

Rice husk bio-based composite panel for buildings construction and refurbishment

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Abstract

Securing sustainable access to raw materials, including agro-industry-based raw materials is of high importance for the EU economy. Strengthen the competitiveness of the European raw materials industries requires to demonstrate that raw materials can be produced in an innovative and sustainable way. This research highlights that economic and ecological bio-based composite based on rice husk and an earthen matrix panels can be used as indoor wall or ceiling coatings, contributing to hygrothermal comfort and health, in new and existing buildings.

Three different composite formulations were produced differing on the content and pre-treatment of the rice husk: 15 % and 30 % rice husk, considered the maximum possible to cast the composite; with 30 % rice husk only dried or previously boiled. Composite samples were tested for cracking and biological development, thermal conductivity, bulk density, ultrasound velocity, dry abrasion, flexural and compressive strength, moisture buffering and behaviour in case of fire. It is shown that some properties clearly depend on the rice husk content and the pre-boiling. Increasing on rice husk content decreases thermal conductivity due to bulk density decrease, decreasing ultrasound velocity, flexural strength, abrasion and fire resistance, but improving the moisture buffering capacity at least in 20%. For high plant-content composites, the pre-boiling of rice husks decreases the biological susceptibility although decreasing resistance to fire, most probably due to destruction of the cellulose wall but significantly increases abrasion resistance and compressive strength, probably due to a better bond between the rice husk and the earthen matrix, quicker reaching a high water vapour adsorption limit.

Keywords: Rice husk; Bio-based composite; Building refurbishment;; Earth; Airlime; Gypsum; Hygrothermal; Insulation; Massive wall; Plant fiber.

1. Introduction

The interest in the use of bio-based composites in the building sector has increased due to the possibility of reusing agricultural waste, their overall low environmental impact and embodied energy, their biodegradability and non-toxic nature [1-4], in comparison with conventional materials. The impact of climatic aging has been studied, for instance on the characteristics of gypsum-fibre composites [5]. Besides their environmental benefits, bio-based composites have generally high hygroscopicity, which is one of the most important factors to maintain a healthy indoor air comfort [6-7]. According to several studies, the indoor air quality is one of the major risk factors for human health, once humans spend many hours of their life indoors. Therefore, it has become a priority to find ways to improve indoor air quality, by using safe building materials with low impact. It is also important to establish indoors a healthy equilibrium between the indoor temperature and the relative humidity (RH), improving the hygrothermal performance of buildings [8-11].

Earth, being a natural and available construction material with a high hygroscopic behaviour [12], becomes ideal to control the indoor air RH, improving the comfort of the occupants [13,14]. The hygroscopic behaviour is translated by the ability of the earth to adsorb the humidity excess in the air, releasing it when the temperature rises and the air dries [15]. This adsorption-desorption cycles have a cooling effect on the indoor conditions, turning earthen products similar to natural air conditioners [15,16]. However, despite all the advantages mentioned, earth materials have also weaknesses like its poor ductility and water resistance [17]. To face these problems several researchers studied the addition of natural fibres and low binder content to produce earth composites. Nevertheless, the use of natural fibres can increase the susceptibility for biological development [18].

Regarding the mechanical properties, the opinions are quite divided. While some authors defend that adding natural fibres to earth composites increases their mechanical resistance, others say the inverse. Of course, this depends on the type of earth composite. Millogo et al. [19] verified that the addition of hibiscus cannabius fibres to earth blocks increased both compressive and tensile flexural strength. Lima & Faria [20] observed that the addition of fibres to earth plasters could have different results. While oat straw decreased the mechanical resistance, typha wool increased it, suggesting that the influence of the natural fibres on these properties is connected to the fibre characteristics. In fact, the type of natural fibres and the fibre content have significant influence on the mechanical behaviour of earth composites [21].

60 Increasing the particle content led to a decrease in the earth content and thus a decrease in the composite dry
61 density. However, the decrease of the density tends to not be significant for a fibre content above 15-20% [10].
62 The addition of natural aggregates to earth composites leads to a decrease in bulk density, improving
63 (decreasing) the thermal conductivity. Ashour et al. [22] concluded that the increase of barley straw content to
64 earth plasters decreased the thermal conductivity to almost half. This conclusion is in accordance with most
65 researchers that studied the theme [12, 20, 23,24]. The addition of natural aggregates to some composites
66 may also increase the risk in case of fire. Laborel-Préneron et al. [25] tested the fire behaviour of earth blocks
67 reinforced with natural fibres. The test consisted in placing a sample below a radiator acting as a source of
68 heat, removing the radiator when the sample started burning. During the test no flame was observed, only the
69 smouldering of the natural aggregates in the beginning of the test producing smoke, showing that a higher
70 fibre content leads to higher smoke production.

71 Hemihydrate gypsum is a binder produced at very low temperatures (120-180°C) and with a very fast drying.
72 When added to earth composites it is known for improving the thermal conductivity and the compressive and
73 flexural strength of the composites [26,27]. Lima et al. [27] concluded that the increase of gypsum content on
74 earth plasters increased their mechanical strength. Also, Binici et al. [28] and Ashour et al. [29] studied the
75 influence of gypsum addition to earth composites reaching the same conclusion. Therefore, it seems that the
76 relatively low mechanical resistance of earth composites can be improved by using binder stabilisers as
77 gypsum.

78 Regarding the thermal conductivity, Binici et al. [28] and Ashour et al. [29] studies showed that the addition of
79 gypsum to earth composites decreased their thermal conductivity. By the other hand, Lima et al. [27] showed
80 that there could be an optimized gypsum content that reduces the thermal conductivity of earth plasters to a
81 lowest value.

82 Other binder commonly used on earth composites is air lime. Air lime is obtained at around 900°C and can be
83 used in composites in different ways [30]. It is known by having a slow hardening, just by carbonation, capturing
84 CO₂ from the environment. This characteristic can overcome the fast hardening of the gypsum when both
85 binders are used together, allowing longer production times for example for composite panels. Santos et al.
86 [31] have shown the influence of air lime to reduce biological development on earth-based plasters, which can
87 be a constrain to the use of earth-fibres composites. Nevertheless, it seems that low additions of air lime can
88 strongly decrease the mechanical strength of earth mortars [31, 32]. Studied by Millogo et al. [19] as an addition
89 to clayish soils, the addition of air lime improved the compressive strength of adobe blocks and decreased
90 their water absorption. Faria et al. [33] studied air lime-earth rendering mortars, showing that for lime minimal

91 contents of 50 % the thermal conductivity of the mortars increased and flexural and compressive strengths of
92 0.25 MPa and 0.5 MPa were registered.

93 Rice husk is an agriculture waste rich in silica that results from the extraction of the rice grains. Rice is often
94 exported with the grains in their husk. Therefore, the rice husk waste can be produced locally - where the rice
95 is cultivated - or where the husk is removed before commercializing the rice. There are huge unused volumes
96 of this waste all over the world, namely in China or Portugal. When rice husk is burned, it releases silica to the
97 environment. When thermal treated up to 900°C, rice husk ashes can be used as an artificial pozzolan, partially
98 replacing lime or cement in mortars and concretes. The results in air lime mortars are significant [34].
99 Nevertheless, the ashes obtained are only 10-15% of the initial volume of the husks. Rice husk has also been
100 used for gypsum-based composites [1] but with complementary additions. Therefore, alternative eco-efficient
101 uses for rice husk are needed. Laborel-Préneron et al. [35] tested the resistance to fungal growth of an earthen
102 composite containing rice husk, generally recognized as rot-proof [36], in comparison with other plant fibre
103 earthen composites. Rice husk composites seem to have a better resistance to molds in comparison to barley
104 straw composites [35].

