Method to recycle corrugated cardboard in eco-friendly composites

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Abstract: *This study aims to explore a sustainable method for recycling corrugated cardboard into eco-friendly composites and their potential uses in different applications. Two types of composites made from recycled cardboard (printed and unprinted) were produced and compared in terms of density, dimensional stability, modulus of elasticity (MOE), modulus of rupture (MOR), internal bonding strength (IB), thermal conductivity, and sound absorption. Samples made from unprinted cardboard demonstrated better overall performance in terms of density, thermal insulation and sound absorption. In contrast, composite B, derived from printed cardboard, exhibited greater strength. The findings suggest these materials can be viable alternatives for thermal insulation panels and acoustic panels.*

Keywords: *Cardboard, Recycling, Composite, Thermal insulation, Sound absorption.*

1. INTRODUCTION

The effective insulation of buildings plays a key role in reducing global energy consumption. Building insulation serves as a passive energy-saving technique, significantly improving energy efficiency. Insulation materials are essential across a variety of applications, due to their versatile properties such as high specific surface area, and low density. Currently, many insulation materials are derived from inorganic or synthetic materials such as expanded polystyrene [1] and polyurethane [2] with harmful environmental effects, so actually, there is a growing interest in eco-friendly alternatives [3]. Corrugated cardboard is a

widely used material composed of multiple layers of paperboard. In light of the environmental implications, recycling practices have gained importance [4], and cardboard fibers can be recycled up to 25 times. According to FAO reports, global annual cardboard production exceeds 50 million metric tons, with 90% of this being recycled [5]. Cardboard consists primarily of cellulose fibers derived from wood pulp. It contains approximately 52.02% cellulose, 6.79% hemicellulose, and 10.43% lignin, 15.71% ash and 15.05% other additives, which improve its overall performance. The fibers have an average length of 192 µm and a width of 53 µm. With a relatively low density, low cost and high recyclability, cardboard is a promising solution, as it helps to reduce energy consumption, minimize waste and promotes sustainability by aligning with circular economy principles [6,7]. Experimental research has explored various applications of recycled cardboard [8-10], except foam panels made of recycled cardboard, which remains underexplored [11].
In this study, recycled cardboard was used to develop and manufacture two types of green composites with low densities. The physical and mechanical properties of the samples were evaluated to understand their behavior.

2. MATERIAL AND METHODS

2.1 Composite panels manufacturing

Under laboratory conditions, two distinct composites were produced using defibrated fibers obtained from unprinted and printed cardboard. The fibers were mixed with sodium bicarbonate (wt.10%), yeast (wt.5%) and water. The mats were heated in a mold at a temperature of 150°C for 15 hours, followed by a gradual cooling. For each type, a total of four panels with final sizes of 320 mm x 250 mm x 12 mm were obtained. The densities of the composites were of 152.73 kg/m³ and 138.83 kg/m³ for unprinted (U-cardboard) and printed cardboard (P-cardboard) respectively (Figure1).

Figure 1: Composites made of recycled cardboard.

2.2 Physical properties

Water absorption (WA) and thickness swelling (TS) were evaluated in accordance with [12] by immersing five samples (sized to 50 mm x 50 mm) in a water bath maintained at 20°C for 24 hours. The sizes and weights of the samples were recorded before immersion, and after 2 and 24 hours. The thermal conductivity coefficient (λ) of the samples was automatically calculated with Fourier's Law with a Netzsch HFM436 Lambda equipment (Netzsch, Selb, Germany), according to [13,14] standards. The heat transfer was assessed between a hot plate (heated up to 20°C) and a cold plate (with temperatures rising from -10°C to 15°C). The sound absorption properties of the specimens were evaluated using a Kundt's impedance tube, across a frequency range of 50 to 1390 Hz, with a test sound level set at 75 dB. For each composite, two specimens were tested.

2.3 Mechanical properties

The mechanical testing procedures were conducted in accordance with relevant European standards [15-17].
The modulus of elasticity (MOE), modulus of rupture (MOR) and internal bonding (IB) strength perpendicular to the board plane were evaluated using a Zwick Roell Z010 Universal Testing Machine (Ulm, Germany) equipped with a 10,000 N capacity load cell.

