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Reed as a Thermal Insulation Material: Experimental Characterisation of the Physical and Thermal Properties

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Abstract. The building sector plays a significant role in reducing global energy use and carbon emissions. In the European Union (EU), the building stock represents 40% of total energy use and in which cooling and heating systems represent over 50%. Portugal is one of the EU countries where the consequences of energy poverty are most evident due to the families' financial inability to adequately climate their homes. The reasons are several, but they are mainly linked to buildings' poor passive thermal performance, resulting from inadequate adaptation to the climatic context and reduced thermal insulation. Thus, it is necessary to develop solutions to increase buildings' thermal performance and reduce their potential environmental impact, which arises mainly from the significant use of active systems. In this sense, natural building materials are a promising solution, reducing energy use and carbon emissions related to buildings. This research studies the potential use of reed found in Portugal (*Arundo donax*) as a thermal insulation material. Its physical characterisation and the influence of geometry configuration on its thermal performance are evaluated. Its durability was studied too. Reed stalks were used to carry out the physical and durability tests. A reed board (150 x 150 mm) was built, and its thermal performance was tested in a hotbox. According to the results, the characteristics of reeds found in Portugal make it suitable to be used as a building material. Furthermore, regardless of the configuration studied, the reeds have a satisfactory thermal performance to be used as thermal insulation, under the requirements defined by Portuguese thermal regulation, $Re \geq 0.30$ (m^2.ºC)/W. There is a trend to the mould growth in the reed, but only under favourable conditions. Additionally, considering the abundance of reed throughout the Portuguese territory, this is an eco-friendly and low-cost option that gathers all requirements to be more used in the construction market.

1 Introduction

Due to its complexity, the building sector has many associated impacts in all sustainability dimensions, especially in the global energy use context. The air conditioning systems consume over 50% of the building sector's energy demand, and they run mainly on fossil fuels. For example, in the European Union, 84% of the heating and cooling systems run on fossil fuels (UN Environment Programme, 2018). According to an International Energy Agency report, it is estimated that due to climate change, the energy demand for cooling will triple by 2050 (IEA, 2018).

In Portugal, because of the low thermal performance of buildings, caused by an inadequate adaptation to the climatic context and lack of adequate thermal insulation, mainly in old buildings, families have more difficulties to adequately heat their homes than in other European countries (Horta et al., 2019).

To reduce energy use in construction, it is essential to carefully choose the building materials besides reducing operational energy needs (Thormark, 2006). This author also showed that with material substitution, the embodied energy could be decreased by 17%, which corroborates the importance of materials choice.

A low embodied energy construction material depends not only on the material itself but also on its availability, manufacturing process, the efficiency of production and transport distance (Cabeza et al., 2013). Investing in natural materials with low embodied energy is a way to increase sustainability. Instead of industrial ones, insulation based on natural materials can provide a comfortable indoor environment with a lower environmental impact.

In this way, it is essential to study natural, renewable, recyclable and biodegradable materials in the search for viable solutions that can contribute to a sustainable built environment. The use of passive strategies combined with local materials can contribute to reducing the environmental impact and energy consumption.

In this context, in Portugal, the *Arundo donax* is identified as a potential insulation material. This type of reed is an invasive plant species found throughout the Portuguese territory, especially along with watercourses. Using the reed as a construction material can also control its dissemination, which is responsible for biodiversity loss and sedimentation on water canals, leading to flooding, erosion and other material and economic damage (Monteiro, Ana; Moreira, Ilídio; Moreira, 2012).

The *Arundo donax* has been identified in Portuguese vernacular architecture as a widely used material due to its abundance. Its applications vary, but this material is mainly used in walls and roofs to provide better thermal insulation to the buildings.

This research contributes to the characterisation of the reed as a bio-based building material since its use can be a challenge due to the variability of properties, which depend on the harvest time and location. By applying specific standards, it was possible to measure and analyse the physical properties of the reed.

Thus, this paper's main objective relies on analysing the reed characteristics that turn it suitable to be used as an insulation material. Although there are already some studies on the characterisation of the Arundo donax's mechanical properties (Molari et al., 2020), there are no studies about the specific plant that grows in Portugal and that analyse the potential of using it as a sustainable thermal insulation material.

