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Eco-friendly Sandwich Panel Based on Recycled Bottle Caps Core and Natural Fibre Composite Facings

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Abstract: This is the first attempt to combine disposed bottle caps and natural fibres into sandwich panels. A full factorial design is performed to identify the effects of the skin type (aluminium or coir fibre reinforced laminates) and bottle cap core packing (cubic and orthotropic) on the mechanical properties of the proposed panels. The coir fibre composite skin provides maximum core shear strength, 29 % higher than the aluminium-based panels, in cubic packing, while the flexural modulus is reduced by 45 %. An interlocking effect between the skin and the core is evidenced when coir fibre composites are used. In addition, the cubic cell packing increases the specific mechanical properties, even though with a higher density. The results highlight a promising association of green components and plastic bottle caps for secondary structural applications.

Keywords: Sandwich panel, Coir fibres, Bottle caps, Sustainability, Design of experiment

Introduction

The sandwich panel is based on the bonding between two thin skins of a stiff material connected to a soft and thick core. The connection, usually made using polymer films or injected adhesive polymers, promotes a uniform stress distribution between the two components [1]. The growth of sandwich panels in different engineering applications has stimulated viable solutions to reduce environmental impacts of panel production and/or disposal. The use of recycled materials as composite main parts [2,3] or the design of a fully recyclable material after its useful life [4] are some of the possible approaches to address ecological concerns. Both attempts have been successfully developed in a significant amount of research reported in the open literature [2-6].

The use of natural fibres in sandwich panel skins and core is in increasing demand due to their satisfactory properties, lightweight and low cost [6,7]. Some concerns regarding natural fibre reinforced composites are low thermal stability, hydrophilic nature, low interfacial adhesion and durability [8]. However, the limitations can be overcome by the use of fibre treatment and coupling agents, which enhance the tensile strength and modulus of these composites [7]. Some studies have investigated the use of natural fibre composites as sandwich panel components. Hoto *et al.* [8] tested an asymmetric sandwich panel based on basalt and flax fibre skins bonded to the agglomerated cork core using a bio-based epoxy polymer. The upper skin made from flax fibres fully availed the potential of flax fibres under compressive loads, with core densification and high energy absorption. The cork core coating by resin enhanced flexural strength and reduced water absorption. Liu *et al.* [9] compared a sandwich panel based on coconut mesocarp bio-core and glass fibre skins with corrugated metal core. The combination of GFRP skins and coconut core resulted in a specific energy absorption seven times greater than the metal core panel. Sadeghian, Hristozov, and Wroblewski [10] compared panels made of synthetic materials, such as glass fibre skin and PP core, to panels consisting of natural components including flax fibres facing and cork agglomerate core. Comparable flexural stiffness between synthetic and natural panels was achieved when using thicker natural skins and cores. Chan *et al.* [11] manufactured a fully green panel composed of hemp fabric laminate as skin, tree sap-based epoxy as adhesive, and a castor oil-based polyurethane core reinforced with rice hull ash, with acceptable results to replace gypsum-based structures. Rao, Jayaraman and Bhattacharyya [12] have tested the use of sisal fibres as PP core filler reinforcement. Although reduced adhesion between the fibres and the matrix was observed, the 4-point bending test revealed significant improvements when compared to non-reinforced samples. The same authors also investigated the reinforcement of a PP honeycomb core with sawdust particles [13], which reached a four-fold increase in energy absorption and specific energy under compression. Vieira *et al.* [6] investigated the incorporation of sisal fabric as a fibre reinforcement in fibre metal laminates (FMLs) structures. The combination of sisal fibres with aluminium alloys resulted in increased specific tensile and flexural strength and stiffness of up to 430 and 973 %, respectively, when compared to the sisal fibre reinforced polymer.

Increases in panel properties can be achieved not only by

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using new components, but also by modifying core geometry. The most common geometry in sandwich panels consists of honeycomb with hexagonal cells. Recent studies have reported the promising responses of circular geometry in terms of energy absorption capacity [21], yield stress [22] and fatigue load [23]. The orthotropic packing system of circular cells is analytically defined by Gotkhindi and Simha [24] and studied along with the commonly used hexagonal and cubic packing systems. This configuration is characterised by the 45 ^{o} angle formed between the adjacent cells. This topology reduces the density of the cores because of the large spacing created between the cells.

