Ana Rita Novais Duarte Antunes

Licenciada em Ciências da Engenharia Civil

Performance of earth based products reinforced with rice husk for indoor refurbishment

Dissertação para obtenção do Grau de Mestre em Engenharia Civil – Perfil de Construção

Orientadora: Prof. Doutora Paulina Faria, Professora Associada, FCT-UNL
Co-orientadora: Prof. Doutora Ana Armada Brás, Professora Associada, Liverpool John Moores University

Júri:

Presidente: Prof. Doutor Mário Vicente da Silva
Arguente(s): Prof. Doutora Maria da Glória de Almeida Gomes
Vogal(ais): Prof. Doutora Paulina Faria

FACULDADE DE CIÊNCIAS E TECNOLOGIA
UNIVERSIDADE NOVA DE LISBOA

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To my mother, thank you.

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Abstract

The use of environment friendly materials, with low environmental impact and low production costs is becoming an issue of great interest in the building sector.

It is known that there is a need to reduce the energy requirement in buildings, once they account for 40% of total energy consumption in European Union (EU). The adoption of sustainable and efficient solutions could be the answer to improve the energy performance of buildings, leading to a reduction of the energy demand and cost for the building sector.

From a global point of view the use of bio-based materials provides low-cost and short-term opportunities to contribute to the EU objective to have nearly zero-energy buildings and reducing the greenhouse gas emissions.

Bio-based materials are known for their environmental benefits but specially for being materials with high hygroscopic behaviour.

The use of natural fibres in earth composites reinforcement has become an interest matter in the construction world, not only due to the availability, embodied energy and hygroscopic behaviour of the earth but also due to the properties and advantages of the use of reinforcement fibres. Earth is a construction material with high advantages but the negative aspects are also relevant, whereas the use of binders to reduce the negative aspects is very common.

Based on these fundaments, the present thesis studies the production of a novel bio-based insulation material with earth, stabilised with gypsum and lime and reinforced with rice husk. The objective was to produce a high-performance material that not only could be used as an insulation material but also as a regulator of the indoor air humidity.

The implementation of an image analysis method enables to assess of the influence of the length and orientation of the natural fibres on the physical and thermal properties of the composite.

In order to evaluate the influence of these factors on the performance of a bio-based material, a comparison was made with previously produced earth blocks, with different natural fibre contents, different production methods and dimensions.

The experimental tests showed promising results, especially on the hygrothermal properties of the earth panels. Despite having a relatively low thermal conductivity, the results still do not allow the panels to be considered an insulation material but they could contribute to the indoor thermal comfort. As a regulator of the humidity the panels show great ability to adsorb and desorb the air moisture with relative humidity changes, proving the effectiveness of earth and natural fibres on the hygrothermal comfort.

Keywords: Bio-based insulation panel; Rice husk; Earth; Gypsum; Air lime; Hygrothermal.

Resumo

A utilização de materiais amigos do ambiente com baixo impacto ecológico e reduzidos custos de produção está cada vez mais a tornar-se uma temática de grande interesse no sector da construção.

É do conhecimento geral que existe uma necessidade de reduzir as necessidades energéticas dos edifícios, uma vez que estes contribuem para cerca de 40% da energia consumida na União Europeia (EU). A adoção de soluções sustentáveis e eficientes pode ser a resposta para melhorar a eficiência energética dos edifícios, conduzindo a uma redução das necessidades de energia e custos para o sector da construção.

De um ponto de vista global, a utilização de bio-materiais providencia soluções de baixo custo a curto prazo, que contribuem para o objetivo de EU de obter edifícios praticamente de energia-zero e reduzir o efeito de estufa.

Os bio-materiais são conhecidos pelos seus benefícios ambientais, mas especialmente por serem materiais com um comportamento higroscópico elevado.

O uso de fibras naturais como reforço de materiais de terra tem-se tornado um tema de grande interesse no mundo da construção, não só devido as propriedades higroscópicas da terra e à sua elevada disponibilidade, mas também devido às vantagens que este reforço traz aos materiais. A terra é um material com grandes vantagens, mas os aspectos negativos também são consideráveis, pelo que é comum o uso de ligantes que os minimizem.

É com base nestes pressupostos que a presente dissertação estuda o desenvolvimento de um bio-material de isolamento com terra e casca de arroz, estabilizado com gesso e cal. O objetivo é produzir um material de desempenho melhorado que possa funcionar não só como isolamento térmico, mas também como um regulador da humidade relativa interior.

A implementação de um método de análise de imagem possibilita aferir a influência do comprimento e orientação das fibras naturais nas propriedades físicas e térmicas dos materiais.

Para avaliar a diferença entre estes fatores na performance de um bio-materiais, foi feita uma comparação com blocos de terra produzidos anteriormente com diferentes quantidades de fibras naturais, diferentes métodos de produção e dimensões.

Ensaios experimentais mostraram resultados promissores especialmente no que diz respeito às propriedades higrotérmicas dos painéis de terra. Apesar de possuírem uma condutibilidade térmica relativamente baixa, os resultados não permitem que os painéis sejam considerados como isolamento térmico, mas podem ser utilizados como um contributo para o conforto térmico do ambiente interior. Como regulador de humidade relativa os painéis mostram uma grande capacidade de adsorver e desadsorver a humidade do ar, provando a eficiência da terra e das fibras naturais no conforto higrotérmico.

Palavras chave: Bio-material para isolamento térmico; Casca de arroz; Terra; Gesso; Cal aérea; Higrotérmica.

Notations

S_3A – Earth block reinforced with 3% barley straw

H_3A – Earth block reinforced with 3% hemp shiv

RH_3A – Earth block reinforced with 3% rice husk

RH_15D – Earth-gypsum-lime panel reinforced with 15% dried rice husk

RH_30D – Earth-gypsum-lime panel reinforced with 30% dried rice husk

RH_30B - Earth-gypsum-lime panel reinforced with 30% boiled rice husk

RH – Relative humidity (%)

W_L – Liquid limit

W_P – Plastic limit

IP – Plasticity index

ρ – Dry density (kg/m^3)

w(t) – water absorption percentage (%)

ʎ - Thermal conductivity coefficient [W/(mK)]

A_{wl} – Abrasion weight loss (g/cm^2)

σ_b – Bending strength (MPa)

σ_{10} – Compressive strength for 10% deformation (MPa)

MBV – Moisture Buffer Value [$g/(m^2/RH\%)$]

US – Ultra sound

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1. Introduction

1.1. Context

The demand for natural and healthy materials with low environmental impact is growing sharply in the construction sector. The use of earthen bio-based insulation materials has strong benefits regarding to inorganic products; their high hygroscopicity (Laborel-Préneron et al. 2016) makes them ideal for contributing to maintain indoor air comfort (McGregor et al. 2014).

The addition of natural fibres has effects on the mechanical and physical properties of the earthen composites; most of all this addition decreases the density and thermal conductivity and increases the ability of the material to adsorb and desorb moisture (Jones & Brischke 2017, Laborel-Préneron et al. 2016).

Based on an analysis of bio-based construction materials, an earthen composite reinforced with rice husk is formulated to produce a high-performance insulation material able to regulate the indoor moisture and contribute to the indoor comfort. With the objective of optimizing these bio-based insulation materials the wettability of the rice husk fibres was studied to evaluate the influence of pre-wetting the natural fibres and its influence on the composite properties.

Despite its high hygroscopic behaviour, earth is a weaknesses material which can be reduced with the addition of stabilisers to improve their mechanical strength and also the thermal behaviour. Additions like gypsum with its good thermal and sound insulation properties may be the ideal stabiliser for this type of composites, once it increases the compressive and flexural strength and decreases the thermal conductivity (Lima et al. 2016). Also, lime can be a good addition to these composites, once it improves the strength, workability and water absorption of earthen composites (Ciancio et al. 2014).

This study is integrated into project PTDC/EPH-PAT/4684/2014: DB-HERITAGE – Database of building materials with architectural heritage and historic importance, COST Action FP1303 “Performance of biobased building materials” and RILEM Technical Committes TCE “Testing and Characterisation of Earth-based building materials and elements” and HDB “Hygrothermal behaviour and Durability of Bio-aggregate based building materials”.

The dissemination of this dissertation already includes an extended abstract entitled “Performance of bio-based insulation panels” that was presented on COST FP1303 Building with bio-based materials: Best practice and performance specification in Zagreb, Croatia (Antunes et al. 2017a), and it also resulted on an abstract and presentation entitled “Comportamento higrotérmico de bio-painéis de isolamento estabilizados com gesso e cal” (Hygrothermal behaviour of bio-based insulation panels stabilised with gypsum and lime) on the I Iberic Symposium “A Cal na Arte e no Património Edificado” (Antunes et al. 2017b).

1.2. Objective and methodology

The main objective of this study is to contribute for the development of a novel bio-based board that can be applied for thermal insulation, relative humidity (RH) equilibrium and eventually aesthetic behaviour on new and existent indoor surfaces of buildings.

The aim was to produce a high-performance bio-based earthen panel reinforced with rice husk and stabilised with gypsum and lime. For that it was necessary to experiment and define an optimized quantity of binders and natural aggregate. Also, aspects like the wettability of the rice husk fibres was studied to find the influence on the mechanical and physical properties of the bio-based composite. An image analysis process was implemented to determine the influence of the length and angle on these properties.

1.3. Dissertation structure

This dissertation is divided in six main chapters.

In this first chapter the main objectives, the adopted methodology and organisation of the work are presented.

Chapter 2 presents a bibliographic review on the use of earth materials in construction, describing the principal types of construction methods, stabilisation of the composites with binder addition and reinforcement with natural fibres. It also describes the use of insulation materials in the construction sector, focusing on the principal characteristics, advantages and materials used on the production process.

In chapter 3 the characterisation of the used materials, methodologies and production process of the specimens are presented.

On chapter 4 the experimental campaign is presented, including the description of the test proceedings and used methodologies.

The results of the experimental tests are presented on chapter 5 as well as the discussion and comparison of the results with previous studies.

The conclusions are presented on chapter 6, referring to the final remarks of the study and proposals for future work.

2. The use of bio-based materials in construction

2.1. Earth as a building material

Earth is one of the oldest building material known and used by men. Even nowadays there is not a certainty about the beginning of use of earth as a construction material but, according to several authors, it has more than 10 000 years (Minke 2006, Quagliarini & Lenci 2010, Galán-Marín et al. 2010), even in Portugal (Bruno et al. 2010). Currently, there are still a lot of earth constructions from the primordial times, in pre-historic sites and more recent ones, like the Great Wall of China built initially of rammed earth and just later covered with stones and bricks, the Temple of Ramés II in Gourna Egypt and the Sun Pyramid in Teotihuacán Mexico (Minke 2006).

Earth construction was very popular in the ancient cultures and building practices but its use has been reduced with the appearance and commercialization of other construction materials, as cement and steel, especially in the economically developed countries (Aubert et al. 2015). Nevertheless, in recent decades and up to nowadays this situation is starting to reverse once the use of earth as construction material has evolved all over the world, mainly for ecological reasons.

There is a constant search for natural and ecological products with lower costs and reduced energy consumption. The building sector is not an exception, earth with its excellent physical properties, low cost, low energy levels and economical design (Ashour et al. 2010), has become a construction material with high potential, once the sustainable development of building industry is directly connected to the use of sustainable and ecological products.

Between 2007 and 2010 some authors estimated that the quantity of people that live in earth houses is about 30% of the world population (Quagliarini & Lenci 2010, Binici et al. 2007, Gonçalves & Gomes 2009); it is estimated that nowadays about two billion people live in earth houses.

In comparison with most the construction materials, earth is one of the most economical, environmentally friendly, abundantly available and recyclable material (Aubert et al. 2015, Cagnon et al. 2014). Allied to these properties, earth has a relatively low thermal conductivity and particularly high hygrospicity making it an excellent material to regulate the relative humidity of the environment (Lima et al. 2016), which will be discussed forward on this dissertation.

2.1.1. Types of earth construction

Earth construction has variants concerning the type of construction, production techniques and addition of binders. For this dissertation, different earth construction techniques were studied and categorized according to Figure 2.1.

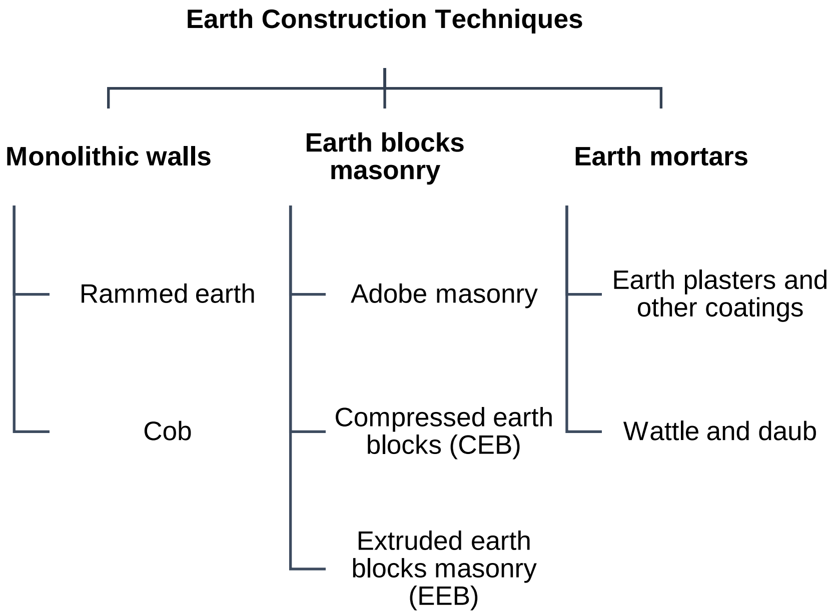

Figure 2.1 - Types of earth construction techniques.

All these techniques have earth as raw material but they are organized in different groups due to the differences concerning the production process, components mixture, curing time, addition of binders and compaction.

- **Monolithic walls**

The monolithic walls group includes two types of techniques the rammed earth and cob. The first consists in placing and ramming humid earth layers in a formwork while cob is a mixture of earth, straw and water pilled in layers generally without formwork. The latest is considered one of the simplest techniques in earth construction (Láborel et al. 2016, Niroumand et al. 2013) as proved elsewhere (Carneiro et al. 2016). Rammed earth and cob can be unstabilized or stabilized with binders. In ancient Portuguese fortresses the rammed earth was stabilized with air lime, producing what is called the Military rammed earth (taipa military) that still nowadays seems to be as hard and durable as stone (Faria 2014).

- **Earth blocks masonry**

Masonry earth walls consists in the construction of walls by stacking up earth blocks like adobe or compressed or extruded earth blocks, commonly with a masonry mortar.

  - **Adobe**

Adobe are earth blocks moulded generally in wood frames with a plastic mixture of fine raw earth, demoulded in the fresh state and dried in the air (not fired) (Láborel et al. 2016). It has a very simple production process whereby many of the ancient earth constructions are made of adobe masonry.

In the literature, each author has its own mixture method to produce adobe but they are all similar. Most references defend that in the first place it is needed to mixture the dry ingredients followed by the addition of water until a homogeneous mixture is obtained. Others say that the raw components should be

mixture separately to avoid granulometric variations (Ghavami et al. 1999, Quagliarini & Lenci 2010, Turanli & Saritas 2011, Millogo et al. 2014, Piattoni et al. 2011, Vilane 2010).

Regarding the curing time, as it was said the adobe blocks only dry in environment conditions which generally takes 28 days to achieve maximum hardening (Vilane 2010). But of course, that depends on environmental conditions and on eventual addition of binders. The most common binder used for adobe production is air lime. In some regions, like the Aveiro region in Portugal, the raw earth has low content on clay and, therefore, the adobe was always stabilized with air lime (Nobre et al. 2017). When the adobe is stabilized with air lime the curing should be longer to achieve carbonation of the lime.

- **Compressed Earth Blocks (CEB) and Extruded Earth Blocks (EEB)**

The production of CEB is different than the one of adobes because for the previous the earth mix is only humid (water content similar to rammed earth) and blocks are compacted manually, mechanically or even with vibro-compacting (Láborel et al. 2016). Earth blocks can also be extruded (EEB) but, in that case, the earth material is mixed with a higher water content to facilitate extrusion.

CEB are most frequently stabilized. The stabilization can be made with the addition of binders as air lime or limes with hydraulic properties (Gullu & Khudir 2014, Binici et al. 2005) or cement (Rim et al. 1999, Obonyo et al. 2010, Binici et al. 2007) but also with organic stabilisers as beetroot (Achenza & Fenu 2006) or bitumen (Kita et al. 2014).

Regarding the mixture process of CEB, some authors have different opinions regarding to the binder addition, Bouguerra et al. (1998), Segetin et al. (2007) and Taallah et al. (2014) defend that the binder should be previously mixed with earth and then the other components and water are added. Others say that the dry components can be all mixed together followed by water addition until a homogeneous mass is obtained (Rim et al. 1999, Binici et al. 2009, Chee-Ming 2011, Aymerich et al. 2012, Bal et al. 2012, Yalley & Kwan 2008, Bouchina et al. 2005).

Mixing can be manual but is frequently mechanical. Some studies defend that a normalized mixture time can be the key to achieve a homogeneous mass, like Bouguerra et al. (1998) that say that a low speed mix guarantees the homogenisation of the mass for 3 minutes, followed by a high-speed mix for 1 minute. CEB studies do not define a specific time for curing but the basic presuppose is to let it dry or cure (if a binder was added) until maximum hardness is achieved. Some studies propose curing for stabilized CEB varying from 7 to 28 days with conditions of 20-25ºC temperature and 50% RH (Obonyo et al. 2010, Ledhem et al. 2000, Taallah et al. 2014, Binici et al. 2009, Khedari et al. 2005). Depending on the binder used, it is important to guaranty moisture to assure the hydration of cement or the transport of CO_2 for carbonation. Sometimes plastic sheets are used to control moisture during the curing. For unstabilized CEB curing conditions may go up to 30-35ºC temperature and 65% RH until maximum hardness (Bouchina et al. 2005, Laborel-Préneron et al. 2015).

EEB mixing method consists on mixing the raw materials by hand, water is added followed by mechanical mix until a homogeneous mixture is obtained (Demir 2006, Demir 2008, Goodhew & Griffiths 2005, Heath et al. 2009). Similar to the CEB mixing process some authors defend that the mechanical mix should take 3 minutes (Simons et al. 2015).

Regarding the curing of the EEB, the blocks can be dried at room conditions (20ºC and 50% RH) or in an oven according to Demir (2006, 2008) that defend that they should be stored in those conditions for 72h and then dried in an oven at 105-110ºC.

- **Earth mortars**

Earth mortars can be used for different applications, namely to fill wattle and daub wood structure, in masonry as layering mortar or for plastering. Plasters are defined by Laborel-Préneron et al. (2016) and Faria et al. (2016) as mixtures composed by clay, water and sometimes plant aggregates. They can also contain stabilizers, namely when used as renders (Santos et al. 2017).

The wattle and daub technique is characterized by covering wooden structures with earth, similar to this concept is the “bahareque” technique studied by Mattone (2005) which consists on an earth and fibre mixture applied to wood or bamboo structures. When it dries it is possible to apply a finishing coat of daub.

It is believed that wattle and daub is the oldest earth construction technique, being used since the nomad lifestyle where men used tree branches and clay mortar to build their houses (Bruno and Faria 2008, Niroumand et al. 2013).

According to the literature, the mix of earth mortars for plastering should be made by previous mix of the dry ingredients and then addition of water until a good workability is obtained (Ashour et al. 2010, Faria et al. 2016, Hamard et al. 2013, Maddison et al. 2009, Lima & Faria 2015). Ashour et al. (2011) defended that the mixture should be left to rest for 30 minutes after mechanically mixture and then manually mix for 15minutes.

There is not a standard procedure for the curing of earth plasters. Basically, the process consists in let them dry at room temperature until the samples harden with temperature of 23-30ºC and RH of 50- 60%. (Ashour et al. 2010, Faria et al. 2016, Hamard et al. 2013, Maddison et al. 2009, Lima & Faria 2015, Ashour et al. 2011).

2.1.2. Influence of earth on relative humidity control and indoor comfort

One of the biggest concern in the construction sector is the impact of buildings materials on the health of their occupants.

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 and are weaker than other living organisms. Therefore, it has become a priority to find ways to improve the indoor air quality, by using safe building materials with low impact. It is also important to find an equilibrium between the heat and the humidity improving the hygrothermal performance of buildings (Láborel-Préneron et al. 2016, Minke 2006, McGregor et al. 2014 a, Janssen & Roels 2009).

The indoor air quality includes hygrothermal comfort that depends on the temperature and the humidity in the air. As the temperature rises or decreases the occupants immediately notice that and take measures. However, regarding humidity changes, the case is not that simple because people do not recognise so easily RH variations and the negative impacts of high and low humidity levels (Minke 2006).

According to the World Health Organization (WHO 2007) it is estimated that these moisture problems affect more than half of the buildings.

With respect to the RH, the indoor air quality (IAQ) and the biological problems associated with it are summarised in Figure 2.2.

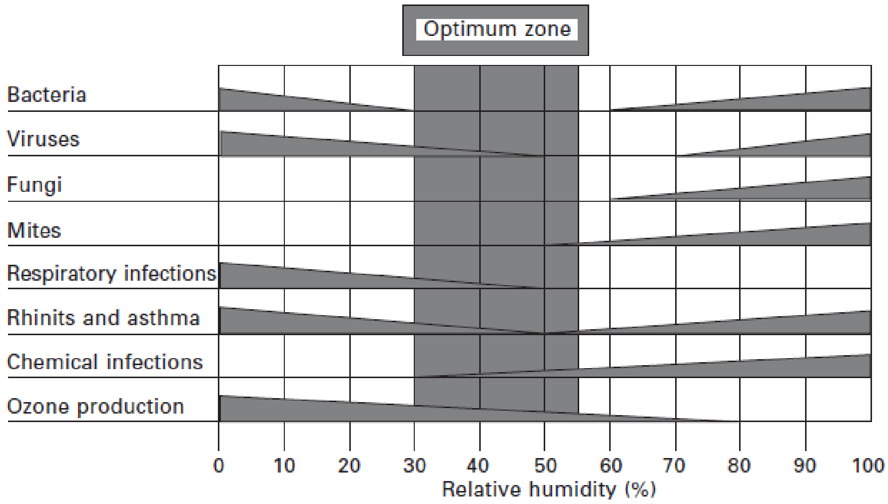

Figure 2.2 - The humidity-related effects on health and indoor air quality (Simonson et al. 2001).

Al Horr et al. (2016), defined the Sick Building Syndrome (SBS) as the group of diseases caused by the uncomfortable levels of humidity and temperature, chemical and biological pollution. Like it was mentioned before these oscillations will reflect on the human health, namely in the eyes, nose, skin irritation and diseases related to the respiratory system, like allergies, asthma, tuberculosis and others (Isik & Tulbentci 2008).

A relative humidity lower that 40% over a long period of time may dry out the mucous membrane, which is responsible for adsorbing the dust and other bacterias and transporting them to the mouth where they can be released (Minke 2006, from Grandjean 1972 and Becker 1986). If the mucous membrane dries out this system will not work and so the foreign bodies will reach the lungs which leads to health problems. In the other hand an excessively high RH, over 70%, leads to fungus formation which can lead to allergies and infections. So, it is established that the RH should range from 40-70%, in which way it increases the protection mechanisms of the skin against foreign aggressions as fungus, dust, microbes and others (Minke 2006). Facing all these issues, it is necessary to improve the use of building materials with higher hygroscopic behaviour.

According to Henriques (2011), the hygroscopic behaviour of a material is defined as the ability that the material has to adsorb and desorb water. The adsorption and desorption are inversed phenomenons that complement each other: adsorption is the adhesion of water molecules to the porous surface when the RH increases, while desorption is the loss of adsorbed water when it suffers a decrease.

