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Development of PALF/Glass and COIR/Glass Fiber Reinforced Hybrid Epoxy Composites

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ABSTRACT

To meet the industrial and environmental policy regarding the selection of a material for structural applications, it becomes necessary to compound recyclable cellulosic material with the high-performance synthetic material. In this regard, the untreated and alkali treated PALF/Glass and Coir/Glass hybrid epoxy-based composites were developed by hand lay-up technique, keeping the total fiber to resin ratio 30:70 v/v. The hybrid composites were characterized in terms of tensile, flexural, impact, and water absorption properties according to the ASTM D 638, 790, 256, and 570 standards respectively. The results showed that the 15/15 (v/v) PALF/Glass hybrid composite has higher tensile and flexural properties as compared to the other hybrid formulations. The alkali treated 15/15 (v/v) PALF/Glass composite possess 35.13% higher flexural strength than that of pure Glass-Epoxy composite. Amongst all the developed materials, the mercerized 15/15 (v/v) Coir/Glass fiber reinforced epoxy composite exhibits the maximum impact strength and resistance to water molecules.

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Coir fiber
Glass fiber
Epoxy matrix
Polymer composite
Mechanical properties

List of abbreviations

NFRC's	*Natural Fiber Reinforced Composites*
PALF	*Pineapple Leaf Fiber*
ASTM	*American Society for Testing and Materials*
OPEFB	*Oil Palm Empty Fruit Bunch Fiber*
DGEBA	*Di-Glycidal Ether Bisphenol A*
TETA	*Tri-Ethylene Tetra-Amine*
PG-EP	*Pineapple Glass-Epoxy Composite*
CG-EP	*Coir Glass-Epoxy Composite*
KP-PE	*Kenaf Pineapple-Polyethylene Composite*

Introduction

Natural fibers and their composites are received a lot of attention for the employment in varieties of engineering applications. This was because of their large number of profitable properties such as low cost, lightweight, high specific strength and stiffness, problem-free disposal at the end of use, energy and ecological balance, non-abrasive to molding and mixing equipment, recyclability, and biodegradability [1]. The progressive consumption of natural fibers in industrial and consumer goods will help to generate the local economy, and widening availability of the products to ordinary people at low cost. Among all the lignocellulosic materials, the pineapple leaf and coconut husk fibers are the most promising and desirable candidates to be select as a reinforcing agent in polymer-based materials. Pineapple and coir are multi-cellular fiber, extracted from the leaves of pineapple and the husk (mesocarp) of coconut fruit respectively. The primary reasons to select PALF and COIR fibers over the other natural fibers are: 1) Pineapple leaf fiber contains high cellulose (70-85%) content which results it has higher tensile and flexural properties than that of flax, sisal, jute, OPEFB, and cotton fibers. 2) Easy availability, low density, favourable aspect ratio, and low microfibrillar angle of PALF. 3) Coir fiber consists of high lignin content (40-45%) which makes it more durable and stable under a wide range of temperature, humid environmental conditions, and also has excellent resistant properties to microbial and fungus attack. Inspite of their fruitful features, the cellulosic fibers are far away to smoothly adopt in structural applications. It was due to the poor match between natural and synthetic fibers in the context of mechanical properties [2-5]. The most commonly used synthetic fiber is E-glass having good tensile and compressive properties. However, the higher cost, non-biodegradability, abrasive nature, and associated health hazards problems favour the exploration and exploitation of natural fibers [6]. In order to increase the probability of natural fibers as a preferred choice for semi-structural and structural applications, it becomes necessary to modify and improve their properties by the exploitation of hybridization and chemical treatment tools. The previous research work mentioned in Table 1 confirmed this fact and provide sufficient assurance to the benefits of fiber hybridization and chemical modifications. Hybrid composites offer the tailor-made properties at low cost according to the requirements for a particular application. The properties of a hybrid composite are mainly depends on the nature of reinforcing fibers and matrix; relative volume content of each kind of reinforcing fiber; arrangement, orientation, and distribution of fibers; morphology of the system; and the compatibility between fibers and matrix. The failing of one kind of fiber can be overcome by the hybridization with a suitable type of fiber. The positive hybridization is a result of synergistic compatibility between reinforcing fibers which results in the balanced combination of strength, stiffness, ductility, and toughness. In most of the cases, the hybrid composites have better and comparable performance to that of natural and synthetic fiber reinforced composites respectively. Therefore, the hybridization with synthetic glass fiber can surmount the problems of natural fibers. A high-performance structural material can be developed at a low cost by employing the hybridization concept. The incorporation of thermoset polymer as a matrix resin leads to the improvement in performance of a structural