Sandwich panels made of thermoplastics promote some advantages such as easy manufacturing process, skin and core versatility, multiple approaches for bonding (adhesive or fusion-based bonding) and possible recyclability [14]. Hassan *et al.* [15] compared a fully recyclable thermoplastic material based on PP self-reinforcing skins and core with a classic panel made of GFRP skins and aluminium honeycomb. Both panels presented similar impact energy at break (drop tower impact test) with enhanced specific energy absorption for panels with increased skin thickness. It shows the promising performance of the thermoplastic as a sandwich core. The use of disposed thermoplastic components is therefore extremely attractive to the mechanical and ecological perspectives. Thermoplastic waste is one of the most relevant disposals in the world. Bottle caps are an example of highly disposed component. Several surveys around the globe highlight the growing danger of plastic disposal. 320,000 tonnes of plastic caps are sent to landfills every year [16]. Plastic caps and lids are one of the ten most discarded items on beaches in the United Kingdom [17], while PET bottles and caps are increasingly produced at a high rate, around 13 billion bottles per year [18]. In the USA, the recycling rate of bottles (PET) and caps (HDPE/PP) main components are 25 % and 9 %, respectively, due to difficulties in recycling components made of different polymers [19]. This scenario is quite similar in Brazil, where PET and HDPE present recycling rates of around 42 % and 23 %, respectively [20].

A fully recyclable PP panel based on small bundled tubes core was investigated by Cabrera, Alcock and Pejis [4]. The findings showed satisfactory properties obtained by sustainable panels based on thermoplastics. Innovative sustainable sandwich panels made with aluminium skins and bottle caps core were also investigated [2,3]. The effects of caps orientation, adhesive type and amount and cell packing system were recently reported [2,3]. Bottle caps panels led to promising flexural results when compared to recycled and classic materials, proving a viable route to reuse bottle caps, addressing ecological concerns and acceptable properties for secondary structural applications.

This work investigates a sandwich panel based on coir fibre laminates as skins and bottle caps honeycomb as core. A reference panel based on aluminium skins and bottle caps core is also produced for comparison. A 2^2 full factorial design is performed to evaluate the effect of skin type (aluminium and coir fibre laminate) and honeycomb configuration (cubic and orthotropic cell packing) on the mechanical properties, such as core shear stress, core shear stiffness, facing stress, flexural stiffness and flexural strength and the density of the panels.

Experimental

Panel Components

The high-density polyethylene (HDPE) caps, obtained from local recycling centre, are used as a tubular cellular core. The caps are from a single brand of water bottle, being washed and dried at room temperature for 24 h. Aluminium sheets type ISO 1200 H14 [25] with a thickness of 0.5 mm are used to fabricate the panels with classic skin. Laminates made from random coir fibres and epoxy polymer are designed and tested as a sustainable skin. Coir fibres are supplied by Deflor Bioengineering (Brazil). The fibres are randomly provided as a single mat, being separated and selected to remove dirt and any impurities. The epoxy polymer consisting of Renlam M resin and HY956 amine hardener (Huntsman) is used as composite matrix phase and panel adhesive.

Full Factorial Design

Two factors (levels) are considered in the Design of Experiment (DoE), such as skin material (aluminium skins and coir fibre laminates) and core cell packing (cubic and orthotropic, see Figure 1). Table 1 shows the full factorial design (2^2) resulting in 4 treatments. Four (4) samples and two (2) replicates are produced for each treatment, totalling 32 samples. A randomisation procedure is performed during fabrication and testing. The Minitab v.17 software [26] is used to manipulate the data.

Panel Manufacturing and Testing

The panel dimension for cubic packing is 177.6 mm in length and 88.8 mm in width, while for the orthotropic packing is 197.1 mm in length and 71.5 mm in width. The aluminium skins are cut according to the previous dimensions and subjected to a cleaning treatment with degreaser. Aluminium skins are sanded under water to remove the

Table 1. Planning matrix, 2^2 full factorial design

Condition	Facing material	Cell packing
C1	Aluminium	Cubic
C2	Aluminium	Orthotropic
C3	Coconut fibre	Cubic
C4	Coconut fibre	Orthotropic

Figure 1. Bottle caps placed in cubic (a) and orthotropic (b) cell packing system.

oxide layer and to avoid poor adhesion, followed by thorough surface cleaning with acetone [27]. A chemical treatment in coir fibres is carried out by immersion in 10 wt% NaOH solution for 15 h at room temperature as described by Oliveira *et al.* [28]. A fibre volume fraction of 30 % is considered for the fabrication of the laminate skin. Coir fibre laminates are produced under cold uniaxial pressing using a 300×300 mm^2 mould shown in Figure 2. A particular model consisting of 1 mm thick circular patterns is used during compaction to create circular cavities in the laminate which fits the cap, improving the interlocking effect between core and skin (see Figure 2(a)), especially for orthotropic packing. The surface is protected with a plastic release film. The first layer of epoxy polymer is spread on

Figure 2. Coir fibre laminate manufacturing process: covered mould with undulations (a), and manufactured plates with resulting skin (b).

