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Rice husk-earth based composites: a novel bio-based panel for buildings refurbishment

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Abstract

With the aim of developing economic and ecological bio-based composite panels to be used on indoor wall or ceiling coating systems, contributing to hygrothermal comfort and health, three different composite formulations were produced, differing on the content and pre-treatment of rice husk: 15 % and 30 %, only dried or previously boiled. Composite samples were tested for biological development and several physic-mechanical characteristics. 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 rice husk-content composites, its pre-boiling decreases 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 because of a better bond between the rice husk and the earthen matrix, quicker reaching a high water vapour adsorption limit.

Keywords: Air lime; Earth; Gypsum; Hygrothermal; Insulation; Massive wall; Mechanical performance; Moisture buffer value; Plant fiber; Thermal conductivity

1. Introduction

Securing sustainable access to 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. Simultaneously, 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, 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 relative humidity, 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].

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

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

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

Other binder commonly used on earth composites is air lime. Air lime is obtained at around 900ºC and can be used in composites in different ways [30]. It is known by having a slow hardening, just by carbonation, capturing CO_2 from the environment. This characteristic can overcome the fast hardening of the gypsum when both binders are used together, allowing longer production times for example for composite panels. Santos et al. [31] have shown the influence of air lime to reduce biological development on earth-based plasters, which can be a constrain to the use of earth-fibres composites. Nevertheless, it seems that low additions of air lime can strongly decrease the mechanical strength of earth mortars [31, 32]. Studied by Millogo et al. [19] as an addition to clayish soils, the addition of air lime improved the compressive strength of adobe blocks and decreased their water absorption. Faria et al. [33] studied air lime-earth rendering mortars, showing that for lime minimal contents of 50 % the thermal conductivity of the mortars increased and flexural and compressive strengths of 0.25 MPa and 0.5 MPa were registered.

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

The objective of this work is to produce a high-performance building composite that can be applied as a coating panel on new and existing buildings, namely those with massive walls like rammed earth, adobe or rubble stone masonry, with the aim of contributing to indoor comfort, not only improving thermal insulation but also regulating indoor relative humidity. Simultaneously it is intended that the composite should be compatible with the supports where it will be applied, namely, to retrofit old massive walls, apart from being able to be applied on new constructions. Thus, it should not constitute a barrier to water vapour transport and keep the advantage of massive walls inertia. Therefore, this study presents the characterisation of a novel bio-based composite panel composed by rice husk and an earthen matrix. The objective of the earthen matrix is to be efficient to agglutinate the rice husk and to be durable, without increasing significatively the composite embodied energy. Therefore, low contents of binders produced at low temperatures, that are known to be compatible with earth and together, and also may give some improvements in terms of biocide behaviour, are 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 20ºC and 65% relative humidity, 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.

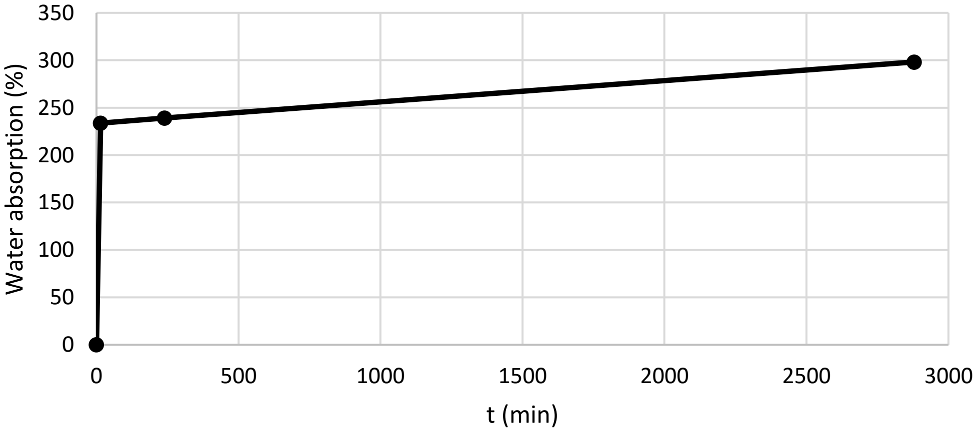

Figure 1. Water absorption of rice husk in function of time of immersion

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 **2**2.

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/m^3)	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/m^3) was obtained by the quotient of the mass of the earth (g) by the volume of the recipient (m^3) 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 retained in each sieve was weighted and the percentage of the retained particles determined, leading to the dry earth particle size distribution curve, presented in Figure 2.

