

# Flatwise Compressive Properties of Kenaf/Polypropylene Honeycomb Core

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**Abstract.** Light weight and sustainable sandwich panels are increasingly sought for an extensive range of applications, from structures in airliners to wall linings in buildings. A study on flatwise compressive properties of honeycomb cores manufactured from kenaf/polypropylene sheets has been conducted. The influences of directionalities, the thickness-to-length ratio of cell walls and the depth to cell size ratio on the stiffness and strength of the cores have been examined. Cell wall thickness, core depth, directionality, and the interaction between core depth and cell wall thickness influenced both absolute and specific compressive strengths of the cores. Directionality and cell wall thickness as well as interaction between cell wall thickness and core depth influenced the absolute compressive modulus of the cores. However, only directionality and interaction between cell wall thickness and core depth affected specific compressive modulus.

## 1. Introduction

Sandwich construction is an attractive structural design concept, where panels having high stiffness- and strength-to-weight ratios can be achieved by appropriate choice of geometry even with moderate-quality constituent materials. The panels are formed by adhering strong and stiff face sheets to a thick, relatively weak yet light core material in proportions such that optimum stiffness and strength can be achieved with minimum structural weight. When a sandwich panel is subjected to transverse loads, the face sheets carry most of the bending moments and in-plane extensional stresses, while the core carries transverse shear and compressive stresses [1].

Figure 1 illustrates the compressive performances of various core materials used in sandwich structures [2-11]. Honeycomb cores and axially-oriented balsa wood exhibit significantly higher compressive strengths in comparison to various polymeric foams over a wide range of core densities. Because of these, honeycomb core structures are of interest in this study.

Currently, the majority of honeycomb sandwich structures are made of materials and polymers that are difficult to recycle and reuse. Due to increasing environmental concerns on the impacts of materials used, from production to end of life, a considerable research has been conducted on the development of new sandwich structures which utilise naturally sourced and recyclable materials. For core materials, traditional metallic structures are being replaced by composite- and polymer-based



foams, corrugations and honeycombs due to cost, weight and manufacturing considerations. Some examples of natural-fibre based cores include sisal/polypropylene (PP) [12], sawdust/PP [13], flax/PP [14], jute/vinylester [15] and plywood [16].

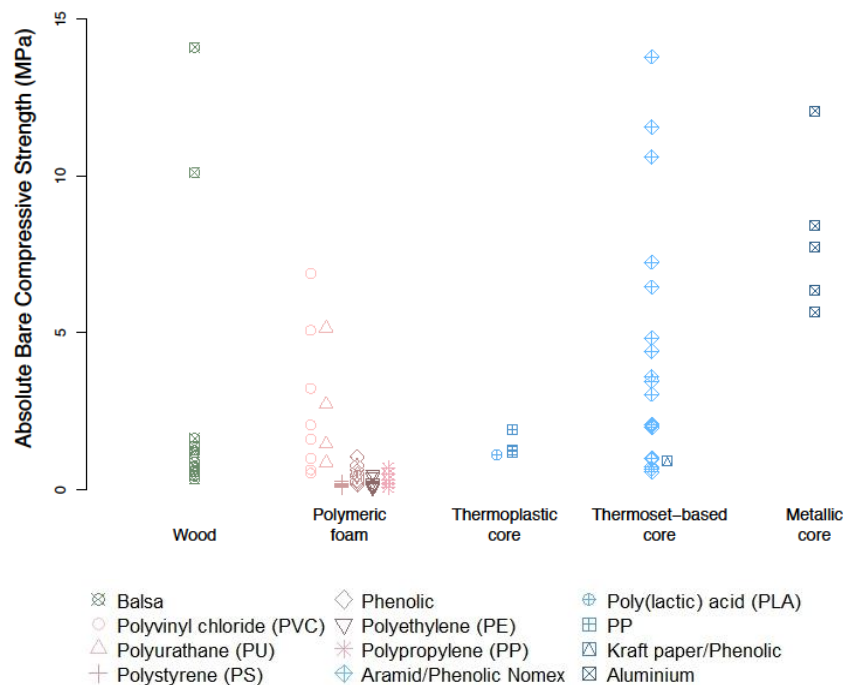


**Figure 1.** Comparison of compressive strengths of various wood, foams, and metallic and composite honeycomb cores published in the literature.

