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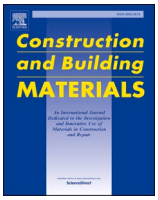

Physical and mechanical properties of foam-type panels manufactured from recycled cardboard

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ABSTRACT

This study investigated different properties of foam-type composites made from recycled cardboard. Two types of panels, type A (237.36 kg/m^3) and type B (284.28 kg/m^3) were manufactured varying the share of corn starch as binder. Dimensional stability to water, vertical density profile (VDP), thermal conductivity, bending characteristics, and internal bond strength tests were conducted. The results revealed that the higher corn starch content improved the modulus of elasticity (MOE), modulus of rupture (MOR), and internal bond strength (IB) by 56%, 33%, and 30% for panel type B, respectively. However, no significant difference was observed for the internal bonding strength test. Statistical analysis revealed that no substantial difference in the thermal conductivity property of the two types of panels was determined at a 95% confidence level. The water absorption and thickness swelling increased for both samples after 24 h water immersion. Foam-type panels made from waste cardboard would have the potential to be used for certain applications such as insulation purposes within the perspective of sustainability and a green approach.

1. Introduction

Efficient insulation of buildings is a significant contributor to overall global energy consumption. The implementation of thermal insulation in buildings is a passive technique that can enhance energy efficiency by decreasing the need for heating and cooling [28]. Insulation materials are required for a wide range of applications such as construction, thermal, and chemical processes, having their versatile features, namely raw material characteristics, large specific surface area, and low-density level [25,9].

Currently, many types of insulation materials have inorganic origin such as vermiculite, cellular, and glass fiber as well as synthetic materials including expanded polystyrene (EPS) [45], and polyurethane (PU) [22,3] which are widely used in buildings. However, most of these materials have an adverse impact on the environment due to their chemical structure. Therefore, there is a great trend to use natural-based green products as insulation materials with an environmentally friendly approach [12,7,6].

Substantial amounts of waste with limited recycling capacity in many industries resulted in the burning or landfilling of these materials creating important environmental problems. Within the perspective of this approach, there is a great trend for future research to focus on the possibility of employing lignocellulosic waste materials such as recycled paper and cardboard for different uses including insulation products. It is a well-known fact that lignocellulosic materials have certain advantages such as their insignificant negative environmental impact, less energy demand, low cost and density, abundant availability, biodegradability, and excellent thermal and mechanical properties [12,9]. The utilization of recycled materials is an effective means of optimizing resource utilization by reducing material consumption [28].

Corrugated cardboard, commonly referred to as cardboard is a popular packaging material composed of layers of paperboard. Its exceptional durability, strength, and adaptability made this product an indispensable commodity in diverse industries. In response to the ecological consequences of cardboard production, usage, and disposal, there has been heightened concern about comprehending its life cycle and adopting eco-friendly methodologies such as recycling [41]. Moreover, cardboard fibers have the susceptibility to get recycled 25 times, approximately. According to the reports of the FAO organization, the annual amount of cardboard production around the world is over 50,000,000 metric tons and 90% of this production is recycled [14].

Cardboard is predominantly comprised of cellulose fibers derived

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from wood pulp, which are bonded together using various types of adhesives and subjected to a corrugation process to enhance its structural properties. In addition, cardboard is relatively lightweight, so it can easily be handled and used for the production of value-added materials with efficient storage. It also has excellent printing capabilities, low costs, and can be effectively recycled. Therefore it has great potential to be used as raw material for widespread applications in various fields [31,9]. However, the production of cardboard involves energy-intensive processes, including pulping, refining, and drying, which contribute to greenhouse gas emissions, water consumption, and air pollution [31]. This has resulted in significant environmental challenges associated with cardboard waste disposal in landfills. Landfills generate methane, a potent greenhouse gas that is exacerbated by the presence of cardboard waste which also occupies valuable space [38]. Recycling cardboard offers a viable solution due to its ability to conserve natural resources, reduce energy consumption, and minimize waste generation [13,32]. The cardboard recycling process typically involves collection, sorting, pulping, and reformation into new value-added products. Advanced technologies such as de-inking and bleaching can be used to enhance the overall quality of recycled cardboard. Effective cardboard recycling requires efficient collection systems as well as public awareness campaigns and collaboration among stakeholders including manufacturers, recyclers, and consumers. By implementing these strategies with the objective of sustainability, the circular economy principles can be aligned with enhanced environmental performance through the promotion of sustainable use and recycling of cardboard material [32,37].

The advantage of utilizing recycled cardboard is the availability of a large amount of waste, preventing landfill filling, low cost, and low CO_2 footprint. Experimental studies were conducted with polypropylene macro-fibre blended recycled cardboard concrete [26], sandwich beams with cardboard cores [30,8], gypsum reinforced with a mixture of cork fibre and cardboard waste for building thermal insulation [36], or cellulose extracted from recycled and shredded newspaper [27]. Although different properties and recyclability of cardboard have been studied in past works there is little or limited information on the production of foam-type of panels from recycled cardboard [21].

Corn starch is used as bio-adhesive [43] in many experimental works, such as wooden based laminates [40], particleboard, medium density fiberboard (MDF), or laminated veneer lumber (LVL) [29].