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Table 1: Previous research work reported on the hybrid and chemically treated natural fiber reinforced composites

Authors	Factors explored by researchers	Results	Reference
A. Atiqah et al. (2014)	Development and mechanical characterization of Kenaf/Glass reinforced polyester hybrid composites.	The hybrid composite reinforced with alkali-treated kenaf fiber and glass fiber in 15/15 (v/v) showed higher tensile, flexural, and impact strength than that of other hybrid formulations.	[7]
M. Jawaid et al. (2012)	Effect of Jute fiber loading on physical and chemical resistant properties of Jute/EFB-Epoxy hybrid composites.	Void content reduced and stability towards chemical reagents (benzene, toluene, CCl_4, HNO_3, CH_3COOH, NaOH, Na_2CO_3) increased with the increase of jute fiber content.	[8]
R. Ranjan et al. (2013)	Effect of alkali treatment on mechanical properties of Banana/Sisal fiber reinforced PLA composites.	The 2 wt% NaOH treated hybrid composite shows better mechanical properties (tensile, flexural, and impact strength) than that of untreated composites.	[9]
S. Panthapulakkal et al. (2006)	Mechanical, water absorption and thermal characterization of hybrid hemp/glass fiber reinforced-polypropylene composites.	Low cost and high performance composite was obtained by the hybridization of hemp and glass fibers. The tensile, flexural, and impact strength of Hemp/PP composite was increased with the incorporation of a small amount (15 wt%) of glass fiber. Glass fiber loading improves the thermal stability of Hemp-PP composite	[10]
A. Shahzad et al. (2011)	Effect of hybridization on impact and fatigue strength of Hemp/Glass fiber reinforced unsaturated polyester composites.	Impact and fatigue strength of Hemp/UPE composite was increased by the replacement of 11% hemp fiber with glass fiber.	[11]
M. Haq et al. (2008)	Development of hybrid composites from blends of UPE and soybean oil reinforced with nanoclay and hemp fiber	A Synergistic hybrid composite having balanced stiffness and toughness properties was developed by the partial substitution (10%) of UPE with EMS and reinforced with 1.5% nanoclay.	[12]
V.S. Chevali et al. (2015)	Effect of the loading of sunflower hull and distiller's dried grains fiber on the physical properties of ABS polymer.	Tensile, Flexural, and impact strength was reduced with the addition of SFH and DDGS filler in ABS polymer. It showed the poor compatibility between reinforcing fillers and polymer.	[13]
M.M Davoodi et al. (2011)	Compared the overall performance of hybrid kenaf/glass-epoxy composite with traditionally used GMT material in car bumper beam	The Kenaf/Glass fiber reinforced hybrid epoxy composite in double hat profile (DHP) has significant potential to be used in small-sized car bumper beam.	[14]
P.J Jandas et al. (2011)	Effect of chemical treatment on mechanical properties of PLA/Banana fiber reinforced composites.	Tensile strength, impact strength, glass transition temperature, and storage modulus was increased by the effect of chemical treatments (NaOH, APS, and Si69) on PLA/Banana fiber biocomposites.	[15]
L.Y. Mwaikambo et al. (2001)	Alkalization of hemp, sisal, jute, and kapok fibers.	Mechanical properties and thermal stability were improved by the alkali treatment.	[16]
M.J. John et al. (2008)	Effect of chemical modification on the properties of Sisal/OPEFB hybrid composite.	The 4% NaOH treated Sisal/OPEFB fiber reinforced natural rubber hybrid composite exhibits maximum tensile strength and torque value with minimum swelling index.	[17]
Xue Li et al. (2007)	Chemical treatments of natural fiber for high strength biocomposite material.	Alkali treatment significantly improves the static and dynamic mechanical properties of NFRC's with the increased resistance to moisture sorption.	[18]
M.J. John et al. (2007)	Characterization of chemically modified NFRC's.	Alkali treatment is one of the most efficient and reliable chemical treatments which favors the formation of a strong covalent bond between fibers and matrix.	[19]
V.S. Uppin et al. (2016)	Interlaminar fracture toughness of Glass/Cellulose fiber reinforced epoxy composites	Interlaminar fracture toughness of Glass-Epoxy composite was increased by 32% with the incorporation of cellulose fiber.	[20]

Table 1: continues….

