ELABORATION OF THERMAL INSULATION COMPOSITES BASED ON PAPER WASTE AND BIO-SOURCED MATERIAL

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Received September 28, 2023

It is well-known that energy consumption is increasing around the world on a daily basis. In the construction sector, a highly effective solution for reducing energy consumption involves exploring both modern and traditional buildings designed to adapt to climate changes. One promising approach is to use paper waste and bio-sourced materials as the basis for insulation. The purpose of this study was to improve the sustainability of buildings by using recycled waste materials that have a positive impact on the environment, people, and the economy. A novel insulating material composed of recycled paper waste and *Ampelodesmos mauritanicus* leaves and fibers was developed and used in non-load-bearing elements. The paper waste was transformed into pulp and mixed with the bio-sourced materials to create a composite material that exhibits excellent insulation properties. The resulting material is lightweight, durable, and cost-effective. Furthermore, different mechanical and thermal analyses were performed on specimens with varying dosage ratios. The results showed that the developed material has good thermal insulation, with a value of 0.027 W/m.K.

Keywords: thermal insulation, waste paper, thermal conductivity, *Ampelodesmos* leaves and fiber, composite

INTRODUCTION

In recent years, climate change has led to an unprecedentedly rapid rise in temperatures, largely due to human activities that increase heat-trapping greenhouse gas levels in the Earth's atmosphere, resulting in global warming.[1,2] This issue has become an increasing focus of concern for the international community. Furthermore, the demand for global energy has become a major challenge for most countries.[3-5] Consequently, there is an urgent need to take serious measures to reduce greenhouse gas emissions and develop environmentally friendly buildings.[6-8]

Controlling the thermal environment of buildings is crucial for ensuring optimal thermal comfort, which can be achieved by managing physical parameters, such as temperature, humidity, and air speed. Designing an architecture that is adapted to the local environment can help to achieve good control of the thermal conditions. Additionally, choosing construction materials judiciously or using active measures that reduce energy consumption can further enhance the thermal comfort, while reducing energy usage.[9-12] These measures play a significant role in ensuring that the thermal environment of buildings is well-maintained, providing a comfortable living or working space, while minimizing the energy consumed. However, insulation levels and placements on interior and exterior surfaces enhance thermal performance in residential spaces with various functions.[13-15]

Extensive studies have been conducted related to the assessment of thermal properties on the walls of traditional and modern buildings.[16-20] One of the most common parameters that are responsible for conducting heat is thermal conductivity. Researchers and engineers worldwide aspire to improve the quality of buildings with high thermal insulation by reducing the thermal conductivity of materials.

Dede *et al*. have used various growing media dependent on municipal agricultural organic waste and rice hull, with different mixture ratios, in green wall systems to assess their effectiveness on the thermal insulation of buildings.[21] The concern over urban waste in general, and paper waste, in particular, has sparked numerous initiatives aimed at reducing their presence in the environment. One notable effort was the research conducted by Jensen and Alfieri, who focused on valorizing paper waste in its various categories, including office paper, newspapers, cardboard, and dyed cardboard.[22] Their findings concluded that the designed and manufactured panels possess the necessary characteristics to replace conventional insulating materials or gypsum plasterboard-type enclosures.[22] This expands the range of materials suitable for this purpose by introducing a new option based on recycled raw materials, cost-effective manufacturing, and minimal energy resources. On the other hand, Benallel *et al*. developed an insulating material using recycled cardboard reinforced with various plant fibers. They demonstrated the significance of the quantity of plant fibers in enhancing the thermal characteristics of materials, along with their economic advantages.[23]

