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# Characterization and utilization of sawdust waste generated from advanced manufacture for its application as a thermal insulation in sustainable buildings using the blowing technique

Carlos Rojas-Herrera [a,c], Aner Martínez-Soto [b,*], Constanza Avendaño-Vera [d], Juan Pablo Cárdenas-R [c]

[a] *Universidad de La Frontera, Av. Francisco Salazar 01145, Temuco, Chile*
[b] *Departamento de Ingeniería de Obras Civiles, Universidad de La Frontera, Av. Francisco Salazar 01145, Temuco, Chile*
[c] *Facultad de Arquitectura, Construcción y Medio Ambiente, Universidad Autónoma de Chile, Av. Alemania 1090, Temuco, Chile*
[d] *Escuela Técnica Superior de Ingeniería de Edificación, Universitat Politècnica de València, Camí de Vera s/n, València, Spain*

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ABSTRACT

The construction industry is vital for economic development, but it accounts for 40% of energy consumption and 45% of global greenhouse gas emissions. In this context, research has focused on reducing energy demand in homes, particularly through the development of insulation materials. Sawdust is a byproduct available annually in Chile in quantities exceeding 4.5 million tons. Therefore, the objective of this study was to characterize the physical and thermal properties of this waste to evaluate its use as a thermal insulation material. Stability and thermal conductivity tests, as well as density and moisture content measurements, were conducted on the sawdust. Additionally, to assess the functionality of this thermal insulator, the material was applied using the blowing technique in partitions, followed by physical tests. The results indicate that the proposed insulation material has thermal stability up to 270 °C. The thermal conductivity was comparable to conventional mineral wool and fiberglass (0.042–0.048 [W/mK]). The density ranged from 123.77 to 198.15 [kg/m$^3$] depending on the filling time of the specimens but remained low compared to other organic materials. The moisture content was 11.31%, suitable for maintaining good thermal conductivity. This study concludes that sawdust is a viable alternative for thermal insulation, especially when applied through blowing. Its stability and thermal conductivity are comparable to conventional materials, while its thermal inertia is 200% higher than that of glass wool. Furthermore, the low moisture content suggests that there would be no proliferation of pathogens, making it a promising thermal insulator for sustainable construction development. Finally, it is mentioned that the material carbonizes within a limited time, leading to self-extinguishment of the flame.

## 1. Introduction

The construction industry plays an essential role in the economic development of any country [1] accounting for approximately 40% of energy consumption [2], 25% of waste generation [3] and 45% of global greenhouse gas emissions [4]. For this reason, various

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* Corresponding author.
*E-mail address:* aner.martinez@ufrontera.cl (A. Martínez-Soto).

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research approaches have been proposed in this industry aimed at reducing energy demand during the operational phase of buildings [5]. In this regard, it has been demonstrated that thermal insulation materials play a crucial role in reducing energy losses in building components, where thermal conductivity being one of the fundamental properties to achieve this goal [6,7]. This property primarily depends on material density, moisture content, application method, and chemical composition [8,9]. In the same context, there has been a suggestion that thermal inertia can lower the energy consumption of air conditioning in buildings, particularly for cooling needs. This positive outcome is attained by utilizing materials with high density and high specific heat [10].

Currently, the thermal insulation market is dominated by synthetic products and other materials that require significant energy and processing for their manufacturing [11]. An environmentally friendly low-impact alternative is thermal insulation biomaterials; however, these biologically sourced alternatives still account for less than 5% of the market share [12]. Thus, it remains a pending challenge to advance sustainable development in the construction industry. One readily available biological raw material for manufacturing thermal insulation materials comes from the wood industry's waste products [13].

In Chile, the timber industry generates approximately 4.5 million tons of waste annually, with production concentrated in the central-southern regions of the country, specifically between the Maule and La Araucanía regions [14]. Furthermore, with the growing adoption of modern construction techniques such as industrialization, modular construction, and digital fabrication, there is a foreseen rise in construction sector waste generation [15,16]. This can be attributed to the processing and cutting of wood boards to produce building components and elements. In this context, due to the presence of cellulose, hemicellulose, and lignin, the waste has found multiple applications and uses, such as energy generation [17], biopolymer development [18], pellets [19], thermal insulation biomaterials [20,21], among others.

In regard to advances in the development of thermal insulation materials from wood waste, Jamal Eldin et al., in 2022 developed a vitreous foam by combining zeolite-poor rock and sawdust using alkaline activation and reactive sintering techniques, achieving thermal conductivity results ranging from 0.058 to 0.178 [W/mK] for a density close to 300 [kg/m$^3$]. They notably increased the material's porosity by incorporating sawdust [22]. In the same vein, Schirtt et al., in 2021 used sawdust to reduce the density of a thermal insulation material made from fungi, controlling their colonization, and obtaining thermal conductivity values close to 0.052 [W/mK] at a density of 200 [kg/m$^3$], highlighting the contribution of wood waste [12]. Li & Huang in 2022 prepared a thermal insulation material from pine sawdust powder, which was cold pressed to obtain a homogeneous and solid mixture. The average thermal conductivity value obtained was 0.062 [W/mK], and the contribution of the internal pores generated between the sawdust particles is highlighted. These interstitial spaces create air gaps, directly improving its thermal insulation capacity [20,23]. In this context, the blowing method emerges as a good alternative for applying material inside walls or construction elements, maintaining homogeneity and increasing the internal porosity of the materials [9]. In previous work, processed (crushed) wheat straw was blown into wood panels, achieving an average thermal conductivity value of 0.034 [W/mK] at a density close to 80 [kg/m$^3$], maximizing the amount of trapped air between the material particles [24].

This process of search and development of solutions to enhance energy efficiency and reduce resource consumption has led to the investigation and development of thermal insulation materials with energy storage capabilities. These materials not only act as barriers to prevent heat transfer but also can retain and release thermal energy in a controlled manner [25]. One of the key technologies in this field is phase change materials (PCM), which can absorb and release large amounts of energy during fusion or solidification processes [26]. Additionally, composite materials combining thermal insulation properties with heat storage capabilities are gaining attention in various applications, from building construction to manufacturing industries [27]. This convergence between thermal insulation and energy storage not only promises to enhance energy efficiency but also to provide more sustainable and resilient solutions to the challenges of climate change and resource scarcity. In this context, wood waste has various applications in thermal insulation and energy storage, as it can be converted into insulation panels, used in composite materials to provide thermal and heat storage properties, or transformed into biomass pellets for heating [19,28].

However, the thermal insulation market still lacks a biomass-based material that is easy to prepare and offers high thermal performance [20]. Furthermore, there is no evidence in the literature of the use of wood waste applied through mechanical techniques without the use of additives or materials that optimize its thermal performance (such as binders, phase change materials, or organics). For this reason, the objective of this study was to characterize the sawdust both physically and thermally from the cutting of structural plywood sheets to evaluate its use as a thermal insulation material in walls. It is worth noting that the application of the material in the test prototypes was done using the blowing technique, analyzing the contribution this technique makes compared to traditional methods of application for lignocellulosic materials. This work aligns with and contributes to Sustainable Development Goal (SDG) 13 set forth by the United Nations General Assembly.

## 2. Materials and methods

### 2.1. Materials

The material analyzed in this research is a byproduct stored in two hoppers, which is generated from cutting structural plywood sheets on a computer numerical control (CNC) router machine. It's worth mentioning that the sheets were being cut to produce wall and floor modules for a modular housing project based on the wikihouse system, and at the time of collecting the material, it was in the facilities of the Sustainable Construction 4.0 Laboratory at the University of La Frontera.

### 2.2. Waste generation

To estimate the generation of waste, it was considered the cutting path of the CNC over 6 structural plywood sheets, specifically 4 sheets for the construction of a floor unit and 2 sheets for a wall unit. We measured the linear meters that the router would travel on each sheet, then collected the waste and weighed it. This way, we related the linear distance in meters to the mass in kilograms, so the ’waste production yield’ will be expressed in kg/m. In this case, the data presented in this study are from a CNC router with dimensions of 1.3 × 2.5 [m] (X, Y axis travel). The CNC has an operating range of 100–400 Hz, and the spindle speed ranges from 6000 to 24,000 revolutions per minute.