Earth, as one of the construction materials with higher hygroscopic behaviour (Laborel-Préneron et al. 2015) becomes ideal to control the RH in the air, improving the indoor comfort and the occupants' health (McGregor et al. 2014, Santos et al. 2014). In 2014, Cagnon et al. (2014) studied the hygrothermal properties of earth blocks proving that the use of earthen materials regulates the relative humidity levels by adsorbing the excess of humidity and damping it when the temperature arises. This evaporation of

the water inside the earth have a cooling effect on the indoor environment which makes the earthen material a natural air conditioner (Gonçalves et al. 2015, Cagnon et al. 2014).

2.2. Stabilisation of earth composites

Despite being a material with good thermal and hygroscopic properties, earth has weaknesses like its poor ductility and water resistance. In this way, it is very often to resource to the stabilisation of earth materials to reduce their negative behaviour and improve strength and resistance towards liquid water. This stabilisation can be:

(i) mechanical via compaction, compression, extrusion;
(ii) physical by the introduction of aggregates and fibres to the mixture or even
(iii) chemical with the addition of binders, where several authors studied the addition of binders like cement, gypsum and lime and its effects on their physical and mechanical properties (Rodrigues & Henriques 2005).

In this study, the term stabilization is only adopted for binder stabilization situations.

2.2.1. Cement

Most of the references addresses to the use of cement for stabilisation of earth composites. It is the most commonly used binder but some issues should be considered derived from its use, specially the environmental impact of this material. In most references, the adopted quantities of cement are quite high.

Zhang et al. (2017) studied the influence of cement addition to the thermal conductivity of earth blocks. There is not a direct relationship between the cement content and the thermal conductivity values, but there is an increase on the compressive strength. Different proportions of cement were used - 3%, 5%, 7% and 9% - and it was showed that the increase of cement content lead to a decrease in porosity and it produced a negative effect on the thermal conductivity.

In 2016 Gomes et al. (2016) studied the influence of Portland and natural cement on the stabilisation of earth-based mortars. It compares the influence of these binders with air and hydraulic lime where the results showed that mortars with Portland cement had the highest water absorption coefficient.

2.2.2. Lime

Millogo et. al. (2008) studied the effect of air lime addition to clayish soils to produce adobe blocks and concluded that the addition of 10% of lime maximized the compressive resistance and minimize the water absorption. Despite that there are few studies concerning the thermal properties of earth-lime composites, which still are poorly understood.

In Gomes et al. (2016) study, four different types of binders were used including air-lime and hydraulic lime, used in earth-based mortars with contents of 5%, 10% and 15% by weight of earth. This research showed that the water absorption coefficient increased with the increase of binder content, also it

showed that both air-lime and hydraulic lime increased significantly the capillary porosity of the earth specimen with is an undesirable effect.

Faria et al. (2013) evaluate the behaviour of air-lime earth mortars for earthen wall renders, using binder contents of 5%, 10%, 25% and 50%. The results regarding the thermal conductivity of the mortars evidenced an increase in the thermal conductivity with the increase of air-lime content, which suggests that there is an optimum lime content for earth mortars stabilisation.

2.2.3. Gypsum

Common gypsum is a binder produced at low temperatures (120-180ºC) that has good thermal and sound insulation properties, with a relatively low thermal conductibility. Nevertheless, different types of gypsum can also be produced at higher temperatures, namely higher than 300ºC produces anhydrite. Some authors studied the addition of gypsum to earth composites and showed that the increase of gypsum content decreased the thermal conductivity of the composite and increase the compressive and tensile flexural strength (Lima et. al 2016, Binici et. al 2005).

Lima et al. (2016) in his work studied the influence of gypsum addition on earth plasters by adding different percentages (5, 10 and 20% by volume of earth) to the earth mix, E1S3_G5, E1S3_G10 and E1S3_G20 respectively.

Based on Figure 2.3 it is clear that Lima et al. (2016) obtained an increase of both compressive and tensile flexural strength with the increase of gypsum content, when compared with other earth materials.

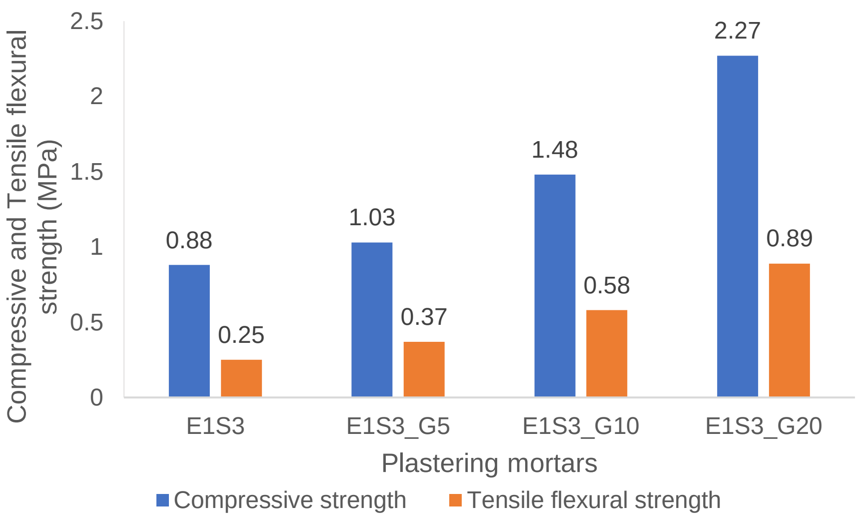

Figure 2.3 - Compressive and tensile flexural strength, values from Lima et al. (2016).

The Figure 2.4 shows the thermal conductivity values for the different gypsum contents specimens and it is showed that a 5 and 10% gypsum content lead to an increase of the thermal conductivity relatively to the reference specimen. But when the gypsum content is increased to 20% the thermal conductivity slightly decreases in relation to the reference, which suggests that there is an optimum gypsum content that optimizes not only the mechanical strength but also the thermal properties of the composite.

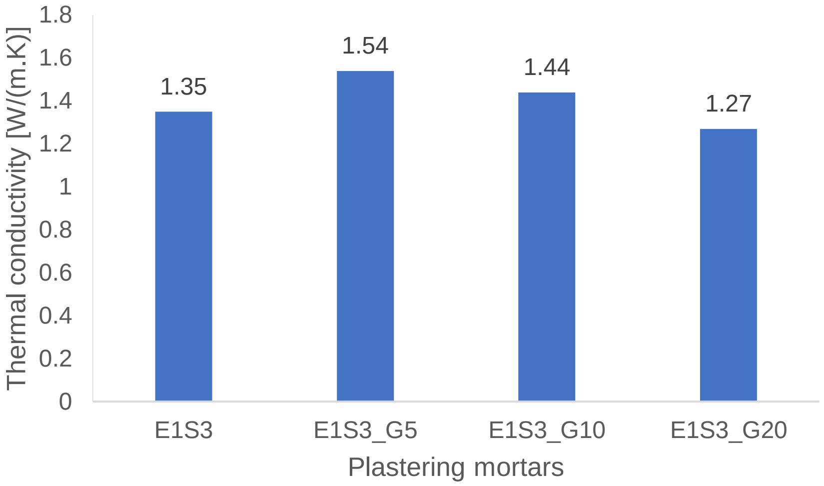

Figure 2.4 - Thermal conductivity results from Lima et al. (2016).

In comparison with other authors it is obvious that all had the same conclusions, like Binici et al. (2007) and Ashour et al. (2015): the addition of gypsum to earth composites increases the mechanical performance and decreases the thermal conductibility of the composite.

Earth already has a relatively good thermal performance, namely due to its thermal inertia; the major problem is its weak mechanical resistance.

This addition, allied to the good properties provided by the addition of natural fibres to earth composites, can produce a high-performance bio-based composite.

Based on the literature review and comparison between the different binders it is clear that it is interesting to study the addition of gypsum to earth composites; also, the addition of a smaller percentage of air lime can improve the performance of the composite and also delay the gypsum hardening.

2.2.4. Organic binder

Stabilisation of earth composites is more often made with the use of cement and lime which increases the strength and the behaviour under water action, but the use of natural fibres for the effect is also very common.

Achenza & Fenu (2006) studied the stabilisation of earth masonry with a compound of natural polymers, and their influence on the porosity, bulk density, water action and compressive strength. This compound is obtained from the residues of beetroot and tomatoes in the production of sugar and tomato sauce. The study shows that the stabilisation with natural polymer lead to a more uniform pore size and a decrease on the porosity, as well as the bulk density. This addition also increased the mechanical strength of the earthen composite and the resistance to water action once the specimens did not disaggregate after eight days of immersion in water.

Mattone (2005) studied the effect of cactus pulp addition as binder to a sisal reinforced soil in comparison with cement addition. This study showed that the use of a natural stabiliser lead to a slower water absorption contrarily to the cement addition; also, the abrasion results showed that the difference

between cement and cactus pulp addition is minimum. The biggest issue laid on the bending stress where the cactus pulp stabilised soil presented the worst results, nevertheless it is still an interesting matter to investigate, a natural and environmental friendly binder.

2.3. Bio-based materials

Nowadays most sectors are moving towards new approaches about the use of natural products. The interest in construction products made from natural components is increasing with the demand for natural materials with low environmental impact (Peñaloza et al. 2016, Korjenic et al. 2011). Therefore, the interest in bio-based insulation materials is increasing because they generally have a lower impact that inorganic insulation materials. According to EN 16575 (2014) a bio-based material is defined as a product wholly or partly derived from biomass as vegetable fibres or animal fibres.

Besides their environmental benefits bio-based materials are hygroscopic, making them ideal for maintain healthy indoor air quality (Jones & Brischke 2017), which means that they have high ability to adsorb and desorb the excess of moisture in the environment.

2.3.1. Fibre addition to earth composites

The interest in traditional earth construction its increasing; in the same way, the addition of natural aggregates to these composites are more often studied. Many authors studied the use of natural aggregates, that can be animal or vegetable and their influence on the performance of earth composites.

The use of natural fibres in construction was registered in the Roman era, where straw and dry grass were added to earth mixtures, which is known to reduce the hygrometric shrinkage and the composites ability to release water slowly (Quagliarini & Lenci 2010). In adobe construction, it was very common to add straw and other natural fibres to reduce cracking.

Through the years, many studies have been made concerning the addition of abundant natural fibres to earth composites, like Ghavani et al. (1999) that studied the influence of bamboo, sisal and coconut fibres in adobe blocks.

The addition of natural fibres has influence on the physical and mechanical properties of the reinforced composites. Table 2.1 resumes the effect of natural fibres addition to earth composites.

In general, the addition of natural fibres produces a positive effect on the ductility, shrinkage and specially on the thermal conductivity. The compressive strength has different conclusions taken by the authors. Regarding to the tensile flexural strength the opinions are divided, possible due to different binder addition or production methods. The pore size it is a dubious property where the consideration of positive or negative effect is influenced by the purpose of the composite. When the principal objective is to reach a high thermal performance, its considered negative the decrease of pore size once it will lead to higher values of thermal conductivity.

Table 2.1 - Influence of fibre addition.

Reference	Properties					
	Compressive strength	Tensile flexural strength	Ductility	Shrinkage	Pore size	Thermal conductivity
Ghavami et al. (1999)	↑ (green)		↓ (red)	↓ (green)		
Quagliarini & Lenci (2010)	↓ (red)					
Millogo et al. (2014)	↑ (green)	↑ (green)			↓ (blue)	↑ (red)
Aymerich et al. (2012)			↑ (green)			
Bal et al. (2013)						↓ (green)
Bouchina et al. (2005)	↑ (green)	↑ (green)	↑ (green)	↓ (green)		
Yalley & Kwan (2013)	↑ (green)					
Demir (2006)	↑ (green)			↑ (red)		
Heath et al. (2009)						↓ (green)
Simons et al. (2015)	↓ (red)		↑ (green)			↓ (green)
Achenza & Fenu (2006)	↑ (green)			↓ (green)	↓ (blue)	
Rim et al. (1999)	↓ (red)		↑ (green)			↓ (green)
Bouguerra et al. (1998)	↓ (red)				↑ (blue)	↓ (green)
Galán-Marín et al. (2010)	↑ (green)					
Khedari et al. (2005)	↓ (red)					↓ (green)
Ledhem et al. (2000)	↓ (red)					↓ (green)
Obonyo et al (2010)	↓ (red)			↓ (green)		
Segetin et al. (2007)			↑ (green)	↓ (green)		
Taallah et al. (2014)	↑ (green)	↓ (red)				
Ashour et al. (2010)						↓ (green)
Lima & Faria (2016)	↓ (red)	↓ (red)		↓ (green)		↓ (green)

– (green) Positive effect

– (red) Negative effect

– (blue) Positive or Negative

The effect of natural fibres in earth composites has been described, but the question remains: what is the optimized quantity? It is known that the fibre content is directly related with the composite resistance; low percentages lead to an increase on the strength of the earth composite but if the quantity is excessively high it will lead to a weakness on the earth matrix reducing the strength (Millogo et al. 2014).

A high fibre content may decrease the strength of the composite, but it also improves the thermal conductivity and the hygroscopic properties of the material. Therefore, the fibre content should be directly connected to the purpose of the material.

Figure 2.5 resumes different fibre contents studied for earth composites; the fibre content is reported in percentage by weight of earth; each number on the abscises axis reports to a reference in Table 2.2.

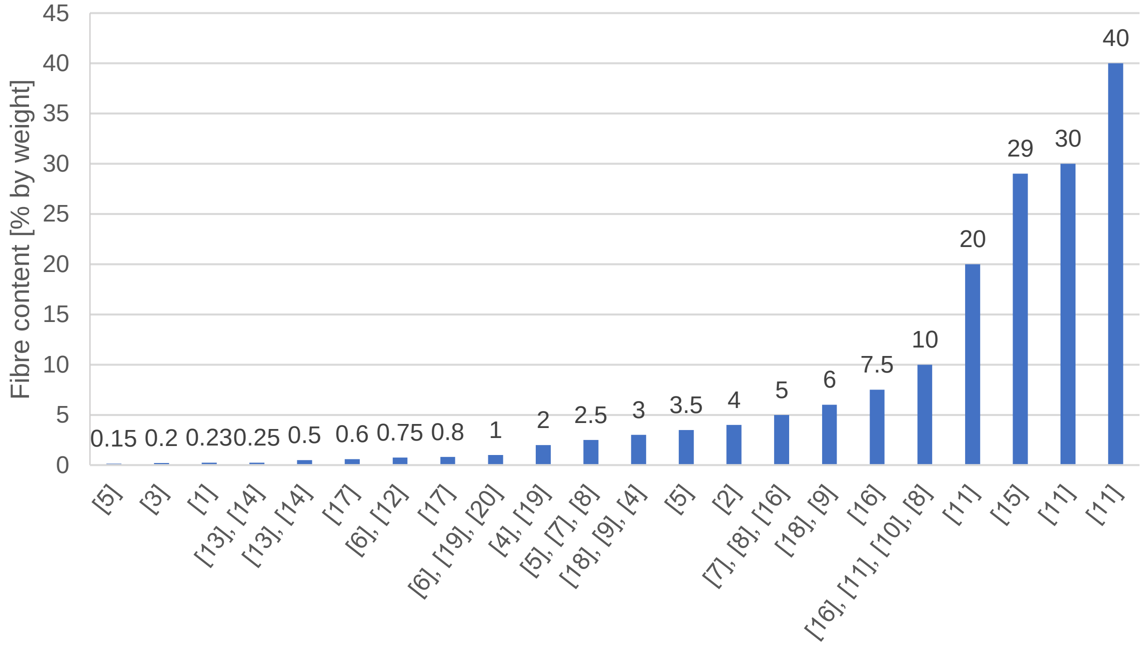

Figure 2.5 - Fibres content in earth composites.

Table 2.2 - References concerning fibre contents in earth composites.

References			
[1]	Aubert et al. (2015)	[11]	Rim et al. (1999)
[2]	Ghavami et al. (1999)	[12]	Chee-Ming (2011)
[3]	Millogo et al. (2014)	[13]	Galán-Marín et al. (2010)
[4]	Aymerich et al. (2012)	[14]	Gullu & Khudir (2014)
[5]	Bouhicha et al. (2005)	[15]	Ledhem et al. (2000)
[6]	Yalley & Kwan (2013)	[16]	Villamizar et al. (2012)
[7]	Demir (2006)	[17]	Segetin et al. (2007)
[8]	Demir (2008)	[18]	Laborel-Préneron et al. (2015)
[9]	Simons et al. (2015)	[19]	Maddison et al. (2009)
[10]	Achenza & Fenu (2006)	[20]	Lima & Faria (2016)

Rim et al. (1999), with the highest fibre content in the literature, studied the influence of wood aggregates on the thermal and mechanical properties of a clayish earth composite stabilised with cement. In the study three different wood contents were tested 10, 20, 30 and 40% by weight. With the increase of wood aggregate content, the compressive strength reduced from 2.42 MPa to 0.14 MPa, with contents of 10 and 40% respectively. In the same way, the tensile flexural strength suffers a decrease but less evident than the compressive strength. The thermal conductivity decreased from 0.22 to 0.10 W/(m.K) with the increase of wood aggregate from 10 to 40%.

Table 2.3 and Table 2.4 present a resume of the best performances regarding thermal conductivity and water absorption in function of the natural fibre content, obtained by different authors.

Table 2.3 - Thermal conductivity best performances of earth composites reinforced with natural fibres.

Thermal conductivity			
Reference	**Fibre**	**Fibre quantity**	**λ [W/(m.K)]**
Millogo et al. (2014)	Hibiscus cannabius	0.2% (by w.s.)	1.47
		0.8% (by w.s.)	1.30
Bouguerra et al. (1998)	Wood aggregate	7.5% by mass	0.43
		37.5% by mass	0.13
Khedari et al. (2005)	Coir	-	0.981
		-	0.651
Ashouret al. (2010)	Barley straw	25% by volume	0.30
		50% by volume	0.24
		75% by volume	0.15
Ashouret al. (2010)	Wheat straw	25% by volume	0.33
		50% by volume	0.27
		75% by volume	0.19
Ashouret al. (2010)	Wood shavings	25% by volume	0.28
		50% by volume	0.24
		75% by volume	0.23
Lima & Faria (2016)	Oat straw	0.5% by w.s.	1.23
		1% by w.s.	0.9
Lima & Faria (2016)	Typha wool	0.1% by w.s.	1.45
		0.3% by w.s.	1.28

Bouguerra et al. (1998) and Ashour et al. (2010) obtained the best values for thermal conductivity. It is known that natural fibres have a lower thermal conductivity and so, an increase of its content leads to a decrease on the thermal conductivity of the composites. Lowerthe value of thermal conductivity, less is the heat that passes through the element and, therefore, the higher is the insulation capacity.

Table 2.4 - Water absorption best performances of earth composites reinforced with natural fibres.

Water absorption			
Reference	**Fibre**	**Fibre quantity**	**%**
Demir (2006)	Processed waste tea	2.5% by w.s.	22.5
		5% by w.s.	27.30
Demir (2008)	Sawdust	10% by w.s.	31.25
Demir (2008)	Tobaco	2.5% by w.s.	21.85
		5% by w.s.	24.70
		10% by w.s.	29.10
Demir (2008)	Grass	5% by w.s.	25.10
		10% by w.s.	29.21
Algin & Turgut (2008)	Cotton	32g	12.6
		65g	14.8
		97g	17.4
		130g	27.2
Binici et al. (2005)	Straw	2kg	34.8
Chee-Ming (2011)	Pineaple	0 by w.s.	1.3 WAR
		0.75 by w.s.	1 WAR
Chee-Ming (2011)	Oil palm fruit	0 by w.s.	1.3 WAR
		0.75 by w.s.	1 WAR
Villamizar et al. (2012)	Cassava peels	2.5% by w.s.	26.65
		5% by w.s.	31.53

The higher the fibre content, higher is the water absorption capacity of the composite. Facing this fact, it is necessary to choose fibres with low water absorption like cotton, or apply treatments that can reduce this effect like the boiling the fibres in water. Despite Algin & Turgut (2008) study, where cotton achieved the lowest water absorption ratio when compared with other authors, it is important to refer that this natural aggregate will lead also to a decrease in the mechanical strength of the composite.

2.3.2. Influence of fibre length and diameter

The geometrical properties have a strong influence on the adhesion to the matrix and, therefore, the mechanical properties of the composite will be affected. It is possible to affirm that properties as length and diameter could have impact on the mechanical strength of materials (Millogo et al. 2014). The length for example has high influence on the propagation of cracks (Laborel-Préneron et al. 2016) and on the flexural strength of the composite (Iucolano et al. 2013).

Millogo et al. (2014) studied the influence of fibre length on the mechanical and thermal properties of adobe blocks. It was showed that shorter fibres improved the thermal behaviour of the adobe but, on the other hand it decreased the compressive strength.

Based on Laborel-Préneron et al. (2016) it is possible to achieve a relation between the length and diameter of natural fibre, being the aspect ratio, AR, the coefficient between these two parameters, as it is seen in Table 2.5 and Figure 2.6.

Table 2.5 - Length and diameter of different natural fibres used in literature.

Number	Reference	Fibre	Length (mm)	Diameter (mm)	AR
[1]	Ghavami et al. (1999)	Sisal	50	0,5	100,0
[2]	Piattoni et al. (2011)	Straw	50	3	16,7
[3]	Aymerich et al. (2012)	Wool	12	0,035	342,9
[4]			30	0,035	857,1
[5]	Bouhicha et al. (2005)	Barley straw	10	1	10,0
[6]			10	4	2,5
[7]			60	1	60,0
[8]			60	4	15,0
[9]	Gullu & Khudir (2014)	Jute fibers	20	1	20,0
[10]			40	1	40,0
[11]	Yetgin et al. (2008)	Wheat straw	50	3	16,7
[12]	Flament et al.	Hemp fiber	20	4	5,0
[13]	Hamard et al. (2013)	Hemp fiber	20	6	3,3
[14]	Gullu et al.(2014)	Jute fiber	30	1	30,0
[15]	Maddison et al. (2009)	Typha wool	20	2	10,0

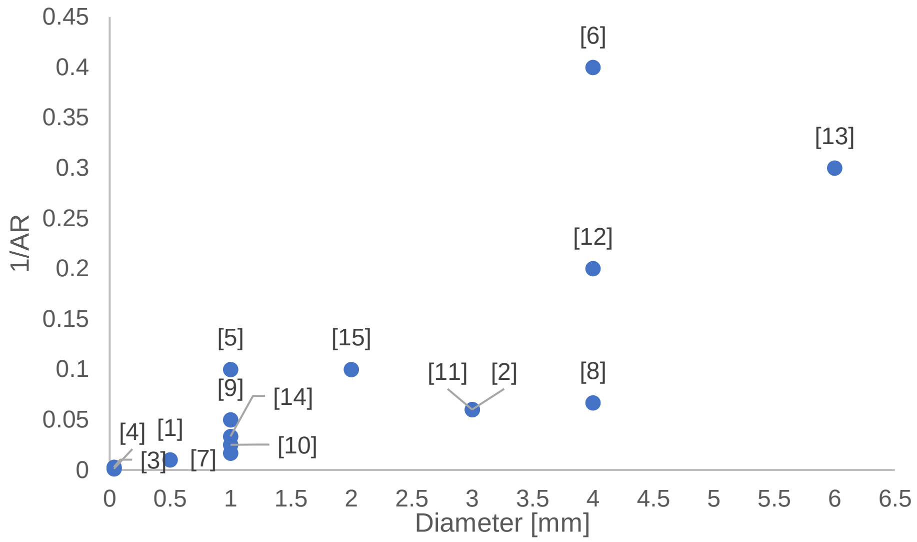

Figure 2.6 - Aspect ratio of natural fibres and their diameter.

If the objective is to improve the thermal conductivity of the composite, it is necessary to add fibres with a low AR, which through Figure 2.6 analysis is translated by the points more to upper right side of the figure. Based on this, point [6] (Bouchina et al. 2005), [12] (Flament) and [13] (Hamard et al. 2013) have the best fibre length-diameter relation.