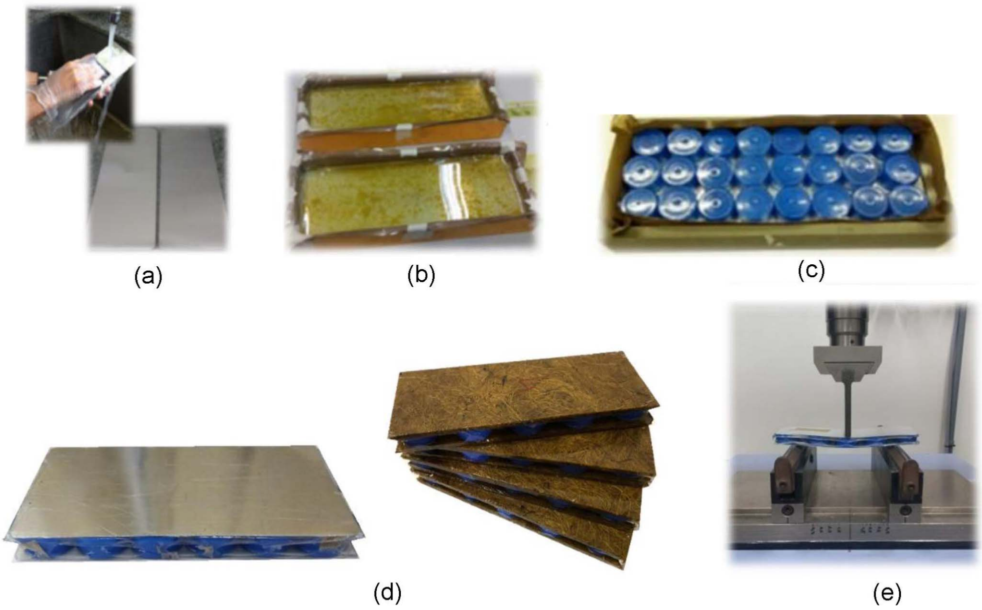

Figure 3. Sandwich panel manufacturing process: aluminium surface treatment (a), adhesive application (b), caps insertion (c), produced samples with aluminium, on the left, and coir fibre skins, on the right (d) and flexural testing (e).

the surface and the fibres are then accommodated in the panel with the impregnation of the remaining polymer. The mould is closed and subjected to a uniaxial pressure of 645 kPa [28] for 24 h. Plates are demoulded and cut into specific dimensions using a band saw (Figure 2(b)).

The skins made of coir laminates are covered with a plastic film and inserted into a wooden mould with release fabric (Armalon). The plastic film prevents polymer leakage to the exposed side of the skin. After preparation and spreading of the adhesive, the bottle caps are placed according to the corresponding packing system and compacted at 3.5 kPa [3]. The second skin is assembled after 24 h cure of the first skin bonding. Single directed caps and adhesive thickness of 1.5 mm are adopted based on previous works with the same type of cap [3,31]. The manufacturing process is summarised in Figure 3.

Samples made only of coir fibre laminates are evaluated in tensile tests according to ASTM D3039 [29], considering a gauge length of 140 mm and a displacement rate of 2 mm/min. In addition, the laminate density and water absorption are determined following the ASTM D792 protocol [30]. The effects of fibre treatment are then assessed to verify the viability of treated coir fibre laminates as skins. Panels with coir laminate skins are characterised by 3-point bending test at room temperature (~23 °C, 55 % RH) following the recommendations of ASTM C393 [32]. The tests are performed on a 100 kN Shimadzu test machine using a span length of 140 mm and a speed of 4 mm/min. Based on ASTM 7250 [33], ASTM C393 [32], and ASTM D790 [34], the following properties are determined: core shear modulus (G_c), core shear (τ_c) and facing (σ_{skin}) stresses, panel flexural stress (σ_f) and flexural stiffness (E_f).

Table 2. Mechanical and physical properties of treated and untreated coir fibre reinforced composites and aluminium

	Untreated coir fibre composite	15 h NaOH coir fibre composite	Aluminium ISO 1200 [25]
Apparent density (g/cm³)	1.14 (0.018)	1.27 (0.019)	2.7
Water absorption (%)	13.76 (0.06)	6.70 (0.02)	-
Tensile modulus (GPa)	2.38 (0.13)	3.54 (0.37)	35.34
Tensile strength (MPa)	16.12 (0.66)	19.45 (1.12)	105.70
Specific tensile modulus (kN·m/g)	2.09	2.75	13.09
Specific tensile strength (N·m/g)	14.17	15.27	39.14
Compressive strength (MPa)	59.34 (5.13)	52.86 (2.60)	-

Mean (standard deviation).

Results and Discussion

Coir Skin Characterisation

Table 2 shows the mechanical properties of coir fibre epoxy composite laminates. The results of aluminium skins used in panel manufacturing are also added as reference. Fibre treatment enhances the tensile properties of epoxy reinforced laminates with a slight increase in density and reduction in water absorption. In contrast, a reduction in compressive strength is obtained for treated fibres. Based on these findings, all panels are fabricated using treated coir fibre laminates as skins. The results of aluminium skins show greater strength and stiffness, with increases in specific tensile strength and stiffness of about 156.3 % and 376 %, respectively.

