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* *Corresponding author: cboieriu@unitbv.ro*

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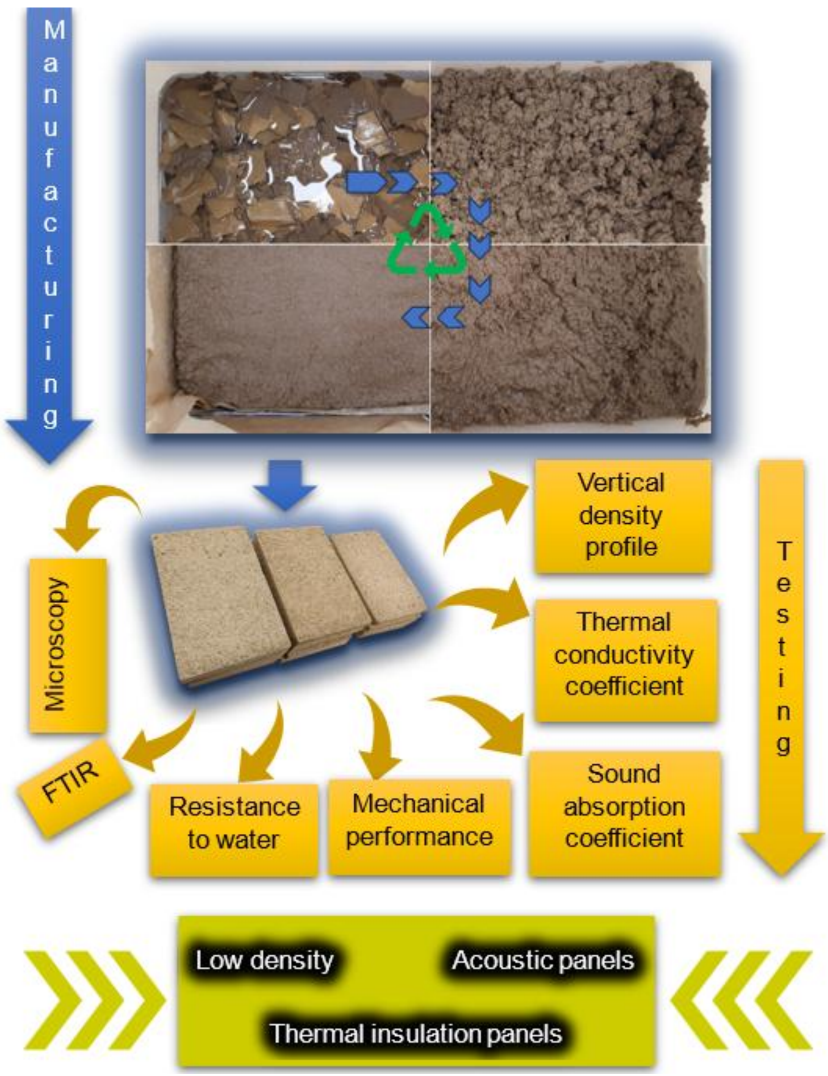
GRAPHICAL ABSTRACT



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The objective of this study was to determine both the physical and mechanical properties of experimental panels made from recycled corrugated cardboard. Two types of composite samples, derived from two different raw materials — namely, unprinted and printed cardboard — were manufactured. The physical characteristics of the specimens, including density, water absorption, dimensional stability, thermal conductivity, and sound absorption, were tested. Additionally, the mechanical properties, such as the modulus of elasticity, modulus of rupture, and internal bond strength, were evaluated. Based on the findings of this research, the samples made from unprinted cardboard exhibited higher density, lower thickness swelling, and slightly better thermal insulation properties than those made from printed raw material. In contrast, the samples containing printed material demonstrated superior mechanical properties, suggesting they may be more suitable to be used where structural properties are desired. Overall, the properties of both types of samples indicate that such panels have an important potential to be used as sustainable products, serving as a green alternative material for indoor applications.

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Keywords: Composite; Recycled cardboard; Thermal insulation; Sound absorption; FTIR

Contact information: Department of Wood Engineering and Wood Products Design, Transylvania University of Brasov, B-dul Eroilor 29, 500036, Brasov, Romania;
** Corresponding author: cboieriu@unitbv.ro*

INTRODUCTION

It is well known that insulation is a key factor in lowering global energy consumption, acting as a passive solution to boost overall energy efficiency. Insulation materials play a critical role across many industries, due to their large surface area and lightweight properties. However, widely used insulation materials, such as expanded polystyrene (Yucel *et al.* 2003) and polyurethane (Kausar 2018), are derived from synthetic or inorganic sources, thereby creating adverse influence on the environment and waste accumulation. Consequently, the search for eco-friendly, sustainable insulation options has intensified in recent years (Benallel *et al.* 2021; Ouakarrouch *et al.* 2022: Liuzzi *et al.* 2023; Garcia *et al.* 2024).

Corrugated cardboard is a layered and robust material that is widely used for packaging with unique potential for sustainable applications. Recycling cardboard is essential for mitigating its environmental footprint, as its fibers can be recycled up to 25 times without substantial quality degradation (Xie *et al.* 2013). Data from the FAO at the level of year 2022 indicated that global cardboard production surpasses 50 million metric tons (FAO 2022). Cardboard and paper represent 17% of the global waste, reaching the second place after food and green waste; furthermore, cardboard takes years to biodegrade in landfills (Ximenes 2010). Primarily composed of cellulose fibers derived from wood pulp, one type of cardboard was found to contain around 52% cellulose, 7% hemicellulose, 10% lignin, 16% ash, and approximately 15% of additives that enhance its durability and performance (Xu *et al.* 2020). With cellulose fiber diameters ranging from 10 μm to 50 μm (Chinga-Carrasco 2011), the mean fiber length and width were measured as 192 μm and 53 μm, respectively (Wang *et al.* 2019), and a low density coupled with high toughness and impact resistance (Venkatesan *et al.* 2023), cardboard is both cost-effective and recyclable material. These attributes align well with the principles of the circular economy by promoting waste reduction, energy conservation, and environmental sustainability (Virtanen and Nilsson 2013; Venkatesan *et al.* 2023).

Moisture significantly impacts the properties of paper-based products. Studies have shown that the presence of moisture softens the paper-based products and alters their behavior by reducing the elastic modulus and tensile strength (Vishtal and Retulainen 2012; Fadiji *et al.* 2017).

Attempts to use recycled cardboard and paper for thermal insulation and sound absorption purposes were investigated in previous studies. Overlapping corrugated cardboard sheets (Asdrubali *et al.* 2015, 2016) achieved thermal conductivity coefficients between 0.049 and 0.054 W/mK, with low sound absorption coefficients around 0.2, and higher peaks at 1000 Hz and in the range 5000 to 6000 Hz. Seven layer corrugated cardboard drilled with 2.3-mm holes reached a sound absorption coefficient of 0.754 at 936 Hz (Kang *et al.* 2021). Composite made of glued and pressed waste paper layer (10 mm) and wool exhibited good acoustic behavior at frequencies above 1000 Hz (Buratti *et al.* 2016). Printed and unprinted cardboard mixed with water and dried exhibited similar thermal and acoustic properties (Jensen and Alfieri 2021). An empty cardboard box had a thermal conductivity of 0.0689 W/mK, while the same box filled with egg boxes and polyester showed a lower value of 0.0528 W/mK (Neri 2022). Panel made of 60% cardboard waste and 40% bagasse fibers achieved a sound absorption coefficient of 0.7 and thermal conductivity coefficient between 0.065 and 0.069 W/mk at a density of 278.6 kg/m^3 (Ouakarrouch *et al.* 2022). Recycled paper mixed with coffee grounds and polyvinyl acetate resulted in composites with a density of 200 kg/m^3, thermal conductivity coefficient of 0.071 W/mK, and sound absorption coefficient below 0.7 (Liuzzi *et al.* 2023). Composite material made from glued recycled newspaper and rise husk particles with borax additive recorded thermal conductivity coefficients values between 0.040 and 0.046 W/mK (Marin-Calvo *et al.* 2023). Sandwich partition beams made from recycled paper faces and agro-waste core demonstrated superior thermal and sound insulation properties compared to homogeneous materials (Garcia *et al.* 2024).

