sustainability

Article

Composite Materials of Rice Husk and Reed Fibers for Thermal Insulation Plates Using Sodium Silicate as a Binder

Alana Silva [1,*], Florindo Gaspar [1] and Aliaksandr Bakatovich [2]

[1] Centre for Rapid and Sustainable Product Development (CDRSP), School of Technology and Management, Polytechnic Institute of Leiria Campus 2, 2430-028 Marinha Grande, Portugal; florindo.gaspar@ipleiria.pt
[2] Faculty of Civil Engineering, Polotsk State University, Blokhin Str., 29, 211440 Novopolotsk, Belarus; a.bakatovich@psu.by
* Correspondence: alana.silva@ipleiria.pt

Abstract: The civil construction industry is responsible for a large part of the world's energy consumption; therefore, in recent years, sustainable practices in this sector have become increasingly common to minimize the environmental impacts of civil construction during the life cycle of buildings. As a result, new materials and more sustainable building techniques are being sought. In Portugal, rice husk is an abundant agricultural waste with great potential to be used as a raw material in thermal insulation materials, as well as giant reed, which is considered an invasive plant. In this study, thermal insulation plates composed of rice husks and/or reed fiber were developed, using sodium silicate as a binder in various proportions and with dimensions of 30 × 30 × 3 cm and density ranging between 0.219 and 0.352 g/cm^3. The main objective of the study is to evaluate the thermal characteristics of the plates, such as thermal conductivity, as well as the mechanical resistance to bending and water absorption. The results of the thermal conductivity tests were promising for all compositions, with values in the range between 0.0602 and 0.0745 W/m·K, meeting the requirements to be considered as thermal insulation materials. The results for bending strength and water absorption presented values within the expected range for materials of vegetal origin.

Keywords: thermal insulation; sustainable building; agricultural waste; rice husk; reed fiber

check for updates

Citation: Silva, A.; Gaspar, F.; Bakatovich, A. Composite Materials of Rice Husk and Reed Fibers for Thermal Insulation Plates Using Sodium Silicate as a Binder. *Sustainability* **2023**, *15*, 11273. https://doi.org/10.3390/su151411273

Academic Editor: Antonio Caggiano

Received: 29 May 2023
Revised: 25 June 2023
Accepted: 17 July 2023
Published: 19 July 2023

1. Introduction

Finding measures to reduce energy consumption from the construction to the demolition of buildings is a major challenge for the construction sector [1]. In addition to searching for more sustainable construction materials solutions, it is extremely important to improve the energy efficiency of buildings, as they are responsible for a significant portion of the total energy consumption and carbon dioxide emissions during their life cycle [2].

The energy consumption in the industrial manufacturing of construction materials is very high, so the use of materials that require less energy in their production process is an alternative to reduce the impact that the high energy demand of this sector has on the environment. Therefore, traditional construction materials may be replaced by materials from renewable sources, either fully or partially [3].

The use of raw materials obtained through plant waste allows for the adoption of a circular model in which waste is transformed into new resources, resulting in the economic valorization of organic waste generated from agricultural and forestry industries [2]. Therefore, it is important to continue research focused on the development of new thermal insulators based on natural raw materials, as well as to seek more ecological binding materials with properties equal to or superior to conventional materials, in order to further reduce the impact [1].

The use of natural materials in insulation plates has advantages over petroleum by-products due to the lower environmental harm caused. The carbon and nitrogen incorporated in natural materials are prevented from being released into the environment as harmful gases and ashes. Natural materials pose no threats to human beings or environmental health, and the embodied energy and life-cycle costs of natural materials are considerably lower [2].

EPS and XPS, for example, are widely used as thermal insulators due to their low thermal conductivity. However, their production requires the use of non-renewable raw materials, such as petroleum, and they have extremely slow decomposition rates and are not easily recyclable [4]. Another widely used material is glass wool, which involves high temperatures and the use of chemicals in its manufacturing process, generating toxic waste and fine particles that can be harmful to human health [5].

Furthermore, the use of natural raw materials as thermal insulation materials can contribute to improving the energy efficiency of buildings as they reduce heat losses. The reduction in energy consumption for the heating and cooling of buildings results in a decrease in gas emissions, making this approach a way to mitigate climate change and environmental impacts [6].

Portugal has a Mediterranean climate, and is characterized by hot and dry summers and mild to cool and humid winters [7]. Although the winter is not as severe as in northern countries in Europe, it is important to ensure thermal comfort for occupants [8]; this means that the energy performance of new building meets the Energy Performance Buildings Directive [9]. During the summer, high temperatures can lead to overheating of indoor spaces. Adequate thermal insulation helps prevent excessive heat gain from the outside, reducing the need for artificial cooling, such as the use of air conditioning [10]. Thermal insulation also helps minimize the effects of the cold daily temperature variations in Portugal. During the day, temperatures can be significantly higher than at night, and insulation helps maintain internal thermal stability, thus avoiding abrupt temperature fluctuations [11].

To find alternative construction materials and low-tech methods using natural materials that will result in more sustainable construction, researchers worldwide are making great efforts to meet the comfort and functionality standards required today. The resulting solutions are intended to be applied by the construction industry, and as the use of these natural materials increases, overall production costs will be reduced [12].

The adoption of natural materials alone may not always be a sustainable alternative. Several factors need to be considered to assess whether their use will provide benefits for the desired application. It is important to evaluate, for example, if the materials have the potential to be recycled, if the raw material is renewable, if there is local availability, and if they perform their intended function [13].

The low thermal conductivity and fibrous characteristics of most organic materials have contributed to significant improvements in thermal insulation properties when incorporated into the structure of the building's exterior envelope [1]. Natural organic materials have a high specific heat capacity and a greater sensitivity to moisture, which are different physical properties compared with common silicate materials [14].

Agricultural waste is generated abundantly worldwide and is typically burned or dumped in landfills. Finding sustainable solutions to manage this waste is considered a significant environmental challenge. Therefore, it is necessary to seek more sustainable alternatives for its proper disposal. The potential use of these waste materials as raw material sources for thermal insulation materials has been widely recognized in various studies and can be considered one of the alternatives to minimize the impacts caused by the agro-industrial sector [15].

Rice cultivation is the third largest cereal crop in the world, behind only maize and wheat, and it feeds over half of the global population [16]. After harvesting, rice undergoes the husking process [17]. Rice husk is the outer and protective layer of the rice grain, which is removed during grain processing [18]. The volume of rice husk generated is enormous and corresponds to approximately 20% of the total mass of the unhusked rice grain, thus generating one ton of husk for every five tons of harvested rice [19].

With growing concerns about the proper disposal of agricultural waste and the search for more sustainable construction materials, there are several studies focusing on the application of agricultural residues as raw materials for thermal insulation materials in the construction industry.

Regarding rice husk, in Yarbrough's study [20], two types of panels were produced using crushed rice husk: one with the husk dried in an oven and another with the husk in its natural state. The study concluded that the husk can be used in its natural state without the need for energy-intensive drying processes. Another study, by Rosa et al. [21], used rice husk along with sunflower stalks to produce panels as a potential substitute for glass wool in thermal insulation for solar water heaters. In Portugal, eco-panels were developed by Rama [22], composed of wood and straw and/or rice husk. In the study by Wang et al. [23], a thermal insulation material was developed using rice husk and geopolymer foam. Buratti et al. [24] evaluated the thermal, acoustic, and environmental performance of panels made from rice husk, produced by bonding and pressing the material. Muthuraj et al. [25] produced biodegradable composites using four byproducts, such as rice husk, wheat husk, wood fibers, and textile waste, all of which exhibited good thermal conductivity. Another study, by Aravind et al., developed panels for external concrete walls by incorporating rice husk into the mixture, resulting in a reduction of up to 19.05% in thermal conductivity [26]. In the research by Marques et al. [27], cement-based composites were developed with the incorporation of rice husk into the mixture, which not only showed a reduction in thermal conductivity, but also exhibited a good acoustic insulation performance.

In addition to rice husk in its natural state, there are also several studies where rice husk has been incorporated into the composition of thermal insulation materials in other forms. For example, in the study by Fernandes et al. [28], a vitreous foam was developed by adding rice husk ash and waste glass powder, achieving thermal conductivity values of 0.021–0.025 W/mK. Another example is the synthesis silica aerogel derived from rice husk, as demonstrated in the study by Abbas et al. [29], where a lightweight cement-based composite with excellent thermal properties was developed by incorporating rice-husk-derived silica aerogel.