In Algeria, the annual production of household waste is about 13.5 million tons/year, with an average of 0.8 kg/inhabitant/d. in 2020.[24] Indeed, out of approximately 3.5 million tons of recyclable household waste, only 7% are exploited by Algerian sectors of recovery, including paper, cardboard, plastic and some metals.[24] Packaging waste, especially paper and cardboard, represents a significant fraction of managed solid waste (MSW) – with 12%.[25] However, during the last five years, Algeria has made progress in terms of recycling. Several companies engage in the recycling of paper, plastic and some metals, but this remains insufficient. The amount of waste paper and cardboard recovered did not exceed 100000 tons in 2020. According to MATE's projection made in 2012, by 2023, 50% of paper and cardboard waste was expected to be recovered, approximately 450000 tons, but unfortunately, this target has not been met.[26]

The purpose of this study was to prepare a thermal insulation material, intended to enhance the energy efficiency of buildings, using recycled waste materials that may impact the environment, people, and the economy. Furthermore, reducing thermal conductivity, while maintaining light weight, high strength, and low cost was considered as the main objective for conducting this work.

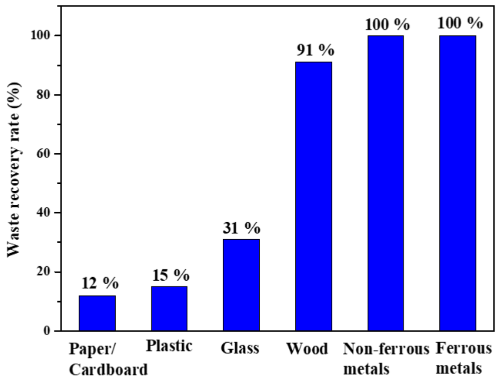

Figure 1: Manager solid waste recovery rate by material in 2019/2021 according to National Waste Agency[25]

EXPERIMENTAL

This work consisted of elaborating a composite insulating material containing waste (used as matrix) and bio-sourced materials (used as reinforcement). The composite was developed in three steps. Firstly, specimens were prepared with different ratios of the matrix and the reinforcement. Next, tests were established to verify the mechanical characteristics of the final product. Finally, thermal conductivity tests were established using appropriate equipment.

Paper preparation

The collection of used office paper was carried out from the source to guarantee its hygienic characteristics. Subsequently, the paper was cut into small pieces to facilitate mixing. Afterwards, a quantity of water was added to the chopped paper, without submerging to make it wet. Finally, the wet chopped paper was put into a chopper machine to obtain homogeneous powder, as shown in Figure 2 (a-c).

Preparation of Diss straw

Ampelodesmos mauritanicus (Diss grass) is found in forests and stands, boasting a full stem that can reach up to 2 m in height. The leaves are large, highly fibrous, linear, and tapering to a point.[27] This plant has been used for an extended period for handicraft applications and for the production of eco-friendly materials based on earth.

(a) (b) (c)

Figure 2: Steps of paper preparation – (a) cut paper, (b) paper with water in a mixer machine, and (c) minced paper

(a) (b) (c) (d)

Figure 3: Steps for preparing straw and Diss fiber – (a) Diss leaves, (b) Diss straw (raw Diss), (c) Diss immersed in NaOH and (d) Diss fiber

The Diss leaves (Fig. 3 (a)) were manually cut to 250 mm in length and thoroughly washed with water to eliminate dust. Subsequently, they were dried in the oven at 60 °C for 24 hours to ensure constant humidity content. From this step, the dried leaves were referred to as Diss straw (Fig. 3 (b)).

Preparation of Diss fiber

First, the Diss straw, cut to 40 mm length, was subjected to low concentration alkali treatment with 1%, 2% and 3% NaOH, for 30 minutes at room temperature. Then, the fibers were washed with running and distilled water. Subsequently, they were dried in an oven at 60 °C for 24 hours (Fig. 3 (c)).

Secondly, the fibers obtained from the first treatment were soaked in a solution containing 20% NaOH at the temperature of 160 °C for 45 minutes. The choice of the duration of the preparation was related to the type of vegetable fibers and the rate of delignification. The fibers were then removed from the oven, washed with distilled water at a temperature of T = 20 ± 3 °C to subject them to a thermal shock. Finally, the fibers were dried in the oven at 60 °C for 24 hours.