Recent studies have also investigated various sustainable uses for recycled cardboard, including waste-based concrete (Mahdi *et al.* 2023), gypsum boards (Sair *et al.* 2019), briquettes (Odusote *et al.* 2016), cardboard beams (Schönwälder and Rots 2007) and wood-plastic composites (Wang *et al.* 2019). Applications in the building and construction industry have also been explored (Venkatesan *et al.* 2023).

The contribution of cardboard as a raw material for composite boards offers several advantages, including waste reduction through recycling, biodegradability, lightweight properties, cost-effectiveness, wide availability, and potential for sound absorption and thermal insulation. However, it also has several disadvantages, such as limited mechanical strength, low moisture resistance, and reduced durability.

Although the above studies evaluated different aspects of such experimental composites, the use of recycled cardboard as foam panels for insulation remains largely unexplored, and there is limited information of their properties (Jensen and Alfieri 2021). Therefore, the objective of this study was to develop two types of experimental green composite panels made from recycled cardboard with low densities to be used as insulating units within the scope of sustainability. The physical and mechanical characteristics of these samples were evaluated in this work so the potential use of such panels for insulation purposes in an effective and efficient way can be considered.

EXPERIMENTAL

Materials and Methods

Raw material preparation

The collected unprinted and printed cardboard was initially reduced into small pieces by hand before they were soaked in water for several hours. Subsequently, the softened cardboard pieces were processed in a blender at 9000 rpm for 1 min to disintegrate the fibers. The ratio of cardboard to water used was 1:4.8. To produce the experimental panels, a mixture was prepared using five components, namely cardboard, water, sodium bicarbonate with 15% of the mixture weight, baking powder with 10% of the mixture weight, and vinegar with 0.1% of the mixture weight. Sodium bicarbonate acts as a foaming agent, creating porosity in the composite. Its reaction with vinegar generates CO_2 gas, which expands the mat when heated. Meanwhile, baking powder, a combination of acid and base, regulates CO_2 release, ensuring controlled expansion. This contributes to uniform porosity, improved fiber bonding, and enhanced structural integrity of the composite.

Composite panels manufacturing

In laboratory conditions, two distinct composite samples were fabricated utilizing defibrated fibers from both unprinted and printed cardboard as the primary materials. The mixtures were supplemented with sodium bicarbonate, baking powder, and vinegar before being placed in molds lined with baking wax paper. The mats were then subjected to a manufacturing process at a temperature of 150 °C for a duration of 15 h, followed by cooling to room temperature. Subsequently, the panels were trimmed to achieve a uniform thickness, removing any excessively baked surfaces. For each type of composite, four panels were produced, with dimensions of 320 mm in length and 250 mm in width, as illustrated in Fig. 1. The final thickness of the panels was 10 mm after cutting and splitting.

Fig. 1. Composite panels made from recycled cardboard

The process is presented in the flowchart shown in Fig. 2.

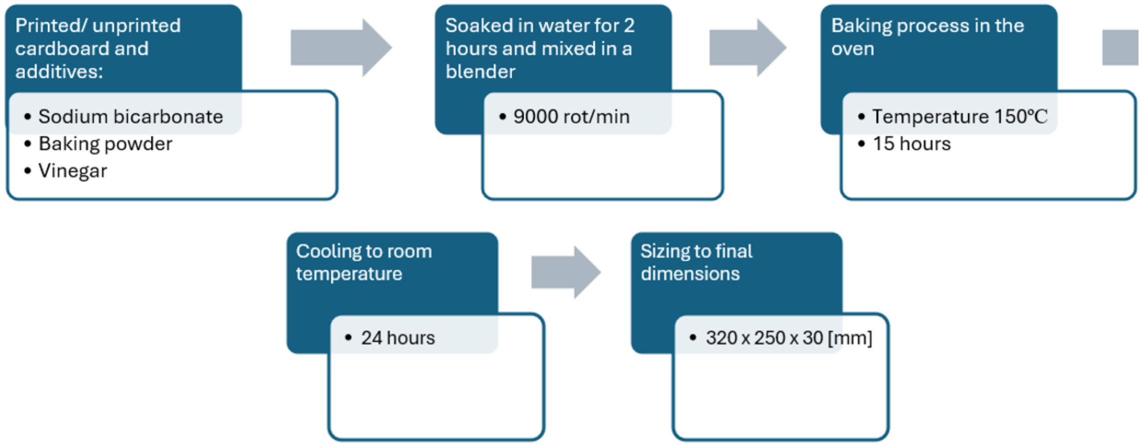

Fig. 2. The process of manufacturing the composites

Vertical density profile of the samples

The vertical density profile (VDP) of the composite panels was evaluated using the DPX300 X-ray density profile analyzer (IMAL, San Damaso, Italy). For each type of composite panel, 50 mm × 50 mm, eight specimens were prepared. The density profile of the specimen was measured through its entire thickness. Before the density profiling, the specimens were weighed using a precision scale (EU C-LCD, Gibertini Elettronica, Novate Milanese, Italy), and their dimensions were determined by the density profile analyzer.

Water resistance of the samples

Water absorption and thickness swelling of the samples were assessed following the EN 317 (1993) standard through immersion in water at room temperature. Five samples with the size of 50 mm × 50 mm of each composite type were submerged in a water bath at a temperature of 20 °C for 24 h. Sample dimensions were measured using an electronic caliper with an accuracy of 0.01 mm. The sample weights were recorded in dry condition and following 2 and 24 h soaking using an electronic scale with 0.01 g accuracy. Thickness measurements were taken at the diagonal cross points of the samples at each time interval.

Thermal conductivity (TC) of the samples

The thermal conductivity coefficient (λ) of the samples was evaluated using the HFM436 Lambda instrument from Netzsch, Selb, Germany.

Table 1. Thermal Conductivity Outline of the Samples

Test No.	Temperature 1 Lower Plate	Temperature 2 Upper Plate	ΔT $T_2 - T_1$	Average $(T_1 + T_2)/2$
1	-10	20	30	5
2	-5	20	25	7.5
3	0	20	20	10
4	5	20	15	12.5
5	10	20	10	15
6	15	20	5	17.5

These measurements were performed in compliance with ISO 8301 (1991) and BS EN 12667 (2001) standards. The experimental procedure involved quantifying the heat transferred from a hot plate (up to 20 °C) to a cold plate (down to -10 °C) across the sandwich type samples. The temperature gradient between the plates was recorded, and Fourier's Law was applied to automatically compute the thermal conductivity coefficient. Prior to the measurements, the equipment was calibrated by adjusting for temperature differences (ΔT) and average temperatures (T_m).

Sound absorption of the samples

The sound absorption of the specimens was also evaluated using a Kundt's impedance tube, model SCS80 FA (Vibro-Acoustic S.R.L., Campodarsego PD – Italy) equipped with two microphones that transmitted the recorded data to specialized software. The sound absorption coefficient of the samples with 100 mm diameter, was measured across a frequency range of 50 to 1390 Hz, with a test sound level set at 75 dB, according to ISO 10534-2. The maximum values of the sound absorption coefficients, computed by the system's software, were used for further analysis.