Similarly, an improve on the mechanical properties would be translated by points more to the lower left side of the figure, with high AR, like [1] (Ghavami et al. 1999), [3] and [4] (Aymerich et al. 2011) did.

2.3.3. Fibre treatments

According to Láborel et al. (2016) one of the most important properties of plant aggregates is the water absorption, since it is the main factor on the ability of the aggregates to regulate the indoor air comfort once it controls the indoor humidity.

There are some treatments that can improve the natural aggregates properties, the ones studied the most were boiling water treatments. In Ledhem et. al (2000) study four different types of treatments were applied to wood shavings, immersing the aggregates in boiling water, in boiling water with lime, boiling water with cement and in linseed oil.

Also, Fertikh et al. (2011) studied the influence of previous immersion of diss fibres in boiling water on the mechanical properties of diss-earth blocks.

Ledhem (2000) studies show that the boiling water treatments improved the compressive and flexural strength of the stabilized earth blocks, contrarily to the linseed oil treatment that slightly reduced the mechanical strength. On the other hand, Fertikh et al. (2011) experiments lead to a decrease in the compressive strength and a small improvement of the flexural strength, which indicates that the treatments reduced the aggregate adhesion to the composite matrix.

Besides the mechanical properties, Ledhem (2000) also studied the influence of the treatments on the thermal conductivity and water absorption of the composites. The thermal conductivity suffered a small increase with the boiling water treatments with cement and lime, as well as the linseed oil treatment,

while the water absorption of the composite decreased with the treatments, especially with the boiling water with cement that reduced the water absorption to half. Table 2.6 resumes the fibre boiling effect studied for the two-mentioned authors.

Table 2.6 - Influence of natural fibre treatments on composites properties.

Author	Treatment	Compressive strength	Tensile flexural strength	Thermal conductivity	Water absorption
Ledhem et al. (2000)	Boiling water	↑ (green)	↑ (green)	-	↑ (red)
	Boiling water+ lime	↑ (green)	↑ (green)	↓ (green)	↑ (red)
	Boiling water+ cement	↑ (green)	↑ (green)	↓ (green)	↑ (red)
	Linseed oil	↓ (red)	↓ (red)	↓ (green)	↑ (red)
Fertikh et al. (2011)	Boiling water	↓ (red)	↑ (green)	-	-

— (green) Positive effect

— (red) Negative effect

It seems of great importance to define the influence of the fibres wettability on the bio-based composite properties. Ledhem et al. (2000) and Fertikh et al. (2011) believed that the boiling of the natural fibres will lead to a break of the cellulose wall which will improve the fibre adhesion to the matrix leading to an increase of the composite strength.

2.4. Production process of bio-based materials

2.4.1. Casting methods

Aggregates geometry influences certain properties in a composite (Silva et al. 2013), such as its orientation on the characteristics of bio composites as bio aggregate concrete (Williams et al. 2016). On the other hand, Williams et al. (2017) defend that the aggregate orientation is directly related to the casting method of the composite; so, the cast of the composite can influence its properties and behaviour (Baghaei et al 2014).

Yoo et al. (2016) and Plagué et al. (2017) studied the influence of different casting methods of reinforced concrete on the flexural behaviour and water permeability. In both studies, the concrete was reinforced with steel fibres with 13 mm in Yoo and with steel and synthetic fibres with 35 mm and 38 mm respectively in Plagué´s study.

Yoo et al. (2016) conceived two types of casting: P1, that consisted in pouring the mixture in one of the edges of the mould and let it flow, and P2 that consisted on pouring the concrete on both edges of the mould and in the middle. Figure 2.7 shows the different casting methods.

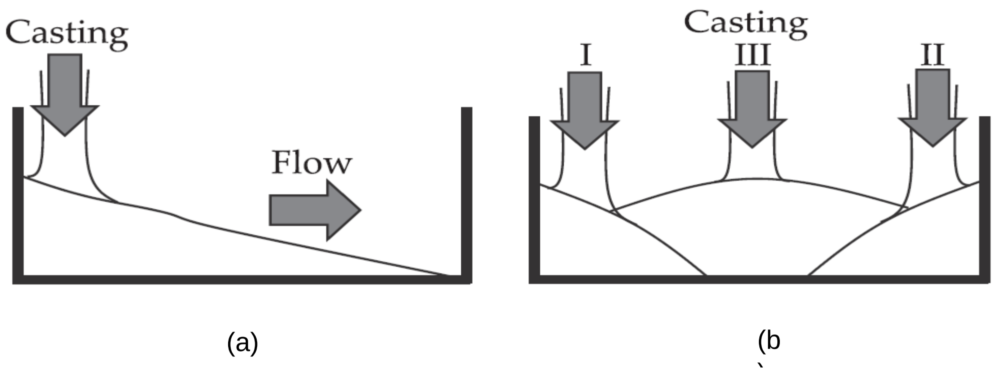

Figure 2.7 - Casting methods P1 (a) and P2 (b) (Yoo et al. 2016).

The samples were studied concerning their compressive and flexural strength and it was observed that samples with P1 casting method showed the best fibre orientation and best values of mechanical strength. A better fibre orientation leaded to a higher number of fibres per unit of area; also, these distributions influenced the post cracking properties (Yoo et al. 2016).

Plagué et al. (2017) determined the influence of fibre orientation on the water permeability of high performance concrete reinforced with steel and synthetic fibres; the study comprises 3 types of casting methods defined as favourable, average and unfavourable orientation (Figure 2.8). The favourable orientation samples were cast by filling a mould with resource to a shovel in the longitudinal axis of the mould. The specimens with the average orientation were cast all together in large formworks as the unfavourable orientation specimens. The average orientation casting consists in placing the mixture resourcing to a tube moved at 45º with respect to the formwork walls. Finally, the unfavourable casting was made by placing the mixture into a reservoir at the extremity of the formwork and then releasing it.

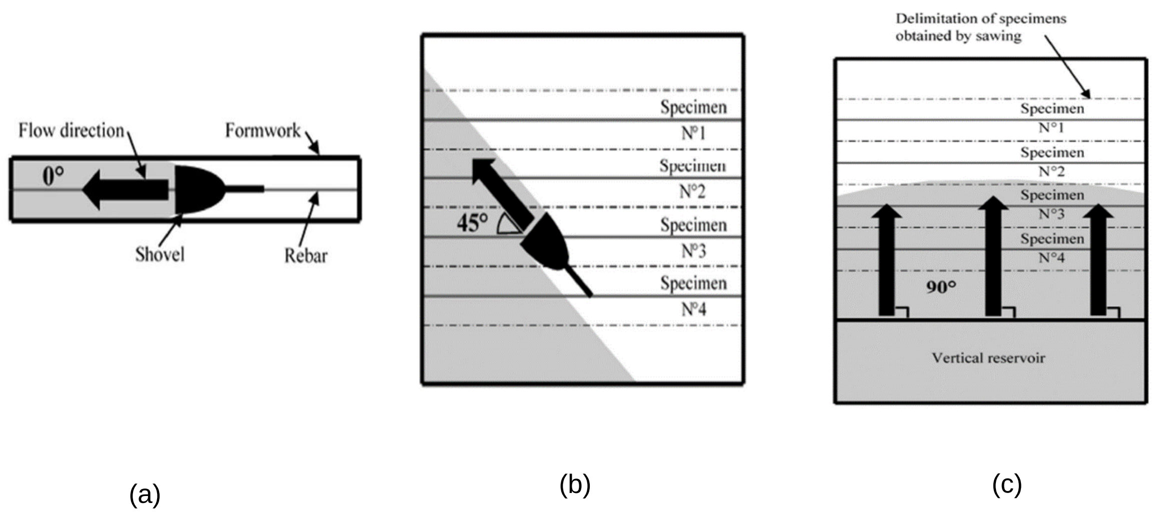

Figure 2.8 - Casting methods: favorable (a), average (b) and unfavorable (c) (Plagué et al. 2017).

The previous casting methods were performed on reinforced concrete specimens which are different from earth mixtures reinforced with organic fibres. These last ones are more flexible and have a lower bulk density than steel fibres, making it harder to obtain a homogeneous orientation. Also, the consistency of the earth mixture will have a strong influence on the casting of the composite.

There are few studies concerning the casting methods of earth mixtures, enhancing the need of a study focus on this subject.

2.4.2. 2D Image analysis

Regarding the 2D analysis of composites several studies were developed on the characterization of hot mixes asphalt whose behaviour is influenced by its aggregates, namely the mechanical and geometric properties. Since aggregates play a very important role on the pavement stability and resistance, their characterization should pass by the knowledge of the length, shape, orientation and texture (Bessa et al. 2012, from Souza 2009).

In this context Bessa et al. (2012) studied the characterization of three types of aggregates (granitic, construction and demolition waste and steel slag) with the use of digital image processing software through a planar technique that involves the digitalization of the planar image of the composites. This image analysis requires some steps: the transformation of the real image on a digital one through digitalization, the enhancement of the image so that the particles can be more evidenced, correction of imperfections and finally the segmentation.

Softwares like ImageTool, ImageJ, the Digital Image Analysis System and Abaqus 2008 were referenced by Bessa et al. (2012) as commonly used for this type of analysis, being the Digital Image Analysis System and ImageJ the used by the authors.

Also, Sebaibi et al. (2014) used the ImageJ software, in this case on a cement matrix reinforced with polyester and glass fibres to analyse the number of fibres, their position and orientation.

Yoo et al. (2016) introduced a different approach to the image analysis with the use of Photoshop to study the influence of fibre orientation on the flexural behaviour of ultra-high-performance fibre reinforced concrete. Firstly, the composite was cut using a diamond blade, then a picture of the surface was taken with a high-resolution camera that is called RGB image, then the image was passed to a binary image in order to have a segmentation between the fibres and the matrix, finally with mathematical expressions the length and orientation of the fibres were measured.

Despite being known that the casting methods have a strong impact on the mechanical and physical properties of bio-based composites, the microscale physics and macroscopic consequences remain poorly understood. So, it could be beneficial for the optimisation of bio-based materials the develop of a method of image analysis to elucidate the inherently 2D pore scale mechanisms and help explaining the macroscopic changes that emerge.

3. Materials and samples

3.1. Rice husk blocks

Rice husk blocks were produced with 3% weight content of rice husk fibres in a previous study by Laborel-Préneron (2017) for the assessment of durability properties, the same content of barley straw, hemp shiv and cork granules was also used to produce blocks (Figure 3.1). The objective of the study was to assess the influence of these and other natural fibres and aggregates on ultra sound velocity, dry abrasion resistance, low pressure water absorption, wet abrasion resistance and impact resistance.

The blocks were produced mixing by hand the natural fibres with an earth before adding water. Then the mixture was poured in 15x15x5 cm^3 moulds and a static compression was applied. After that, the blocks were first dried at 40ºC for 24h and then placed at increasing temperature from laboratory environmental temperature until 100ºC and kept at that same temperature until the weight variation was lower than 0.1% between two weighing 24 hours apart. Finally, the blocks were stored in a conditioned room at 20ºC and 65% relative humidity (RH) until they reached equilibrium with the room environment.

Figure 3.1- Earth blocks produced by Laborel-Préneron et al. (cited in Laborel-Préneron 2017).

Simultaneously to the study of the formulated bio-based insulation panels, these fibre reinforced blocks were also characterized. Several blocks were fractured so the barley straw and hemp shiv were only characterized regarding the 2D image analysis, the rice husk blocks (Figure 3.2) were used in other experimental tests as it will be seen forward on this work.

The following symbology was used to identify these earth blocks:

- S_3A: Earth blocks reinforced with barley straw;
- H_3A: Earth blocks reinforced with hemp shiv;
- RH_3A: Earth blocks reinforced with rice husk.

Figure 3.2- Rice husk blocks, with previous marks from abrasion and ultra-sound tests.

3.2. Materials

3.2.1. Earth

The earth used to produce the insulation panels was the same used by Laborel-Préneron (2017) in previous studies regarding the reinforced blocks. The earth is composed by quarry Fines from Washing Aggregate Sludge (FWAS) and it is obtained from the washing of limestone aggregates produced for the concrete industry.

The material properties were previously characterized by Laborel-Préneron (2017), the Atterberg limits, that defined the consistency of a soil in function of the water content are defined in Table 3.1, namely the liquidity limit W_L, plasticity limit W_P and plasticity index PI. The mineralogical composition is presented in Table 3.2.

Table 3.1 - Atterberg limits of FWAS (Laborel-Préneron et al. in review).

Atterberg limits	W_L (%)	30
	W_P (%)	21
	PI (%)	9

Table 3.2 - Mineralogical composition of FWAS (Laborel-Préneron 2017).

Mineralogical composition	Calcite (%)	63
	Dolomite (%)	3
	Kaolinite (%)	11
	Quartz (%)	10
	Illite (%)	9
	Goethite (%)	3

The dry density of the earth was measured by filling a recipient with a volume of 0.749 L with resource of a filler placed 5 cm above the recipient. The recipient was filled, levelled and then weight; this process was repeated three times – three tests. The dry density ρ (g/m³) is obtained by the quotient of the mass of the earth m (g) by the volume of the recipient V (m³). The dry density of the earth is presented in Table 3.3.

Table 3.3 - FWAS dry density determination.

Earth (kg)	ρ (kg/m³)
0,5702	0,756
0,5598	
0,5699	

To determine the particle size distribution and the granulometric curve of the earth, a sample with 1 kg was dried until the mass was constant, with less than 0.1% weight variation. The determination of these properties was conducted based on a sieve analysis that consists on shaking the sample through a defined set of sieves with different openings. The used sieves and respectively opening are defined on Table 3.4.

Table 3.4 - Sieves and openings.

Sieve number	Opening (mm)
4	4,76
8	2,38
16	1,19
30	0,595
50	0,297
100	0,149
200	0,075

A mechanical sieving was made for 2 minutes; after that the earth retained in each sieve was weight and the percentage retained in each sieve was determined, which lead to the particle size distribution curve (Figure 3.3).

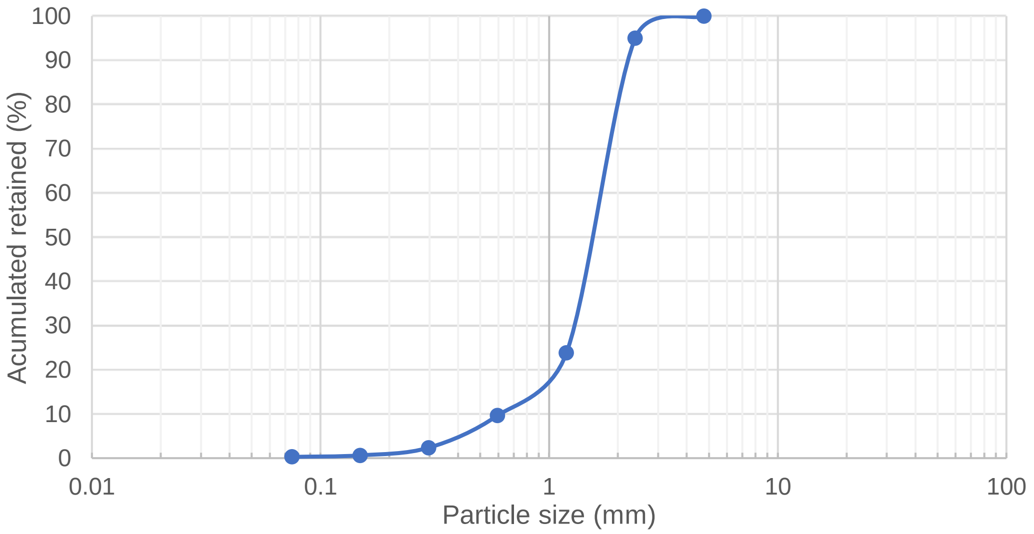

Figure 3.3 - FWAS granulometric curve.

It can be seen that the earth is monogranular, with the main percentage of particles with 1.5-2.5 mm.

3.2.2. Rice husk

Rice husk used for this study was provided by the company Orivárzea located in Salvaterra de Magos to the Department of Civil Engineering of FCT UNL (Figure 3.4).

Rice is the second cereal most consumed in the world, the world production was estimated in 661,3 million ton (FAO 2008 in Lacerda et al. 2010).

Figure 3.4 - Rice husk.

Regarding its chemical composition, rice husk was previously characterized by Xiong et al. (2009) which is presented in Table 3.5.

Table 3.5 - Chemical composition of rice husk (Xiong et al. 2009).

Chemical composition	C (%)	37,05
	H (%)	8,8
	N (%)	11,06
	Si (%)	9,01
	O (%)	33,03

The characterization was based on the work of the RILEM TC 236-BBM (Amziane et al. 2017) and Laborel-Préneron et al. (2017), once there is no standardized method for vegetal fibres. Therefore, the fibres were characterized concerning their geometry, bulk density, thermal conductivity and water absorption.

The geometry analysis of the rice husk was made with the ImageJ software presented on Table 3.6. According to RILEM TC 236-BBM this analysis should be made in a sample between 3 and 6 g or with more than 1000 particles. Then the particles were sieved at 500 µm to remove dust and finally photographed to be processed in ImageJ (Figure 3.5).

Figure 3.5 - Rice husk sieving.

To determine the bulk density of the rice husk, first the samples was dried at 60ºC until the weight was constant with variations lower than 0.1% between two weightings 24 hours apart. Then the same process described previously for bulk density determination of the earth was used. The bulk density of the rice husk is presented on Table 3.6.

According to RILEM TC 236-BBM for the determination of the thermal conductivity, the sample needed to be first dried until the weight became constant and then measured with a hot plate apparatus. In this case the sample was dried until the weight was constant and then the thermal conductivity was measured with an ISOMET 2104 Heat Transfer Analyzer equipment and a 60 mm contact probe, by filling a mould with 40 mm high and diameter 120 mm (Figure 3.6). The thermal conductivity results are presented in Table 3.6.

Figure 3.6 - Thermal conductivity measurement of rice husk.

Table 3.6 - Legth, bulk density and thermal conductivity of 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 three samples with about 25 g were dried at 60ºC until the weight was constant. Then the samples were placed in net bags and immersed in water for 15 minutes, 4 hours and 48 hours (Figure 3.7). After immersion, the samples were drained inside the net bags and their weight measured.

Figure 3.7 - Samples used for water absorption determination.

After weighting the water absorption percentage is obtained based on the Equation 1.

$$w(t) = \frac{m(t) - m_0}{m_0} \times 100\ (\%)\ (1)$$

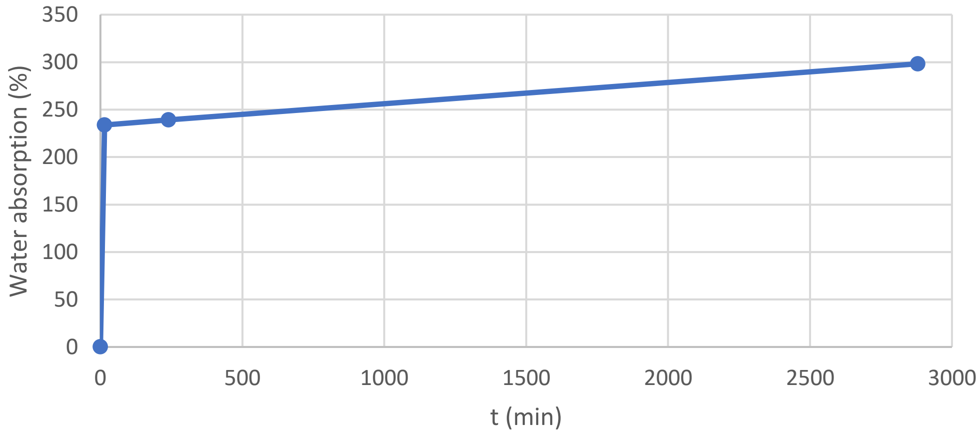

Figure 3.8 - Rice husk water absorption in function of time.

The water was mainly absorbed in the first 15 minutes, showing that rice husk has a high absorption capacity.

3.2.3. Gypsum

Gypsum used as the principal binder for the production of the earth panels was hemi-hydrated from Sival (EN 13279-1:2008) special gypsums and was bought by the Civil Engineering Department of FCT UNL. From the technical sheet of the producer, it was produced at low temperatures - between 120 and 180ºC – and has “good thermal and sound insulation properties, with a low thermal conductivity” (Sival, 2013).

Table 3.7- Gypsum properties from Sival Gessos especiais (Sival, 2013).

Gypsum properties	
Water/gypsum ration (kg/l)	1,25
Hardness time (min)	13 ± 4
Linear expansion (1h) (%)	max 0,20
Tensile flexural strength (kg/cm^2)	40

3.2.4. Air lime

Being one of the most studied additions to earth composites, hydrated air lime was added to the panels not only by its ability to increase the compressive strength and decrease the water absorption of earth composites, but also as a delayer of the hardness process of the gypsum. This lime requirements are defined in EN 459-1 (CEN, 2010).

The air lime used in this work was made available by Lusical Hoist Group and was previously characterized by Gameiro et al. (2014). The chemical composition of the binder in weight percentage is presented in Table 3.8.

Table 3.8- Chemical composition of air lime in wt.% from Lusical (Gameiro et al. 2014).

Air lime	
Al_2O_3	0,01
Fe_2O_3	0,15
MnO	0,01
MgO	3,09
CaO	76,74
K_2O	0,02
TiO_2	0,04
P_2O_5	0,01
Loss on ignition	20,45

3.3. Samples production

3.3.1. Composition

Like it was previously said, the formulation of these innovative panels was never studied before. It is important to refer that the production process was initially by trial and error, with the objective of maximizing the rice husk content and, therefore, minimizing the earth-gypsum-lime paste to agglomerate the husk.

Based on the literature review it was defined a gypsum and lime content of 10% and 5% in volume respectively. Firstly, different mixtures were made, with and without natural fibres and different quantities, to see the influence and reaction between the different components.

The samples were left to dry at room environment for three days and placed two days on an oven at 60ºC, but it was observed that the mixture was not hardened enough. So, after ponderation the gypsum and lime contents were doubled: 20% gypsum and 10% lime.

Stablished the binders content, it was needed to define the rice husk percentage but once the objective was to achieve the maximum content possible this was defined after several mixtures. Firstly a 15% in volume fibre content was used, after what it was needed a bigger water addition to make it possible to add more rice husk. Therefore, the final content used was of 30% in volume.

As it was seen in the literature review the wetting of the natural fibres can have a strong impact on the resistances and thermal properties of bio-based materials, although the results of the studies do not reach a consensus. Therefore, and based on the experiment of optimized contents, three panels types were made:

- RH_15D: Panels with earth-gypsum-lime and 15% by volume dried rice husk;
- RH_30D: Panels with earth-gypsum-lime and 30% by volume dried rice husk;
- RH_30B: Panels with earth-gypsum-lime and 30% by volume boiled rice husk.

The composition of each panel is presented on Table 3.9.

Table 3.9 - Rice husk panels composition.

<table>
<tr><th rowspan="2">Specimen</th><th colspan="2">Earth</th><th colspan="2">Gypsum</th><th colspan="2">Lime</th><th colspan="2">Rice husk</th><th>Water</th></tr>
<tr><th>%</th><th>g</th><th>%</th><th>g</th><th>%</th><th>g</th><th>%</th><th>g</th><th>ml</th></tr>
<tr><td>RH_15D</td><td rowspan="3">100</td><td rowspan="3">908</td><td rowspan="3">20</td><td rowspan="3">169,1</td><td rowspan="3">10</td><td rowspan="3">44,475</td><td>15</td><td>141,45</td><td>1292,5</td></tr>
<tr><td>RH_30D</td><td rowspan="2">30</td><td rowspan="2">282,4</td><td rowspan="2">1622</td></tr>
<tr><td>RH_30B</td></tr>
</table>

3.3.2. Mixing and casting

The optimized mixing method consists on the mixing of the dry ingredients and then addition of the fibres, following the recommendations of several authors that study earth composites.