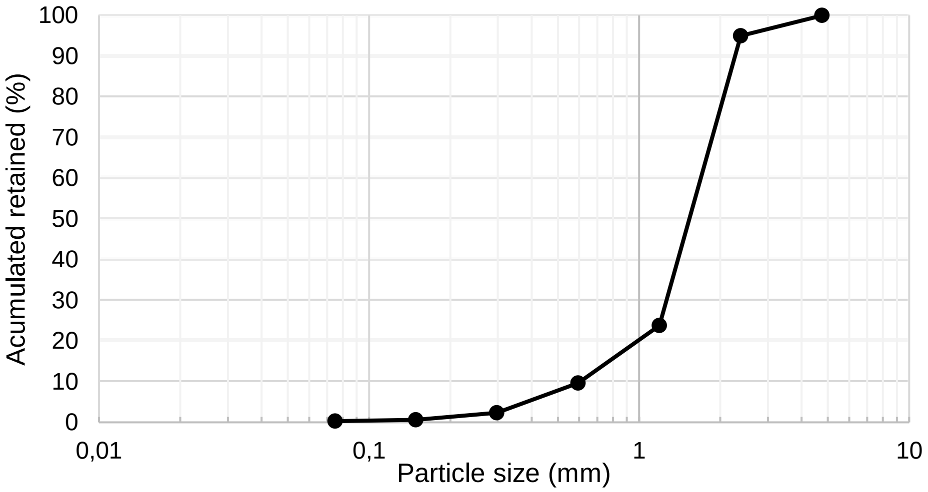

Figure 2. Dry earth particle size distribution curve

2.1.3. Gypsum

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

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

2.1.4. Air lime

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

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

Table 2. Chemical composition of air lime [42]

(%)	**SIO_2**	**Al_2O_3**	**Fe_2O_3**	**MnO**	**MgO**	**CaO**	**Na_2O**	**K_2O**	**TiO_2**	**P_2O_5**	**Loss on ignition**
Air lime	-	0.01	0.15	0.01	3.09	76.74	-	0.02	0.04	0.01	20.45

2.2. Samples production

2.2.1. Composition

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

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

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

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

2.2.2. Casting and curing

Following the recommendations of previous studies concerning the production of earth composites [10, 26, 28, 45-48], the dry components – earth, gypsum and lime – were mixed previously to the addition of the rice husk, with a shovel. Then the water was added while mixing with a hand mixing machine until the matrix was homogenised. According to the DIN 18497 [49] an unstabilized earth mortar should be mechanical mixed during 60 seconds with a 5 minutes resting period and, after that, another 30 seconds with mechanical mixing. Since the composition includes gypsum, which has a very quick hardening process, the protocol was adapted based on Lima et al. [27]. Therefore, the matrix was mixed during 90 seconds without resting period. After that the rice husk was added to the matrix and mixed mechanically with the same device until a homogeneous consistency was obtained (around 1 minute).

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

2.3. Testing methods

2.3.1. Visual observation

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

2.3.2. Thermal conductivity and bulk density

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

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

2.3.3. Ultra sound propagation velocity

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

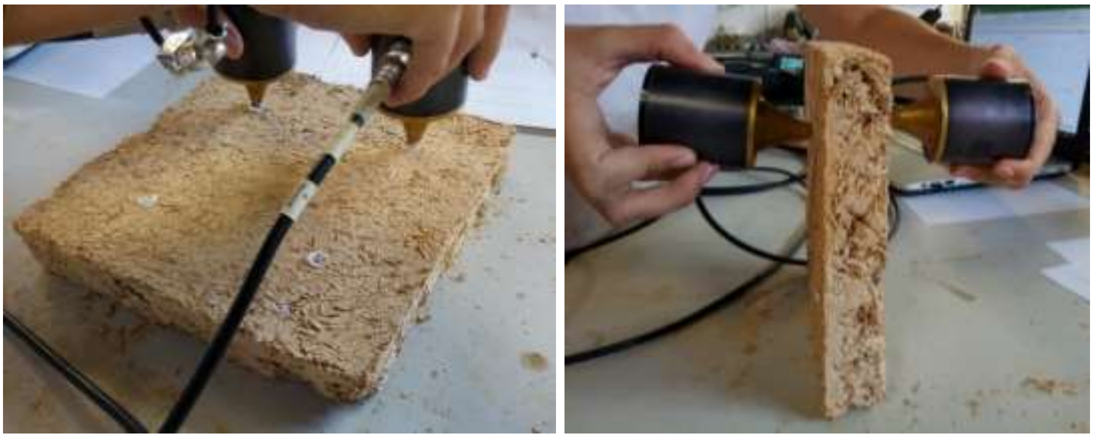

Figure 1. Ultra sound test procedure: (a) Indirect method (b) Direct method.