Porosity volume of the samples

The porosity volume of the samples was evaluated by determining their total volume and density, along with the density of the cardboard fibers. The density of the cardboard fibers was precisely measured using the AccuPyc III 1350 Gas Pycnometer. Measurements were performed on rectangular specimens with 10 mm × 10 mm × 35 mm dimensions.

Mechanical properties of the samples

The mechanical tests of the samples were carried out based on European standards, ensuring compliance with the prescribed testing methodologies and specifications for specimen number, shape, and dimensions. The modulus of elasticity (MOE) and modulus of rupture (MOR) of the samples were determined using the Zwick Roell Z010 Universal Testing Machine (Zwick Roell manufacturer, Ulm, Germany), which was equipped with a 10000 N capacity load cell, following the EN 310 (1993) European standard. The flexural tests were conducted on twelve specimens per composite panel type, following the dimensions specified in the EN 326-1 (1994) standard. The internal bonding (IB) values perpendicular to the board plane were determined following the EN 319 (1993) standard. This evaluation was performed using the same Zwick/Roell Z010 universal testing machine. The tests involved eight square specimens of 50 mm × 50 mm for each composite panel type.

Microscopic evaluation of the samples

Stereo-microscopy analysis was performed using the NIKON SMZ 18-LOT2 (Nikon Corporation, Tokyo, Japan). This analysis focused on measuring the fibers and gaps within the composite structures, emphasizing the fiber adhesion. Images were captured at magnifications of 0.75×, 2×, and 6× on both the edges and surfaces of samples cut from the two composite types.

Fourier transform infrared (FTIR) analysis

An Alpha Bruker (Bruker, Ettlingen, Germany) spectrometer with attenuated total reflectance unit (ATR) was employed for the comparative FTIR investigation of the raw materials, prepared mixtures and formed composite panels. Spectra were recorded in the 4000 to 400 cm^{-1} wavenumber range, at a resolution of 4 cm^{-1} and 24 scans per spectrum. Six individual spectra were recorded for each type of sample. These were processed for baseline correction and smoothing, before calculating an average spectrum, which was further normalized as minimum and maximum values employing the OPUS software. Corresponding data from the previous studies were used for interpretation of the results.

Statistical analysis

Statistical analysis using Microsoft Excel (Microsoft Corp., Redmond, WA, USA) was conducted to calculate the standard deviation within a 95% confidence interval and at a significance level of 0.05 ($p < 0.05$). Additionally, the Minitab software package was utilized to perform two-sample t-tests, comparing the mean values of the modulus of elasticity and the modulus of rupture values of the samples as well as their density, and thermal conductivity.

RESULTS AND DISCUSSION

Physical and mechanical properties of the samples are displayed in Table 2, including standard deviation and p-values for all the performed tests using the T-Test method.

Table 2. Physical and Mechanical Properties of the Experimental Panels

Panel Type*	Density (kg/m^3)	WA (%)		TS (%)		Thermal Conductivity (W/mK)	Porosity (%)	Flexural (N/mm^2)		Internal bond (N/mm^2)
		2 h	24 h	2 h	24 h			MOE	MOR	
A	140.3 (7.9)**	566.8 (36.2)	-	3.5 (1.0)	-	0.051 (0.001)	87	28.75 (4.2)	0.153 (0.2)	0.031 (0.006)
B	107.3 (6.7)	671.4 (30.8)	680.6 (27.3)	5.2 (0.7)	9.5 (0.5)	0.05 (0.0009)	90	19.97 (4.6)	0.111 (0.03)	0.030 (0.007)
p-values	0.049	0.000	-	0.153	-	0.357	-	0.099	0.093	0.691

* A: Unprinted cardboard composite panel; B: Printed cardboard composite panel
** The values in parenthesis are standard deviations;
WA = water absorption; TS = Thickness swelling

Physical Properties

VDP of the samples

The density for panel type A, produced using unprinted cardboard, was 140.3 kg/m³, while panel type B, those made from printed cardboard, had a lower value of 107.3 kg/m³. Approximately 31% higher density of panel A than type B could be due to more compaction fiber matrix in the samples. Furthermore, according to the statistical analysis, the VDP values of two types of specimens at the 95% confidence level were determined. The graphs (Fig. 3) indicate a linear density profile across the thickness of the panels, demonstrating consistent density variation between the core and surface layers.

The higher density values observed in panel A could be due to its unprinted cardboard base, which, in the absence of additional ink and surface treatments, resulting in more effective compaction and fiber bonding. Conversely, the lower density in panel B could be attributed to the printed cardboard, which often includes added inks, coatings, or adhesives that could create micro voids or reduce fiber bonding efficiency during the panel production process. This difference in density directly affects mechanical properties, of the samples as higher-density composites are generally associated with improved rigidity and load-bearing capacity, which agrees with observations in previous studies (Ahmad *et al.* 2021).

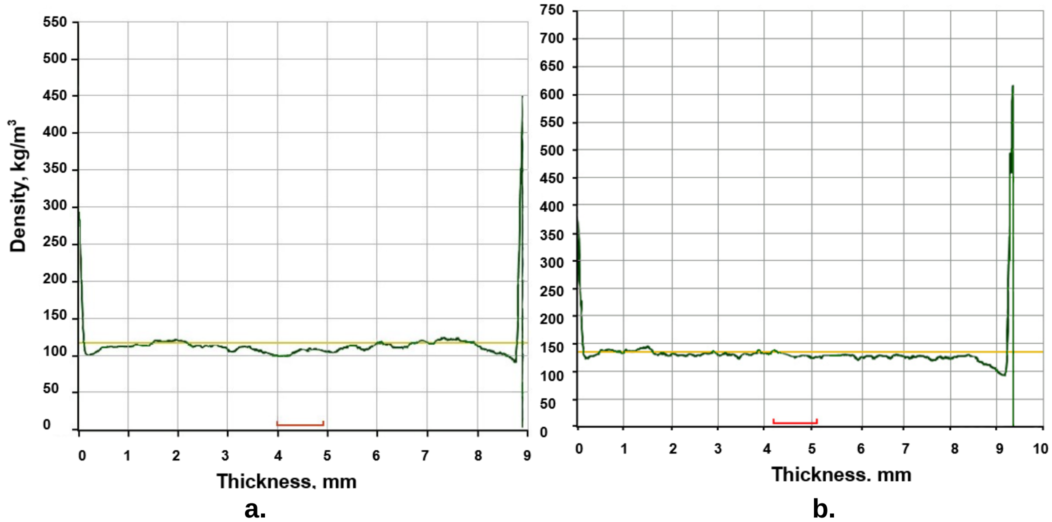

Fig. 3. VDP of the experimental composites: a. Composite A with unprinted cardboard; b. Composite B with printed cardboard

Water resistance of the samples

Panel A exhibited a 2-h water absorption value of 567%, while Panel B demonstrated a significantly higher absorption value of 671%. For the 24-h soaking, only samples from Panel B were available for measurement, reaching an absorption level of 681% as illustrated in Fig. 4. Such increased water absorption value of printed cardboard suggests that the printing process could enhance their moisture resistance, likely due to chemical treatments or additives influencing the overall fiber bonding and porosity.