2 Materials and Methods

2.1 Harvest and drying conditions

The reed specie studied is *Arundo donax*. This reed is widespread throughout the Portuguese territory, and it is considered an invasive plant. The specimens analysed were harvested in Serpa, inland Southern Portugal, during the winter. It is in winter when the plant has lower sap content (it is drier) and, therefore, the cut plant can regenerate quickly, and the cut stalks of the plant has less moisture, dries faster, and it is less susceptible to aggressive agents.

The harvested reeds were kept in an environment with controlled temperature and humidity (20 ± 2ºC and 60 ± 2 % RH) for 6 months (natural drying). After, the reeds with cracks or some other defects were discarded, and their geometric parameters were identified: diameter between 11 and 15 mm; average wall thickness of 1.6 mm.

2.2 Physical characterization

Three physical properties were evaluated: moisture content, apparent density and retraction. Since there are no normative procedures specific for reeds' characterisation, the procedures used were adapted from wood. Five samples were used to carry out each test.

The moisture content (MC) test, based on the Portuguese Standard NP – 614 (LNEC, 1973a), consisted of drying the sample in an oven (103 ±2ºC) until reaching a constant mass. The MC is the difference between the wet mass, m_0 (g), and the dry mass, m_1 (g), divided by the dry mass, according to Equation 1. The apparent density (ρ) test, based on the Portuguese Standard NP – 616 (LNEC, 1973b), consisted of determining the specimen's mass and volume at a specific MC. The apparent ρ is the mass, m (g), divided by the volume, ν (m^3), calculated using Equation 2.

$$MC = \frac{(m_0 - m_1)}{m_1} x100 \quad (1)$$

$$\rho = \frac{m}{v} \quad (2)$$

The linear retraction (ε) test, based on the Portuguese Standard NP – 615 (LNEC, 1973c), consisted of analysing the variation in the studied dimension (length) after their saturation and drying. The ε is the difference between the saturated specimen dimensions, l_1 (mm), and the air-dried specimen dimensions, l_2 (mm), divided by the oven-dried specimen dimensions, l_3 (mm), according to Equation 3.

$$\varepsilon = \frac{(l_1 - l_2)}{l_3} x100 \quad (3)$$

Dimensional variations in the length were monitored in four different reed wall locations: 1-1, 2-2, 3-3, 4-4 (Fig. 1).

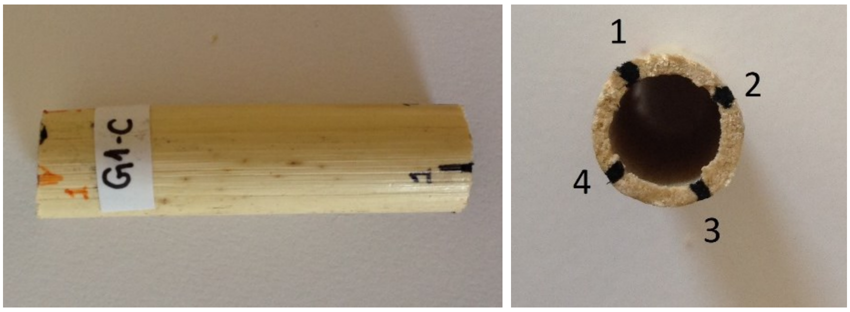

Fig. 1: Reed sample used in the retraction test.

2.3 Thermal characterization

A reed board with 150 x 150 mm (density = 208.98 kg/m^3) was built to evaluate the following thermal properties: thermal transmittance, thermal resistance and thermal conductivity. The reed stalks were placed in overlapping layers to reach a thickness of 100 mm. This thickness was defined using preliminary analytical methods, which results showed that it is the optimised thickness to reach adequate insulation levels for walls. The board was tied with steel wire, as presented in Fig. 2, to contain the reed stalks.

