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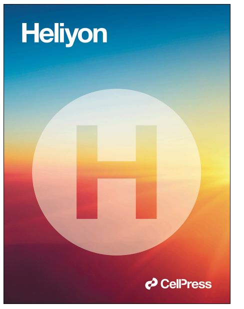

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PII: S2405-8440(23)09007-2

DOI: https://doi.org/10.1016/j.heliyon.2023.e21799

Reference: HLY 21799

To appear in: *HELIYON*

Received Date: 19 August 2023

Revised Date: 25 October 2023

Accepted Date: 28 October 2023

Development of eco-friendly wall insulation layer utilising the wastes of the packing industry

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Abstract

Efficient thermal insulation materials considerably lower power consumption for heating and cooling of buildings, which in turn minimises CO_2 emissions and improves indoor comfort conditions. However, the selection of suitable insulation materials is governed by several factors, such as the environmental impact, health impact, cost and durability. Additionally, the disposal of used insulation materials is a major factor that affects the selection of materials because some materials could be very toxic for humans and the environment, such as asbestos-containing materials. Therefore, there is a continuous research effort, in both industry and academia, to develop sustainable and affordable insulation materials. In this context, this work aims at utilising the packing industry wastes (cardboard) to develop an eco-friendly insulation layer, which is a biodegradable material that can be disposed of safely after use. Experimentally, wasted cardboard was collected, cleaned, and soaked in water for 24 hours. Then, the wet cardboard was minced and converted into past papers, then cast in square moulds and left in a ventilated oven at 75 ^{o}C to dry before de-moulding them. The produced layers were subjected to a wide range of tests, including thermal conductivity, acoustic insulation, infrared imaging and bending resistance. The obtained results showed the developed material has a good thermal and acoustic insulation performance. Thermally, the developed material had the lowest thermal conductivity (λ) (0.039 W/m.K) compared to the studied traditional materials. Additionally, it successfully decreased the noise level from 80 to about 58 dB, which was better than the efficiency of the commercial polyisocyanurate layer. However, the bending strength of the developed material was a major drawback because the material did not resist more than 0.6 MPa compared to 2.0 MPa for the commercial polyisocyanurate and 70.0 MPa for the wood boards. Therefore, it is recommended to investigate the possibility of strengthening the new material by adding fibres or cementitious materials.

Keywords: Cardboards; waste; insulation layer; thermal; acoustic; bending resistance; eco-friendly; biodegradable.

1. Introduction

The buildings sector, especially residential buildings, is recognised as one of the main consumers of energy due to the significant growth in heating and cooling equipment. For example, the building sector is responsible for approximately 40% of the energy consumption in Europe [1], approximately 25% of the energy consumption in Thailand [2], and about 29% of the power consumption in the USA [3]. On average, the buildings sector is responsible for over 40% of global energy consumption, and the majority of this high energy demand (about 60% of the global consumption) is consumed by heating and cooling of buildings and providing hot water [4]. In addition, this high demand for energy has serious environmental impacts; for example, the building sector in the USA is responsible for approximately 20% of CO_2 emissions [3] and 33.3% of global greenhouse gas emissions [5].

This dilemma is increasing due to the impacts of climate change that increase the need for the use of heating and cooling equipment in buildings. For instance, about 85% of the small residential units in Mexico are located in scorching areas, forcing the residents to depend on air conditioning equipment to achieve comfortable conditions [3]. Invidiata and Ghisi [6] reported that climate change will raise the yearly energy consumption in the range of 56%–112% in 3 Brazilian cities by 2050 and 112%–185% by 2080. Frank [7] demonstrated that climate change would cause severe changes in energy consumption in Switzerland; energy demand for cooling purposes will increase by 223–1050% for the period 2050 to 2100, while the heating energy demand will decrease by 36–58%. A similar trend was noticed in China; Wan, *et al.* [8] studied the impact of climate change on the energy demand for cooling purposes in different office buildings in China and demonstrated that by 2100, the energy demand would be increased by 18.5%, 20.4%, 11.4%, 24.2%, and 14.1% in the office buildings in the cities of Harbin, Beijing, Shanghai, Kunming and Hong Kong, respectively.

Some passive design strategies were suggested in the literature to reverse this downward trend, such as solar shading, naturally ventilated envelopes, and the use of thermal insulation layers [6,9].