First the dry ingredients – earth, gypsum and lime - were weighted on the defined proportions and homogenised with the help of a shovel. Then using an electric mixture arm, water was added until the mixture was homogenised.

According to the DIN 18497 (DIN, 2013) an earth mortar should be mechanically mixed during 60 seconds with a 5 minutes resting period and after that another 30 seconds with mechanical mixing. The protocol was adapted since the composition includes gypsum, which has a very quick hardening process. Therefore, and based on the previous study from Lima et al. (2016), after homogenisation the mixture was mixed during 90 seconds without resting period (Figure 3.9 a). After that the rice husk was added to the mixture and mixed until a homogeneous consistency was obtained (Figure 3.9 b).

Based on different studies, a specific casting process was adopted, according to previous works letting the mixture flow into the mould lead to not only a better fibre orientation but also to a more homogeneous microstructure. In Figure 3.10 there is a scheme of the casting method.

Figure 3.9 - Dry ingredients mixture with water (a) and rice husk addition (b).

Figure 3.10 - Casting method adopted (representative).

The specimens were casted on 20x20x4 cm wooden moulds, Figure 3.11. To simplify and to avoid fractures on the demoulding process, a transparent plastic paper was wrapped around the moulds. Also for formulations RH_30D and RH_30B specimens with 4x4x16 cm were produced.

Figure 3.11 - Rice husk specimens.

In the first mixture for the RH_15D specimens, quickly the mass started to gain hardness due probably to the fast hardness period of gypsum and lack of water. So, this mixture was casted by layering of the mixture on the moulds. After this it was clear that the next mixtures needed more water once the goal was to produce panels with the highest rice husk content possible on a fluid mixture.

The production of the RH_30D was identical to the previous except for the rice husk and water content. For achieving the pretended consistency almost 5 L of water were added.

For the boiled rice husk panels, the fibres were previously boiled for 1h ensuring that the cellulose walls were break and 1h later they were added to the mixture (Figure 3.12).

Figure 3.12 - Rice husk boiling.

3.3.3. Curing

Based on the literature review in chapter 2, section 2.1, earth composites have an estimated curing period of 28 days in a dried environment. The specimens were left to dry at laboratory conditions with a temperature of 23ºC and 50% RH.

Some authors use ovens to accelerate the curing process but in this case, it was chosen not to use this method, mostly because with high temperatures, there was a risk to burn the rice husk at the surface.

Two weeks after the production of the RH_30D specimens, it was observed the appearance of biological contamination not only on the moulds but also on the specimens, Figure 3.13. There may be a relation between the boiling of the fibres and the appearance of contaminations only in specimens made with dry husk, once the boiling water destroys all the cellulose and organic matter on the vegetable fibres. Also, the fact that the production of the RH_30D panels requires a higher water content, when compared with the others allied to the RH of the laboratory may be a cause for these appearances.

The panels were demoulded after 2 weeks of curing and let to dry for another two weeks. The specimens were placed slightly elevated so that the drying can occur on all the surfaces and not just on the top surface.

Figure 3.13 - Biological contamination of RH_30D panels.

4. Testing methods

Table 4.1 resumes the experimental procedures conducted and the respective tested specimens.

Table 4.1 - Experimental procedures (√ - performed; x – not performed).

Experimental procedures		Specimen					
Test	**Normative**	**RH_15D**	**RH_30B**	**RH_30D**	**RH_3A**	**S_3A**	**H_3A**
2D Image Analysis Image J	-	x	x	√	√	√	√
Thermal conductivity	-	√	√	√	√	√	√
Ultra sound propagation velocity	EN 12504-4 (CEN, 2004)	√	√	√	√	√	√
Dry abrasion resistance	DIN 18947 (DIN, 2013)	√	√	√	x	x	x
Tensile Flexural strength	EN 12089 (CEN, 1997)	√	√	√	x	x	x
Compressive strength	EN 826 (CEN, 1996) ; EN 1015-11 (CEN, 1999)	√	√	√	√	x	x
Moisture Buffer Value	NORDTEST	√	√	√	√	x	x
Fire resistance test	EN ISO 11925-2 (CEN, 2010)	√	√	√	√	x	x

RH_15D: 15% dried rice husk panels; RH_30D: 30% dried rice husk panels; RH_30B: 30% boiled rice husk panels; RH_3A: 3% rice husk blocks; S_3A: 3% barley straw blocks; H_3A: 3% hemp shiv blocks.

4.1. 2D Image Analysis – ImageJ

The main issue of these digital image processes is the segmentation of the images. Segmentation is a process that separates shapes, sorting out particles from the respectively matrix, like the granitic aggregate from the matrix in Bessa et al. (2012) study or the glass fibre from the cementitious matrix from Sebaibi et al. (2014).

According to the bibliography, ImageJ is commonly used on image analysis and was adopted to the present study. Because of the colours similarity between the fibres and the earth matrix and the difficulty on knowing the shape of the fibres, a segmentation process was not a possibility, making it impossible to perform an automatically analysis of the block surface.

The analysis was performed on all the earthen reinforced blocks, namely on barley straw, hemp shiv and rice husk.

The rice husk panels analysis was made only for the dried rice husk specimens, once it was hard to identify the fibres on the RH_15D and RH_30B. The boiled rice husk specimens presented a coat that covered the fibres making it almost impossible to identify.

Being cast with an optimized method the RH_30D are presented as the best comparison with the earthen blocks.

First a high-quality picture was taken with a 15 megapixels' camera. Then the contrast was slightly adjusted for better perception of the fibres outline from the earthen matrix. Then with the ImageJ tool the scale was set based on the horizontal and vertical dimensions of the specimens. Finally, the length

and the angle with the horizontal plane was measured for each fibre, Figure 4.1 exemplifies a measured samples before and after the ImageJ analysis.

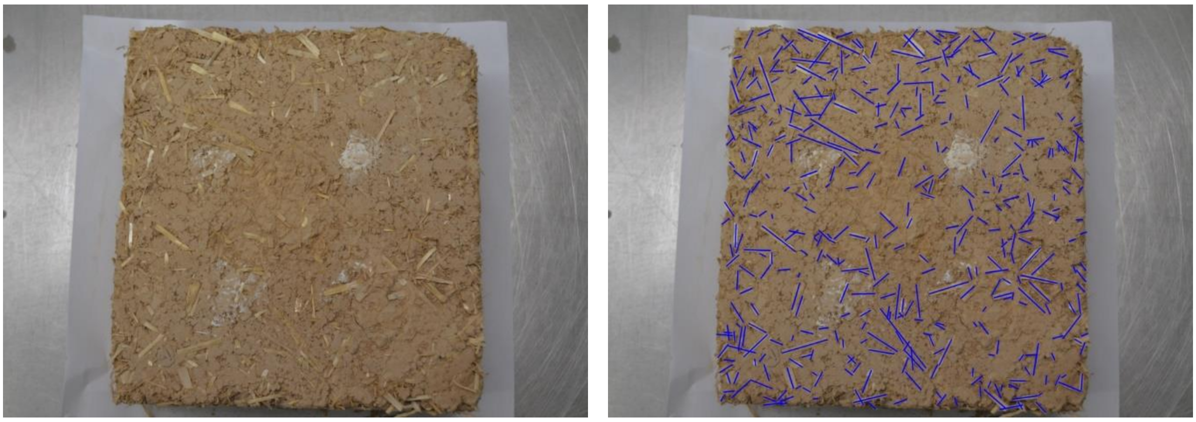

Figure 4.1- Barley straw block before and after Image J analysis.

These measurements were taken to determine the influence of fibre length and orientation on the properties of the earth specimens. It is important to retain that this method is made manually for about 400 fibres in each surface; whereby there is an error associated to these measurements.

4.2. Thermal conductivity

The thermal conductivity test objective is the determination of the thermal conductivity coefficient ʎ [W/(m.K)] of a homogeneous material. The thermal conductibility translates the ability of the material to conduct heat, namely the heat quantity that passes through the material thickness. A material with high thermal conductivity easily conducts heat; contrarily a low thermal conductivity coefficient means that the material is a good thermal insulation once it does not conduct the heat so fast (Henriques 2007).

To evaluate the thermal conductivity of the earth blocks and panels the same equipment described previously for the rice husk thermal conductivity test. The specimens were previously stored in a laboratory with controlled climatic conditions with a temperature of 23ºC and 50% RH, for about 3 weeks which allowed the equilibrium between the samples and the environment.

The test protocol followed was very simple: at first the specimens were placed on a 4 cm EPS panel to prevent possible interventions, then, using the same equipment previously described a probe with 60 mm diameter was placed on the measure point. There are two types of probes, one with a range value of 0.04-0.30 W/m.K and 0.3-0.6 W/m.K.

For the earth blocks, three measurements were performed with the probe for values between 0.3-0.6 W/(m.K), attending that the sensor should not be too close to the edges so the values could not be influenced. After the first measurements, it was showed that the measurement on three points was irrelevant, once the difference was reduced; so the blocks were measured only on a central point, Figure 4.2.

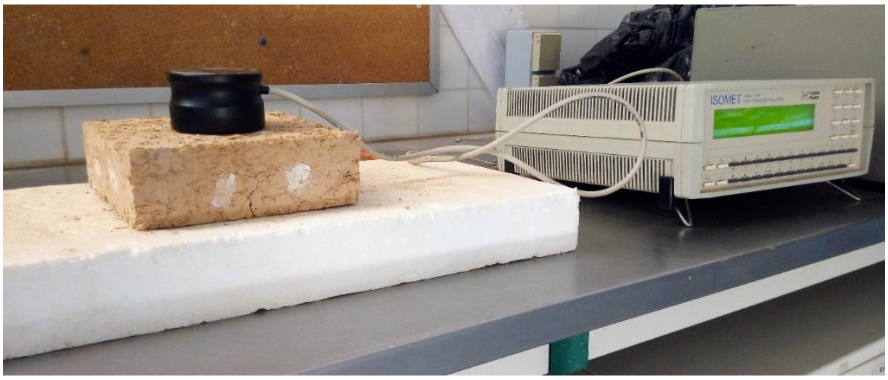

Figure 4.2 - Thermal conductivity measurement of rice husk blocks.

For the earth panels, five initial points were measured using a 0.04-0.3 W/(m.K) probe: four points on the vertices and one at the centre of the panels, Figure 4.3. Three measurements were performed on each point.

Figure 4.3- Thermal conductivity measurement of rice husk panels.

4.3. Ultra-sound propagation velocity

The ultra sound speed test evaluates the homogeneity of the material and the presence of voids, fractures and imperfections; their existence influences the velocity of the impulse.

The test was performed based on the EN 12504-4 (CEN, 2004) with a Proceq Pundit Lab equipment. It is a non-destructive test that determines the time that an impulse takes between two transducers, the transmitter and receiver, outputting the time in µs. Two different measurements were made, the direct measurements where the transducers are placed in opposite surfaces and the indirect measurements with both transducers on the same surface, Figure 4.4.

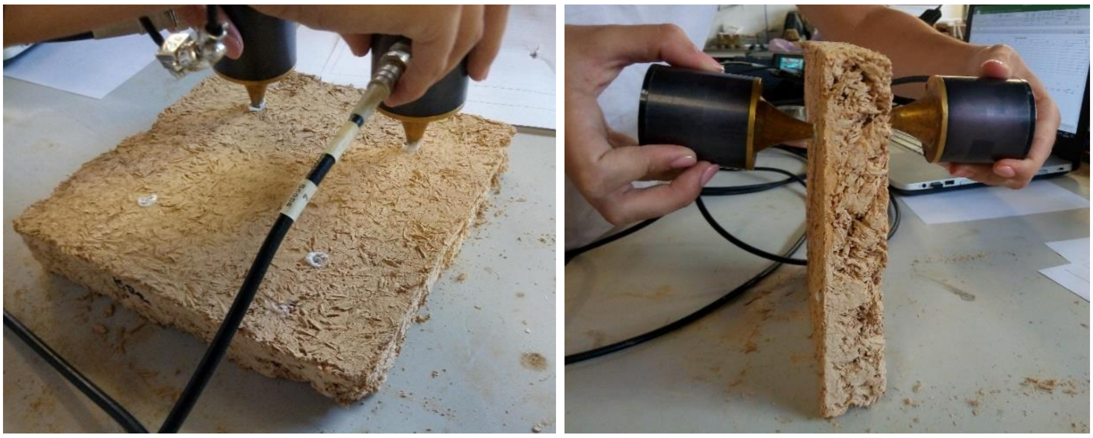

Figure 4.4 - Ultra sound velocity test procedures, indirect method (a) and direct method (b).

Four points were marked on the top and bottom face of the samples, blocks and panels. Then a conductive gel was applied on both transmitter and receiver to perform the readings (Figure 4.5).

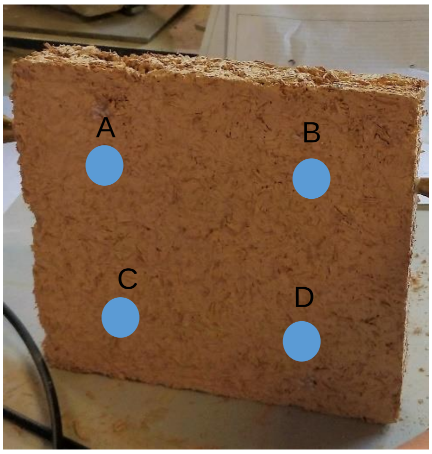

Figure 4.5 - Ultra sound measurement points.

4.4. Dry abrasion resistance

The dry abrasion resistance test evaluates the resistance of a certain material to superficial erosion. This analysis was conducted based on previous work from Faria et al. (2016) according to the DIN 18947 (DIN, 2013).

This test evaluates the weight loss of the specimens after 20 rotations with a polyethylene brush with a 2 kg pressure, Figure 4.6. The earth blocks were previously tested (Laborel-Preneron et al. in revision); so, they were not used for this characterisation. The insulation panels were divided and three measurements were made on each one.

Figure 4.6 - Dry abrasion resistance equipment.

After each test, the specimens were weight to register the mass loss. Then the abrasion weight loss A_{wl} was evaluated determined by the ratio between the mass loss and the brush area, Equation 2.

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

where m_i is the initial mass, m_b the mass after brush action and S the initial contact area of the brush in cm^2.

4.5. Tensile flexural strength

The tensile flexural strength test was performed based on the EN 12089 (CEN, 1997), resourcing to a Zwick Rowell Z050 equipment, Figure 4.7. The test was performed on the rice husk panels which were tested 36 days after casting. The test was conducted at a velocity of 10 mm/min with a distance between supports of 100 mm.

The test was performed on 4x4x16 cm specimens. In the case of RH_15D specimens a panel was sliced to obtain 4x4x20 cm specimens. Three specimens of each formulation were tested and were previously left for 72 hours in a controlled environment at 23ºC and 50% RH.

The bending flexural strength was determined based on the Equation 3.

$$\sigma_b = \frac{3}{2} \times \frac{P \times L}{b \times h^2}\ \ (MPa)\ (3)$$

where σ_b (MPa) is the bending strength, P (N) is the obtained load, L (mm) is the distance between the supports, b (mm) is the height of the section and h (mm) the section width.

Figure 4.7 - Zwick Rowell Z050 equipment testing a prismatic sample.

4.6. Compressive strength

Compressive strength test was performed according to the EN 826 (CEN, 1996) for the panels and to EN 1015-11 (CEN, 1999) for the blocks. The test specimen should be placed in the movable plate and compressed at a constant rate of 0.1d per minute, where d is the thickness of the specimen in millimetres.

The specimens were tested after 36 days of their production, and were previously left for 72 hours on laboratory conditions previously described.

The tested specimens were fragments provided from the tensile flexural strength test. They were placed on the support of the equipment Zwick/Rowell and loaded at a constant velocity of 0.4 mm/min. The RH_15D specimens were cut to perform the test.

For the insulation panels specimens, it was necessary to create a higher support so that the specimen had liberty to deform. Initially the specimens were confined to the support which preclude them from deforming, Figure 4.8.

Figure 4.8 - Compressive strength test procedure.

As dealing with a very deformable material it was necessary to limit the applied load. Therefore, the equipment was programmed to stop when 10% of the deformation was achieved. This way the specimen was loaded until it deformed 4 mm and then stopped for 30 seconds. This measure was needed; otherwise the strength will be infinite, the specimen will continue to deform without reaching the ultimate load. It is important to analyse the resilience of the material, to observe if the sample recovers some of its initial shape. If it does it could have interesting application for acoustic insulation materials in pavements.

The compressive strength to 10% of deformation σ_{10} (MPa) is determined by the quotient of the compressive load F (N) by the area of the compression load A (mm^2).

4.7. Moisture Buffer Value

The Moisture Buffer Value (MBV) concept was developed by a Norden group of investigators within NORDTEST (Rode et al. 2005) which also defines the MBV experimental protocol for its determination. The MBV is a characteristic of the material based on this absorption and desorption of moisture; it translates the ability of the material to regulate the indoor air humidity (Ramos 2007).

According to the NORDTEST protocol a minimum of 3 specimens should be exposed to RH cycles. First the specimens should be wrapped in aluminium tape leaving the top surface exposed; this facilitates the moisture exchanges. Then they should be placed inside a climatic chamber (Fitoclima 300) at defined temperature and RH to stabilise. The relative humidity cycles are divided in two phenomenons, the adsorption period, exposing the specimens to maximum relative humidity for 8h, followed by the desorption period, with minimum relative humidity for 16h (Rode et al. 2005).

For each formulation 3 specimens were tested, including three earth blocks. They were wrapped in aluminium tape and let to stabilise for 5 days (Figure 4.9). Then the specimens were exposed to relative humidity cycles of 60 to 90% at 16ºC temperature.

Figure 4.9 - Rice husk panels pre-conditioning.

During the absorption period, the specimens were weight every two hours; in the desorption period only three measurements were considered, Table 4.2.

Table 4.2 - Measurements hours during MBV test.

	Weigthings
Adsorption RH 90%	0h
	2h
	4h
	6h
	8h
Desorption RH 60%	10h
	12h
	24h

The practical determination of the MBV is based on Equation 4;

$$MBV = \frac{\Delta m}{m \times \Delta HR} \quad (4)$$

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

4.8. Fire behaviour

The fire behaviour test was performed based on the EN ISO 11925-2 (CEN, 2010), that consists on the exposure of a certain material to a small flame, that could be applied to one of the edges or direct on the surface. The test should take place inside a test chamber where the specimen is mounted vertically and then subjected to a gas flame with a certain duration. Specimens with surface dimensions of 90x250 mm^2 should be analysed regarding their weight loss, the high of the flame and visual aspects. The time

of ignition should be defined according to the classification of the material: for example a material with fire classification between B and D should have 30 seconds of exposure and between D and E 15 seconds (CEN, 2010).

In the present study, once earth majorly composes the materials, it was adopted an ignition time of 30 seconds, with a flame applied to the edge of the specimen. As there was not a test chamber available for the procedure, the specimens were placed on a metallic support at 15 cm from the ground and exposed to a flame with resource to a torch (Figure 4.9).

Figure 4.10 - Fire resistance test procedure.

5. Results and discussion

5.1. Thermal conductivity

The results of the thermal conductivity test show that the thermal conductivity decreases with the increase of rice husk content, as presented in Figure 5.1, which is in accordance with the literature review in chapter 2, Table 2.1.

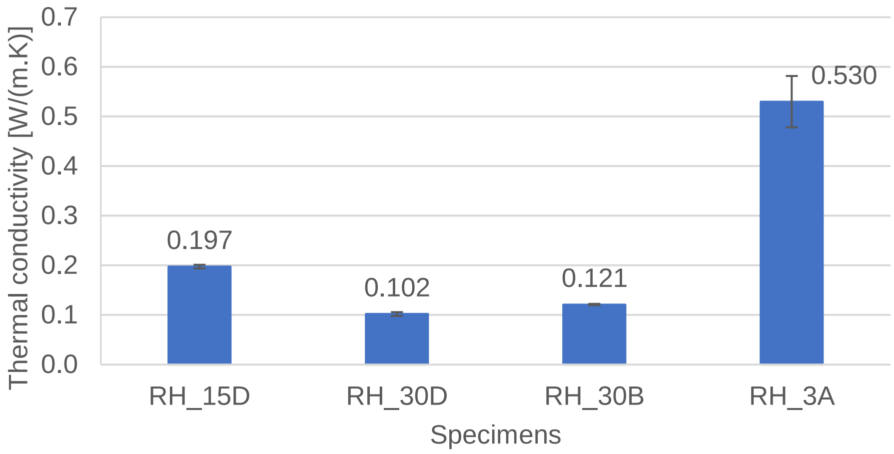

Figure 5.1 - Thermal conductivity results of rice husk panels and blocks.

When increasing the rice husk content from 15% to 30%, the thermal conductivity has a decrease of almost 0.1 W/(mK). The dried rice husk panels, RH_30D, have results slightly lower than the boiled rice husk panels RH_30B, suggesting that the boiling of the fibres leads to a composite with less voids that justifies the higher thermal conductivity. Figure 5.2 shows the bulk density of the specimens in function of the thermal conductivity, showing that the RH_30D have lower bulk density, which justifies its lower thermal conductivity when compared with the RH_30B.

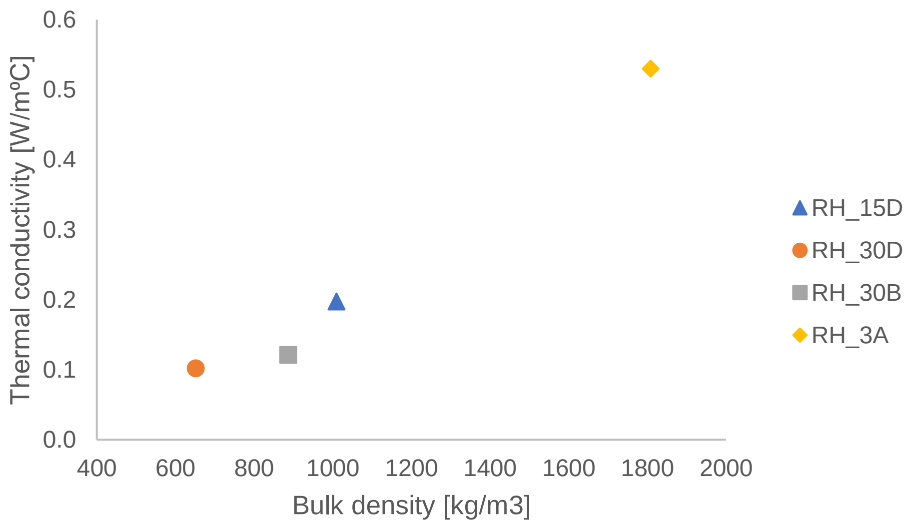

Figure 5.2 - Thermal conductivity as a function of specimens bulk density (rice husk panels and blocks).

The bulk density decreases with the increase on rice husk content. Like it was seen on chapter 2, Table 2.1, the porosity increases with the increase of natural fibre content, leading to lower bulk density and thermal conductivity.

It was observed that the bulk density of the RH_30B is higher than the RH_30D, which is contradictory to Ledhem et al. (2000) study, where the boiled fibres had no influence on this parameter or in the thermal conductivity.

Ashour et al. (2010) studied the thermal conductivity of earth composites reinforced with 25%, 50% and 75% barley straw, wheat straw and wood shavings. The thermal conductivity and bulk density values are presented in Table 5.1.

Table 5.1 - Thermal conductivity results for earth composites reinforced with barley straw, wheat straw and wood shavings (Ashour et al. 2010).

Fibre	Fibre content (by volume)	Bulk density (kg/m^3)	Thermal conductivity [W/(m.K)]
Barley straw	25%	1790	0,349
	50%	1359	0,241
	75%	876	0,154
Wheat straw	25%	1699,55	0,335
	50%	1416,3	0,272
	75%	1123	0,194
Wood shavings	25%	16772	0,281
	50%	1419	0,250
	75%	1311	0,234

Comparing these results with the obtained on the present study, is clear that the rice husk panels have lower thermal conductivity values for similar fibre contents, suggesting that the panels have a better thermal behaviour.