A recent study [28] proposes a type of composite panel obtained by the combination of different weight fractions of recycled cardboard with corn starch as binder and boric acid 5% as additive, using a long technological process of incremental compression loading between 30 kg and 60 kg for two days, followed by demoulding after 5 days and air drying for two weeks. The resulted panels had densities between 423 kg/m^3 and 564 kg/m^3 and thermal conductivity in the range from 0.071 W/mK to 0.092 W/mK. Therefore, in this study, recycled cardboard with a combination of corn starch and sodium bicarbonate was used in order to develop and manufacture two types of experimental green foam composites with target low densities between 200 kg/m^3 and 250 kg/m^3 by conducting a shorter manufacturing process based on high temperature, without using either cold or hot press, and without using any chemical or synthetic materials that could harm or negatively affect the environment during the production or the final use. The anticipated application of these foam composites is in thermal insulation, as a potential alternative for inorganic and synthetic thermal insulation materials. Thermal conductivity, the vertical density profile (VDP), bending properties, and internal bonding strength of the samples were evaluated to have a better understanding of the behavior of such samples. It is well known that the mechanical properties values of the foam-type composite are low. However, we aimed to evaluate the effects of different fractions of cornstarch upon the magnitude of the panels' strength, in order to reach enough compactness of the structures, so to be not destroyed during handling. Furthermore, FTIR investigation of the raw materials and of the foam composites was conducted in order to observe the chemical changes.

2. Material and method

2.1. Raw material preparation

Unprinted cardboard was acquired from a service's recycling bin. Initially, the cardboard was manually ripped into small pieces (Fig. 1.a) before they were immersed in water for several hours. In the next step, a blender with a speed of 9000 rpm was employed to defibrate the softened cardboard pieces for one minute. The consumption rate of cardboard and water was 1:12, respectively. The physical [4], chemical [42], and morphological [39] characteristics of the defibrated cardboard fibers are display in the Table 1.

Four types of ingredients were mixed to manufacture the experimental panels: commercial cornstarch (100 g and 200 g respectively), 500 g cardboard, 2.4 l of water and sodium bicarbonate (20% of the mixture weight). Unmodified starch, in the powder state, with granules with sizes in the range between 10 μm and 30 μm and bulk density of 540 kg/m^3 was used in this study..

2.2. Composite panels manufacturing

Two different foam composite samples were produced in laboratory conditions using defibrated unprinted cardboard fibers as the base material. Sodium bicarbonate and corn starch were added to the mixture before the mats were placed on mold-lined baking wax paper. The mats were manufactured at a temperature of 105 °C for 24 h before they were cooled off at room temperature (Fig. 1.b). Panels were trimmed and any overcooked surfaces were sanded off to have a uniform thickness (Fig. 1.c). For each category, a total of four composites with sizes of 270 mm × 150 mm (length x width) were produced. After sanding, the panels thicknesses varied between 6.5 mm and 7.5 mm.

2.3. Vertical density profile (VDP) of the samples

The X-ray density profile analyzer DPX300,IMAL, San Damaso, Italy was used to determine the VDP. Testing was conducted on six square-shaped specimens of each composite panel type. The dimensions of the samples were 50 mm by 50 mm and the density profile was measured throughout their entire thickness. Prior to analysis, the specimens were weighed using an EU C-LCD precision scale (Gibertini Elettronica, Novate Milanese, Italy), and their dimensions were assessed by the density profile analyzer.

2.4. Dimensional stability

The water absorption and thickness swelling were determined by immersion in normal water according to SR EN 317: 1996 standard [15]. The samples with five replicates for each composite type with the dimensions of 50 mm by 50 mm were cut in order to immerse in the water bath for 24 h at the temperature of 20 °C. An electronic caliper with an accuracy of 0.01 mm was applied to measure the sample sizes. Furthermore, the weight of the samples before, after 2 h, and after 24 h were measured by using an electronic scale with an accuracy of 0.01 g. The thickness of the sample at the diagonal cross point was evaluated every time.

2.5. Thermal conductivity (TC) of the samples

Thermal conductivity coefficient (λ) measurements of the samples were conducted on two experimental composite structures using HFM436 Lambda equipment from Netzsch, Selb, Germany. The tests were carried out in accordance with ISO 8301 [19] and DIN EN 12667 [18]. The testing method entailed measuring the amount of heat transferred from a hot plate (maximum 20 °C) to a cold plate (minimum −10 °C) through the sandwich composite structure. The temperature difference between the two plates was recorded and Fourier's Law was

Fig. 1. Panels manufacturing phases; a. recycled unprinted cardboard ripped into small pieces; b. mixture; c. sanded composite panels.

Table 1
Cardboard fiber features.

	Fiber size		Density (Kg/m^3)	Cellulose %	Hemicellulose %	Lignin %	Ash %	Other additives %
	Length (μm)	Width (μm)						
Cardboard fiber	192	53	1.05	52.02	6.79	10.43	15.71	15.05

Table 2
Thermal conductivity testing protocol.

Number of Tests	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

used to automatically calculate the TC coefficient. Prior to testing, calibration of the equipment was performed based on temperature differences (ΔT) and mean temperatures (Tm).

2.6. Porosity volume of the samples

The porosity volume for both composite samples A and B was determined according to the volume and density of each sample and cardboard fiber density. Firstly, the volume of the cardboard fibers was computed for each composite sample; based on the proportionality of its fiber density, sample density and volume. Ultimately, the porosity volume (regardless of the present amount of cornstarch) was calculated by subtracting the volume of cardboard fibers from each sample volume. Testing was accomplished on square-shaped specimens with dimensions of 50 mm by 50 mm for both composite types. An electronic caliper with an accuracy of 0.01 mm was applied to measure the sample sizes.