In a study about reeds by Ferrández-García et al. [30], a panel was developed consisting of three layers of reeds, with the outer layers composed of crushed material and the inner layer made of whole stalks. The composition of urea–formaldehyde was used as a binding material. Andreu-Rodriguez et al. [31], conducted a study using reed stalk panels with 18 different compositions, varying the particle size and using different types of resins as the binding materials. Research carried out in Belarus, by Baltrushevich et al. [32], developed ecological thermal insulation panels based on ground reeds and crushed rye straw. Sodium silicate mixed with lime and gypsum was used as a binding material to improve water resistance. Alternatively, a wood resin was also used as a binder. The study by Benalel et al. [33] was conducted to develop and characterize thermal insulation materials from cardboard waste and plant fibers, such as reeds, fig tree branches, and olive leaves. Another research evaluated the physical, mechanical, and thermal properties of incorporating reed fiber into a green and sustainable concrete composite [34].

This work presents research in the field of sustainable building materials, addressing the combined use of rice husk and reed fiber, both agricultural residues found abundantly in Portuguese territory. The aim is to valorize local raw materials efficiently and incorporate them into a circular economy model, promoting the development of more ecological and economically viable solutions for the construction industry.

The main objective is the development and evaluation of sustainable composite material solutions for the thermal insulation of buildings. The work consists specifically of experiments using various compositions in the form of plates containing rice husk and/or reed fiber, using sodium silicate as a binding material. These plates have been developed to be applied on walls and ceilings of buildings. Through experimentation, the aim is to evaluate the physical and mechanical properties of the different compositions, such as the thermal conductivity, bending strength, and water absorption.

2. Materials and Methods

2.1. Materials

2.1.1. Fibers

The rice husk (Figure 1) used in this study was from the *Oryza sativa* species, Japonica subspecies, obtained from the Beira Litoral region in Portugal. The material did not undergo any processing or special treatment, it was simply stored in bags protected from light, heat, and humidity. Rice husk has dimensions ranging from 3 to 5 mm. The gradation curve of rice husk is shown in Figure 2. Its density varies between 0.118 and 0.150 g/cm^3, depending on various factors such as moisture content, particle size, porosity, and compaction [35]. It is a waste generated in large daily volumes and is still not well-utilized [19]. Because of its low nutritional value and high percentage of silica in its composition, rice husk is not used as animal feed [36].

Figure 1. Rice husk.

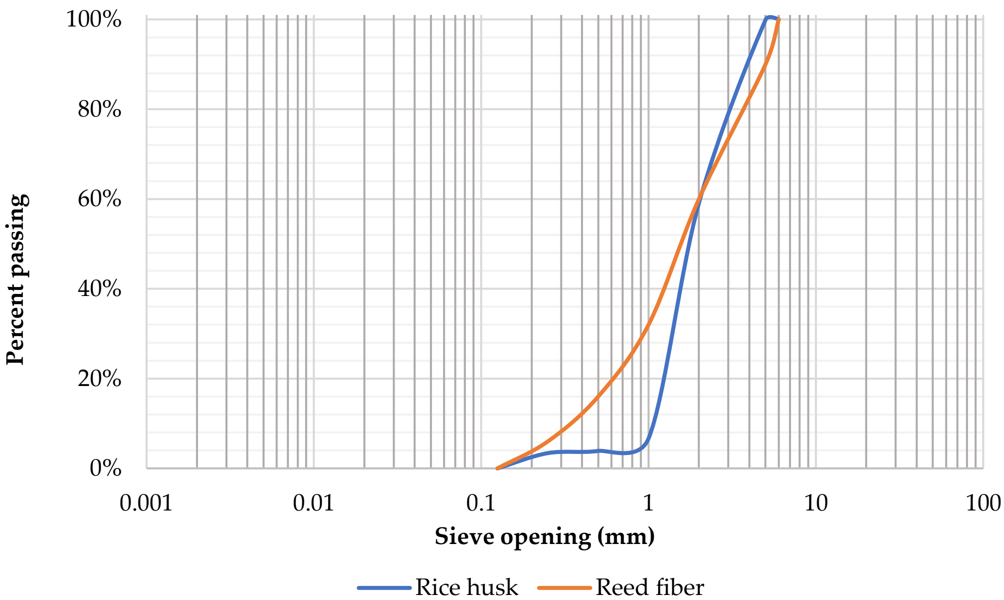

Figure 2. Gradation curve of rice husk and reed fiber.

The reed fiber (Figure 3) used in this study was obtained from the stems of the *Arundo donax L.* species, also known as the giant reed, obtained from the Leiria region in

Portugal. Despite reeds having significant economic potential in certain regions of the world, it is considered an invasive species in Portuguese territory according to Decree-Law No. 92/2019 [37].

Figure 3. Reed fiber.

The process to obtain the material involved manual harvesting of the plant, followed by cleaning of the stems to remove the leaves. Subsequently, the stems were cut into small cylinders approximately 50 mm in length, dried in a 50 °C oven, and then placed in a ball mill for the milling process. After milling, the material was sieved and separated into fractions based on particle size, according to Table 1. The gradation curve of rice husk is shown in Figure 2.

Table 1. Percentage of fractions of reed fiber particles.

Size of Particles (mm)	(%)
>5	10
2–5	30
1–2	28
0.50–1	16
0.25–0.50	10
<0.25	6

Particles larger than 2 mm represented 40% of the material and were partially crushed raw material, which were reused and added to a new raw material mixture for further milling. Particles smaller than 0.25 mm accounted for only 6% of the total mixture and were discarded. The fractions in the range of 0.25–2 mm accounted for the large quantity of material (54% of the milled and sieved material) and were selected to be used in this study; according to a previous study from Baltrushevich's [32], this size has the best performance for thermal insulation applications.

2.1.2. Binder

Sodium silicate solution, provided by Quimialmel, also known as liquid glass, was used as the binder. The material is a viscous liquid, and is transparent or slightly whitish in color. It has a pH between 10.5 and 13, a viscosity of 135 cP, and a density of 1.368 g/cm^3. One of the advantages of using liquid glass as a binder in this study is its non-combustibility, providing increased safety in case of building fires, in addition to its good adhesion to plant-based substrates [38,39].

FTIR analysis was conducted on sodium silicate in both its liquid and solid states after drying in an oven at 50 °C. The main purpose was to characterize the chemical composition differences between the two states. The analysis was conducted on a Bruker Alpha-p FTIR ATR spectrometer, which operated in the frequency range from 4000 to 400 cm^{-1}. Figure 4 presents the FTIR spectra of the sodium silicate samples.