2.4 Microscopic evaluation

Stereo-microscopy analysis was carried out using a NIKON SMZ 18-LOT2 microscope (Nikon Corporation, Tokyo, Japan) to examine the fiber structures and gaps within the composite materials, with particular attention given to fiber adhesion. Images were taken at magnifications of 60×, and 180×.

2.5 Statistical analysis

Statistical analysis was performed using Microsoft Excel to compute the standard deviation, with a 95% confidence interval and a significance threshold of 0.05 ($p < 0.05$). Additionally, Minitab software was employed to conduct two-sample t-tests, comparing the mean values of the MOR, MOE, IB, WA, TS, and λ.

3. RESULT AND DISCUSSION

Table 2 displays the physical and mechanical properties of the samples.

Table 2. Properties of the panels

Panel type	Density kg/m^3	λ, W/mK	WA, %		TS, %		MOE, N/mm^2	MOR, N/mm^2	IB, N/mm^2
			2h	24h	2h	24h			
U-cardboard	152.7 (7)	0.053 (0.001)	590.2 (31.1)	597.3 (29.5)	7.08 (1.90)	9.99 (1.87)	42.78 (13.4)	0.23 (0.08)	0.063 (0.17)
P-Cardboard	138.8 (17)	0.055 (0.002)	568.2 (31.2)	597.8 (36.5)	8.22 (3.76)	12.07 (2.06)	41.32 (13.4)	0.30 (0.09)	0.061 (0.3)

The values in the parenthesis represent the standard deviation.

3.1 Physical properties

The WA results indicates that U-cardboard absorbs moisture faster than P-cardboard composite, which may be attributed to coatings typically applied to printed materials, which can reduce the moisture uptake. The similar values after 24 hours suggest that long-term water absorption capacity converges, indicating that both types can reach a saturation point after prolonged exposure. The high values of WA are typical for materials with low densities, which exhibit higher moisture uptake due to their greater internal voids [18]. The greater TS value for P-cardboard may be explained by the presence of inks and coatings that can alter the structural integrity of the composite.
Both materials demonstrated low thermal conductivity coefficient, the characteristic of good insulating materials (Figure 2)

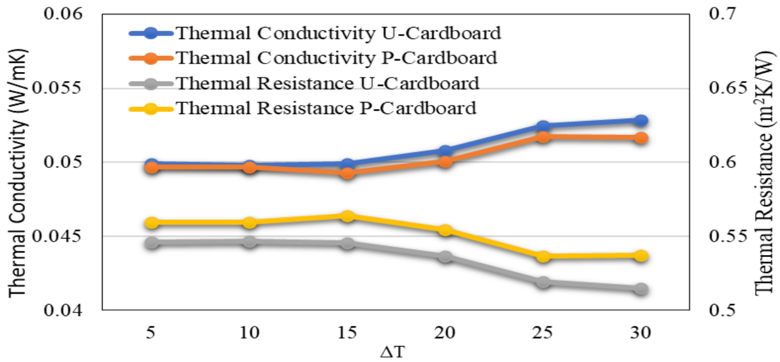


Figure 2: Thermal insulation parameters

The higher thermal conductivity observed in the P-cardboard composite can be attributed to its lower density compared to the U-cardboard composite.
On average, both U-cardboard and P-cardboard exhibited impressive sound absorption coefficients of approx. 0.85, demonstrating their effectiveness in mitigating mid-frequency noise (Figure 3). U-cardboard maintained this coefficient over the frequency range of 600 Hz to 900 Hz, with a peak of 0.88 at 800 Hz, whilst the P-cardboard maintained it in a slightly narrower range of 600 Hz to 800 Hz, with a peak of 0.87 at 675 Hz.