2.7. Mechanical properties of the samples

The mechanical testing procedures followed the appropriate European standards with regard to the testing methodology and the specifications of the specimens used, including their number, shape, and dimensions. The modulus of elasticity (MOE) and modulus of rupture (MOR) of the samples were evaluated employing the Zwick/Roell Z010 Universal Testing Machine, equipped with a load cell having a capacity of 10000 N based on the EN 310:1993 standard. The flexural test was carried out on six specimens with the required shape and dimension of EN 326–1 standard for each composite panel type.

The determination of internal bonding (IB) values perpendicular to the plane of the board was carried out in accordance with EN 319 standard. The Zwick/Roell Z010 universal testing machine from Ulm, Germany, with a maximum force of 10000 N was utilized for conducting these tests. Testing was executed on six 50 mm by 50 mm square-shaped specimens of each composite panel type.

2.8. Evaluation of the samples using FTIR

Fourier Transformed Infrared spectroscopy (FTIR) was employed in this research. Investigation was carried out with an Alpha-Bruker FTIR spectrometer (Ettlingen, Germany) equipped with ATR (Attenuated Total Reflectance) module. The spectra were recorded in the range 4000–600 cm^{-1}, at a resolution of 4 cm^{-1} and 24 scans, on the materials employed to prepare the foamed panels and on the resulted products. Minimum 3 spectra were recorded on each type of material. The recorded spectra were further processed for baseline correction and smoothing and average spectra were computed for each category of sample using the OPUS software (version 7.2, Bruker, Ettlingen, Germany). Average spectra were further normalized (Min-Max normalization) and compared to highlight the characteristic chemical features. Literature reference data were employed for the absorption bands (peaks) assignment and interpretation of the results.

2.9. Microscopic evaluation of the samples

Stereo-microscopy analysis was conducted using NIKON SMZ 18-LOT2 (Nikon Corporation, Tokyo, Japan) instrument. The fibers and gaps in the structure of the composites were measured, highlighting the presence of corn starch and the adherence between fibers. Images with 30 × , 60 × and 180 × magnification were taken on the edge and on the surface of the samples cut from the two types of composites.

2.10. Statistical analysis

The statistical analysis employed the determination of standard deviation in Microsoft Excel for a confidence interval of 95% and a significance level of 0.05 ($p < 0.05$). Two sample t-test method was performed with the Minitab package for analyzing how the average values of modulus of elasticity and modulus of rupture for flexural, density, and thermal conductivity were significantly affected by the participation of corn starch in the structure of the composites.

3. Result and discussion

Table 3 displays the physical and mechanical properties of the samples.

3.1. Thermal conductivity

Thermal conductivity values of panel types A and B were found as 0.048 W/mK and 0.049 W/mK, respectively. Based on the statistical analysis, no significant difference between the thermal conductivity values of the two types of samples was determined at a 95% confidence level. Although sample type B has a 46.9 kg/m^3 higher density than that of sample type A it appears that their overall porosity (80% and 76% of the total sample volume for sample A and B, respectively) and homogeneity were quite similar to each other (Figs. 5a and 5b) resulting in almost the same value of thermal conductivity. Similar conclusions were almost found in previous studies [16,28]. Based on the findings of the work, the use of two different amounts of corn starch as a binder in panels did not create any significant difference in their thermal conductivity characteristics, as illustrated in Fig. 2b. The low densities of the panels (237.4 kg/m^3 and 284.3 kg/m^3) accompanied by the low values of the thermal conductivity coefficients (0.048 W/mK and 0.049 W/mK) recommend the composites presented in this paper for thermal insulation applications in building industry. Compared to other thermal insulation panels made from recycled cardboard and cornstarch [28], but manufactured with different technology, the composites from the present research have lower densities than 423 kg/m^3 and 564 kg/m^3 and lower thermal conductivities than 0.071 W/mK to 0.092 W/mK, as obtained by the mentioned researchers. In the same category can be included the composites based on waste cardboard (60%) and natural fibers (40%) [7], which recorded thermal conductivities between 0.072 W/mK and 0.099 W/mK. Thermal insulation biocomposites from rice husk [33] recorded also higher densities (378 kg/m3) and higher thermal conductivity coefficient (0.08 W/mK) compared to the foam composites proposed in this paper, but similar values of thermal conductivity coefficient (0.041–0.046 W/mK) were obtained by other researchers [27] for cellulose and rice-husk based materials.

3.2. Vertical density profile

The typical vertical density profiles (VDP) of both types of samples are illustrated in Figs. 2c and 2d. The VDP value was evaluated in a constant mass of 237.4 and 284.3 kg/m^3 for A and B panels, respectively. Panel B had approximately 17% higher density as compared to that panel A due to having a higher amount of corn starch. Such results are in agreement with those of previous studies [11]. Furthermore, according to the statistical analysis, the VDP values of two types of specimens at the 95% confidence level were appraised. Regarding the graphs, the higher density of both the top surface and bottom surface of the panels is owing to more contact with high temperatures in the oven. However, it is observed in thin surfaces and possibly increases flexural test results. Although, the density profile along the thickness has a linear trend showing the homogeneity of the profile, as in the case of the fiber boards [5]. The higher peaks of the density on the faces indicate that during the treatment of the composition at high temperature, the faces are plasticized and set a higher density than in the core, where the heat penetrates later.