Diss fiber has a tensile strength of about 100 MPa, a density of 850 kg/m^3 and a spinose structure, which can offer strong adhesion to different mixtures. The modulus of elasticity of Diss fibers is 2.17 GPa. The constituents of Diss fibers are cellulose (44.1%), hemicelluloses (27%), lignin (16.80%), extractives (9%), and ashes (3.1%).

Preparation of specimens

In this work, the matrix was defined as paper, which was used in dosages of 60% or more. The reinforcement was provided by the Diss straw and fiber, with a dosage less than or equal to 40%. In addition, white glue was considered as a binder. Its quantity depended on the composition of the matrix and the reinforcement. In our case, the quantity of glue used was approximately 10% to 15% of the volume of the dry substance.

The preparation of specimens proceeded in five main steps for different types of composites. Firstly, the weight of materials involved was measured according to the chosen dosage. Next, the raw material was mixed dry to ensure homogeneity, after which the binder was added and mixing continued until a homogeneous and manageable mixture was achieved. Subsequently, the mixture was molded into 160 x 40 x 40 mm molds for flexural strength tests, 300 x 300 x 25 mm molds for thermal conductivity tests, and 150 x 100 x 20 mm for absorption tests.

It should be noted that the composite types S.pd 2/8 and S.W. consisted of a single layer of homogeneous mixture. Specimens of types S.pd 3/7 and S.pd 4/6 consisted of three layers (Fig. 5). The difference between these last two specimens was the thickness of the Diss straw layer used as a middle layer. The ply thickness of S.pd 3/7 was about 5 mm, and that of S.pd 4/6 was about 10 mm. The drying process was meticulously conducted under pressure to prevent any potential deformation of the specimens. This procedure took place over a period of 48 hours within a controlled environment, specifically, in an oven maintained at a temperature of 60 °C. Finally, the specimens were demolded.

Table 1
Different formulations of specimens

Matrix	Reinforcement	Reinforcement/matrix ratio	Binder	Denotation
Paper	Diss fiber + Diss straw	4/6	10%	S.pd 4/6
Paper	Diss fiber + Diss straw	3/7	10%	S.pd 3/7
Paper	Diss fiber	2/8	15%	S.pd 2/8
Paper	/	0	15%	S.W.

S: specimen, pd: paper + Diss, 4/6, 3/7, 2/8 are the reinforcement/matrix ratios; W: witness (control sample)