### 2.3. Material application and sample preparation

The blowing tests were conducted using a MINIFANT M99 machine, which has a hopper with a capacity of 200 L. Its maximum blowing capacity is 440 [$m^3/h$], and it has a power of 3.6 [kW]. The machine features a control panel that allows you to turn on the machine, control the two levels of blowing power, and adjust the percentage of blowing power.

The test specimens used for applying the material using the blowing technique were made of pine wood with a plywood cover. These specimens had a central hole through which the nozzle of the hose was inserted to blow the material. The dimensions of the test specimen were 60 × 42 × 9 cm, simulating the void created by two studs and two headers of a full-scale wood wall.

### 2.4. Physical characterization

#### 2.4.1. Thermal stability

The thermal stability of the waste was determined using thermogravimetric analysis (TGA), and the instrument used was the Perkin Elmer STA 6000 model. This equipment operates in a temperature range from 15 °C to 1000 °C with a heating rate of 0.1–100 °C/min, while nitrogen gas ($N_2$) was adjusted to 40 ml/min. The sample mass was 20.388 [mg], and the temperature program used was as follows: heating from 25 °C to 120 °C at a rate of 50 °C/min, held at 120 °C for 3 min, then heated from 120 °C to 950 °C at a rate of 100 °C/min. Cooling from 950 °C to 450 °C at a rate of 100 °C/min, followed by a gas switch to oxygen at a flow rate of 40 ml/min, and then heating from 450 °C to 800 °C at 100 °C/min. Finally, a constant temperature of 800 °C was maintained for 3 min.

#### 2.4.2. Moisture

To determine the moisture content of the waste, the BOECO BMA H50 moisture analyzer was used. This device operates with a halogen light heating module and has a reading accuracy of 0.001%. In this study, 3 measurements were taken for independent samples with masses of 1.0, 1.2, and 1.4 g.

#### 2.4.3. Thermal conductivity

The thermal conductivity of each sample was determined using the transient line source method with the KD2Pro device manufactured by Decagon Devices. The KD2Pro is a handheld device used to measure thermal properties and consists of a handheld controller and sensors that can be inserted into the medium to be measured. This equipment measures at 1-s intervals during a 90-s heating and cooling cycle. The KD2 complies with the specifications of IEEE 442–1981 and ASTM D5334 standards [29,30]. To determine the conductivity of the sample, measurements were taken at 4 different points on each sample (4 samples analyzed) to obtain an average with its standard deviation. Additionally, each sample had the same volume but different mass.

#### 2.4.4. Density

The density was determined manually by relating the volume of the test specimens (as described earlier) to the mass of material that was blown into each of the four repetitions performed. It is important to note that the mass was expressed in kilograms, while the volume was expressed in cubic meters, so the density results are expressed in $kg/m^3$.

#### 2.4.5. Thermal inertia

The thermal inertia of the material was calculated using the online tool Ubakus. The Ubakus tool is based on calculation procedures established in DIN 4108 and DIN EN ISO 6946 standards to assess the thermal behaviors of building systems. DIN 4108 sets requirements for thermal and energy protection in buildings, while DIN EN ISO 6946 provides guidelines for evaluating thermal resistance and thermal conductivity of building components. Additionally, Ubakus incorporates infinite element methods to calculate the thermal resistance and thermal transmittance of building components. By integrating the principles and descriptions of both standards, Ubakus offers a robust and reliable tool for assessing and improving the thermal performance of building systems [31]. This tool has been previously used in the literature, either to calculate thermal properties [32] or to compute and analyze the thermal transmittance in facades with different construction alternatives [33]. In Ubakus for the calculation of thermal capacity, the temperature profile within the structure is calculated for two different internal temperatures that differ by 1 °C, each for the static case ($t \rightarrow \infty$). Using these two curves, the average temperature change, dT, is calculated for each individual layer, and from this, the amount of heat deposited in the layer is calculated using Equation (1).

$$dQ = dT \bullet density \bullet specific\ heat\ capacity \bullet thickness \tag{1}$$

The properties used to determine the influence of material properties on the thermal inertia of the building element were time lag, decrement factor, thermal capacity of inner layers, and heat storage capacity of the entire component. To do this, a simulation of the temperature profile within the construction component was carried out over 24 h (plus a transient period of 72 h) at 10-min intervals. For this simulation, an external air temperature that periodically fluctuates sinusoidally between 15 and 35 °C is assumed. The result of the simulation is the temporal temperature profile on the internal and external surfaces of the building component.

The time lag is the temporal delay of the temperature wave, which is the time in hours between the maximum temperature on the external and internal surfaces.

The decrement factor is the ratio between the amplitude of the temperature profile on the external and internal surfaces, describing how much the temperature varies between the two surfaces of the building component.

In the calculation of the heat storage capacity of the inner layers, only the change in room air temperature is considered, determining how much heat the component absorbs when the internal temperature increases by 1 °C while the external temperature remains constant. The building element used to assess the influence of the developed material on thermal inertia is a component of the Skylark 250 system, a block wall-M version 0.1 (Fig. 1).

Two cases were conducted for comparison. The first case considers the core of the element insulated with a conventional material, glass wool. In the second case, the same thickness is considered with the material developed based on sawdust. The properties of the materials used for these analyses are listed in Table 1, including values obtained from Ubakus and measurements conducted in the laboratory.

*2.4.5.1. Fire behavior.* To determine the fire behavior of the waste, a drip analysis adapted from the UNE 23-725-90 standard was conducted [34]. The sawdust sample was placed in a container, following the procedure below: a direct flame was applied to the center of the sample (contained in the container) for a period of 3 s, using a portable torch that reaches a temperature of 1200 °C. The flame was then removed to measure the ignition time and subsequent extinguishment. The procedure extended for a total time of 2 min, and all ignition and extinguishment times were recorded [9].

## 3. Results and discussion

### 3.1. Waste generation

Fig. 2 shows the drawing or path that the CNC followed when cutting the plywood sheets to generate the floor and wall modules mentioned earlier. The total travel distance for the machine for these cuts was 185.58 [m] in an approximate time of 40 min per sheet. The generated waste amounted to 15.51 [kg], resulting in an average waste generation rate of 0.084 [kg/m], or equivalently, 83.57 g for every meter of linear cutting.

Table 2 represents the construction of a small prototype house with an area of 15 [$m^2$]. It indicates the quantity of blocks required for its construction, the sawdust production for each of the modules, and the total amount of waste generated by each element.

In total, approximately 204 kg of sawdust are generated. This mass could be insufflated into any of the building elements of a house, but based on the forthcoming results, it may be suggested that the material be applied to the building's roof. This is primarily because a much smaller surface area needs to be covered (compared to the walls), at just over 6.6 [$m^2$], which represents 38% of the roof surface. However, the main reason is to maximize the energy storage potential and this analysis is only for reference if the residual sawdust were to be used in the same building.

### 3.2. Material application and sample preparation

Fig. 3 shows the material applied to a test specimen. This successful application was done with the following configuration: 40% blowing power, which is equivalent to 176 [$m^3/h$], an opening at its first level, and the hopper movement at maximum revolutions capacity. Experimental tests determined that under these criteria, the material can be blown properly, preventing hose and nozzle clogging.

This application allows the thermal insulation material to cover the entire empty space, achieving a minimum density and maximizing internal porosity. It is worth noting that the channels of the sawdust pores, which are aligned unidirectionally, delay the time it takes for heat to flow from one end to the other, contributing to the improvement of the thermal performance of the element [35,36]. Furthermore, by using this method, the need for binders or additives that would increase the material's environmental burden is avoided, reducing the environmental impact of buildings [20,37].