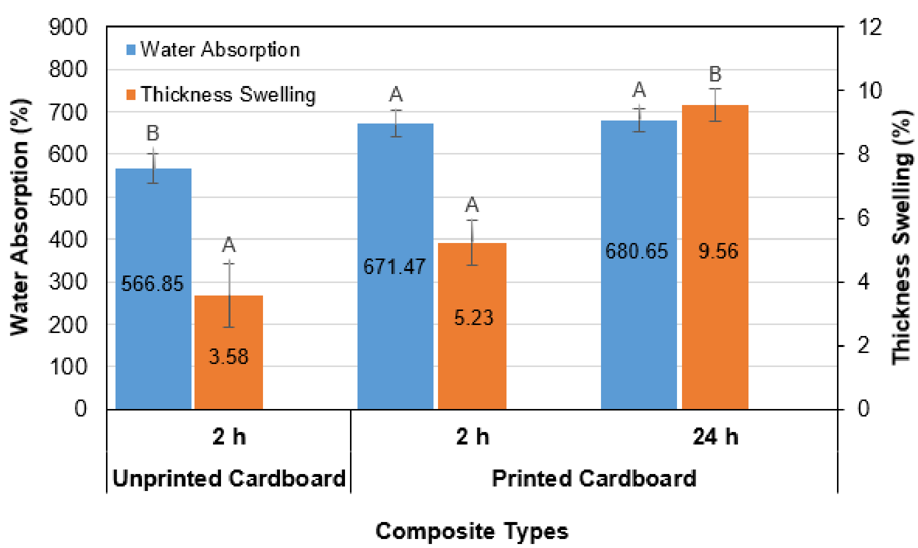

Fig. 4. Water absorption and thickness swelling of the samples

Thickness swelling, another key indicator of dimensional stability, was measured over the same intervals. In the 2-h test, Panel A showed 3.5% thickness swelling, while Panel B exhibited a higher swelling value of 5.2%. After 24 h, Panel B reached a swelling level of 9.5%, although data for Panel A was unavailable due to complete disintegration of the samples. These findings indicate that Panel A maintained better dimensional stability under short-term moisture exposure, as evidenced by its lower water absorption and thickness swelling at the 2-h soaking.

The elevated water absorption and swelling in printed cardboard imply that the printing process may reduce the material's structural integrity under prolonged moisture exposure, possibly due to increased porosity and disruption of the fiber structure. Consequently, unprinted cardboard (Panel A) would be more suitable for applications requiring higher dimensional stability, particularly in moisture-prone or humid environment.

Additionally, the relationship between low density and increased porosity in the cardboard panels further contributed to the observed differences in moisture absorption and dimensional stability. Low-density materials tend to have a higher porosity, as seen with Panel B for 90% while the same value is 87% for Panel A, which exhibited greater moisture uptake and swelling. This correlation is consistent with previous research (Ouakarrouch *et al.* 2022), which has shown that materials with lower densities typically exhibit increased moisture absorption due to their higher internal voids. These voids provide more surface area for water to penetrate, thereby compromising the material's stability.

TC of the samples

The thermal conductivity of both unprinted (Panel A) and printed (Panel B) cardboard panels was evaluated to assess their heat transfer properties. Panel A exhibited a thermal conductivity of 0.051 W/mK, while Panel B showed a slightly lower value of 0.05 W/mK. These results indicate that both materials possessed similar thermal conductivity, with only a marginal difference. Statistical analysis revealed that, despite the small difference, the values were significantly different at the 95% confidence level (Fig. 5).

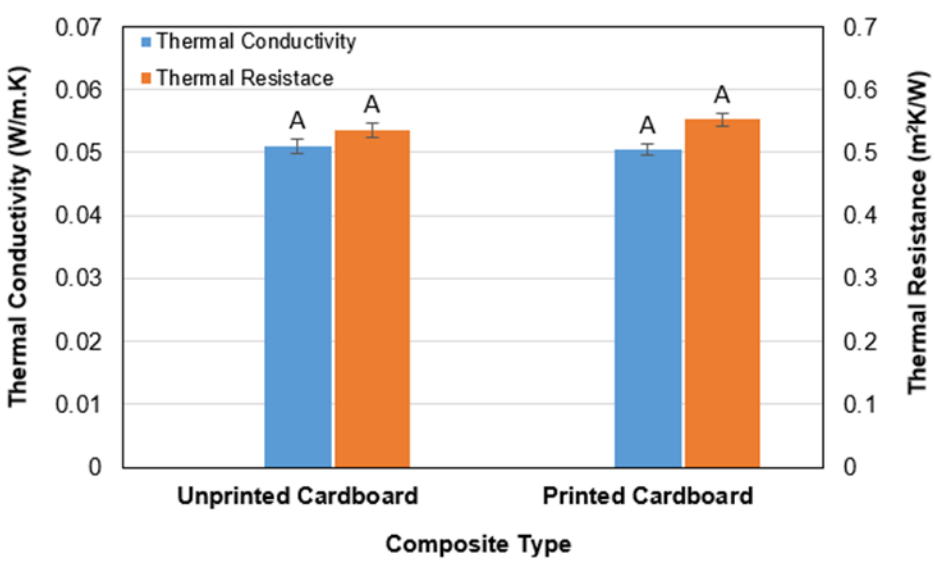

Fig. 5. Thermal conductivity coefficient and thermal resistance of the samples

Both types of panels made from unprinted and printed cardboard were relatively poor conductors of heat, which is an expected characteristic for materials with high porosity and low density. The minimal difference in thermal conductivity between the two types of cardboard implies that the printing process does not significantly affect the material's thermal insulating properties. Furthermore, the relationship between material density and thermal conductivity can help explain the observed thermal behavior.

Higher-density materials typically have fewer air voids, increasing their ability to conduct heat. The correlation between density and thermal conductivity is well documented (Mathews et al. 2023; Benallel et al. 2024), as denser materials tend to contain fewer microscopic air gaps, reducing thermal resistance and allowing heat to transfer more efficiently. The higher density of Panel A, for instance, likely contributed to its slightly higher thermal conductivity value compared to Panel B, supporting the idea that increased material density can lead to an increased capacity for heat transfer. Consequently, the relatively low density of both cardboard types likely contributes to their similar thermal conductivity, reinforcing their suitability for applications where efficient heat resistance is required.

Compared to conventional insulation materials such as polystyrene or glass/mineral wool, which have a thermal conductivity coefficient in the range of 0.03 to 0.04 W/mK (The Engineering ToolBox), recycled cardboard panels exhibited lower insulating performance. While they may not be the optimal choice for applications requiring high thermal resistance, they offer significant advantages as environmentally friendly, recyclable, and cost-effective materials. Their sustainability and potential in eco-conscious construction make them a promising alternative. Further research could focus on improving their thermal insulation properties through the incorporation of additives or structural modifications.

The thermal conductivity values of 0.051 W/mK for unprinted cardboard composite (with a density of 140 kg/m^3) and 0.05 W/mK for printed cardboard composite (density of 107 kg/m^3) align with expectations for porous, low-density materials. While the difference was statistically significant due to density variations, its practical impact remained minor. Compared to sustainable insulation materials such as polystyrene or glass wool, the tested composites exhibited slightly higher thermal conductivity but remain viable for insulation applications. The slight variation is unlikely to have a significant impact on energy efficiency, particularly in multi-layered systems. Positioning the insulation material at the core of the wall section can reduce heat transfer and, consequently, lower energy consumption, as observed in previous research on polystyrene with four density levels (Khoukhi *et al.* 2021).

Sound absorption of the samples

The sound absorption properties of composites made from unprinted and printed cardboard were determined across a wide frequency range of 50 to 1400 Hz, which is critical for assessing their potential application in acoustical environments.

