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SUSTAINABLE FOAM COMPOSITES MADE FROM RECYCLED CARDBOARD

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Abstract

The present study explores the physical and mechanical properties of innovative and sustainable foam composite boards developed by recycling corrugated cardboard in a baking manufacturing process. The recycled cardboard originated from printed packaging boxes (for SYP 300-150 composite) and unprinted cardboard boxes (for SYU 300-150 composite). The resulted light boards were evaluated for their density, thermal conductivity coefficient, sound absorption coefficient, modulus of rupture (MOR), modulus of elasticity (MOE), and internal bonding (IB) under flexural stresses. The results of this study demonstrate the comparable performances of the two composites in terms of physical, mechanical, thermal, and acoustic properties. Both materials exhibited low densities, making them suitable for applications where lightweight materials, thermal insulation, and sound absorption are important. This research demonstrates the potential of recycling cardboard waste into new value-added products, aligning thus to the circular economy principles. The findings highlight the feasibility of integrating recycled cardboard composites into sustainable building materials designed for the interior purpose, offering an environmentally friendly alternative to traditional insulation products.

Key words: *cardboard; recycling; light board; thermal insulation; sound absorption.*

INTRODUCTION

Currently, efforts are directed toward reducing global energy consumption and promoting the circular economy (Venkatesan et al. 2023). One key approach is the development of eco-friendly materials with low density and a reduced carbon footprint, specifically designed to enhance building thermal insulation. At the same time, researchers are focusing on recycling waste materials that negatively impact the environment, transforming them into sustainable products with diverse applications, such as thermal insulation and sound absorption (Liuzzi *et al*. 2023, Garcia *et al.* 2024).

Corrugated cardboard is extensively used as a packaging material and is commonly collected for recycling. Research has shown that cardboard fibres can be recycled up to 25 times without significant loss of their primary characteristics (Xie *et al.* 2013). According to previous studies (Xu *et al.* 2020), cellulose is the main component of cardboard (52.02%), followed by lignin (10.43%), hemicellulose (6.79%) and a high percentage of additives of 15.05%. These additives are due to the inks used to print the surfaces of the packaging boxes.

Studies on the acoustic and thermal properties of recycled cardboard indicate that overlapped cardboard sheets provide effective thermal insulation but exhibit low sound absorption coefficients (Asdrubali *et al.* 2016). However, introducing perforations into these structures can enhance the absorption coefficient by up to 3.5 times at frequencies slightly below 1000 Hz (Kang *et al.* 2021). Composites produced by bonding and pressing waste materials such as cardboard and paper with other components, including bagasse fibres (Ouakarrouch *et al.* 2022), coffee grounds (Liuzzi *et al.* 2023), and rice husk particles (Marin-Calvo et al., 2023), have demonstrated low densities along with favorable thermal and acoustic properties. Additionally, research has explored the utilization of cardboard waste in various construction applications, including concrete (Mahdi *et al.* 2023), gypsum boards (Sair *et al.* 2019), cardboard beams (Schönwälder and Rots 2007), and wood-plastic composites (Wang *et al.* 2019).

There are several research studies in the literature on the use of natural fibres and starch to produce foam composites through a baking process (Anderson and Hodson 2000, Glenn *et al.* 2001, Cinelli *et al.* 2006), primarily for food container applications. However, the use of paper or cardboard to create foam composites for thermal or sound insulation remains largely unexplored (Jensen and Alfieri 2021).

OBJECTIVE

The objective of this study is to develop sustainable foam composite boards made from recycled cardboard using a baking process and to evaluate their physical properties (density, thermal conductivity coefficient, sound absorption coefficient) and mechanical properties (flexural strength and internal bond strength) to assess their potential applications.