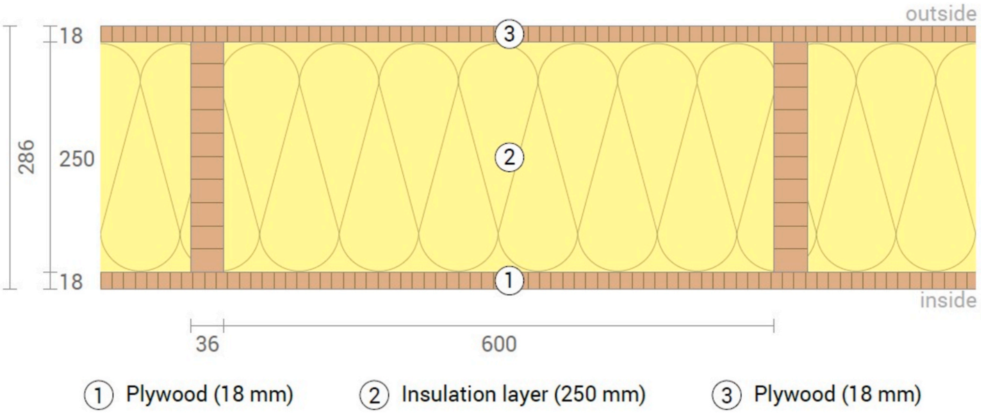

**Fig. 1.** Detail of building element.

**Table 1**

Properties of materials for thermal inertia calculation.

| Material | Thermal conductivity [W/mK] | Density [kg/m$^3$] | Specific heat [J/kgK] |
|---|---|---|---|
| Plywood | 0.17[a] | 490.6[a] | 1,600[a] |
| Glass wool | 0.04[a] | 15[a] | 830[a] |
| Sawdust | 0,048[b] | 124[b] | 1,822[b] |

[a] Values extracted from Ubakus.

[b] Values measured in the laboratory.

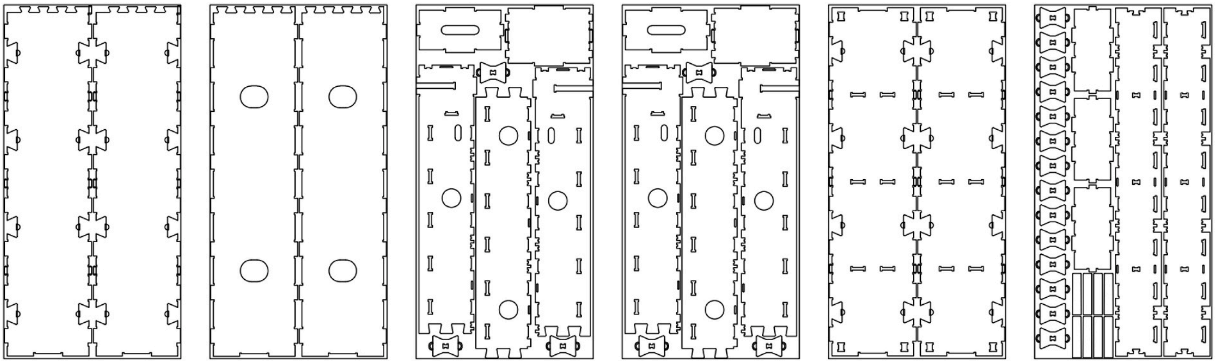

**Fig. 2.** CNC cutting path, first 4 sheets for the floor and last 2 sheets for the wall.

**Table 2**

Waste generation per construction element for a small home.

| Element | Quantity | Sawdust [kg/block] | Sawdust [kg] |
|---|---|---|---|
| Floor | 6 | 12.29 | 73.72 |
| Wall | 17 | 3.30 | 56.15 |
| Roof | 6 | 12.29 | 73.72 |
| | | **Total** | 203.58 |

**Fig. 3.** Material applied to a test specimen.

### 3.3. Physical characterization

### 3.3.1. Thermal stability

Fig. 4 shows the result of the test, where the analysis of the data reveals a mass loss between 33 °C and 197 °C, which corresponds to 10.73% of the initial mass and is associated with the evaporation of water in the sample. These data are similar to the results associated with the degradation of zeolite and sawdust vitreous foam, which experienced a mass loss of 7% up to 190 °C [22]. Subsequently, a larger loss was observed, ranging from 238 °C to 477 °C, corresponding to 72.76%, which is associated with the loss of volatile solids related to wood such as cellulose, hemicellulose, and lignin. This result is more promising than those obtained for Chinese fir sawdust, which releases these components at temperatures of 200 °C–375 °C [38]. Once the maximum temperature is reached, the environment is switched to oxygen, allowing the identification of a 19.04% mass loss, corresponding to fixed carbon.

According to this analysis, the waste is stable up to 270 °C, suggesting that the processing temperature of the waste should be below this value to prevent thermal degradation of the material. In this context, it is indicated that the blowing application process does not raise the temperature of the material, so there is no material degradation during application.

### 3.3.2. Moisture

The measurement of moisture content in the samples yielded an average result of 11.31 ± 0.09%. This means that the samples have a low moisture content, which favors the material's ability to maintain good thermal conductivity, as moisture content directly affects this property [39]. This behavior can be explained by the fact that wood and its byproducts have a greater ability to distribute moisture uniformly and in a more advantageous manner compared to mineral wool insulation [40]. The results suggest that there would be no proliferation of pathogens in the material if it were installed in homes in Chile. According to the analyses conducted by Soto M., et al., 2023, where cellulose fiber was evaluated in combination with wheat straw, there is no proliferation of fungi or region-specific pathogens within this moisture range [9].

Expanded polystyrene and polyurethane, thanks to their water-repelling properties, only increase their thermal conductivity by 38% and 70% (respectively) when saturated with water. However, for mineral wools, the scenario is highly unfavorable, as conductivity increases from 0.041 to 0.9 [W/mK] [8,41]. In general, materials with open porosity, which is favorable for reducing the energy passage time, are unfavorable in terms of energy performance because the thermal conductivity of the material will increase. Therefore, researchers have proposed methods to predict the physical properties of materials based on the region and climate in which they will be used, allowing them to anticipate the performance and energy demand of buildings [42]. In this context, the movement of moisture in materials can be driven by vapor pressure gradients, gravity forces, and capillary action. However, in closed-cell insulation, vapor flow is likely dominant instead of gravitational or capillary forces. Therefore, the high moisture levels observed in service could be caused by vapor diffusion [43].

### 3.3.3. Thermal conductivity

Fig. 5 shows a measurement of thermal conductivity in the sample insufflated within one of the test specimens. (a) is refers to the KD2Pro measurement device, and (b) denotes the sample being measured for thermal conductivity.

The results of the measurements are shown in Table 3, where it can be observed that the highest (average) thermal conductivity