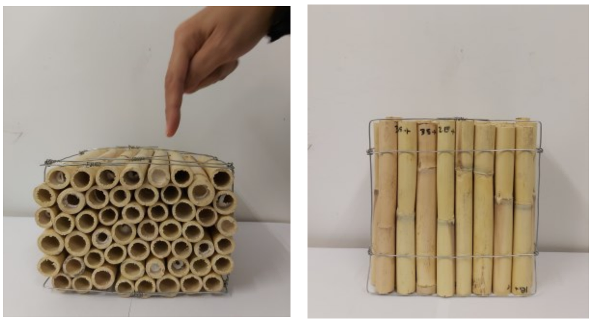

Fig. 2: Reed board.

The reed board was tested in a calibrated guarded hotbox designed and built at the Department of Civil Engineering of the University of Minho (Teixeira et al., 2020), based on ASTM specifications C1363 (ASTM, 2014). The hot box is composed of two chambers, the cold and the hot one, and one mounting ring placed between the two chambers. The reed board was placed in the centre of the mounting ring. It was enclosed between two Medium Density Fibreboard (MDF) boards to provide a flat surface for installing the flux meter and controlling the air permeability between the two chambers. The relative humidity in the chambers was monitored during the test. The variation of the board mass during the test was also evaluated. The board was tested in vertical and horizontal positions to verify the geometry configuration's influence on its thermal performance.

The tests were carried out considering the heat flow meter method, defined in ISO 9869-1 standard (BSI, 2014). The heat flux is measured through a heat flux sensor installed in the reed board's central part, and thermocouples measured the temperatures. With the values of the heat flux (q) and the surface temperatures (T), it was possible to determine the thermal resistance (Re) of the set of materials (reed board + MDF), using Equation 4. ΔT is the difference between the surface MDF temperature in the hot and cold chambers. The thermal resistance of the reed board was determined using Equation 5. The thermal transmittance (U) and thermal conductivity (λ) of the reed board were assessed using Equations 6 and 7, where e is the board's thickness.

$$Re_{set}[(m^2.{}^{\text{º}}C)/W] = \frac{\Delta T}{q} \tag{4}$$

$$Re_{reed}[(m^2.{}^{\text{º}}C)/W] = Re_{set} - (2 * Re_{MDF}) \tag{5}$$

$$U_{reed}[W/(m^2.{}^{\text{º}}C)] = \frac{1}{Re_{reed}} \tag{6}$$

$$\lambda_{reed}[W/(m.{}^{\text{º}}C)] = \frac{e}{Re_{reed}} \tag{7}$$

2.4 Durability study

The mould is one of the aggressive agents that can compromise the reed durability. The exploratory overstress test was carried out to evaluate the resistance of reed for mould growth. The test consisted of assessing the emergence and development of mould in the reed samples through visual analysis: bare eyes and optical microscope. Four reed samples were put in a Petri dish, visually evaluated and placed in the ARALAB FitoClima 1000EC45 climatic chamber (22 ±2 ºC and 90 ±5 % HR) for 43 days. The chamber conditions are the appropriate ones to mould development in reed (Bergholm, 2012). The samples were evaluated weekly. During the visual analysis, the quantification of mould growth was based on the mould index classification (Tab. 1).

Tab. 1: Mould indexing classifications adapted from (Viitanen, 2014).

Mould index	Coverage	Description of classification
0	0	No growth
1	0	Some growth detected only with microscopy
2	> 10%	Moderated growth detected with microscopy
3	0-10%	Some growth detected visually
4	10-50%	Visually detected
5	50-80%	Visually detected
6	80-100%	Visually detected

3 Results and Discussion

3.1 Physical characterization

The graphs presented in Fig. 3 show the values of density and MC (dry state) achieved in this study for the Portuguese reed and their comparison with bamboo and other wood used in the civil construction.