To date, there is no extensive study on how this a class of kenaf/PP hexagonal-cell honeycomb core materials would behave under compressive loadings. This paper investigates the influences of directionalities, cell wall thickness and core depth on the stiffness and strength of the structures under flatwise bare compression.

## 2. Experimental Details

### 2.1. Materials

Kenaf yarns were purchased from Jute-Bangladesh Ltd., Bangladesh. PP homopolymer HP422M (8.5 g/10 min) was supplied by Lyondell Basell. Licocene PP MA 6452, a maleic-anhydride modified PP (acid number: 43 mg KOH/g) supplied by Clariant, was chosen as a compatibiliser for PP.

### 2.2. Production of Honeycomb Core

Kenaf/HP422M PP/MAPP (40/57/3 wt%) composite sheets of two different thicknesses (0.6 mm and 1.2 mm) were manufactured using a twin-screw extruder. The mechanical properties of the composite sheets are listed in Table 1. The sheets were then thermoformed into half-hexagonal corrugations. The corrugations were joined together using an ultrasonic welder to form honeycomb cores.

### 2.3. Testing

The flatwise bare compressive properties of honeycomb core materials were determined using ASTM C365 with the cross-head speed set to 0.5 mm/min. The specimens consisted of seven and six cells in directions parallel and transverse to ribbon, respectively. The width of the specimens (in ribbon direction) was set to 101 mm. The lengths of the specimens (in direction transverse to ribbons) vary depending on the cell wall thickness of the specimens; the lengths of specimens with cell wall thicknesses of 0.6 mm and 1.2 mm were 96–98 mm and 106 mm, respectively.

**Table 1.** Mechanical properties of Kenaf/HP422M PP/MAPP (40/57/3 wt%) composite sheets of two different thicknesses (0.6 mm and 1.2 mm). MD and TMD refer to pulling axis being parallel and transverse to machine direction, respectively. B-TMD and B-MD refer to bending axis (cylindrical axis around which the sample curves) being parallel and transverse to machine direction, respectively.

| Properties                  | Directions | 0.6 mm          | 1.2 mm          | Units |
|-----------------------------|------------|-----------------|-----------------|-------|
| Tensile strength            | MD         | $46.4 \pm 0.87$ | $46.3 \pm 0.87$ | MPa   |
|                             | TMD        | $24.4 \pm 2.76$ | $27.4 \pm 0.36$ |       |
| Tensile modulus             | MD         | $5.64 \pm 0.33$ | $6.00 \pm 0.40$ | GPa   |
|                             | TMD        | $2.76 \pm 0.24$ | $2.63 \pm 0.06$ |       |
| Flexural strength           | B-TMD      | $87.5 \pm 1.64$ | $88.0 \pm 1.91$ | MPa   |
|                             | B-MD       | $47.7 \pm 0.93$ | $51.6 \pm 1.96$ |       |
| Flexural modulus            | B-TMD      | $5.30 \pm 0.12$ | $5.26 \pm 0.12$ | GPa   |
|                             | B-MD       | $2.67 \pm 0.09$ | $2.58 \pm 0.04$ |       |
| Out-of-plane shear strength |            | $41.9 \pm 0.66$ | $40.5 \pm 0.85$ | MPa   |