Developing efficient insulation layers could be one of the most effective solutions to this dilemma as it helps to maintain the comfort condition within the building for a long time, significantly minimising the energy demand for cooling and heating. Therefore, a clear increase in research efforts was recently directed towards developing efficient and eco-friendly insulation layers [10]. For instance, Briga-Sa, *et al.* [11] studied the possibility of using woven fabric wastes (WFW) and woven fabric sub-waste (WFS) as thermal insulation materials for buildings. The results showed that using WFW and WFS in the external double wall improves thermal insulation by 56% and 30%, respectively. Khalaf, *et al.* [12] studied the possibility of developing a new insulation material using a chitosan matrix reinforced with different sizes of miscanthus (0.2–0.5 cm and 1–2 cm), rice husk (1–2 cm) and recycled textile. It was found that the thermal conductivity of the new material ranged between 0.07 and 0.09 $W.m^{-1}.K^{-1}$, and it can resist bending stress of 0.48–0.45 MPa and compression stress of 0.65–0.56 MPa. Another trial was carried out by Gounni, *et al.* [13] to develop an eco-friendly insulation material using wasted acrylic spinning waste (As), acrylic knitting waste (Ak), washed wool washed (Wr) and carpet waste wool (Wc), and the performance of the new material was compared to commercial insulation materials, such as rock wools (RW) and expanded polystyrenes (EPS). The new material had a performance competitive to that of commercial materials; for example the annual heating and cooling loads of As, Ak, Wr, Wc, RW and EPS were 19.14, 19.26, 16.61, 17.69, 19.61 and 16.45 kWh/(m^2.year), respectively.

Due to the clear lack of research on the development of eco-friendly insulation materials and the increasing effects of climate change, the current article aims to develop and test a new eco-friendly wall insulation layer utilising the wastes of the packing industry (wasted cardboard). The latter was selected as a raw material for the insulation layer for many reasons, most importantly, their vast volumes. For example, it has been reported that the generated paper and cardboard packaging waste by households in the UK in 2021 was 5,400,000 metric tons [14]. Moreover, the demand for paper is increasing rapidly, alarming a massive increase in the generation of this type of waste. For example, the demand for papers in Europe is expected to increase by about 28% in 2030 compared to 2015 [15].

This aim will be achieved through a set of objectives: the preparation and manufacturing of the insulation layer, testing the thermal insulation efficiency, testing the acoustic insulation efficiency, and testing the mechanical properties of the layers (bending strength). Additionally, this study aims to compare the properties of the new insulation layer with those of commercial insulation layers.

2. Materials and Methods

Wasted cardboard boxes were collected from local shops in Liverpool, UK. The preparation of the new insulation layers was collectively adopted from relevant literature [16,17]. The cardboard boxes were manually inspected to remove all staples and Scotch tapes, and then the boxes were shredded into small pieces (20-25 cm in length) and soaked in water for 24 hours.

The wet cardboard pieces were removed from the water and mixed (to make past of papers) for 10 minutes using a bench-top mixer (HOST Planetary Mixer 20L). The produced paper paste was cast in a metallic mould (55 cm × 55 cm × 4 cm) that already contains nonsticking papers to prevent the sticking of the dry layer to the mould, as shown in Figure 1(A and B). The paper paste was compressed and then dried at 75 ^{o}C for 48 hours using a ventilated oven.

It is noteworthy that special samples ($42.5cm \times 10cm \times 2.5\ cm$) were prepared to carry out the bending strength test. It was noticed that the dimensions of the dried layer shrank to (51.4 cm × 51.4 cm × 2.1 cm). The dry layers were removed from the moulds and cut down into smaller samples according to the required test; see Table 1.

Two types of samples were prepared; one was left without treatment (S1), and another was wrapped with aluminium insulation tape (S2).

The results were compared with the properties of commercial insulation layers, namely polyisocyanurate (PO) and wood boards (WB)). All samples were subjected to a series of tests: infrared thermal imaging, thermal conductivity, acoustic insulation and bending strength test (three-point bending flexural test).

Figure 1. A) Fresh cardboard paste, and B) Dreid cardboard layer.

Table 1. Dimensions of tested samples.

Sample type	Dimensions (cm)
Thermal conductivity	20 × 20 × 2.1
Infrared test	50 × 50 × 2.1
Bending strength test	42.5 × 10 × 2.5
Acoustic insulation	Box (25 ×10 ×15)

2.1. Infrared thermal imaging

Infrared thermal imaging is one of the important methods of experimental research to determine the thermal performance of materials in different fields, such as buildings, aerospace, and electronics [18]. This technology is classified as non-destructive (non-contact surface) temperature measurement technology that converts the temperature variation into images, which can be analysed to evaluate thermal efficiency or detect any industrial defects (such as holes and cracks) [19,20].

