NC STATE
Wilson College of Textiles

JTATM
Journal of Textile and Apparel, Technology and Management

Special Issue: 2022

Comparative Analysis of Mechanical Properties of Sisal and Glass Fiber Reinforced 3-D Woven Honeycomb Composite

Lekhani Tripathi and Bijoya Kumar Behera,
Department of Textile and Fibre Engineering,
Indian Institute of Technology,
Delhi

ABSTRACT

Several natural fibers such as sisal, jute, kenaf and ramie have been used as low-cost fillers in the plastic industry for a long time, but they are now beginning to replace glass fibers in composite constructions due to their weight, cost, and environmental (biodegradability) benefits. Natural fibers have been used as low-cost fillers in the plastic industry for a long time, but they are now beginning to replace glass fibers in composite constructions due to their weight, cost, and environmental (biodegradability) benefits. One of the most intriguing uses of natural fiber composites is the manufacture of honeycomb cores for sandwich panels, which increase mechanical qualities and functional capabilities such as vibration control, heat and energy dissipation. In this paper, sisal fiber was used to form 3D woven honeycomb composite as a core for sandwich panel. The mechanical properties such as flatwise, edgewise compression and bending behavior of sisal fiber honeycomb composite were compared with those of glass fiber honeycomb composite with similar areal density and cell size. The results reveal that sisal fiber composite gives better results for compression and significant improvement for bending as compared to the glass fiber honeycomb composite.

Keywords: honeycomb cores, sisal fiber, composites

Introduction

Lightweight composite constructions have recently experienced a rapid increase in automotives, aircrafts, and satellites, where weight savings are most important. Two thin and stiff face sheets (or skins) are connected to a thick and light core in sandwich panels. The face sheets provide the panel its flexural stiffness and strength, while the core's role is to transfer shear between the face sheets. Composite sandwich constructions have a high strength-to-weight ratio, as well as good specific bending stiffness and strength under distributed loads [1]. Sandwich panels are frequently employed in the construction of high-performance lightweight buildings [2, 3]. Sandwich panels are employed not only because of their weight-saving and structural benefits, but also because they are a cost-effective way to save expenses [4] .

Simultaneously, there is growing interest in natural fibers as a replacement for glass and carbon fibers [5]. Natural-fiber reinforced materials have found usage in a variety of unique applications, ranging from furniture and packaging to more complicated engineering applications such as building materials and structural elements for vehicle [6–8] . Natural fibers are being used to strengthen sandwich-panel cores, which is a growing trend. Demand for highly lightweight per unit ratio and green products has risen in recent years among industrial applications, posing new problems for manufacturing core structures employing natural fiber composites, particularly for a rice husk fiber base. Several research works have been carried out in recent past to predict the internal geometry, tensile behavior [9], and impact behavior [10] by mathematical modeling of the 3D solid woven structure. A detailed review has been given regarding the concepts of honeycomb structural materials, their manufacturing techniques, and engineering design of the structure. Research findings report that 3D-woven honeycomb composites have amazing properties for extensive structural applications[11].

Sisal fibers have better tensile strength, but palm fibers have excellent toughness, according to Zampaloni et al. [12] . Researchers have developed a variety of recyclable materials based on natural fibers such as flax, hemp, kenaf, jute, oil palm, coconut, and many more in response to growing environmental concerns. Natural fibers are inexpensive materials with low density, high specific qualities, biodegradability, and recyclability [13, 14] . A lot of study has been made on these so-called 'green' or 'eco-friendly' materials throughout the years. Fundamental research on natural fibers, on the other hand, has only recently accelerated due to rising demands for greater environmental protection. Many studies have demonstrated that composites made of natural fibers can have qualities equivalent to those made of conventional fibers if properly developed. Mallaiah et al. [15] evaluated the attributes of bio-based and synthetic fiber-based sandwich constructions and found that a hybrid structure made of bamboo and glass fibers had higher core shear stress and face bending stress than structures made entirely of glass or bamboo fibers. Toyota has started using natural fiber composites in its products and plans to expand their use in the future [16] .

A recent pioneering work investigated the compression damage utilizing acoustic emission to characterize natural flax fiber honeycomb. This research represents a unique honeycomb core made from epoxy composites reinforced with short flax fibers. Based on a flat compression response, an experiment was conducted for three core densities with the same cell size. The honeycomb damage was monitored via acoustic emission [17] .The compressive properties of square and triangular honeycomb core materials based on co-mingled flax fiber reinforced polypropylene (PP) and polylactide (PLA) polymers are investigated in the paper [18] . This research investigates the mechanical properties such as flatwise compression, edgewise compression and three-point bending behavior of sisal fiber 3D woven honeycomb composites. The results were then compared with glass honeycomb composite with similar areal density and cell size of the woven honeycomb structure.