F. Cheng et al. (2014)	Characterization of Glass/Coir fiber reinforced polyester composites.	The improvement in flexural strength (419%), modulus of elasticity (708%), and impact strength (562%) was observed by the addition of glass fabrics in coir-polyester composites.	[21]
L. Uma Devi et al. (2011)	Effect of chemical treatment (NaOH and vinyl silane) and glass fiber content on the water absorption behavior of PALF/GF reinforced polyester composites.	Alkaline treated hybrid composites having 0.46 V_f content of glass fiber possess lowest water sorption affinity.	[22]
V.K. Bhagat et al. (2014)	Study of physical and mechanical properties of Coir/Glass hybrid epoxy composites.	The hybrid epoxy based composite consists of 10 wt% coir fiber (15 mm length) and 20 wt% glass fiber revealed the maximum mechanical strength.	[23]
M. Rahman et al. (2018)	Effect of alkali treatment, fiber content, and fiber volume ratio on the mechanical properties of Banana/PALF fiber reinforced hybrid polypropylene composites.	The hybrid composite reinforced with NaOH treated PALF and Banana fiber at a ratio of 3:1 with a 5 wt% total fiber content showed the best set of mechanical properties.	[24]
V. Arumugaprabhu et al. (2016)	Mechanical characterization of Palmyra/Coir fiber reinforced polyester hybrid composites.	Tensile, flexural, and impact strength of Palmyra/Polyester composite was increased by the hybridization with Coir fiber in ratio of 40:60 (Palmyra/Coir).	[25]
N.M. Nurazzi et al. (2018)	Effect of fiber hybridization on mechanical properties of Sugar palm/Glass fiber reinforced polyester composites.	The hybrid composite reinforced with 40 wt% fiber in the ratio of 50:50 (Sugar palm yarn: Glass fiber) revealed the higher tensile, flexural, and compressive strength than that of other hybrid formulations.	[26]
H.P.S Abdul Khalil et al. (2017)	Effect of the loading of coconut shell nano-fillers on the mechanical properties of kenaf/coconut fiber reinforced composites.	The incorporation of coconut shell nano-fillers up to 3 wt% leads to the increment in tensile, flexural, and impact strength of kenaf/coconut fiber reinforced composites.	[27]
A. Atiqah et al. (2018)	Effect of chemical treatment on the mechanical properties of Sugar Palm/Glass fiber reinforced polyurethane composites.	The tensile, flexural, and impact strength of a hybrid composite was improved by 16%, 39%, and 18% respectively by the chemical treatment with 6 wt% alkaline + 2 wt% silane.	[28]
IS. Aji et al. (2012)	Effect of hybridization on mechanical properties and water absorption behavior of Kenaf/PALF fiber reinforced HDPE composites.	Tensile and flexural properties of Kenaf/HDPE composite were increased by the hybridization with pineapple leaf fiber. The equal volume content of PALF and Kenaf in HDPE matrix possess the optimum mechanical properties.	[29]
B. Bakri et al. (2017)	Effect of relative fiber volume content on the mechanical properties of Coir/Angustifolia Haw Agave fiber reinforced epoxy composites.	The hybrid composite reinforced with 15:15 v/v (Coir: Agave) yields higher tensile strength, tensile modulus, and flexural modulus than that of other hybrid formulations (Coir: Agave = 10:20 and 20:10).	[30]
A. Oushabi et al. (2017)	Effect of alkali treatment on mechanical and thermal properties of date palm fiber-polyurethane composites.	The tensile strength, interfacial bond strength, and thermal stability of DPF composites were increased by the effect of alkali treatment. The optimal concentration for alkali treatment of DPF is 5 wt%.	[31]
K. Panyasart et al. (2014)	Effect of alkaline treatment on the mechanical properties of PALF/Polyamide 6 composites.	The tensile strength and modulus of composites was increased by the alkali treatment of pineapple leaf fiber which leads to the increased interfacial adhesion between treated PALF and polyamide matrix resin.	[32]