In this study, the infrared thermal imaging analysis was performed using a Teledyne FLIR E5-XT Thermal Imaging Camera (temperature range -20˚C to 400˚C) to detect any industrial defects (cracks or holes) and also to compare insulation efficiency of the tested materials (S1, S2, PO and WB). Experimentally, samples (with net dimensions of (50 cm × 50 cm × 2.1 cm) of the studied materials were installed vertically. Then, the FLIR camera was installed firmly at a distance of 50 cm away from the surface of the layer, and a heat source was installed at a distance of 30 cm on the other side of the layer, providing a steady air temperature of 50 °C, as shown in Figure 2. The images were taken at intervals of 5 minutes for 20 minutes, and the final surface temperature of each material was recorded and compared with the rest of the materials.

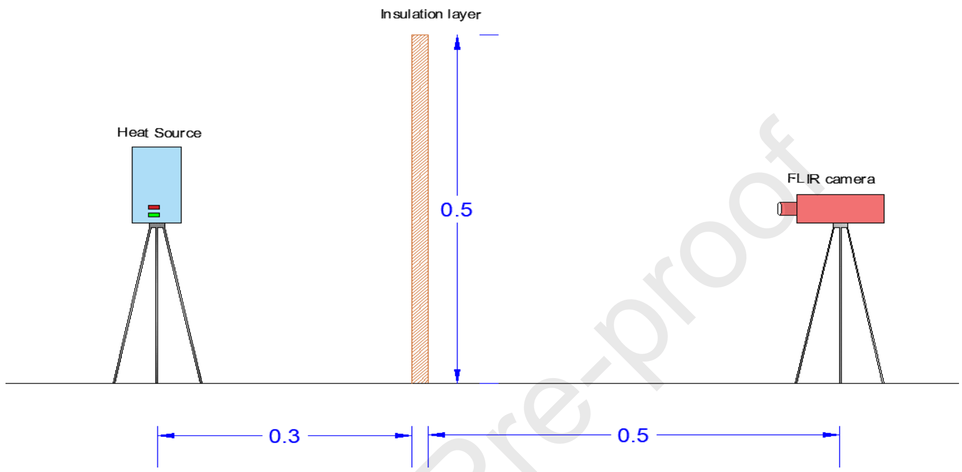

Figure 2. Setup of the infrared imaging experiments.

2.2. Thermal conductivity (λ)

Thermal conductivity is the measurement of the steady-state heat transfer through a flat slab sample and the estimate of the heat transfer properties of a sample [21]. The thermal conductivity of the produced layer was measured using an ISOMET 2114 device following the procedures stated by Cetiner and Shea [21]. According to Cetiner and Shea [21], the thermal conductivity was measured by attaching the surface probe of the ISOMET 2114 device to the surface of the sample of the insulation material. Taking into account that the dimensions of the tested sample were 20 × 20 cm because larger samples (more than 25 × 25 cm) should be tested using another method (such as Lasercomp FOX 600 Heat Flow Meter) [21].

In this study, samples of S1, S2, PO and WB with dimensions of 15 × 15 × 2 cm were tested using an ISOMET 2114 device that was supplied with a surface probe, as shown in Figure 3(A and B).

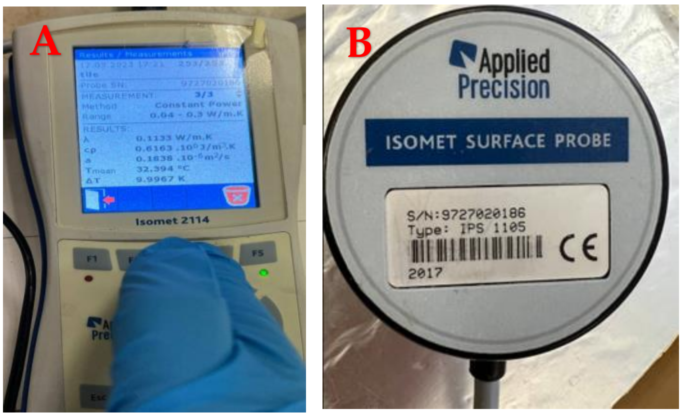

Figure 3. A) ISOMET 2114 device, and B) The surface probe of the ISOMET device.

2.3. Acoustic insulation

Acoustic insulation, also known as noise insulation, is another crucial property of insulation materials. The acoustic insulation efficiency of the developed insulation material (S1 and S2) and the reference materials (PO and WB) was experimentally measured using an ATP DT-8820 multi-function environment meter. Initially, boxes with dimensions of (25 cm in length,10 cm in width and 15 cm in height) with their lids were manufactured from each material, as shown in Figure 4 (A-C).

A noise source (80 dB) was placed inside each box and closed with the lid, and then the ATP DT-8820 meter was placed directly on the external side of the lid to measure the noise level.