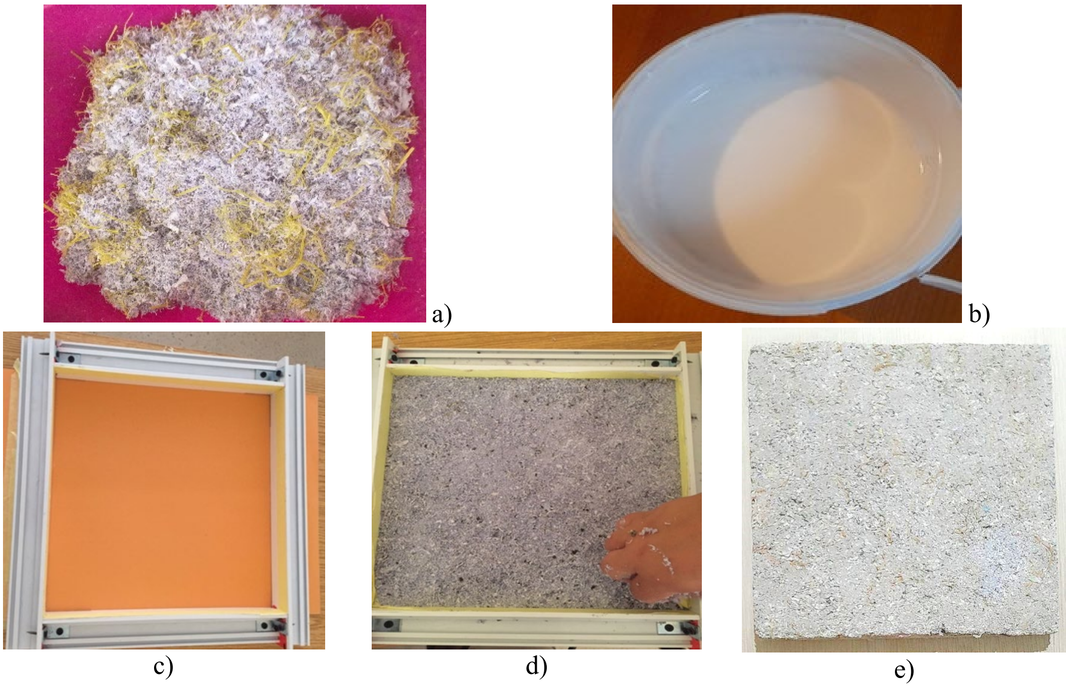

Figure 4: Steps for specimen preparation (a) paper powder + dry mixed dissolving fiber, (b) white adhesive, (c) mold, (d) mixture of composite in the mold, and (e) final obtained specimen

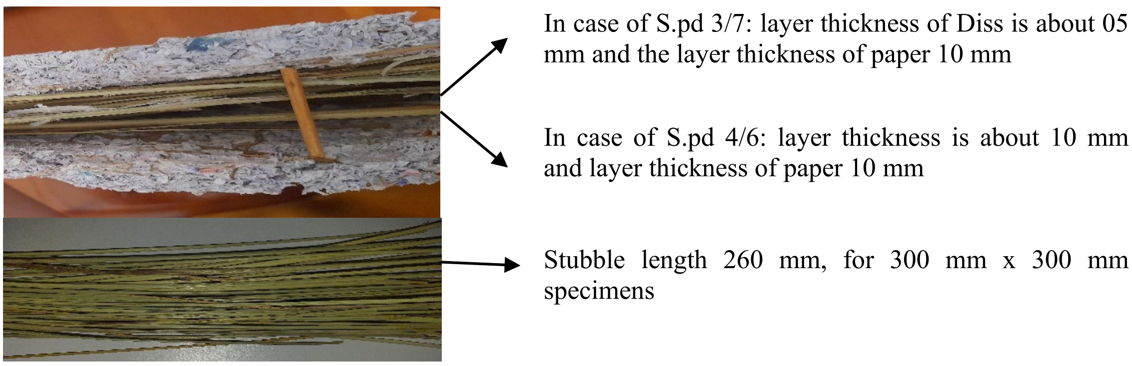

Figure 5: Components of the specimen

The test specimens were weighed and subjected to standard laboratory climatic conditions, at a temperature of 22 °C and relative humidity of 64%. Subsequently, in a second phase, the specimens underwent drying in an oven at 100 °C until a constant mass was achieved. The obtained specimens were further subjected to various characterization tests.

The mechanical experiment was conducted according to ISO 178 using the three-point flexural test. This procedure involves placing a bar of 160 x 40 x 40 mm between two supports, then applying a perpendicular force at the midpoint between the supports on the upper face of the bar. The flexural test was performed on three specimens for the same formulation. Then, the average values were calculated.

Conductivity tests were performed using an H112N Thermal Conductivity Tester (P.A. Hilton Ltd.) for measuring the thermal conductivity of the materials. These tests were conducted at the Mechanical, Structural and Energy Research Laboratory (LMSE), University of Tizi Ouzou. The conductivity tests were investigated on three specimens for the same formulation. The fluxmetric method, known as the Heat Flow Meter Method (HFM), was used to perform this test. The operating principle of the method relies on the circulation of thermal flux through the sample. The sample is inserted in contact between the two plates of the apparatus – one hot and the other one cold. A heat flux, generated by the temperature gradient between these two plates, passes through the sample in a steady state. The flux is quantified on either side of the sample by flux transducers. Subsequently, the thermal conductivity is calculated using an equation provided by the manufacturer of the apparatus.