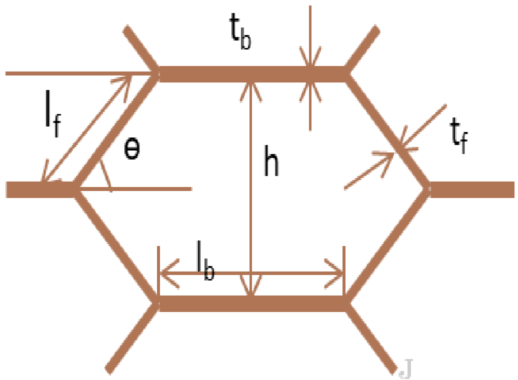
Materials and methods

Materials

3D woven honeycomb fabric samples were produced from E-glass tow of 600 Tex and sisal fiber of 1000 Tex. Epoxy LY556 (resin) and Aradur HY951 (hardener) were used to prepare the composites. E-glass tow of 600 Tex was used to produce 2D woven fabric for face sheets.

Methodology

All designs are created using the double cloth technique, which involves two unique layers that are separated from one another. The structural parameters for the honeycomb structure are shown in Fig. 1. A honeycomb structure is formed when both layers of the fabric are combined at one place. The honeycomb fabric samples of similar areal density and cell size were produced from glass and sisal fibers. The fabric samples were woven with fixed free wall (l_f) and bonded wall (l_b) length by deciding number of picks. Other honeycomb cell parameters such as the height of the cell (h) and the opening angle (θ) were managed by fabricating the molds of required honeycomb cell size. The cross-sectional view of woven honeycomb structure is shown in Fig. 2 in which the straight lines represent weft yarn the curved lines represent warp yarns coded as 5P4L60 [19].



θ :: Opening angle

l_b :: Bonded wall length

l_f :: Free wall length

t_b :: Bonded wall thickness

t_f :: Free wall thickness

h :: Height of cell

Figure 1. Parameters of single honeycomb cell

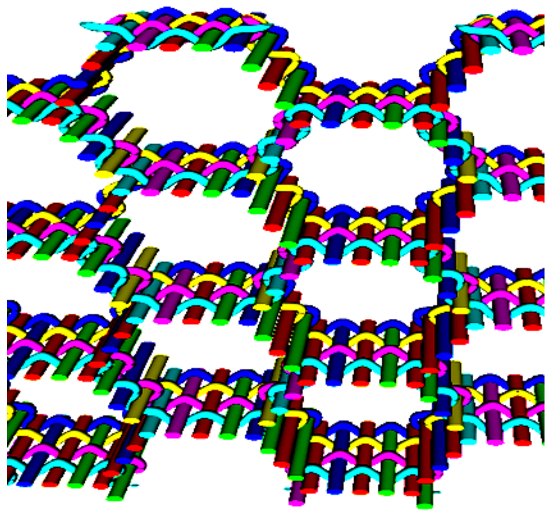


Figure 2. Cross-section representation of honeycomb structure 5P4L60 sample

Both honeycomb samples were made with the same opening angle of 60 degrees. Table 1 lists the characteristics of each fabric layer. The structural parameters of honeycomb fabric samples for both fibers are listed in Table 2.

Table 1. Specification of individual fabric layers in E-Glass and sisal honeycomb samples

Parameters	Ends per meter	Picks per meter	Warp yarn density (kg/m)	Weft yarn density (kg/m)	Fiber density(kg/m^3)
E-Glass samples	394	394	0.6x10^{-3}	0.6x10^{-3}	2540
Sisal fiber sample	197	197	1x10^{-3}	1x10^{-3}	1450

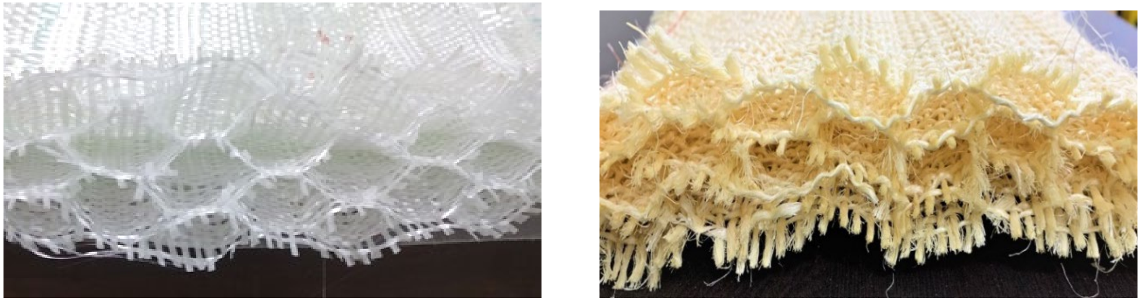
Table 2. Structural parameters of honeycomb fabric