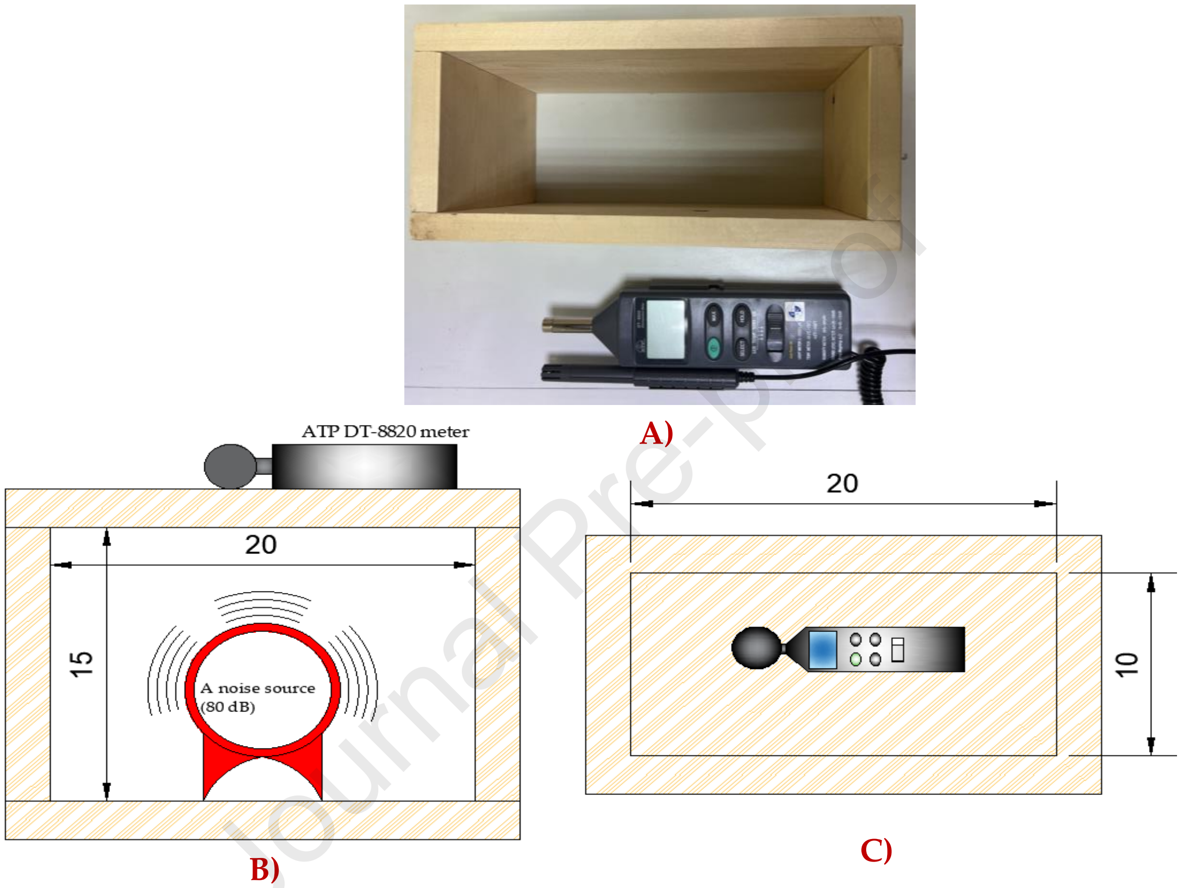

Figure 4. A) The box and the ATP DT-8820 meter, B) Side view of the set-up, and C) Top view of the set-up.

2.4. Bending strength test

The bending test determines the tensile strength of the materials, and it is usually performed using either 3- or 4-point bending. Three prism samples ($42.5cm \times 10cm \times 2.5\ cm$) of S1, S2, PO and WB were prepared and tested using a PILOT machine following the procedures stated by Panyakaew and Fotios [2]. The bending strength was calculated using equation 1 [2]:

$$Bending\ strength\ (MPa)\ = \frac{3\times P\times L}{2\times b\times t^2} \qquad 1$$

Where P, L, b and t represent *the* highest load (N), the effective length of the sample (between supporters) (mm), the width of the sample (mm) and the thickness of the sample (mm), respectively.

3. Results

Infrared imaging experiments were initially performed to detect invisible cracks or holes in the developed (S1 and S2) and reference (PO and WB) samples. Additionally, the results of the infrared tests were used to determine the insulation efficiency. Experimentally, infrared images were taken at intervals of 5 minutes for 20 minutes for each studied sample.

