dealt with earth bricks where plant aggregates are incorporated into the earth matrix [Danso 2015] and few studies focus on straw incorporated in raw earth. Among the references available, some have shown that shrinkage stabilization occurs earlier with the use of barley straw because the hollow structure of the stems permits accelerated evaporation [Bouhicha 2005]. The addition of straw also modifies mechanical strengths. For instance, compressive strength was improved by 10 to 20% by adding 1.5% of barley straw, but only for the most clayey earth (between 28% and 40% of clay) [Bouhicha 2005]. On the contrary, other studies showed that an increase in the proportion of straw led to a decrease of compressive strength [Yetgin 2008, Mohamed 2013], which was explained by a lower density. The literature also shows differences concerning tensile strength. Tensile resistance was improved by 30% with the addition of 1% of wheat straw [Mohamed 2013], which was justified by the cementation between clay particles. However [Yetgin 2008] observed a decrease in the strength, explained by the weakness of the adhesion between the fibers and the matrix even when there were only 0.6% of fibers. Concerning thermal conductivity, all the results show the same trend: an increase in the fiber content leads to a decrease in thermal conductivity. For example, the thermal conductivity of an earthen plaster containing about 16% by weight of barley straw was reduced by about 56% in comparison with a specimen made only of earth (0.154 and 0.350 W/m/K respectively) [Ashour 2010]. There are very few references to straw included in earth material, especially with more than 3% by weight [Ashour 2010, Ashour 2011, Bouhicha 2005].

This study was carried out in the context of the Bioterra project. This ANR collaborative project aims (i) to characterize earth-based products in terms of their mechanical, hygroscopic and thermal properties, (ii) to characterize the proliferation of microorganisms on these products as a function of various environmental parameters and (iii) to propose solutions to limit the proliferation of harmful microorganisms at the surface of bio-based earth products.

This paper presents the results of an experimental study performed on unfired earth materials with a weight content of 0 to 6% of barley straw. Straw is a local agricultural waste that can lighten the material and improve some of its characteristics. Mechanical and thermal properties were thus measured to enrich the databases of bio-based earth construction materials.

2 MATERIAL AND METHODS

2.1 Materials

Fines from washing limestone aggregate sludge (FWAS) were used for this investigation. These fines have a high proportion of limestone (around 60%) and only around 20% of clay. Before being used, they were stored in plastic bags at room temperature. Barley straw, in pieces 10 to 30 mm long, was also tested in different proportions in the earth matrix. The straw was also stored in plastic bags at room temperature.

2.2 Manufacturing

Three different mixtures were prepared for the various tests: (i) specimens made with FWAS only and specimens containing (ii) 3% and (iii) 6% of straw by weight content, marked S3 and S6, respectively. The water content of the mixtures was determined by the Proctor test. The water content was around 14% for FWAS, 19% for S3 and 21% for S6 (Fig. 1).

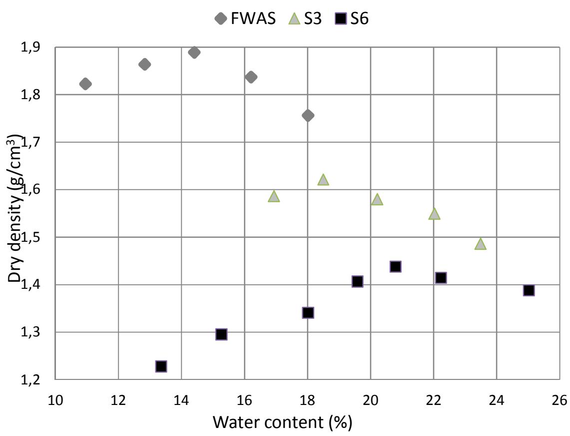

Fig. 1: Proctor curves of the three materials

To manufacture the specimens, earth and straw fractions were poured into a blender and mixed by hand. Then, water was added and the materials were mixed mechanically in the blender until a homogeneous mix was obtained. The raw materials were mixed the day before molding.

Cylindrical specimens 5 cm in diameter and 5 cm high (Φ5H5) Fig. 2, intended for compressive strength tests were manufactured by double static compression at the Proctor density. Specimens (150x150x50 mm^3, Fig. 2) for thermal conductivity measurements were rectangular prisms, manufactured in the same way.