RESULTS AND DISCUSSION

Table 2 illustrates the density of the composite product prepared in the present work. Table 3 presents the difference in specimen weight before and after drying at room temperature. It is noted that the layer of Diss introduced inside the material has significantly impacted its moisture content. Moreover, the material made solely from paper waste (S.W.) had the lowest absorption coefficient in the absorption tests, as shown in Table 4. The absorbed water quantity resulted in partial deformation of the sample (Fig. 6 (a)). The specimen reinforced with Diss fiber (S.pd 2/8) had a higher absorption coefficient than the previous sample, but exhibited better water resistance due to the introduced fiber (Fig. 6 (b)). The specimen (S.pd 3/7) had a higher absorption coefficient than the first two specimens, attributed to the voids of Diss tubes introduced into the material. This layer weakened the specimen and underwent significant deterioration (Fig. 6 (c)).

Flexural strength testing

The material developed in the present study is intended to be utilized for non-load-bearing elements in construction. However, the focus has solely been on its flexural strength, without considering compressive strength. The mechanical experiment was conducted according to ISO 178 using the three-point flexural test. The flexural test was performed on three specimens for each formulation. Therefore, the results presented in Figure 7 represent the average of three replicates. The standard deviation for this analysis was calculated and obtained as 0.40972.

Specimens crafted from shredded paper bonded solely with white glue (S.W.) exhibited good flexural strength. The addition of Diss fiber (S.pd. 2/8) significantly improved the specimen's flexural performance due to the elastic modulus of the Diss fiber. The incorporation of a layer of Diss straw (S.pd. 3/7) further reinforced the material's resistance to bending forces, thanks to the mechanical properties of the straw.

Table 2
Density of insulating composite material

Property	Paper	Diss fiber	Diss straw	Material		
				S.pd 3/7	S.pd 2/8	S.W.
Density (kg/m^3)	700-800	914	100	413.3	441.5	550

Table 3
Weight of specimens at various dosages before and after drying at room temperature

Sample	Weight before drying (g)	Weight after drying (g)	Relative humidity (%)	Temperature (°C)
S.pd 3/7	986	930		
S.pd 2/8	574	543	64	22
S.W.	715	685		

Table 4
State of the samples before and after saturation

Sample (150 x 100 x 20 mm)	S.pd 3/7	S.pd 2/8	S.W.
Dry weight (g)	123	132	165
Saturated weight (g)	256	244.2	289
Absorption coefficient (%)	52	46	43
State of the sample after saturation	Remarkable partial deformation (Fig. 6c)	Superficial deformation (Fig. 6b)	Partial deformation (Fig. 6a)