A high degree of similarity in the sound absorption coefficients of both materials, highlighting their comparable effectiveness in sound attenuation and their suitability for sound control applications as depicted in Fig. 6.

The unprinted cardboard composite exhibited a peak sound absorption coefficient of 0.84 within the frequency range of 670 to 700 Hz, indicating its strong capability to attenuate sound energy in this mid-frequency range. This particular frequency range is important for applications where sound clarity and control are essential, such as in recording studios, concert halls, and other performance spaces, suggesting that unprinted cardboard could be a viable material for acoustical treatment for such applications.

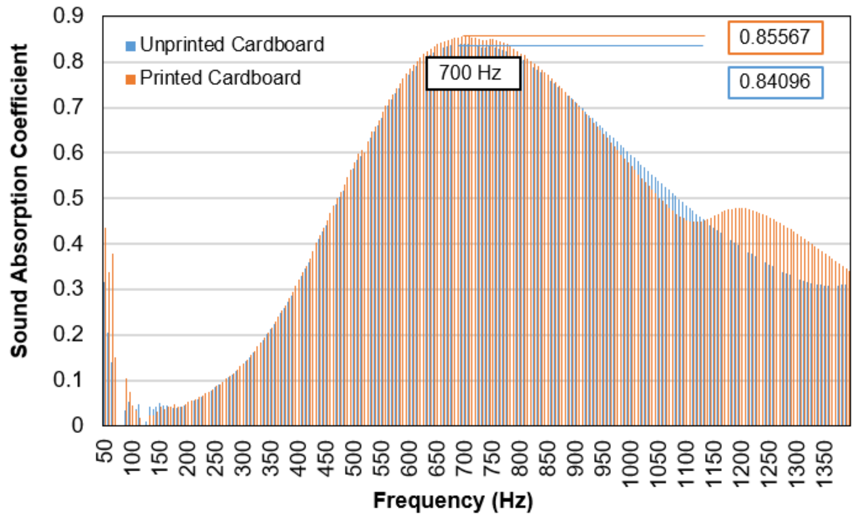

Fig. 6. Sound absorption of the samples

Similarly, the printed cardboard composite demonstrated a slightly higher average sound absorption coefficient of 0.85 within the frequency range of 675 to 725 Hz, outperforming its unprinted counterpart in this specific range. Such finding suggests that the printing process does not detract from the material's ability to absorb sound energy and, in some instances, may even enhance its acoustic performance. Such results of printed cardboard would be considered having a good potential as a competitive alternative for soundproofing and acoustic treatment, particularly in environments where the precise tuning of acoustics is critical.

Small variation in sound absorption coefficients can be attributed to the density and porosity of the cardboard composites. Lower-density materials generally exhibited higher porosity, which enhanced their ability to absorb sound by providing more internal air pockets for sound waves to dissipate. The relationship between density and sound absorption is well-documented in past studies, where higher porosity improves sound attenuation (Gokulkumar *et al.* 2019), particularly in the mid-to-high frequency range. Also, increasing the thickness of the foam composite leads to improved sound absorption, especially for low frequencies (Sun *et al.* 2025).

From the graph presented in Fig. 6 it can be noticed that the sound absorption behavior of the two composites varied across different frequency ranges. At low frequencies, specific to bass sounds (in the range 50 to 300 Hz) there was poor sound absorption (around 0.2), meaning that the sound may pass through the panels rather than dissipated, since the panels were relatively thin. Mid-frequencies (in the range 300 to 800 Hz) include common speech sounds and musical instruments, for which a high sound absorption was recorded. This finding means that these panels can be recommended for indoor environment for recording studios, or concert halls. At high-frequencies (in the range 800 to 1375 Hz) including sharp sounds like alarms, a moderate absorption was recorded, decreasing gradually after 800 Hz to around 0.35 at 1375 Hz.

Despite the difference in density, both materials demonstrate effective sound energy absorption for mid frequencies due to their structural characteristics, highlighting the importance of porosity in sound attenuation. Since sound absorption relies on both material structure and thickness, the composites may be optimized both for low and high frequencies in further research. Since the p-value is much greater than 0.05 (Table 2), there was no statistically significant difference between the sound absorption performance of the printed and unprinted cardboard composites. These values suggest moderate sound absorption. Compared to high-performance acoustic panels (NRC > 0.70) such as glass wool or mineral wool (Aural Exchange, Acharya and Dedraauw 2019), these composites would be less effective for soundproofing but could help with echo reduction.

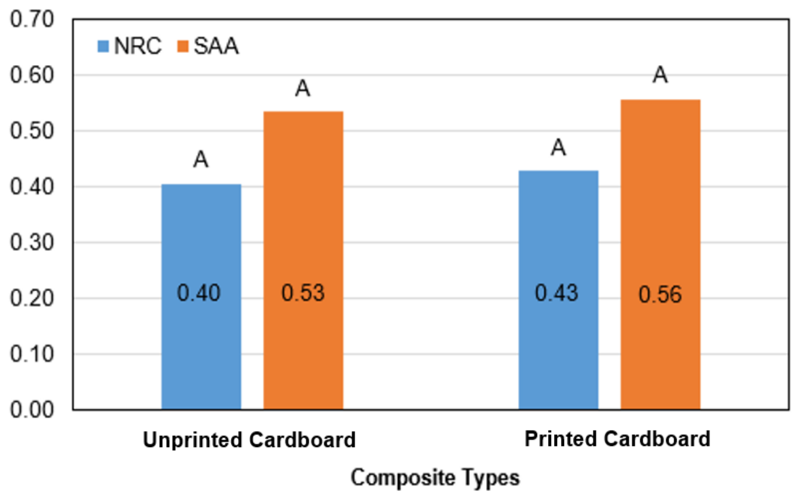

Fig. 7. NRC and SAA of the samples

The Noise Reduction Coefficient (NRC) and Sound Absorption Average (SAA) are presented in Fig. 7., calculated for the frequency range where noise is perceived by humans. Similar values were recorded for mycelium-based composites with densities ranging from 145 to 180 kg/m^3 (Sun *et al.* 2025). In this case, perforations with holes of 4 mm diameter improved the SAA at high frequencies.

Microscopic evaluation of the samples

As shown in Fig. 8a, the composite samples exhibited a porous structure with visible voids and interwoven cellulose fibers, randomly oriented, suggesting that porosity is a dominant feature. These voids are formed as the result of the contribution of baking powder and sodium bicarbonate, contributing together to the gas releasing and material expanding. Sodium bicarbonate acts as a foaming agent, creating porosity in the composite by releasing CO_2 gas when it reacts with vinegar. This reaction expands the material, forming the voids that create the high porosity of the composite, as seen in Figs. 8a and 8b. The contribution of baking powder, which is composed of an acid and a base is to regulate the CO_2 release, ensured gradual expansion and a more uniform pore distribution, preventing the formation of large voids and improving internal fiber bonding (white spots in Fig. 8b and Fig. 8c). Vinegar also had a beneficial influence on fiber softening and adhesion. From an environmental perspective, these additives are non-toxic and biodegradable, making them a sustainable alternative to synthetic foaming agents.

The large voids that can trap air and the fibrous structure suggest that the composite has low density, and it is beneficial for applications requiring lightweight materials, thermal insulation, and sound absorption characteristics. The image in Fig. 8b shows more clearly the dense and interwoven structure around the voids formed by cellulosic fibers.