The use of bio-based insulation materials has been studied in the literature. Table 5.2 presents the thermal conductivity values obtained in six different studies and the comparison with the rice husk panels developed in the present work.

Based on the presented table, it is seen that the results for the rice husk panels are above the values obtained by other authors. This could be explained by the high bulk density values of the panels in comparison with the rest of the products.

According to ITE50 (Pina dos Santos & Matias 2006), a product is considered an insulation material if the thermal conductivity is less than 0.065 W/(m.K), which does not happen with the produced panels that present an average thermal conductivity of 0.1 W/(m.K). In this way, the rice husk panels cannot be considered as thermal insulation materials. Nevertheless, they present acceptable thermal conductivity values to contribute to the indoor thermal comfort.

Table 5.2 - Thermal conductivity results for bio-based insulation materials.

Reference	Insulation product	ρ (kg/m³)	ʎ [W/(m.K)]
Neira & Marinho (2005)	Sisal blanket	120-140	0,067
Manohar et al. (2006)	Sugar cane fibre	70-120	0,0461-0,0531
Rodríguez et al. (2011)	Coconut fibre	60-174	0,048-0,1
Pinto et al. (2012)	Corn cob	-	0,139
Palumbo et al. (2016)	Hemp lime	286	0,064
	Hemp fibre	41,1	0,04
	Wood wool	60,2	0,038
	Wood fibre	212,2	0,054
	Barley straw and corn starch	107,5	0,042
	Corn pith-alginate	48,1	0,038
Antunes (2017)	RH_15	1009	0,197
	RH_30D	651	0,102
	RH_30B	886	0,121

5.2. Ultra sound propagation velocity

The average ultra sound propagation velocity of the rice husk panels and the rice husk blocks is presented in Figure 5.3.

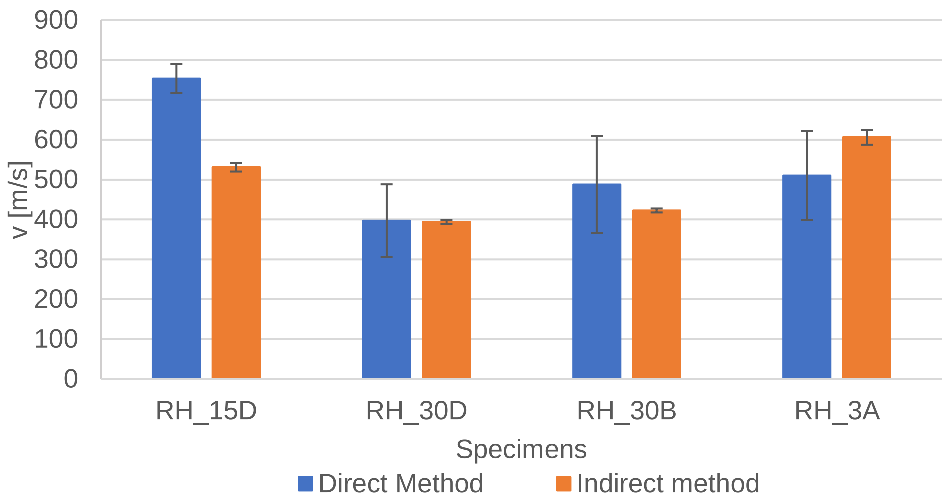

Figure 5.3 - Ultra sound velocity results on the rice husk panels and blocks.

It is showed that the increase of rice husk content decreases the US propagation velocity, which was predictable due to the bulk density results previously presented. A porous composite will lead to lower propagation velocity than a composite with less voids.

RH_15D have the highest propagation velocity, despite the RH_3A being the denser specimen. These results can be justified by the fact that the rice husk blocks were in a previous study subjected to destructive tests. The RH_30D panels have the lowest US velocity, meaning that this specimen has a more discontinuous internal structure.

Comparing the boiled and dried rice husk panels, it is seen that in the RH_30B the ultra sound propagation is higher, which is in accordance with the bulk density results previously presented. A higher bulk density means a more homogeneous composite. It is possible to affirm that boiling the natural fibres leads to a more continuous internal structure.

Binici et al. (2016) tested a bio-based insulation product made of compressed corn and epoxy resin, obtaining for the ultra sound velocity values between 120 m/s and 490 m/s for different compaction pressure, minimum and maximum respectively. Comparing both experimental campaigns is clear that the rice husk panels have a higher velocity related to the fact that these composites have less voids than the corn panels studied by Binici.

Nevertheless, the obtained results are low comparatively to other construction materials like concrete that has an average value of 5000 m/s (Benaicha et al. 2015) or bricks with a value of 1610 m/s (Binici et al. 2016).

This test can be a method for accessing not only the internal structure of the material but also its durability. High propagation velocity results mean that the composite is more durable, once its internal structure is more homogeneous leading to a more resistant material.

5.3. 2D Image Analysis – ImageJ

5.3.1. Length and orientation analysis

For each specimen, the length and orientation of the fibres were assessed to each type of fibre and composite. An average of the obtained results and a frequency distribution for both length and orientation were registered. The same procedure was adopted for the ultra sound and thermal conductivity results.

The fibre length and angle distribution for barley straw blocks is presented in Figure 5.4 and Figure 5.5 respectively.

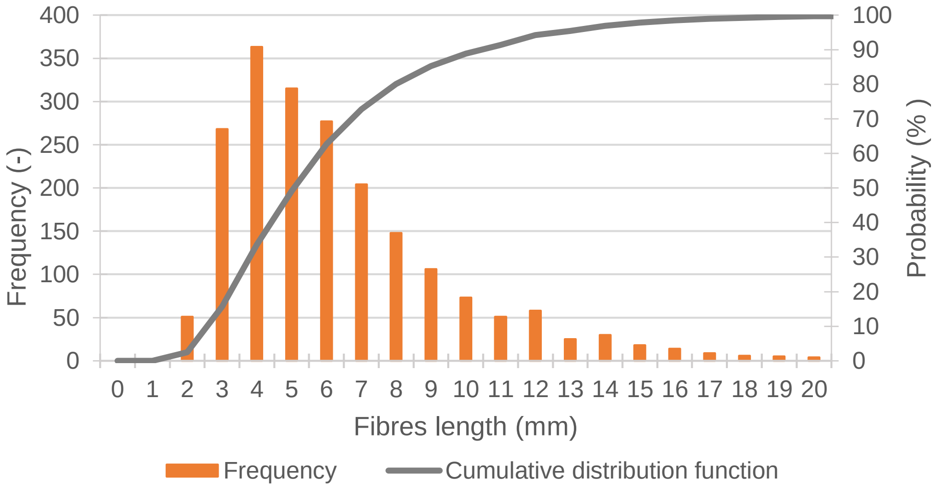

Figure 5.4 - Fibre length distribution for barley straw blocks.

Through Figure 5.4 it is seen that the length tends to an average value of 5 mm.

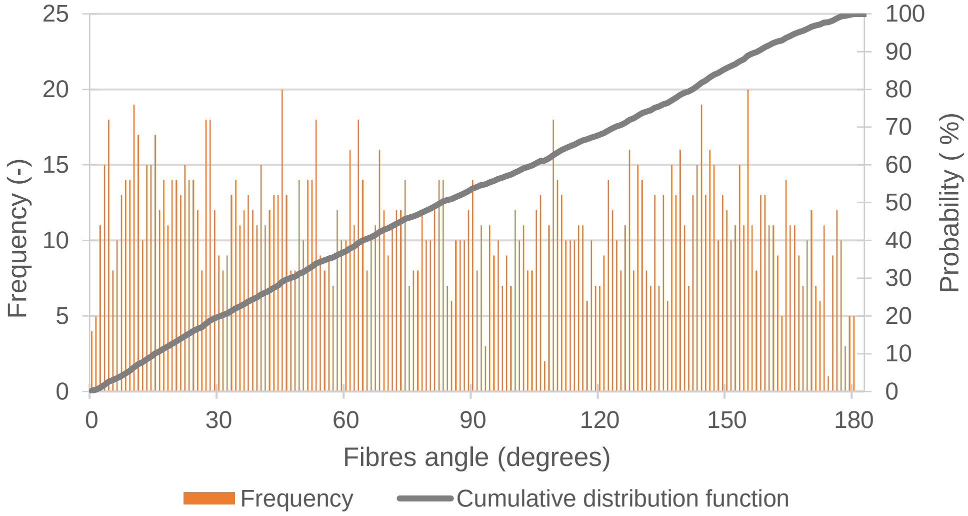

Figure 5.5 - Fibre angle distribution for barley straw blocks.

Figure 5.5 shows that the probability of achieving a fibre angle of 0 or 90 º is the same, which means that a uniform distribution is detected for the fibre angle distribution.

The fibre length and orientation of hem shiv blocks is presented in Figure 5.6 and 5.7.

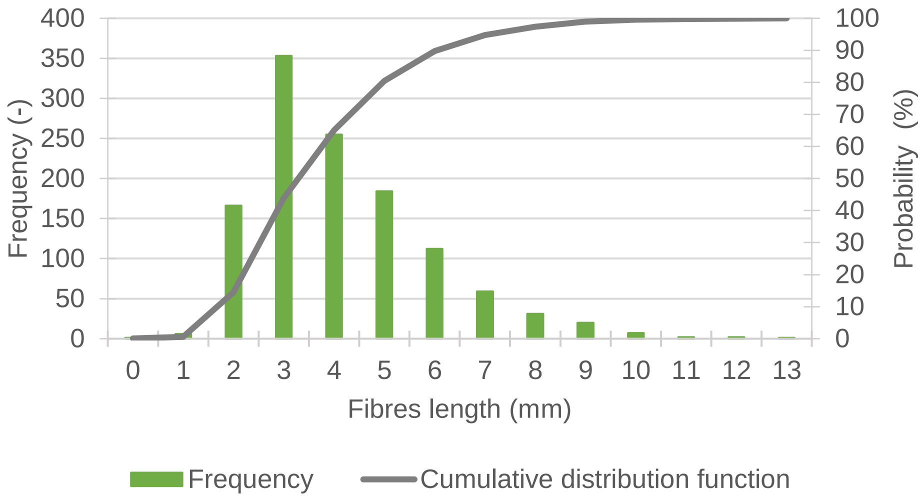

Figure 5.6 - Fibre length distribution for hemp shiv blocks.

Similar to what was observed for the barley straw length distribution, the hemp shiv average length tends to a 5 mm value, which was also verified for the rice husk blocks in Figure 5.5.

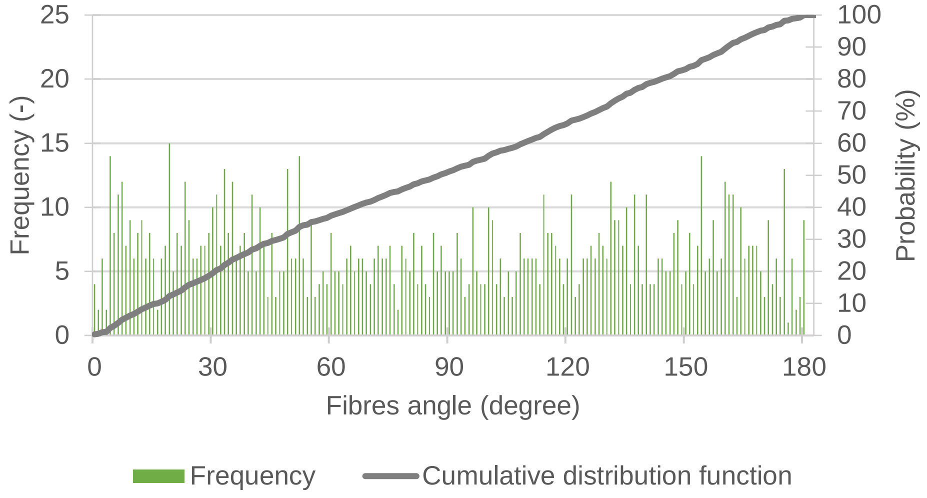

Figure 5.7 - Fibre angle distribution for hemp shiv blocks.

As it was seen in Figure 5.7, for the hemp shiv blocks the probability of achieving a fibre orientation of 0 or 90º is the same, meaning that the fibre angle presents a uniform distribution. The same happens to the rice husk blocks as is presented in Figure 5.9.

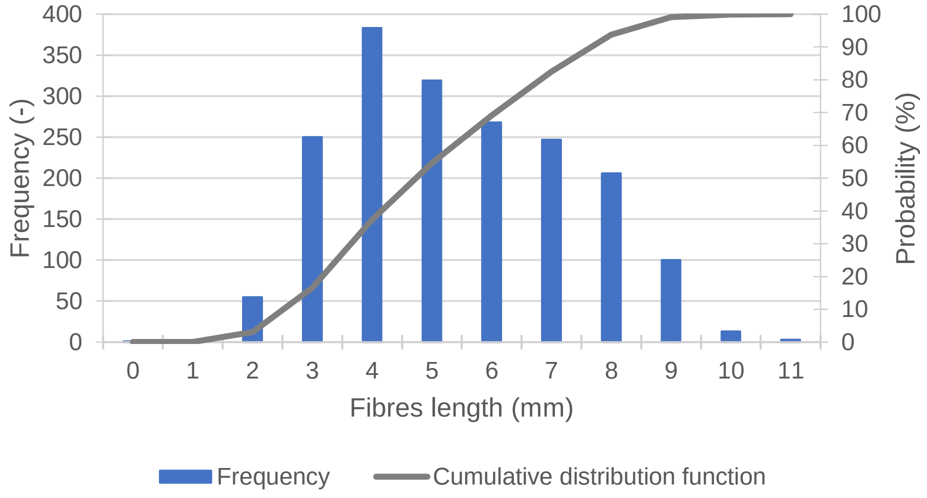

Figure 5.8 - Fibre length distribution for rice husk blocks.

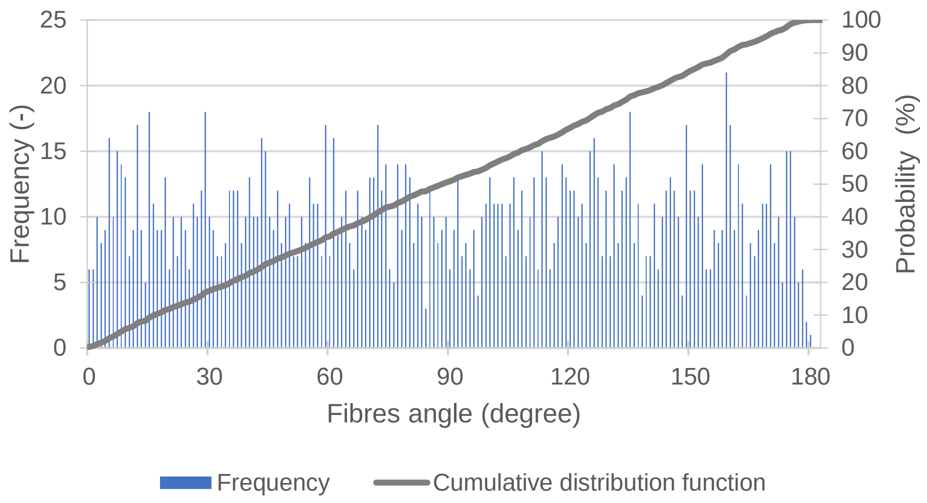

Figure 5.9 - Fibre angle distribution for rice husk blocks.

Figure 5.10 and Figure 5.11 present the fibre length and angle distribution for rice husk panels, respectively.

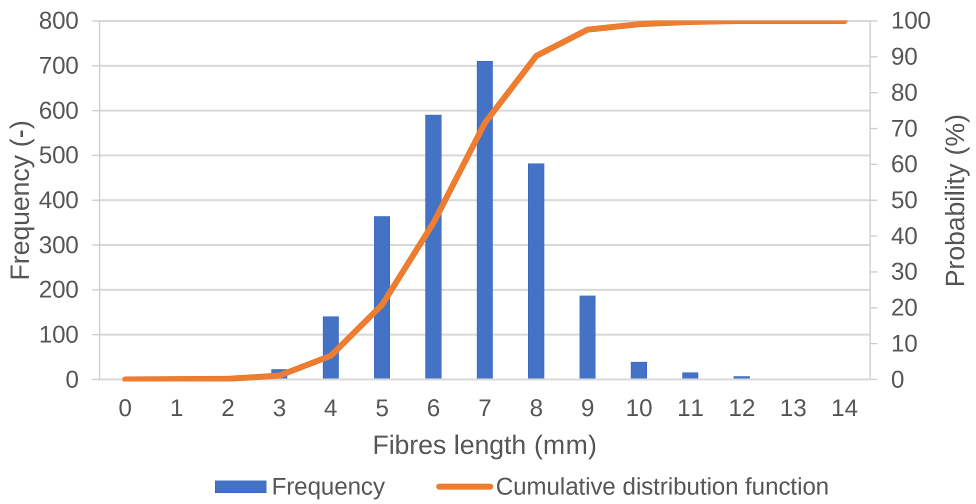

Figure 5.10 - Fibre length distribution for rice husk panels.

Through Figure 5.10 it is seen that the fibres length tends to an average value of 6 mm. Despite being a small difference when compared with the rice husk blocks it could mean that the different casting method. The, rice husk blocks were produced with no defined casting method which could lead to the fibres breaking. By the other hand the rice husk panels were casted according to a defined method, reflecting on the fibres length, being in accordance with the mean length value obtained in the rice husk characterization in Chapter 3.

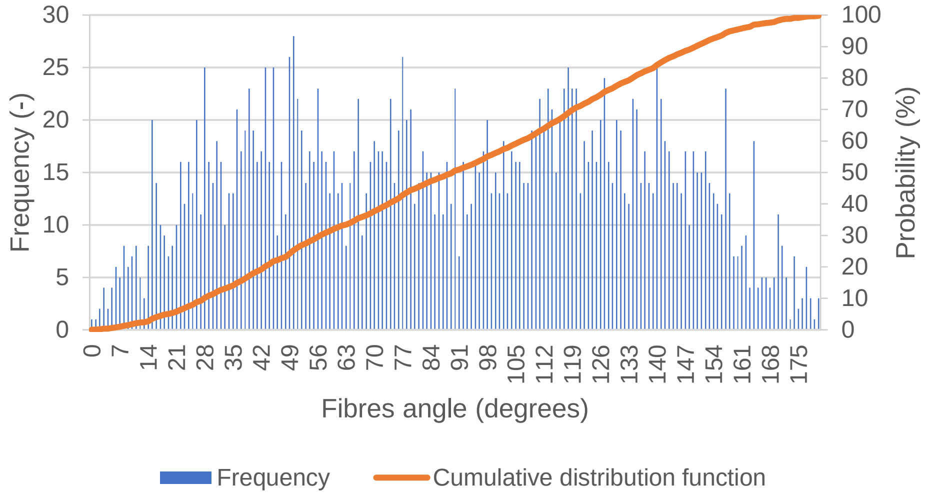

Figure 5.11 - Fibre angle distribution for rice husk panels.

Regarding the fibre angle in the rice husk panels it is showed that the casting method, as well as the fibre content, can have a strong influence on the fibres orientation. It is seen on Figure 5.11 that the angle distribution is not uniform and that the probability of achieving a fibre with 0 or 90º is not the same.

Comparing both Figure 5.9 and Figure 5.11 is possible to see that the different casting of the products have stronger influence on the fibre orientation angle that in the fibre length. It is also possible to see that an optimized casting method, as the one used on the rice husk panels, could lead to a more homogeneous fibre distribution.

5.3.2. Ultra sound propagation velocity analysis

Regarding the ultra sound propagation velocity results, the average values and the frequency distribution curve were determined for both direct and indirect methods.

Figure 5.12 and Figure 5.13 show the distribution curves for the direct and indirect measurements for barley straw blocks.

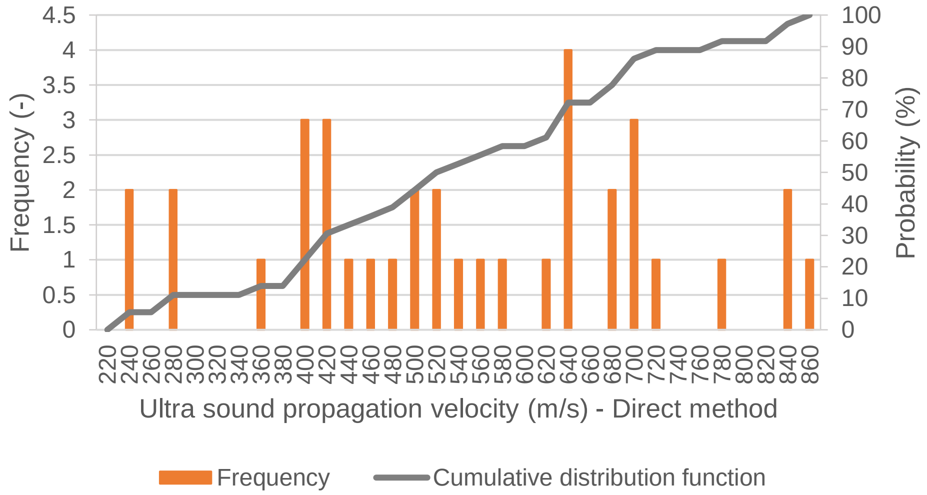

Figure 5.12 - Ultra sound propagation velocity distribution for barley straw blocks - Direct method.

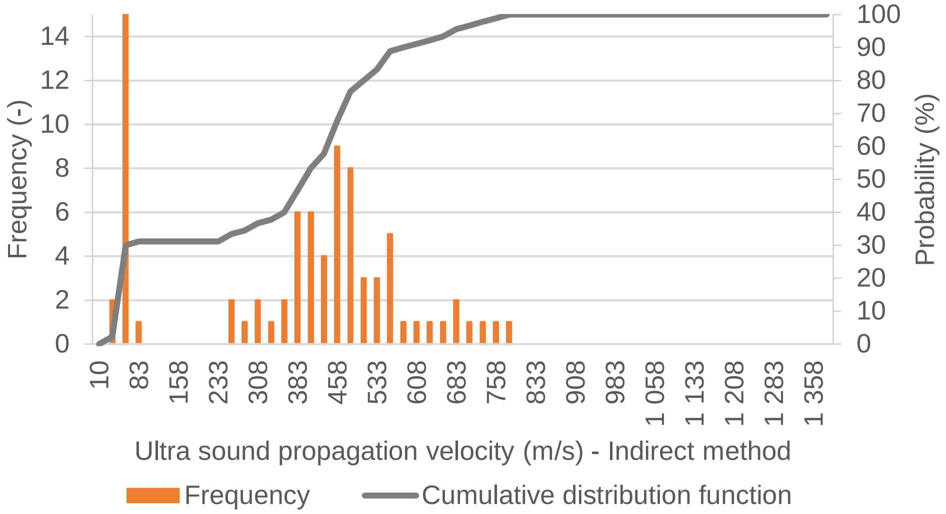

Figure 5.13 - Ultra sound propagation velocity distribution for barley straw blocks - Indirect method.

Through the analysis of the previous figures and the comparison with the fibre length and orientation angle distributions (Figure 5.4 and Figure 5.5) it is possible to see that both these parameters seem to have influence on the direct method for ultra sound test, once there is a similarity on the frequency curves, which does not happen for the indirect method.

During the measurements, the indirect method showed more difficulties than the direct one, once the readings were slower and sometimes impossible to perform.

The direct method showed the most interesting results, presenting higher frequency on higher propagation velocities, which makes it possible to draw better conclusions regarding the mechanical resistance of the blocks.

The frequency and distribution curves referent to the ultra sound results of hemp shiv blocks are presented on Figure 5.14 and Figure 5.15, for direct and indirect method respectively.