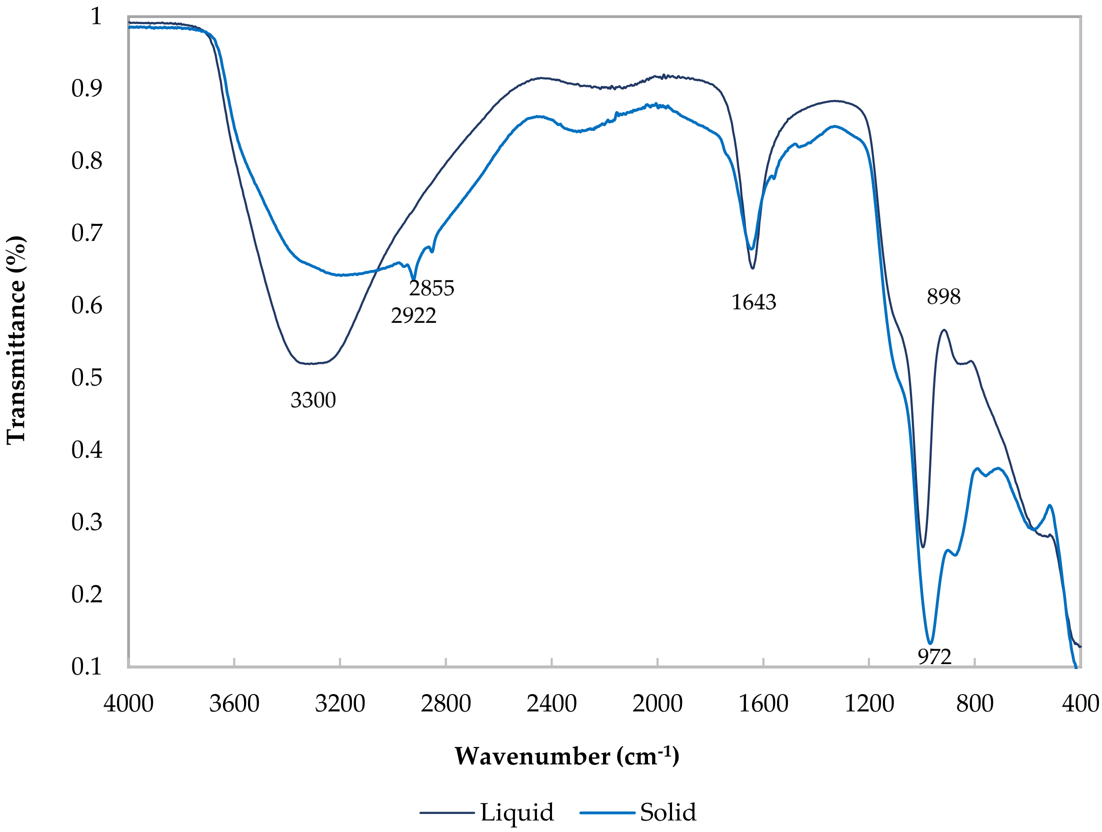

Figure 4. FTIR spectra of the sodium silicate in liquid solution and solid state.

The peak at 3300 cm^{-1} confirms the presence of hydroxyl groups in the samples, indicating the presence of water, which is more pronounced in the liquid-state solution. The peaks at 1643 cm^{-1}, 972 cm^{-1}, and 898 cm^{-1}, present in both spectra, can be attributed to the presence of H-O-H, Si-O-Si stretching and SiO_4 tetrahedron [40]. It is observed that in the dry state of sodium silicate, two small peaks emerge in the region of 2922 cm^{-1} and 2855 cm^{-1}, which are characteristic bands of sodium silicate for silanol OH groups and adsorbed water [41].

2.2. Composition and Preparation of Specimens

In this study, 22 different compositions of panels were tested (Table 2) using rice husk and/or reed fiber as aggregates and sodium silicate as the binder.

The range of sodium silicate quantity, ranging from 350 g to 600 g, was established to examine different ratios of sodium silicate in relation to the natural components present. Thus, the amount of sodium silicate used in the mixtures for the manufacturing the panels varied from 40% to 60%.

Table 2. Compositions, proportions, dimensions, and conditions of plates.

Sample	Composition (g)			Proportion Aggregatess:Silicate (%)	Dimensions (cm)
	Rice Husk	Reed Fiber	Sodium Silicate		
1	400	-	350	53:47	29.8 × 29.8 × 3.0
2			400	50:50	29.8 × 29.8 × 2.9
3			500	44:56	29.9 × 29.8 × 2.9
4			600	40:60	29.6 × 29.6 × 3.0
5	450	-	400	53:47	30.0 × 29.9 × 3.0
6			500	47:53	29.9 × 29.9 × 3.0
7			600	43:57	29.9 × 29.9 × 3.0
8	200	300	400	56:44	29.8 × 29.7 × 3.0
9			500	50:50	29.6 × 29.7 × 3.0
10	250	250	400	56:44	30.0 × 29.9 × 3.0
11			500	50:50	30.0 × 29.9 × 3.0
12	300	200	350	59:41	29.8 × 29.8 × 3.0
13			400	56:44	29.8 × 29.8 × 3.0
14			500	50:50	29.7 × 29.8 × 3.0
15	300	300	400	60:40	29.8 × 29.8 × 3.0
16			500	55:45	30.0 × 29.9 × 3.0
17			600	50:50	29.9 × 29.9 × 3.0
18	350	50	400	50:50	29.8 × 29.8 × 3.0
19			500	44:56	29.8 × 29.8 × 3.0
20	400	100	400	56:44	29.9 × 29.9 × 3.0
21			500	50:50	29.9 × 29.9 × 3.0
22	-	800	400	67:33	30.0 × 29.9 × 3.0

The lowest quantity (350 g) was determined after observing that lower amounts did not provide satisfactory integrity to most of the mixtures, compromising the mechanical performance of the panels. On the other hand, the maximum quantity (600 g) was defined based on previous tests that showed that increasing the binder content in the mixture also tends to increase the thermal conductivity of the panels, reducing their thermal performance. Additionally, the panels already exhibited sufficient stiffness and consistency, making it unnecessary to use larger quantities of binder.

All of the plates were prepared using a metallic mold with dimensions of 300 × 300 × 30 mm. The mixture for each composition was manually prepared until the binder material evenly coated the aggregates. After mixing, the material was placed in the mold with the lid fixed and remained closed for a minimum period of 6 h. Then, the sides of the mold were removed, and the material was placed in an oven for drying at a temperature of 50 °C until reaching a constant mass. In this study, we chose not to completely remove the plate from the mold, keeping the lid fixed for the first 24 h to ensure a completely flat surface for the plates. Without the lid, the material tended to experience some deformations on the surface due to the heat from the oven, which can affect the accuracy of the tests, particularly the thermal conductivity test. Once the plate was completely dry, it was removed from the oven and stored in a dry and protected place. Table 2 shows the average final dimensions of the plates for each composition. No relevant deviations from the target dimensions were obtained. An example of a finished plate can be seen in Figure 5.

2.3. Testing Methods

This study evaluated the physical–mechanical properties of the plates. Table 3 presents a summary of the tests conducted, including the respective parameters obtained, as well as the number of specimens tested for each composition.

(a) (b)

Figure 5. Composite plate after being removed from the mold: (a) top view and (b) side view.

Table 3. Testing parameters.

Test	Parameters	No. of Compositions	No. of Specimens per Composition
Heat flow	Thermal conductivity	22	5
Bending	Bending strength, modulus of elasticity	22	5
Water absorption	Moisture content	10	3

2.3.1. Thermal Conductivity

To determine the thermal conductivity (λ) of the different compositions, the plates were subjected to testing on LM.PLUS 305 heat flow meter equipment, in accordance with the ISO 8301 [42] standard. The equipment consisted of a cooling plate at the bottom and a heating plate at the top. The temperature of the cooling plate set for this test was 10 °C, and the heating plate was set to 40 °C. With the defined temperatures, the equipment operated for an average of 120 min to achieve a stable thermal conductivity value. The test was repeated five times for each composition.

2.3.2. Bending Strength

The bending strength test was conducted on five specimens for each composition, following the EN 12089 [43] standard, using the Universal Testing Machine–Instron 4505 equipment. The specimens consisted of plates cut into small beam shapes, with dimensions of 30 mm thickness, 50 mm width, and 300 mm length. The test involved a three-point bending test, using three cylinders with a diameter of 80 mm, where two cylinders served as support and one as the load. The supporting cylinders were spaced 200 mm apart from the center, and the loading cylinder was positioned at the center of the specimen. The load was applied at a speed of 10 mm/min.

Bending strength was calculated from the followingequation:

$$\sigma_f = \frac{3 \times F_m \times L}{2 \times b \times d^2} \tag{1}$$

where:

σ_f is the bending strength (MPa), F_m is the maximum load (N), L is the distance between supports (mm), b is the width of the specimen (mm), and d is the thickness of the specimen (mm).

The modulus of elasticity (E) for the bending of each specimen was also calculated. The modulus of elasticity is an important property of many materials as it allows for the calculation of elastic deformation that occurs in a structure when it is subjected to an external load.

The modulus of elasticity was calculated from the linear part of the graph obtained through the bending test of each specimen (Figure 6), where the deformation is directly proportional to the applied load.

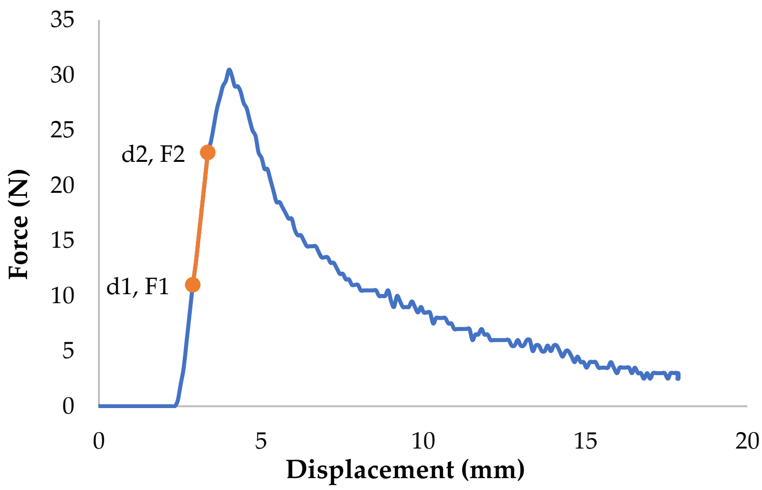

Figure 6. Example of a bending strength test graph for the calculation of the modulus of elasticity.