Honeycomb Sample	Bonded wall length (mm)	Free wall length (mm)	Cell height (mm)	Opening angle (°)
Glass and sisal fiber	12.7	12.7	22	60

Fabrication of 3D honeycomb fabric

3D woven honeycomb fabric samples were produced on a modified 3D weaving system shown in Figure 3. The 3D machine has four beam configurations with a modified take-up system that are well synchronized with the let-off and take-up mechanisms. The machine has an electronic dobby and 24 heald shafts, and it can make multilayer solid constructions, spacer fabrics, and hollow honeycomb textiles, among other things. To create 3D woven honeycomb textiles, four warp beams were used. The end density of the connected wall is double that of the free wall, while the pick density kept constant. Figure 4(a) and (b) illustrate the honeycomb fabric examples made from glass fiber and sisal fiber, respectively.

Figure 3. Customized rapier weaving machine



(a) (b)

Figure 4. 3D woven honeycomb fabric sample (a) Glass fiber (b) Sisal fiber

Production of the 3D woven honeycomb composite

To keep the hexagonal cross-section in the composite, the necessary size of wooden molds were developed and put into the honeycomb fabric before infusion of resin, as illustrated in Fig. 5. The honeycomb composite was created using the vacuum-assisted resin infusion molding (VARIM) process. All 3D woven honeycomb composites were cured for 24 hours at room temperature. The honeycomb composites' fiber volume fraction (FVF) is maintained at 50%. To examine the influence of natural and synthetic fiber on flatwise and edgewise compressional characteristics, a composite structure was developed as illustrated in Fig. 6.

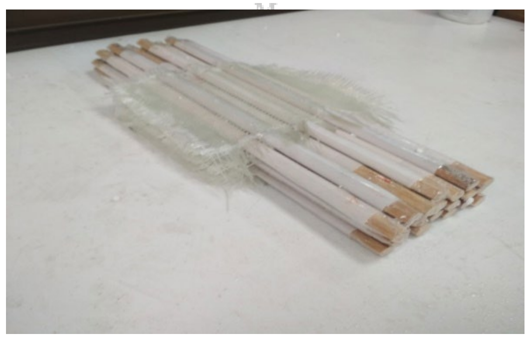
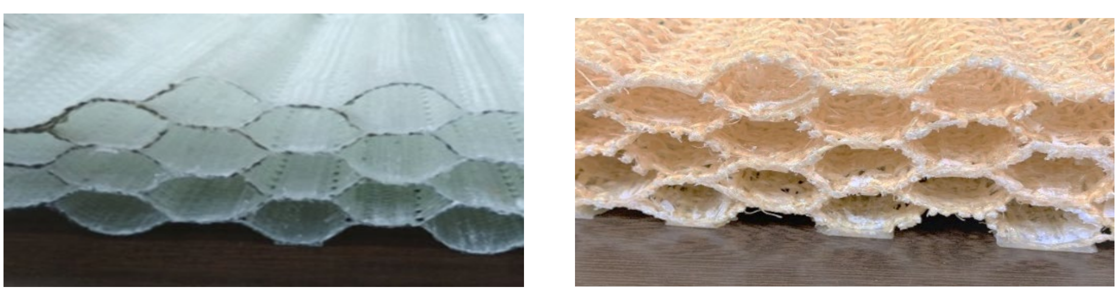


Figure 5. Teflon coated wooden block used for composite making



(a) (b)

Figure 6. 3D woven honeycomb composite (a) glass fiber (b) sisal fiber

Flatwise compressive properties characterization

The honeycomb structure's ability to absorb energy is a significant feature. On the Zwick/ Roell universal testing equipment, flatwise compression testing of honeycomb composite was performed according to ASTM C365 at a loading rate of 2mm/min (shown in Fig. 7). Sandwich panels were created as illustrated in Fig.8 using simple woven composites as upper and bottom sheets and an adhesive (Fast setting epoxy) to adhere the core to the face sheets. Honeycomb samples had the same core height (20 mm) and number of cells (9) throughout. After evaluating 5 samples, the average values were used to calculate final results.