105 The objective of this work is to produce a high-performance building composite that can be applied as a coating
106 panel on new and existing buildings, namely those with massive walls like rammed earth, adobe or rubble
107 stone masonry, with the aim of contributing to indoor comfort, not only improving thermal insulation but also
108 regulating indoor relative humidity (RH). Simultaneously it is intended that the composite should be compatible
109 with the supports where it will be applied, namely, to retrofit old massive walls, apart from being able to be
110 applied on new constructions. Thus, it should not constitute a barrier to water vapour transport and keep the
111 advantage of massive walls inertia. Therefore, this study presents the characterisation of a novel bio-based
112 composite panel composed by rice husk and an earth matrix. The objective of the earthen matrix is to be
113 efficient to agglutinate the rice husk and to be durable, without increasing significantly the composite
114 embodied energy. Therefore, low contents of binders produced at low temperatures, that are known to be
115 compatible with earth and together, and also may give some improvements in terms of biocide behaviour, are
116 foreseen, such as hemihydrated gypsum and air lime.

2. Materials and methods

2.1. Materials

2.1.1. Rice husk

The rice husk used for the composite formulations was provided by Orivárzea company located in Salvaterra de Magos, Portugal, resulting from rice produced locally. Its average length was characterised based on the state-of-the-art report of the RILEM TC 236-BBM [37] and Laborel-Préneron et al. [38].

The rice husk loose bulk density was determined through an identical process as the one used for the earth. After the previous drying needed for the loose bulk density determination and in laboratory conditions of 20°C and 65% relative humidity (RH), the rice husk thermal conductivity was measured with an ISOMET 2104 Heat Transfer Analyzer equipment. A PVC mould with 40 mm high and diameter 120 mm was filled with rice husk and the thermal conductivity coefficient determined with resource to a 60 mm diameter contact probe API 210412 with ranging values between 0.04-0.3 W/(m.K). Table 1 presents the average length, the loose bulk density and the thermal conductivity of the rice husk particles.

Table 1. Average length, loose bulk density and thermal conductivity of the rice husk

Average length (mm)	6.6
Bulk density (kg/m ³)	85.09
Thermal conductivity [W/(m.K)]	0.047

For the water absorption assessment rice husk samples with 25 g, previously sieved and dried in the conditions described for bulk density and thermal conductivity, were placed in tulle bags and immersed in water for 15 minutes, 4 and 48 hours. After each period of immersion the tulle bags were drained and weighted. Figure 1 shows the average water absorption of the rice husk in function of time. It can be observed that the absorption of water is mainly made in the first 15 minutes of the test.

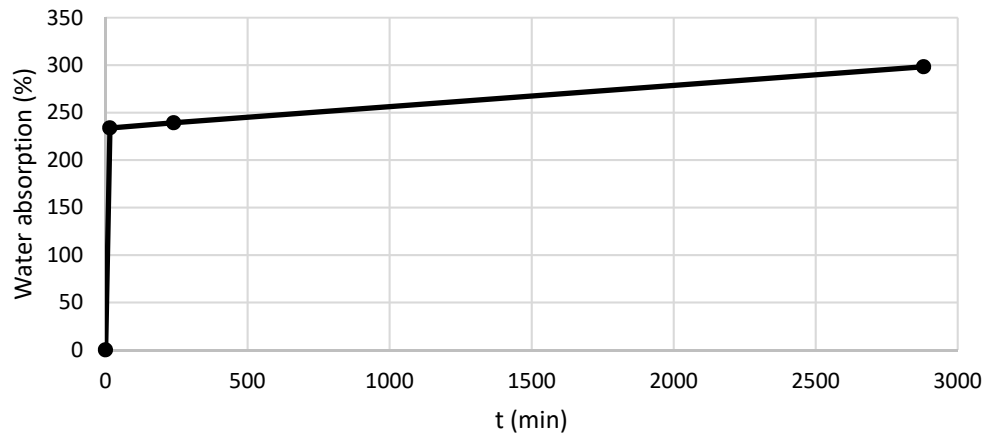


Figure 1. Water absorption of rice husk in function of time of immersion

2.1.2. Earth

The earth used for the composite formulation is composed by quarry fines from washing aggregate sludge. It is, therefore, an inert waste. The Atterberg limits and the mineralogical composition of this material were previously determined by Laborel-Préneron [39] and are presented in Table 22.

Table 2. Atterberg limits, mineralogical composition and loose bulk density of the earth (based on Laborel-Préneron [39])

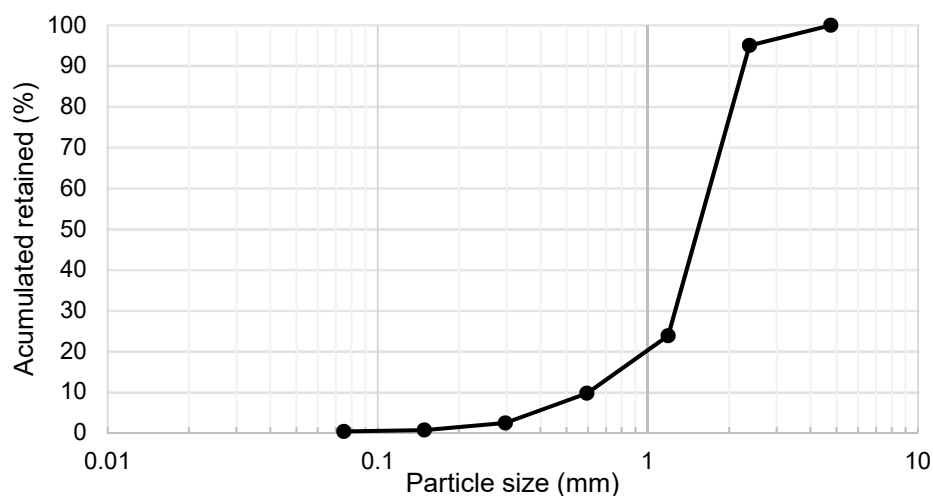
Atterberg limits (%)	W_L	30
	W_P	21
	PI	9
Mineralogical composition (%)	Calcite	63
	Dolomite	3
	Kaolinite	11
	Quartz	10
	Illite	9
	Goethite	3
Bulk density (g/m³)	ρ	0.756

W_L – Liquid limit; W_P – Plasticity limit; PI – Plasticity index

The loose bulk density of the earth was calculated using a sample previously dried at 60°C until the weight variation was less than 0.1% within two weighing 24 hours apart. A cup with a defined volume was filled with the earth, levelled and weighted. The loose bulk density ρ (g/m³) was obtained by the quotient of the mass of the earth (g) by the volume of the recipient (m³) and is presented in Table 2.

The dry particle size distribution of the earth was determined by sieve analysis that consists on shaking the earth samples through a defined set of sieves with different openings. The samples of earth were dried until their mass was constant, with less than 0.1% weight variation, and a mechanical sieving was made. The earth

153 retained in each sieve was weighted and the percentage of the retained particles determined, leading to the
154 dry earth particle size distribution curve, presented in Figure 2.



155
156 **Figure 2.** Dry earth particle size distribution curve

157 2.1.3. Gypsum

158 Gypsum, used as the main stabilizer for the production of the rice husk-earth composites, was a hemi-hydrated
159 gypsum from Sival company (Table 1). This type of gypsum is produced at low temperatures - between 120
160 and 180°C – being this the lowest range of firing temperature for chemical binders production. Hemi-hydrated
161 gypsum is known for having a very fast drying.

162 **Table 1.** Hemi-hydrated gypsum properties [40]

Water/gypsum ratio (kg/l)	1.25
Hardness time (min)	13 ± 4
Linear expansion (1h) (%)	max 0.20
Tensile flexural strength (MPa)	3.92

163 164 2.1.4. Air lime

165 Being one of the most studied additions to earth composites, hydrated air lime, classified by EN 459-1 [41],
166 was added to the panels with the aim of acting as a delayer of the hardness process of the gypsum and to
167 decrease susceptibility for biological development [18].

168 The air lime used in this work was a hydrated lime powder provided by Lusical Hoist Group and its chemical
169 composition was previously characterized by Gameiro et al. [42] (Table 2).