With the determined region of the graph, the following expression was applied:

$$E = \frac{(F_2 - F_1) \times L^2}{(d_2 - d_1) \times 48 \times \left(\frac{b \times h^3}{12}\right)} \tag{2}$$

where:

E is the modulus of elasticity (MPa), F_2 is the maximum load (N), F_1 is the minimum load (N), L is the length (mm), d_2 is the maximum displacement (mm), d_1 is the minimum displacement (mm), b is the width (mm), and d is the thickness (mm).

The result is a measure of the material's stiffness, expressed in MPa. It is important to note that the modulus of elasticity can vary with test conditions and specific material properties, such as density, temperature, humidity, and other factors.

2.3.3. Water Absorption

In this study, the water absorption of the materials was determined using a climate chamber, model Sunrise SU340ES 2010, which allowed for temperature and humidity control. For this test, the plates were cut into specimens measuring 150 × 50 × 30 mm. Because of space limitations inside the chamber, only 10 compositions were selected to undergo this test, with three specimens for each composition, totalings 30 specimens. Aiming to vary the types of compositions as much as possible, the influence of each material in the mixture was evaluated.

After cutting the specimens, they were weighed and placed in the climate chamber, using an ambient temperature of 20 °C and a relative humidity of 60%, until reaching a constant mass value. This step ensured that all specimens had the same temperature and humidity conditions. Once the mass of the specimens stabilized, the relative humidity was increased to 95%, while maintaining the temperature at 20 °C. The specimens were kept under these conditions inside the chamber and periodically weighed until they reached a constant mass again at this humidity level.

After exposure to the high humidity level in the climate chamber, water absorption was calculated according to the following equation.

$$W_m = \frac{m_2 - m_1}{m_2} \times 100 \quad (3)$$

where:

W_m is water absorption (%), m_1 is the dry mass (g), and m_2 is the wet mass (g).

3. Results and Discussion

3.1. Thermal Conductivity

3.1.1. Rice Husk Plates

Table 4 shows the thermal conductivity results obtained for compositions 1–7, composed of rice husk (RH) and sodium silicate, along with their respective composition and density. Additionally, a classification of the condition of the boards was also performed, being classified as not-rigid (material easily detaches), semi-rigid (rigid plate but still loses some surface material), and rigid (plate maintains its shape).

Table 4. The density and thermal conductivity of the samples with rice husk and sodium silicate.

Sample	Composition (g)		Density (g/cm^3)	Thermal Conductivity (W/mK)	Plate Condition
	Rice Husk	Sodium Silicate			
1	400	350	0.240	0.0613	Not-rigid
2		400	0.245	0.0629	Semi-rigid
3		500	0.257	0.0656	Rigid
4		600	0.268	0.0672	Rigid
5	450	400	0.255	0.0637	Semi-rigid
6		500	0.273	0.0669	Rigid
7		600	0.280	0.0689	Rigid

Based on the data presented in Table 4, the graph in Figure 7 illustrates the curves for the increase in thermal conductivity in relation to the increase in sodium silicate in the compositions with 400 g and 450 g of rice husk.

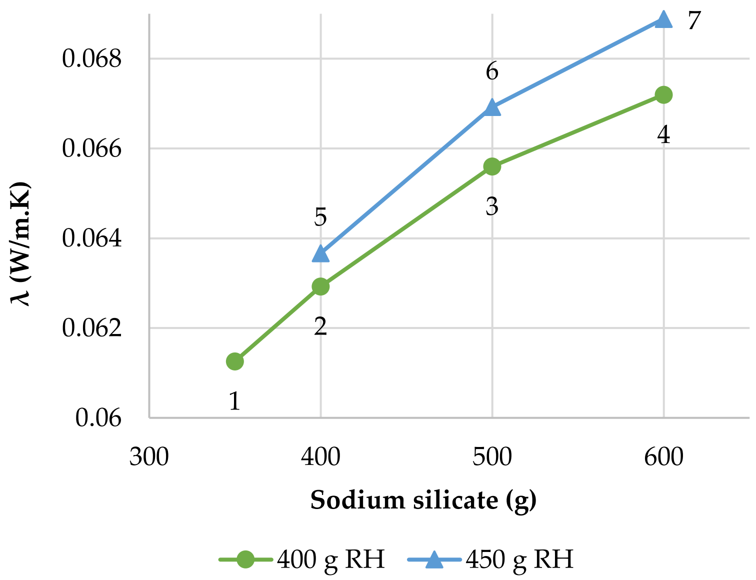

Figure 7. Thermal conductivity of rice husk and sodium silicate compositions.

Composition 1 showed the best thermal conductivity results, with the lowest density (0.213 g/cm^3). However, the low amount of binder in this mixture made the plate more fragile. An attempt was made to apply 350 g of sodium silicate to a mixture with 450 g of rice husk, but the plate disintegrated easily, so this sample was discarded.

Composition 2 had an additional 50 g of sodium silicate in the mixture compared with composition 1, resulting in a 2.1% increase in density and a 2.6% increase in thermal conductivity value. Composition 3, with an additional 100 g of sodium silicate compared with composition 2, had a 4.9% increase in density and a 4.3% increase in thermal conductivity value. Composition 4, with an additional 100 g of sodium silicate compared with composition 3, had a 4.2% increase in density and a 2.5% increase in thermal conductivity. This indicates that for every 100 g of sodium silicate added to the compositions, there was an increase in density ranging from 4.2% to 4.9% and a consequent increase in thermal conductivity in the range of 2.5% to 4.3%.

When an additional 50 g of rice husk was added to the compositions, an increase in thermal conductivity was observed. Composition 5, compared with composition 2, had a 4.1% increase in density and a 1.3% increase in thermal conductivity. The same trend was observed for composition 6 compared with composition 3, and for composition 7 compared with composition 4, where the addition of 50 g of rice husk resulted in a 6.2% and 4.4% increase in density, and a 1.9% and 2.5% increase in thermal conductivity, respectively.

When comparing compositions 5, 6, and 7, it can be observed that the addition of 100 g of sodium silicate to these compositions led to an increase in density ranging from 2.5% to 7.1% and an increase in thermal conductivity ranging from 2.9% to 5%.

Based on these analyses, it was observed that the density of these compositions was directly related to the thermal conductivity, meaning that lower density resulted in lower thermal conductivity of the composite plate. The increase in density caused by the addition of sodium silicate showed that for every 100 g added, there could be an increase of up to 7.1% in density, which translates to an increase of 2.5% to 7.8% in the thermal conductivity of the material.

Materials with a lower density tend to have better thermal insulation performance due to the presence of air-filled pores in their structure, which restrict heat transfer. Therefore, the lower the density, the higher the potential for thermal insulation [44].

3.1.2. Rice Husk and Reed Fiber Plates

Table 5 presents the results of thermal conductivity obtained for compositions 8–22, composed of rice husk, reed fiber (RF), and sodium silicate, along with their respective composition, density, and plate condition.

Based on the data presented in Table 5, it can be observed that the addition of reed fiber to the mixtures resulted in an increase in the density and thermal conductivity of the boards compared with the compositions analyzed previously in Table 4. The graph in Figure 8 illustrates the curves of thermal conductivity increase in relation to the increase in sodium silicate in the compositions with reed fiber and rice husk.

Composition 22, consisting solely of reed fiber and sodium silicate, exhibited a density of 0.270 g/cm^3 and a thermal conductivity of 0.0983 W/mK. The achieved thermal conductivity value was relatively high when compared with compositions with similar densities that only contained rice husk in their mixture. For instance, composition 6 had a density very close to composition 22, but its thermal conductivity was approximately 47% lower.