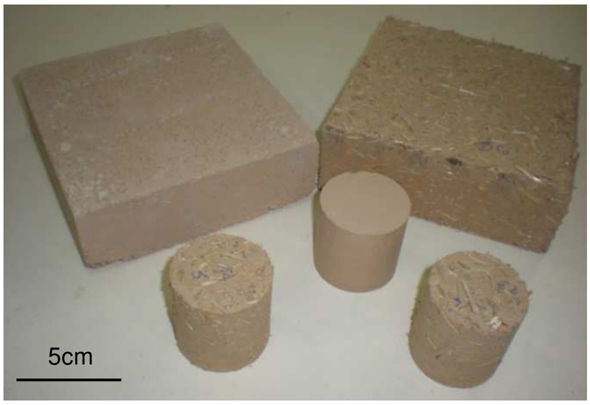

Fig. 2: Cylindrical and rectangular specimens.

The specimens were first dried at 40°C for 24 hours, then the temperature was increased by 0.1°C/min 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) Fig. 3. This rise in temperature was kept slow to keep shrinking homogeneous and to avoid mechanical stresses. The specimens were then stored in a room regulated at 20°C and 50% relative humidity (RH) and were tested from the moment when they were in equilibrium with the environment (about one week later).

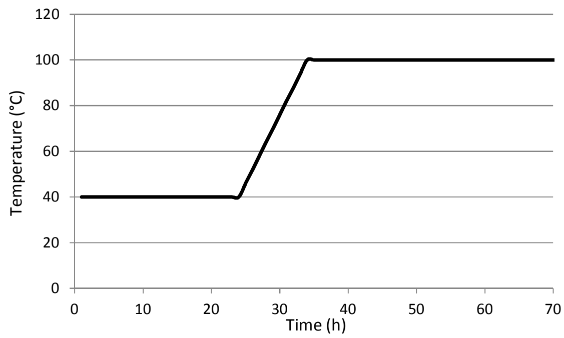

Fig. 3: Specimen drying temperature

2.3 Mechanical and thermal characterization methods

Compressive strength

The compressive strength tests on the Φ5H5 specimens were performed using a 100kN capacity hydraulic press. The load was applied at a constant deflection rate of 3mm/min. This speed was chosen as an intermediate value between the 1.2mm/min specified in the French standard XP P 13-901 [AFNOR 2001] (intended for compressed earth blocks) and the 5mm/min used in [Cerezo 2005] (intended for hempcrete). Three specimens of each mixture were tested in two different tests: one test with the specimen in direct contact with the steel plates (generating friction) and the other including a system avoiding friction. In the latter case, shown in Fig. 4, a 2-mm-thick piece of Teflon and a thin neoprene piece - with a drop of oil between the layers - were put between the earth specimen and the steel (neoprene in contact with the specimen, and Teflon in contact with the steel). Teflon was used because of its low friction coefficient and neoprene because of its high mechanical resistance. Displacements and loads were measured in each case. The Young modulus of each specimen was then calculated from the linear part of the stress-strain curve.

Fig. 4: The compressive test with reduced friction

Thermal conductivity

Thermal conductivity properties were assessed on three 150x150x50 mm^3 rectangular prisms for each composition. The measurements were carried out with the EP500 guarded hot plate apparatus for earth alone and for earth with 6% of barley straw. Before testing, the specimens were dried at 100°C and placed in a desiccator to cool. They were wrapped in a thin plastic film to avoid any humidity uptake during the measurement, which was performed at 25°C with a difference of temperature of 10K between the two plates. Steady state was assumed to have been reached when the change in conductivity was less than 1% in 60 minutes.

3 RESULTS AND DISCUSSION

3.1 Compressive strength

The average of dry density, the maximum compressive strength, the strain corresponding to the maximum compressive strength, the stress corresponding to a strain of 1.5% and the Young modulus of each typology of specimen and for each testing protocol are reported in Tab. 1.