170 Table 2. Chemical composition of air lime [42]

(%)	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	MnO	MgO	CaO	Na ₂ O	K ₂ O	TiO ₂	P ₂ O ₅	Loss on ignition
Air lime	-	0.01	0.15	0.01	3.09	76.74	-	0.02	0.04	0.01	20.45

171

172 2.2. Samples production

173 2.2.1. Composition

174 The composite formulations were defined with the objective to maximize the rice husk content of the insulation
 175 composite and, therefore, to minimise the stabilised earthen matrix. Knowing that the decrease of the density
 176 tends to not be significant for a fibre content above 15-20%, 15% was defined as the minimum value for fibres.
 177 Based on the literature review and on a preliminary study, it was defined a gypsum and lime content of 20%
 178 and 10% (in volume of the earth), respectively. Composites samples with two different rice husk contents were
 179 produced: with 15% and 30% (in volume of the earth), being the latest the higher amount that was considered
 180 possible to cast with.

181 According to Fertikh et al. [43] and Ledhem et al. [44], the boiling of natural fibres can have a strong impact on
 182 the mechanical resistances of bio-based composites. To assess the influence of the boiled rice husk on the
 183 composite, samples were produced also with 30% of boiled rice husk. The rice husk was previously boiled for
 184 1h, drained but not completely dried, and then added to the earthen-based paste.

185 The formulation of the three different types of composites that were produced is given in Table 3. For the
 186 RH_15D composite production a defined volume of water was added; for the RH_30D and RH_30B
 187 composites, having a double percentage of rice husks, the volume of water had an increase of 50% to ensure
 188 workability.

189 **Table 3.** Formulation of the rice husk-earth composites

Samples	Gypsum*	Air lime*	Rice husk*	
RH_15D	20%	10%	15%	Dried
RH_30D			30%	Dried
RH_30B				Boiled

* percentages by volume of earth

190 2.2.2. Casting and curing

191 Following the recommendations of previous studies concerning the production of earth composites [10, 26,
 192 28, 45-48], the dry components – earth, gypsum and lime – were mixed previously to the addition of the rice
 193 husk, with a shovel. Then the water was added while mixing with a hand mixing machine until the matrix was
 194 homogenised. According to the DIN 18497 [49] an unstabilized earth mortar should be mechanical mixed

195 during 60 seconds with a 5 minutes resting period and, after that, another 30 seconds with mechanical mixing.
196 Since the composition includes gypsum, which has a very quick hardening process, the protocol was adapted
197 based on Lima et al. [27]. Therefore, the matrix was mixed during 90 seconds without resting period. After that
198 the rice husk was added to the matrix and mixed mechanically with the same device until a homogeneous
199 consistency was obtained (around 1 minute).

200 The samples were casted in 20 cm x 20 cm x 4 cm wooden moulds protected with a plastic film (panel
201 specimens), and on 4 cm x 4 cm x 16 cm metallic moulds (prismatic specimens). After casting the samples
202 were left to dry at laboratory conditions with 23 °C temperature and 50 % RH. They were demoulded 2 weeks
203 after the production and tested after a total of 4 weeks.

204 2.3. Testing methods

205 2.3.1. Visual observation

206 Opposing to the recommendation of producers that plant-based building materials should dry with strong
207 ventilation, composite samples were left to dry in laboratory environment, with very low ventilation, to propitiate
208 biological development. Two weeks after the production, the surface of three panels of each formulation was
209 visually observed and analysed to register the appearance of cracks, biological development and other
210 significant changes.

211 2.3.2. Thermal conductivity and bulk density

212 The thermal conductivity of the panel samples was determined with the same equipment used to assess the
213 rice husk, with the same 60 mm diameter contact probe. The samples were previously stored in the laboratory
214 and left to reach equilibrium with the environment conditions of 23 °C temperature and 50 % RH. Five
215 measurements were performed in each sample, near the four vertices and in the centre.

216 Before the thermal conductivity test and with the panels in equilibrium with the environmental conditions, the
217 bulk density of three panels of each formulation was determined based on EN 1097-3 [50].

218 2.3.3. Ultra sound propagation velocity

219 To evaluate the internal homogeneity of the earth panels, the ultra sound (US) velocity test was performed
220 based on EN 12504-4 [51]. The velocity of the US impulse between two transducers is determined by the ratio
221 of the distance between the transmitter and the receiver, and the time that the impulse takes between them,
222 in m/s. The measurements were made based on two methods: the indirect (Figure 3 a) and the direct method
223 (Figure 3 b). In the indirect method the transmitter is fixed in one position, and the receiver changes position,
224 varying the distance between them. Three samples per formulation were tested.

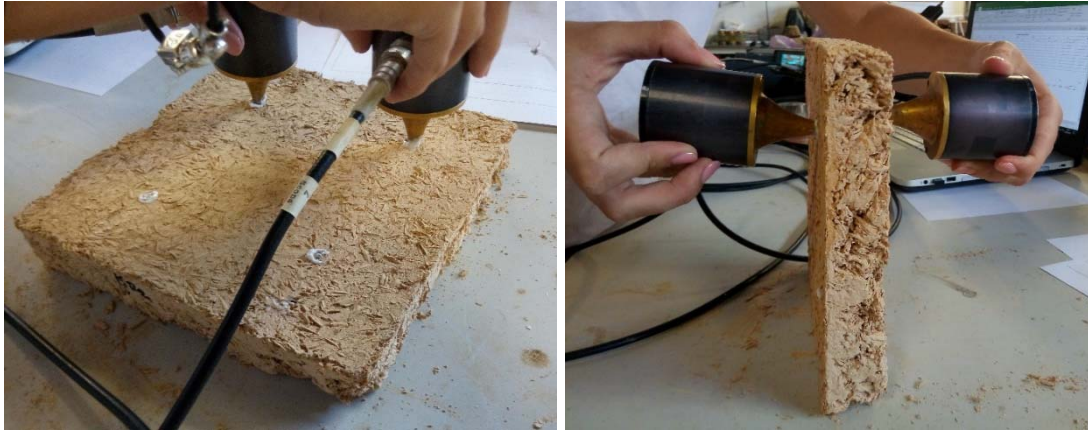


Figure 1. Ultra sound test procedure: (a) Indirect method (b) Direct method.

2.3.4. Dry abrasion resistance

The resistance to superficial erosion was determined based on the dry abrasion test according to the DIN 18947 [49] for earth plasters. The test consists on measuring the weight loss of the samples after 20 rotations with a polyethylene brush applied with a pressure of 2 kg. The abrasion weight loss, A_{wl} (in g/cm^2), is determined by the ratio between the mass loss and the brush area (eq. 1).

$$A_{wl} = \frac{m_i - m_b}{S} (g/cm^2) \quad (1)$$

where m_i is the initial mass of the sample, m_b the mass after brushing, both in g, and S the initial contact area of the brush to the sample, in cm^2 . Three tests per formulation were performed.

2.3.5. Flexural and compressive strength

The flexural strength was performed based on the EN 12089 [52] using a Zwick Rowell Z050 equipment, at a velocity of 10 mm/min with 100 mm between supports. The test was performed after 36 days of production on the 4 cm x 4 cm x 16 cm samples and three samples per formulation were tested.

Compressive strength test was performed according to the EN 826 [53], on the six half samples per formulation, obtained by the flexural test, with the same equipment previously used. A constant velocity of 0.4 mm/min was applied. As the composite samples were very deformable it was necessary to limit the applied load. Therefore, the equipment was programmed to stop when 10% of the deformation was achieved.

2.3.6. Moisture Buffer Value

The Moisture Buffer Value (MBV) translates the ability of the material to adsorb and desorb air humidity [54]. The test was conducted based on the NORDTEST protocol but exposing the samples to different RH and temperature cycles. First the panels were wrapped in aluminium tape, leaving only the top surface exposed, and then left inside a climatic chamber to stabilise at 16°C and 60% RH. Then the samples were exposed to

248 RH cycles each divided in two periods: the first with maximum RH during 8h – adsorption – and the second
249 with minimum RH for 16h – desorption. The exposure conditions were set for 60-90% RH cycles with 16°C
250 temperature. These conditions were chosen because they were recorded in many Portuguese unheated
251 dwellings during Winter.