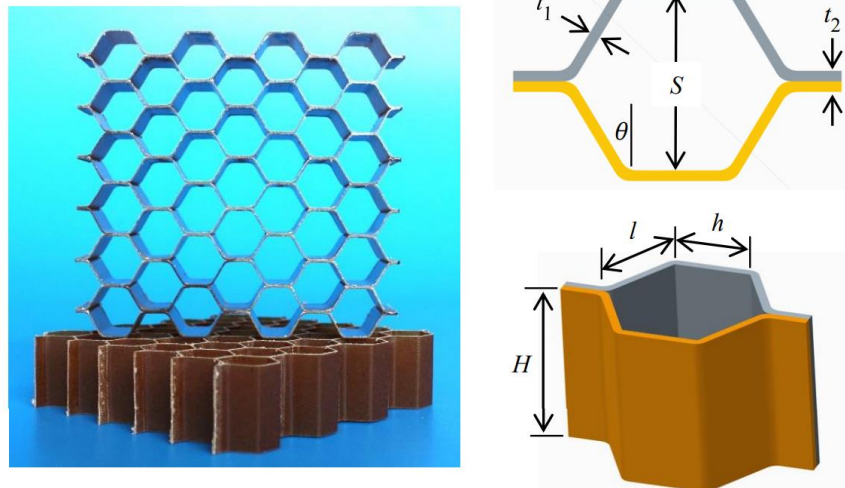


**Figure 2.** Samples (7 by 6 cells) for bare flatwise compression test, and nomenclature for a typical unit cell.

### 2.3.1. Experimental Design.

The purpose of the tests was to determine the sensitivity of the core materials' stiffness and strength under compressive loadings to the microscopic and macroscopic directionalities, the thickness-to-length ratios of cell walls and the core height-to-cell size ratios. Three factors were identified as likely to impact compressive properties. A full factorial Taguchi  $L_8$  design, with eight experimental runs in which each factor was alternated between a "high" and "low" level, was used to determine if a change within those levels had an effect on mechanical properties.

#### Factor 1 - Directionality (A)

Low ( $A_1$ ): F-MD, High ( $A_2$ ): F-TMD

Kenaf/PP/MAPP composite sheets are anisotropic in nature due to the fibre and PP alignments in the extrusion direction [17]. During thermoforming, the resistance to forming deformation is, therefore, expected to be much higher when the bending axis is transverse to the extrusion direction (here refers to F-TMD) as opposed to being parallel (F-MD). Minor differences in conformability are expected in corrugated sheets. Furthermore, the strength and stiffness of the honeycomb are dependent on the loading directions and structural configurations (i.e. macroscopic directionality) with respect to the

fibre and PP alignments (i.e. microscopic directionality). The ribbons in the hexagonal cores are approximately twice the thickness of the free walls, and thus the former are expected to be stiffer than the latter especially when flexed in the direction perpendicular to bending direction [18-20]. At the moment, with the use of anisotropic composites as parent materials, the interaction effects of the fibre and PP alignments (i.e. mechanical properties of parent materials) with respect to the forming axes (i.e. formability of corrugated sheets) and loading directions, when coupled with principal cell orientations (i.e. ribbons or free walls) are not precisely known.

### Factor 2 - Cell wall thickness (B)

Low ( $B_1$ ): 0.6 mm, High ( $B_2$ ): 1.2 mm

The lower limit of cell wall thickness has been set to 0.6 mm because the minimum thickness of composite sheets that can be successfully produced using 1 mm thick sheet die is 0.6 mm. The upper limit of 1.2 mm has been chosen to represent a reasonably high cell wall thickness which can be thermoformed easily and to avoid in producing cores with higher densities.

### Factor 3 - Core height (C)

Low ( $C_1$ ): 20 mm, High ( $C_2$ ): 30 mm

Although core height does not influence compressive properties, the shear strength of honeycomb cores reduces with an increase in core height. The lower limit of 20 mm has been set to provide enough depth for separating face sheets in later applications so as to significantly increase the stiffness and strength of sandwich panels in bending. The upper limit of 30 mm has been chosen so as to avoid significant reduction in the shear strength of the cores. Note that the thickness of 20 mm and 30 mm cores ended up being 18.55 mm and 28.27 mm, respectively, after surface milling process which was meant to ensure that faces of the cores were parallel and flat.

A Taguchi full factorial experimental design, as shown in Table 2, was used to investigate the effects of these factors on the flatwise bare compressive and shear properties.