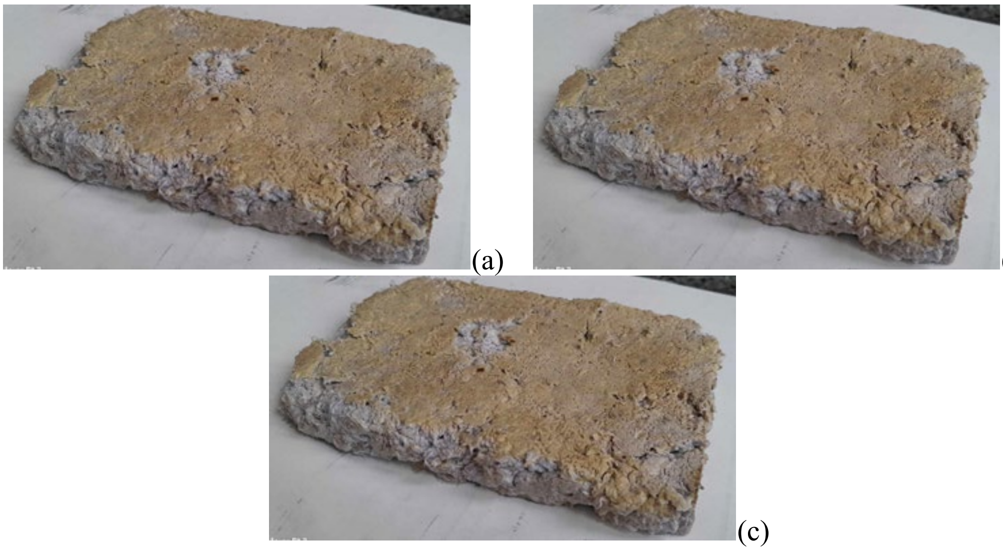

Figure 6: State of the samples after saturation (a) S. W., (b) S.pd 2/8 and (c) S.pd 3/7

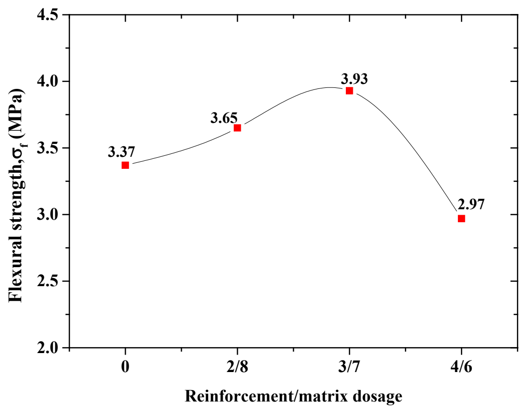

Figure 7: Flexural strength for different formulations of the composites

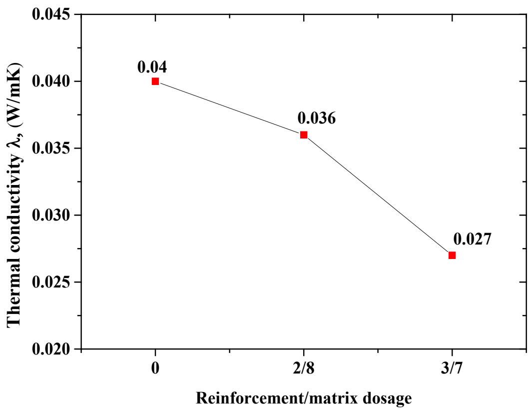

Figure 8: Thermal conductivity for different formulations of the composites

In a subsequent phase, the thickness of the Diss straw layer (S.pd. 4/6) was increased, unfortunately weakening the specimen due to the disproportionate relationship between the paper layers and the straw layer. Consequently, this type of specimens was excluded from the remaining experiments.

Thermal characteristics

Conductivity tests were performed for measuring the thermal conductivity of the developed materials. These tests were conducted at the Mechanical, Structural and Energy Research Laboratory (LMSE), University of Tizi Ouzou. The conductivity tests were investigated on three specimens for the same formulation. Figure 8 presents the average results of thermal tests calculated for three specimens. It illustrates the evolution of the thermal conductivity and shows the impact of Diss fiber and straw on the thermal behavior of the used material (paper).

The recorded results of the thermal tests attest to the good thermal behavior of the studied specimens, with a thermal conductivity of 0.04 W/m.K, in the absence of any additives. This is superior to the conductivity of conventional paper, which stands at 0.05 W/m.K.[28] This improvement is attributed to the low compression of the material and the presence of pores that trap air inside, considering that this air slows down thermal transfer.

However, the addition of Diss fiber (S.pd 2/8) had significantly reduced the conductivity of the specimen, from 0.04 to 0.036 W/m.K. This decrease is specifically attributed to the presence of Diss fiber, consisting of 44.1% cellulose renowned for its insulation properties. In parallel with our approach, the Balticfloc research team endeavored to create a test insulating composite material comprising 80% low-grade recycled paper and 20% hemp fibers, mirroring the composition of our specimen. Their efforts yielded a thermal conductivity within the range of λ = 0.038 to 0.040 W/mK.[29]

The addition of a layer of Diss straw in the middle of the specimen significantly reduced the conductivity value from 0.036 to 0.027 W/m.K, with a standard deviation of 0.006658, as shown in Figure 8. The conductivity value of sample S.pd 3/7 is close to that of still air. This is attributed to the tubular shape of the Diss straw, which traps air inside the tubes (Fig. 9). This tubular shape further prevents thermal transfer.