composite material for outdoor applications. The epoxy resin is a best suitable thermoset matrix for use in primary construction and marine industry. It was due to the high mechanical and electrical properties; good resistance to chemicals, moisture, and environmental degradation; good adhesive properties; low viscosity with easy processing; and easily cured at a temperature from 5^0C to 150^0C. In the present research work, the two different kinds of epoxy based hybrid composites (PALF/Glass and Coir/Glass) were developed and characterized their mechanical properties. Moreover, the effect of relative fiber volume content and the alkaline treatment on mechanical properties and water absorption behavior of PALF/Glass and Coir/Glass fiber reinforced hybrid epoxy composites have been also investigated.

Experimental

Materials

The chopped strand glass fiber mat (E-glass), coconut husk fiber (*Cocos-nucifera*), and pineapple leaf fiber (*Ananas-comosus*) were all obtained from M/s Go Green Products Chennai, India. Both type of cellulosic fibers (PALF and COIR) were of the long form and cut into the length of 20 mm by scissor. The glass fiber mat was also cut according to the size of the mold (200 X 100 X 4 mm^3). To impregnate the dried cellulosic and synthetic fibers in an open glass mold cavity, the medium viscosity epoxy thermoset resin was used. The epoxy resin (DGEBA) and curing agent (hardener, TETA) were procured from M/s Sakshi Dies and Chemicals, Delhi, India. The physical properties of reinforcing fibers (PALF, COIR, and E-GLASS) and the matrix resin are reported in Table 2 and 3 respectively. Sodium hydroxide (NaOH) used for mercerization (alkali treatment) was of laboratory reagent and received from the Chemistry Department, DTU (Delhi), India. The surface morphology of untreated and alkali treated pineapple leaf and coir fibers are depicted in Figure 1 and 2 respectively.

Table 2: Physical properties of Pineapple leaf, Coir, and E-Glass fiber

Physical properties	Pineapple leaf fiber	Coir fiber	E-Glass fiber
Density (g/cm^3)	0.98	1.2	2.55
Cellulose (%)	70-82	32-43	-
Hemicellulose (%)	18.8	0.15-0.25	-
Lignin (%)	5-12.7	40-45	-
Pectin (%)	1.1	3-4	-
Moisture content (%)	11.8	8	-
Microfibrillar angle (deg)	14	30-49	-
Diameter (μm)	20-80	100-460	<17
Tensile strength (MPa)	413-1627	131-220	3400
Young's modulus (GPa)	34.5-82.5	4-6	73
Elongation at break (%)	1.6	15-40	2.5

Table 3: Physical properties of epoxy thermoset matrix

The appearance of liquid resin	A clear pale yellow
Density (Kg/m^3)	1200-1250
Viscosity at 25^{0}C (cps)	550
Tensile strength (MPa)	11-15
Tensile modulus (GPa)	0.45-0.52
Flexural strength (MPa)	23-28
Flexural modulus (GPa)	1.3-1.7
Max. Elongation (%)	4.2-5.6
Impact strength (kJ/m^2)	1.2
Flashpoint	> 200^{0}C

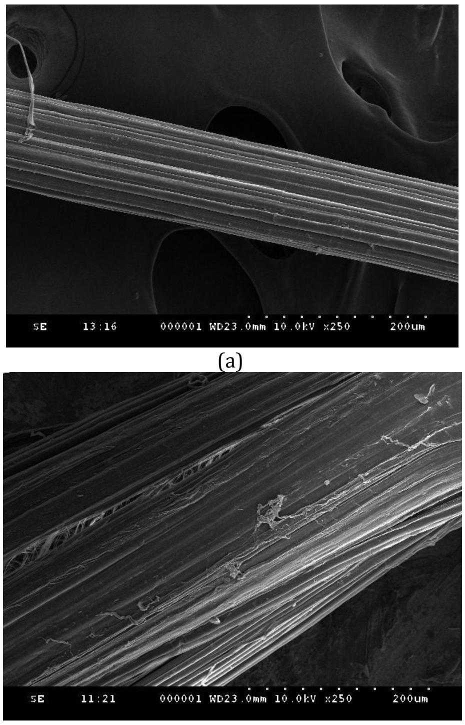

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Figure 1: Surface morphology of Pineapple leaf fiber (a) Untreated, (b) 4% alkaline treated