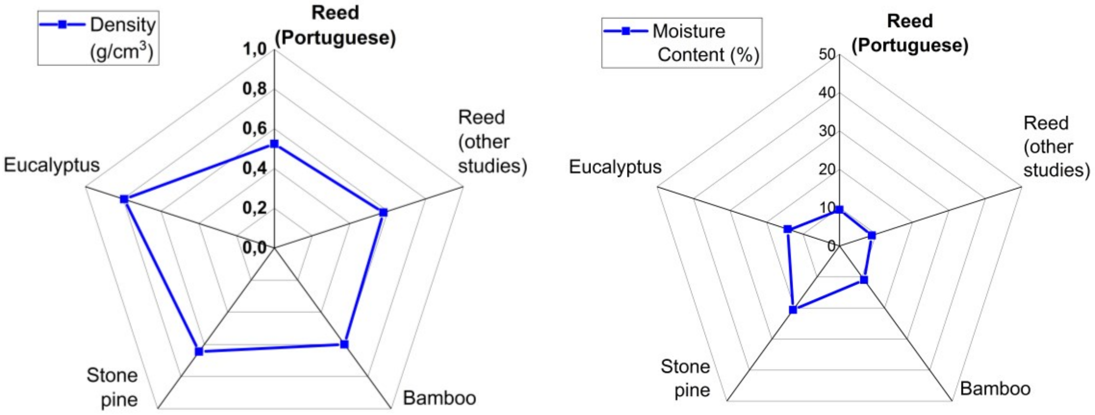

Fig. 3: Physical characteristics of materials: density (left); MC (right).

Concerning the density (Fig. 3 (left)), the value obtained for reed is 0.524 g/cm^3, which is in accordance with other studies, namely with the result of 0.577 g/cm^3 (Molari et al., 2021). Comparing reed and bamboo species, it is possible to conclude that there are high similarities. For instance, the reed density is quite similar to bamboo (0.600 g/cm^3) obtained in a previous study (Freitas, 2019). Regarding the wood used in construction, Portuguese reed's medium density value is close to stone pine density (Dias, 2017).

The MC of the green studied reed is high, 64%. However, the dry state's MC is low, i.e. 9.43%, and quite similar to the bamboo and eucalyptus (Fig. 3 (right)). The mass variation was only 0.1062 g in the 24 h test period (m_0= 1.2326 g and m_1= 1.1264 g). There was a marked loss of mass during the first 30 minutes of the test, followed by a residual loss up to 24 h. The low MC can be the reason for the low retraction (0.18%) observed for reed. This retraction value is similar to the bamboo retraction (0.23%) obtained in other studies (Freitas, 2019). Concerning the retraction, due to the marked difference in geometry and consequent adaptation in the test method, the comparison with wood used in civil construction does not apply.

These results show that the studied reed has density and MC values similar to other biobased materials used in the construction. The reed has satisfactory dimensional stability, proven by its low linear retraction, making it compatible with rigid connection accessories.

3.2 Thermal characterisation

Tab. 2 shows the parameters monitored in the hotbox and average values achieved in assessing reed boards' thermal properties. The mass variation during the test was residual (mass loss < 0.3%) and, therefore, has no impact on the presented values.

Tab. 2: Parameters monitored in the hot box and thermal properties.

Reed Board position	**Cold chamber**		**Hot chamber**		**Heat flux (W/m²)**	**Re_{set} (m².ºC) /W**	**Re_{MDF} (m².ºC)/ W**	**Re_{reed} (m².ºC)/ W**	**U_{reed} W/ (m².ºC)**	**λ_{reed} W/ (mº.C)**
	T* (ºC)	**HR (%)**	**T* (ºC)**	**HR (%)**						
Vertical	25.6	46	35.5	22	5.808	1.707	0.147	1.413	0.708	0.071
Horizontal	24.3	44	34.7	22	5.870	1.728	0.147	1.434	0.697	0.070

*Superficial temperature

Analysing the information presented in Tab. 2, it is possible to conclude that the reed board shows a satisfactory thermal performance regardless of the geometric configuration. The thermal conductivity values are in accordance with the literature (Asdrubali et al., 2015) and very close to the requirements defined by Portuguese thermal regulation, where the thermal conductivity of insulation materials must be lower than 0.065 W/(m.ºC) (*Decree-Law No. 80/2006*, 2006). The thermal resistance of reed is according to the limits of the Portuguese thermal regulation, Re ≥ 0.30 (m².ºC)/W. Furthermore, considering the thickness of the reed board (100 mm), its thermal resistance represents almost 60% of the thermal resistance of some commercially used insulation materials such as rock wool, XPS and cork (approximately 2.60 (m².ºC) / W) (Danosa, 2020; Insulation, 2020; Termolan, 2020). These results confirm the potential of the reed harvested in Portugal to be used as a thermal insulation material.