Panel Characterisation

Three-point Bending

The results obtained for the sandwich panels are shown in Table 3. In general, the panels based on coir fibre composites skins obtain higher loads compared to aluminium panels, which can be attributed to the higher thickness of the skins (4 mm for coir fibre composites and 0.5 mm for aluminium skins) which also contributed to increase the moment of inertia of the area. Higher panel strength and stiffness are obtained for aluminium-based samples, while the core shear strength and stiffness are quite similar considering both skins. The effect of each factor and its interactions on the responses is verified by ANOVA. Tables 4 and 5 present the P-values for the absolute and specific properties investigated, respectively. A factor or an interaction is considered significant within a 95 % confidence interval when the P-Value is less than or equal to 0.05 [35], which is highlighted in boldface in Tables 4 and 5. An interaction of two or more factors occurs when the effect of a factor is dependent on the level of other factors [35]. Significant factors and interactions

Table 3. Results of flexural tests for absolute and specific properties

	Absolute							Specific				
	F_{max} (N)	τ_{core} (MPa)	σ_{facing} (MPa)	G_{core} (MPa)	$E_{flexural}$ (MPa)	$\sigma_{flexural}$ (MPa)	ρ (kg/m³)	τ_{core} (MPa)	σ_{facing} (N·m/g)	G_{core} (N·m/g)	$E_{flexural}$ (N·m/g)	$\sigma_{flexural}$ (N·m/g)
C1	1,537.35	0.52	72.57	13.98	1065.54	12.75	477.49	0.0011	0.1519	0.0293	2.2319	0.0267
C2	1,018.59	0.43	59.60	13.58	1093.01	10.74	465.30	0.0009	0.1281	0.0303	2.3468	0.0231
C3	2,344.56	0.67	11.77	13.14	583.24	10.67	567.91	0.0012	0.0208	0.0240	1.0441	0.0189
C4	1,312.58	0.49	8.64	10.56	428.09	7.78	540.43	0.0009	0.0147	0.0195	0.7958	0.0136

Table 4. DoE results for absolute properties

	Factors	P-value ≤ 0.05				
		τ_c	σ_{skin}	G_c	E_f	σ_f
Effects	Type of facing (TF)	**0.000**	**0.004**	**0.000**	**0.000**	***0.000***
	Cell packing system (CS)	**0.000**	**0.001**	**0.000**	**0.000**	***0.000***
	TF*CS	***0.007***	***0.004***	***0.000***	***0.000***	0.077
	R^2 (adj) (%)	98.54	99.86	99.76	99.96	98.09
	Anderson darling (P ≥ 0.05)	0.128	0.160	0.114	0.170	0.246

Table 5. DoE results for specific properties

	Factors	P-value ≤ 0.05				
		$\tau_{c\,(spec)}$	$\sigma_{skin\,(spec)}$	$G_{c\,(spec)}$	$E_{f\,(spec)}$	$\sigma_{f\,(spec)}$
Effects	Type of facing (TF)	0.144	**0.000**	**0.000**	**0.000**	***0.000***
	Cell packing system (CS)	**0.000**	**0.001**	**0.001**	**0.000**	***0.000***
	TF*CS	***0.009***	***0.006***	***0.000***	***0.000***	0.070
	R^2 (adj) (%)	97.35	99.87	99.57	99.99	99.13
	Anderson-darling (P ≥ 0.05)	0.248	0.124	0.105	0.137	0.558

are displayed in italics and underlined. The value of R^2 (adjusted) is also reported in Table 4 and 5, which shows the predictive capacity for new observations when R^2 (adj) is near 100 %. The reported values range from 97.35 to 99.99 %, revealing good model adjustments. The Anderson Darling test reveals whether the data follow a normal distribution, which is a requirement to validate the ANOVA findings [35]. In this case, P-Values must be greater than 0.05, which is verified for all the responses (Tables 4 and 5).

Figure 4 shows a typical Force vs Displacement curve for each of the four conditions tested. A reduction in panel stiffness is noted when orthotropic packing is applied, since the slope for C2 and C4 samples is lower. Higher loads are

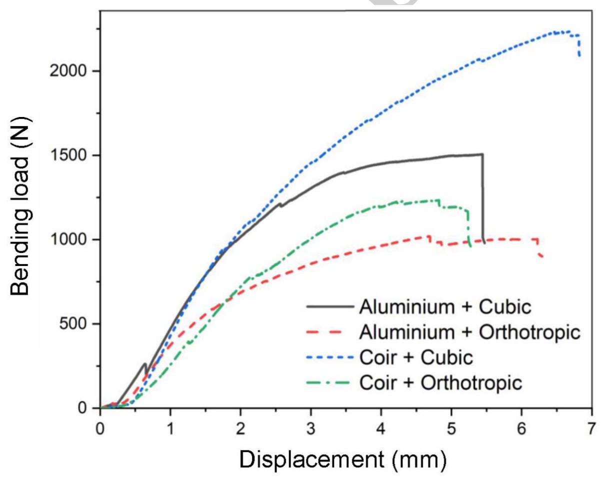

Figure 4. Typical three-point bending force vs. displacement curves.

achieved by panels made of coir composite skins. An interaction effect on the panel toughness will be discussed in DoE analysis.