Fig. 5 summarizes the compressive strength of the specimens for the various straw contents (0%, 3% and 6% by weight) and for both protocols: with friction at the interface between the specimen and the press, and with reduced friction. For each composition, the compressive strength measured in the tests with friction was greater than that in tests with reduced friction because of the confinement. The compressive strength of the specimen composed of earth alone was higher than that of S6 and S3, which is in accordance with density values of the various specimens. The average strengths were 4.1MPa for the FWAS, 3.2MPa for S3 and 3.8MPa for S6. The ultimate compressive strength of S6 specimens was higher than that of S3 specimens. This can be explained by a consolidation phenomenon due to the compressibility of the straw. All the results were above the minimal value of 2 MPa imposed by the New Mexico standards for adobe construction [Construction Industries Division 1991] and the value of 1.3 MPa specified by the New-Zealand Earth Building standard NZS 4298 [Standards New Zealand 1998].

However, it is important to note that the ultimate strain was high for S3 and S6 specimens: between 5% and 8% for S3 and between 15% and 20% for S6, whereas it was only between 1% and 1.3% for FWAS. The addition of straw increases the ductility of the composite. In calculating building structures, such deformations of the material cannot be tolerated.

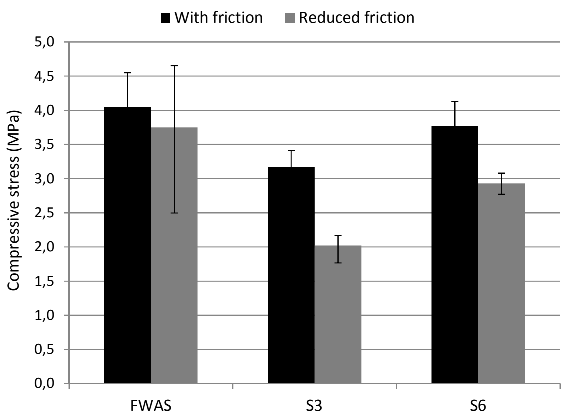

Fig. 5: Average compressive strength of the three compositions with and without friction at the plate-specimen interface.

Tab. 1: Measured mechanical properties of the materials: dry density (d_{dry}) average compressive strength (σ_c), average ultimate strain (ε_a), average compressive strength at 1.5% strain ($\sigma_{c,1.5\%}$) and average experimental Young modulus (E_a)

Test	**With friction**			**Reduced friction (RF)**		
Type	FWAS	S3	S6	FWAS RF	S3 RF	S6 RF
ρ_{dry} (g/cm^3)	1995±0	1519±1	1315±27	1982±10	1520±1	1075±30
σ_c (MPa)	4.0±0.4	3.2±0.2	3.8±0.3	3.9±0.9	2.0±0.2	2.9±0.1
ε_a (%)	1.3±0.1	7.8±0.6	19.9±1.1	1.0±0.1	5.6±0.5	16.6±1.4
$\sigma_{c,1.5\%}$ (MPa)	3.9±0.7	0.7±0.1	0.4±0.0	1.6±0.5	0.6±0.0	0.3±0.0
E_a (MPa)	439±54	62±3	31±1	564±161	43±5	25±0

To limit these deformations and to compare the materials, we chose to limit the strain to 1.5% and to keep the corresponding compressive strength value, as described by [Cerezo 2005] for hemp concrete. The maximal compressive strength was kept in cases when the failure occurred before 1.5% strain (for the specimens of FWAS alone). These values are compared with the values at failure in Fig. 6. For a given deformation, compressive strength is higher for FWAS specimens. The value does not reach 1 MPa for the S3 and S6 specimens. S3 specimens present higher compressive strength for a strain of 1.5% than S6 specimens, which is in accordance with their respective densities.

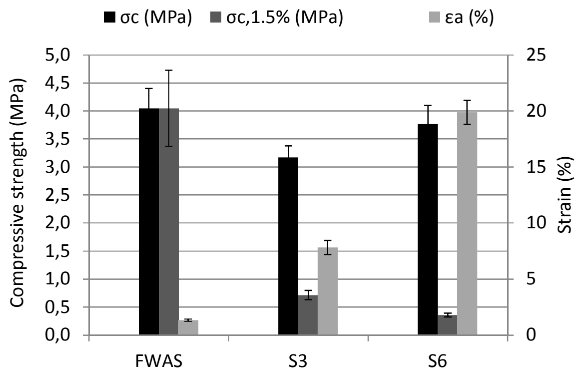

Fig. 6: Maximal compressive strength (σ_c), compressive strength at 1.5% strain ($\sigma_{c,1.5\%}$) and strain at maximal compressive stress (ε_a) for the test with friction.