MATERIAL, METHOD, EQUIPMENT

Waste cardboard from two different sources was used to produce composites under laboratory conditions. The first source supplied clean, unprinted cardboard packaging boxes (for composite SYU 300-150), while the second provided color-printed packaging cardboard (for composite SYP 300-150). The cardboard was cut into small pieces and soaked in water. After fiber separation, the cardboard-water mixture, with a ratio of 1:4.8, was mechanically blended at 9000 rpm for one minute. Sodium bicarbonate (10%) and yeast (5%) of the cardboard weight were then added to the mixture. The mixture was poured into a mould with sizes (Length x width x thickness) of 350 mm x 270 mm x 30 mm, which was first lined with baking paper. The mat thus formed was baked at a temperature of 150°C for 15 hours, and cooled for 24 hours at the ambient temperature. The composite resulted by baking process is presented in Fig. 1a. After conditioning for 24 hours, the resulted composites were sized to 320 mm x 250 mm x 12 mm and the overcooked areas were removed (Fig.1b). Four replicates were manufactured for each composite type.

a. b.

Fig. 1.
Composites made of recycled cardboard, sodium bicarbonate and yeast; a. after the baking process; b. after sizing the panels.

The assessed physical properties of the samples were, as follows: vertical density profile (VDP), water absorption (WA) and thickness swelling (TS), thermal conductivity coefficient (λ), pores volume and sound absorption coefficient. VDP of the samples was determined on six square specimens of 50 mm size by using the X-ray density profile analyzer DPX300 (IMAL, San Damaso, Italy). WA and TS were determined according to SR EN 317:1996 standard for five samples with sizes of 50 mm × 50 mm. The dimensions were measured using an electronic caliper with an accuracy of 0.01 mm and the samples were weighed using an electronic scale with an accuracy of 0.01 g. The measurements were taken after 2 hours and 24 hours of immersion in the water bath. λ was assessed by using the HFM436 Lambda equipment (Netzsch, Selb, Germany) according to standards ISO 8301 and DIN EN 12667. The Fourier's Law was applied to calculate λ automatically. Six measurements were made according to the protocol presented in Table 1.

Table 1

Thermal conductivity protocol

Test no.	Temperature 1 Lower Plate	Temperature 2 Upper Plate	ΔT T2 – T1	Average (T1 + T2)/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

The pores volume was determined with high precision using the AccuPyc III 1350 Gas Pycnometer (Micromeritics Instrument Corporation, Norcross, Georgia, USA) on rectangular specimens with dimensions of 10 mm × 10 mm × 35 mm. This equipment is used to determine the true density of a porous material. The sample is placed in a sealed and pressurized chamber and the gas fills the gaps (pores). The volume of the chamber is compared to a reference chamber of known volume. True density and volumes of pores are calculated by the software of the equipment. The sound absorption coefficient was determined according to ISO 10534-2, using the impedance tube Kundt SCS80 FA (Vibro-Acoustic S.R.L., Campodarsego PD – Italy) and samples of 100 mm diameter.

Mechanical testing of the samples included modulus of elasticity (MOE), modulus of rupture (MOR) and internal bonding (IB). The tests were performed using the Zwick/Roell Z010 Universal Testing Machine (ZwickRoell GmbH, Ulm, Germany), and followed the specific international standards EN 310 and EN 319, respectively.

A microscopic investigation of the samples was performed using a NIKON SMZ 18-LOT2 stereo-microscope (Nikon Corporation, Tokyo, Japan) in order to measure the cardboard fibres and voids found on the surface of the composites, emphasizing the presence of additives and the adhesion between fibres. Images were taken with magnifications of 60×, and 180×, respectively.

The statistical analysis was conducted using Microsoft Excel to determine the standard deviation, with a 95% confidence interval and confidence level of 0.05 ($p < 0.05$). A two-sample t-test was performed using the Minitab software package.

RESULTS AND DISCUSSION

Table 2 presents the results of the physical and mechanical testing of the samples.