3.3. Dimensional stability

Table 3 displays the dimensional stability characteristics of the samples in the form of thickness swelling (TS) and water absorption (WA).

Samples made with 100 g corn starch had TS average values of 12.04% and 16.4% for 2 h and 24 h water exposure, respectively (Fig. 2a). Corresponding values for the samples having 200 g corn starch are 10.94% and 19.6%. Having higher amount of starch in the samples improved their thickness swelling 9.14% as compared to 2 h water exposure. However, the highest TS value of 19.6% was determined for the same type of samples when the water exposure time was extended to 24 h. It is well known any types of starch is hydrophilic which is the most important drawback when they are used as the binder in biocomposites [1]. It appears that having 200 g corn starch in the samples had certain level of resistance against to water exposure. However its dissolving was expedited with extended exposure time due to their very porous structure with possibly non-uniform distribution of the starch in those made with higher starch content.

Overall, WA values of the samples followed a relatively similar trend of TS characteristics. Large WA of composite bodies is correlated to both size of the porosity and connectivity through the walls of pores. Based on the findings in this work it seems that higher amount of starch content resulted in 17.4% and 14.6% lower WA values as a result of 2 h and 24 h water exposure, as can be seen in Fig. 2a.

The negative aspect of using starch as a binder with unsatisfying values of WA and TS is addressed by using either waterproof materials such as wax, oil, and so on [20] or consideration of fiber treatment [1].

3.4. Mechanical properties

Modulus of elasticity (MOE) and modulus of rupture (MOR) values of 235.7 N/mm^2, 535.2 N/mm^2, and 22.1 N/mm^2, 33.1 N/mm^2 were determined for sample types A and B, respectively (Fig. 3a). It has been well established that there is a linear relationship of almost any fiber-based composites between flexural bending characteristics and their density levels [17,23,35].

In addition to that, fiber-based composites without regarding their types and manufacturing parameters would have enhanced MOE and MOR values with increasing binder content [2,24,44]. This trend is depicted in Fig. 3a for the two types of panels, for which the increase in corn starch content resulted in higher MOR and MOE.

Sample type B having 200 g corn starch content had 2.27 and 1.48 times higher MOE and MOR values than those of sample type A, respectively.

In previous studies, experimental particleboard and fiberboard panels made with low percentage of urea formaldehyde and modified starch revealed that having a higher amount of starch in the panels improved their overall bending properties [10,11].

Although there is no well-established linear relationship between panel density and their internal bond strength (IB) values in various wood and fiber-based composites it is clear that a general trend exists, namely the IB strength values of the samples increase with increasing

Table 3
Properties of the panels.

Panel type	Density (kg/m^3)	Thermal Conductivity (W/mK)	Water Absorption (%)		Thickness Swelling (%)		Flexural (N/mm^2)		Internal Bonding (N/mm^2)
			2 h	24 h	2 h	24 h	MOE	MOR	
A	237.4	0.048	336	377	12.04	16.4	235.7	22.1	0.30
B	284.3	0.049	277	321.9	10.94	19.6	535.2	33.1	0.43

A: 100 g corn starch/composition (20% of the cardboard weight)
B: 200 g corn starch/composition (40% of the cardboard weight)