Another comparison for mixture 22 can be made with compositions 7 and 5, which had the same amount of sodium silicate in the mixture, but exhibited thermal conductivities 42% to 54% lower than the composition with reed fiber. These analyses of composition 22 confirm that reed fiber significantly contributed to the increase in thermal conductivity when incorporated into the compositions.

Table 5. Density and thermal conductivity of samples with rice husk, reed fiber, and sodium silicate.

Sample	Composition (g)			Density (g/cm^3)	Thermal Conductivity (W/mK)	Plate Condition
	Rice Husk	Reed Fiber	Sodium Silicate			
8 9	200	300	400 500	0.269 0.299	0.0712 0.0736	Semi-rigid Rigid
10 11	250	250	400 500	0.275 0.297	0.0699 0.0726	Semi-rigid Rigid
12 13 14	300	200	350 400 500	0.254 0.273 0.302	0.0634 0.0666 0.0681	Not-rigid Semi-rigid Rigid
15 16 17	300	300	400 500 600	0.288 0.323 0.352	0.0704 0.0732 0.0745	Semi-rigid Rigid Rigid
18 19	350	50	400 500	0.219 0.240	0.0602 0.0627	Semi-rigid Rigid
20 21	400	100	400 500	0.255 0.273	0.0689 0.0706	Semi-rigid Rigid
22	-	800	400	0.270	0.0983	Rigid

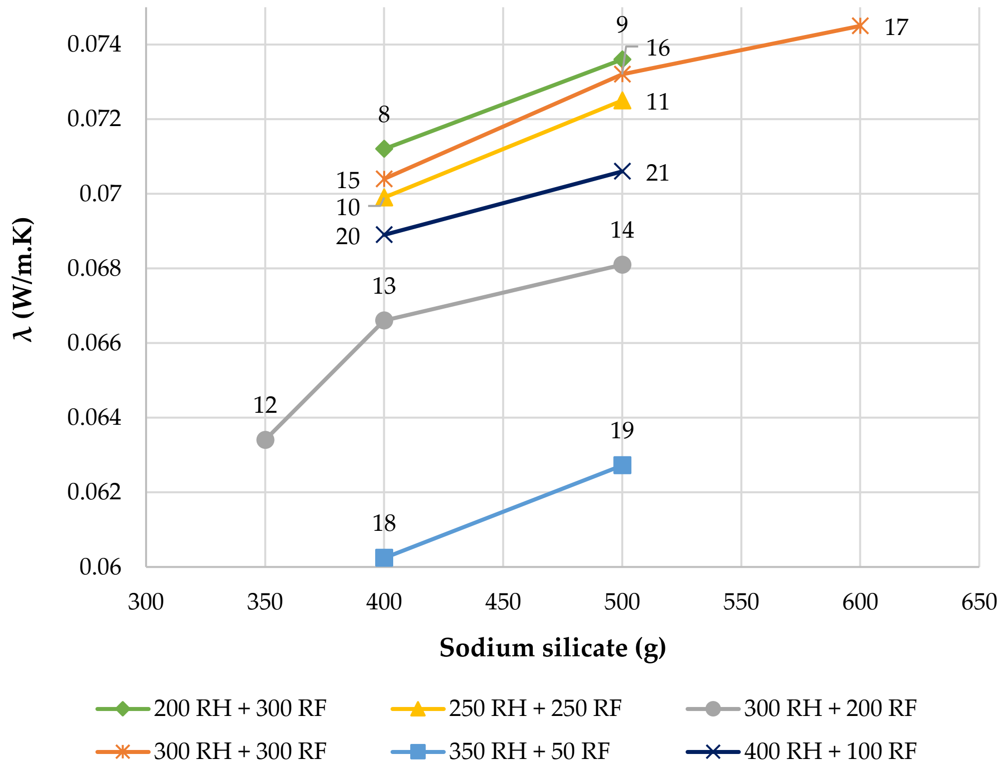

Figure 8. Thermal conductivity of rice husk, reed fiber, and sodium silicate compositions.

Therefore, reed fiber acting alone with sodium silicate did not yield satisfactory thermal conductivity values in order to be considered a thermal insulation material in the tested sample. However, by combining this material with rice husk in the other compositions, it was possible to achieve acceptable values, albeit slightly higher than those obtained in the compositions solely with rice husk.

The compositions with reed fiber and rice husk that had the best thermal performance were compositions 18 and 19, which had the lowest densities and achieved values of

0.0602 and 0.0627 W/mK. These compositions had the least amount of reed fiber in the mixture. What differentiated these two compositions was the addition of 100 g of sodium silicate in composition 19, resulting in an increase of 8.8% in density and 4.0% in thermal conductivity compared with composition 18.

Next, compositions 12, 13, and 14 achieved the lowest thermal conductivity values, ranging from 0.0634 to 0.0681 W/mK. It was observed that by decreasing 50 g of rice husk and increasing 150 g of reed fiber compared with compositions 18 and 19, there was a significant increase in thermal conductivity in the range of 8.6% to 10.6% for the same amount of binder.

From the presented results, it is generally observed that an increase in the amount of reed fiber in the panels led to higher thermal conductivity. However, compositions 20 and 21 did not follow this expected trend. The thermal conductivity was higher than that of compositions 13 and 14, which had a greater amount of reed fiber in the mixture. The explanation for this atypical behavior may be related to factors other than the amount of reed fiber, such as the packing effect. It is possible that the distribution and structure of rice husk and reed fiber in compositions 20 and 21 contributed to creating more air pathways inside the samples, allowing for easy heat transfer through convection mode. This may have increased the thermal conductivity of the material, despite the lower amount of reed fiber compared with compositions 13 and 14.

When comparing composition 14 to composition 16, which differed by 100 g of reed fiber, while keeping the amount of rice husk and sodium silicate unchanged, an increase of 6.9% in density and 7.5% in thermal conductivity can be observed. Both the increase in the amount of reed fiber and thermal transfer by conduction should have influenced these results.

It is also important to compare the plates containing reed fiber with those composed solely of rice husk and sodium silicate. For example, compositions 2 and 3, which contained 400 g of rice husk, when compared with compositions 20 and 21, which contained 400 g of rice husk plus 100 g of reed fiber, showed an increase in thermal conductivity ranging from 7.1% to 8.7% by adding reed fiber to the mixture.

Another comparison can be made between compositions 5 and 6 with compositions 20 and 21, as they had very similar densities. Among these compositions, the influence of adding reeds to the mixture can be observed, where thermal conductivity increased by 5.2% to 7.5% while maintaining the same density.

3.2. Bending Strength

The results obtained from the bending strength test can be visualized in Tables 6 and 7, which present the average results of the five specimens for each composition regarding the maximum supported force (Fmax), bending strength (σf), and respective modulus of elasticity (E).

Table 6. Bending strength and modulus of elasticity for specimens with rice husk and sodium silicate.

Sample	Composition (g)		Fmax (N)	σ_f (MPa)	E (MPa)
	Rice Husk	Sodium Silicate			
1	400	350	27.50	0.17	16.40
2		400	33.50	0.23	47.50
3		500	33.67	0.24	45.70
4		600	35.67	0.25	32.94
5	450	400	34.83	0.23	26.29
6		500	33.25	0.28	42.36
7		600	40.25	0.29	45.05

Table 7. Bending strength and modulus of elasticity of specimens with rice husk, reed fiber, and sodium silicate.

Sample	Composition (g)			Fmax (N)	σ_f (MPa)	E (MPa)
	Rice Husk	Reed Fiber	Sodium Silicate			
8	200	300	400	17.50	0.12	19.45
9			500	21.33	0.13	23.69
10	250	250	400	19.00	0.13	20.56
11			500	25.25	0.16	27.62
12	300	200	350	16.83	0.12	16.45
13			400	19.33	0.13	28.67
14			500	25.83	0.17	36.45
15	300	300	400	22.75	0.15	21.15
16			500	32.33	0.22	31.59
17			600	34.17	0.25	29.86
18	350	50	400	18.25	0.12	20.46
19			500	19.00	0.13	26.50
20	400	100	400	28.50	0.18	17.25
21			500	32.75	0.22	31.54
22	-	800	400	16.33	0.11	14.66

It is observed that the specimens composed solely of rice husk and sodium silicate achieved the highest strength, with the maximum value obtained being 0.29 MPa for composition 7. Among all of the tested compositions, the lowest result was obtained by composition 22, composed solely of reed fiber and sodium silicate, with a value of 0.11 MPa, indicating that rice husk was more resistant under these conditions. These values are expected for natural materials, as similar results have been achieved in other studies, ranging from 0.08 to 0.26 MPa for reed [45] and 0.34 MPa for rice husk [46].