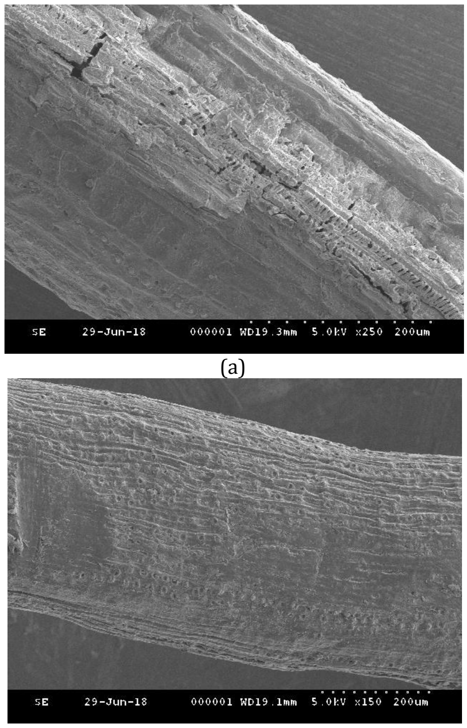

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Figure 2: Surface morphology of Coir fiber (a) Untreated, (b) 4% alkaline treated

Alkaline treatment of natural fibers

In order to ameliorate the interfacial interaction between natural fibers (PALF and COIR) and epoxy thermoset resin, the most commonly used chemical treatment known as 'mercerization' was employed. Initially, both type of fibers were washed in tap water and dried in sunlight for 3 days to remove the surface impurities and absorbed water molecules. The cleaned and dried cellulosic fibers were immersed in 4 wt% alkali (NaOH) solution for 24 hr at room temperature, followed by the treatment with 2 wt% acetic acid (CH_3COOH) solution and then rinsed in distilled water to control the pH level at 7. The neutralized wet fibers were dried again at room temperature for 24 hr and then followed by oven drying at 70^{0}C for 24 hr (until the constant weight was obtained).

Development of hybrid composites

For the molding of a biocomposite sheet, two thick glass plates of same dimensions (250 mm X 150 mm X 3mm) are used. A hand lay-up method was employed to position the reinforcing fibers in the desired pattern and to impregnate them with the viscous thermoset resin. Before the sheet molding process, it is highly desirable to treat the mold surface with a releasing wax (*Mirror Glaze*) to avoid the sticking of adhesive polymer epoxy matrix to the mold surface and for easy removal of the developed composite parts. Figure 3 shows the arrangement of glass and cellulosic fibers with an epoxy matrix in a glass mold cavity. Before the molding process, ensure that the epoxy resin (DGEBA) and the hardener (TETA) were uniformly mixed and no air bubbles were present. The surface of the mold must be smoothen and flatten which confirms the good surface finish of a molded part. During the fabrication of a laminate sheet, the air bubbles are abstracted carefully by using a steel roller. To obtain good results, ensure that the fiber and matrix content per unit area of the mold is constant and the fibers were completely impregnated with the matrix resin. In the end, closed the mold and then pressed with external heavy weight for 24 hrs curing at room temperature. Table 4 depicts the designation and composition of developed hybrid composites. The four samples of each composite specimen were cut from the molded sheet as per ASTM standard for tensile, flexural, impact, and water absorption tests.

Characterization of developed composites

To characterize the physical properties of developed hybrid composites, the tensile, flexural (*3 point bending*), impact, and water absorption tests were performed as per ASTM D 638, 790, 256, and 570 standards respectively. The tensile and flexural bending tests were carried out on calibrated Table Top Tinius Olsen Horizon H50KS, Universal Testing Machine. While the impact strength was determined by using an Izod impact tester (installed in the SOM Laboratory, DTU (Delhi), India). All the tests were performed at room temperature and their important details with standardized dimensions of test specimens are reported in Table 5. The total of four samples for each composite specimen was tested and their mean values were reported.