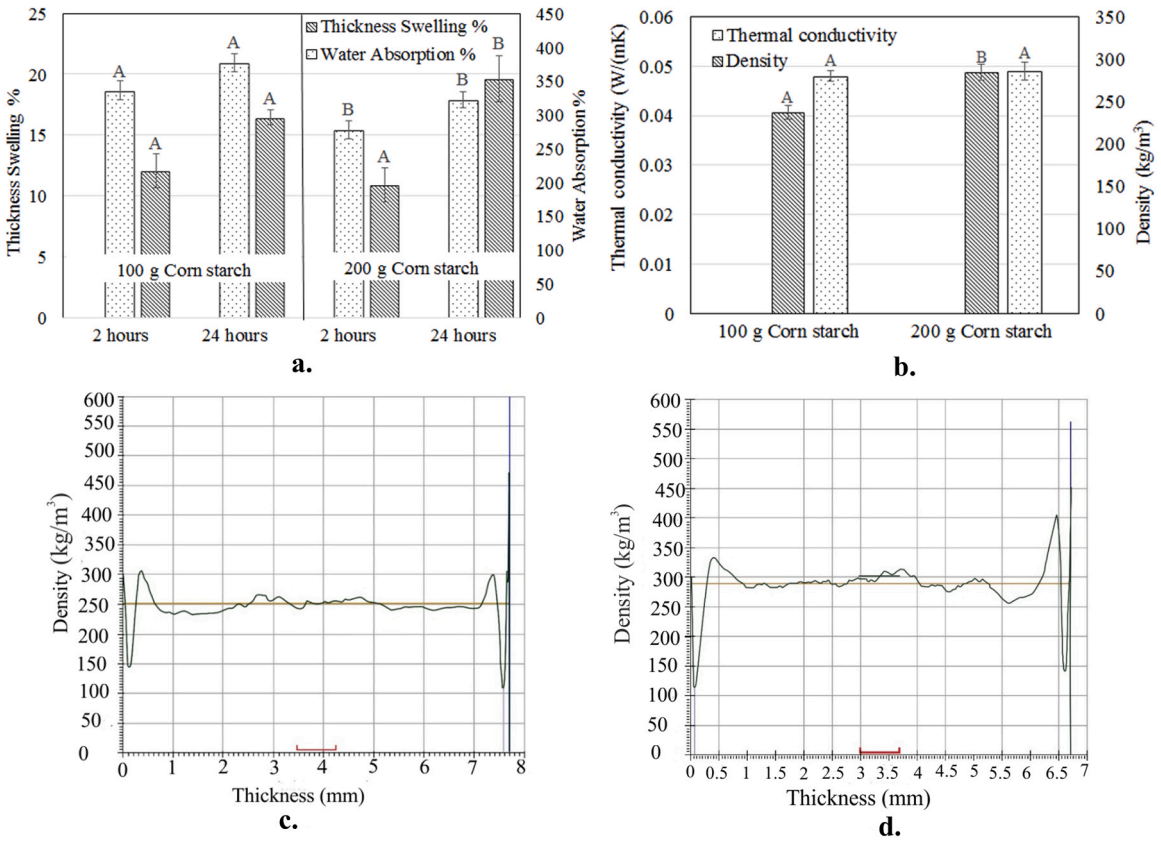

Fig. 2. Water absorption and thickness swelling after 2 h and 24 h water immersion (a); thermal conductivity coefficient vs. density (b); typical vertical density profile of the samples type A (c); vertical density profile of the samples type B (d).

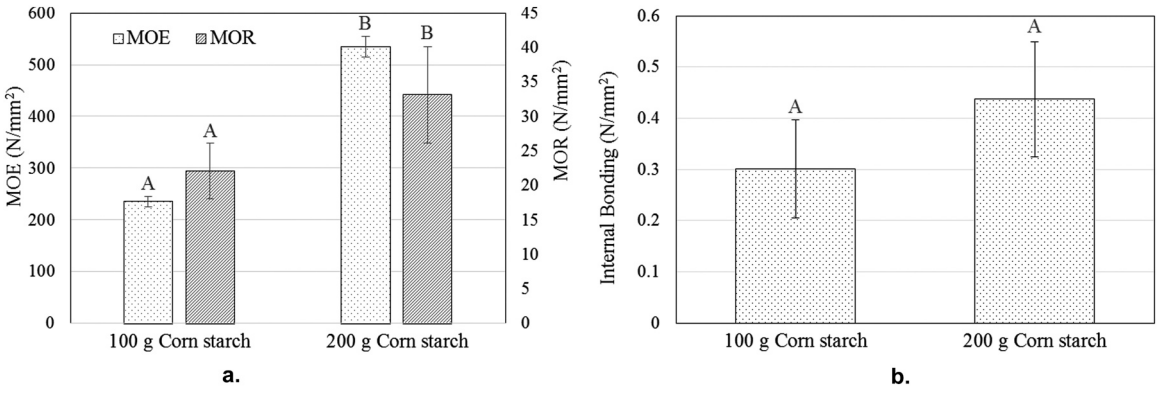

Fig. 3. (a) Flexural properties, (b) Internal bond strength values of the samples.

their density [17,23,34].

Samples B made with 200 g starch had 0.43 N/mm^2 IB value, which is 1.43 times higher than that of sample type A manufactured using 100 g starch as binder, as illustrated in Fig. 3b. It is clear that higher amount of binder along with higher density value contributed to improved IB values of these panels. As stated previously, the main objective of the experimental panels made in this study was to use such products for insulation purposes rather than where high strength properties are desired. However, if such panels are overlaid with thin medium-density fiberboard or any other overlays, their utilization could be extended to low weight panels for furniture or door manufacturing. Therefore, it could be a good approach to have a general idea of their mechanical properties which may contribute positively on the service life of the final products mentioned above.

3.5. FTIR characterization of the samples

The FTIR spectra of the main materials employed for manufacturing the experimental foamed composite panels, namely recovered corrugated cardboard residues as fibrous material and corn starch as binder, are comparatively depicted in Fig. 4. For the corrugated cardboard obtained from three layers of paper glued together, FTIR investigations were carried out on the surface papers (sp) on both their faces (f) and verso sides (v) and on the inner paper sheet (ip). A first visual examination of the spectra high light the similarity of all these materials as chemical structure by the common absorption bands in the ranges 3600–2800 cm^{-1}, 1800–1200 cm^{-1} and 1200–800 cm^{-1}, with small differentiations in terms of shifting of some peaks to lower or higher wavenumbers or relative intensities of other absorptions. This should