252 The practical determination of the MBV, obtained after 8 cycles, is based on equation 2 [55]:

253
$$MBV = \frac{\Delta m}{m^2 \times \Delta RH} \quad (2)$$

254 where Δm is the average between the weight gain on adsorption and loss on desorption, m (mm) is the surface
255 area exposed and ΔRH (%) is the variation of RH.

256 2.3.7. Behaviour in case of fire

257 To evaluate the fire behaviour of the composites, the samples were exposed to a flame and the affected area
258 was photographed and quantified. This test was performed based on the EN ISO 11925-2 [56]: the samples
259 were placed on a metallic support at 15 cm from the ground and exposed to a flame near a border with resource
260 to a torch for 30 seconds like it is seen on Figure 4.



261
262 **Figure 2.** Fire behaviour test procedure

263 3. Results and discussion

264 3.1. Visual observation – cracking and biological development

265 Two weeks after the production of the panel samples no shrinkage cracks were visually observed.
266 Biological contamination was observed only on the surface of the RH_30D panels, two weeks after production,
267 has it can be seen in Figure 5. Probably, this happened due to the weak ventilation of the laboratory
268 environment during the curing period. However, it seems that the susceptibility to biological development of
269 the composites increases with the content on rice husk, because it does not appear in panels with only 15%
270 husks. Nevertheless, that susceptibility seems to decrease when the husks are previously boiled, what can be

271 justified by the destruction of the cellulose wall of the rice husks by the boiling treatment [43] and not to the
 272 water content used for the composite mixing.



273
 274 **Figure 3.** Biological contamination on the RH_30D samples

275 3.2. Thermal conductivity and bulk density

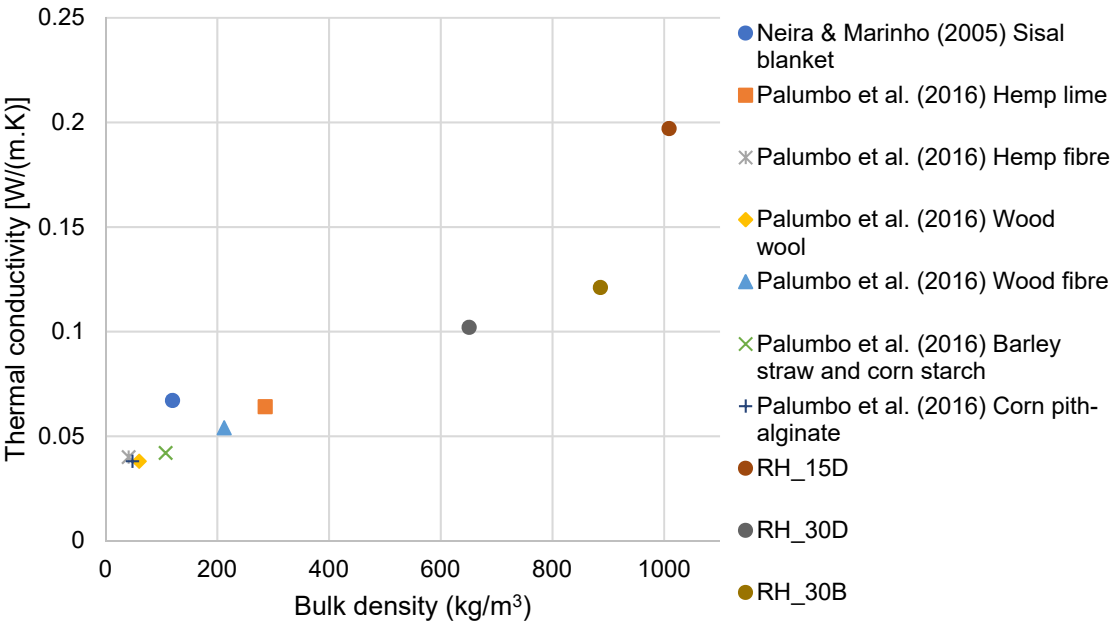
276 The thermal conductivity and bulk density of the composites are presented in Table 7, showing that, as
 277 expected, both properties decrease with the increase on rice husk content.

278 **Table 4.** Thermal conductivity and bulk density average results

Specimen	λ [W/(m.K)]		ρ (kg/m3)	
	Average	S.D.	Average	S.D.
RH_15D	0.197	0.004	1021.6	16.8
RH_30D	0.102	0.004	650.8	14.6
RH_30B	0.121	0.001	886.2	65.3

279
 280 Comparing the composites reinforced with 15 % and 30 % of dried rice husk, it is seen that the thermal
 281 conductivity decreases almost half. Those dried rice husk composites have slightly lower thermal conductivity
 282 when compared to the boiled rice husk samples. The difference may be justified by the destruction of the
 283 cellulose wall of the rice husks by the boiling, leading to a higher adherence to the earth matrix [43]. Therefore,
 284 probably a less porous material is produced, confirmed by the bulk density results presented in Table 7.
 285 It is seen that despite being a small difference, the boiled rice husk composite has higher bulk density than the
 286 others, justifying the higher thermal conductivity.
 287 The obtained results are lower than those obtained by Ashour et al. [22] for an earth sample with 30 cm x 30
 288 cm x 5 cm, reinforced with a 75 % volume content of barley straw, wheat straw and wood shavings, reaching
 289 thermal conductivity values of 0.154 W/(m.K), 0.194 W/(m.K) and 0.234 W/(m.K), respectively. This shows
 290 that, although having a lower natural fibre content, the rice husk composites have a better thermal behaviour,
 291 having a greater contribute to thermal insulation. Nevertheless, when compared with other bio-based insulation

292 materials, namely tested by Neira and Marinho [57] and Palumbo et al. [2], the rice husk composites have
 293 higher thermal conductivity (Figure 6).

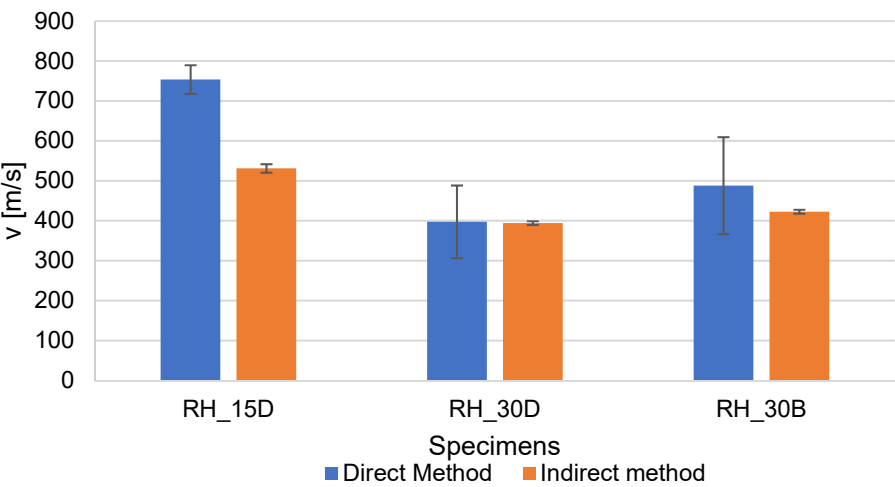


294
 295 **Figure 4.** Bulk density vs thermal conductivity of rice husk composites and other bio-based insulation
 296 materials

297 The rice husk composites, having an earthen-based matrix, have higher bulk density than the insulation
 298 materials presented in Figure 6, that are very light composites. Despite this, the higher bulk density could mean
 299 a more resistant material. That will be assessed in following sections.