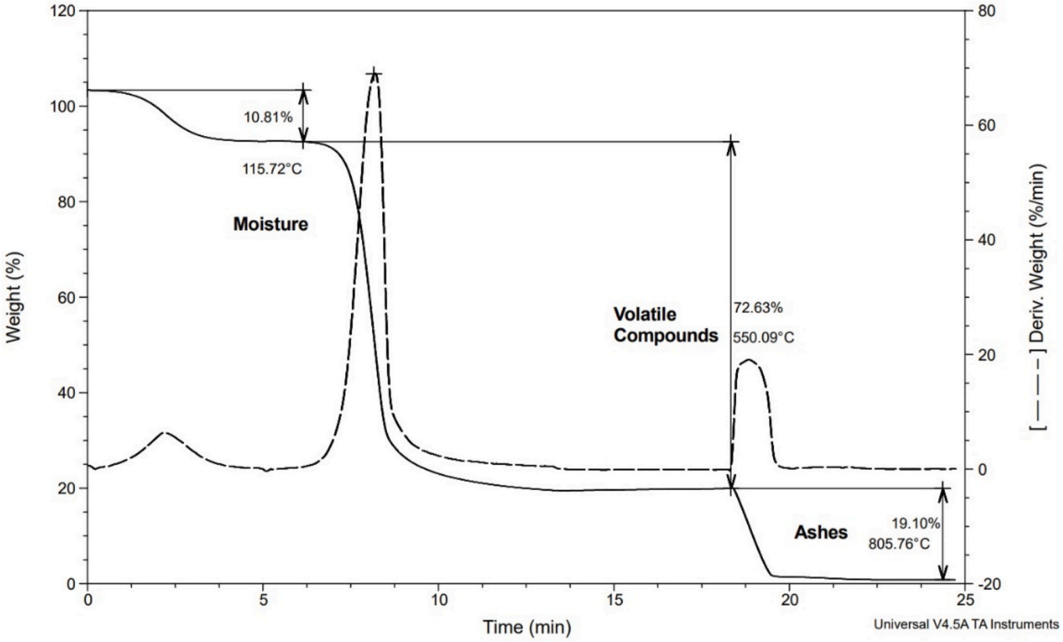

**Fig. 4.** Results of the thermal stability test.

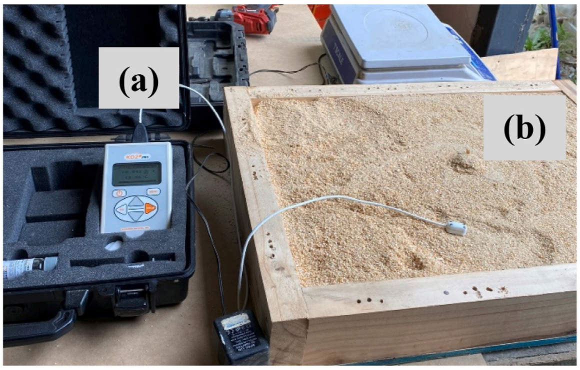

**Fig. 5.** Measurement of thermal conductivity.

among the 4 test specimens was 0.048 ± 0.001 [W/mK], while the lowest (average) value was 0.042 ± 0.001 [W/mK]. Considering the average result of the measurements, it can be indicated that, for the global market, the waste, without any treatment or additives, exhibits a thermal property like mineral wool and fiberglass, which have thermal conductivity values of 0.045 [W/mK] [44,45]. The most favorable result of the waste is equal to the thermal conductivity of expanded polystyrene with a density of 15 [kg/m$^3$], while the least favorable result is only 16% higher [46,47].

Zine et al., 2023, developed a material from wood sawdust in block form, using epoxy as a binder. This material has a thermal conductivity of 0.078 [W/mK] at a density of 350 [kg/m$^3$] [37]. Both results are significantly higher than the values obtained in this study, which is grounded in the fact that the blowing method does not require a binder material, allowing for a reduction in both density and thermal conductivity of the material. It is important to note that the energy performance of buildings is directly related to the properties mentioned above, but energy storage should not be neglected, since thermal inertia allows to reduce energy consumption for heating, but also for cooling. To take advantage of the positive effects of thermal inertia and reduce cooling demand, materials with high density and high specific heat should be used [48]. Even so, other factors must be considered, such as climatic conditions, temperature requirements, density and the arrangement of materials in building systems, since thermal inertia has only been approached from a theoretical perspective; there are no empirical demonstrations that provide results in a real environment [49,50]. In addition, energy storage must be aligned to the thermal conductivity and density of the material, as this property is directly related to and influenced by solar radiation and outside air temperature [51].

These results are interesting since wood and plywood sheets have an average thermal conductivity of 0.12 [W/mK] [52]. This decrease in thermal conductivity compared to the base conductivity is attributed to the porosity that was generated when the material was placed in bulk, as the air content is the key to better thermal insulation materials. Specifically, air can account for up to 66% of the thermal properties of materials [53].

### *3.3.4. Density*

Table 4 provides a summary of the density results, showing that the lowest value corresponds to sample 1, which had a filling time of 55 s and a density of 123.77 [kg/m$^3$], while the highest-density specimen took 79 s to fill, resulting in a density of 198.15 [kg/m$^3$]. These values are much higher than traditional synthetic materials on the market, such as fiberglass, expanded polystyrene, and polyurethane, which typically fall in the range of 10–47 [kg/m$^3$] [54,55]. However, the density is similar to other materials made from organic and cellulose-rich materials, such as wheat waste, recycled paper cellulose, and vegetable residues, which can reach densities around 100 [kg/m$^3$] [56,57].

The correlation coefficient for thermal conductivity is 0.9737, while for density, it is 0.9293. Fig. 6 graphically displays the thermal conductivity results of the samples and their relationship with density. It can be observed that higher density corresponds to higher thermal conductivity, meaning that thermal conductivity is directly proportional to density. This behavior is also observed in other types of lignocellulosic fibers that have been characterized for the development of thermal insulation materials in buildings [58]. This relationship is typical for other fibers like hemp, flax, bagasse, among others, where it is important to ensure that the density is sufficient to apply the material in the structure without affecting thermal performance [59].

**Table 3**
Results of thermal conductivity measurements.

| Thermal conductivity [W/mK] | | | | |
|---|---|---|---|---|
| Measurement | Sample 1 | Sample 2 | Sample 3 | Sample 4 |
| **1** | 0.041 | 0.045 | 0.045 | 0.047 |
| **2** | 0.043 | 0.045 | 0.051 | 0.048 |
| **3** | 0.043 | 0.043 | 0.045 | 0.049 |
| **Average** | 0.042 | 0.044 | 0.047 | 0.048 |
| **SD** | 0.001 | 0.001 | 0.003 | 0.001 |

**Table 4**
Results of density measurements.

| | Unit | Sample 1 | Sample 2 | Sample 3 | Sample 4 |
|---|---|---|---|---|---|
| Weight | kg | 2.807 | 2.929 | 2.828 | 3.210 |
| Volume | $m^3$ | 0.0227 | 0.0227 | 0.0162 | 0.0162 |
| **Density** | **[$Kg/m^3$]** | 123.77 | 129.14 | 174.57 | 198.15 |

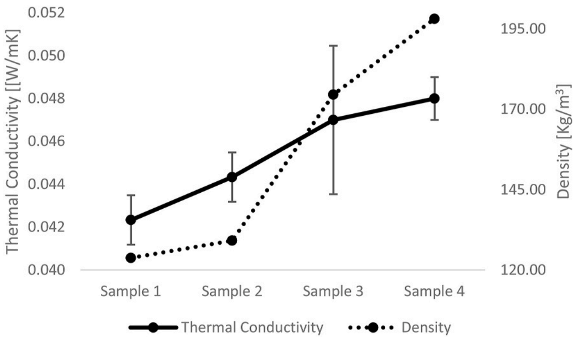

**Fig. 6.** Relationship between density and thermal conductivity.

### 3.3.5. Thermal inertia

Table 5 shows the findings from the thermal inertia analysis, indicating that the sawdust material used in the test samples possesses an energy storage capacity of 93 [$kJ/m^2K$]. This means, when incorporated into a building component, this material exhibits over twice the energy storage capacity compared to the use of glass wool.

These results are positive for a thermal insulation material, as its high thermal inertia contributes to improve the energy performance of buildings, especially during the summer [60]. This property of the material is attributed to its high density, which can be up to 10 times greater than the thermal insulation materials available in the market. Considering all the physical properties of materials is crucial in thermal simulations since their impact on indoor thermal comfort conditions (up to a 7 °C variability) is relevant for the design of air renovations, glazed surfaces, and orientation [61]. Fig. 7 shows the surface temperatures of the building element in two different scenarios: glass wool (a) and sawdust (b). Significantly, when the thermal insulation material is changed, there is a pronounced increase in the delay of the temperature wave, going from 6.7 h to 14.5 h, which provides greater thermal storage capacity, reduces energy consumption, and enhances thermal comfort, contributing to higher energy efficiency in buildings, even in warm climates where the risk of overheating is high [62,63]. Fig. 8 shows the temperature profiles of the building element in the same scenarios, with glass wool (a) and sawdust (b). Here, it can clearly discern a substantial reduction in the amplitude of temperature fluctuations when sawdust is employed. This reduction is highly advantageous as it helps mitigate the impact of external temperature peaks on buildings. This positive energy enhancement in residential structures is not commonly achieved when using conventional materials like glass wool, primarily because they tend to maintain a closer alignment between indoor and outdoor temperatures. This is because synthetic materials, despite having low thermal conductivity, also exhibit low density, which reduces their energy storage capacity.