Young moduli were obtained from compressive strength tests and they are recapitulated in Fig. 7, in function of the testing protocol (with reduced friction or not). Friction did not seem to have any great influence on the modulus, which was of the same order of magnitude for both situations. The most striking result visible in the figure is that the FWAS specimen had the highest value (around 500 MPa). The Young moduli of the specimens containing 3% and 6% of straw were far lower (around 50 MPa and 30 MPa respectively). The FWAS specimens presented the highest stiffness of the different types. The increase of straw content significantly decreases the Young modulus.

This result is in agreement with various references [Al Rim 1999, Chee-Ming 2011, Piattoni 2011, Quagliarini 2010, Yetgin 2008], in which it is stated that the straw addition controls the plastic behavior of the specimen due to a lower homogeneity of the mixture.

Fig. 8 presents typical stress-strain plots for the different compositions and protocols. Specimens not reinforced with straw showed brittle rupture after the maximum load. The manners of breaking were similar for the S3 and S6 mixtures. Although these specimens were weaker, they were also more ductile, with a larger zone of plasticity. Ductility improved with increasing barley straw content. These curves also show that the elastic modulus decreased with the straw content and that it was only slightly influenced by the type of test.

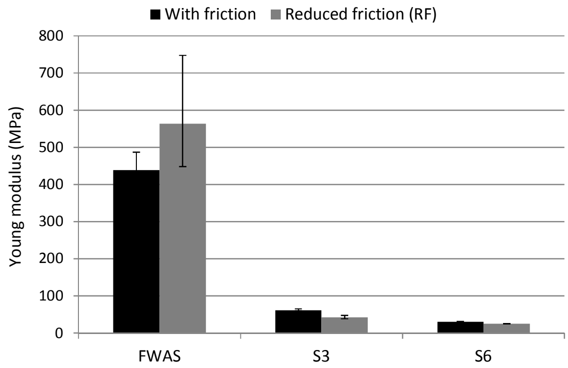

Fig. 7: The Young modulus of the materials for both protocols

3.2 Thermal conductivity

Tests were performed on three specimens for the two compositions. Fig. 9 presents the average values of thermal conductivity obtained: 0.57±0.04 $W.m^{-1}.K^{-1}$ for FWAS specimens and 0.14±0.01 $W.m^{-1}.K^{-1}$ for S6 specimens. The results show that the thermal conductivity decreased by about 75% with the addition of straw in comparison with the FWAS specimen. This decrease of thermal conductivity with an addition of plant aggregate has been widely reported in the literature [Al Rim 1999, Ledhem 2000]. It is linked with a decrease in density of the composite material. The improvement of thermal insulation demonstrates the interest of studying fibered earth bricks.