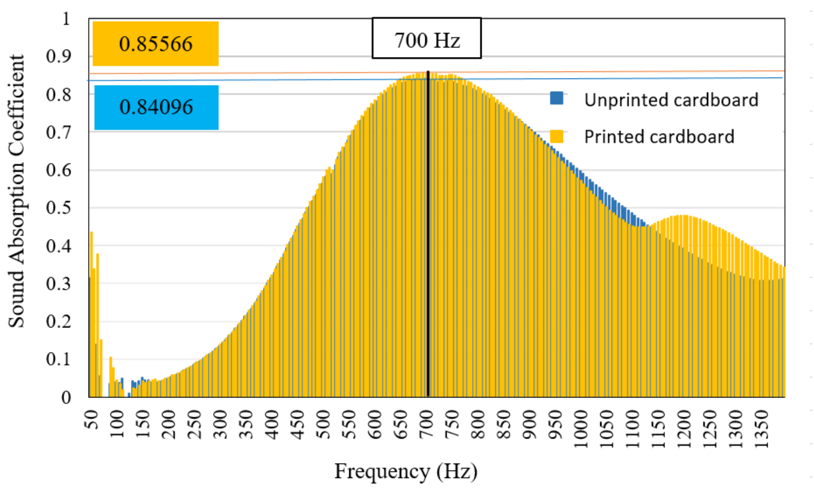
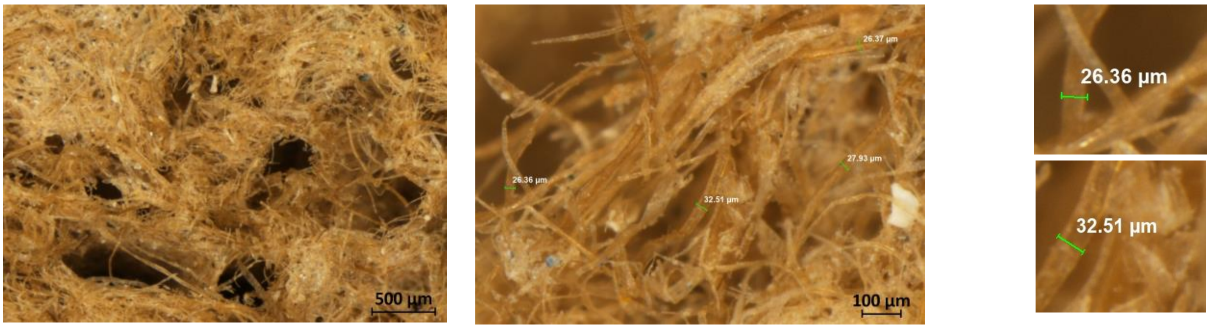


Figure 3: Sound absorption coefficient at various frequencies.

3.2 Mechanical properties

Both composites demonstrated similar trends in mechanical behavior. U-cardboard exhibited a slightly higher MOE compared to the P-cardboard, proving to be stiffer and more resistant to bending deformation. In contrast, P-cardboard displayed a higher MOR, which suggests that it can withstand greater stress before failure, likely due to the reinforcing effect of printing inks and coatings, as found also by other researchers [19]. The IB of the two composites was nearly identical, indicating that they have similar features regarding the internal bonding and proves the conclusion from [20], stating that the IB of fiber-based composites is more strongly influenced by the fiber network itself than by the surface treatments.

3.6 Microscopic investigation



a. b. c.

Figure 4: Microscopic images of the U-composite; a. magnification 60×; b. magnification 180×; details of the fiber measurements from b. image.

The images in Figure 4 illustrate the porous structure of the composites with defined dimensions of the cardboard fibers, complying with the literature in the field [21]. Pore sizes of the composites are correlated to the utilization of sodium bicarbonate and yeast, resulting in numerous and larger pores for both composite structures and proves the high porosity volumes of 87% and 86% for U-cardboard and P-cardboard, respectively.

4. Conclusion

When referring to WA and TS, both materials ultimately reach similar levels of saturation and swelling after extended exposure. In terms of thermal insulation, U-cardboard composite provides slightly better thermal insulation compared to P-cardboard, but both of them exhibited impressive sound absorption coefficients of approximately 0.85, value that recommend them for environments where sound clarity is crucial, such as recording studios and performance venues, where no high MOE, MOR and IB are needed. However, the statistical analysis revealed no significant differences in the tested physical and mechanical properties between the two types of samples at a 95%

confidence level. These results suggest that both materials could be effectively used in a range of applications, including those requiring acoustic treatments or lightweight insulation composites.

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