**Table 2.** Two-level Taguchi full factorial experimental layout. (Example: Trial one consists of a low directionality, cell wall thickness and core depth).

| Trial | Direction (A) |    | Cell wall (B) |    | Core depth (C) |    | AB |    | AC |    | BC |    |
|-------|---------------|----|---------------|----|----------------|----|----|----|----|----|----|----|
|       | LO            | HI | LO            | HI | LO             | HI | LO | HI | LO | HI | LO | HI |
| 1     | ✓             |    | ✓             |    | ✓              |    |    | ✓  |    | ✓  |    | ✓  |
| 2     | ✓             |    | ✓             |    |                | ✓  |    | ✓  | ✓  |    | ✓  |    |
| 3     | ✓             |    |               | ✓  | ✓              |    | ✓  |    |    | ✓  | ✓  |    |
| 4     | ✓             |    |               | ✓  |                | ✓  | ✓  |    | ✓  |    |    | ✓  |
| 5     |               | ✓  | ✓             |    | ✓              |    | ✓  |    | ✓  |    |    | ✓  |
| 6     |               | ✓  | ✓             |    |                | ✓  | ✓  |    |    | ✓  | ✓  |    |
| 7     |               | ✓  |               | ✓  | ✓              |    |    | ✓  | ✓  |    | ✓  |    |
| 8     |               | ✓  |               | ✓  |                | ✓  |    | ✓  |    | ✓  |    | ✓  |

## 3. Results and Discussion

The typical compressive stress-strain plots for bare honeycomb core specimens are shown in Figure 3. It should be noted that the stress is based on the projected area of the honeycomb. In comparison to any typical metallic or thermoset-based honeycomb cores, kenaf/PP cores demonstrated a significant drop in compressive stress after the peak stress has been attained. This shows that kenaf/PP cores lack of energy absorption capability. This is possibly related to the lack of reinforcing effect contributed by neighbouring cells as they are folded during crushing stage simply because the cell size in the honeycombs used is larger than the typical size used in the literature (3.2–9.5 mm).

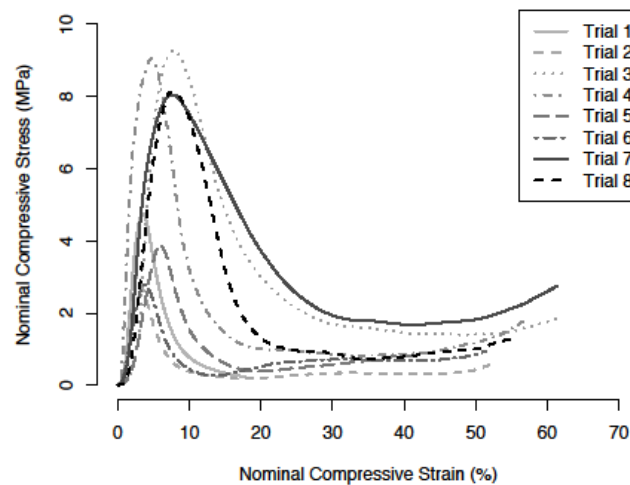


**Figure 3.** Typical compressive stress-strain plots for bare honeycomb cores of various combinations of directionality, cell wall thickness and core depth.

Figure 4 illustrates the sequence of microstructural change during the compressive deformation of honeycomb cores. The deformation process varies depending on the cell wall thickness of honeycomb cores. The initial response was stiff and nearly linear. The compressive modulus was calculated based on stress-strain response at this region. As the strain increases, the free walls of honeycomb cores were observed to buckle.