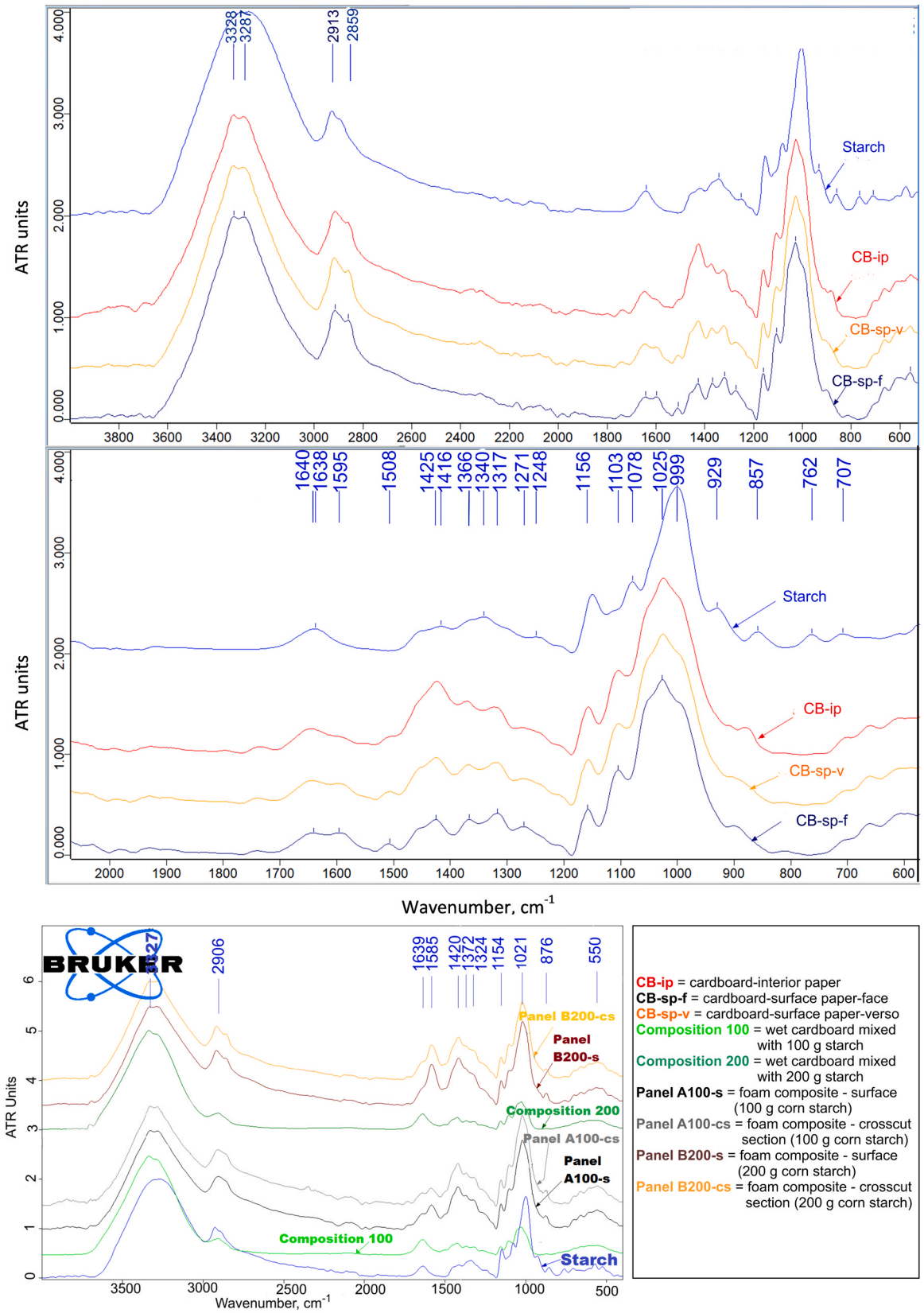

Fig. 4. Comparative FTIR spectra of the main materials employed for the foamed panels preparation and comparative FTIR spectra of the wet compositions with different amounts of starch content (100 g, 200 g) and of the resulting composite materials (Panel A 100, Panel B 200), investigated on the surface (s) and cross-section (cs) (IR rage 4000–600 cm^{-1}).

not be unexpected because these materials are based on natural polymers with a polysaccharide structure. The main component of the papers is cellulose which is pulp extracted by different procedures from lignocellulosic resources, starch is also a natural polysaccharide composed of two polymers: amylose and amylopectin, while the adhesive employed to produce the corrugated cardboard is most often a starch based one. For both cellulose (pulp) and starch the basic unit is glucose in the two anomeric forms: α in the case of starch and β in the case of cellulose.

The absorption at around 3300–3400 cm^{-1} are assigned to the H –bonded hydroxyl groups present in large number in all the polysaccharides, while the double peak at around 2860–2913 cm^{-1} is due to the C-H stretching vibration in methylene groups (Fig. 4 top). The main characteristic absorption bands for polysaccharides, including starch, are in the region 1200–1000 cm^{-1}, arising from C-O, C-C, C-O-C and C-O-H stretching, C-O-H bending and pyranose ring asymmetric valence vibration (Schwanninger 2004, Warren 2016). Absorptions bands at 1156 cm^{-1}, 1103 cm^{-1}, 1025 cm^{-1}, 896 cm^{-1}, respectively 1147 cm^{-1}, 1076 cm^{-1}, 1000 cm^{-1}, 929 cm^{-1} are present in the fingerprint region of spectra of the cardboard paper sheets and corn starch powder, as can be observed in Fig. 4 (middle). The absorption bands at 1425 cm^{-1}, 1366 cm^{-1}, 1317 cm^{-1}, respectively at around 1595 cm^{-1}, 1508 cm^{-1} (small band) and 1270 cm^{-1} (small shoulder), present only in the spectra of cardboard sheets can be associated to cellulose and residues of lignin, respectively. The absorption at 1640 cm^{-1}, present in the spectra of both cardboard and starch could be assigned mainly to the absorbed water, more pronounced in starch (Kaczmarska, 2019) than cardboard, where a contribution of residual lignin might be considered (Schwaninger 2004). This absorption also corresponds to amide I vibration and may indicate some protein impurities in starch (Warren 2016).