The results show that by adding 100 g of sodium silicate to a composition, without changing the other materials, there was a significant increase in bending strength, ranging from 3.4% to 31.8%.

The influence of reed fiber on the bending strength of the compositions was also observed. When comparing the different compositions, it can be noticed that the mixtures with reed fiber decreased the bending strength from 1.1 to 2.2 times compared with those without this material in their mixture with the same amount of sodium silicate.

In the samples tested in the bending strength test, the calculated modulus of elasticity ranged from 16.40 MPa to 47.50 MPa in compositions with rice husk and sodium silicate, and 16.45 MPa to 36.45 MPa in compositions containing rice husk, reed fiber, and sodium silicate. In the composition using only reed fiber and sodium silicate, the value of the modulus of elasticity was even lower, reaching a value of 14.66 MPa. With these results, it is possible to observe the influence of reed fiber on the stiffness of the material, as the compositions containing this material in the mixture showed lower values for the modulus of elasticity when compared with the compositions using only rice husk.

3.3. Water Absorption

The first cycle of the test, in which the specimens were maintained at a temperature of 20 °C and a relative humidity of 60%, lasted approximately 14 days. The second cycle, in which the specimens were exposed to a relative humidity of 95%, lasted 35 days until reaching a stable mass.

For this test, 10 compositions (Table 8) were selected, comprising 5 compositions of rice husk and sodium silicate, and 5 compositions containing reed fiber in their mixture. Table 8 also presents the obtained results for the average water absorption (W_m) calculated based on the recorded mass variation for each sample during the 35-day test.

Table 8. Water absorption of the selected specimens.

Sample	Composition (g)			Wm Media (%)
	Rice Husk	Reed Fiber	Sodium Silicate	
2 3 4	400	-	400 500 600	45.03 43.77 40.27
5 6	450	-	400 500	43.75 46.83
13 14	300	200	400 500	47.83 48.44
16 17	300	300	500 600	45.67 44.33
22	-	800	400	38.02

In the graph of Figure 9, composition 22 can be observed, which obtained the lowest water absorption value of 38.02%. On the other hand, the specimens that achieved the highest values of water absorption among the analyzed compositions were the specimens from compositions 14 with 48.44% and 13 with 47.83%. Composition 4, despite initially showing a higher water absorption, ended up having one of the lowest results at the end of the test.

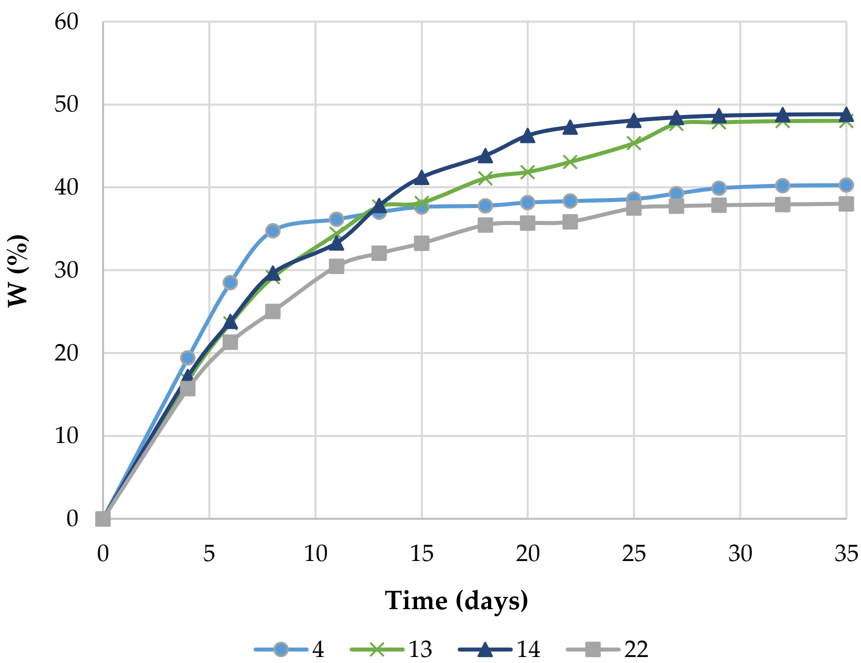

Figure 9. Water absorption of compositions 4, 13, 14, and 22.

As a result, it is evident that a higher amount of sodium silicate in the composition can accelerate the water absorption process. This can be attributed to the hygroscopic nature of sodium silicate. However, a faster increase in water absorption does not necessarily mean that the final absorption value will be higher. The compositions that achieved the highest water absorption at the end of the test were not necessarily the ones with the highest initial absorption.

The results indicate that the compositions with rice husk and sodium silicate exhibited higher water absorption values compared with the compositions with reed fiber. In the case of composition 22, composed solely of reed fiber and sodium silicate, the compositions with rice husk alone showed a 15% to 23% higher water absorption rate.

Although the water absorption results were high for all compositions, it was observed that the water absorption content of the reed fiber was relatively lower than that of rice husk. This difference may be attributed to variations in the physical structure and chemical composition of the materials. Both materials contain cellulose and lignin, but in different proportions, and depending on the quantity of these components, the material becomes more or less hydrophilic. Additionally, the physical structure of reed fiber is more compact and denser compared with rice husk. Reed fiber is composed of long, straight fibers, while rice husk contains many pores and gaps [35,47].

The acceptable water absorption content for thermal insulation materials can vary depending on the material type, project specifications, and service conditions. In general, plant-based materials tend to exhibit relatively higher water absorption compared with other insulation materials. This is because many of these materials are porous and possess a fibrous structure that can retain water. However, the water absorption content can vary significantly depending on the nature of the material, its compaction level, density, thickness, and other factors [48].

In another study, various samples containing reed fiber, straw, and sodium silicate were tested. With a relative humidity of 97%, the recorded water absorption for the samples with reed fiber and sodium silicate was approximately 33%, a value very close to the results obtained in this study [39].

In this test, the specimens were exposed to extreme humidity conditions, which are unlikely to be encountered in real-world applications [49]. Some plant-based materials can be treated with hydrophobic additives to reduce water absorption and enhance moisture resistance, especially when applied without any coating layer [50].

In addition to calculating the water absorption content, this test allowed for the visual analysis of degradation and susceptibility to the emergence of fungi and molds of the specimens exposed to a relative humidity of 95%.

In the specimens of composition 22, consisting solely of reed fiber and sodium silicate, dark spots began to appear scattered throughout the body of the specimen from the 7th day of the cycle at 95% relative humidity, indicating the presence of fungi in the material.

No visible fungal manifestations were observed in the other specimens composed of a mixture of reed fiber with rice husk or solely rice husk. Figure 10 shows the final appearance of the specimens of composition 22 after 35 days in a climatic chamber.

Figure 10. Proliferation of fungi on the surface of sample 22.

It is somewhat expected that some manifestation of biological attack would occur in the specimens when exposed to a relative humidity of 95%, mainly because they were composed of organic raw materials from a plant without any type of prior treatment. Building materials composed of organic raw materials are highly susceptible to the emergence of fungi, especially when exposed to high relative humidity or direct contact with water. This is because most fungi develop in warm and humid environments, as these conditions provide a favorable environment for the proliferation of their mycelia and the germination of their spores, which are structures that form a significant part of the fungal body [50].

The presence of fungi in reed cultivation is well-known and studied. There are various types of fungi that attack the plant, from the leaves to the roots, thus impeding its growth. Therefore, it is possible that the material was already contaminated at the time of harvesting. Reed is highly sensitive to biological attacks, allowing for the appearance of fungi on its surface [51], because of the nutrient content and hygroscopic nature of the plant, as well as being highly susceptible to fungal growth [50].

In Ansolin's study [51], a very similar manifestation of biological attack was observed, where some samples of reed bundles, 20% dried in an oven and 80% air dried, were subjected to a climatic chamber with a temperature of 22 °C and a relative humidity of 95%. After 7 days inside the chamber, fungi and molds were detected on the surface of all of the samples.

Although the samples containing rice husk did not show any visible signs of biological attack during this test, it cannot be concluded that the material would not exhibit any fungal manifestations in the long term. Therefore, fungicide treatment of the organic materials should be considered in further developments of these types of composites to prevent any future attacks that may affect the durability and quality of the material.