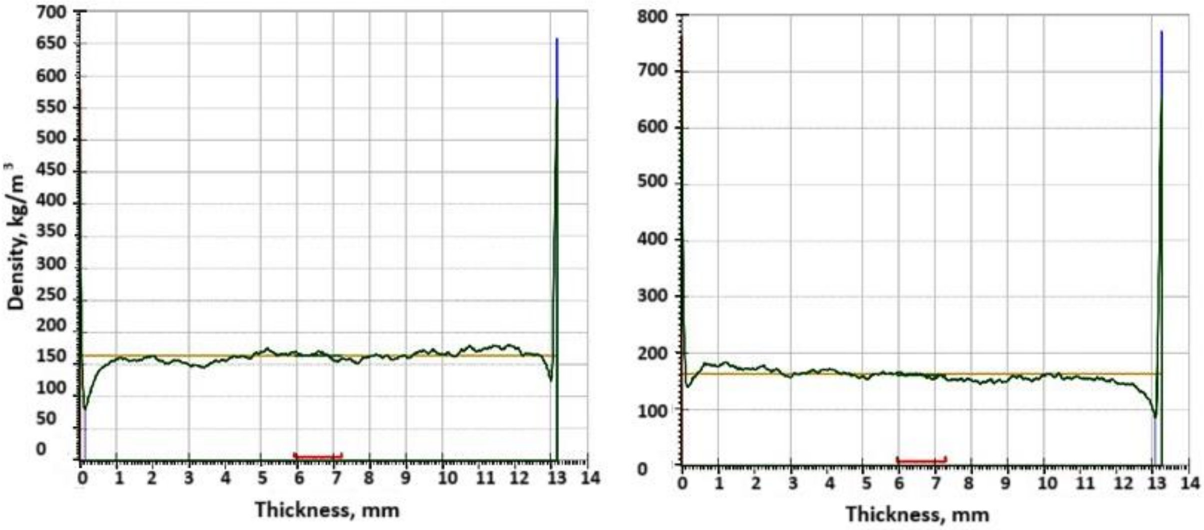
Table 2

The results of the physical and mechanical testing of the samples

Panel type	Density (kg/m^3)	WA (%)		TS (%)		λ (W/mK)	Porosity (%)	Flexural tests (N/mm^2)		IB (N/mm^2)
		2 h	24 h	2 h	24 h			MOE	MOR	
SYU 300-150	152.73	590.16	597.31	7.08	9.99	0.053	87	42.78	0.23	0.063
SYP 300-150	138.83	568.17	597.83	8.22	12.07	0.055	86	41.32	0.30	0.061

Vertical Density Profile (VDP)

As seen in Table 2, the composite made from unprinted cardboard (SYU 300-150) had approximately 9% higher density value compared to the one made of printed cardboard (SYP 300-150). Based on the statistical analysis, no significant difference between the density values of the two types of samples was determined at a 95% confidence level.



a. b.

Fig. 2.
VDP of the experimental composites: a. Composite SYU 300-150 with unprinted cardboard; b. Composite SYP 300-150 with printed cardboard.

Higher-density materials typically offer greater mechanical strength (Ahmad *et al.* 2021) and reduced porosity, leading to decreased moisture absorption (Benallel *et al.* 2024). In this context, the lower density of printed cardboard panels may result in increased porosity, leading to its relatively higher thermal conductivity and water absorption values. As concluded by (Ahmad *et al.* 2021), the materials with higher density often exhibit improved sound insulation properties, as they can better absorb and dampen sound waves due to their reduced air voids and more solid structure. As seen in Fig. 2a and Fig. 2b, the VDP is similar for both type of composites, indicating almost a constant density profile along the thicknesses of the panels.

Afinity to water

Table 2 presents the thickness swelling (TS) and water absorption (WA) values after 2 and 24 hours of water immersion. After 2 hours, the SYP 300-150 composite exhibited a slightly lower absorption rate than SYU 300-150. Despite having a lower density than SYU 300-150, SYP 300-150 showed reduced WA, contradicting the theory proposed by (Benallel *et al.* 2024). This discrepancy may be attributed to surface treatments or coatings commonly applied to printed cardboard, which can potentially reduce moisture uptake during the initial hours. However, after 24 hours of immersion, both cardboard composites displayed comparable water absorption levels (Fig. 3).