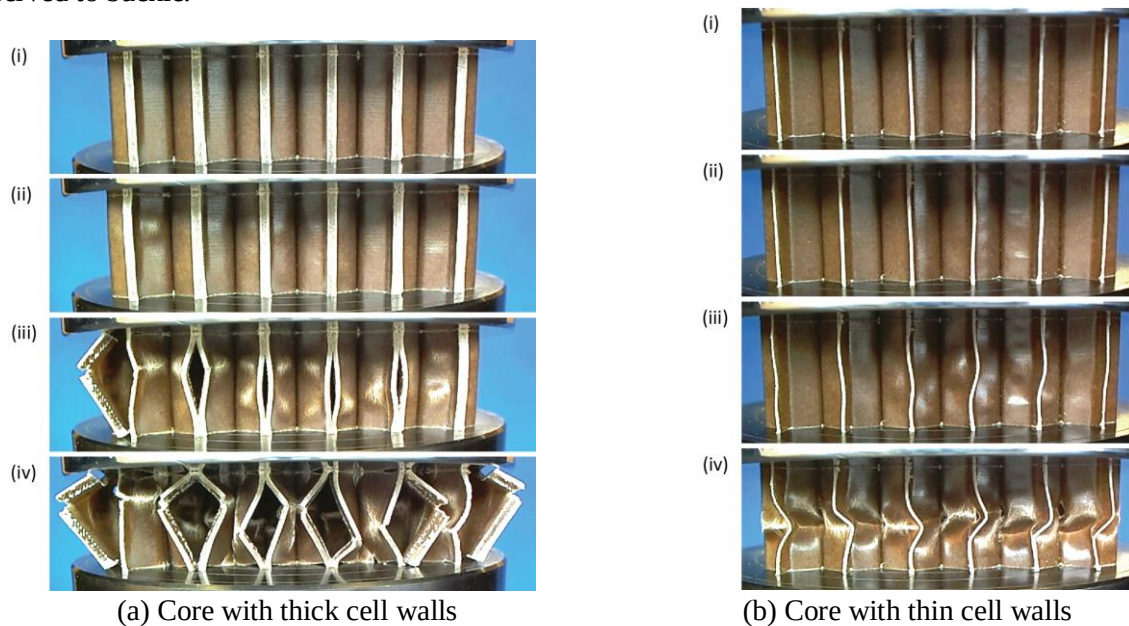


**Figure 4.** Sequence of photographs of honeycomb cores with (a) thin and (b) thick cell walls at various stages of compression: (i) initial condition. (ii) onset of failure by buckling at the free walls. (iii) for (a): buckling at the ribbons and for (b): compressive failure at the ribbons, which is initiated by debonding at the cell wall interfaces. (iv) further material yielding and fracture. The plane is viewed from the direction transverse to ribbon direction.

Further increase in strain resulted in two different responses depending on the cell wall thickness — the ribbons in cores with thin (0.6 mm) cell walls started to buckle while the ribbons in cores with thick (1.2 mm) cell walls demonstrated compressive failure, which was initiated by debonding at cell

wall interfaces of walls at the ends of the specimens. The maximum stress achieved represents the compressive strength of the honeycomb cores and the onset of crushing. As compression continued, the stress dropped due to material yielding and consequently fracture as the cells folded.

### 3.1. Compressive Strength

The effects of each factor on absolute compressive strengths of bare honeycomb cores are shown in Figure 5(a). The grand mean of absolute strength is 6.1 MPa. Since honeycomb cores are mainly applied in lightweight structures, their compressive strength relative to their weight (refers to here as specific compressive strength) is also important. The grand mean of specific strength is 0.0458 MPa/kg.m<sup>-3</sup>.

ANOVA shows that the cell wall thickness (B), core depth (C), directionality (A) as well as interaction between core depth and wall thickness (BC) are significant at the 95% confidence level for both absolute and specific compressive strengths. Corrugated sheets formed in F-MD are preferable because kenaf fibres and PP molecular alignments are mainly oriented in the same direction as the compressive loading in comparison to those formed using F-TMD. Under uniaxial compression, cell wall's resistance towards buckling deformation is dependent on the cell width-to-wall thickness ( $l/t$  or  $h/t$ ) and the cell width-to-core depth ( $l/H$  or  $h/H$ ), as described by Timoshenko and Gere [21] — the resistance of the cell walls towards buckling deformation increases with the decrease in the cell width-to-wall thickness ratio and with the increase in the cell width-to-core depth ratio. This explains why cores with thicker cell walls (for the same width of cell walls) and shallower cores resulted in higher compressive strength in comparison to their counterparts.