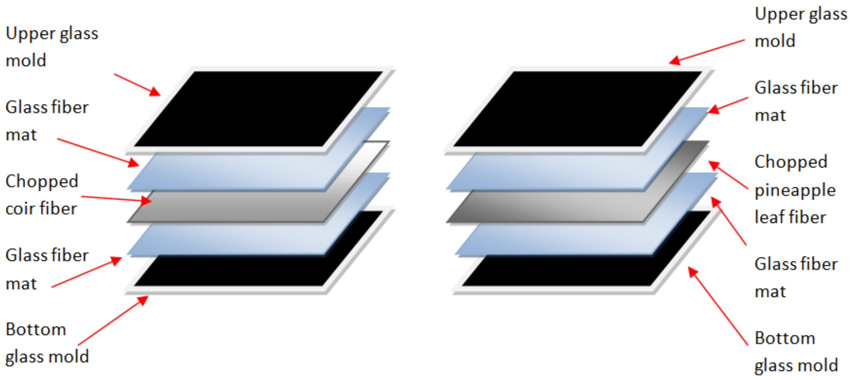


Figure 3: Schematic diagram of fibers sequence in an open glass mold

Table 4: Designation and composition of developed PALF/Glass and Coir/Glass hybrid composites

Designation		Composition
Un-treated	S1	Epoxy (70 vol.%) + untreated pineapple leaf fiber (30 vol.%)
	S2	Epoxy (70 vol.%) + untreated pineapple leaf fiber (20 vol.%) + chopped E-glass fiber mat (10 vol.%)
	S3	Epoxy (70 vol.%) + untreated pineapple leaf fiber (15 vol.%) + chopped E-glass fiber mat (15 vol.%)
	S4	Epoxy (70 vol.%) + untreated pineapple leaf fiber (10 vol.%) + chopped E-glass fiber mat (20 vol.%)
	S5	Epoxy (70 vol.%) + chopped E-glass fiber mat (30 vol.%)
	S6	Epoxy (70 vol.%) + untreated coir fiber (10 vol.%) + chopped E-glass fiber mat (20 vol.%)
	S7	Epoxy (70 vol.%) + untreated coir fiber (15 vol.%) + chopped E-glass fiber mat (15 vol.%)
	S8	Epoxy (70 vol.%) + untreated coir fiber (20 vol.%) + chopped E-glass fiber mat (10 vol.%)
	S9	Epoxy (70 vol.%) + untreated coir fiber (30 vol.%)
Treated	S1	Epoxy (70 vol.%) + treated pineapple leaf fiber (30 vol.%)
	S2	Epoxy (70 vol.%) + treated pineapple leaf fiber (20 vol.%) + chopped E-glass fiber mat (10 vol.%)
	S3	Epoxy (70 vol.%) + treated pineapple leaf fiber (15 vol.%) + chopped E-glass fiber mat (15 vol.%)
	S4	Epoxy (70 vol.%) + treated pineapple leaf fiber (10 vol.%) + chopped E-glass fiber mat (20 vol.%)
	S6	Epoxy (70 vol.%) + treated coir fiber (10 vol.%) + chopped E-glass fiber mat (20 vol.%)
	S7	Epoxy (70 vol.%) + treated coir fiber (15 vol.%) + chopped E-glass fiber mat (15 vol.%)
	S8	Epoxy (70 vol.%) + treated coir fiber (20 vol.%) + chopped E-glass fiber mat (10 vol.%)
	S9	Epoxy (70 vol.%) + treated coir fiber (30 vol.%)

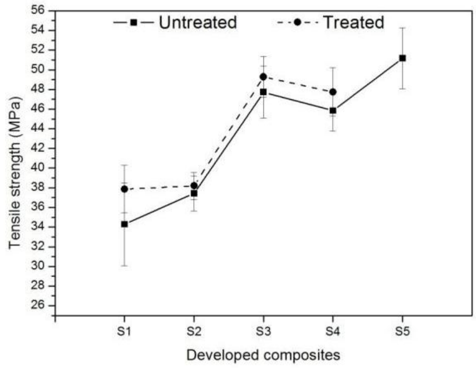
Table 5: Important test details and standardized dimensions of test specimens