Absolute Properties

Figure 5 shows the interaction effect plots for panel properties obtained under 3-point bending tests. The second order interactions between the Cell packing and the Facing Type are identified for core shear stress and facing stress, revealing P-values below 0.05 (Table 4). Higher core shear stress is obtained for samples based on coir fibres and cubic cell packing (Figure 5(a)). The number of caps per area in cubic packing is 14.9 % greater than the orthotropic packing, leading to increased core shear stress. The interlocking effect assigned to the face cavities is also enhanced by cubic packing. Aluminium samples are less resistant to shear loads in orthotropic packing (about 17 %). A higher facing stress (Figure 5(b)) is achieved for panels made of aluminium skins and cubic cell core, attributed to their higher mechanical performance and large contact bonding area, respectively. Aluminium skins achieve about 6 to 7 times more facing stress than coir composite facings. Figure 5(c) shows the main effect plots for the flexural strength of the panel. The panel strength is increased by 27 % when fabricated with aluminium skins and cubic core.

The core shear stiffness (Figure 6(a)) increases when aluminium skins are used, especially for the orthotropic core. Coir fibre panels achieve improved core shear stiffness when combined with cubic packing, being attributed to the interlocking effect associated with the design of the skin cavities. Higher panel stiffness is obtained for aluminium skins (Figure 6(b)). Coir fibre panels are most affected by core packing levels, revealing greater stiffness for the cubic

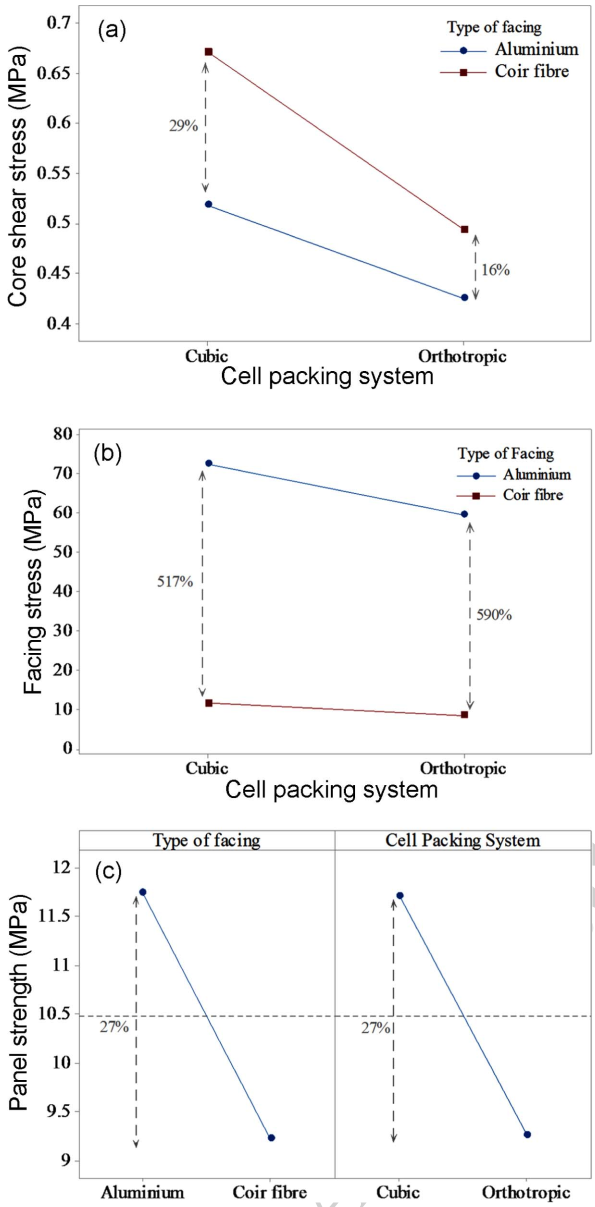

Figure 5. Interaction and main effect plots for the core shear stress (a), facing stress (b), and panel flexural strength (c).

configuration. The panel stiffness is highly dependent on the properties and thickness of the skin. Although higher mechanical loads and steeper force-displacement curves obtained for coir fibre-based panels in both core topologies (Figure 4), the resulting panel stiffness is significantly reduced (Figure 6(b)).

Specific Properties

The specific properties reveal similar behaviours of the absolute properties, as shown in ANOVA (Table 5). Figure 7 shows the plots of main and interaction effects of the mean specific strength properties for the panel and its constituents. The specific core shear stress is also increased with the