The obtained results are shown in Figure 5(A-D), which shows that the surfaces of the developed samples (S1 and S2) and the reference samples do not have industrial defects (cracks or holes).

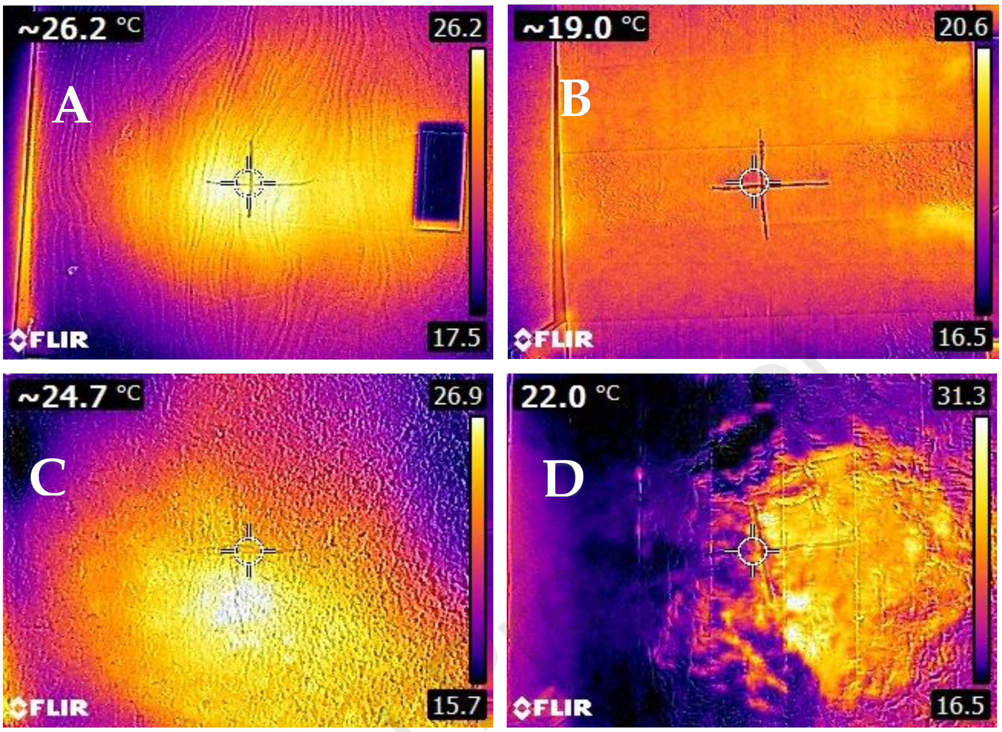

Figure 5. Infrared images for A)WB , B) PO, C) S1, and D) S2.

Figure 6 shows the recorded temperatures on the surfaces of the studied materials after 20 minutes of exposure to the hot air. It can be seen that the best insulation efficiency was obtained by the PO, which did not record more than 19 °C, followed by S2 at a temperature of 22 °C, then S1, which recorded 24.7 °C, while the WB showed the lowest efficiency at a temperature of 26.2 °C. The efficiency of S1 and S2 compared to WB could be attributed to the air voids in the developed materials, where the trapped air in voids improves the material' s thermal resistance [22]. The S2 layer (wrapped with aluminium insulation tape) showed a better performance than the S1 layer, which could be attributed to the aluminium insulation tape, which delays the flow of temperature through the body of the layer. In summary, it can be said the developed material showed a performance better than traditional insulation layers (WB), but less than the advanced industrial materials (OP), and this could make it a promising alternative for some of the currently used insulation materials.

Thermal conductivity (λ), which is a measure for the ease of heat travel through a material by conduction, was measured in this study using an ISOMET 2114 device that was supplied with a surface probe and following the procedures stated by Cetiner and Shea [21]. It should be noticed that the smaller the λ, the better the thermal performance and energy-saving efficiency [23].

The measured values of λ for the studied materials are shown in Figure 7. The latter clearly shows that the S1 layer has the lowest λ value (0.039 W/m.K) followed by WB and PO, while S2 has the highest λ values, which means the S1 has the best thermal performance and energy-saving efficiency. The explanation for the low λ value of S1 could be related to the extent of spaces and voids in the material, where it has been proven that the higher the voids ratio, the lower λ value [24].

The calculated λ value of S1 is within the expected range of λ values for traditional materials; for example, the λ value of mineral wools and polyurethane ranges between 0.02 and 0.04 W/m. K [25], 0.03–0.046 W/m.K for glass wool and 0.033–0.046 W/m.K for rock wool [26].