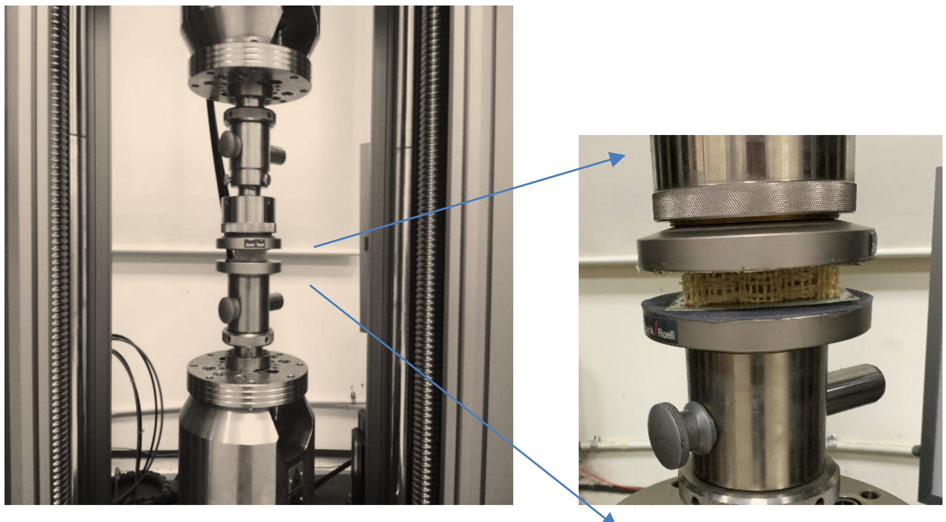
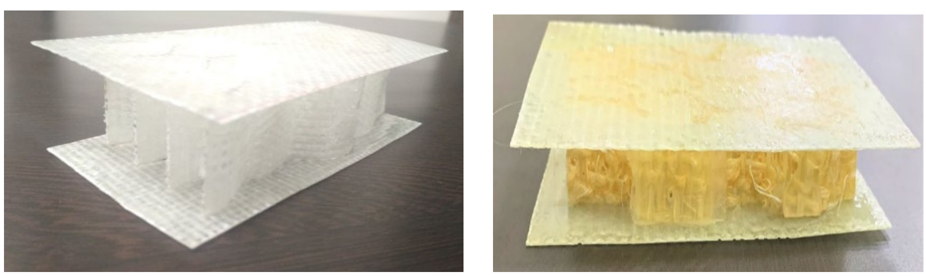


Figure 7. Experimental setup for flatwise compression test



(a) **(b)**

Figure 8. Sandwich panel of honeycomb core with the core height of 20mm (a) Glass fiber (b) Sisal fiber

Edgewise compressive properties characterization

Edgewise compression testing of honeycomb was performed according to ASTM C 364 – 99 with a crosshead movement of 0.5 mm/min (shown in Fig. 9) on the Zwick/ Roell universal testing equipment. Honeycomb samples had the same core height (20 mm) and number of cells (9) throughout. After evaluating 5 samples, the average values were used to calculate final results.

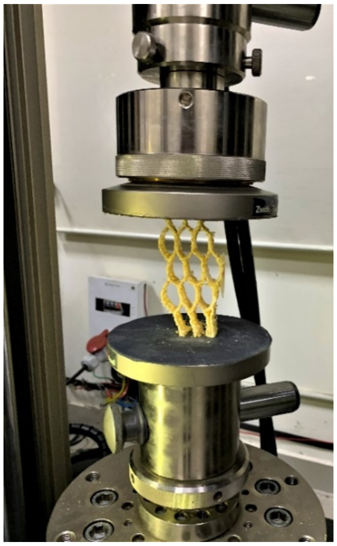


Figure 9. Experimental setup for edgewise compression test

Characterization of bending properties

ASTM C 393 procedure was used to evaluate the bending performance of composite samples for each honeycomb composite. On the Zwick/ Roell universal testing machine, a three-point bending test was performed at a cross-head speed of 1 mm/min with a span length of 150mm (shown in Fig. 10). For the bending test, three rollers with a diameter of 40mm were used. The width of the sample was determined by the form of the cells. After evaluating 5 samples, the average values were used to calculate the final results.

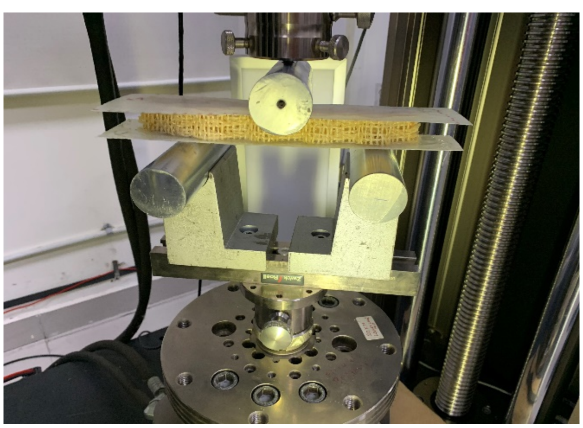


Figure 10. Experimental setup for three-point bending test

Results and Discussion

Principle of compressive and flexural characterization of honeycomb composites

The mechanical properties of honeycomb structural composites such as compressive and flexural deformations are significantly influenced by the honeycomb cell geometry. The cell geometry of 3D honeycomb hollow structures also determine the mass and volume of the entire composite structure. Therefore, in case of compression, the specific compressive strength of different composite structures are normalized with mass of the specimen. Although the specific compressive strength includes the effect of the mass of the composite specimen, it may not be considered as true representative of their performance against the compressive load, owing to their considerably different volumes. Therefore, the strain energy up to maximum compressive load needs to be calculated from the load-deformation curves, and the values should be normalized with the volume of the corresponding specimen. In a typical load-deformation curve of a honeycomb composite structure, the failure mode can be examined by analyzing various stages of the curve. The structure initially deforms elastically up to a peak load with elastic buckling of walls, after which buckling failure of walls lead to sudden drop in load, followed by a long deformation plateau corresponding to which the curve remains flat and parallel to deformation axis. Finally, the structure fails, and densification stage is reached. Moreover, honeycomb structural composites are also characterized for both flatwise and edgewise compressive load.