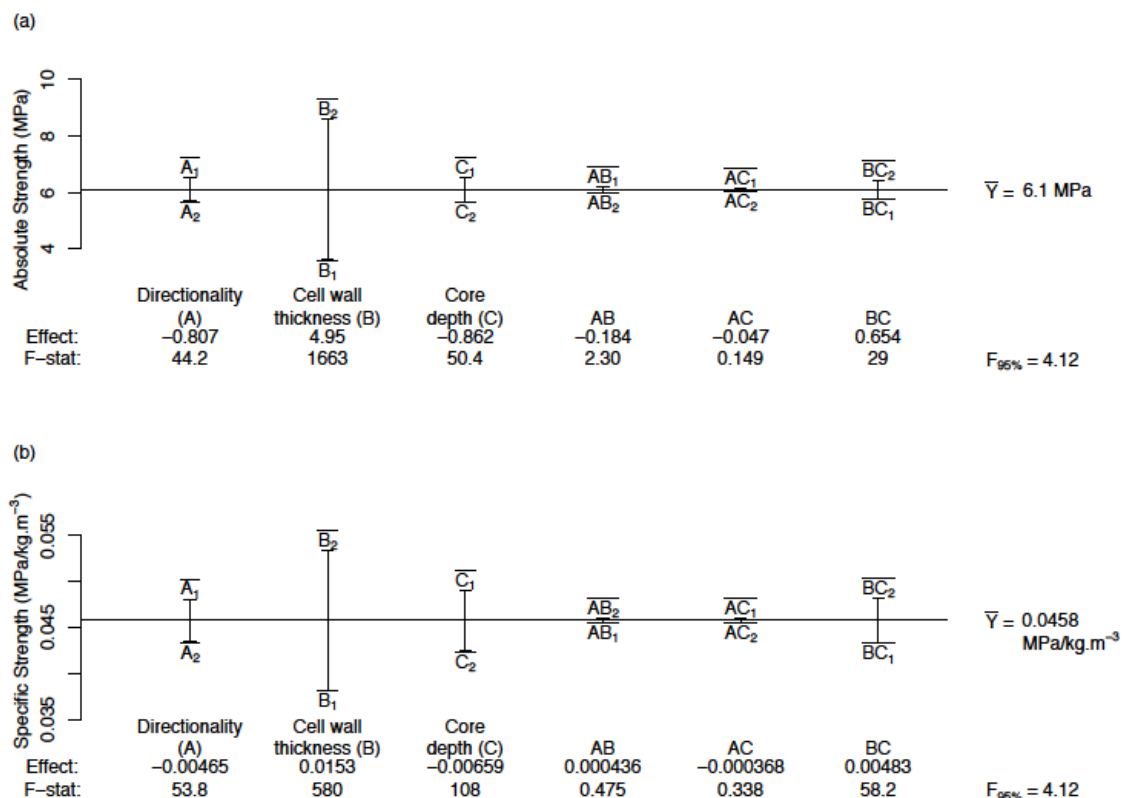


**Figure 5.** Effects of various factors on (a) absolute and (b) specific (relative to weight) flatwise bare compressive strengths of honeycomb cores.

As illustrated by the parallel lines in Figure 6, it is noted that there is no interaction between directionality and

cell wall thickness (AB), and directionality and core depth (AC). Unparallel lines in cell wall thickness and core depth (BC) plot indicate that these factors interact with each other. At a lower cell wall thickness (i.e. 0.6 mm), a lower core depth (i.e. 20 mm) resulted in higher absolute and specific compressive strengths. However, the effects of core depth become insignificant at a higher cell wall thickness (i.e. 1.2 mm). This phenomenon can be explained based on the dominant failure mode for each case. The cores with thick cell walls failed by compressive failure, and this failure is dependent on composites' compressive strength while the cores with thin cell walls failed by buckling, and this failure is limited by core depth. So, it is natural to observe a strong interaction between core depth and cell wall thickness for cores with thin walls and such effect diminishes for cores with thick walls because the compressive strength of the core is bounded by the compressive strength of the parent material.

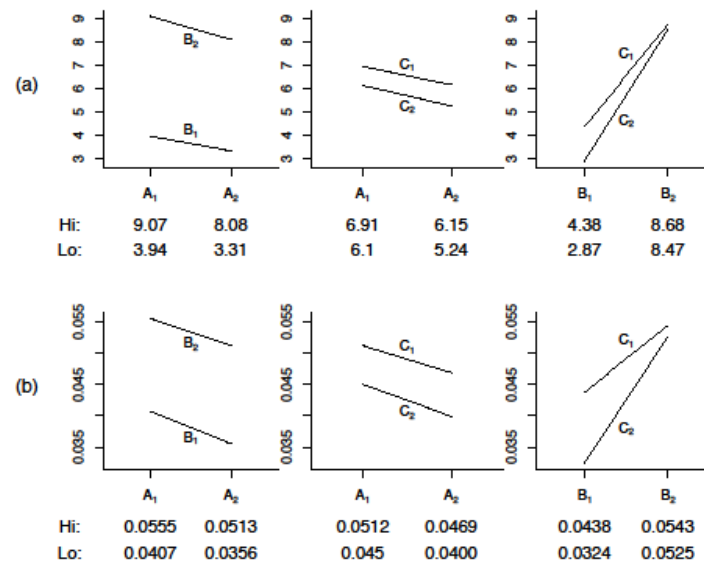


**Figure 6.** Interaction effects on (a) absolute and (b) specific (relative to weight) flatwise bare compressive strengths of honeycomb cores.