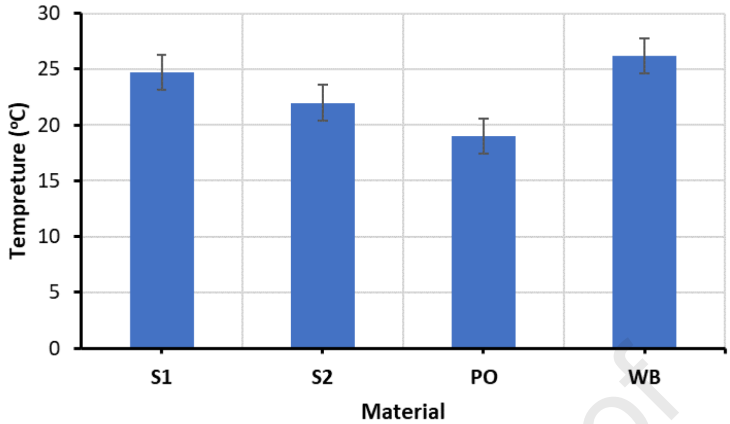

Figure 6. Recoded temperatures on the surfaces of the studied materials after 20 minutes of heating.

Additionally, the obtained results agree with the general outcomes of the relevant literature. For example, Ekpunobi, *et al.* [27] developed a paper-based insulation material and stated that the thermal conductivity of this material ranges between 0.6 and 1.6 W/m.k depending on the ratio of fibres. Also, Pathak and Mandavgane [22], who used the paper mill waste and cement to develop an insulation material, found that the thermal conductivity of the paper-based insulation material was 0.4 W/m.k.

It can be concluded that the thermal conductivity of the developed insulation material (S1) meets the requirements of traditional insulation materials, and it has a better environmental performance as it utilises waste materials without adding external chemicals, which makes it a promising eco-friendly insulation material.

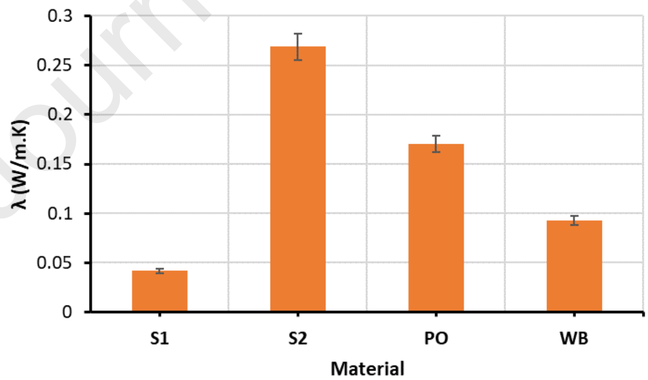

Figure 7. Thermal conductivity values of the studied materials.

The acoustic insulation results of the studied materials are shown in Figure 8, which shows that WB had the best performance in terms of noise control, where it minimised the noise level from 80 to about 37 dB, followed by S1, which decreased the noise level from 80 to about 58 dB and S2 that decreased the noise from 80 to about 62 dB, while the PO had the lowest performance at a reduction value of 16 dB.

It can be seen that the materials covered with a metallic layer (S2 and PO) had the lowest acoustic insulation efficiency due to the ability of metals to transfer the sound better than wood (WB) and organic materials (S1). Additionally, the air voids play an important role in noise control (as noticed in WB and S1).

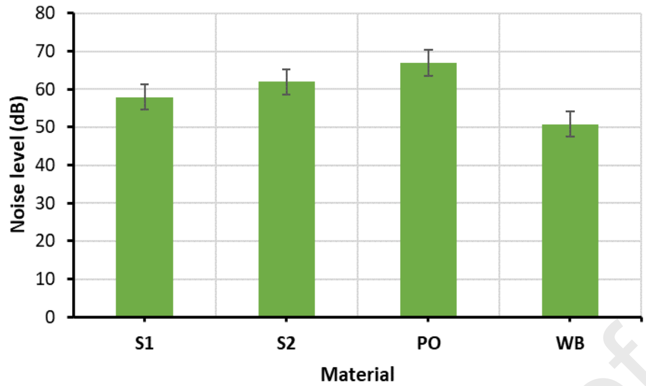

Figure 8. Noise reduction by the studied materials.

Finally, the bending strength test was performed using prism samples (42.5cm×10cm×2.5 cm) of each material (S1, S2, PO and WB) to calculate the tensile strength of the materials.

The obtained results are shown in Figure 9. This figure shows the main drawback of the developed material, which is the bending strength, where it can be seen that both S1 and S2 had the lowest bending strengths (less than 1 MPa). The same problem was noticed in the PO, which showed a bending strength of about 2.0 MPa. On the contrary, WB showed an excellent bending strength that reached the vicinity of 70.0 MPa.