Determination of flatwise compressive properties

The compression energy of honeycomb structure composites was calculated according to the principle described above for all the specimens up to the initiation of densification or the completion of the plateau area, since this number reflects the honeycomb composite structure's effective measure of energy absorption capacity. The size of the specimen was chosen depending on the number of layers. As a result, the weight of the specimen was varied for each composite sample due to the varying number of picks. Different processes for energy absorption in man-made cellular solids [20] have been proposed, and they are linked to elastic, plastic, and cell wall deformation. The absorption of energy (W) up to a strain (ε) is usually represented as Eq. 1:

$$\mathbf{W}=\int_0^{\varepsilon} \boldsymbol{\sigma}(\boldsymbol{\varepsilon})\,d\boldsymbol{\varepsilon} \qquad (1)$$

where σ (ε) is the stress up to the strain (ε) in a deformed structure [21].

Hence, to compare the properties of these structures, the absorption of energy of each structure was normalized by using their respective mass and volume using Equations 2 and 3.

$$Ew = W/M \qquad \ldots\ldots (2)$$
$$Ev = W/V \qquad \ldots\ldots. (3)$$

Where Ew and Ev denote the energy per unit mass and energy per unit volume respectively.

'M' and 'V' are the mass and volume of the honeycomb composite specimen respectively.

Determination of edgewise compressive properties

The honeycomb composite structure's ultimate load (P) was determined. A comparable number of layers was used to determine the specimen size. As a result, because the number of picks in each composite sample differed, the weight of the specimen varied. To compare the attributes of various structures, the ultimate load by each structure was normalized using their respective mass and volume, as described in Equations 4 and 5.

$$Pw = P/M \qquad \ldots\ldots (4)$$
$$Pv = P/V \qquad \ldots\ldots. (5)$$

Where Pw and Pv denote the ultimate load per unit mass and ultimate load per unit volume respectively. M and V are the mass and volume of the honeycomb composite specimen respectively.

Determination of three point bending properties

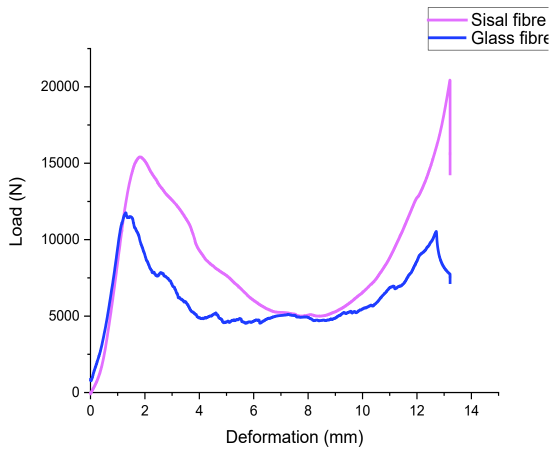
The honeycomb composite structure's ultimate load (B) was determined. A comparable number of layers was used to determine the specimen size. To compare the attributes of various structures, the ultimate load by each structure was normalized using their respective mass and volume, as expressed in equations 6 and 7 respectively.

$$Bw = B/M \qquad \ldots\ldots (6)$$
$$Bv = B/V \qquad \ldots\ldots. (7)$$

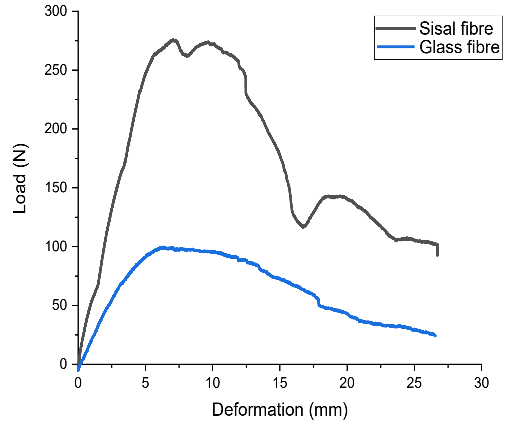
here Bw and Bv denote the ultimate load per unit mass and ultimate load per unit volume respectively. M and V are the mass and volume of the honeycomb composite specimen respectively.