Another method to increase the thermal capacity of a construction element has involved integrating phase change materials, resulting in improvements in thermal performance [64]. In the current market, there is a wide variety of products available for use in construction solutions for projects, and researchers continue to work on developing new materials that can further optimize the imbalance between energy supply and demand [26]. In this scenario, many studies focusing on bolstering thermal capacity accomplish this by introducing extra layers to the building component [65]. However, in this investigation, the inclusion of an extra layer was avoided, as the utilization of the same thermal insulating material was found to be sufficient in optimizing the building's thermal efficiency, thanks to its low thermal conductivity and high thermal storage.

**Table 5**
Summary of thermal inertia results.

| Property | Unit | Wall M Glass wool | Wall M Sawdust |
|---|---|---|---|
| U Value | $W/m^2K$ | 0.17 | 0.20 |
| Time lag | h | 6.70 | 14.50 |
| Decrement factor | – | 7.20 | 30.40 |
| Heat storage capacity (whole component) | $kJ/m^2K$ | 42.00 | 93.00 |
| Thermal capacity of inner layers | $kJ/m^2K$ | 21.00 | 47.00 |

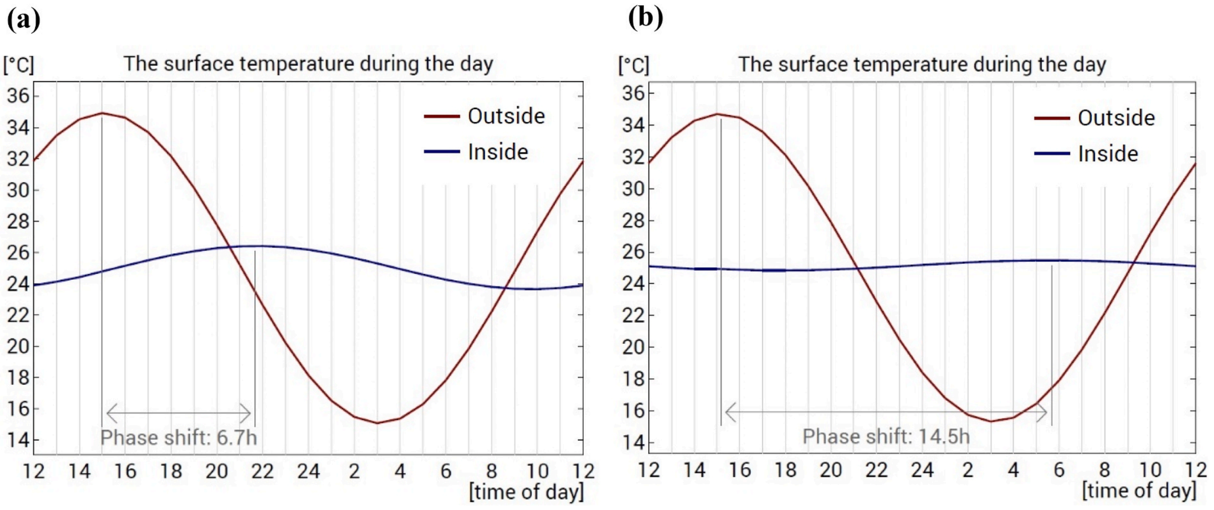

**Fig. 7.** Surface temperature glass wool (a) and sawdust (b) during the day.

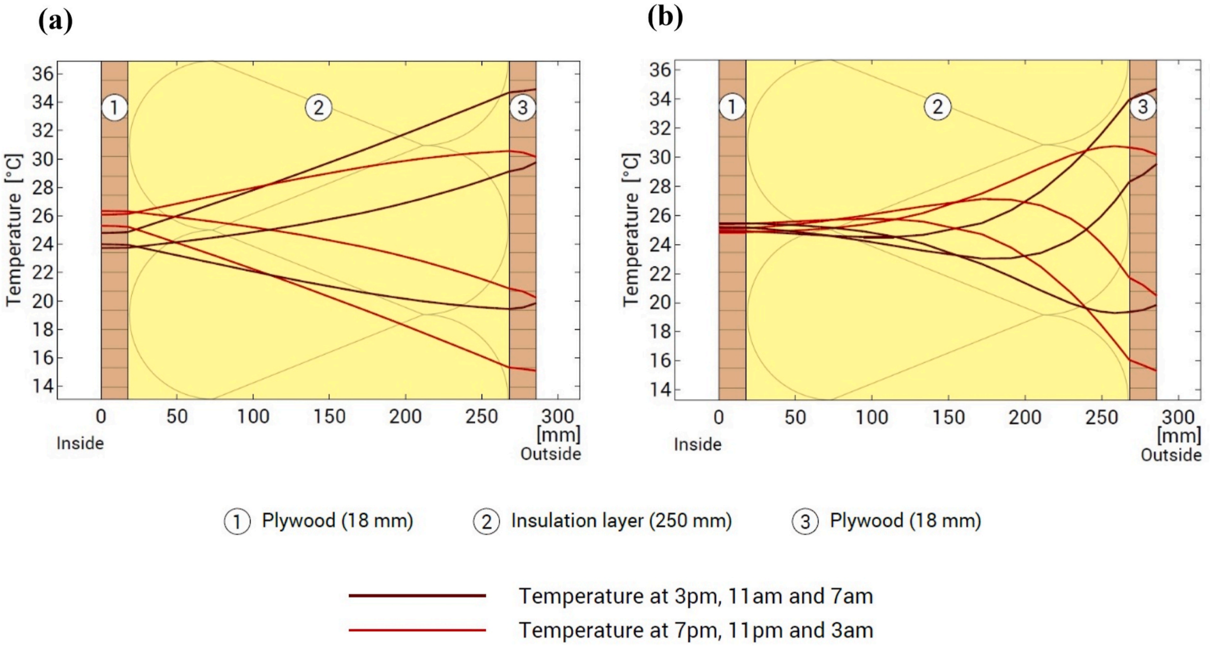

**Fig. 8.** Profiles temperature glass wool (a) and sawdust (b) during the day.

### 3.3.6. *Fire behavior*

Fig. 9 shows the flame extinction time (fixed ignition in 3 s), for a total of 13 applications, reaching a total test time of 126 s. The average of all the extinguishing times is 7 s, but if it is considered from application 7, when the material begins to carbonize, a much lower average extinguishing time is obtained, close to 3 s. It is worth mentioning that, at some points, the extinguishing time was slightly longer, but this is attributed to the fact that the perimeter material had not been in contact with the flame. So far, effective safety strategies for flame retardant materials in fires are primarily divided into passive and active fire protection. Passive fire protection mainly refers to the use of fire retardants to reduce the flammability and spread of flames from combustible materials. Compared to traditional passive fire protection, an active fire safety strategy could potentially provide greater fire safety for thermal insulation aerogels without compromising their flame-retardant property. For example, fire-resistant garments have flame retardancy, achieving a self-extinguishing time of 1.5 s after exposure to fire for 10 s [66].

Fig. 10 shows the state of the material after the seventh flame application, when the surface material is already carbonized, generating much lower extinction times with respect to the beginning of the test. The behavior of the material is like those reported by other authors, since in the first stage its moisture is released, and then the decomposition of cellulose and hemicellulose begins and

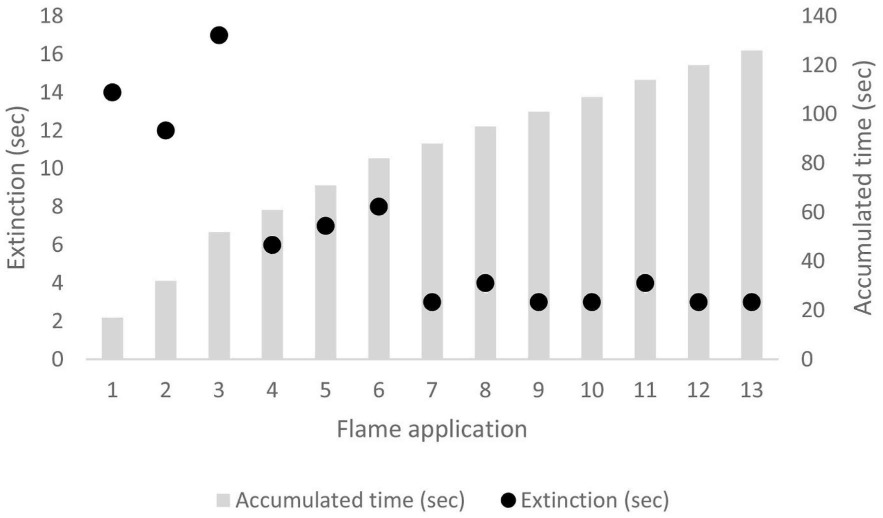

**Fig. 9.** Extinction times and accumulated test times.

**Fig. 10.** Carbonization of the material.

finally the carbonization is visualized, which gives way to the self-extinguishing of the flame [9,67]. It is important to note that noxious gases are released in the combustion process, since the sawdust comes from boards that use traditional adhesives in their manufacturing stage. In this context, its behavior is like conventional materials, whose origin is synthetic [68], although this has been justified by mentioning that the coating layer of the construction elements is the one that supports the direct flame, and the fire resistance time is determined by this same layer.