Economic analysis

The utilization of paper waste (37 USD/m^3) as the base material for insulation ensures low manufacturing costs of the thermal insulation material. Additionally, the use of Diss plant (59 USD/ton), in the form of both fibers and straw, as reinforcement also involves low costs, due to the widespread availability of the plant in the Northern regions of Algeria. The assembly of the matrix and the reinforcement was achieved using white glue, which is readily available at a reasonable price (1.20 USD/kg). Table 5 shows the characteristics of the material developed in the present work compared to the products available on the Algerian market in terms of efficiency and price. By comparing our material with the insulation products available on the market, it can be observed that the developed composite offers advantages, in terms of both thermal conductivity and production costs.

Figure 9: Tubular form of Diss leaf

Table 5
Thermal properties and cost for S.pd 3/7, glass wool, and polystyrene

Insulation material	Thickness, t (mm)	Thermal conductivity, λ (W/m.K)	Thermal resistance, R (m^2K/w)	Heat transfer coefficient, U (W/m^2K)	Cost (USD)
S.pd 3/7	50	0.027	1.85	0.54	2.32
Glass wool	50	0.035	1.42	0.70	3.08
Polystyrene	50	0.034	1.47	0.68	4.29

Scope of application

The final composite insulation material will be produced in the form of a 1 m x 1.5 m x 0.05 m panels (1000 x 1500 x 50 mm), protected by a 5 mm layer of plaster (the assembly of the insulation with the plaster layer will be dry). The material is primarily produced for educational facilities, given that these facilities generate the most significant amount of paper waste. Nevertheless, it can be used in various types of construction, such as residential buildings, administrative buildings, cold storage warehouses *etc*., for both new and existing structures. For new constructions, it is recommended to use panels of the insulation material instead of an air gap between the two exterior partitions. In this case, the plaster layer can be omitted and replaced with a plastic film. In the case of thermal rehabilitation of existing buildings, it is advisable to use the insulation material on the interior side of exterior walls, fixed onto a lightweight metal structure. The implementation does not require skilled labor.

CONCLUSION

Recently, there has been renewed interest in the topic of thermal insulation of buildings, and new questions have emerged regarding the best methods of insulation. It is not enough to simply insulate a building, it is crucial to carefully consider the choice of the insulation material. This study highlights the potential of using recycled paper waste and bio-sourced materials as sustainable solutions for insulation in building construction, aiming to reduce the quantity of waste that gets into the environment by turning it into value-added materials.

Paper waste was chosen due to its abundance throughout almost the entire tertiary sector of the economy, and the inability to absorb these immense quantities of waste. Paper is known for its thermal characteristics that can also be enhanced. From this perspective, shredded paper was used as a matrix reinforced by a bio-sourced reinforcement, namely *Ampelodesmos mauritanicus*.

Thermal resistance is an essential parameter used to evaluate the effectiveness of building insulation. The inclusion of Diss fibers (*Ampelodesmos mauritanicus*) and straw has significantly improved the mechanical and thermal properties of insulating panels made from recycled paper.

The resulting composite material exhibits improved thermal resistance and mechanical strength, making it a promising option for sustainable and eco-friendly insulation. The obtained results proved that the developed material has good thermal insulation behavior, with the thermal conductivity of paper at 0.050 W/m.K. The addition of Diss fiber with recycled papers has a significant influence on the thermal conductivity, reducing it from 0.050 W/m.K to 0.027 W/m.K. The tests have revealed the material's advantages, such as excellent thermal conductivity and good resistance to bending, but also some weaknesses, such as fragility towards water, thus, pointing towards a future research direction, seeking solutions to overcome these weaknesses.

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