The spectra in Fig. 4 (bottom), illustrate the changes brought about by the temperature treatment during the baking phase at 105 °C for 24 h, in the preparation process of the composites. The main difference between the spectra of the wet compositions containing the fibrous material, the starch as binder (two compositions with amounts of 100 g and respectively 200 g for 500 g of cardboard fibers) and sodium bicarbonate as foaming agent and the resulting solid / cured panels would result from the loss of water, so that the characteristic absorption peaks are better highlighted. The absorption at 1640 cm^{-1}, characteristic to the starch (adsorbed water) becomes barely visible as a shoulder after the production process, and this change is more obvious for the panels B, obtained from mixtures with a higher (double) content of starch.

At the same time, a distinct and increased absorption band with a maximum at 1585 cm^{-1} (assignable to aromatic ring structures) appears, in the spectra of the cured composites (higher for panels B than A). This would suggest dehydration (elimination of adsorbed water) and a possible chemical transformation of the corn starch, though literature data indicate that major irreversible chemical changes in the structure of starch, excepting dehydration and some oxidative processes, will normally appear at temperatures exceeding 320–350 °C. These transformations may include new bands appearing in the FTIR spectra in area of the wavenumber 3000–3100 cm^{-1} (peak at 3055 cm^{-1}), 1700–1500 cm^{-1}, (with maximum at 1574 cm^{-1}) and 900–650 cm^{-1}, all indicating a progressive process of formation of aromatic compounds (Kaczmarska 2017, Kaczmarska 2019). The temperature of 105 °C employed in this research is far beyond the specified temperatures, but the extended period of this treatment (24 h) may explain such transformations. However, alternative investigation methods should be employed to clarify this aspect of possible chemical modifications.

Moreover, the long thermal treatment process at 100 °C, started in presence of water must have induced physical and morphological changes affecting the properties of starch (Fonseca et al., 2021). It was reported that hydro-thermal processes of starch (e.q. annealing) result in an increase of crystallinity, thermal stability, reduced swelling power and amylose leaching of starch granules. The reduction in solubility increases the number of bonds, with an increase in the interactions between amylose and amylopectin molecules, forming a more stable structure and reducing the leaching of amylose (Liu et al., 2016). This would explain the properties of the experimental panels. The FTIR spectra recorded on the face and cross-sections of the panels were similar, indicating a homogeneous process throughout the thickness of the obtained composites.

3.6. Microscopic analysis of the samples

The stereo-microscopy images of the porous structure of the experimental foam composites with defined boundaries of the gaps and of the cardboard fibers are illustrated in Fig. 5. The maximum sizes (length x width) of the gaps measured on the surface of the foam composites were up to 3.65 mm × 0.87 mm for the panel type A (Figs. 5a) and 1.78 mm × 0.55 mm for the panel type B (Fig. 5b). Pores sizes of the foam composites are correlated to the amount of starch content resulted in numerous and larger pores for the structure with lower corn starch content (panel A). The fibers were measured at 180x magnification (Fig. 5c), the measured values being in the range 24.28 μm - 41.13 μm, complying with the literature in the field (Chinga-Carrasco 2011), mentioning that typical widths of wood pulp fibers are between 10 μm and 50 μm, whilst the fiber wall thickness is roughly between 1 μm and 5 μm. The image in Fig. 5d supports the conclusion of the FTIR analysis about possible chemical transformation of the corn starch and increased strengthening of the bonds, visible with 300x magnification as a good adhesion between fibers and highlighted in the squared area in Fig. 5d. The circled area in the same figure shows also the presence of corn starch particles in the structure.

4. Conclusions

The experimental research presented in this paper revealed that the potential of using recycled corrugated cardboard in manufacture of foam composites and extending this way its life cycle and contributing thus to the reduction of environmental challenges associated with cardboard waste disposal in landfills. Foam composites made from a mixture of recycled cardboard as raw material and corn starch as the binder in the presence of water and produced at a temperature of 105 °C for 24 h resulted in robust and porous structures. Low density composites (237.4 kg/m^3 and 284.3 kg/m^3, 17% higher when the amount of corn starch is doubled), the panels investigated in the present research proved to have good thermal insulation properties, found as 0.048 W/mK and 0.049 W/mK, respectively, for the thermal conductivity coefficient. Based on the statistical analysis determined at a 95% confidence level, no significant difference between the thermal conductivity coefficient values of the foam composites with different corn starch content, the small difference between the two values being attributed to the more numerous and larger pores of the foam composite having the lower content of binder.

Due to their low density, such composites have low mechanical performance, but if they are overlaid with thin high-density fiberboard or medium-density fiberboard their application could be extended to low weight panels for furniture manufacturing, which can be the subject of a further research. Also, the negative aspect of high values of WA and TS can be corrected by using waterproof materials such as wax or oil, and this could be the next step of the present research. In the context of circular economy, the use of recycled corrugated cardboard into new value-added products such as foam composites contribute to the objective of sustainability and to reduce the environmental impact. The results of this research show that the possible applications of these panels are related to building materials with good thermal insulation properties. In addition, various types of natural fibers such as rice husk, wheat husk, wood fiber, sugarcane, banana, oil palm, and coconut have been utilized in thermal insulation composites production in the previous literatures, but the results in terms of density and thermal conductivity were not as performant as those obtained in the present research.