Comparative analysis of mechanical behavior of glass and sisal fiber honeycomb composites

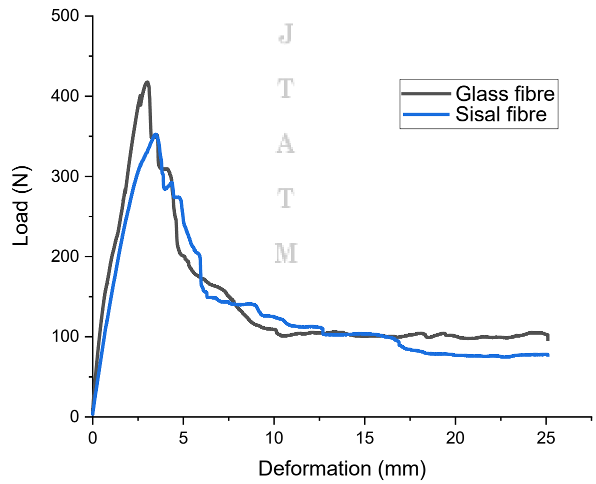
The load-deformation curve for glass and sisal honeycomb composite for flatwise, edgewise compression and bending behavior are shown in Fig. 11 (a), (b) and (c) respectively. The Load-deformation behavior shows that sisal fiber is showing good result for compression while significant result for bending as compared to glass fiber composite. The stress is calculated based on the overall area of the structure, which includes the cells between the skins. During the elastic loading phase, both traces rise fast until reaching a peak and afterwards rapidly dropping as the core walls buckled. The sisal fiber composite outperforms its glass equivalent in terms of strength.



(a) Flatwise compression



(b) Edgewise compression

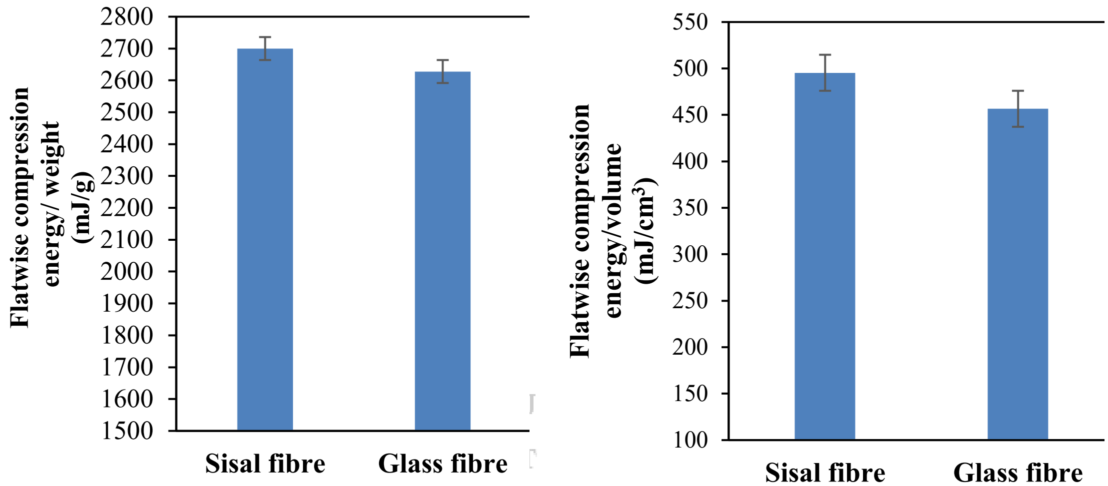


(c) Bending deformation

Figure 11. Load deformation curve of glass and sisal honeycomb composite (a) Flatwise compression (b) Edgewise compression and (c) Three-point bending