Test details	Formulas used	Specimen dimensions
Tensile test (Cross head speed = 1mm/min)	$\sigma_t = \frac{F}{bt}$ Young's modulus = Tensile stress/Tensile strain	Flat dog-bone shape (50 mm gauge length, 13 mm width, and 4 mm thickness)
Flexural test (Cross head speed = 3mm/min)	$\sigma_f = \frac{3FL}{2bt^2}$ Flexural strain = $\frac{6st}{L^2}$ Flexural modulus = $\frac{L^3F}{4sbt^2}$	80 mm (l) X 15 mm (b) X 4 mm (t); Span length to depth ratio = 20:1
Izod impact test	Impact strength = Total absorbed energy (kJ)/Area (m^2)	65 mm (l) X 13 mm (b) X 4 mm; Notch angle = 45^0;
Water absorption test (Immersion time = 120 hr)	$Weight\ gain\ (\%) = \frac{(W_t - W_O)}{W_O} \times 100$ where W_t and W_0 are the weight of the specimen after immersion time "t" and the oven dried weight respectively	20 mm (l) X 20 mm (b) X 4 mm

Results and Discussion

Tensile Properties

The tensile properties (strength and modulus) of developed PALF/Glass and Coir/Glass hybrid epoxy composites are shown in Figure 4 and 5 respectively. It was observed that the tensile properties of alkali treated hybrid composites were slenderly better than the untreated composite materials. The strength and modulus values of specimens S1 (pure PALF-Epoxy composite) and S9 (pure COIR-Epoxy composite) were increased by (9.45% and 3.7%) and (44.75% and 48.93%) respectively by alkali treatment. This was because of the better compaction, consolidation, and adhesion of treated reinforcements in the thermoset polymer matrix. Similar results of mercerization were reported by M.J John et al. [17] on sisal and OPEFB reinforced natural rubber composites. From Figure 4, it is clear that the NaOH treated 15/15 (v/v) PALF/Glass hybrid material possess higher and comparable tensile strength than that of other hybrid formulations and to the pure E-glass/epoxy composite respectively. This can be attributed to the synergistic compatibility between cellulosic and glass fiber at this relative volume fraction which results in the effective and uniform transfer of load from fiber to fiber and matrix to fibers without the cracking of matrix. The NaOH treated coir fiber reinforced composite having equal volume content of coir and glass fiber (15/15 v/v, sample S7) showed higher stiffness as compared to the other hybrid specimens (S6, S8, and S9). It was due to the rapid and effective stress transfer from viscoelastic medium to reinforcing fibers without the substantial deformation of thermoset matrix, an absence of localized stress concentration, and the presence of optimum total fiber to resin ratio and coir to glass fiber relative volume content. The surface of treated coir fiber being roughens with regularly placed pinholes due to the removal of fatty, waxy, and lignin compounds (Figure 2) which leads to the improvement in the interfacial interaction between fiber and matrix. The PALF reinforced epoxy material has higher tensile strength and modulus than that of Coir/Epoxy composite (As expectedly). This was because of the better inherent tensile properties of pineapple leaf fiber.



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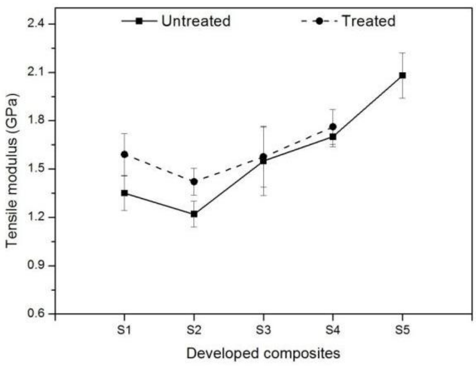

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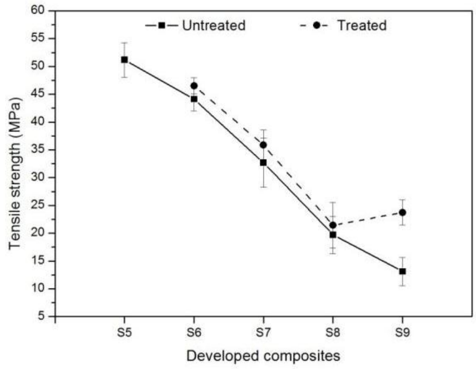
Figure 4: Tensile properties of untreated and alkali treated PALF/Glass fiber reinforced hybrid epoxy composites (a) Tensile strength, (b) Tensile modulus