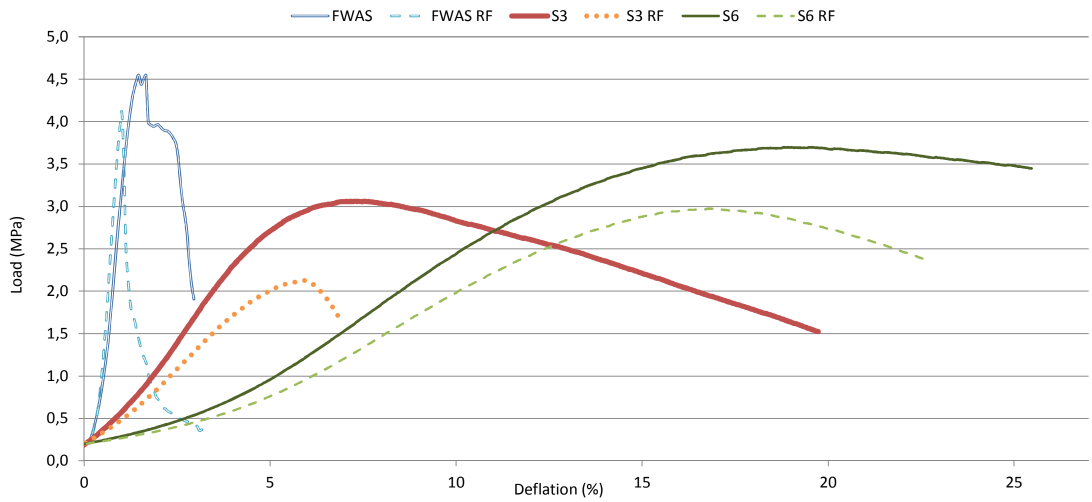

Fig. 8: Typical stress-strain curves of the different specimens with friction at the interface with the plates and with reduced friction (RF)

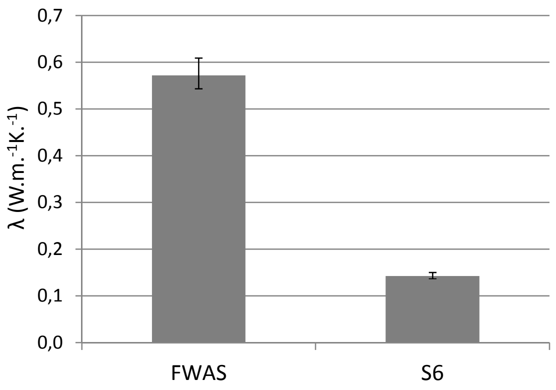

Fig. 9: Thermal conductivity of the materials

Fig. 10 represents the thermal conductivity in function of the dry density of the studied materials and other bio-based materials from the literature, in general with an earth matrix. All the results come from experiments except those of [Laurent 1987] which are from a theoretical model. This graph allows the materials of the present study to be compared with others. The values are of the same order of magnitude as those in the literature. It also confirms that thermal conductivity decreases with the dry density.

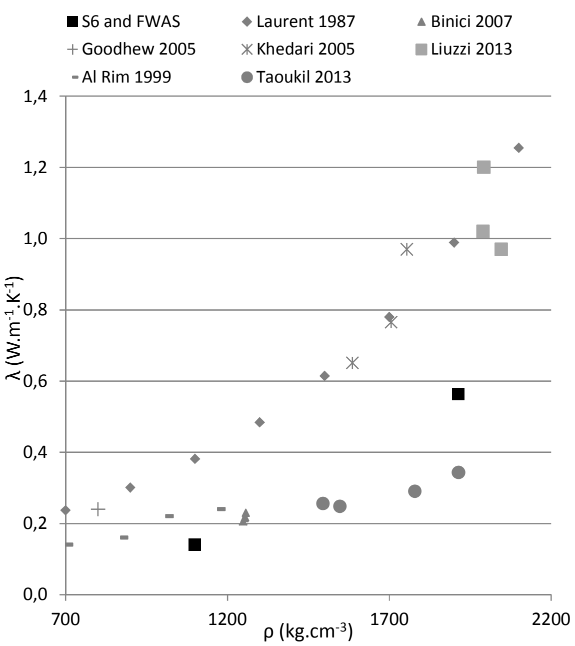

Fig. 10: Comparison of thermal conductivity of experimental values and values from literature.

4 CONCLUSION AND OUTLOOK

This work investigated the effects of additions of 3% and 6% of barley straw on the compressive strength of earth blocks and their thermal insulation properties.

The compressive test results showed that a FWAS specimen had the highest strength. Adding straw decreased the compressive strength, but only by 5% for the S6 specimens and 20% for the S3 specimens. The tests carried out with reduced friction generated lower strength values than the higher friction test. These values give more accurate values for the compressive strength of the materials but the values with confinement were kept for comparison with measurements found in the literature.

By increasing the straw content to 6% by mass, the thermal insulation was increased by 75%. The results confirmed that the thermal conductivity decreased when the material was lightened. These results confirm the interest of using light plant aggregates in earth bricks to improve the thermal insulation provided by these materials and thus to make significant savings in the energy used for heating buildings. The effect of the addition of other types of plant aggregates will be studied in further experiments. Moreover, it will be necessary to study the hygroscopic properties of the bio-based earth products in greater depth because these properties will strongly influence the possible development of microorganisms.

5 ACKNOWLEDGEMENT

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