300 **3.3. Ultra sound propagation velocity**

301 Figure 7 shows the average results and standard deviation of the US propagation velocity.



302
 303 **Figure 5.** Ultra sound propagation velocity of the composites

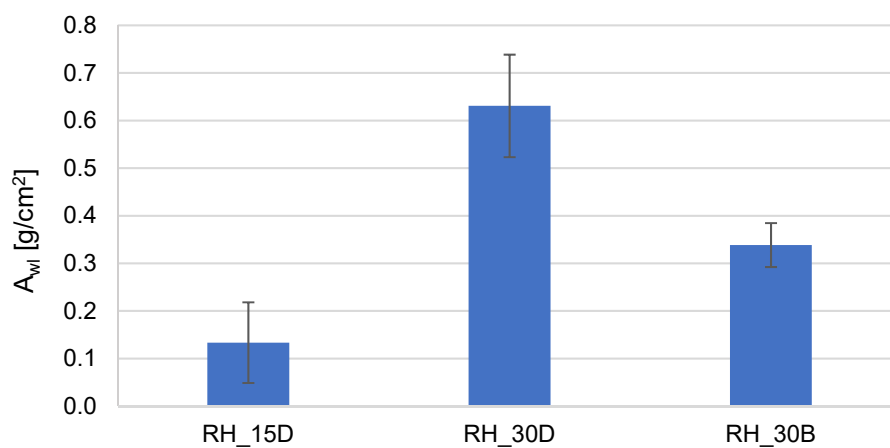
304 The results show that the increase in rice husk content decreases the US velocity, which was predictable due
305 to the previous bulk density results, meaning that a higher rice husk content leads to a less
306 compacted/homogeneous internal structure. The boiling of the rice husk fibres did not have a great influence
307 on the US velocity because the obtained velocity values of the RH_30B are close to the ones of the RH_30D
308 composite.

309 Binici et al. [58] tested a bio-based insulation composite made of compressed corn and epoxy resin, obtaining
310 US velocity between 120 m/s and 490 m/s for different compaction pressure. The rice husk composites present
311 a higher US velocity, which should mean that they have a more continuous internal structure. Nevertheless,
312 and as expected, the obtained results are effectively low comparatively to other construction materials, like
313 masonry blocks with a value of 1610 m/s [58].

314 Probably the evaluation of the internal structure of the composites allows to take conclusions concerning their
315 durability, where higher velocities lead to more compacted/homogenous internal structure and so, a more
316 resistant and durable material.

317 3.4. Abrasion resistance test

318 This test accesses the durability of the materials when applied exposed to abrasion actions: a lower abrasion
319 weight loss corresponds to a more durable composite. The abrasion weight loss of the earth-rice husk
320 composites is presented in Figure 8 (average and standard deviation).



321
322 **Figure 6.** Abrasion weight loss of the composites

323 With 0.13 g/cm² mass loss by abrasion, RH_15D has the highest resistance to abrasion and the RH_30D the
324 lowest, which is in accordance with Millogo et al. [19] that studied the abrasion resistance of adobe blocks
325 reinforced with hibiscus cannabius fibres. In that study the researchers concluded that a high fibre content and
326 fibre length decreased the adhesion to the earth matrix, reducing the abrasion resistance. Nevertheless,

abrasion resistance of earthen-plant fibres composites also depends on the type and content of plant fibres, as shown by Giroudon et al. [21], the matrix formulation and production process, namely compaction level. In the present study it is probable that the boiling of the rice husks increased the fibre adhesion to the earth matrix because the RH_30B abrasion loss is almost half of RH_30D (0.34 to 0.63 g/cm², respectively). This is considered very positive, allowing to improve the composite efficiency even with a high content on rice husk. Faria et al. [14] analysed the dry abrasion effect of earth plasters reinforced with oat fibres. The average value obtained for the weight loss by abrasion with the same brush was 18.1 g, while in the present study the highest weight loss was 4.1 g for the dried rice husk composite, RH_30D, showing that the earth-rice husk panels have a much higher abrasion resistance.

3.5. Flexural and compressive strength

Table 8 presents the average and standard deviation of the tensile flexural strength of composite prismatic samples.

Table 5. Flexural strength and compressive strength of the composites

Specimen	Flexural Strength (N/mm ²)		Compressive Strength (N/mm ²)	
	σ_b	S.D.	σ_{10}	S.D
RH_15D	0.12	0.03	0.37	0,05
RH_30D	0.08	0.01	0.13	0.001
RH_30B	0.08	0.01	0.40	0.25

There is no significant difference between the dried and boiled rice husk panels, which shows that the pre-boiling of the natural fibres has almost no influence on the tensile flexural strength of the composites. However, the increase of rice husk content decreases the tensile flexural strength of the composites. Vilamizar et al. [59] tested the tensile flexural strength of earthen blocks reinforced with 2.5 % and 5 % (by weight) of cassava peels, obtaining values of 0.66 N/mm² and 1.09 N/mm², respectively, showing that the increase in fibre content increased the tensile flexural strength of the earthen blocks. Also, Bouchicha et al. [60] and Millogo et al. [19] reached the same conclusions also with earthen-plant fibre blocks. On the other hand, Rim et al. [46] tested higher fibre contents, reinforcing earth blocks with 10 %, 20 %, 30 % and 40 % (by volume of earth) wood aggregates, obtaining flexural strength values of 0.59 N/mm², 0.66 N/mm², 0.41 N/mm² and 0.14 N/mm², respectively. Through these previous studies it is possible to see that there might be an optimal fibre content, varying with the type of fibre and the composite formulation, that optimizes the mechanical strength of each earthen composite. In Rim et al. [46] studies, the tensile flexural strength seemed to increase up to 20 % fibre content; with higher fibre content the resistance started to decrease. Therefore, the obtained results on the

354 present study were expected and are in accordance with the literature, because the composites with 30 %
355 husks were considered with the maximum husks possible to cast with.

356 The average and standard deviation results of compressive strength of the composites are presented in Table
357 8. As expected, the increase of rice husk content from 15 % to 30 % lead to a significant decrease on the
358 compressive strength: the RH_30D are more than twice lower than the RH_15D. The pre-boiling of the rice
359 husk leads to a significant increase of compressive strength comparing the two composites with 30 % rice
360 husk; in fact it even leads to a slight increase in the compressive strength when compared to the 15 %
361 reinforced composite. Ledhem et al. [44], studying the pre-boiling in water of plant fibres, also achieved an
362 increase in the compressive strength. This shows that the pre-boiling of rice husk has a positive influence on
363 the compressive strength of the earthen-based composites. The pre-boiling most probably increases the rice
364 husk adhesion to the earthen matrix, resulting in a stronger composite.

365 3.6. Moisture Buffer Value

366 Figure 79 presents the mass change for each rice husk composite for the relative humidity range tested in the
367 adsorption and desorption stages, after 8 cycles.