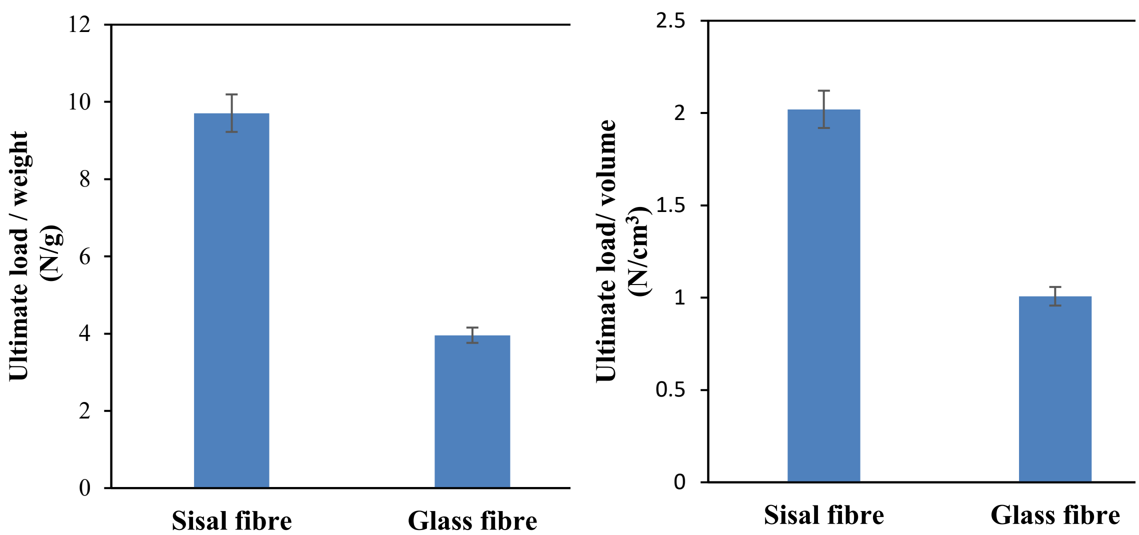
Energy-absorbing structures and systems are one possible application for these natural fiber-based cores. By calculating the specific energy absorption (SEA) of the cores, the energy-absorbing properties of the cores were compared in this study. The mass or volume of the sample was divided by the energy under the load–displacement trace up to the initiation of densification (defined as the displacement at which the load reached the peak load in the crush process). The specific compression energy (energy per unit weight and unit volume) is shown in Fig.12(a) and (b) respectively. The results shows that specific compression energy is higher for sisal honeycomb composite. The specific ultimate load (ultimate load per unit weight and unit volume) for edgewise compression is shown in Fig.13 (a) and (b) respectively. These results also show the similar trend for edgewise compression as well. The specific ultimate load (ultimate load per unit weight and unit volume) for bending behavior is shown in Fig.14 (a) and (b) respectively.

It was concluded that sisal fiber has good potential for the replacement of synthetic fiber composite. The fibers differ on the structural level: sisal fibers have longer cellulose chains in their structure, which favors the absorption of energy. Sisal fibers have a honeycomb structure in their cross sections. This structure has been produced over millions of years by the biological development of fibers and possesses exceptional resistance to external stresses [22].



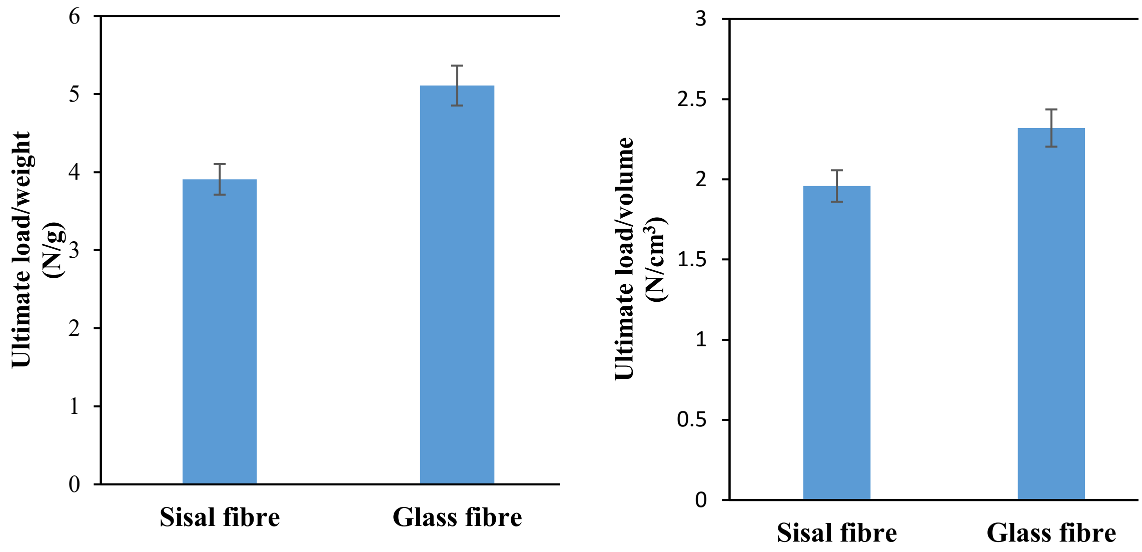
(a) (b)

Figure 12. Flatwise compression energy of honeycomb composite of different fiber (a)per unit weight (b) per unit volume



(a) (b)

Figure 13. Ultimate load for edgewise compression of honeycomb composite of different fiber (a) per unit weight (b) per unit volume



(a) **(b)**

Figure 14. Ultimate load for three-point bending of honeycomb composite of different fiber (a) per unit weight (b) per unit volume

Conclusion

In this research sisal natural fiber based 3D woven honeycomb composites were successfully developed from the honeycomb preforms of similar areal density cell size. The compressive properties such as flatwise and edgewise compression and bending behavior of these composites along with glass tow 3D woven honeycomb composites were examined to compare their mechanical performance. The results revealed that specific flatwise compression energy is higher for sisal fiber composite. Similar trends were observed for edgewise compression and shows higher specific ultimate load for sisal honeycomb composite. The results of this study indicate that sisal-reinforced cores might be a viable alternative to traditional cores like glass in compressive stress applications.