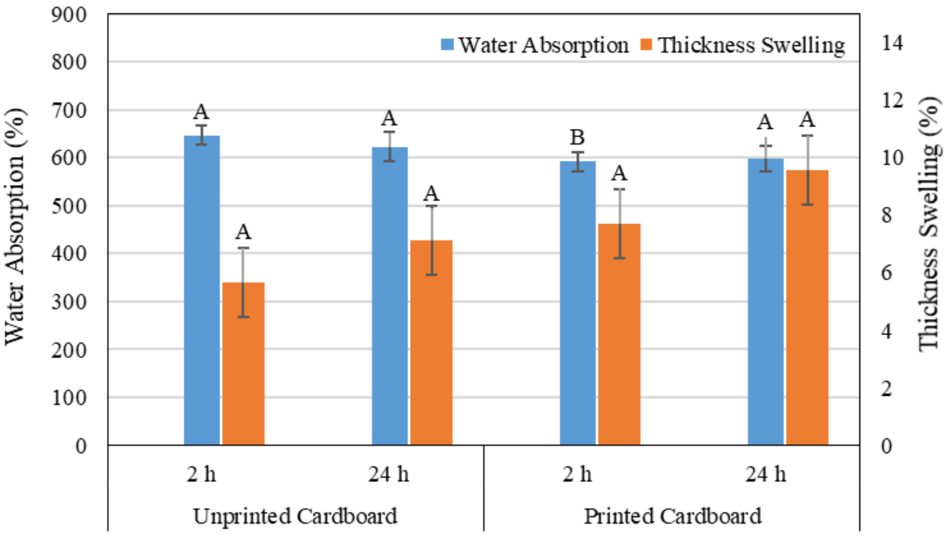


Fig. 3.
Water absorption and thickness swelling of the samples after 2h and 24h water immersion.

The high WA values can be attributed to the composites' large pores and high porosity (86%–87%), which correlate with their low density. These findings align with previous research, which indicates that materials with lower densities typically exhibit higher moisture uptake due to their increased internal voids (Ouakarrouch *et al.* 2022). In contrast, the SYU 300-150 composite demonstrated lower thickness swelling than the SYP 300-150 composite (Fig. 3), suggesting that the presence of inks and coatings may influence the material's structural response to water exposure. The increased TS observed in the printed cardboard composite after 2 and 24 hours of immersion indicates a potential susceptibility to moisture-related degradation. However, statistical analysis revealed no significant difference in water absorption and thickness swelling between the two sample types (made from printed and unprinted cardboard) at a 95% confidence level.

Thermal Conductivity (λ)

As shown in Table 2, the composite made from unprinted cardboard (SYU 300-150) recorded a thermal conductivity coefficient of 0.053 W/mK, while the printed cardboard composite (SYP 300-150) exhibited a slightly higher value of 0.055 W/mK. Both materials demonstrated low thermal conductivity, indicating their effectiveness as insulating materials. The slight difference between the two suggests that the unprinted cardboard composite provides marginally better thermal insulation than the printed one. However, statistical analysis revealed no significant difference in thermal conductivity between the composites at a 95% confidence level.

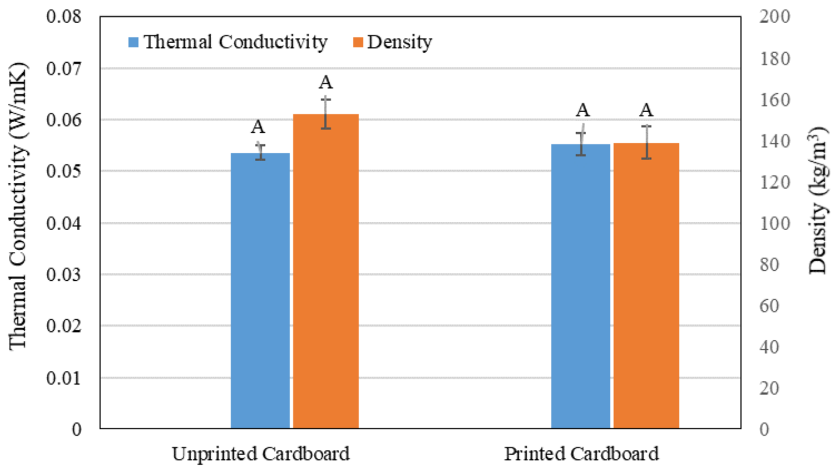


Fig. 4.
Thermal conductivity coefficient vs. density.

Sound Absorption

This study investigated the sound absorption characteristics of composites SYU 300-150 and SYP 300-150 over a frequency range of 50 Hz to 1400 Hz. The results reveal notable similarities in the sound absorption coefficients of both materials (Fig. 5).