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).

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

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

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

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

where Δm is the average between the weight gain on adsorption and loss on desorption, $m\ (mm)$ is the surface area exposed and ΔRH (%) is the variation of relative humidity.

2.3.7. Behaviour in case of fire

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

Figure 2. Fire behaviour test procedure

3. Results and discussion

3.1. Visual observation – cracking and biological development

Two weeks after the production of the panel samples no shrinkage cracks were visually observed.

Biological contamination was observed only on the surface of the RH_30D panels, two weeks after production, has it can be seen in Figure 5. Probably, this happened due to the weak ventilation of the laboratory environment during the curing period. However, it seems that the susceptibility to biological development of the composites increases with the content on rice husk, because it does not appear in panels with only 15% husks. Nevertheless, that susceptibility seems to decrease when the husks are previously boiled, what can be justified by the destruction of the cellulose wall of the rice husks by the boiling treatment [43] and not to the water content used for the composite mixing.

Figure 3. Biological contamination on the RH_30D samples

3.2. Thermal conductivity and bulk density

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

Table 4. Thermal conductivity and bulk density average results

Specimen	**ʎ [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

Comparing the composites reinforced with 15 % and 30 % of dried rice husk, it is seen that the thermal conductivity decreases almost half. Those dried rice husk composites have slightly lower thermal conductivity when compared to the boiled rice husk samples. The difference may be justified by the destruction of the cellulose wall of the rice husks by the boiling, leading to a higher adherence to the earth matrix [43]. Therefore, probably a less porous material is produced, confirmed by the bulk density results presented in Table 7.

It is seen that despite being a small difference, the boiled rice husk composite has higher bulk density than the others, justifying the higher thermal conductivity.

The obtained results are lower than those obtained by Ashour et al. [22] for an earth sample with 30 cm x 30 cm x 5 cm, reinforced with a 75 % volume content of barley straw, wheat straw and wood shavings, reaching thermal conductivity values of 0.154 W/(m.K), 0.194 W/(m.K) and 0.234 W/(m.K), respectively. This shows that, although having a lower natural fibre content, the rice husk composites have a better thermal behaviour, having a greater contribute to thermal insulation. Nevertheless, when compared with other bio-based insulation materials, namely tested by Neira and Marinho [57] and Palumbo et al. [2], the rice husk composites have higher thermal conductivity (Figure 6).