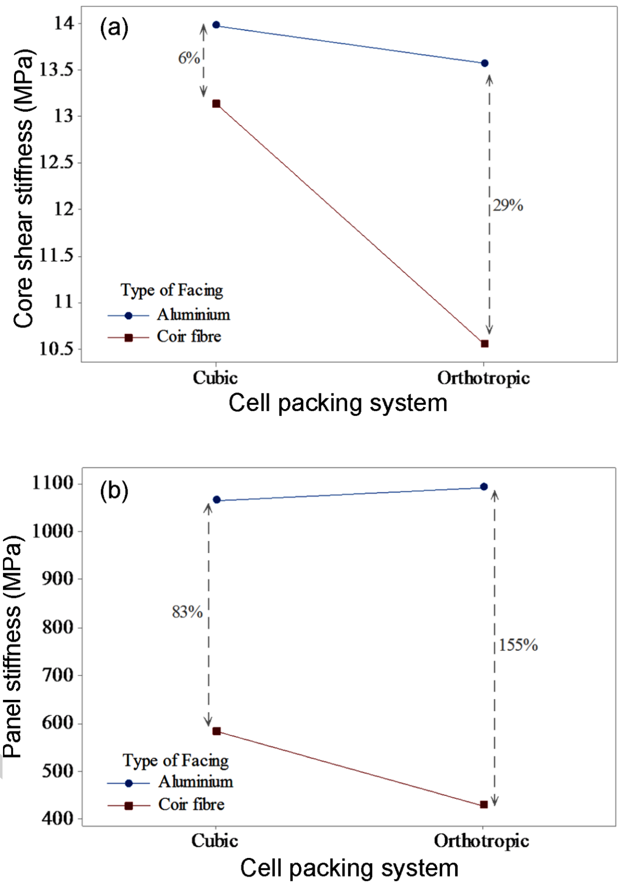

Figure 6. Interaction plots for the core shear stiffness (a), and flexural panel stiffness (b).

composite skin cavities, especially in the cubic packing (Figure 7(a)). On the other hand, orthotropic packing leads to a decrease in core strength, especially when composite facings are used, revealing a 33 % reduction. Figure 7(b) reveals higher specific facing stress for aluminium skins and cubic cores. Figure 7(c) shows the main effect plots for the specific panel strength. A larger variation (53 %) is observed for the skin type factor in relation to the absolute property (Figure 5(c)), due to the increased density of coir fibre composites, and consequent reduction of their specific strength. The packing system provides a similar behaviour of the absolute panel strength (Figure 5(c)), in which the cubic core leads to a higher mechanical performance.

Figure 8 shows the specific core shear stiffness and panel stiffness responses that behave similarly to absolute properties (Figure 6). Both responses are affected by a second-order interaction of the factors. The orthotropic core and aluminium skins increase the specific core shear stiffness (Figure 8(a)) and specific panel stiffness (Figure 8(b)). In contrast, orthotropic packing reduces these properties by almost 56 % when combined to composite skins. Significant improvements in panel stiffness are obtained

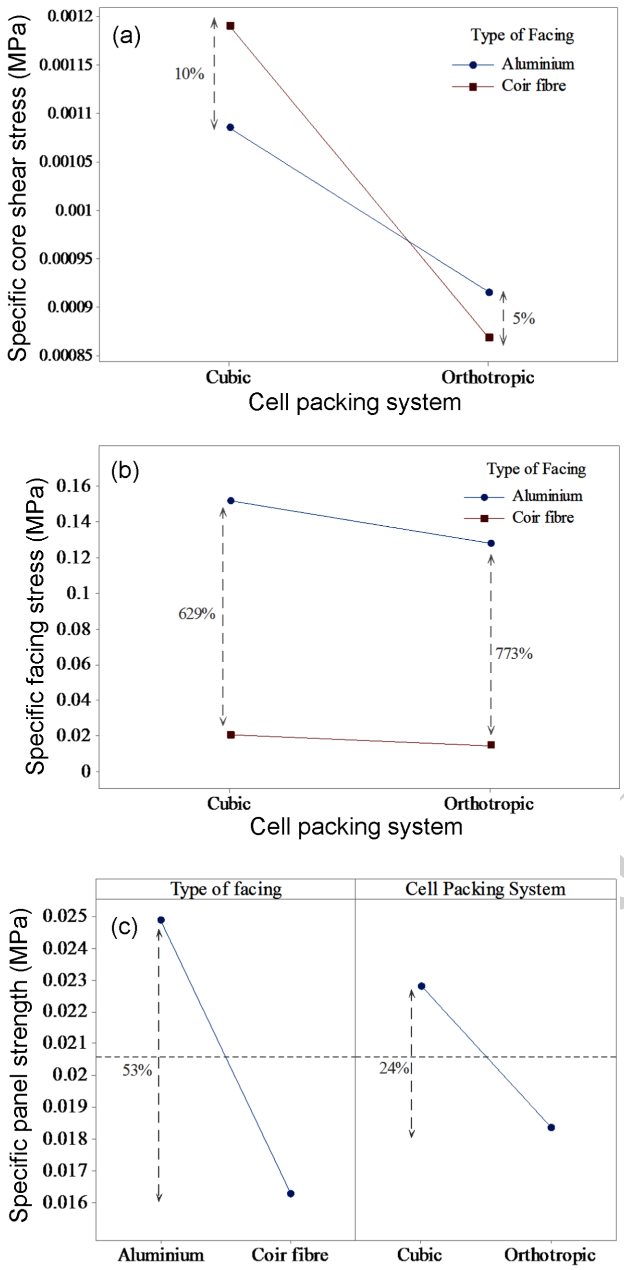

Figure 7. Interaction and main effect plots for specific core shear stress (a), specific facing stress (b), and specific panel strength (c).