The results of the bending strength test indicated the need for strengthening the developed material, which could be done by adding fibres or cementitious materials.

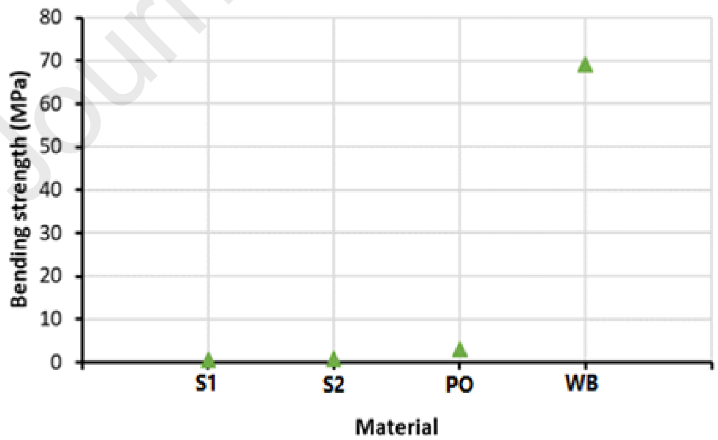

Figure 9. Bending strength of the studied materials.

5. Conclusions

This article investigated the visibility of recycling the packing industry wastes (cardboard) to develop an eco-friendly insulation layer. The experimental work focused on identifying the key properties of the developed insulation material, such as thermal conductivity, acoustic insulation and bending strength. The obtained results indicated that the developed material has a good performance in terms of thermal and acoustic insulation. Thermally, the developed material had the lowest thermal conductivity (λ) (0.039 W/m.K) compared to the studied traditional materials. Additionally, it successfully decreased the noise level from 80 to about 58 dB, which was better than the efficiency of the commercial polyisocyanurate layer.

However, the bending strength of the developed material was a major drawback because the material did not resist more than 0.6 MPa compared to 2.0 MPa for the commercial polyisocyanurate and 70.0 MPa for the wood boards. Therefore, it is recommended to investigate the possibility of strengthening the new material by adding fibres or cementitious materials.

In summary, the developed material in this study could be a promising eco-friendly alternative to traditional insulation materials as it does not consume a high amount of energy during the manufacturing process, which in turn minimises the CO_2 emission. Additionally, the new material could be considered an eco-friendly recycling method for the wastes of the packing industry. Finally, it is noteworthy that the new insulation layer could be disposed of safely because it is mainly made from biodegradable organic materials.

Funding: This research received no external funding.

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

Data Availability Statement: Data can be requested from the corresponding author.

References

1. Sierra-Pérez, J.; Boschmonart-Rives, J.; Dias, A.C.; Gabarrell, X. Environmental implications of the use of agglomerated cork as thermal insulation in buildings. Journal of cleaner production 2016; 126(97-107.
2. Panyakaew, S.; Fotios, S. New thermal insulation boards made from coconut husk and bagasse. Energy and buildings 2011; 43(7): 1732-1739.
3. Rosas-Flores, J.A.; Rosas-Flores, D. Potential energy savings and mitigation of emissions by insulation for residential buildings in Mexico. Energy and buildings 2020; 209(109698.
4. Kalbasi, R.; Shahsavar, A.; Afrand, M. Incorporating novel heat recovery units into an AHU for energy demand reduction-exergy analysis. Journal of Thermal Analysis and Calorimetry 2020; 139(4): 2821-2830.
5. Tettey, U.Y.A.; Dodoo, A.; Gustavsson, L. Effects of different insulation materials on primary energy and CO2 emission of a multi-storey residential building. Energy and Buildings 2014; 82(369-377.
6. Invidiata, A.; Ghisi, E. Impact of climate change on heating and cooling energy demand in houses in Brazil. Energy and Buildings 2016; 130(20-32.
7. Frank, T. Climate change impacts on building heating and cooling energy demand in Switzerland. Energy and buildings 2005; 37(11): 1175-1185.
8. Wan, K.K.; Li, D.H.; Pan, W.; Lam, J.C. Impact of climate change on building energy use in different climate zones and mitigation and adaptation implications. Applied Energy 2012; 97(274-282.
9. Omrany, H.; Ghaffarianhoseini, A.; Ghaffarianhoseini, A.; Raahemifar, K.; Tookey, J. Application of passive wall systems for improving the energy efficiency in buildings: A comprehensive review. Renewable and sustainable energy reviews 2016; 62(1252-1269.
10. Mellaikhafi, A.; Tilioua, A.; Benallel, A.; Babaoui, A.; Hamdi, M.A.A. Thermal study of environmentally-friendly thermal insulation material based on clay bricks reinforced by date palm fibers. In Proceedings of the AIP Conference Proceedings, 2021;
11. Briga-Sa, A.; Nascimento, D.; Teixeira, N.; Pinto, J.; Caldeira, F.; Varum, H.; Paiva, A. Textile waste as an alternative thermal insulation building material solution. Construction and Building Materials 2013; 38(155-160.
12. Khalaf, Y.; El Hage, P.; Mihajlova, J.D.; Bergeret, A.; Lacroix, P.; El Hage, R. Influence of agricultural fibers size on mechanical and insulating properties of innovative chitosan-based insulators. Construction and Building Materials 2021; 287(123071.