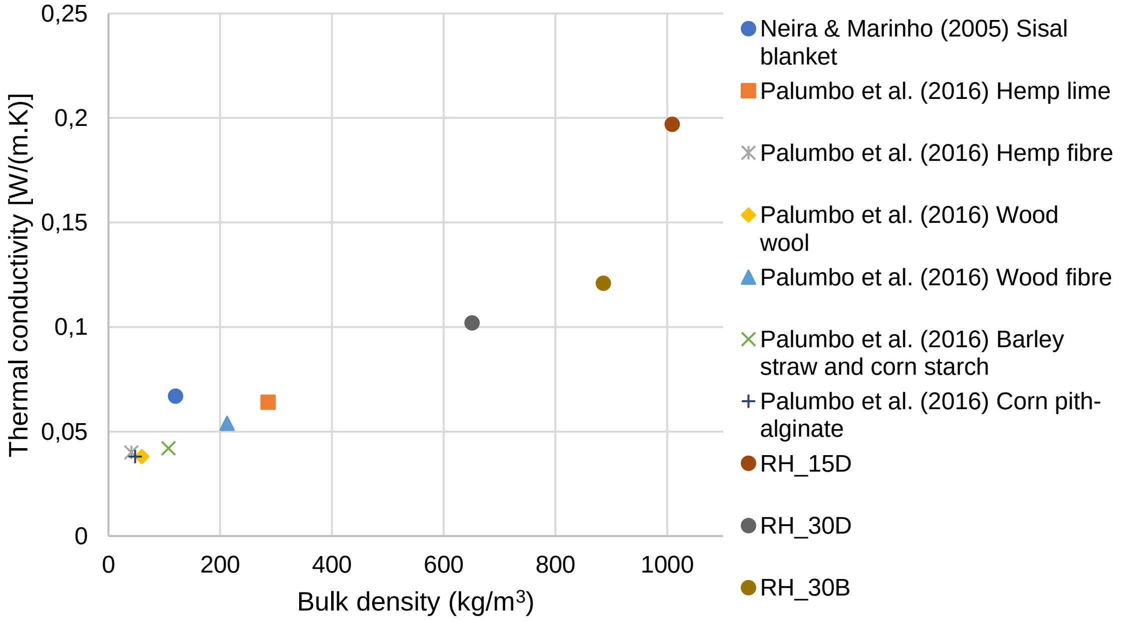

Figure 4. Bulk density vs thermal conductivity of rice husk composites and other bio-based insulation materials

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

3.3. Ultra sound propagation velocity

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

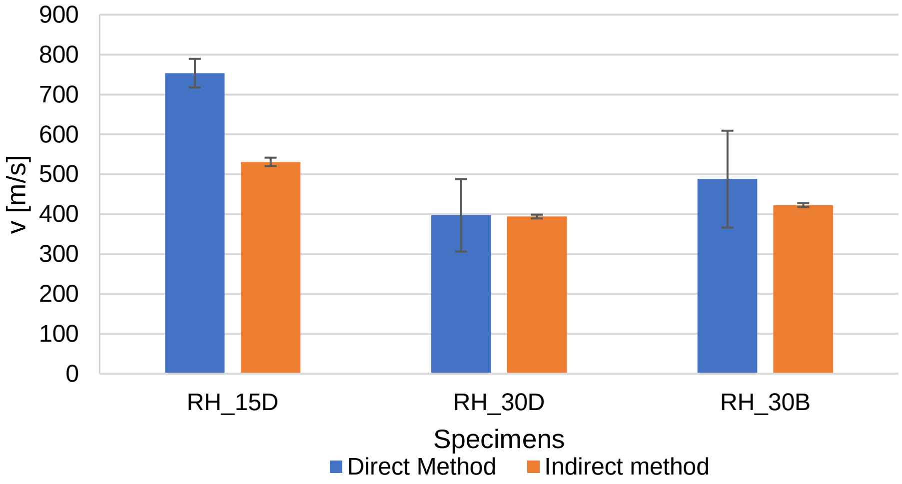

Figure 5. Ultra sound propagation velocity of the composites

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

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

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

3.4. Abrasion resistance test

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

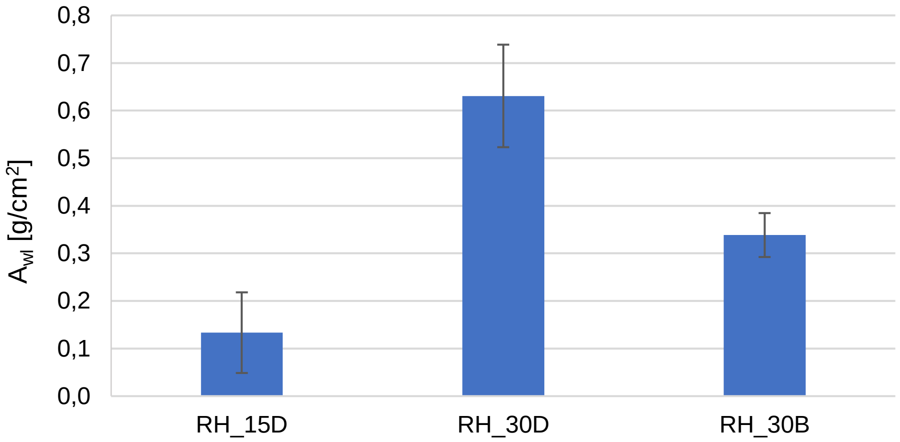

Figure 6. Abrasion weight loss of the composites

With 0.13 g/cm^2 mass loss by abrasion, RH_15D has the highest resistance to abrasion and the RH_30D the lowest, which is in accordance with Millogo et al. [19] that studied the abrasion resistance of adobe blocks reinforced with hibiscus cannabius fibres. In that study the researchers concluded that a high fibre content and 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/cm^2, 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/mm2)		Compressive Strength (N/mm2)	
	σb	S.D.	σ10	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/mm^2 and 1.09 N/mm^2, 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/mm^2, 0.66 N/mm^2, 0.41 N/mm^2 and 0.14 N/mm^2, 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 present study were expected and are in accordance with the literature, because the composites with 30 % husks were considered with the maximum husks possible to cast with.