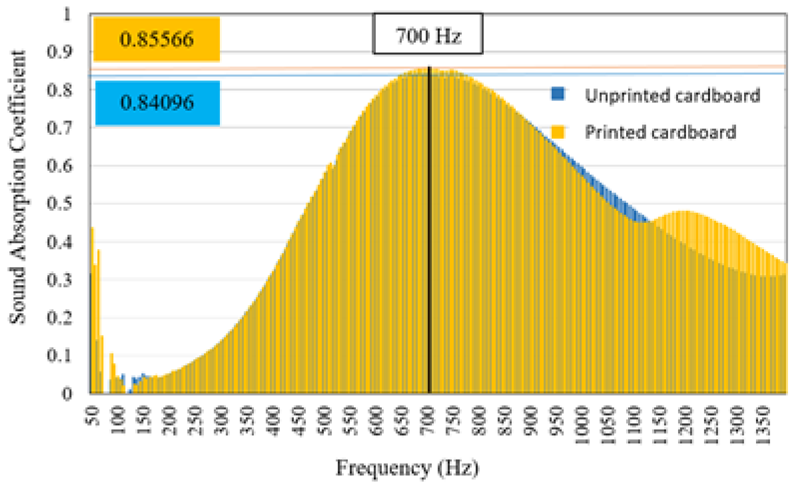
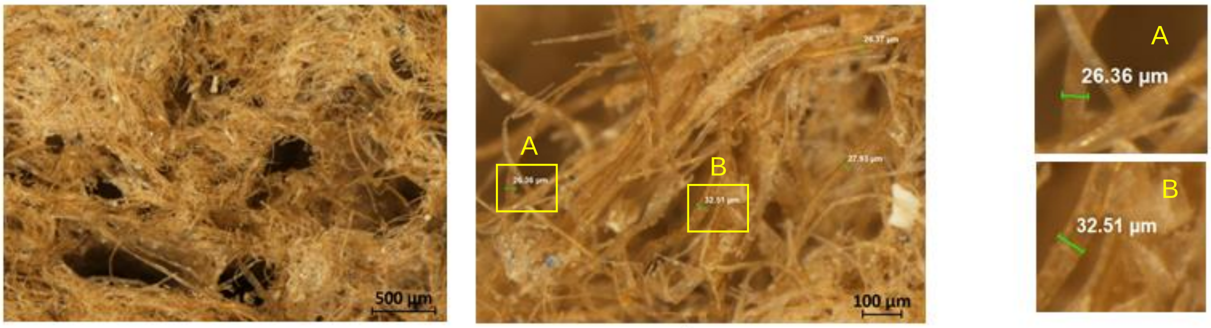


Fig. 5.
Sound absorption of the samples.

Both tested composites recorded impressive sound absorption coefficients of approximately 0.85 at a frequency of 700 Hz, demonstrating their effectiveness in mitigating mid-frequency noise. These results suggests that both composites are suited for environments where sound clarity is crucial, such as recording studios and performance venues.

Microscopic Evaluation

The images in Fig. 6 illustrate the porous structure of the composites with defined dimensions of the cardboard fibres, complying with the literature in the field (Chinga-Carrasco 2011). Porous structure of the composites is owed to the utilization of sodium bicarbonate and yeast, resulting in numerous and larger pores for both composite structures and proving the high porosity volumes of 86% and 87%, respectively. The white spots can be attributed to the particles of sodium bicarbonate, and also to the bonding areas between the fibres.



a. b. c.

Fig. 6.
Microscopic images of the U-composite; a. magnification 60×; b. magnification 180×; details of the fiber measurements from b. image.