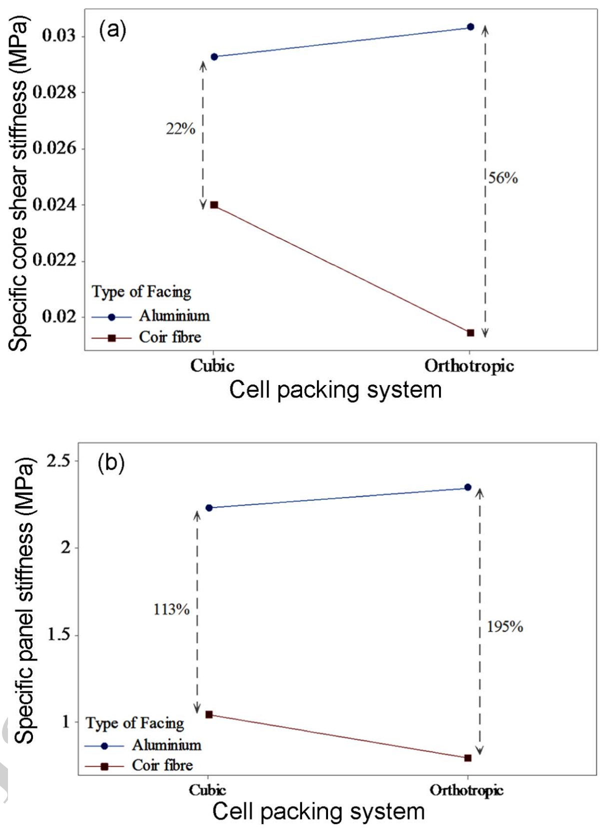

Figure 8. Interaction plots for the specific core shear stiffness (a) and specific flexural panel stiffness (b).

when aluminium skins are used, with increases of 113 % and 195 % for cubic and orthotropic cores, respectively.

Failure Analysis

The failures of the panels made of aluminium and coir fibre composite skins are shown in Figure 9. Figure 9(a) shows the failure of samples made of aluminium skins and cubic packing. The aluminium surface treatment is effective in reducing the debonding between the skin and the adhesive with only a localised rupture of the adhesive at the interface with the plastic caps. In general, the smooth and inert surface of HDPE prevents strong bonding conditions. Figure 9(b) shows the failure of samples with aluminium skin and orthotropic core. An evident debonding between the adhesive and the skin, followed by adhesive cracks, is observed in the peripheral areas of the panel which do not have adjacent cap support. The rupture of the adhesive from the caps surface is also shown with an additional reduction in panel performance. Composite panels made with core cubic packing exhibit a progressive failure reaching higher loads. In general, some local debonding is observed between the caps and the adhesive, while the overall panel remains bonded and deformed. The cubic configuration leads to failure in both composite skins (Figure 9(c)). Samples made with orthotropic packing fail by progressive crack propagation on the lower side of the beam with reduced cap support, followed by localised debonding of the caps in the peripheral areas. Although the maximum supported load is significantly reduced due to the lower core skin support, there is no sudden drop in load.

Specific Performance Analysis

The objective of the proposed panels is to determine an adequate design of a sustainable sandwich panel based on