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

3.6. Moisture Buffer Value

Figure **7**9 presents the mass change for each rice husk composite for the relative humidity range tested in the adsorption and desorption stages, after 8 cycles.

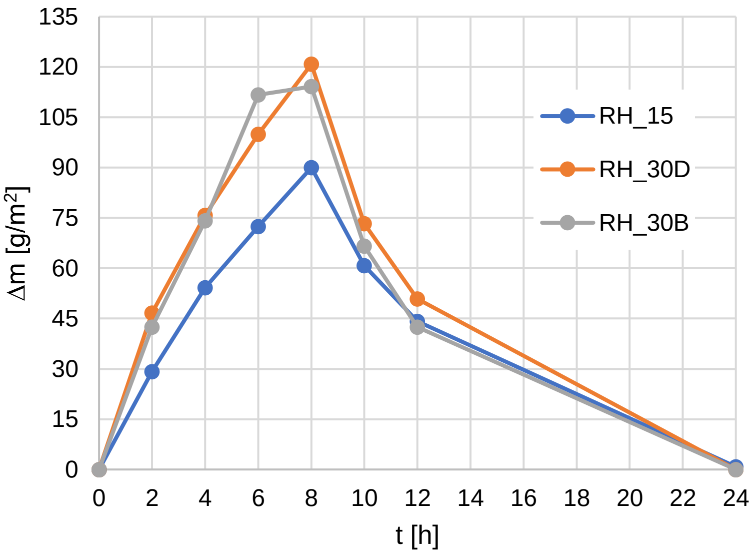

Figure 7. Adsorption-desorption curves after 8 cycles for the rice husk composites

The RH_30B samples reach their adsorption limit quicker than the RH_30D, showing the influence of the pre-boiling of the husks. Considering the exposure conditions were set for 60-90% relative humidity (RH) cycles, MBV results for the tested composites are: 2.97 g/(m^2.RH) for RH_15, 4.11 g/(m^2.RH) for RH_30D and 4.94 g/(m^2.RH) for RH_30B. These results show the increase of MBV values with the rice husk content, meaning that the RH_30D and RH_30B composites have higher ability to adsorb and desorb moisture in comparison to the RH_15D. They also show 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/(m^{2}RH) are classified as excellent, for conditions of 23 °C temperature and relative humidity 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 % relative humidity 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/(m^2.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/(m^2.RH) and 3.3 g/(m^2.RH), showing that the earthen-husk rice composites produced in the present study seem to have higher hygroscopic capacity. However, the temperature and relative humidity cycles of all these works were different from the one of the present study.

3.7. Behaviour in case of fire

Figure 10 presents the degradation of the composites after the fire test. The results show that, as expected, the composite with 30 % rice husk content have a largest area affected by the fire in comparison with the 15 % rice husk composite (RH_15D - 11.16 cm^2). The burned area of the boiled rice husk panels (RH_30B - 17.73 cm^2) is slightly bigger than the one with dried fibres RH_30D - (18.59 cm^2). That may be justified by the protective cellulosewall destruction in the rice husk by the boiling treatment.

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

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

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

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

4. Conclusions

Knowing that the decrease of the density tends to not be significant for a fibre content above 15-20%,15% was defined as the minimum value for rice husk content of the earthen composites. Based on a preliminary study, it was defined a hemihydrate gypsum and air lime content of 20% and 10% (in volume of the earth), respectively for the earthen matrix. Composites samples with two different rice husk contents were produced: with 15% and 30% (in volume of the earth), being the latest the higher amount that was considered possible to cast with. The aim was that the blend of rice husk with the gypsum and lime stabilised earthen matrix produced bio-based composites that may be optimised for application as indoor coating due to its high hygroscopicity and, therefore, ability to control indoor comfort, contributing to reduce energy requirements of buildings and to maintain occupants´ health. The three composite formulations allowed to assess the influence of both the rice husk content and the previous boiling treatment.

In terms of mechanical properties the earth-rice husk composites have shown acceptable results when compared with other bio-based materials. The increase on rice husk content from 15 % to 30 % decreased both flexural and compressive strength. The pre-boiling of the rice husk did not have a significant influence on the flexural strength but had a very positive effect regarding both increase on compressive strength and abrasion resistance of the composite. This could be connected to the higher bulk density that this fibre treatment implies, probably because the pre-boiling of the rice husk increases its adhesion to the earth matrix, leading to a stronger composite.

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

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

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

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

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

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

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