After analyzing the results of all of the tests, it can be observed that the compositions containing only rice husk performed better, except for water absorption. It should be considered that in a real-world application, the panels will unlikely be exposed to such aggressive humidity. Therefore, compositions 1, 2, and 5 can be considered as having the best thermal conductivity and mechanical strength results.

4. Conclusions

The present research aimed to investigate the use of agricultural waste, namely rice husk and reed fiber, as raw materials for thermal insulation plates in order to assess the feasibility and effectiveness of these composites.

Rice husk showed excellent results, outperforming reed fiber in all aspects, except for water absorption. The thermal conductivity values achieved ranged from 0.0613 to 0.0689 W/mK. The addition of 100 g sodium silicate to the rice husk mixtures resulted in an increase in thermal conductivity from 2.4% to 5.0%. Therefore, compositions 1, 2, and 5 can be considered as having the best overall performance in terms of thermal and mechanical properties.

Regarding the use of reed fiber in the composition of the plates, although positive results were achieved when the material was used in conjunction with rice husk, with thermal conductivity values ranging from 0.0602 to 0.0745 W/mK, it was observed that the addition of reed fiber to the mixtures increased the thermal conductivity of the compositions up to 12% compared with those made solely of rice husk and of a similar density.

Regarding the bending strength, the results indicate that compositions with rice husk and sodium silicate had a higher strength than mixtures containing reed fiber. It was observed that the addition of reed fiber to the mixtures led to a decrease in mechanical strength. Compositions made solely of rice husk and the same amount of sodium silicate as the reed fiber compositions exhibited values up to 2.2 times higher. Furthermore, the influence of sodium silicate on mechanical strength was noted, as compositions with an additional 100 g of this material showed an increase in bending strength ranging from 3.4% to 31.8%. Analyzing the results for the modulus of elasticity, there was also a tendency for compositions with reed fiber to have lower values, ranging from 16.45 MPa to 36.45 MPa, while compositions composed solely of rice husk and sodium silicate exhibited values between 16.40 MPa and 47.50 MPa.

Another important point to highlight regarding reed fiber was the occurrence of fungi when exposed to a very high relative humidity. This is a problem that should be further studied, namely through the use of pre-treatment using appropriate fungicidal products.

Rice husk proved to be more resistant to biological attack than reed fiber when exposed to the same conditions.

The use of these composite plates can significantly contribute to reducing the environmental impacts caused by the construction and agriculture industries. By utilizing locally available agricultural waste, it is also possible to address issues related to sustainable resource management and the mitigation of specific environmental problems. Therefore, this study stands out as an important contribution to the advancement of sustainable practices in the construction industry and paves the way for practical applications of these materials.

Author Contributions: Methodology, F.G. and A.B.; Investigation, A.S.; Writing—original draft, A.S.; Writing—review and editing, F.G. and A.B.; Supervision, F.G. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Fundação para a Ciência e a Tecnologia (FCT) through the support of CDRSP (Strategic Projects UIDB/04044/2020 and UIDP/04044/2020, and Associate Laboratory ARISE LA/P/0112/2020) and funded within the scope of the project ECO4fibers—*Materiais de isolamento térmico de base vegetal*—CENTRO-01-0145-FEDER-181262, co-financed by the Regional Operational Program of the Centre (CENTRO2020), under the Portugal 2020 Program, supported by the European Regional Development Fund (ERDF) of the European Union.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Asdrubali, F.; D'Alessandro, F.; Schiavoni, S. A review of unconventional sustainable building insulation materials. *Sustain. Mater. Technol.* **2015**, *4*, 1–17. [CrossRef]
2. Dikmen, N.; Ozkan, S.T.E. Unconventional Insulation Materials. In *Insulation Materials in Context of Sustainability*; IntechOpen: London, UK, 2016. [CrossRef]
3. Melo, A.B.; Barbosa, N.P.; Lima MR, F.; Silva, E.P. Desempenho estrutural de protótipo de alvenaria construída com blocos de terra crua estabilizada. *Ambiente Construído* **2011**, *11*, 111–124. [CrossRef]
4. Mendes, P.F.S. Isolamentos Térmicos em Edifícios e seu Contributo para a Eficiência Energética. Master's Dissertation, Universidade Fernando Pessoa, Porto, Portugal, 2012.
5. Mendonça, P. Habitar Sob Uma Segunda Pele: Estratégias para a Redução do Impacto Ambiental de Construções Solares Passivas em Climas Temperados. Ph.D. Thesis, Universidade do Minho, Braga, Portugal, 2005.
6. Navroski, M.C.; Lippert, D.B.; Camargo, L.; Pereira, M.O.; Haselein, C.R. Avaliação do Isolamento Térmico de Três Diferentes Materiais Usados na Construção e Preenchimento de Paredes Externas. *Rev. Ciência Madeira—RCM* **2010**, *1*, 41–51. [CrossRef]
7. Nunes, L.; Meireles, C.; Gomes, C.P.; Almeida Ribeiro, N. Impacts of Climate Change in Portugal: Common Perception of Causes and Consequences in Forest Development. *Res. Ecol.* **2019**, *1*, 45–51. [CrossRef]
8. Directive (EU) 2010/31 of the European Parliament and of the Council of 10 May 2010 on the Reduction of the Enerdy Performance of Buildings. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A02010L0031-20210101 (accessed on 28 May 2023).
9. Chavatal, K.M.S. Relação Entre o Nível de Isolamento Térmico da Envolvente Dos Edifícios e o Potencial de Sobreaquecimento no Verão. Ph.D. Thesis, Universidade do Porto, Porto, Portugal, 2007.
10. Gonçalves, H.; Graça, J.M. Conceitos Bioclimáticos para os Edifícios em Portugal. FEDER. 2004. Available online: https://repositorio.lneg.pt/bitstream/10400.9/1323/1/Conceitos_20Bioclim%C3%A1ticos.pdf (accessed on 28 May 2023).
11. Raimundo, A.M.; Saraiva, N.B.; Oliveira, A.V.M. Thermal insulation cost optimality of opaque constructive solutions of buildings under Portuguese temperate climate. *Build. Environ.* **2020**, *182*, 107107. [CrossRef]
12. Jelle, B.P. Traditional, state-of-the-art and future thermal building insulation materials and solutions—Properties, requirements, and possibilities. *Energy Build.* **2011**, *43*, 2549–2563. [CrossRef]
13. Pacheco-Torgal, F. Eco-efficient construction and building materials research under the EU Framework Programme Horizon 2020. *Constr. Build. Mater.* **2014**, *51*, 151–162. [CrossRef]
14. Zach, J.; Hroudová, J.; Brožovský, J.; Krejza, Z.; Gailius, A. Development of Thermal Insulating Materials on Natural Base for Thermal Insulation Systems. *Procedia Eng.* **2013**, *57*, 1288–1294. [CrossRef]
15. Gaspar, F.; Bakatovich, A.; Davydenko, N.; Joshi, A. Building insulation materials based on agricultural wastes. In *Bio-Based Materials and Biotechnologies for Eco-Efficient Construction*, 1st ed.; Woodhead Publishing: Southton, UK, 2020; pp. 149–170. [CrossRef]