## 4. Conclusions

Insulating materials are crucial for minimizing energy losses in buildings. Thermal conductivity and thermal inertia are highly significant properties for achieving this objective. Therefore, various authors, to reuse waste, have advanced in the characterization of fibers, prototyping, and conducting experimental measurements. Several of these studies have considered the preparation of thermal insulation materials using sawdust or wood waste. However, all of them have involved the creation of blocks that used binders in their manufacturing stage, increasing the density and reducing the internal porosity of the material, thereby raising its thermal conductivity.

In this work, the material characterized after releasing its moisture is thermally stable up to 270 °C; therefore, its processing, for such applications, should not exceed this value. The average moisture content was 11.31%, which is crucial, as a material with high moisture content must be air-dried or oven-dried; otherwise, its thermal properties will be altered, leading to a reduction in its thermal insulation capacity. The thermal conductivity of the material was 0.045 [W/mK] for the least favorable sample. In this regard, the application through the blowing technique stands out, allowing the material to be applied uniformly in all the spaces of the samples, maintaining the internal pores, which favors thermal performance. Additionally, the density is like that of other lignocellulosic materials, and its variation with respect to density is low. In the worst case, when the density approaches 200 [kg/m$^3$], the thermal conductivity reaches 0.050 [W/mK]. However, this high density is advantageous for energy retention, as the thermal inertia of the material is significantly higher than that of glass wool. The developed material is very promising since most thermal insulation materials typically have low thermal conductivities due to their low density, which often translates to a limited energy storage capacity. In this regard, the storage capacity of the material compared to glass wool is 121% higher. In this study, the material was applied in prototypes simulating the cavity of a wall, but it could also be applied in ventilated roofs and floors. It is observed that the waste analyzed in this document exhibits good fire behavior, considering that the flame extinction time for the material after the carbonization stage is, on average, 3 s. Finally, considering the results of thermal conductivity and density from this study, to achieve a thermal resistance of 1 [$m^2K/W$], the material should be applied with a thickness of 4.5 cm, requiring a mass of 5.5 [kg] for that space. In other words, with the cutting of 70 linear meters of sheet, that space could be covered.

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## CRediT authorship contribution statement

**Carlos Rojas-Herrera:** Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **Aner Martínez-Soto:** Writing – review & editing, Validation. **Constanza Avendaño-Vera:** Writing – original draft, Methodology. **Juan Pablo Cárdenas-R:** Supervision, Resources, Writing – review & editing.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

No data was used for the research described in the article.

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## References

[1] A.N. Meshref, El.A.F.A. Elkasaby, A. Abdel Kader Mohamed Farid, Reducing construction waste in the construction life cycle of industrial projects during design phase by using system dynamics, J. Build. Eng. 69 (2023) 106302, https://doi.org/10.1016/J.JOBE.2023.106302.

[2] J.M. Mathews, B. Vivek, M. Charde, Thermal insulation panels for buildings using recycled cardboard: experimental characterization and optimum selection, Energy Build. 281 (2023) 112747, https://doi.org/10.1016/J.ENBUILD.2022.112747.

[3] Z. Bao, Developing circularity of construction waste for a sustainable built environment in emerging economies: new insights from China, Dev. Built. Environ 13 (2023) 100107, https://doi.org/10.1016/J.DIBE.2022.100107.

[4] M. Fattahi, E. Taban, P. Soltani, U. Berardi, A. Khavanin, V. Zaroushani, Waste corn husk fibers for sound absorption and thermal insulation applications: a step towards sustainable buildings, J. Build. Eng. 77 (2023) 107468, https://doi.org/10.1016/J.JOBE.2023.107468.

[5] G. Romero Quidel, M.J. Soto Acuña, C.J. Rojas Herrera, K. Rodríguez Neira, J.P. Cárdenas-Ramírez, Assessment of modular construction system made with low environmental impact construction materials for achieving sustainable housing projects, Sustainability 15 (2023), https://doi.org/10.3390/su15108386.

[6] J. Mu, S. Yu, S. Hao, Quantitative evaluation of thermal conductivity of earth materials with different particle size distributions, Renew. Sustain. Energy Rev. 184 (2023) 113574, https://doi.org/10.1016/J.RSER.2023.113574.

[7] V. Annibaldi, F. Cucchiella, M. Rotilio, Economic and environmental assessment of thermal insulation. A case study in the Italian context, Case Stud. Constr. Mater. 15 (2021) e00682, https://doi.org/10.1016/J.CSCM.2021.E00682.

[8] W. Pei, F. Ming, M. Zhang, X. Wan, A thermal conductivity model for insulation materials considering the effect of moisture in cold regions, Cold Reg. Sci. Technol. 207 (2023) 103770, https://doi.org/10.1016/J.COLDREGIONS.2022.103770.

[9] M. Soto, C. Rojas, J.P. Cárdenas-Ramírez, Characterization of a thermal insulating material based on a wheat straw and recycled paper cellulose to Be applied in buildings by blowing method, Sustainability 15 (2023), https://doi.org/10.3390/su15010058.

[10] S.C. Ng, K.S. Low, N.H. Tioh, Newspaper sandwiched aerated lightweight concrete wall panels—thermal inertia, transient thermal behavior and surface temperature prediction, Energy Build. 43 (2011) 1636–1645, https://doi.org/10.1016/J.ENBUILD.2011.03.007.

[11] C. Rojas, K. Rodriguez, J.P. Cárdenas-R, Evaluation of two Chilean native macroalgae: "Pelillo" (Gracilaria chilensis) and "Lamilla" (Ulva sp.) for thermal insulation application, Buildings 13 (2023), https://doi.org/10.3390/buildings13102622.

[12] H. Schritt, S. Vidi, D. Pleissner, Spent mushroom substrate and sawdust to produce mycelium-based thermal insulation composites, J. Clean. Prod. 313 (2021) 127910, https://doi.org/10.1016/J.JCLEPRO.2021.127910.

[13] I. Cetiner, A.D. Shea, Wood waste as an alternative thermal insulation for buildings, Energy Build. 168 (2018) 374–384, https://doi.org/10.1016/J.ENBUILD.2018.03.019.

[14] Y. Casas-Ledón, M. Flores, R. Jiménez, F. Ronsse, J. Dewulf, L.E. Arteaga-Pérez, On the environmental and economic issues associated with the forestry residues-to-heat and electricity route in Chile: sawdust gasification as a case study, Energy 170 (2019) 763–776, https://doi.org/10.1016/J.ENERGY.2018.12.132.

[15] K. Zhang, Y. Qing, Q. Umer, F. Asmi, How construction and demolition waste management has addressed sustainable development goals: exploring academic and industrial trends, J. Environ. Manag. 345 (2023) 118823, https://doi.org/10.1016/J.JENVMAN.2023.118823.

[16] O.D. Atoyebi, T.F. Awolusi, I.E.E. Davies, Artificial neural network evaluation of cement-bonded particle board produced from red iron wood (Lophira alata) sawdust and palm kernel shell residues, Case Stud. Constr. Mater. 9 (2018) e00185, https://doi.org/10.1016/J.CSCM.2018.E00185.