Acknowledgments

The project team sincerely acknowledges the Ministry of Textiles, Government of India for sponsoring this project to Focus Incubation Centre of 3D Fabric and Structural Composite.

References

1. Abrate S (1997) Localized impact on sandwich structures with laminated facings. Appl Mech Rev. https://doi.org/10.1115/1.3101689
2. Thomsen OT (2009) Sandwich materials for wind turbine blades - Present and future. J Sandw Struct Mater. https://doi.org/10.1177/1099636208099710
3. Hou S, Zhao S, Ren L, et al (2013) Crashworthiness optimization of corrugated sandwich panels. Mater Des. https://doi.org/10.1016/j.matdes.2013.04.086
4. Pflug J, Verpoest I (2006) Sandwich materials selection charts. In: Journal of Sandwich Structures and Materials
5. Santulli C, Sarasini F, Tirillò J, et al (2013) Mechanical behaviour of jute cloth/wool felts hybrid laminates. Mater Des.https://doi.org/10.1016/j.matdes.2013.02.079
6. Singh B, Gupta M, Verma A (2000) The durability of jute fibre-reinforced phenolic composites. Compos Sci Technol. https://doi.org/10.1016/S0266-3538(99)00172-4

7. Mwaikambo LY, Ansell MP (2002) Chemical modification of hemp, sisal, jute, and kapok fibers by alkalization. J Appl Polym Sci. https://doi.org/10.1002/app.10460
8. Dweib MA, Hu B, O'Donnell A, et al (2004) All natural composite sandwich beams for structural applications. Compos Struct. https://doi.org/10.1016/S0263-8223(03)00143-0
9. Jayan VR, Tripathi L, Behera PK, et al (2021) Prediction of internal geometry and tensile behavior of 3D woven solid structures by mathematical coding. J Ind Text 152808372110013. https://doi.org/10.1177/15280837211001348
10. Tripathi L, Chowdhury S, Behera B (2020) Modeling and simulation of impact behavior of 3D woven solid structure for ballistic application. J Ind Text 152808372098046. https://doi.org/10.1177/1528083720980467
11. Tripathi L, Behera BK (2021) Review: 3D woven honeycomb composites. J. Mater. Sci.
12. Zampaloni M, Pourboghrat F, Yankovich SA, et al (2007) Kenaf natural fiber reinforced polypropylene composites: A discussion on manufacturing problems and solutions. Compos Part A Appl Sci Manuf. https://doi.org/10.1016/j.compositesa.2007.01.001
13. Alix S, Marais S, Morvan C, Lebrun L (2008) Biocomposite materials from flax plants: Preparation and properties. Compos Part A Appl Sci Manuf. https://doi.org/10.1016/j.compositesa.2008.08.008
14. Nabi Saheb D, Jog JP (1999) Natural fiber polymer composites: A review. Adv Polym Technol. https://doi.org/10.1002/(SICI)1098-2329(199924)18:4<351::AID-ADV6>3.0.CO;2-X
15. Mallaiah S, Sharma K, Eng MK-IJSC, 2012 U (2010) Development and comparative studies of bio-based and synthetic fiber based sandwich structures. Int J Soft Compos Eng 2 332–5
16. Holbery J, Houston D (2006) Natural-fiber-reinforced polymer composites in automotive applications. JOM
17. Selmi S, Habibi M, Laperrière L, Kelouwani S (2020) Characterisation of Natural Flax Fibers Honeycomb: Compression Damage Analysis Using Acoustic Emission. J Nat Fibers. https://doi.org/10.1080/15440478.2020.1789531
18. Zuhri MYM, Guan ZW, Cantwell WJ (2014) The mechanical properties of natural fibre based honeycomb core materials. Compos Part B Eng. https://doi.org/10.1016/j.compositesb.2013.10.016
19. Tripathi L, Neje G, Behera BK (2020) Geometrical modeling of 3D woven honeycomb fabric for manufacturing of lightweight sandwich composite material. J Ind Text 152808372093147. https://doi.org/10.1177/1528083720931472
20. Schwaber DM (1973) Impact Behavior of Polymeric Foams: A Review. Polym Plast Technol Eng 2:231–249. https://doi.org/10.1080/03602557308545019
21. Gibson LJ, Ashby MF (1997) Cellular Solids. Cambridge University Press, United Kingdom
22. Sun Z, Zhao X, Ma J (2013) Characterization of microstructures in sisal fiber composites by Voronoi diagram. J Reinf Plast Compos. https://doi.org/10.1177/0731684412461191