### 3.2. Compressive Modulus

Figures 7 shows the effects of various factors on both absolute and specific flatwise bare compressive moduli of honeycomb cores. The grand means of absolute and specific moduli are 238 MPa and 1.83 MPa/kg.m<sup>-3</sup>, respectively. ANOVA shows that directionality (A) and cell wall thickness (B) as well as the interaction between directionality and cell wall thickness (AB), and the interaction between cell wall thickness and core depth (BC) significantly affect the absolute compressive modulus of cores. In terms of specific compressive modulus, however, only directionality (A) and the interaction between cell wall thickness and core depth (BC) affect the property significantly. As expected, the modulus of F-MD honeycomb cores is higher than those of F-TMD due to the alignment of fibres and PP molecular chains in the compressive loading direction. The theoretical equation presented by Gibson and Ashby [22] for predicting the compressive modulus of hexagonal honeycomb cores based on the modulus of parent materials ( $E_s$ ) and cell configuration shows that by doubling the cell wall thickness, the compressive modulus is doubled (refer to Equation 1).

$$E_3 = \left(\frac{t}{l}\right) \frac{1 + \frac{h}{l}}{\left(\frac{h}{l} + \sin \theta\right) \cos \theta} E_s \quad (1)$$

This explains why absolute compressive modulus for cores with 1.2 mm thick cell walls is almost double that of cores with 0.6 mm thick cell walls. However, by doubling the thickness of the cell walls, the mass of the cores (for the same number of cells) increases proportionately too. As expected, the effects of cell wall thickness on the specific modulus of honeycomb cores would diminish. The effects of core depth appear not to be very important in relation to the compressive modulus, which is inline with the observations made by Meraghni et al. [23].