Regarding the geometric configuration, under the conditions studied, it is evident that the reed position does not influence the thermal properties.

3.3 Durability study

Fig. 4 shows the mould index evolution during the test period and the reed images at the beginning and end of the test.

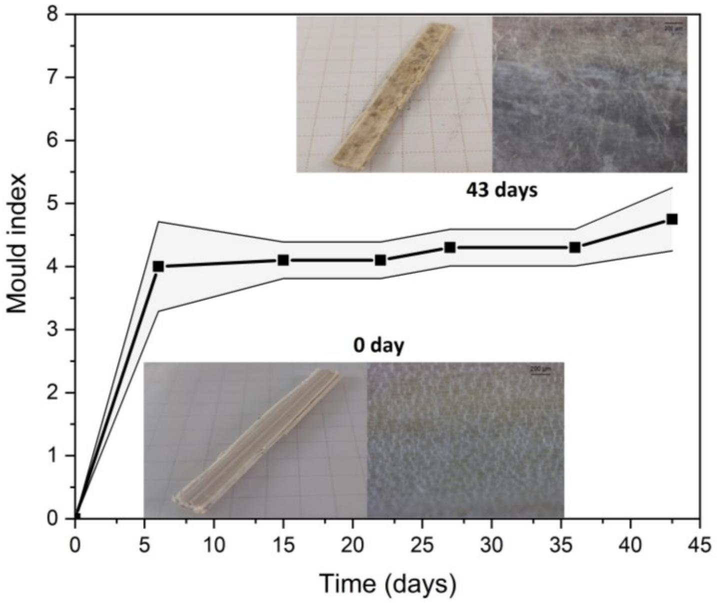

Fig. 4: Mould evolution in the studied reed (Portuguese).

The graph in Fig. 4 shows a quick evolution of mould growth in the first week. At this point, the mould surface coverage that was visually detected was around 30% (mould index – 4). From this point, the evolution in the mould growth is moderate and reached the peak at the end of the test period. The images showed in Fig. 4 also represent the evolution of mould growth. Comparing the reference images (0 days) to the final ones (43 days), the reed is observed covered by a grey and black mould at the end of the test. The bare eyes final image shows a coverage of around 80%. In the final microscopy image, a high density of mould is highlighted.

These results confirm the trend in the development of mould in the studied reed (Portuguese). However, these results must be analysed carefully. There are two main aspects to consider. First, the chamber conditions are the ones that maximise mould development in the reed (Bergholm, 2012). Similar conditions can occur in particular real environments. In Portugal, for example, only the coastal region reaches temperature and humidity conditions similar to those studied. This situation can happen during the summer, for a short time, usually at night (Fernandes et al., 2020). Second, the reed was studied considering the resistance to the mould of the inner face, i.e. the most vulnerable one. This is the less dense side of the reed (Couvreur and Alejandro Buzo, 2019) and, therefore, more vulnerable to aggressive agents.

4 Conclusions

The experimental study was carried out to evaluate the potential of reed harvested in Portugal (*Arundo donax*) as a thermal insulation material. In this sense, its physical, thermal-physical and durability characteristics were studied.

The studied reed's thermal conductivity is close to the Portuguese thermal regulation requirements, <0.065 W/(m.ºC). Its thermal resistance represents almost 60% of the thermal resistance of some commercially used insulation materials in Portugal. The studied reed's density and moisture content are similar to the ones of organic materials conventionally used in the construction sector. Furthermore, the reed has satisfactory dimensional stability, making it compatible with rigid connection accessories. Regarding durability, there is a trend to the mould growth under favourable conditions (22 ±2 ºC and 90 ±5 % HR). Nevertheless, these specific temperature and humidity are uncommon in Portuguese climatic conditions.

Based on the obtained results, it is possible to conclude that, under the studied conditions, the reed harvested in Portugal showed satisfactory thermal performance. Taking into account its physical and durability characteristics, it presented significant potential applicability. However, the issue of air permeability in this type of material must be considered. In real environments, an earth mortar coating can be used to control the air permeability of the insulation layer. Additionally, considering the abundance of reed throughout the Portuguese territory, this is an eco-friendly and low-cost option that gathers all conditions to be more used in the construction market.

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