[17] A. Al-Kassir, J. Gañán-Gómez, A.A. Mohamad, E.M. Cuerda-Correa, A study of energy production from cork residues: sawdust, sandpaper dust and triturated wood, Energy 35 (2010) 382–386, https://doi.org/10.1016/J.ENERGY.2009.10.005.

[18] J.E. Roldán-San Antonio, E. Martín-Hernández, R. Briones, M. Martín, Process design and scale-up study for the production of polyol-based biopolymers from sawdust, Sustain. Prod. Consum. 27 (2021) 462–470, https://doi.org/10.1016/J.SPC.2021.01.015.

[19] M. Ståhl, J. Berghel, Energy efficient pilot-scale production of wood fuel pellets made from a raw material mix including sawdust and rapeseed cake, Biomass Bioenergy 35 (2011) 4849–4854, https://doi.org/10.1016/J.BIOMBIOE.2011.10.003.

[20] D. Li, C. Huang, Thermal insulation performances of carbonized sawdust packed bed for energy saving in buildings, Energy Build. 254 (2022) 111625, https://doi.org/10.1016/J.ENBUILD.2021.111625.

[21] S. Zou, H. Li, S. Wang, R. Jiang, J. Zou, X. Zhang, L. Liu, G. Zhang, Experimental research on an innovative sawdust biomass-based insulation material for buildings, J. Clean. Prod. 260 (2020) 121029, https://doi.org/10.1016/J.JCLEPRO.2020.121029.

[22] J.E.F.M. Ibrahim, M. Tihtih, E. Kurovics, L.A. Gömze, I. Kocserha, Innovative glass-ceramic foams prepared by alkali activation and reactive sintering of clay containing zeolite (zeolite-poor rock) and sawdust for thermal insulation, J. Build. Eng. 59 (2022) 105160, https://doi.org/10.1016/J.JOBE.2022.105160.

[23] N. Zhangabay, A. Tagybayev, A. Utelbayeva, S. Buganova, A. Tolganbayev, G. Tulesheva, A. Jumabayev, A. Kolesnikov, M. Kambarov, K. Imanaliyev, P. Kozlov, Analysis of the influence of thermal insulation material on the thermal resistance of new facade structures with horizontal air channels, Case Stud. Constr. Mater. 18 (2023) e02026, https://doi.org/10.1016/J.CSCM.2023.E02026.

[24] C. Rojas, K. Rodriguez, J.P. Cárdenas-R, Valorization of wheat crop waste in Araucanía, Chile: blowing technique and geographical analysis, Buildings 13 (2023), https://doi.org/10.3390/buildings13051152.

[25] W. Villasmil, L.J. Fischer, J. Worlitschek, A review and evaluation of thermal insulation materials and methods for thermal energy storage systems, Renew. Sustain. Energy Rev. 103 (2019) 71–84, https://doi.org/10.1016/J.RSER.2018.12.040.

[26] S. Liu, H. Wu, Y. Du, X. Lu, J. Qu, Shape-stable composite phase change materials encapsulated by bio-based balsa wood for thermal energy storage, Sol. Energy Mater. Sol. Cell. 230 (2021) 111187, https://doi.org/10.1016/J.SOLMAT.2021.111187.

[27] H. Yang, Y. Wang, Q. Yu, G. Cao, X. Sun, R. Yang, Q. Zhang, F. Liu, X. Di, J. Li, C. Wang, G. Li, Low-cost, three-dimension, high thermal conductivity, carbonized wood-based composite phase change materials for thermal energy storage, Energy 159 (2018) 929–936, https://doi.org/10.1016/J.ENERGY.2018.06.207.

[28] H. Yang, W. Chao, X. Di, Z. Yang, T. Yang, Q. Yu, F. Liu, J. Li, G. Li, C. Wang, Multifunctional wood based composite phase change materials for magnetic-thermal and solar-thermal energy conversion and storage, Energy Convers. Manag. 200 (2019) 112029, https://doi.org/10.1016/J.ENCONMAN.2019.112029.

[29] D5334 - 00, Standard Test Method for Determination of Thermal Conductivity of Soil and Soft Rock by Thermal Needle Probe Procedure, ASTM International (n.d.). https://doi.org/10.1520/D5334-00..

[30] doi: 10. 1109/IEEESTD. 1980. 8684505 "IEEE guide for soil thermal resistivity measurements,", 30 Nov, in: IEEE Std 442-1981, IEEE, 1980, pp. 1–16, 442-981, (n.d.).

[31] R. Plag, UBAKUS (2024). Https://Www.Ubakus.de/u-Wert-UBAKUSRechner/.

[32] F.M. Amoruso, M.H. Sonn, T. Schuetze, Carbon-neutral building renovation potential with passive house-certified components: applications for an exemplary apartment building in the Republic of Korea, Build. Environ. 215 (2022) 108986, https://doi.org/10.1016/J.BUILDENV.2022.108986.

[33] S. Habibi, O. Pons Valladares, D. Peña, New sustainability assessment model for Intelligent Façade Layers when applied to refurbish school buildings skins, Sustain. Energy Technol. Assessments 42 (2020) 100839, https://doi.org/10.1016/J.SETA.2020.100839.

[34] Asociación Española de Normalización y Certificación, UNE 23-725-90: Ensayos de reacción al fuego de los materiales de construcción. Ensayo de goteo aplicable a los materiales fusibles, Ensayo complementario, 1990, p. 725.

[35] J.N. de Oliveira Júnior, F.P.D. Lopes, N.T. Simonassi, H.A.C. Lopera, S.N. Monteiro, C.M.F. Vieira, Ecofriendly panels for building with eucalyptus sawdust and vegetal polyurethane resin: a mechanical evaluation, Case Stud. Constr. Mater. 18 (2023) e01839, https://doi.org/10.1016/J.CSCM.2023.E01839.

[36] V. R, K. Prabhakaran, Porous eco-ceramics of low thermal conductivity and high EMI shielding effectiveness from sawdust and sucrose by paste molding, Ceram. Int. 47 (2021) 34595–34610, https://doi.org/10.1016/J.CERAMINT.2021.08.374.

[37] O. Zine, D. Taoukil, I. El Abbassi, N. Laaroussi, E.-H. Kadri, M. lhassane Lahlaouti, A. El bouardi, Experimental and theoretical thermal investigation of bio-composite panels based on sawdust particles, J. Build. Eng. 76 (2023) 107251, https://doi.org/10.1016/J.JOBE.2023.107251.

[38] S. Zou, H. Li, L. Liu, S. Wang, X. Zhang, G. Zhang, Research on improving comprehensive properties of a new sawdust composite insulation material by torrefaction, Process Saf. Environ. Protect. 152 (2021) 361–374, https://doi.org/10.1016/J.PSEP.2021.06.015.

[39] M. EL Assaad, T. Colinart, T. Lecompte, Thermal conductivity assessment of moist building insulation material using a Heat Flow Meter apparatus, Build. Environ. 234 (2023) 110184, https://doi.org/10.1016/J.BUILDENV.2023.110184.

[40] I. Mehrez, H. Hachem, A. Jemni, Thermal insulation potential of wood-cereal straws/plaster composite, Case Stud. Constr. Mater. 17 (2022) e01353, https://doi.org/10.1016/J.CSCM.2022.E01353.

[41] F. Ming, M. Zhang, W. Pei, L. Chen, Correction of the thermal conductivity of polyurethane insulation material under freeze-thaw and water absorption conditions and its application, Cold Reg. Sci. Technol. 211 (2023) 103859, https://doi.org/10.1016/J.COLDREGIONS.2023.103859.

[42] W. Pei, F. Ming, M. Zhang, X. Wan, A thermal conductivity model for insulation materials considering the effect of moisture in cold regions, Cold Reg. Sci. Technol. 207 (2023) 103770, https://doi.org/10.1016/J.COLDREGIONS.2022.103770.

[43] F. Tariku, Y. Shang, S. Molleti, Thermal performance of flat roof insulation materials: a review of temperature, moisture and aging effects, J. Build. Eng. 76 (2023) 107142, https://doi.org/10.1016/J.JOBE.2023.107142.