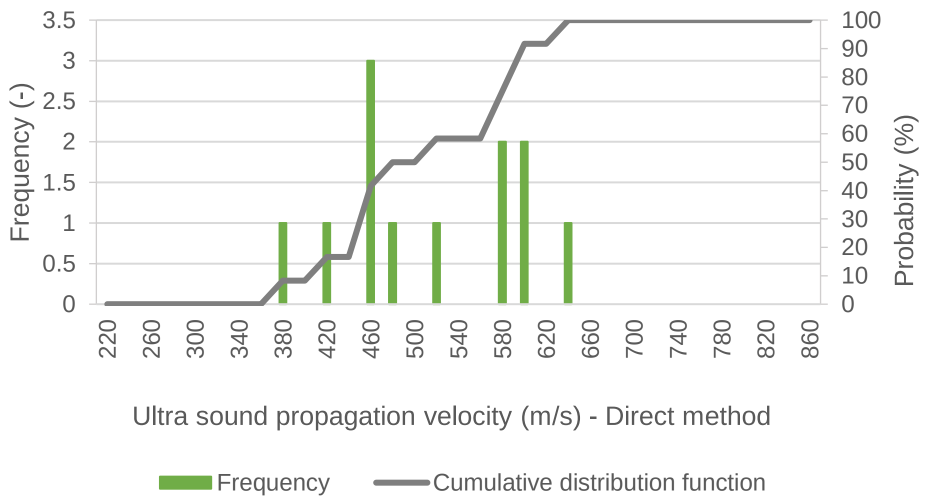

Figure 5.14 - Ultra sound propagation velocity distribution for hemp shiv blocks - Direct method.

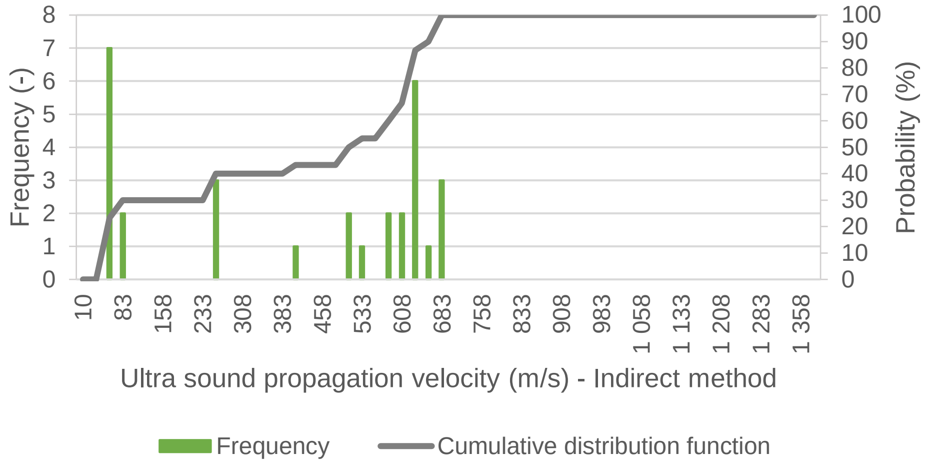

Figure 5.15 - Ultra sound propagation velocity distribution for hemp shiv blocks - Indirect method.

The hemp shiv blocks presented the biggest difficulties on the ultra sound propagation velocity measurements, not only due to the fractures on the tested blocks but also since there was not a significant number of specimens to perform the test. This can be showed by the lack of results in the presented figures, making it impossible to assume a relation between the length and the fibres angle with the ultra sound propagation velocity.

The rice husk blocks frequency and distribution curves, for ultra sound results are presented in Figure 5.16 and Figure 5.17.

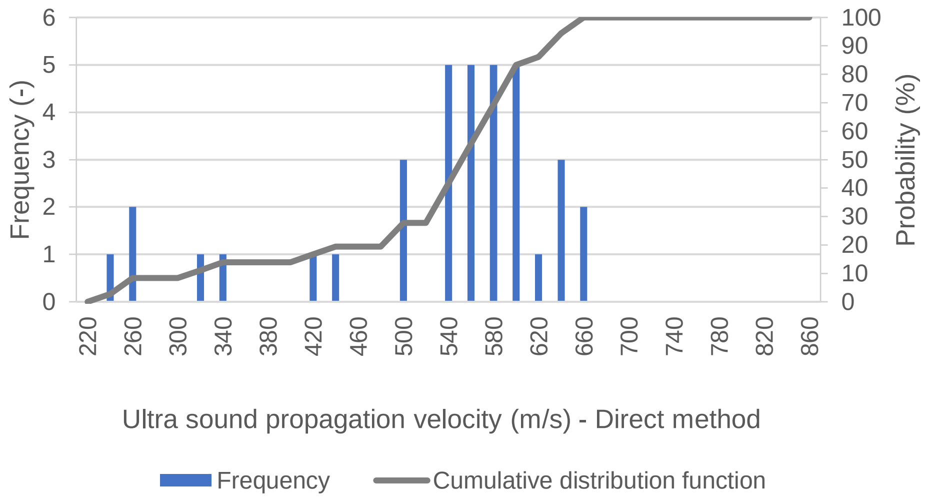

Figure 5.16 - Ultra sound propagation velocity distribution for rice husk blocks - Direct method.

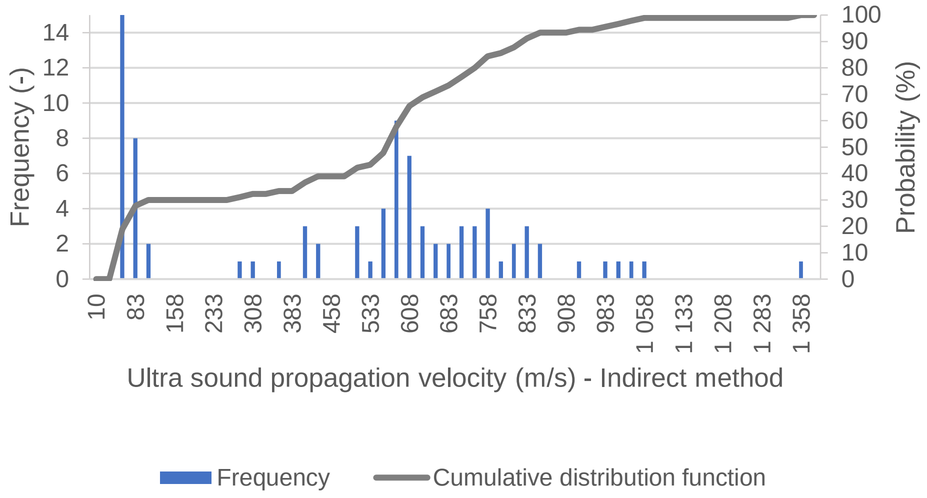

Figure 5.17 - Ultra sound propagation velocity distribution for rice husk blocks - Indirect method.

Like the barley straw blocks, it is possible to see a resemblance between the distribution curves of the ultra sound propagation velocity and the distribution of the rice husk length and orientation angle. This suggests that it seems to be a relation between two referred parameters and the ultra sound propagation velocity.

The direct method showed more homogeneity on the results that the indirect method, which shows that the rice husk blocks have a more homogeneous structure than the barley straw and hemp shiv blocks.

For the rice husk panels, the frequency and distribution curves of the ultra sound results are presented in Figure 5.18 and 5.19.

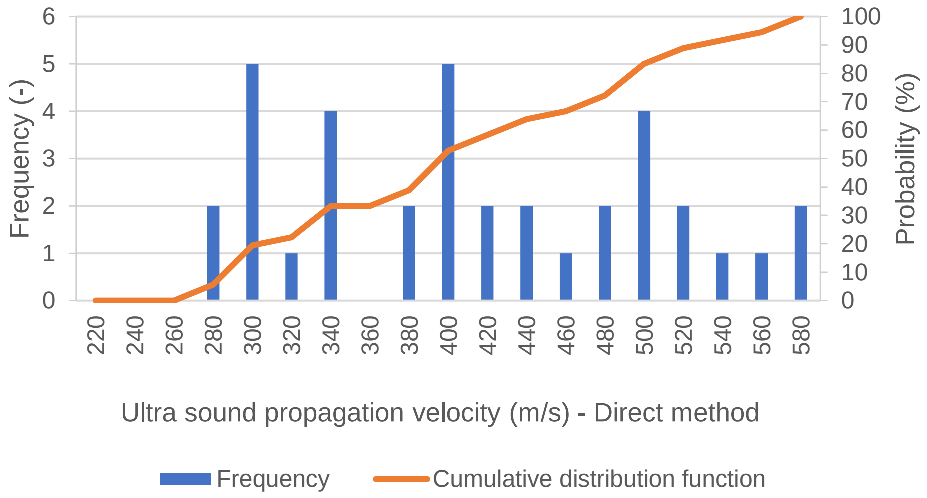

Figure 5.18 - Ultra sound propagation velocity distribution for rice husk panels (RH_30D) - Direct method.

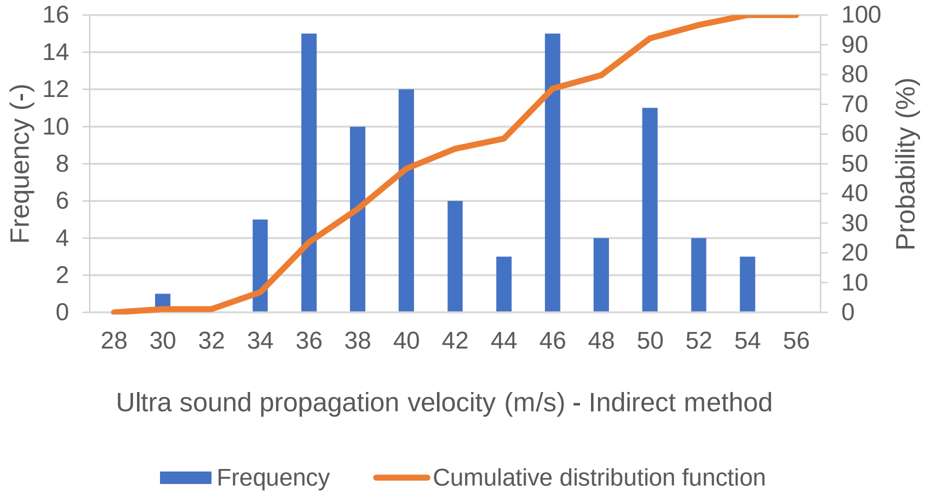

Figure 5.19 - Ultra sound propagation velocity distribution for rice husk panels (RH_30D) - Indirect method.

Through the figures analysis and making a comparison with the curves obtained for the length and angles of the rice husk fibres, it is showed that these properties can have influence on the ultra sound propagation velocity. The results obtained for the rice husk panels are clearer than those obtained for the natural fibre blocks, suggesting that the casting method adopted can have a strong influence on the properties of the composites.

The distribution curve obtained for both direct and indirect method is similar, showing that the internal structure of the panels is uniform in different directions, which could be related to the casting method used.

Comparing the distribution curves obtained for the earth blocks and panels, it is possible to say that the relation between fibre length and orientation with the ultra sound propagation velocity is more evident in the rice husk panels, which could mean that the casting method has a strong influence on the results.

5.3.3. Thermal conductivity analysis

For the thermal conductivity, a normal distribution was considered, and the curves were drawn for the different blocks, barley straw, hemp shiv and rice husk and for the rice husk panels.

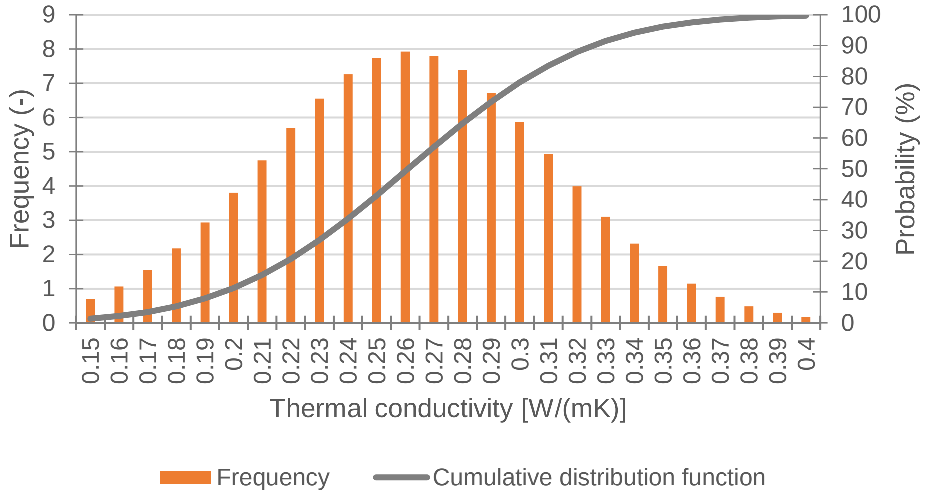

Figure 5.20 - Thermal conductivity distribution for barley straw blocks.

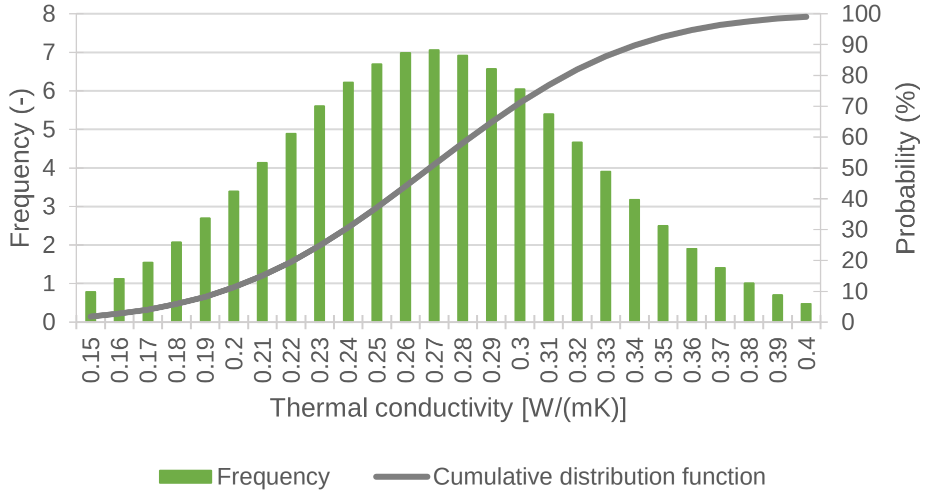

Figure 5.21 - Thermal conductivity distribution for hemp shiv blocks.

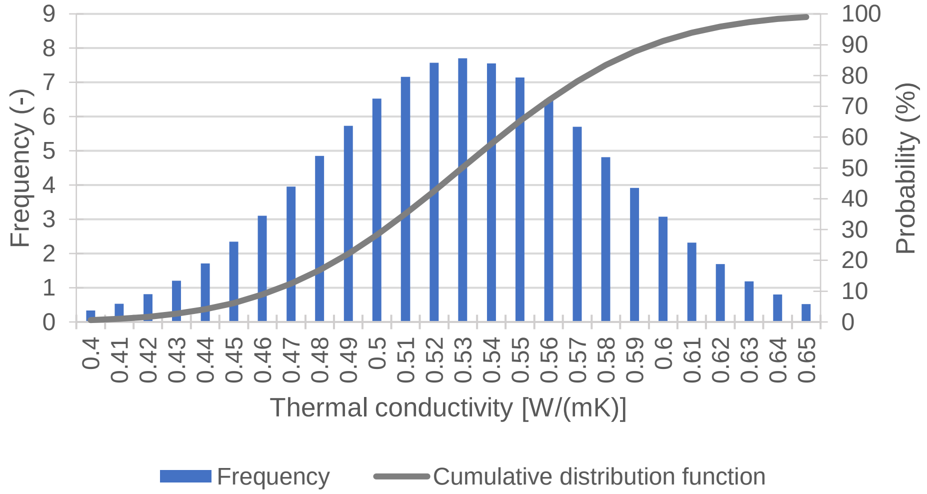

Figure 5.22 - Thermal conductivity distribution for rice husk blocks.

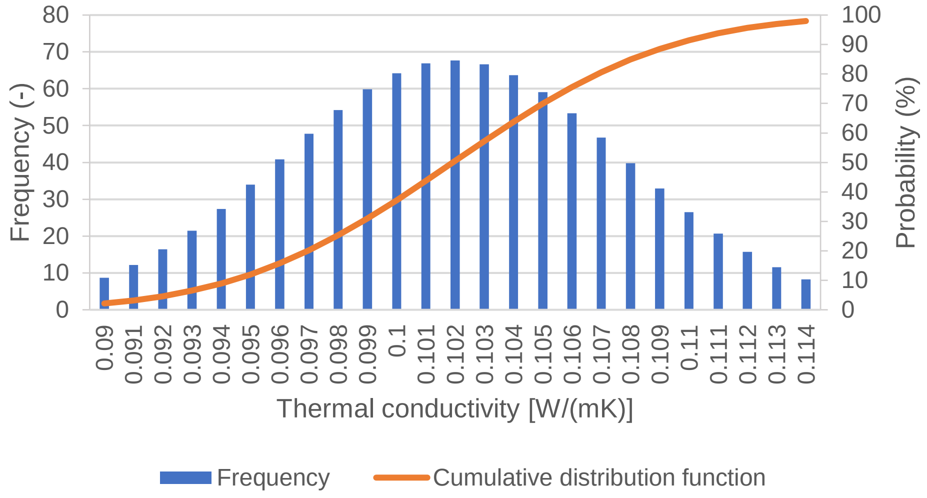

Figure 5.23 - Thermal conductivity distribution for rice husk panels (RH_30D).

Through the analysis of Figure 5.20 to Figure 5.23, and making a comparison with the distribution curves obtained for the fibres length and orientation, it is possible to see that the fibre length could have influence on the thermal conductivity of the composites. This does not happen with the orientation angle of the fibres which seems to be an irrelevant factor. Larger the area occupied with natural fibres, the higher the effect that it will have on the thermal behaviour of the composite.

Comparing the different results obtained for the earth blocks and panels, it seems that the casting method has a very small influence on the thermal conductivity of the earth composites. Despite this, the casting method could be important in the way that it influences the fibre length, once an accurate casting method could prevent the fibres from breaking.

Based on this analysis it is possible to say that an optimised casting method could lead to improvements on the composites properties and performance.

5.4. Dry abrasion test

This test accesses the durability of the materials, where a lower abrasion weight loss leads to a more durable composite. The abrasion weight loss of the rice husk panels is presented in Figure 5.24.

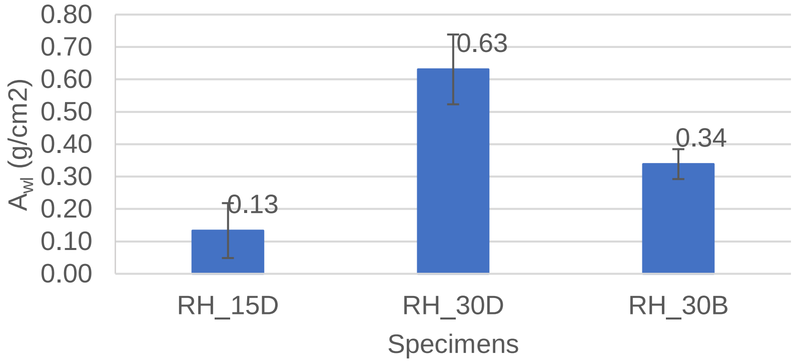

Figure 5.24 - Abrasion loss results for rice husk panels.

The increase on the rice husk content decreases the abrasion resistance. RH_15D present the highest resistance and the RH_30D the lowest, which is in accordance with Millogo et al. (2014), that studied the abrasion resistance of adobe reinforced with hibiscus cannabius fibres. In his study, the researchers concluded that a high fibre content and the fibre length decrease the adhesion to the earth matrix, reducing the abrasion resistance. For a fibre content of 0.2% and 0.8% (by weight) the abrasion loss was approximately 0.02 g/cm^2 and 0.04 g/cm^2 respectively.

This analysis shows that boiling the rice husk fibres increases the fibre adhesion to the earth matrix and the RH_30D abrasion loss is almost the double of RH_30B. Figure 5.25 shows the effect of the dry abrasion test, where it is visible the stronger influence on the dried rice husk panels.

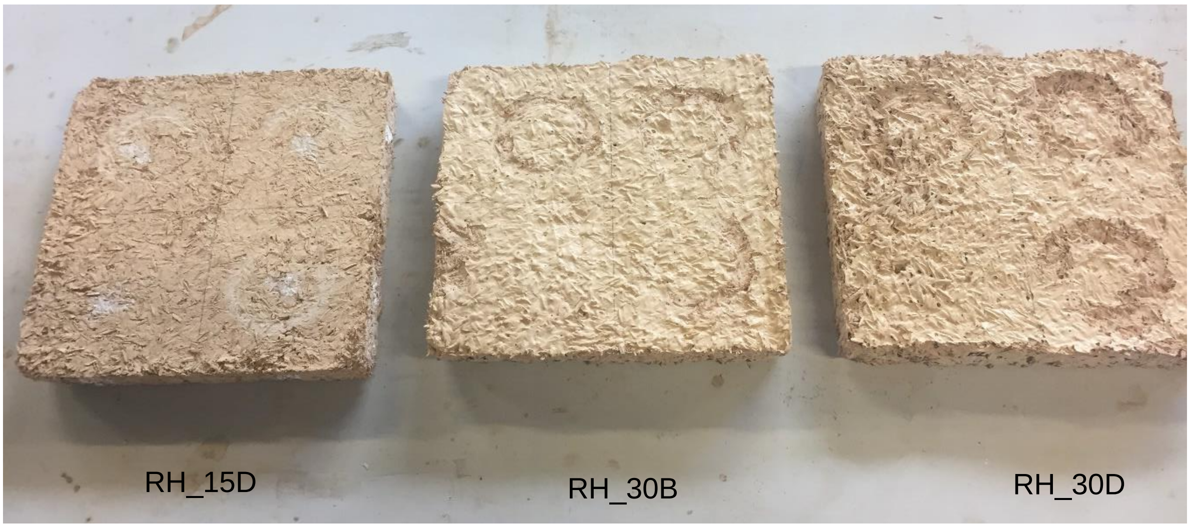

Figure 5.25 - Rice husk panels after dry abrasion test.

In a previous study Faria et al. (2016) analysed the dry abrasion effect of earth plasters reinforced with oat. The average value obtained for the weight loss by abrasion was 18.1 g, while in the present study the highest weight loss was 4.1 g for the dried rice husk panels, RH_30D, showing that the rice husk panels have a higher abrasion resistance.

Laborel-Préneron (2017) studied the dry abrasion resistance of barley straw, hemp shiv and rice husk earth blocks. The hemp shiv blocks showed the lower abrasion loss with a value of 0.04 g/cm^2, followed by the rice husk and barley straw bocks, with abrasion loss values of 0.05 g/cm^2 and 0.06 g/cm^2 respectively.

Through an analysis of the results obtained in the present thesis it is possible to see that the rice husk panels have a much higher abrasion loss than other materials studied by the mentioned authors. It shows that the produced panels are less durable and less resistance.

5.5. Tensile flexural strength

The average results for the tensile flexural strength of the panels is presented in Figure 5.26.

Based on the presented results, the increase of rice husk content decreases the tensile flexural strength of the composites, contrary to some studies like Bouchina et al. (2005), Vilamizar et al. (2012) and

Millogo et al. (2014), that concluded that by increasing the natural fibre content the tensile flexural strength of the composite also increased. Vilamizar et al. (2012) tested the tensile flexural strength of earthen blocks reinforced with 5% and 2.5% (by weight) of cassava peels, obtaining results of 1.09 MPa and 0.66 MPa respectively.