The uneven distribution of the fibers might lead to variations in mechanical and thermal properties across the material. The 180× magnification of the composite sample provided context for the fiber dimensions, ranging from approximately 26.4 to 32.5 µm, as shown in Fig. 8c. The white spots visible in the image may correspond to undissolved or unreacted particles of sodium bicarbonate or baking powder. It is also possible that during the curing process, the salts from sodium bicarbonate may crystalize, forming white deposits.

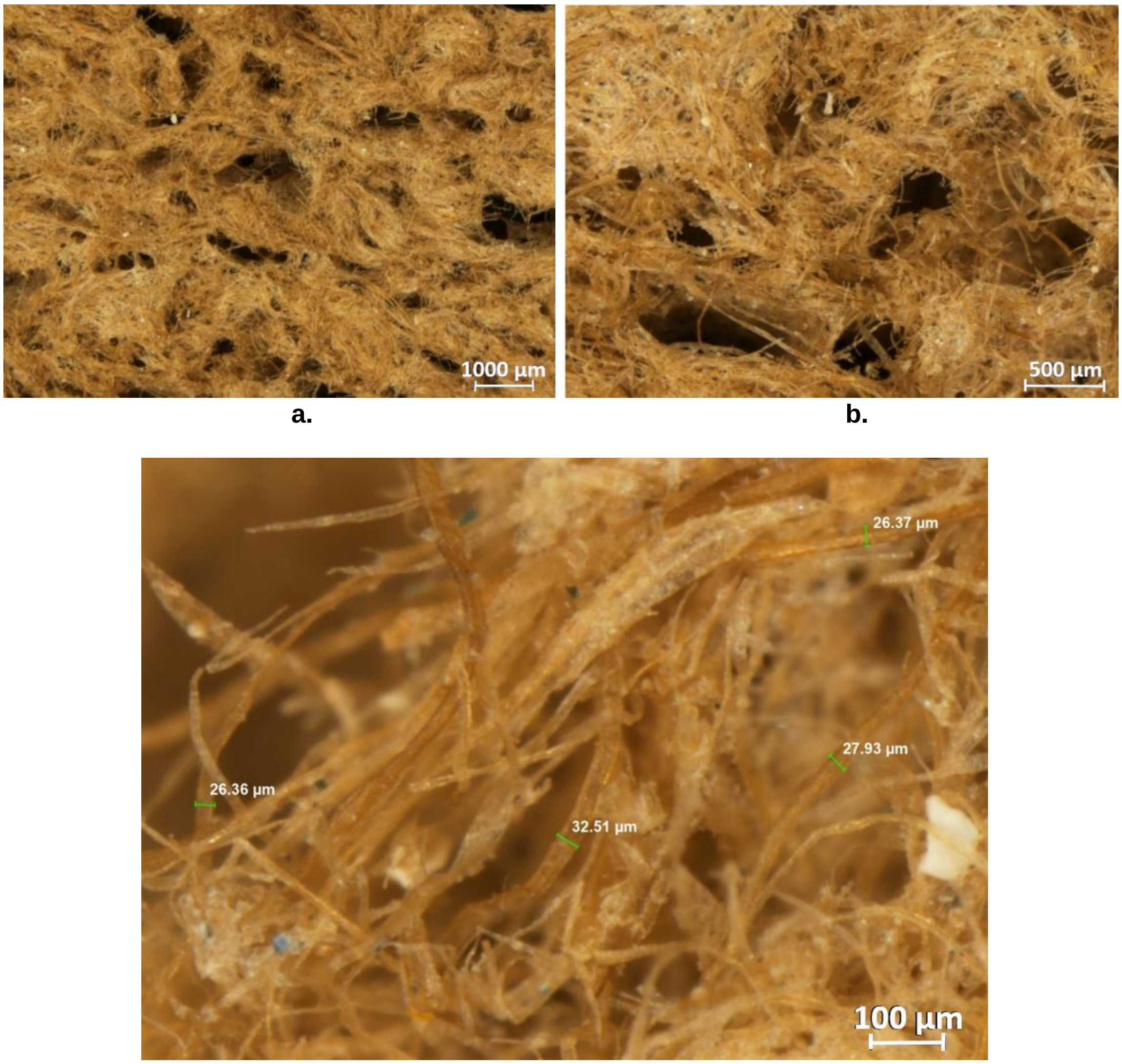

Fig. 8. Microscopic investigation: a. 22.5×; b. 60×; c. 180× magnification

Mechanical Properties

The mechanical performance of the unprinted (Panel A) and printed (Panel B) cardboard composites was evaluated through flexural tests, including measurements of MOE and MOR, as well as IB strength (Fig. 9).

Panel A had a significantly higher MOE value of 28.8 N/mm² compared to the value of 20.0 N/mm² for Panel B. Fibre-reinforced polyurethane foams with density of 100 kg/m^3 exhibited similar values of MOE (Pech-Can *et al.* 2024). This indicates that unprinted cardboard exhibited greater stiffness and resistance to deformation under applied loads, which can be attributed to its higher density (Jones and Ashby 2018) and potentially stronger inter-fiber bonding. Similarly, Panel A exhibited superior MOR, with a value of 0.153 N/mm², outperforming Panel B, which had a value of 0.111 N/mm². These results highlight the stronger flexural capacity of unprinted cardboard, making it more suitable for applications where strength properties of the panels are essential.

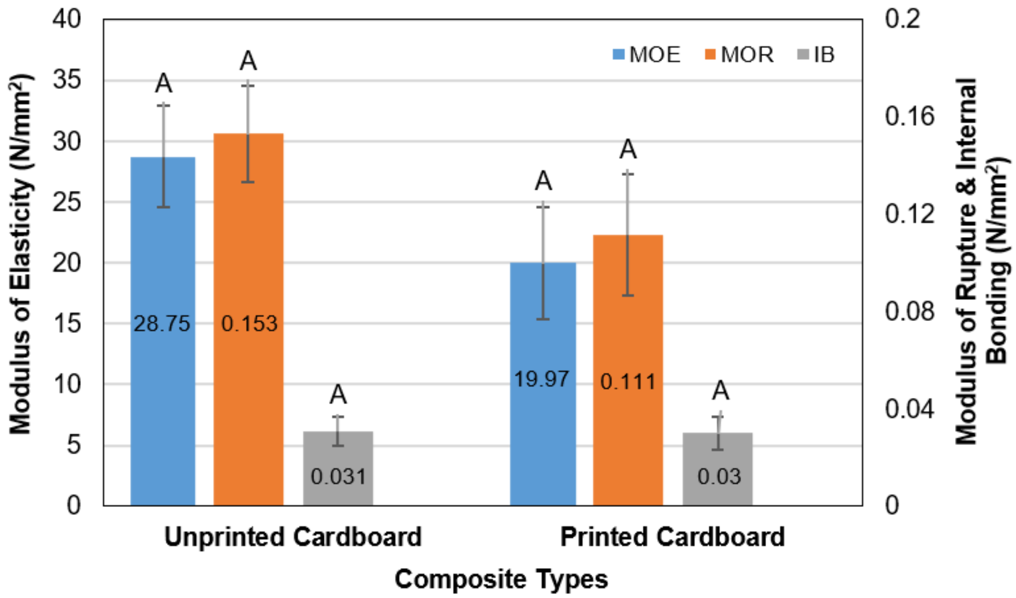

Fig. 9. Mechanical properties of the samples

In terms of IB strength, which reflects the adhesive properties and fiber cohesion within the material, Panel A again outperformed Panel B, with values of 0.031 N/mm² and 0.030 N/mm², respectively. Although the difference is marginal, it reinforces the trend that unprinted cardboard exhibits slightly better mechanical integrity, potentially due to the absence of chemical or structural modifications associated with the printing process.