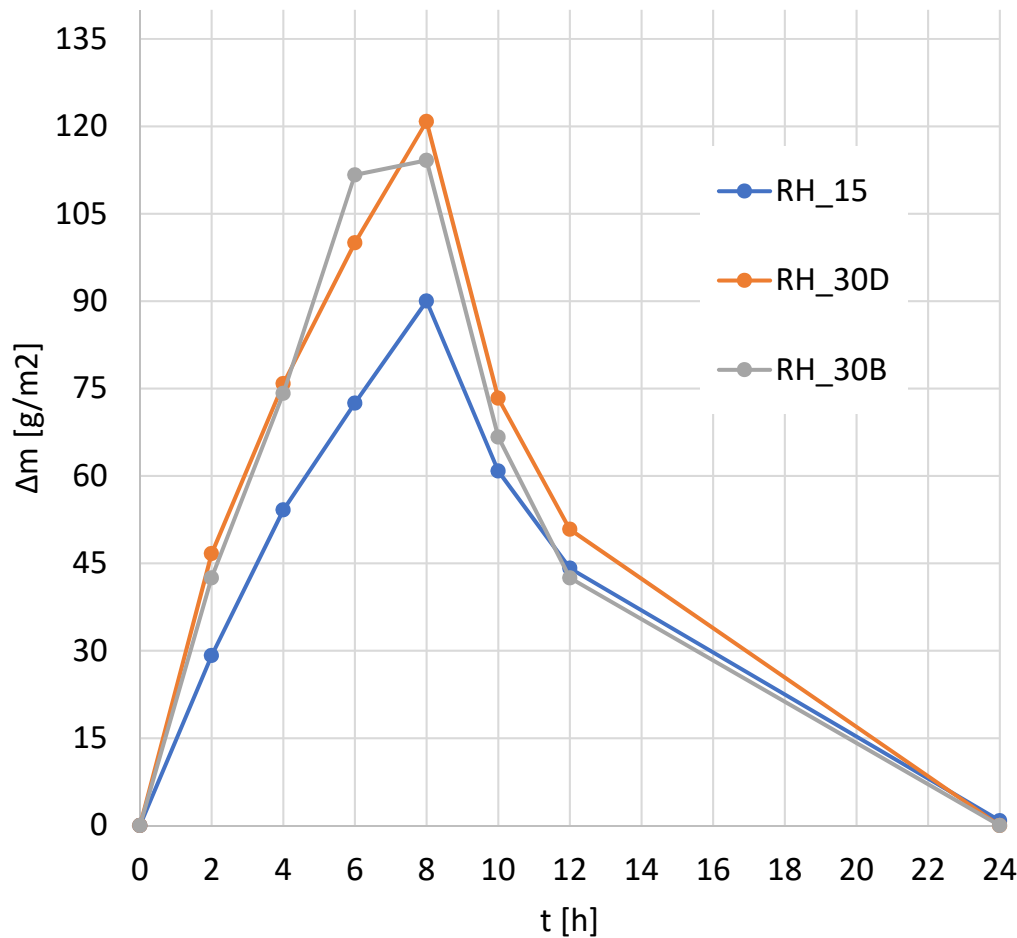


Figure 7. Adsorption-desorption curves after 8 cycles for the rice husk composites

The RH_30B samples reach their adsorption limit quicker than the RH_30D, showing the influence of the pre-boiling of the husks. Moisture Buffer Value (MBV) results for the tested composites are: 2.97 g/(m².RH) for RH_15, 4.11 g/(m².RH) for RH_30D and 4.94 g/(m².RH) for RH_30B. These results show that the increase of MBV values with the rice husk, meaning that the RH_30D and RH_30B composites have higher ability to adsorb and desorb moisture and that boiling the bio-fibres can increase the MBV in 20%.

Regarding the materials classification in function of their MBV, Rode et al. [55] defined that materials with an MBV superior to 2 g/(m².RH) are classified as excellent, for conditions of 23 °C temperature and RH varying between 33 % and 75 %. Other authors, as Holcroft and Shea [61] and Palumbo et al. [2], tested bio-based insulation materials regarding to their adsorption-desorption ability, with test conditions of 53-75 % RH and 23 °C. They obtained MBV lower than the ones of the rice husk composites. Holcroft and Shea [61] studying only a hemp lime composite obtained a higher MBV, reaching 4.4 g/(m².RH). The bio-based composites tested by Palumbo et al. [2] had the same thickness than the rice husk composites, and the MBV results were between 1.9 g/(m².RH) and 3.3 g/(m².RH), showing that the earthen-husk rice composites produced in the present study

383 seem to have higher hygroscopic capacity. However, the temperature and RH cycles of all these studies were
384 different from the one of the present study.

385 3.7. Behaviour in case of fire

386 Figure 10 presents the degradation of the composites after the fire test. The results show that, as expected,
387 the composite with 30 % rice husk content have a largest area affected by the fire in comparison with the 15
388 % rice husk composite (RH_15D - 11.16 cm²). The burned area of the boiled rice husk panels (RH_30B -
389 17.73 cm²) is slightly bigger than the one with dried fibres RH_30D - (18.59 cm²). That may be justified by the
390 protective cellulose wall destruction in the rice husk by the boiling treatment.



391
392 **Figure 8.** Effect of fire behaviour test (RH_15D- left, RH_30D - centre, RH_30B -right)

393 One of the major concerns of building materials is the susceptibility to combustion. In the tested composites,
394 when the fire source is extinguished the composite immediately stop burning; therefore, there is no fire
395 propagation. Also, there was no significant release of smoke and odours through the test, what is very
396 important.

397 Laborel-Préneron et al. [25] tested the fire behaviour of earth blocks reinforced with plant fibres. Despite
398 differences on the testing method, some similar conclusions were obtained.

399 Presenting acceptable fire behaviour, the earth-rice husk composites may be applied as indoor wall and ceiling
400 coating material. In comparison with common insulation products as polystyrene or polyurethane that have a
401 high combustion power and releases toxic gases, the earth-rice husk composites present a huge advantage.

402 4. Conclusions

403 In terms of mechanical properties the earth-rice husk composites show acceptable results when compared
404 with other bio-based materials. The blend of rice husk with the gypsum and lime stabilised earthen matrix
405 produces bio-based composites that may be optimised for application as indoor coating due to its high
406 hygroscopicity and, therefore, ability to control indoor comfort, contributing to reduce energy requirements of

407 buildings and to maintain occupants' health. The increase on rice husk content from 15 % to 30 %, the
408 maximum that allowed casting (by volume of earth), decreased both flexural and compressive strength. The
409 pre-boiling of the rice husk did not have a significant influence on the flexural strength but had a very positive
410 effect regarding both compressive strength and abrasion resistance of the composite. This could be connected
411 to the higher bulk density that this fibre treatment implies, probably because the pre-boiling of the rice husk
412 increases its adhesion to the earth matrix, leading to a stronger composite.

413 The increase of rice husk content showed a negative influence on ultra sound propagation velocity and
414 resistance to abrasion because it seems to decrease compaction/homogenous internal structure of the
415 composites and the superficial resistance to erosion.

416 The increase of rice husk content, decreasing the bulk density, has a positive effect on the thermal conductivity
417 of the composite panels. The pre-boiling in water of the rice husk leads to a slight increase on bulk density
418 and, therefore, on thermal conductivity. The increase of rice husk content results on higher MBV (at least 20%),
419 meaning that the 30 % rice husk composites (RH_30D and RH_30B) have higher ability to adsorb and desorb
420 moisture in comparison to the 15 % rice husk composite, and that pre-boiling the fibres can decrease in 15%
421 the performance in terms of the MBV. The pre-boiling of the rice husk fibres shows that the RH_30B specimens
422 reach their adsorption limit quicker than the RH_30D.

423 Despite low, thermal conductivity is still too high to allow these earth-rice husk composites to be considered
424 as thermal insulation materials. Nevertheless, they could be applied as interior wall and ceiling coating and
425 contribute to thermal comfort and to control the relative humidity variations of the indoor air.

426 Despite their excellent hygrothermal properties, the composites have acceptable mechanical resistance and,
427 due to the earthen-based matrix, acceptable fire behaviour, becoming a great candidate to a novel eco-friendly
428 interior coating material. Adjustments on the formulations can allow achieving composite panels with
429 characteristics adapted to different types of applications.

430 The optimisation of this type of composites still needs further development but it seems they could be used as
431 solutions for new construction where natural materials are foreseen and for refurbishment of massive walls
432 with high thickness. Being known for their high thermal inertia, the application of these composite panels as
433 interior coating could be an efficient solution, not significantly compromising the walls inertia but improving
434 their thermal resistance and acting as hygrothermal buffers.

435 Therefore, these bio-based composites can be a low cost, eco-friendly and efficient solution to reduce the
436 energy requirements of buildings, being a possible key to reach nearly zero energy and healthy low-cost
437 building.