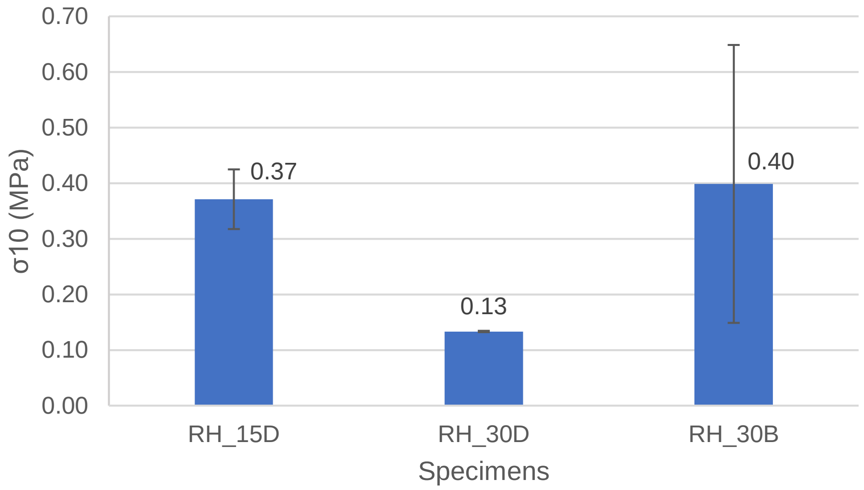

Figure 5.26 - Tensile flexural strength results for rice husk panels.

Rim et al. (1999) obtained opposite results by testing earth blocks reinforced with wood aggregates. In his study, the researchers tested four different fibre contents - 10%, 20%, 30% and 40% by volume -, obtaining results of 0.59 MPa, 0.66 MPa, 0.41 MPa and 0.14 MPa respectively. It is observed that there is a strength decrease for 30-40% fibre content showing that the addition of fibres increases the tensile flexural strength until a certain content.

Algin & Turgut (2008) tested the same amount of cotton waste content on earth blocks and obtaining similar results, defending that there is an optimized fibre content of 30% by volume that reaches the ideal flexural strength values.

These different conclusions, may be related not directly to the fibre content but with the tensile flexural strength of the fibres, which is corroborated by Lima & Faria (2016). In this study, two earth plasters formulations were tested, one with 10% and 20% by volume oat straw and the other with 20%, 40% and 80% by volume of typha wool. The results for both formulations are presented in Table 5.3.

Table 5.3 - Tensile flexural strength results for earth plaster reinforced with oat straw and typha wool (Lima & Faria 2016).

Fibre	Fibre content (by volume)	Tensile Flexural Strength (Mpa)
Reference		0.25
Oat straw	10	0.20
	20	0.23
Typha wool	20	0.29
	40	0.31
	80	0.26

Comparing the results with the reference, it is seen that despite the addition of oat straw decreases the tensile flexural strength, the typha wool increases it, reinforcing the statement that the flexural strength of the fibres could has strong influence on the composite strength.

The boiling of the rice husk fibres slightly decreases the flexural strength, which is contrary to the work of Ledhem et al. (2000) and Fertikh et al. (2011). In both studies the researchers defend that the extinguish of the substances on the fibres lead to an increase on the mechanical properties, even with noinfluence on the bulk density of the composite.

5.6. Compressive strength

The average results for the compressive strength of the rice husk panels and blocks is presented in Figure 5.27.

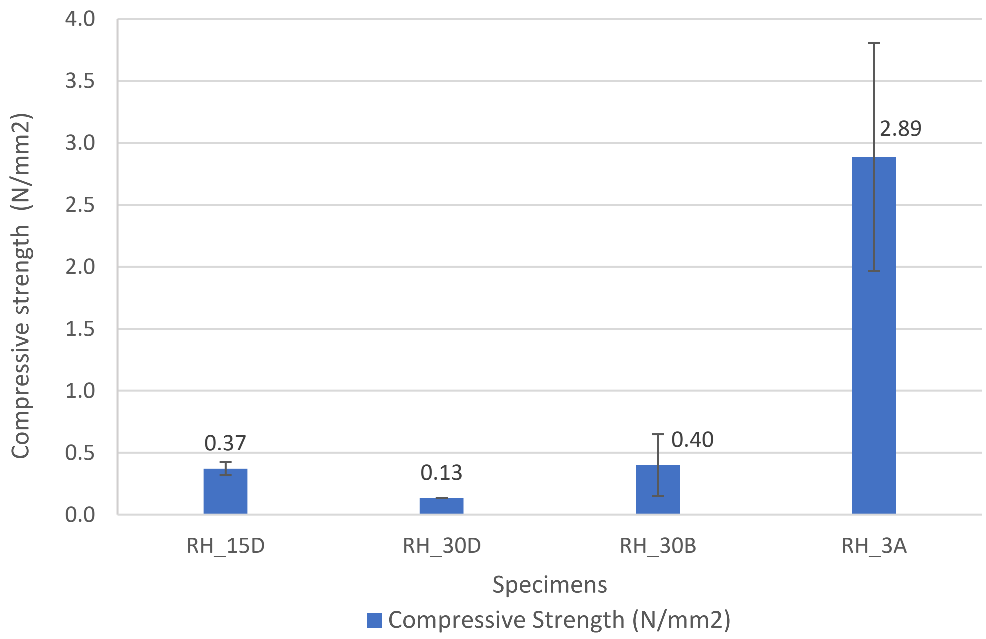

Figure 5.27 - Compressive strength results for rice husk panels and blocks.

The rice husk blocks present the highest values for the compressive strength, which was expected due to the production process of these specimens and the bulk density values obtained.

Increasing the rice husk content leads to a significant decrease on the compressive strength of the composites: the results of RH_30D are twice lower than the RH_15D that have half the rice husk content.

Regarding the natural fibre content and the compressive strength in earth composites the conclusions are divided as it was seen in the literature review. Researchers defend that the increase in fibre content decreases the compressive strength, as Bouguerra et al. (1998), Khedari et al. (2005) and Rim et al. (1999). On the other hand, other researchers defend that a certain content of natural fibres could increase this parameter.

Similar to what happen to the tensile flexural strength, the fibre properties seem to have a strong influence on the compressive strength, namely their adhesion to the earth matrix. Lima & Faria (2016)

showed that same amounts of different fibres may lead to different results: the addition of oat fibres decreased the compressive strength of the reference specimen, but typha wool addition increased it.

The pre-boiling of the rice husk fibres leads to a significant increase of the compressive strength being in the same ranging values as the RH_15D. These results are in agreement with Ledhem et al. (2000), where the pre-boiling of the fibres lead to an increase in the compressive strength from 8.9 MPa to 9.7 MPa. This shows that the boiling had a strong impact in the compressive strength of the composites, which reinforces the statement previously presented: the boiling of the rice husk fibres leads to a higher matrix adhesion, resulting on a stronger composite.

5.7. Moisture Buffer Value

The stable cycle from the MBV test of the three rice husk panels formulations and rice husk blocks is presented in Figure 5.28.

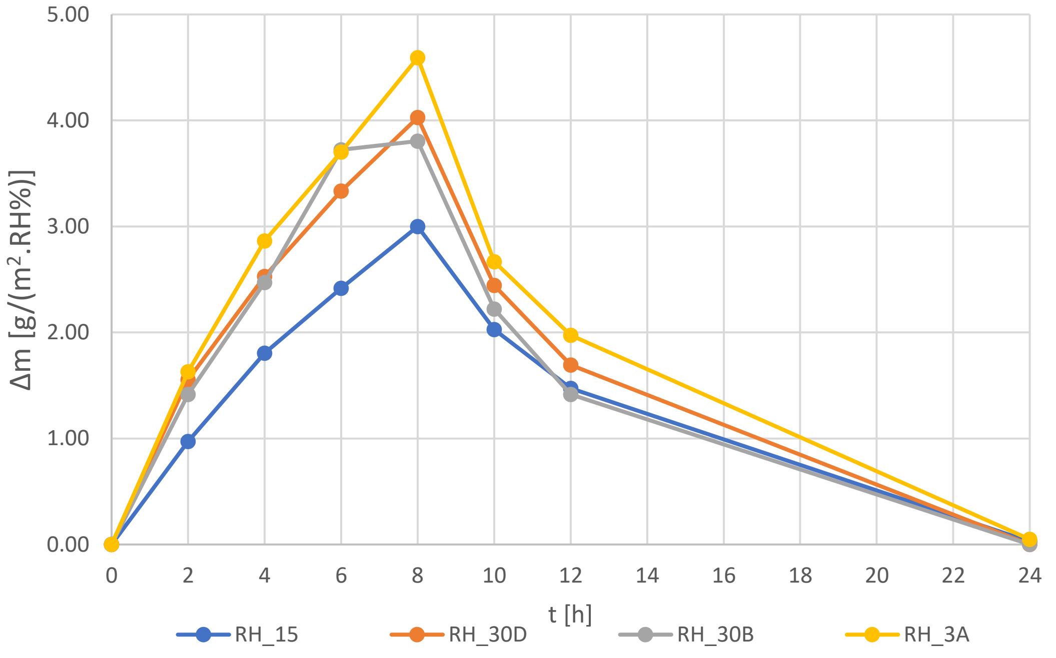

Figure 5.28 - Moisture Buffer Value of rice husk panels and blocks.

The rice husk blocks have the highest Δm reaching a value of 4.59 g/(m^2.RH). It is important to consider that these blocks have higher thickness that the panels; when compared with RH_30D the Δm has a small difference.

Comparing the three formulations for rice husk panels, a higher fibre content leads to higher MBV values, which means that the panels with higher fibre content have a higher ability to adsorb and desorb moisture, which is in accordance with the literature review in chapter 2.

The boiling of the natural fibres did not show a large difference when compared to the dried ones. RH_30D reached a Δm value of 4.03 g/(m^2.RH) and RH_30B of 3.81 g/(m^2.RH). The adsorption curve of the RH_30B shows that the specimens reached their adsorption limit quicker than the others, reaching their maximum adsorption value 6 hours after the beginning of the adsorption period. Figure 5.29 presents the MBV results for the four tested specimens.

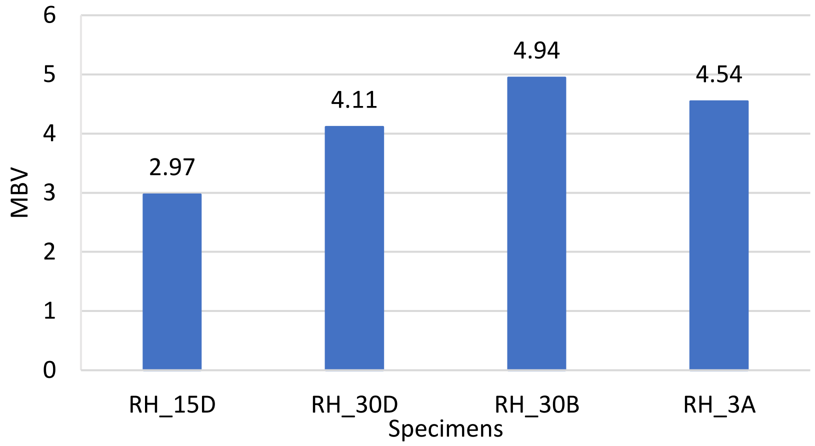

Figure 5.29 - MBV results.

It is possible to classify the specimens as a function of their MBV, based on Figure 5.30 that show the classification of building materials regarding their MBV from the NordTest protocol.

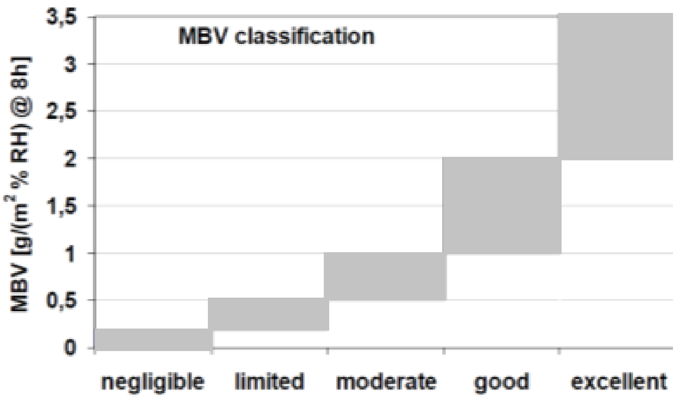

Figure 5.30 - Moisture Buffer Value classes (Moisture Buffering of Building Materials Rode et al. 2005).

Based on the NordTest classification it is possible to classify the rice husk specimens as excellent materials regarding their adsorption behaviour, being that the specimens with 30% boiled rice husk presented the highest value, showing that not only the fibre addition may have influence but also the pre boiling of the rice husk fibres.

Holcroft & Shea (2013) tested natural fibre insulation materials namely hemp lime, sheep wool and hemp fibre based materials, with RH cycles of 53-75% and temperature 23ºC obtaining the results presented on Table 5.4.

For the same conditions Palumbo et al. (2016) tested six different insulation materials.

Table 5.4 - MBV results for bio-based insulation materials.

Reference	Material	MBV conditions	MBV [g/(m^2.ΔRH)]
Holcroft & Shea (2013)	Hemp lime	53-75% ; 23°C	4,4
	Sheep's wool		2,5
	Hemp fibre		2,0
Palumbo et al. (2016)	Hemp lime	53-75% ; 23°C	3,3
	Hemp fibre		2,3
	Wood wool		2,6
	Wood fibre		1,9
	Barley straw and corn starch		3,2
	Corn pith-alginate		3
Antunes (2017)	RH_15	60-90% ; 16°C	3
	RH_30D		4,03
	RH_30B		3,81
	RH_3A		4,59

Comparing the results obtained in the present study with the mentioned authors, it is possible to see that the rice husk specimens have a higher ability to adsorb and desorb the environment moisture. It is important to refer that the specimens tested by Palumbo et al. (2016) had the same thickness that the rice husk panels.

5.8. Fire behaviour

Figure 5.31 shows the effect of flame exposure test on the rice husk blocks and panels surface.

Through the figure analysis it is seen that the fire test has a stronger influence on the composites with higher fibre content, because only the rice husk burns. This is visible on the RH_3A specimens: the earth gains a pink colour, similar to the colour of fired earth bricks, and the fibres burn out.

The panels having a higher content of rice husk have a largest area affected by the test, where among the three formulations RH_15D is the less affected. Comparing the boiled and dried husk panels, the RH_30B are the most affected by the test, what suggests that the substances present on the rice husk fibres work like a protection, delaying the burning.

Visually the rice husk blocks are the least affected by the small flame exposure, but when analysing the weight loss over the fire behaviour test they show the highest difference, like is presented on Figure 5.32.

Comparing the weight loss results for rice husk panels, is possible to confirm that the fire influence is higher on specimens with higher fibre content, but this is contrary to the results obtained for the blocks: they possessed the smallest rice husk content but had the highest weight loss. This suggests that, despite the smouldering of the rice husk, the baking of the earth has a strong influence on the composite weight.

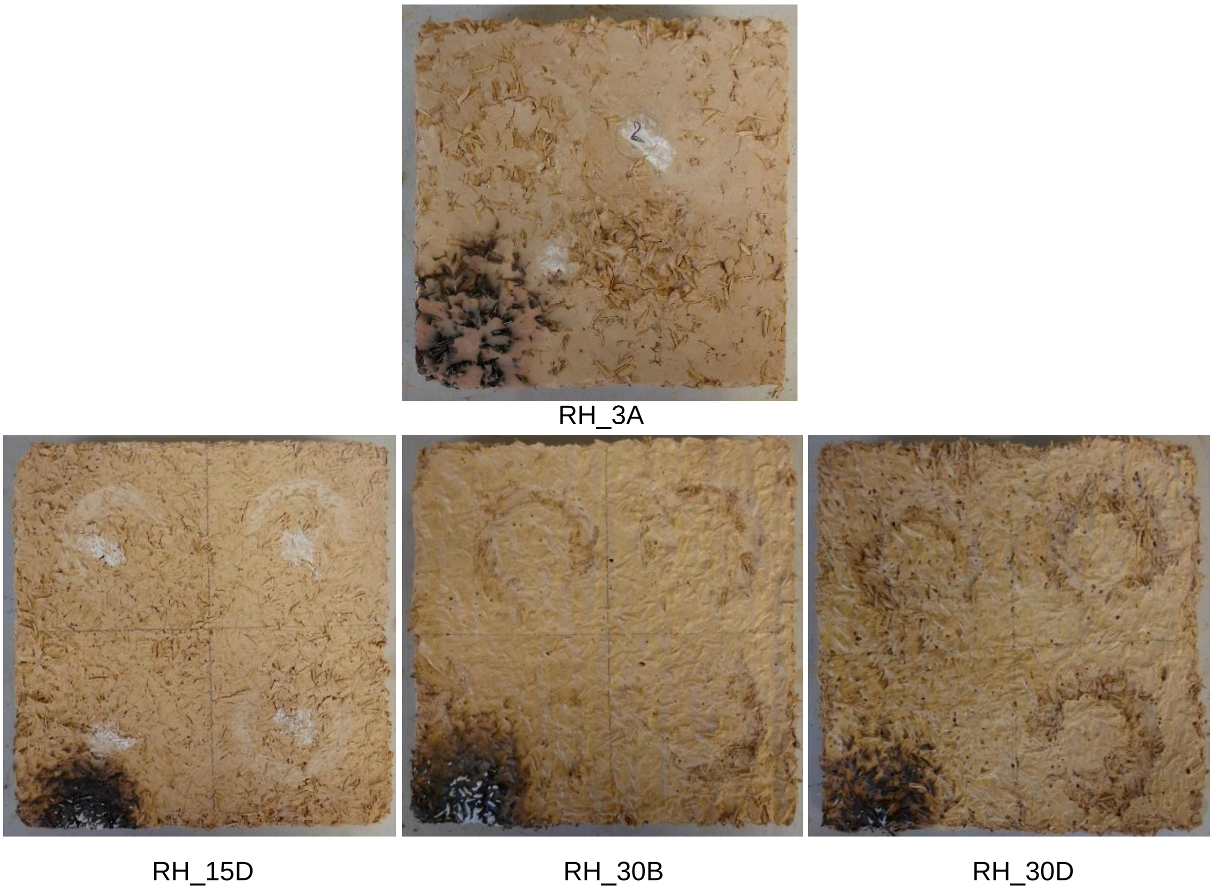

Figure 5.31 - Rice husk blocks and panels after fire resistance test.

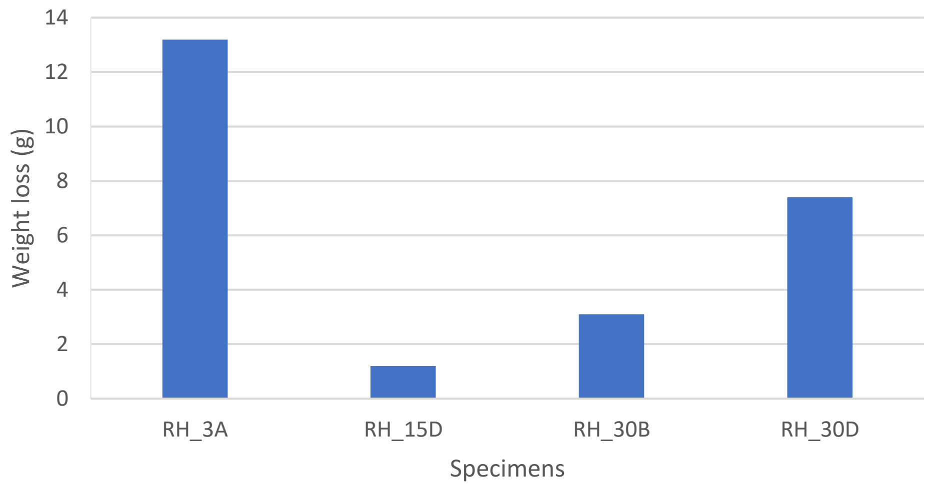

Figure 5.32 - Weight loss of rice husk blocks and panels after fire resistance test.

One of the major concerns of building materials, is the combustion of the material. In the tested specimens, when the fire source is extinguished the composite immediately stop burning; there is no fire propagation. Also, there was no significant release of smoke and odours through the test, being that the panels had a more intense odour of burned rice than the blocks due to its higher fibre content.

Laborel-Préneron (2017) also tested the fire behaviour of earth blocks reinforced with natural fibres. Despite the difference on the testing method, some similar conclusions were obtained. 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.

Based on both studies it is possible to see that the fibre content has influence on the fire behaviour of earth composites.

5.9. Comparison with commercial insulation products

Table 5.5 resumes the results obtained from the experimental campaign and a small comparison with commercial insulation materials, namely Extruded Polystyrene (XPS), Expanded Polystyrene (EPS) and Insulation Cork Board (ICB). The used results for the three mentioned insulation materials were adapted from Sotecnisol (2017).

Table 5.5 - Comparison between rice husk panels properties and commercial insulation materials.

Specimen	Bulk density (kg/m^3)	Thermal conductivity [W/(m.K)]	Dry abrasion resistance (g)	Tensile Flexural strength (MPa)	Compressive strength (MPa)	Moisture Buffer Value [$g/(m^2$. RH)]
RH_15D	1009	0,197	0,87	0,116	0,37	3
RH_30B	886	0,121	2,2	0,075	0,4	3,81
RH_30D	651	0,102	4,1	0,08	0,13	4,03
RH_A3	1808	0,53	-	-	2,89	4,59
XPS	25-40	0,037	-	-	0,3	-
EPS	13-15	0,042	-	0,05	0,03	-
ICB	90-140	0,045	-	0,05	0,15	-

When compared with commercial insulation materials, it is showed that the rice husk panels have higher thermal conductivity, being not eligible to be used as insulation materials, as it was seen before. Despite this, it is important to refer that these materials have lower environmental impact than the commercial products and, being composed by natural and available materials, their costs are reduced, besides their hygroscopic behaviour.

Regarding the mechanical properties, the bio-based panels present higher resistance in comparison with some of the commercial products, especially on the compressive behaviour, showing a compressive strength close to the one of XPS.

XPS and EPS are insulation materials that are not able to be exposed, because of fire behaviour and aesthetics; they need to be covered/coated. On the contrary, earth-rice husk panels have very good hygroscopic performance and can be exposed in indoor surfaces with low abrasion. Their relatively low insulation capacity may even be appropriate for indoor insulation of massive walls, like rammed earth, adobe or compressed earth masonry or even rubble stone walls.

Of course, much more work is still to be done in order to optimize the earth-rice husk panels but, from a global point of view, the dried rice husk specimens seem to be able to achieve high performance, combining a good thermal and hygroscopic behaviour to an acceptable mechanical resistance.

6. Conclusions

6.1. Final remarks

The present dissertation had the objective to produce a high-performance bio-based insulation product made with an earth-gypsum-lime matrix reinforced with rice husk fibres, reaching an optimized production process for these types of materials.

The experimental campaign allowed to access the influence of increasing the natural fibre content on the properties of earth based composites, as well as the effect of boiling the fibres.

Through the image analysis results, it is showed that the casting method could have a strong influence on the natural fibres arrangement and, therefore, on the composite properties, once it was seen that the fibre length and orientation angle seem to have influence on the US propagation velocity and thermal conductivity. This proves that there is a need for a thorough study to obtain an optimized casting method for bio-based insulation materials to improve their properties.

The increase of fibre content decreases the thermal conductivity of the composite as well as the bulk density, once it produces a more porous composite.

The ultra sound propagation velocity also decreased with the increase in rice husk content, but the results were still higher than other bio-based materials. Despite that the results are lower than many construction materials. This test presented some difficulties, due to the heterogeneous internal structure of the composites making it hard to perform readings.

Regarding the mechanical properties, the increase of fibre content produces a significant decrease on the compressive and tensile flexural strength. It is believed that this reduction may be caused by the weak flexural resistance and adherence of the rice husk to the matrix.

The MBV results were expected once it is known that the natural fibres have high adsorption-desorption capacity, which allied to the earthen matrix of the composite produces a material with high hygrothermal performance.

Regarding the pre-boiling of the rice husk fibres, it was seen that it had almost no influence on the thermal conductivity, ultra sound propagation velocity and tensile flexural strength. This treatment showed highest influence on the dry abrasion and compressive strength results, where through the comparison with the dried rice husk specimens, it was seen that it improved the fibre adherence to the earth-gypsum-lime matrix. It was also seen that the boiling of the natural fibres prevents the biological contamination of the panels, once it destroys the cellulose substances present of the natural fibres.