Mechanical Properties

The resulted mechanical properties of the cardboard composites, including MOE, MOR and IB strength (Fig. 7) demonstrated similar trends in mechanical behaviour, with some notable distinctions. The SYU 300-150 composite exhibited a slightly higher modulus of elasticity (42.78 N/mm²) compared to the SYP 300-150 composite (41.32 N/mm²), but the statistical analysis revealed no significant difference in MOE values between the two types of samples at a 95% confidence level. The resulted values illustrate that little difference was made for the stiffness by the presence of the inks in the structure of the composite made from printed cardboard. In contrast, SYP 300-150 composite displayed a higher MOR (6.08 N/mm²), outperforming the SYU 300-150 composite, which recorded 4.77 N/mm². This suggests that the printed cardboard composite can withstand greater stress before failure, possible due to the reinforcing effect of printing inks and coatings. These treatments may increase the material’s surface strength, making it more resilient to bending loads. This observation is consistent with existing research, where surface modifications, such as printing or coating, have been shown to improve the mechanical resistance of composite materials by contributing to their overall structural integrity under load (Jonoobi *et al.* 2018). However, the statistical analysis revealed no significant difference in the MOR values between the two cardboard composites at a 95% confidence level. The internal bonding strength of the two composites was nearly identical, indicating the same cohesion between fibres. This outcome is in line with other research works, which emphasizing that the internal bonding of fiber-based composites is more strongly influenced by the fiber network itself than by the surface treatments (Van den Oever *et al.* 2000). The statistical analysis revealed no significant difference in the IB values between the two composites at a 95% confidence level.

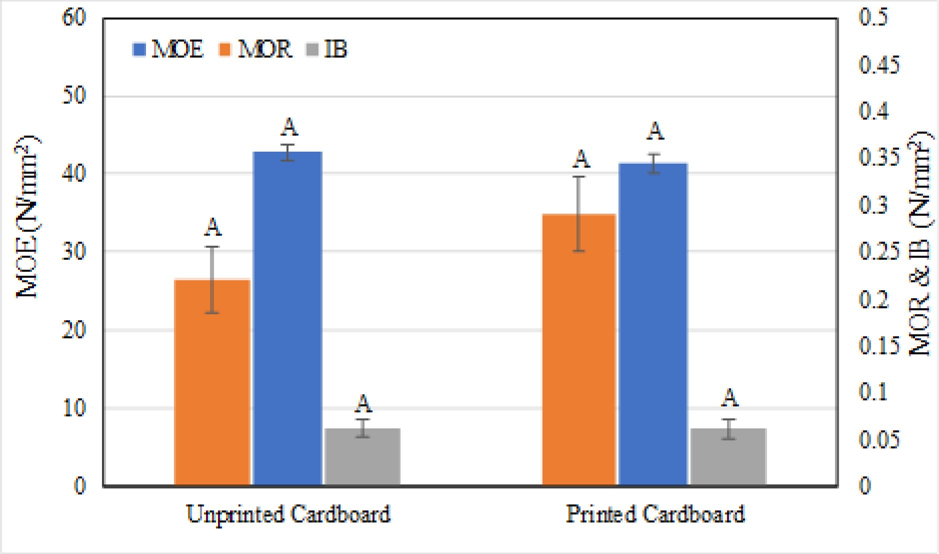


Fig. 7.
Mechanical properties of the samples.

CONCLUSIONS

- The findings of this study demonstrate the comparable performance of composites made from printed and unprinted cardboard across physical, mechanical, thermal, and acoustic properties. Both materials exhibited low densities, making them suitable for applications where lightweight materials, thermal insulation, and sound absorption are important.
- The presence of ink and coatings in the composite made from printed cardboard had a negligible impact on water absorption, thickness swelling, density, and flexural strength compared to the composite made from unprinted cardboard.
- Both composites exhibited high water absorption, confirming their hydrophilic nature, which makes them suitable for indoor applications.
- The slightly higher modulus of rupture (MOR) observed in the composite made from printed cardboard suggests a potential reinforcing effect of inks and coatings.
- In terms of acoustic performance, both materials demonstrated excellent sound absorption capabilities within the 600–900 Hz range.
- With a thermal conductivity coefficient of approximately 0.054 W/mK, these composites are well-suited for thermal insulation applications.
- Recycled unprinted and printed cardboard offer significant advantages in the production of foam composites via the baking process, particularly in terms of sound absorption and thermal insulation, with only minor differences in performance. Therefore, future research will not distinguish between printed and unprinted recycled cardboard as raw materials for composites manufactured through this process.

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