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References

- [1] Khalil A., Tawfik A., Hegazy A., El-Shahat M. (2014). Effect of some waste additives on the physical and mechanical properties of gypsum plaster composites. *Construction and Building Materials*, 68, 580-586. <https://doi.org/10.1016/j.conbuildmat.2014.06.081>
- [2] Palumbo M., Lacasta A. M., Holcroft N., Shea A., Walker P. (2016). Determination of hygrothermal parameters of experimental and commercial bio-based insulation materials. *Construction and Building Materials* 124, 269-275. <http://dx.doi.org/10.1016/j.conbuildmat.2016.07.106>
- [3] Liu L.F., Li H.Q., Lazzaretto A., Manente G., Tong C.Y., Liu Q.B., Li N.P. (2017) The development history and prospects of biomass-based insulation materials for buildings. *Renewable and Sustainable Energy Reviews* 69, 912-932. <https://doi.org/10.1016/j.rser.2016.11.140>
- [4] Brouard Y., Balayachi N., Hoxha D., Ranganathan N., Méo S. (2018). Mechanical and hygrothermal behavior of clay-sunflower (*Helianthus annuus*) and rape straw (*Brassica napus*) plaster bio-composite for building insulation. *Construction and Building Materials* 161, 196-207. <https://doi.org/10.1016/j.conbuildmat.2017.11.140>
- [5] Belayachi N., Hoxha D., Slaimia M. (2016). Impact of accelerated climatic aging on the behavior of gypsum plaster-straw material for building thermal insulation. *Construction and Building Materials* 125, 912–918. <http://dx.doi.org/10.1016/j.conbuildmat.2016.08.120>
- [6] Lima J., Faria P., Santos Silva A. (2016). Earthen plasters based on illitic soils from Barrocal region of Algarve: contributions for building performance and sustainability. *Key Engineering Materials* 678, 64-77. Doi:10.4028/www.scientific.net/KEM.678.64
- [7] Faria P, Brás A (2017), *Building physics. Performance of Bio-based Building Materials*. D. Jones & C. Brischke (eds.), Woodhead Publishing Series in Civil and Structural Engineering, 335-344.
- [8] Minke G. (2006). *Building with Earth. Design and technology of a sustainable Architecture*, Birkhauser.
- [9] Janssen H., Roels S. (2009). Qualitative and quantitative assessment of interior moisture buffering by

enclosures. *Energy and Buildings*, 41(4), 382–394. <https://doi.org/10.1016/j.enbuild.2008.11.007>

[10] Laborel-Préneron A., Aubert J.-E., Magniont C., Tribout C., Bertron A. (2016). Plant aggregates and fibers in earth construction materials: A review. *Construction and Building Materials* 111, 719–734. <https://doi.org/10.1016/j.conbuildmat.2016.02.119>

[11] Liuzzi S., Rubino C., Stefanizzi P., Petrella A., Boghetich A., Casavola C., Pappalettera G. (2018). Hygrothermal properties of clayey plasters with olive fibers. *Construction and Building Materials* 158, 24–32. <https://doi.org/10.1016/j.conbuildmat.2017.10.013>

[12] Laborel-Préneron A., Aubert J.-E., Magniont C., Bertron A. (2015). Influence of straw content on the mechanical and thermal properties of bio-based earth composites. 1st International Conference on Bio-Based Building Materials, Clermont-Ferrand, 517–522.

[13] McGregor F., Heath A., Fodde E., Shea A. (2014). Conditions affecting the moisture buffering measurement performed on compressed earth blocks. *Building and Environment* 75, 11–18. <https://doi.org/10.1016/j.buildenv.2014.01.009>

[14] Faria P., Santos T., Aubert J.-E. (2016). Experimental characterization of an earth eco-efficient plastering mortar. *J. Materials in Civil Engineering* 28 (1), 04015085, [http://dx.doi.org/10.1061/\(ASCE\)MT.1943-5533.0001363](http://dx.doi.org/10.1061/(ASCE)MT.1943-5533.0001363)

[15] Cagnon H., Aubert J.-E., Coutand M., Magniont C. (2014). Hygrothermal properties of earth bricks. *Energy and Buildings* 80, 208–217. <https://doi.org/10.1016/j.enbuild.2014.05.024>

[16] Gonçalves T., Brito V., Vidigal F., Matias L., Faria P. (2015). Evaporation from porous building materials and its cooling potencial. *J. of Materials in Civil Engineering* 27(8), 04014222. [https://doi.org/10.1061/\(ASCE\)MT.1943-5533.0001174](https://doi.org/10.1061/(ASCE)MT.1943-5533.0001174)

[17] Aymerich F., Fenu L., Meloni P. (2012). Effect of reinforcing wool fibres on fracture and energy absorption properties of an earthen material. *Construction and Building Materials* 27(1), 66–72. <https://doi.org/10.1016/j.conbuildmat.2011.08.008>

[18] Santos T., Nunes L., Faria P. (2017). Production of eco-efficient earth-based plasters: influence of composition on physical performance and bio-susceptibility. *J. Cleaner Production* 167, 55–67. <https://doi.org/10.1016/j.jclepro.2017.08.131>

[19] Millogo Y., Morel J.C., Auber, J.-E., Ghavami K. (2014). Experimental analysis of pressed adobe blocks reinforced with Hibiscus cannabinus fibers. *Construction and Building Materials* 52, 71–78. <https://doi.org/10.1016/j.conbuildmat.2013.10.094>

[20] Lima J., Faria P. (2016) Eco-efficient earthen plasters: the influence of the addition of natural fibers. Figueiro, R., Rana, S. (eds.), *Natural Fibres: Advances in Science and Technology Towards Industrial*

501 Applications, RILEM Bookseries 12.

502 [21] Giroudon M., Laborel-Préneron A., Aubert J.-E., Magniont C. (2019). Comparison of barley and lavender
503 straws as bioaggregates in earth bricks. *Construction and Building Materials* 202, 254–265.
504 <https://doi.org/10.1016/j.conbuildmat.2018.12.126>

505 [22] Ashour T., Wieland H., Georg H., Bockisch F.J., Wu W. (2010). The influence of natural reinforcement
506 fibres on insulation values of earth plaster for straw bale buildings. *Materials and Desig*, 31(10), 4676–4685.
507 <https://doi.org/10.1016/j.matdes.2010.05.026>

508 [23] Bal H., Janno, Y., Quenette N., Chenu A., Gaye S. (2012). Water content dependence of the porosity,
509 density and thermal capacity of laterite based bricks with millet waste additive. *Construction and Building*
510 *Materials* 31, 144–150. <https://doi.org/10.1016/j.conbuildmat.2011.12.063>

511 [24] Simons A., Laborel-Préneron A., Bertron A., Aubert J.E., Magniont C., Roux C., (2015) Development of
512 bio-based earth products for healthy and sustainable buildings: characterization of microbiological, mechanical
513 and hygrothermal properties. *Matériaux et Techniques* 103

514 [25] Laborel-Préneron A., Aubert J.-E., Magniont C., Lacasta, A., Haurie, L. (2017a). Fire behavior of bio-based
515 earth products for sustainable buildings. 2nd International Conference on Bio-based Building Materials,
516 Clermont-Ferrand.

517 [26] Binici H., Aksogan O., Shah T. (2005). Investigation of fibre reinforced mud brick as a building material.
518 *Construction and Building Materials* 19(4), 313–318. <https://doi.org/10.1016/j.conbuildmat.2004.07.013>

519 [27] Lima J., Correia D., Faria P. (2016b). Earth plasters: the influence of gypsum addition and particle size
520 distribution of sand (in Portuguese). *Argamassas 2016 – II Simpósio de Argamassas e Soluções Térmicas de*
521 *Revestimento, Coimbra*.

522 [28] Binici H., Aksogan O., Bodur M.N., Akca E., Kapur S. (2007). Thermal isolation and mechanical properties
523 of fibre reinforced mud bricks as wall materials. *Construction and Building Materials* 21(4), 901–906.
524 <https://doi.org/10.1016/j.conbuildmat.2005.11.004>

525 [29] Ashour T., Korjenic A., Korjenic S. (2015). Equilibrium moisture content of earth bricks biocomposites
526 stabilized with cement and gypsum. *Cement and Concrete Composites* 59, 18–25.
527 <https://doi.org/10.1016/j.cemconcomp.2015.03.005>

528 [30] Faria P., Henriques F., Rato V. (2008). Comparative evaluation of aerial lime mortars for architectural
529 conservation. *J. Cultural Heritage* 9 (3), 338-346. <https://doi.org/10.1016/j.culher.2008.03.003>

530 [31] Santos T., Faria P., Silva A. (2017b). In situ assessment of the behavior of earth renders with low addition
531 of limes (in Portuguese). *Conservar Património* 26, 11-21. <https://doi.org/10.14568/cp2016022>.