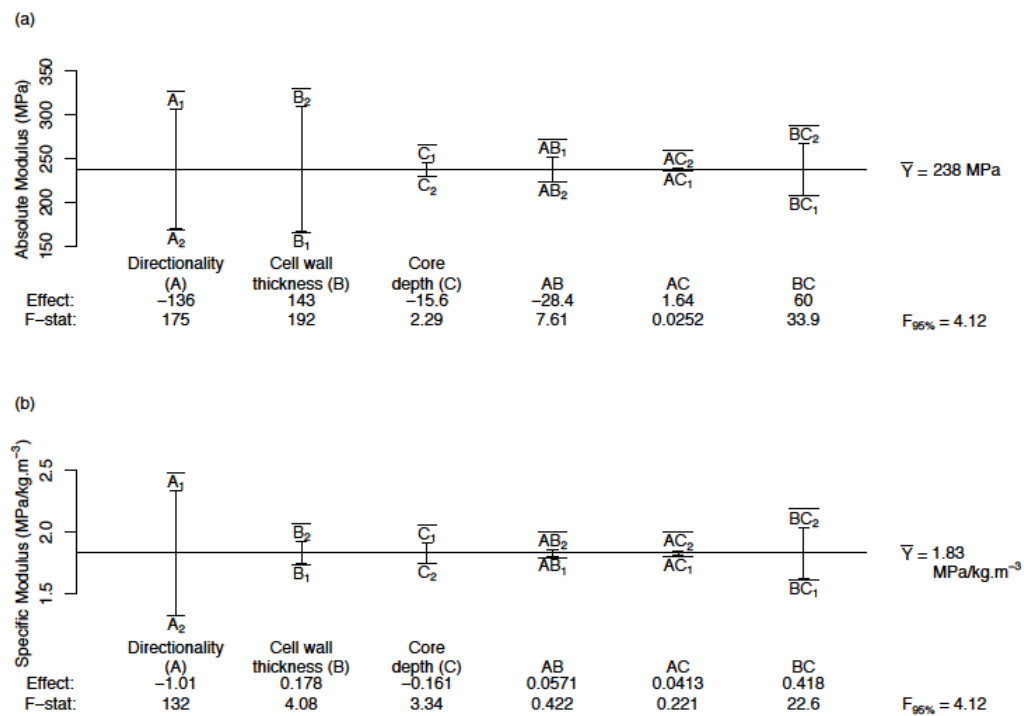


**Figure 7.** Effects of various factors on (a) absolute and (b) specific (relative to weight) flatwise bare compressive moduli of honeycomb cores.

The distinctive unparallel lines in the interaction plots, shown in Figure 8, indicate the presence of strong interaction between cell wall thickness and core depth for both absolute and specific compressive moduli. At a higher cell wall thickness (1.2 mm), a higher core depth (30 mm) resulted in higher compressive moduli and vice versa.

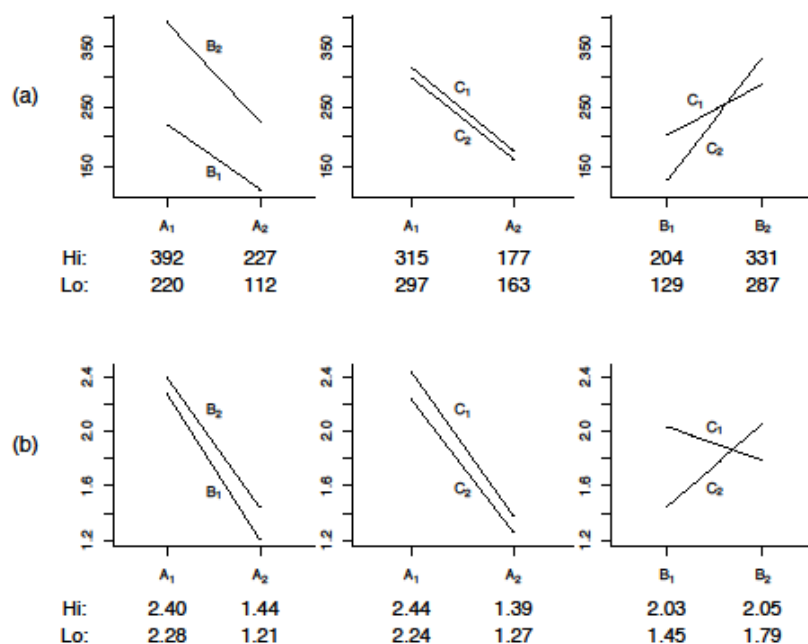


**Figure 8.** Interaction effects on (a) absolute and (b) specific (relative to weight) flatwise bare compressive moduli of honeycomb cores.

As explained earlier, buckling is dependent on the cell width-to-thickness ( $l/t$  or  $h/t$ ) and the cell width-to-core depth ( $l/H$  or  $h/H$ ) ratios. For cores with thin cell walls, a shallower core has more resistance towards buckling deformation and thus possesses a higher compressive modulus in comparison to a thicker core. On the other hand, cores with thicker cell walls are not susceptible to buckling deformation. Because of this stable structure, it allows for the core to have a higher core depth. Besides this, a mild interaction between directionality and cell wall thickness was observed — both F-MD and 1.2 mm thick cell wall resulted in a higher compressive modulus in comparison to their counterparts, as expected.

#### 4. Conclusion

To date, there has been no extensive study on core materials made of natural fibre/thermoplastic composites, let alone kenaf/polypropylene honeycomb cores. This characterization has shed light on the mechanical performance of this new class of material.

The effects of directionalities, cell wall thickness and core height on flatwise compressive and shear properties of the cores were examined. Cell wall thickness, core depth, directionality, and the interaction between core depth and cell wall thickness influenced both absolute and specific compressive strengths of kenaf/polypropylene honeycomb cores. Directionality and cell wall thickness as well as interaction between cell wall thickness and core depth influenced the absolute compressive modulus of honeycomb cores. However, only directionality and interaction between cell wall thickness and core depth affected specific compressive modulus.

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