In the MBV test, it was seen that the specimens with the boiled fibres reached their maximum adsorption capacity sooner than the dried ones, running out their adsorption capacity after 6h exposure to maximum RH.

From a global point of view, it was showed that this novel bio-based material has high ability to regulate the indoor humidity. Being a natural and sustainable material, it could contribute to the reducing of the energy requirements in buildings, although it cannot be used as an insulation material, it can contribute

to the indoor thermal comfort and be used as a regulator of the indoor environment, reducing the use of electric devices that control the air moisture and temperature.

6.2. Proposals for future work

Based on the 2D image analysis, it is required a study of an improved method for fibre arrangement in the surface and in the interior of the composites, to reach a more homogeneous internal structure that improves the composite properties, which could be tested by different casting methods.

Having the potential to be applied in the interior surfaces of buildings, a study of compatible finishing coats is required.

A more thorough study should be carried out regarding the biological contamination of the panels and assess, with more detail, the influence of boiling the natural fibres in this matter.

Being evaluated the effectiveness of the rice husk panels in the indoor hygrothermal comfort, it is also a matter of interest the effect and contribution of this bio-based material on the indoor air quality.

Although the panels cannot be used as insulation material, it is a matter of interest the application of this novel material on current constructive solutions to study the heat transmission coefficient of the solutions and to assess it accomplishment of the normative standards.

Still, two scientific articles were developed and are currently in review: one regarding the implementation of an image analysis method for optimisation of bio-based materials ("Optimisation of bio-based materials for refurbishment using image analysis method") and the other on the evaluation of the rice husk panels performance: ("High performance of rice husk insulation panels").

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Appendix

A.1. Specimens characterization

Table A.1 – Dimensions, volume, mass and bulk density of earth based panels and blocks.

Specimen			Dimensions (mm)			Volume			Mass (g)	$Mass_{avg}$ (g)	ρ (kg/m^3)	$ρ_{avg}$ (kg/m^3)
			L1	L2	H	V (mm^3)	V_{avg} (mm^3)	V_{avg} (m^3)				
Panels	RH_15	D1	198,2	191,78	32,86	1249034,8	1254973,7	0,0013	1288,5	1281,3	1031,6	1021,6
		D2	196,51	196,36	34,12	1316578,3			1313,8		997,9	
		D3	191,38	197,25	31,77	1199308,1			1241,5		1035,2	
	RH_30B	B1	191,4	191,64	30,55	1120570,8	1173062,1	0,0012	1100,6	1094,2	873,8	886,2
		B2	192,72	189,4	32,93	1201983,5			1138,6		953,6	
		B3	192,06	188,45	33,34	1206698,2			1148,1		932,4	
		B4	193,44	189,36	31,75	1162996,1			989,3		785,0	
	RH_30D	D1	193,76	188,47	34,49	1259504,0	1236263,1	0,0012	745,9	763,4	665,6	650,8
		D2	191,88	194,03	32,07	1193981,4			784,1		652,3	
		D3	193,6	193,97	32,79	1231349,5			794,5		658,4	
		D4	194,06	189,66	34,24	1260217,6			729,1		626,9	
Blocks	S_3A	1	151,71	150,89	54,37	1244612,0	1220945,0	0,0012	1815,0	1818,9	1458,3	1490,1
		2	150,32	148,98	53,26	1192740,3			1817,7		1524,0	
		3	150,68	150,11	53,65	1213486,5			1822,0		1501,5	
		5	151,39	150,97	53,45	1221618,4			1818,9		1488,9	
		9	151,65	151,43	53,66	1232267,5			1821,1		1477,8	
	H_3A	4	152,21	152,98	51,4	1196853,4	1183385,7	0,0012	1787,4	1795,6	1493,4	1517,6
		5	150,61	150,54	51,6	1169918,0			1803,7		1541,7	
	RH_3A	2	150,12	149,6	48,87	1097520,1	1092551,9	0,0011	1974,9	1984,1	1799,4	1808,3
		3	150,35	150,99	49,78	1130073,0			1972,3		1745,3	
		4	150,4	149,47	48,52	1090743,6			1990,5		1824,9	
		6	150,36	149,38	47,64	1070031,4			1994,0		1863,5	
		7	149,42	150,49	47,78	1074391,4			1989,1		1851,3	

A.2. Thermal conductivity test

Table A.2 - Thermal conductivity results for earth based panels and blocks.

Specimen			λ_1 [W/(m.K)]	λ_2 [W/(m.K)]	λ_3 [W/(m.K)]	λ_4 [W/(m.K)]	λ_5 [W/(m.K)]	λ_{1avg} [W/(m.K)]	λ_{2avg} [W/(m.K)]	λ_{3avg} [W/(m.K)]	λ_{4avg} [W/(m.K)]	λ_{5avg} [W/(m.K)]	λ_{avg} [W/(m.K)]	S.D.
Panels	RH_15	D1	0,176	0,166	0,194	0,191	0,196	0,191	0,199	0,202	0,199	0,196	0,197	0,004
		D2	0,208	0,207	0,208	0,206	0,186							
		D3	0,190	0,225	0,204	0,200	0,205							
	RH_30B	B1	0,121	0,134	0,114	0,123	0,112	0,123	0,119	0,122	0,120	0,122	0,121	0,001
		B2	0,121	0,121	0,139	0,122	0,127							
		B3	0,121	0,112	0,108	0,121	0,130							
		B4	0,127	0,110	0,127	0,113	0,118							
	RH_30D	D1	0,094	0,103	0,100	0,107	0,107	0,098	0,099	0,101	0,108	0,105	0,102	0,004
		D2	0,094	0,094	0,098	0,114	0,109							
		D3	0,106	0,097	0,111	0,105	0,104							
		D4	0,096	0,101	0,096	0,105	0,098							
Blocks	S_3A	S1	-	-	-	-	0,236	-	-	-	-	-	0,261	0,050
		S2					0,257							
		S3					0,304							
		S5					0,325							
		S9					0,183							
	H_3A	H4					0,212						0,269	0,056
		H5					0,325							
	RH_3A	RH2					0,504						0,530	0,052
		RH3					0,447							
		RH4					0,531							
		RH6					0,591							
		RH7					0,576							

A.3. Ultra sound propagation velocity test

Table A.3 - Ultra sound propagation velocity results for earth based panels and blocks - Direct method.

Direct Method			Time (µs)												Distance (mm)
			AA'			BB'			CC'			DD'			AA' BB' CC' DD'
Specimen			t_1	t_2	t_3	t_1	t_2	t_3	t_1	t_2	t_3	t_1	t_2	t_3	
Panels	RH_15D	RH15_D1	41,8	42,7	41,1	41,3	39,7	42,5	41,8	44,7	42,6	45,4	45,7	43,7	32,86
		RH15_D2	44,4	46,7	45	40,2	41,3	40,9	43,5	47,4	45,6	43,5	43,3	43	34,12
		RH15_D3	39,6	41,5	40,9	42,5	43,5	41,8	40,2	40	42,2	43,2	44	40,5	31,77
	RH_30B	RH30_B1	97,5	108,4	101,4	85,5	75,3	76,6	101,7	101,1	100,6	111,4	120,8	117,7	34,49
		RH30_B2	69,3	67,1	62,2	59,3	58,4	56,7	52,1	50,8	55,3	61,3	58	61,2	32,07
		RH30_B3	54,5	55,2	55,1	64,7	67,6	66,1	66,8	63	64,2	50,5	51,5	55	32,79
	RH_30D	RH30_D1	70,4	64,5	72,1	109,9	108,1	101,5	61,3	62,6	60,4	108,5	111,6	108	30,55
		RH30_D2	91,1	85,6	56,8	92,9	74,6	66	95,2	92,5	58	75,5	77,2	74,8	32,93
		RH30_D3	59,5	60,4	86,8	115,8	82,9	107,6	91,8	101,9	78,9	61,4	62,2	64,1	33,34
Blocks	S_3A	S 5	70,4	60,9	73,5	80,3	72,1	79,3	58,7	60,3	80,3	72,5	64,9	73,6	50
		S 3	87,4	120,4	121,3	110,5	115,6	120,8	103,5	183,7	130,7	226,8	183,3	222,3	50
		S 4	90,6	96,7	80,4	106,3	98,7	100,3	94,1	81,6	74,2	140,4	126,9	130,7	50
	H_3A	H5	87,9	85,3	80,2	86	113,5	110,8	109	88,4	97,6	105,9	137	120,4	50
	RH_3A	RH7	81,7	77,8	79,6	103,4	100,8	101,1	94,3	85,6	89	94,5	95,2	94,7	50
		RH4	148,9	159,7	84,9	204,4	198,3	205,6	95,8	120,8	117,3	90,9	90,8	90,4	50
		RH6	78,9	79,3	76,8	86,3	91,1	86,6	84,6	86,3	90,3	84,7	83,5	86,6	50

Direct Method			Velocity (m/s)												Avg.	S.D.
			AA'			BB'			CC'			DD'				
Specimen			v_1	v_2	v_3	v_1	v_2	v_3	v_1	v_2	v_3	v_1	v_2	v_3		
Panels	RH_15D	RH15_D1	786,1	769,6	799,5	795,6	827,7	773,2	786,1	735,1	771,4	723,8	719,0	751,9	771,5	35,9
		RH15_D2	768,5	730,6	758,2	848,8	826,2	834,2	755,4	693,2	720,6	755,4	758,9	764,2		
		RH15_D3	802,3	765,5	776,8	747,5	730,3	760,0	817,4	821,5	778,7	760,6	746,8	811,4		
	RH_30B	RH30_B1	353,7	318,2	340,1	384,3	436,4	429,0	339,1	341,1	342,8	309,6	285,5	293,0	496,9	121,4
		RH30_B2	462,8	477,9	515,6	575,4	584,2	601,8	662,0	678,9	623,7	562,6	594,7	563,6		
		RH30_B3	601,7	594,0	595,1	491,0	470,0	480,6	516,3	547,5	537,2	683,0	669,7	627,1		
	RH_30D	RH30_D1	433,9	473,6	423,7	299,0	304,0	323,7	498,4	488,0	505,8	281,6	273,7	282,9	404,9	90,9
		RH30_D2	361,5	384,7	579,8	367,3	457,4	517,0	320,9	330,3	526,7	404,6	395,7	408,4		
		RH30_D3	560,3	552,0	384,1	274,4	383,2	295,3	332,8	299,8	387,2	497,6	491,2	476,6		
Blocks	S_3A	S 5	710,2	821,0	680,3	622,7	693,5	630,5	851,8	829,2	622,7	689,7	770,4	679,3	535,4	167,2
		S 3	572,1	415,3	412,2	452,5	432,5	413,9	483,1	272,2	382,6	220,5	272,8	224,9		
		S 4	551,9	517,1	621,9	470,4	506,6	498,5	531,3	612,7	673,9	356,1	394,0	382,6		
	H_3A	H5	659,8	680,0	723,2	674,4	511,0	523,5	532,1	656,1	594,3	547,7	423,4	481,7	583,9	89,9
	RH_3A	RH7	612,0	642,7	628,1	483,6	496,0	494,6	530,2	584,1	561,8	529,1	525,2	528,0	520,0	111,4
		RH4	335,8	313,1	588,9	244,6	252,1	243,2	521,9	413,9	426,3	550,1	550,7	553,1		
		RH6	633,7	630,5	651,0	579,4	548,8	577,4	591,0	579,4	553,7	590,3	598,8	577,4		

Table A.4 - Ultra sound propagation velocity results for earth based panels and blocks - Indirect method.

Indirect method			Time (μs)																		Distance (mm)	
			AB			AC			AD			BC			BD			CD			AB / AC / BD / CD	AD / BC
Sample			t_1	t_2	t_3	t_1	t_2	t_3	t_1	t_2	t_3	t_1	t_2	t_3	t_1	t_2	t_3	t_1	t_2	t_3		
		RH15_D1	191,2	184,4	184,8	198,2	196,2	199,1	254,8	267,8	269,8	316,9	314,5	311,7	177,9	193,3	176,1	161,7	164,7	160,7		
	RH_15D	RH15_D2	168,7	167,7	173,5	284,1	265,8	265,0	194,8	194,1	180,2	184,2	183,4	185,3	276,2	275,3	295,7	192,4	168,8	176,9	100	141,4
		RH15_D3	173,4	173,7	172,8	231,0	243,1	217,0	309,6	317,9	307,1	288,3	295,8	266,6	213,3	203,7	179,4	200,4	186,0	203,8		
		RH30_B1	227,5	225,4	234,3	278,0	233,5	223,3	331,2	349,3	385,4	446,6	517,6	451,9	230,9	232,3	239,6	211,7	178,8	202,0		
Panels	RH_30B	RH30_B2	208,7	201,9	214,7	218,9	220,0	222,7	371,9	372,0	364,7	389,4	392,6	390,6	264,2	263,0	265,5	215,2	212,9	218,4	100	141,4
		RH30_B3	231,8	210,5	216,0	217,2	214,3	222,6	339,7	338,3	363,4	350,3	341,7	349,2	236,9	241,0	227,2	218,5	235,6	220,6		
		RH30_D1	202,7	200,5	204,8	227,2	224,5	223,3	343,2	356,5	340,4	342,2	357,2	361,6	277,3	277,8	273,1	267,4	276,9	267,6		
	RH_30D	RH30_D2	222,1	225,3	224,2	225,9	221,6	223,7	392,9	359,1	360,3	355,8	352,3	357,1	275,5	280,4	281,6	240,8	290,9	270,5	100	141,4
		RH30_D3	211,6	219,3	222,5	269,7	273,3	350,6	371,1	396,7	360,1	394,2	402,1	392,4	281,5	292,0	302,6	301,7	302,1	308,1		
		S 5	106,3	114,2	115,1	139,0	120,1	166,7	199,0	196,4	179,3	251,9	283,9	200,3	124,5	1255,0	126,8	146,8	149,4	144,4		
	S_3A	S 3	92,0	91,4	94,1	140,8	164,5	158,3	150,6	153,6	158,4	138,9	138,3	142,3	81,3	134,7	90,4	102,7	122,1	126,7	50	70,7
		S 4	87,9	104,9	110,6	108,2	110,1	107,9	155,1	142,0	157,3	138,9	138,3	140,1	104,6	102,4	108,6	180,0	179,1	183,5		
Blocks	H_3A	H5	88,1	84,9	100,8	129,8	94,1	99,3	187,1	208,3	150,1	180,0	130,7	201,4	206,0	200,8	198,6	114,1	120,9	102,8	50	70,7
		RH7	51,4	47,9	49,2	86,6	84,2	89,8	139,0	148,4	152,1	91,0	128,6	146,8	91,2	98,8	49,8	94,0	116,7	116,0		
	RH_3A	RH4	72,7	81,7	65,3	86,1	90,5	76,6	202,4	180,0	170,3	122,9	118,5	119,8	82,9	84,8	85,1	100,0	92,5	76,0	50	70,7
		RH6	71,5	66,0	69,1	84,4	126,5	129,9	151,8	156,5	159,6	140,9	133,4	134,6	37,5	61,2	82,2	67,5	96,1	95,1		

Indirect method			Velocity (m/s)																			
			AB			AC			AD			BC			BD			CD			Avg.	S.D.
Sample			v_1	v_2	v_3	v_1	v_2	v_3	v_1	v_2	v_3	v_1	v_2	v_3	v_1	v_2	v_3	v_1	v_2	v_3		
		RH15_D1	523,0	542,3	541,1	504,5	509,7	502,3	555,0	528,1	524,2	446,3	449,7	453,7	562,1	517,3	567,9	618,4	607,2	622,3		
	RH_15D	RH15_D2	592,8	596,3	576,4	352,0	376,2	377,4	726,0	728,6	784,8	767,8	771,1	763,2	362,1	363,2	338,2	519,8	592,4	565,3	530,9	106,4
		RH15_D3	576,7	575,7	578,7	432,9	411,4	460,8	456,8	444,9	460,5	490,5	478,1	530,5	468,8	490,9	557,4	499,0	537,6	490,7		
		RH30_B1	439,6	443,7	426,8	359,7	428,3	447,8	427,0	404,9	366,9	316,7	273,2	312,9	433,1	430,5	417,4	472,4	559,3	495,0		
Panels	RH_30B	RH30_B2	479,2	495,3	465,8	456,8	454,5	449,0	380,3	380,2	387,8	363,2	360,2	362,1	378,5	380,2	376,6	464,7	469,7	457,9	422,6	49,8
		RH30_B3	431,4	475,1	463,0	460,4	466,6	449,2	416,3	418,0	389,2	403,7	413,9	405,0	422,1	414,9	440,1	457,7	424,4	453,3		
		RH30_D1	493,3	498,8	488,3	440,1	445,4	447,8	412,1	396,7	415,5	413,3	395,9	391,1	360,6	360,0	366,2	374,0	361,1	373,7		
	RH_30D	RH30_D2	450,2	443,9	446,0	442,7	451,3	447,0	359,9	393,8	392,5	397,5	401,4	396,0	363,0	356,6	355,1	415,3	343,8	369,7	394,0	47,5
		RH30_D3	472,6	456,0	449,4	370,8	365,9	285,2	381,1	356,5	392,7	358,8	351,7	360,4	355,2	342,5	330,5	331,5	331,0	324,6		
		S 5	470,4	437,8	434,4	359,7	416,3	299,9	35,5	36,0	39,4	28,1	24,9	35,3	401,6	39,8	394,3	48,2	47,3	49,0		
	S_3A	S 3	543,5	547,0	531,3	355,1	304,0	315,9	47,0	46,0	44,6	50,9	51,1	49,7	615,0	371,2	553,1	68,9	57,9	55,8	239,3	209,3
		S 4	568,8	476,6	452,1	462,1	454,1	463,4	45,6	49,8	45,0	50,9	51,1	50,5	478,0	488,3	460,4	39,3	39,5	38,5		
Blocks	H_3A	H5	567,5	588,9	496,0	385,2	531,3	503,5	37,8	33,9	47,1	39,3	54,1	35,1	242,7	249,0	251,8	62,0	58,5	68,8	236,3	211,0
		RH7	972,8	1043,8	1016,3	577,4	593,8	556,8	50,9	47,6	46,5	77,7	55,0	48,2	548,2	506,1	1004,0	75,2	60,6	61,0		
	RH_3A	RH4	687,8	612,0	765,7	580,7	552,5	652,7	34,9	39,3	41,5	57,5	59,7	59,0	603,1	589,6	587,5	70,7	76,4	93,0	377,1	351,4
		RH6	699,3	757,6	723,6	592,4	395,3	384,9	46,6	45,2	44,3	50,2	53,0	52,5	1333,3	817,0	608,3	104,8	73,6	74,4		

A.4. Dry abrasion test

Table A.5 - Dry abrasion test results for earth based panels reinforced with rice husk.

Specimen	Weight loss (g)								Abrasion coefficient				
	m_i (g)	m_{b1} (g)	m_{b2} (g)	m_{b3} (g)	Δ_1	Δ_2	Δ_3	Δ_{avg}	Ca_1	Ca_2	Ca_3	Ca_{avg}	S.D.
RH_15D	1213,6	1213,3	1212,2	1212,7	0,3	1,4	0,9	0,87	0,05	0,22	0,14	0,13	0,08
RH_30B	909,1	906,9	906,6	907,2	2,2	2,5	1,9	2,20	0,34	0,38	0,29	0,34	0,05
RH_30D	715,1	711	710,3	711,7	4,1	4,8	3,4	4,10	0,63	0,74	0,52	0,63	0,11

A.5. Mechanical tests results

Table A.6 - Tensile flexural strength test results for earth based panels reinforced with rice husk.

Specimen		Fm (N)	L (mm)	b (mm)	d (mm)	σ_b (MPa)	σ_{bavg} (MPa)	S.D.
RH_15D	RH15_D1	51,3	100	40	40	0,12	0,12	0,03
	RH15_D2	30,5				0,07		
	RH15_D3	66,1				0,15		
RH_30B	RH30_B1	33,1				0,08	0,08	0,01
	RH30_B2	36,4				0,09		
	RH30_B3	26,6				0,06		
RH_30D	RH30_D1	30,3				0,07	0,08	0,01
	RH30_D2	37,5				0,09		
	RH30_D3	34,7				0,08		

Table A.7 - Compressive strength test results for earth based panels and blocks reinforced with rice husk.

Specimen			F (N)	d (mm)	b (mm)	σ_{10} (MPa)	σ_{10avg} (MPa)	S.D.
Panels	RH_15D	RH_15D1	423,0	39,4	32,2	0,334	0,371	0,054
		RH_15D2	559,9	39,3	31,9	0,447		
		RH_15D3	435,8	40,9	32,0	0,333		
	RH_30B	RH_30B1	451,5	39,2	38,6	0,298	0,399	0,250
		RH_30B2	1133,8	38,8	39,4	0,742		
		RH_30B3	226,6	39,4	37,0	0,156		
	RH_30D	RH_30D1	197,5	40,0	37,5	0,132	0,133	0,001
		RH_30D2	193,5	39,0	36,9	0,134		
		RH_30D3	202,0	39,5	38,1	0,134		
Blocks	RH_A3	RH_A1	17020,2	72,0	70,0	3,377	2,888	0,920
		RH_A2	7278,7	72,0	73,0	1,385		
		RH_A3	14076,4	66,0	72,0	2,962		
		RH_A4	21797,6	73,0	78,0	3,828		

A.6. Moisture Buffer Value

Table A.8 - MBV test results for earth based panels reinforced with 15% dried rice husk.

RH_15D					
Time	**m_0 (g)**	**m (g)**	**Δm (g)**	**Δm (g/m^2)**	**Δm (g/m^{2}HR)**
0	1290,07	1290,07	0,00	0,00	0,00
2		1291,23	1,17	29,17	0,97
4		1292,23	2,17	54,17	1,81
6		1292,97	2,90	72,50	2,42
8		1293,67	3,60	90,00	3,00
10		1292,50	2,43	60,83	2,03
12		1291,83	1,77	44,17	1,47
24		1290,10	0,03	0,83	0,03

Table A.9 - MBV test results for earth based panels reinforced with 30% boiled rice husk.

RH_30B					
Time	**m_0 (g)**	**m (g)**	**Δm (g)**	**Δm (g/m^2)**	**Δm (g/m^{2}HR)**
0	1021,90	1021,90	0,00	0,00	0,00
2		1023,60	1,70	42,50	1,42
4		1024,87	2,97	74,17	2,47
6		1026,37	4,47	111,67	3,72
8		1026,47	4,57	114,17	3,81
10		1024,57	2,67	66,67	2,22
12		1023,60	1,70	42,50	1,42
24		1020,53	0,00	0,00	0,00

Table A.10 - MBV test results for earth based panels reinforced with 30% dried rice husk.

RH_30D					
Time	**m_0 (g)**	**m (g)**	**Δm (g)**	**Δm (g/m^2)**	**Δm (g/m^{2}HR)**
0	786,17	786,17	0,00	0,00	0,00
2		788,03	1,87	46,67	1,56
4		789,20	3,03	75,83	2,53
6		790,17	4,00	100,00	3,33
8		791,00	4,83	120,83	4,03
10		789,10	2,93	73,33	2,44
12		788,20	2,03	50,83	1,69
24		786,07	0,00	0,00	0,00

Table A.11 - MBV test results for earth based blocks reinforced with 3% rice husk.

RH_3A					
Time	**m_0 (g)**	**m (g)**	**Δm (g)**	**Δm (g/m^2)**	**Δm (g/m^{2}HR)**
0	2008,10	2008,10	0,00	0,00	0,00
2		2009,20	1,10	48,89	1,63
4		2010,03	1,93	85,93	2,86
6		2010,60	2,50	111,11	3,70
8		2011,20	3,10	137,78	4,59
10		2009,90	1,80	80,00	2,67
12		2009,43	1,33	59,26	1,98
24		2008,13	0,03	1,48	0,05