532 [32] Gomes M.I., Faria P., Gonçalves T.D. (2018). Earth-based mortars for repair and protection of rammed

533 earth walls. Stabilization with mineral binders and fibers. *J. Cleaner Production* 172, 2401-2414.
534 <https://doi.org/10.1016/j.jclepro.2017.11.170>

535 [33] Faria P., Silva V., Jamú N., Dias I., Gomes M.I. (2015). Evaluation of air lime and clayish earth mortars
536 for earthen wall renders. *Vernacular Heritage and Earthen Architecture: Contributions for Sustainable*
537 *Development*, M. Correia, G. Carlos, S. Rocha (eds.), CRC Press / Taylor & Francis Group, 407–413.

538 [34] Almeida N.G., Faria P., Pinto A.P. (2008). Lime mortars with rice husk ash for ancient masonry. HMC08 -
539 Historic Mortars Conference, Lisbon.

540 [35] Laborel-Préneron A., Ouédraogo K., Simons A., Labat M., Bertron A., Magniont C., Roques C., Roux C.,
541 Aubert J.-E. (2018). Laboratory test to assess sensitivity of bio-based earth materials to fungal growth. *Building*
542 *and Environment* 142, 11–21. <https://doi.org/10.1016/j.buildenv.2018.06.003>

543 [36] Chabannes M., Bénézet J.C., Clerc L., Garcia-Diaz E. (2014). Use of raw rice husk as natural aggregate
544 in a lightweight insulating concrete: an innovative application. *Construction and Building Materials* 70, 428–
545 438. <https://doi.org/10.1016/j.conbuildmat.2014.07.025>

546 [37] Amziane S., Collet F. (Eds.) (2016). Bio-aggregates based building materials. State-of-the-art report of
547 the RILEM TC 236-BBM.

548 [38] Laborel-Préneron A., Magniont C., Aubert J.-E. (2017b). Characterization of barley straw, hemp shiv and
549 corn cob as resources for bioaggregate based building materials. *Waste and Biomass Valorization*.
550 <https://doi.org/10.1007/s12649-017-9895-z>

551 [39] Laborel-Préneron A. (2017). Formulation and characterization of unfired clay bricks with plant aggregates.
552 PhD Thesis, Université Fédérale de Toulouse.

553 [40] Sival (n.d.) Gypsum – fine plaster (in Portuguese). Technical sheet.
554 http://sival.pt/img/cms/pdfs/fichas_tecnicas_pt/gesso%20estruque%20fino_1.pdf

555 [41] EN 459-1 (2015), Building lime. Part 1: Definitions, specifications and conformity criteria. CEN, Brussels.

556 [42] Gameiro A., Santos Silva A., Faria P., Grilo J., Branco T., Veiga R., Velosa A. (2014). Physical and
557 chemical assessment of lime-metakaolin mortars: Influence of binder:aggregate ratio. *Cement and Concrete*
558 *Composites* 45, 264–271. <https://doi.org/10.1016/j.cemconcomp.2013.06.010>

559 [43] Fertikh S., Merzoud M., Habita M.F., Benazzouk A. (2012). Comportement mécanique et hydrique des
560 composites à matrice cimentaire et argileuse à base de diss «*Ampelodesma mauritanica*». XXe Rencontres
561 Universitaires de Génie Civil, Chambéry.

562 [44] Ledhem A., Dheilly R.M., Benmalek M.L., Quéneudec M. (2000). Properties of wood-based composites
563 formulated with aggregate industry waste. *Construction and Building Materials* 14(6–7), 341–350.
564 [https://doi.org/10.1016/S0950-0618\(00\)00037-4](https://doi.org/10.1016/S0950-0618(00)00037-4)

565 [45] Güllü H, Khudir A. (2014). Effect of freeze–thaw cycles on unconfined compressive strength of fine-grained
566 soil treated with jute fiber, steel fibre and lime. *Cold Regions Science and Technology* 106–107, 55–65.
567 <https://doi.org/10.1016/j.coldregions.2014.06.008>

568 [46] Rim K., Ledhem A., Douzane O., Dheilly R.M., Queneudec M. (1999). Influence of the proportion of wood
569 on the thermal and mechanical performances of clay-cement-wood composites. *Cement and Concrete*
570 *Composites* 21, 269–276. [https://doi.org/10.1016/S0958-9465\(99\)00008-6](https://doi.org/10.1016/S0958-9465(99)00008-6)

571 [47] Obonyo E., Exelbirt J., Baskaran M. (2010). Durability of compressed earth bricks: assessing erosion
572 resistance using the modified spray testing. *Sustainability* 2, 3639–3649. Doi:10.3390/su2123639

573 [48] Achenza M., Fenu L. (2007), On earth stabilization with natural polymers for earth masonry construction.
574 *Materials and Structures* 39, 21–27. <https://doi.org/10.1617/s11527-005-9000-0>

575 [49] DIN 18497 (2013), Earth plasters - Terms and definitions, requirements, test methods. DIN, Berlin

576 [50] EN 1097-3 (2002), Tests for mechanical and physical properties of aggregates; Part 3: Determination of
577 loose bulk density and voids. CEN, Brussels.

578 [51] EN 12504-4 (2004), Testing concrete. Determination of ultrasonic pulse velocity. CEN, Brussels.

579 [52] EN 12089 (2013), Thermal insulating products for building applications - Determination of bending
580 behaviour. CEN, Brussels.

581 [53] EN 826 (2013), Thermal insulating products for building applications - Determination of compression
582 behaviour. CEN, Brussels.

583 [54] Ramos (2007). The importance of hygroscopic inertia on the hygrothermal behavior of buildings (in
584 Portuguese). PhD, Universidade do Porto.

585 [55] Rode C., Peuhkuri R., Hansen K.K., Time B., Svennberg K., Arfvidsson J., Ojanen T. (2005). Nordest
586 project on moisture buffer value of materials. AIVC Conference Energy Performance Regulation.

587 [56] EN ISO 11925-2 (2010), Reaction to fire tests - Ignitability of building products subjected to direct
588 impingement of flame - Part 2: Single-flame source test. CEN, Brussels.

589 [57] Neira D.S. , Marinho G.S. (2005). Sisal fibre (*Agave sisalana*) as thermal insulator of manifold. 18th
590 International Congress of Mechanical Engineering, Ouro Preto.

591 [58] Binici H., Aksogan O., Demirhan C., (2016). Mechanical, thermal and acoustical characterizations of an
592 insulation composite made of bio-based materials. *Sustainable Cities and Society* 20, 17-26.
593 <http://dx.doi.org/10.1016/j.scs.2015.09.004>

594 [59] Villamizar M.C., Araque V.S., Reyes C.A., Silva R.S. (2012). Effect of the addition of coal-ash and cassava
595 peels on the engineering properties of compressed earth blocks. *Construction and Building Materials* 36, 276–
596 286. <https://doi.org/10.1016/j.conbuildmat.2012.04.056>

597 [60] Bouhicha M., Aouissi F., Kena, S. (2005). Performance of composite soil reinforced with barley straw.
598 Cement and Concrete Composites 27(5), 617–621. <https://doi.org/10.1016/j.cemconcomp.2004.09.013>
599 [61] Holcroft N., Shea A. (2012). Moisture buffering and latent heat effects in natural fibre insulation materials,
600 Portugal SB13 - Contribution of Sustainable Building to Meet EU 20-20-20 Targets, 221–228.
601 <https://doi.org/10.13140/2.1.4503.6162>