16. FAO. Food and Agriculture Organization of the United Nations. 2023. Available online: https://www.fao.org/faostat/en/#data/QCL/visualize (accessed on 28 May 2023).
17. Brás, T.F.C. A Utilização da Casca de Arroz Como Carga em Pastas de Preenchimento para a Conservação e Restauro. Master's Dissertation, Instituto Politécnico de Tomar, Tomar, Portugal, 2020.
18. Kumar Das, S.; Adediran, A.; Rodrigue Kaze, C.; Mohammed Mustakim, S.; Leklou, N. Production, characteristics, and utilization of rice husk ash in alkali activated materials: An overview of fresh and hardened state properties. *Constr. Build. Mater.* **2022**, *345*, 128341. [CrossRef]
19. Walter, M.; Marchezan, E.; Avila, L.A. Rice: Composition and nutritional characteristics. *Ciência Rural* **2008**, *38*, 1184–1192. [CrossRef]
20. Yarbrough, D.W.; Wilkes, K.E.; Olivier, P.A.; Graves, R.S.; Vohra, A. Apparent Thermal Conductivity Data and Related Information for Rice Hulls and Crushed Pecan Shells. *Therm. Conduct.* **2005**, *27*, 222–230.
21. Rosa, L.C.; Santor, C.G.; Lovato, A.; da Rosa, C.S.; Güths, S. Use of rice husk and sunflower stalk as a substitute for glass wool in thermal insulation of solar collector. *J. Clean. Prod.* **2015**, *104*, 90–97. [CrossRef]
22. Rama, J.P.F. Eco-Painéis Construídos a Partir de Madeira e Resíduos de Palha/Casca de Arroz. Master's Dissertation, Universidade de Coimbra, Coimbra, Portugal, 2014.
23. Wang, S.; Li, H.; Zou, S.; Zhang, G. Experimental research on a feasible rice husk/geopolymer foam building insulation material. *Energy Build.* **2020**, *226*, 110358. [CrossRef]
24. Buratti, C.; Belloni, E.; Lascaro, E.; Merli, F.; Ricciardi, P. Rice husk panels for building applications: Thermal, acoustic and environmental characterization and comparison with other innovative recycled waste materials. *Constr. Build. Mater.* **2018**, *171*, 338–349. [CrossRef]
25. Muthuraj, R.; Lacoste, C.; Lacroix, P.; Bergeret, A. Sustainable thermal insulation biocomposites from rice husk, wheat husk, wood fibers and textile waste fibers: Elaboration and performances evaluation. *Ind. Crops Prod.* **2019**, *135*, 238–245. [CrossRef]
26. Aravind, N.; Sathyan, D.; Mini, K.M. Rice husk incorporated foam concrete wall panels as a thermal insulating material in buildings. *Indoor Built Environ.* **2020**, *29*, 721–729. [CrossRef]
27. Marques, B.; Almeida, J.; Tadeu, A.; António, J.; Santos, M.I.; de Brito, J.; Oliveira, M. Rice husk cement-based composites for acoustic barriers and thermal insulating layers. *J. Build. Eng.* **2021**, *39*, 102297. [CrossRef]
28. Fernandes, F.A.d.S.; Costa, D.d.S.d.O.; Martin, C.A.G.; Rossignolo, J.A. Vitreous Foam with Thermal Insulating Property Produced with the Addition of Waste Glass Powder and Rice Husk Ash. *Sustainability* **2023**, *15*, 796. [CrossRef]
29. Abbas, N.; Khalid, H.R.; Ban, G.; Kim, H.T.; Lee, H.K. Silica aerogel derived from rice husk: An aggregate replacer for lightweight and thermally insulating cement-based composites. *Constr. Build. Mater.* **2019**, *195*, 312–322. [CrossRef]
30. Ferrández-García, C.E.; Ferrández-Villena, M.; Ferrández-Cuartero, J.; Ortuño, T.G.; Ferrández-García, M.T.; Andreu-Rodríguez, J. Manufacture and Properties of Three-Layered Low Density Particleboard from Giant Reed. In Proceedings of the International Conference of Agricultural Engineering—CIGR-AgEng, Valencia, Spain, 8–12 July 2014.
31. Andreu-Rodriguez, J.; Medina, E.; Ferrández-Garcia, M.T.; Ferrández-Villena, M.; Ferrández-Garcia, C.E.; Paredes, C.; Bustamante, M.A.; Moreno-Caselles, J. Agricultural and Industrial Valorization of *Arundo donax* L. *Commun. Soil Sci. Plant Anal.* **2013**, *44*, 598–609. [CrossRef]
32. Baltrushevich, M. Thermal Insulation Materials Containing Reed Fiber Filler. Master's Dissertation, Instituto Politécnico de Leiria, Leiria, Portugal, 2020.
33. Benallel, A.; Tilioua, A.; Ettakni, M.; Ouakarrouch, M.; Garoum, M.; Ahmed Alaoui Hamdi, M. Design and thermophysical characterization of new thermal insulation panels based on cardboard waste and vegetable fibers. *Sustain. Energy Technol. Assess.* **2021**, *48*, 101639. [CrossRef]
34. Shon, C.-S.; Mukashev, T.; Lee, D.; Zhang, D.; Kim, J. Can Common Reed Fiber Become an Effective Construction Material? Physical, Mechanical, and Thermal Properties of Mortar Mixture Containing Common Reed Fiber. *Sustainability* **2019**, *11*, 903. [CrossRef]
35. Siddique, R. Rice Husk Ash. In *Waste Materials and By-Products in Concrete*, 1st ed.; Springer Science & Business Media: Berlin/Heidelberg, Germany, 2008; Volume 1.
36. Mejía, L.D. Using wholegrain rice to promote small and medium enterprises. *Agric. Food Eng. Technol.* **2006**, *55*, 128–138.
37. Decreto-Lei no 92/2019 da Presidência do Conselho de Ministros. Lista Nacional de Espécies Invasoras, Diário da República: I Série A, n° 130. 2019. Available online: https://dre.pt/dre/legislacao-consolidada/decreto-lei/2019-124568069 (accessed on 28 May 2023).
38. Bialosau, A. Composite Heat-Insulating Materials Based on Natural Raw Materials and Mineral Binders. Master's Dissertation, Instituto Politécnico de Leiria, Leiria, Portugal, 2017.
39. Bakatovich, A.; Gaspar, F.; Boltrushevich, N. Thermal insulation material based on reed and straw fibres bonded with sodium silicate and rosin. *Constr. Build. Mater.* **2022**, *352*, 129055. [CrossRef]
40. Sahiron, N.; Rahmat, N.; Hamzah, F. Characterization of sodium silicate derived from sugarcane bagasse ash. *Malays. J. Anal. Sci.* **2017**, *21*, 512–517. [CrossRef]
41. Abo-El-Enein, S.A.; Eissa, M.A.; Diafullah, A.A.; Rizk, M.A.; Mohamed, F.M. Removal of some heavy metals ions from wastewater by copolymer of iron and aluminum impregnated with active silica derived from rice husk ash. *J. Hazard. Mater.* **2009**, *172*, 574–579. [CrossRef] [PubMed]

42. *ISO 8301*; Thermal Insulation—Determination of Steady-State Thermal Resistance and Related Properties—Heat Flow Meter Apparatus. International Organization for Standardization: Geneva, Switzerland, 1991.
43. *EN 12089*; Thermal Insulating Products for Building Applications—Determination of Tensile Strength Perpendicular to Faces. European Committee for Standardization: Brussels, Belgium, 1999.
44. Incropera, F.P.; Bergman, T.L.; Dewitt, D.P. *Fundamentos de Transferência de Calor e de Massa*, 6th ed.; LTC: Rio de Janeiro, Brazil, 2011.
45. Bakatovich, A.; Gaspar, F. Composite material for thermal insulation based on moss raw material. *Constr. Build. Mater.* **2019**, *228*, 116699. [CrossRef]
46. Bakatovich, A.; Davydenko, N.; Gaspar, F. Thermal insulating plates produced on the basis of vegetable agricultural waste. *Energy Build.* **2018**, *180*, 72–82. [CrossRef]
47. Neto, C.P.; Seca, A.; Nunes, A.M.; Coimbra, M.A.; Domingues, F.; Evtuguin, D.; Silvestre, A.; Cavaleiro, J.A.S. Variations in chemical composition and structure of macromolecular components in different morphological regions and maturity stages of Arundo donax. *Ind. Crops Prod.* **1997**, *6*, 51–58. [CrossRef]
48. Kabir, M.M.; Wang, H.; Lau, K.T.; Cardona, F. Chemical treatments on plant-based natural fibre reinforced polymer composites: An overview. *Compos. B Eng.* **2012**, *43*, 2883–2892. [CrossRef]
49. Ansolin, A.P. Caracterização da Cana Arundo Donax L. e Avaliação do seu Potencial Como Material de Isolamento Térmico em Portugal. Master's Dissertation, Universidade do Minho, Braga, Portugal, 2021.
50. Vitanen, H.; Vinha, J.; Salminen, K.; Ojanen, T.; Peuhkuri, R.; Paajanen, L.; Lähdesmäki, K. Moisture and Bio-Deterioration Risk of Building Materials and Structures. *J. Build. Phys.* **2010**, *33*, 201–224. [CrossRef]
51. Lautkankare, R. Determination of Thermal Conductivity of Reed in TRC of Finland. In *Guidebook of Reed Business*; Tallinn University of Technology: Tallinn, Estonia, 2013; pp. 28–29.