While Panel A demonstrated higher values for MOE, MOR, and IB as compared to those of Panel B, statistical analysis revealed no significant difference between such properties of the two composites at a 95% confidence level. This indicates that the observed differences in mechanical properties of the specimen could be due to natural variability in the material properties.

These findings suggest that while printed cardboard offers acceptable mechanical performance, unprinted cardboard is mechanically superior across all tested parameters. The lower values observed in printed cardboard may result from increased porosity or weakened inter-fiber bonding introduced during the printing process, which reduces the overall structural strength. Consequently, Panel A emerges as the more suitable option for applications requiring higher mechanical strength and durability.

FTIR Analysis

The comparative FTIR spectra of the main raw materials used for the manufacturing of the foamed panels type A and B from recycled unprinted and printed cardboard fibers are depicted in Fig. 10.

The FTIR spectrum of the cardboard fibrous material (obtained by hammer milling the cardboard) aligns with previously published research (Wang *et al.* 2019) and highlights features characteristic for cellulosic rich fibers from lignocellulosic materials. The high absorbance at around 3330 cm^{-1} is assigned to stretching of hydrogen bonded hydroxyl groups, while the absorbance at around 2900 cm^{-1} is assigned to asymmetric and symmetric stretching of C-H bonds in aliphatic methylene and methyl groups, confirmed by scissoring vibration of C-H in methylene at 1423 cm^{-1} (Wang *et al.* 2019), assigned to cellulose (Schwanninger *et al*. 2004).

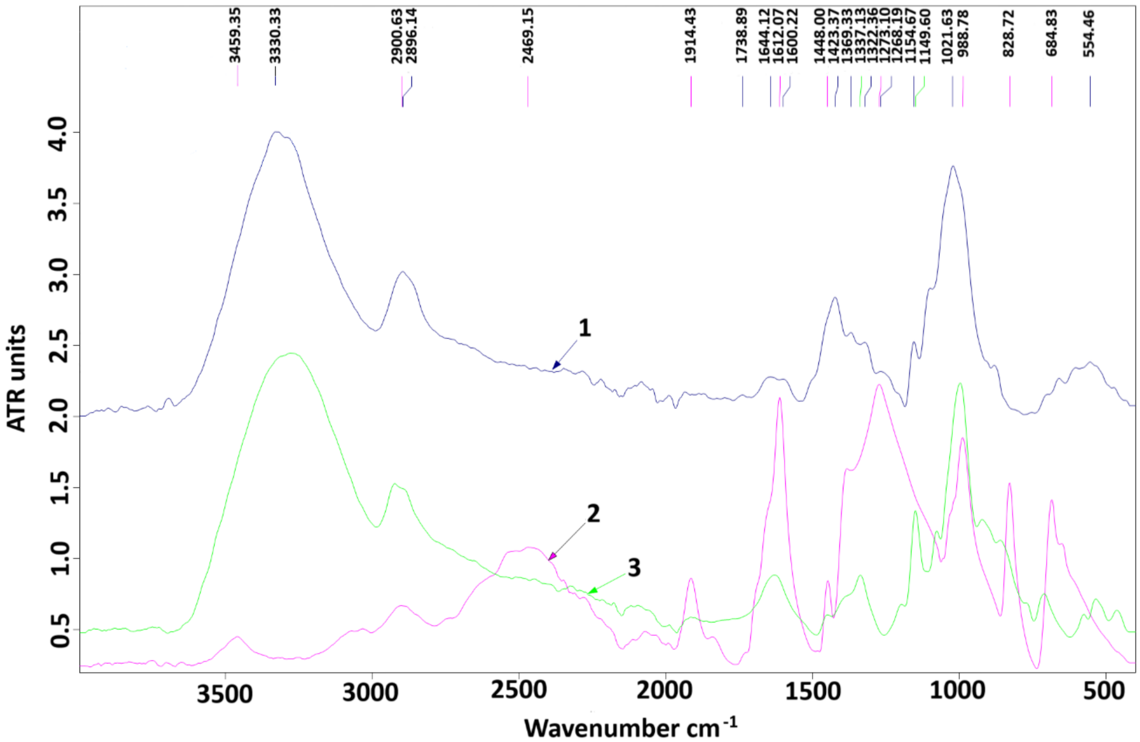

Fig. 10. FTIR spectra of the main raw materials for manufacturing the insulating composites; 1 – defibrated cardboard; 2 – baking powder; 3 – sodium bicarbonate

The small absorbance at around 1738 cm^{-1}, characteristic of unconjugated carbonyl groups, might be assigned to the acetyl groups in hemicelluloses, while the absorbances at around 1369 and 1322 cm^{-1} are assignable to the C-H vibration in carbohydrates (cellulose, hemicelluloses), respectively, to the C-H vibration in cellulose and C-O vibration in syringyl derivatives. The absorbances at 1155 and 1021 cm^{-1} are assignable to the C-O-C and C-O vibrations in carbohydrates (Pandey and Pitman 2003). The absorbance at around 1644 cm^{-1} could be assigned to either conjugated and aromatic carbonyls or to absorbed water, which seems most likely in the present case. The absorbance at 1600 cm^{-1} is attributed to an aromatic ring, very likely from the structure of lignin fragments still present in cardboard fibers, though the most characteristic aromatic skeletal vibration of lignin (1505 to 1510 cm^{-1}) was not detected. A contribution of lignin ring structures could be present though in the absorbances at 1268 cm^{-1} (guaiacyl ring breathing) and 1322 cm^{-1} (syringyl ring breathing). Accordingly, FTIR analysis results are in accordance with literature data referring the chemical composition of corrugated cardboard, composed of cellulose fibres as the main component, alongside smaller amounts of hemicelluloses and lignin (Xu *et al.* 2020), though for the fibrous material analyzed in this research the content of hemicelluloses and lignin seems to be much lower.

Sodium bicarbonate and baking powder are the ingredients added to ensure the formation of a foamed expanded and light structure during the thermal treatment phase of the manufacturing procedure, due to their decomposition with release of gases under the influence of acidic medium (vinegar) and temperature. The FTIR spectra of these raw materials (curves 2 and 3 in Fig. 10) present several absorptions on the whole wavelengths range, similarly to reference spectra from literature data bases (Chemical Book 2017; NIST Chemistry Webbook 2023) and previous research papers (Khosronia *et al*. 2023).

The FTIR spectra of the mixtures of ingredients prepared for obtaining two types of composites, as air dried material in comparison with the final composite panels A and B, resulting after the thermal treatment process is depicted in Fig. 11. An average spectrum of cardboard fibrous material is also included to facilitate comparison with the resulting panels to reveal any potential chemical structure changes occurring during the manufacturing process.