As showed by FTIR analysis, the long process of heating at 100 °C in

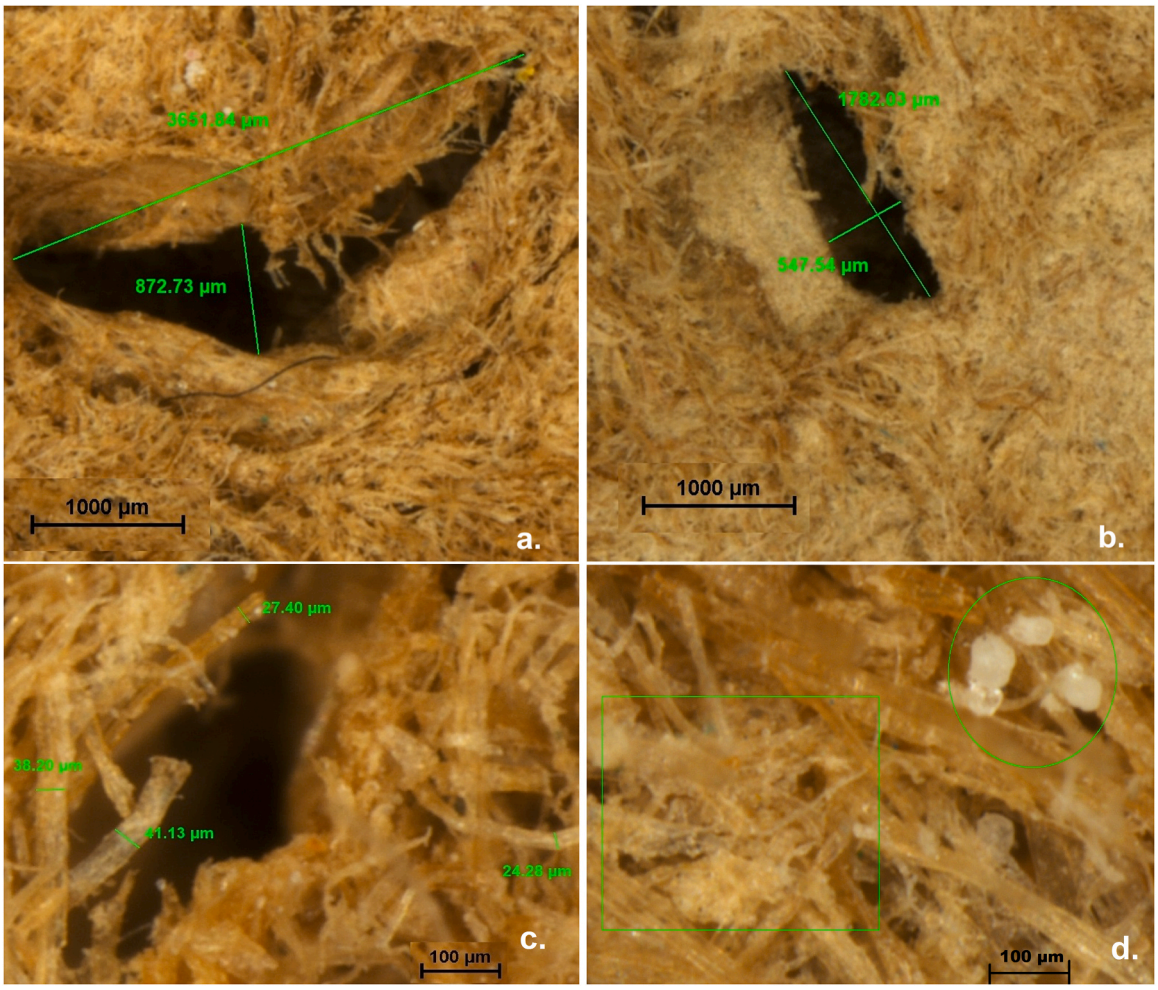

Fig. 5. Measured gaps (30 × magnification) of the composites with different amounts of corn starch content: 100 g (a); 200 g (b); sizes of the cardboard fibers (180 × magnification) of the composites (c); adhesion between fibers (squared area) and the presence of corn starch (circled area) with 300 × magnification(d).

the presence of water affects the properties of starch related to the increasing of crystallinity, strengthening the bonds, and forming a stable structure. This transformation is reflected by the compactness of the panels and their homogeneity, proved by the linear trend of the VDP. On the other hand, the porous structure of this foam-type composite is generated by the gas generated by the sodium bicarbonate in the presence of water, which disperses the defibrated cardboard fibers and the cornstarch performs as a binder between fibers. The strength of the bonds created by cornstarch in the presence of water is higher with the increase of corn starch share, so the mechanical performance of the panels is better and the density is higher, but with no significant modification of the thermal insulation property. Both panels proved a good compactness with no danger in their maneuverability during application as thermal insulating material, so an increase of cornstarch content in this type of foam composite is not justified.

CRediT authorship contribution statement

Mazaherifar Mohammad Hassan: Writing – original draft, Visualization, Methodology, Investigation, Conceptualization. **Coșereanu Camelia:** Writing – review & editing, Validation, Supervision, Resources, Methodology, Formal analysis, Data curation, Conceptualization. **Timar Cristina Maria:** Writing – review & editing, Visualization, Validation, Supervision, Software, Investigation, Formal analysis, Data curation. **Georgescu Sergiu-Valeriu:** Software, Methodology, Investigation.

Declaration of Competing Interest

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.

Data Availability

Data will be made available on request.

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