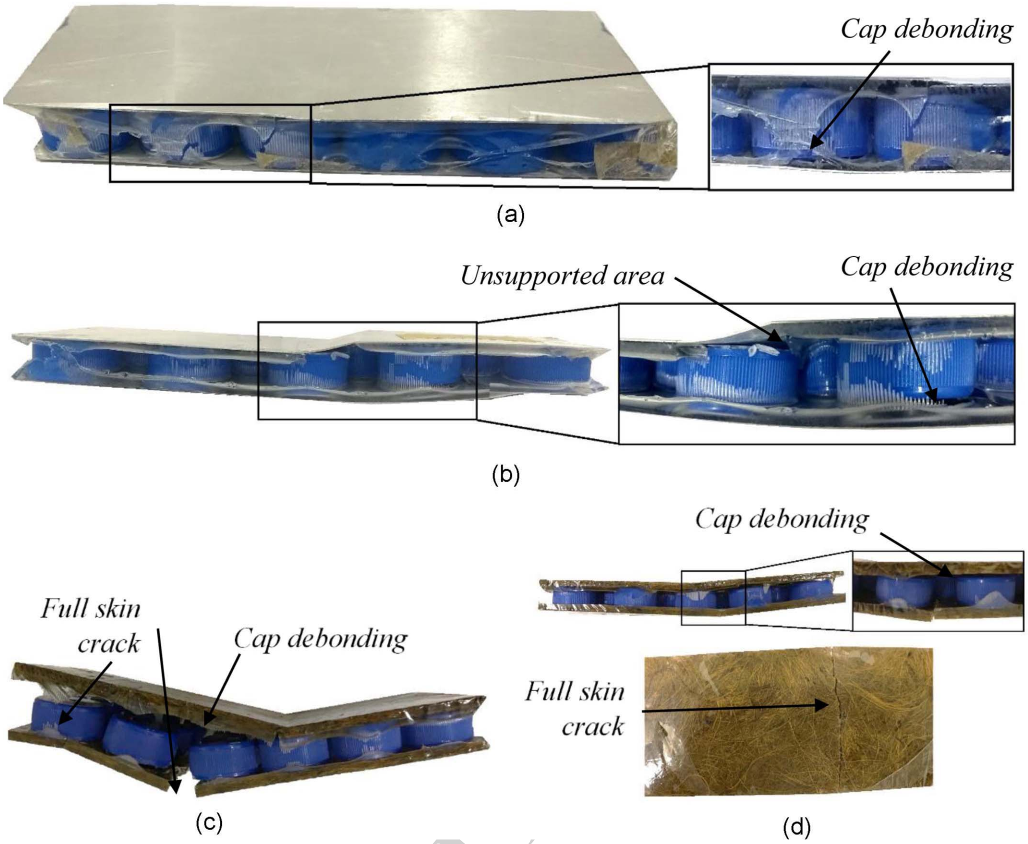

Figure 9. Failure analysis for the panels; C1, Al-Cubic (a), C2, Al-Ortho (b), C3, Coir-Cubic (c), and C4, Coir-Ortho (d).

natural and recycled components, which could be comparable to the classic structures when considering panel efficiency for lightweight design (strength- or stress-to-weight ratio). Ashby [36] states that performance indices can help in the process of selecting materials for a particular application. In this case, as a structural panel for secondary applications, the index to be maximised for stiffness is $E^{1/3}/\rho$, where E is the panel Young's modulus and ρ is the panel density. The assessment of strength performance should consider the index $\sigma^{1/2}/\rho$, where σ is the flexural strength of the panel. The resulting indices for the conditions analysed and the comparisons between skins for each packing are shown in Table 6. It is noted that the ratio of stiffness index of coir composite to aluminium skins is 68.8 % and 63 % for cubic and orthotropic packings, respectively, showing higher efficiency for C1 and C3 panels. Similar conclusions are obtained for strength index, ranging from 73.3 % to 76.9 % for the ratio between coir fibre panels (C3 and C4) and aluminium skin panels (C1 and C2, respectively).

These results show a promising use of natural fibres as an additional sustainable component in the bottle caps panel design. Further improvements in composite facings and interfacial adhesiveness can enhance the overall properties of panels and contribute to the high efficiency of both structures.

Conclusion

This paper investigated an eco-friendly sandwich panel design based on disposed bottle caps as a honeycomb core

Table 6. Performance indices for the proposed design

Condition	Skin	Packing	Stiffness index ($E^{1/3}/\rho$)	Coir composite to Al-skin index ratio (%)	Strength index ($\sigma^{1/2}/\rho$)	Coir composite to Al-skin index ratio (%)
C1	Aluminium	Cubic	0.0214	68.8	0.0075	76.9
C3	Coir fibre	Cubic	0.0147		0.0058	
C2	Aluminium	Orthotropic	0.0221	63.0	0.0070	73.3
C4	Coir fibre	Orthotropic	0.0139		0.0052	

and skins made from coir fibre composites or aluminium sheets. The main conclusions of this work are:

1. The treatment of the coir fibres increases the tensile strength and stiffness of the compacted fibre reinforced composites by 21 % and 49 %, respectively;
2. Reduced water absorption and higher adhesion to the polymer matrix are also attributed to coir fibre treatment;
3. Panels made of aluminium skins achieve higher skin stress, flexural strength and stiffness, due to their higher tensile and compressive properties. Similar trends are verified for specific properties, with higher increments due to the higher density of coir fibre skins;
4. The core shear stress and stiffness and their respective specific properties are improved when the coir fibre skin is combined with the cubic packing. The interlocking feature due to the composite skin cavities also contributes to increased adhesion between the skins and the caps, especially in the peripheral area of the panel, preventing early shear failure;
5. In general, orthotropic packing leads to reduced panel strength when compared to cubic packing, especially when combined with the coir laminates. In contrast, some stiffness properties are slightly enhanced by the orthotropic core when aluminium skins are considered;
6. The rupture of coir fibre skins is the main cause of panel failure. The core packing system affects the skin-cap bonding until failure. Aluminium skins show a progressive failure with a low debonding between the skin and the adhesive;
7. Performance indexes for stiffness- and strength-to-weight ratio indicate good performance of the proposed sustainable panels, reaching between 63 % and 77 % of the performance of panels made with aluminium skins.

In general, the proposed design achieved promising results, indicating a viable route to reuse bottle caps as a core of sandwich panels and towards sustainability by associating it with natural fibre skins.

Acnowledgments

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