13. Gounni, A.; Mabrouk, M.T.; El Wazna, M.; Kheiri, A.; El Alami, M.; El Bouari, A.; Cherkaoui, O. Thermal and economic evaluation of new insulation materials for building envelope based on textile waste. Applied Thermal Engineering 2019; 149(475-483.
14. Alves, B. Packaging waste arisings and recovery in the United Kingdom (UK) 2021, by material. Statista 2023; https://www.statista.com/statistics/476098/packaging-waste-and-reclycing-uk/#:~:text=Packaging%20waste%20arisings%20and%20recovery,(UK)%202021%2C%20by%20material&text=In%202021%2C%205.4%20million%20metric,rate%20of%20roughly%2071%20percent.(Accessed on 23/09/2023).
15. Gaur, V.K.; Sharma, P.; Sirohi, R.; Awasthi, M.K.; Dussap, C.-G.; Pandey, A. Assessing the impact of industrial waste on environment and mitigation strategies: A comprehensive review. Journal of hazardous materials 2020; 398(123019.
16. Noor, S.; Yao, T.; Muhammad, K.; Yahya, N. Thermal Insulation Improvement in Wall using Recycled Cellulose as An Alternative and its Physical Properties. Journal of Advanced Research in Engineering Knowledge 2019; 9(1): 26-31.
17. Stanislas, T.T.; Tendo, J.F.; Teixeira, R.S.; Ojo, E.B.; Komadja, G.C.; Kadivar, M.; Junior, H.S. Effect of cellulose pulp fibres on the physical, mechanical, and thermal performance of extruded earth-based materials. Journal of Building Engineering 2021; 39(102259.
18. Zhu, G.; Jing, H.; Wu, J.; Chen, S.; Gao, Y.; Yin, Q.; Yu, Z.; Qiao, Y.; Ren, J. Study on heat transfer characteristics of cement-based honeycomb structures based on infrared imaging. Journal of Building Engineering 2023; 68(106134.
19. Deraman, R.; Hamzah, H.; Abdul Kadir, A.; Abdullah, A.; Nagapan, S.; Yunus, R. Assessment of thermal surface temperature of empty fruit bunch (EFB) fired clay brick masonry model using infrared thermography (IRT). Ecol Environ Conserv 2017; 23(46-55.
20. Briga-Sá, A.; Gaibor, N.; Magalhães, L.; Pinto, T.; Leitão, D. Thermal performance characterisation of cement-based lightweight blocks incorporating textile waste. Construction and Building Materials 2022; 321(126330.
21. Cetiner, I.; Shea, A.D. Wood waste as an alternative thermal insulation for buildings. Energy and Buildings 2018; 168(374-384.
22. Pathak, C.S.; Mandavgane, S.A. Application of recycle paper mill waste (rpmw) as a thermal insulation material. Waste and biomass valorisation 2019; 10(2343-2352.
23. Li, T.; Huang, F.; Li, L.; Zhu, J.; Jiang, X.; Huang, Y. Preparation and properties of sulphoaluminate cement-based foamed concrete with high performance. Construction and Building Materials 2020; 263(120945.
24. Sangrutsamee, V.; Srichandr, P.; Poolthong, N. Re-pulped waste paper-based composite building materials with low thermal conductivity. Journal of Asian Architecture and Building Engineering 2012; 11(1): 147-151.
25. Krarti, M. *Optimal design and retrofit of energy efficient buildings, communities, and urban centers*; Butterworth-Heinemann, Portsmouth, USA: 2018.
26. Pásztory, Z. An overview of factors influencing thermal conductivity of building insulation materials. Journal of Building Engineering 2021; 44(102604.
27. Ekpunobi, U.; Ohaekenyem, U.; Ogbuagu, A.; Orjiako, E. The mechanical properties of ceiling board produced from waste paper. 2015.

Declaration of interests

☒ 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.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Best regards
Dr Khalid Hashim