[44] Y. Yin, Y. Song, W. Chen, Y. Yan, X. Wang, J. Hu, B. Zhao, S. Ren, Thermal environment analysis of enclosed dome with double-layered PTFE fabric roof integrated with aerogel-glass wool insulation mats: on-site test and numerical simulation, Energy Build. 254 (2022) 111621, https://doi.org/10.1016/J.ENBUILD.2021.111621.

[45] J. Yoo, S.J. Chang, S. Yang, S. Wi, Y.U. Kim, S. Kim, Performance of the hygrothermal behavior of the CLT wall using different types of insulation; XPS, PF board and glass wool, Case Stud. Therm. Eng. 24 (2021) 100846, https://doi.org/10.1016/J.CSITE.2021.100846.

[46] D.P.P. Meddage, A. Chadee, M.T.R. Jayasinghe, U. Rathnayake, Exploring the applicability of expanded polystyrene (EPS) based concrete panels as roof slab insulation in the tropics, Case Stud. Constr. Mater. 17 (2022) e01361, https://doi.org/10.1016/J.CSCM.2022.E01361.

[47] B.R. Vinod, H.J. Surendra, R. Shobha, Lightweight concrete blocks produced using expanded polystyrene and foaming agent, Mater. Today Proc. 52 (2022) 1666–1670, https://doi.org/10.1016/J.MATPR.2021.10.503.

[48] S.C. Ng, K.S. Low, N.H. Tioh, Newspaper sandwiched aerated lightweight concrete wall panels—thermal inertia, transient thermal behavior and surface temperature prediction, Energy Build. 43 (2011) 1636–1645, https://doi.org/10.1016/J.ENBUILD.2011.03.007.

[49] J. Karlsson, L. Wadsö, M. Öberg, A conceptual model that simulates the influence of thermal inertia in building structures, Energy Build. 60 (2013) 146–151, https://doi.org/10.1016/J.ENBUILD.2013.01.017.

[50] G.M. Soret, P. Vacca, J. Tignard, J.P. Hidalgo, C. Maluk, M. Aitchison, J.L. Torero, Thermal inertia as an integrative parameter for building performance, J. Build. Eng. 33 (2021) 101623, https://doi.org/10.1016/J.JOBE.2020.101623.

[51] Y. Han, Z. Zhou, W. Li, J. Feng, C. Wang, Exploring building component thermal storage performance for optimizing indoor thermal environment – a case study in Beijing, Energy Build. 304 (2024) 113834, https://doi.org/10.1016/J.ENBUILD.2023.113834.

[52] Q. Qiu, Thermal conductivity assessment of wood using micro computed tomography based finite element analysis (μCT-based FEA), NDT E Int. 139 (2023) 102921, https://doi.org/10.1016/J.NDTEINT.2023.102921.

[53] S.S. Shrestha, J. Tiwari, A. Rai, D.E. Hun, D. Howard, A.O. Desjarlais, M. Francoeur, T. Feng, Solid and gas thermal conductivity models improvement and validation in various porous insulation materials, Int. J. Therm. Sci. 187 (2023) 108164, https://doi.org/10.1016/J.IJTHERMALSCI.2023.108164.

[54] A. Bala, S. Gupta, V. Matsagar, Influence of glass wool fiber reinforcement and heat resistant coating on behavior of self-compacting mortar at elevated temperatures, Construct. Build. Mater. 392 (2023) 131876, https://doi.org/10.1016/J.CONBUILDMAT.2023.131876.

[55] C.A. Calles-Arriaga, J. López-Hernández, M. Hernández-Ordoñez, R.A. Echavarría-Solís, V.M. Ovando-Medina, Thermal characterization of microwave assisted foaming of expandable polystyrene, Ing. Invest. Tecnol. 17 (2016) 15–21, https://doi.org/10.1016/J.RIIT.2016.01.002.

[56] C. Rojas, M. Cea, F. Rosas-Díaz, J.P. Cárdenas-R, Physical , chemical and mechanical characterization of a prototype insulating material based on eucalyptus bark fiber, IEEE Lat. Am. Trans. 16 (2018), https://doi.org/10.1109/tla.2018.8789566.

[57] M. Soto, M. Vera, K. Parra, C. Rojas, J.P. Cárdenas, Potential of the residual fibers of pisum Sativum (PS), for use in a development of a thermal insulator material, IOP Conf. Ser. Earth Environ. Sci. 503 (2020), https://doi.org/10.1088/1755-1315/503/1/012084.

[58] C. Rojas, M. Cea, A. Iriarte, G. Valdés, R. Navia, J.P. Cárdenas-r, Thermal insulation materials based on agricultural residual wheat straw and corn husk biomass , for application in sustainable buildings, Sustain. Mater. Technol. 17 (2019) e00102, https://doi.org/10.1016/j.susmat.2019.e00102.

[59] J.A. Trobiani Di Canto, W.J. Malfait, J. Wernery, Turning waste into insulation – a new sustainable thermal insulation board based on wheat bran and banana peels, Build. Environ. (2023) 110740, https://doi.org/10.1016/J.BUILDENV.2023.110740.

[60] C. Avendaño-Vera, A. Martinez-Soto, V. Marincioni, Determination of optimal thermal inertia of building materials for housing in different Chilean climate zones, Renew. Sustain. Energy Rev. 131 (2020) 110031, https://doi.org/10.1016/J.RSER.2020.110031.

[61] E. Mehdi El Khattabi, M. Zouini, O. Jamil Mohammed, A thermal simulation method based on the thermal resistance/inertia coupling, Therm. Sci. Eng. Prog. 41 (2023) 101835, https://doi.org/10.1016/J.TSEP.2023.101835.

[62] M.K. Nematchoua, J.C.V. Noelson, I. Saadi, H. Kenfack, A.Z.F.R. Andrianaharinjaka, D.F. Ngoumdoum, J.B. Sela, S. Reiter, Application of phase change materials, thermal insulation, and external shading for thermal comfort improvement and cooling energy demand reduction in an office building under different coastal tropical climates, Sol. Energy 207 (2020) 458–470, https://doi.org/10.1016/J.SOLENER.2020.06.110.

[63] J. Kośny, J. Thakkar, T. Kamidollayev, M.J. Sobkowicz, J.P. Trelles, C. Schmid, S. Phan, S. Annavajjala, P. Horwath, Dynamic thermal performance analysis of PCM products used for energy efficiency and internal climate control in buildings, Buildings 13 (2023), https://doi.org/10.3390/buildings13061516.

[64] F. Kuznik, J. Virgone, J. Noel, Optimization of a phase change material wallboard for building use, Appl. Therm. Eng. 28 (2008) 1291–1298, https://doi.org/10.1016/J.APPLTHERMALENG.2007.10.012.

[65] Y. Chihab, M. Garoum, N. Laaroussi, Dynamic thermal performance of multilayer hollow clay walls filled with insulation materials: toward energy saving in hot climates, Energy Built. Environ. 5 (2024) 70–80, https://doi.org/10.1016/J.ENBENV.2022.08.001.

[66] Z. Yu, Y. Wan, Y. Qin, Q. jiang, J.P. Guan, X.W. Cheng, X. Wang, S. Ouyang, X. Qu, Z. Zhu, J. Wang, H. He, High fire safety thermal protective composite aerogel with efficient thermal insulation and reversible fire warning performance for firefighting clothing, Chem. Eng. J. 477 (2023) 147187, https://doi.org/10.1016/J.CEJ.2023.147187.

[67] M. Palumbo, J. Formosa, A.M. Lacasta, Thermal degradation and fire behaviour of thermal insulation materials based on food crop by-products, Construct. Build. Mater. 79 (2015) 34–39, https://doi.org/10.1016/J.CONBUILDMAT.2015.01.028.

[68] K. Sałasińska, M. Leszczyńska, M. Celiński, P. Kozikowski, K. Kowiorski, L. Lipińska, Burning behaviour of rigid polyurethane foams with histidine and modified graphene oxide, Materials 14 (2021) 1–23, https://doi.org/10.3390/ma14051184.