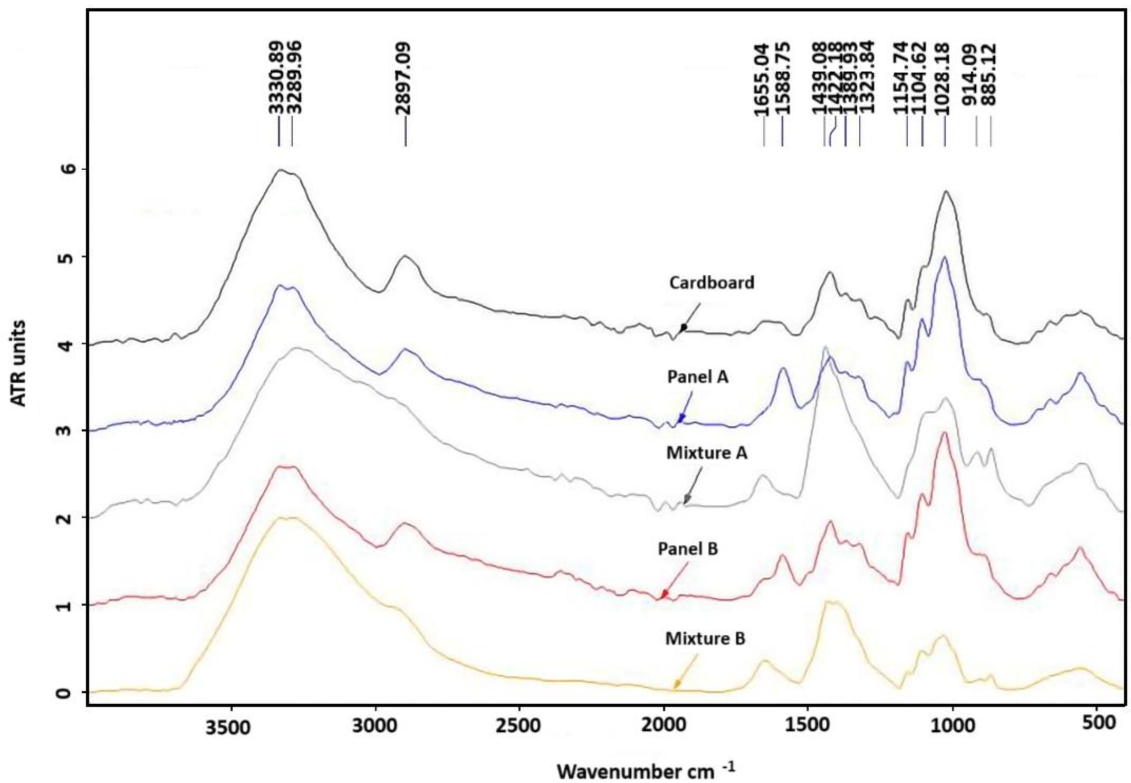

Fig. 11. FTIR spectra of the ingredients mixtures (mixture A, mixture B) for the preparation of the composites (air-dried samples) and the final panels (A, B) resulting following thermal treatment

It can be clearly observed from the depicted spectra that there were quite similar patterns for both the air-dried ingredients mixtures (A, B) and the resulting panels (A, B), regardless of the type of corrugated recycled cardboard (unprinted, printed).

In contrast, there were obvious differences between the spectra of the mixtures before thermal treatment and those of the final panels resulting after thermal treatment, for both A and B variants. The spectra of the prepared mixtures (air-dried) are a combination of the spectra of ingredients and retained water, so that some absorbance bands were superimposed or combined into large unresolved absorptions bands in the ranges 3700 to 2700 cm^{-1}, 1500 to 1250 cm^{-1}, and 1200 to 1000 cm^{-1}. The absorbances of sodium bicarbonate at 2900, 1612, 1448, 1273, 988 cm^{-1} and the high absorbances of baking powder at around 3300, 1600, 1400, and the range 1200 to 800 cm^{-1}, as well as the contributions of retained water, explain the shape of these spectra.

Following the long thermal treatment process, the foaming agents and water will be eliminated, so that the spectra of the resulting panels became different and closer as a general pattern to the spectrum of cardboard fibrous material, as observed in Fig. 11. When the spectra of cardboard fibrous raw material were compared with the spectra of the resulting panels A and B it can be observed that the main differences were the disappearance of the small absorbance at 1644 cm^{-1} alongside the increase and well differentiation of absorbance at around 1587cm^{-1}, which denotes an increase of aromatic structures. This might be just an apparent increase of aromatics due to some thermal degradation of carbohydrates, especially the more labile hemicelluloses, including by dehydration, as also suggested by the decrease of hydroxyl groups absorbance at around 3330 cm^{-1}. Such a change was also reported by Wang *et al*. (2016) for corrugated cardboard after pyrolysis at higher temperatures of 350 ºC. However, processes of aromatic compounds formation, as result of hydro-thermal treatment of carbohydrates seem also possible, as reported for starch at temperatures exceeding 320 to 350 ºC (Kaczmarska *et al.* 2017; Kaczmarska *et al.* 2019). The authors' previous research focusing on obtaining foamed panels from recycled corrugated cardboard and starch revealed a similar FTIR feature (increased absorption at 1585 cm^{-1} suggesting increased aromatics content) for the panels obtained after thermal treatment at lower temperature but longer time (105 ºC/ 24 h) (Mazaherifar *et al.* 2024). More research and alternative investigation methods are needed to understand the chemical processes occurring during the long thermal treatment of cardboard fibers and the structure and role of those aromatic compounds in defining the properties of the experimental panels.

A qualitative comparative evaluation of the spectra of panels A and B revealed only minor differences, such as slightly higher absorbances at 3330 and 1587 cm^{-1} for panel A compared to B, whilst the absorbance at 1422 cm^{-1} was slightly higher for panel B compared to panel A. It appears that two types of panels A and B were quite similar from a chemical point of view, with only small differences, supporting their quite similar physical and mechanical properties.

CONCLUSIONS

1. A systematic evaluation of the dimensional stability, thermal conductivity, sound absorption, and mechanical properties of composites prepared from unprinted (Panel A) and printed (Panel B) cardboard to assess their suitability for various applications was carried out within the scope of this study. The findings of this work revealed that significant differences in performance across these properties of the samples were apparent, offering valuable insights into the implications of printing processes on material behavior.
2. Panel type A (from unprinted board) demonstrated superior dimensional stability and mechanical performance, exhibiting lower water absorption, reduced thickness swelling, and higher flexural strength (MOE and MOR) compared to those of panel type B (from printed board). These characteristics highlight its robustness and suitability for applications requiring moisture resistance and structural integrity.

Conversely, Panel B showed higher water absorption and thickness swelling, potentially attributed to modifications in fiber bonding and porosity introduced during the printing process.

3. Thermal conductivity results of the samples indicated minimal differences between the two composites, with statistical analysis revealing a significant but subtle impact of the printing process. Both materials were confirmed to be poor conductors of heat, making them equally suitable for applications where thermal insulation is critical.
4. In terms of acoustic performance, both cardboard composites displayed effective sound absorption capabilities, with slight variations in their sound absorption coefficients linked to density and porosity differences. Further research on optimization of the composites will increase their acoustic performance to a broad spectra of sound frequencies.
5. The relationships between density, porosity, and the observed material properties highlight the critical role of microstructural characteristics in determining cardboard performance. These findings suggest that the unprinted cardboard was more suitable for applications prioritizing mechanical strength and dimensional stability – for example, as a core in lightweight boards for furniture manufacturing, where MDF or other thin wooden based materials are used for the faces. In contrast, printed cardboard remains a viable alternative for thermal and acoustic applications, such as wall and ceiling paneling, which can help reduce echo.
6. Overall, this study provides a comprehensive understanding of the effects of printing on cardboard composites, offering valuable insights for their optimized use in sustainable and cost-effective applications. Future research should explore the long-term durability under UV-exposure, biological resistance, aging and environmental impact of these materials under various operating conditions to further refine their practical applications.
7. Cardboard-based composite panels are an excellent choice for lightweight, eco-friendly, and cost-effective applications suitable for reducing reverberation in spaces like offices, classrooms, or home studios. However, their limitations in mechanical strength, moisture resistance, and durability must be addressed through coatings, reinforcements, or hybrid material designs for more demanding applications, which are the subjects of further research.

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