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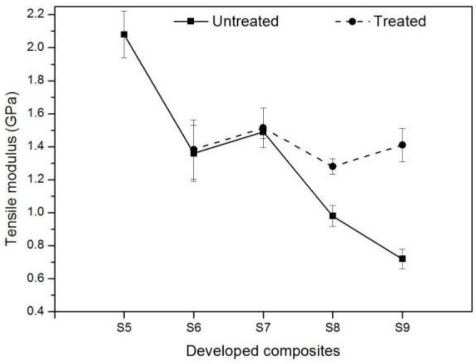


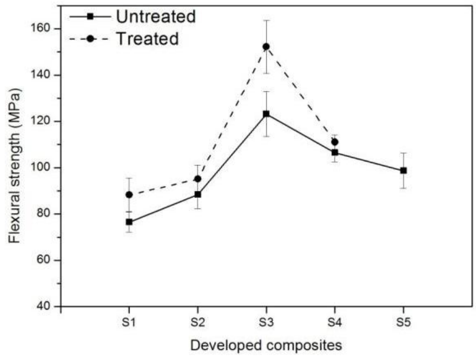
(b)

Figure 5: Tensile properties of untreated and alkali treated Coir/Glass fiber reinforced hybrid epoxy composites (a) Tensile strength, (b) Tensile modulus

From Fig. 4 and 5, it can be observed that the tensile properties of Glass/Epoxy composite were reduced with the increase of pineapple leaf or coir fiber volume content. This outcome was attributed to the better strength and stiffness of glass fiber than that of PALF and COIR fibers (Table 2). However, the hybrid composite consists of alkaline treated 15/15 (v/v) PALF/Glass fiber shows soundly mechanical behavior which results it can compete with pure synthetic fiber reinforced composites and can be employed as a structural material in automotive application.

Flexural Properties

The flexural or 3 point bending test on fabricated composites (PALF/Epoxy, Coir/Epoxy, PALF/Glass/Epoxy, Coir/Glass/Epoxy, and Glass/Epoxy) was performed as per ASTM D 790 standard and the test results are reported in Figure 6 and 7. Similar to the tensile test results, the chemically treated (4% NaOH) fiber reinforced unhybridized and hybridized epoxy-based composites exhibit typically greater values of flexural strength and modulus as compared to the untreated composites. The treated PALF/Glass hybrid composites (Specimen S3 and S4) possess higher values of flexural properties than that of pure Glass/Epoxy material. It is worth to note that the flexural strength and modulus of treated 15/15 (v/v) PALF/Glass hybrid composite was highest amongst all the composite specimens. This was mainly because of the rapid and effective stress transfer from matrix to fiber, restrictions to crack propagation along the fiber-matrix interface, and increased shear and tear resistance of fibers with better dispersion and distribution. Moreover, fiber fibrillation (*avulsion of fiber bundles into individual fibers*) as a result of mercerization takes place which elevates the fiber effective surface area for bonding with the matrix resin. In a flexural bending test, the specimen was subjected to tensile, compressive, and shear load at the lower, upper, and axisymmetrical plane respectively. As we increase the coir fiber volume content in Coir/Glass-epoxy composite, the flexural strength decreases considerably. However, this trend was in opposite situation as compared with PALF/Glass hybrid composites in which the flexural strength increases with the incorporation of pineapple leaf fiber up to 15% V_f ($V_f = 0.3V_c$). This kind of different behavior was due to the poor interaction between coir and glass fiber as compared to the PALF-Glass fiber. The alkali treated pineapple leaf fiber reinforced 15/15 (v/v) PALF/Glass hybrid composite revealed 35.13%, 41.98%,



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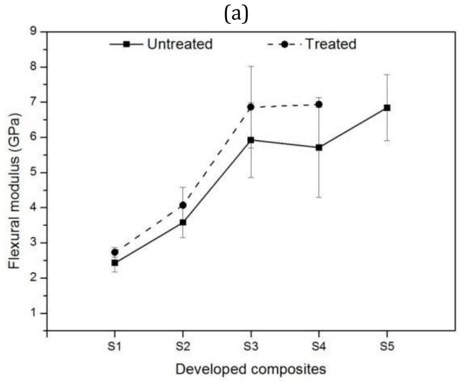

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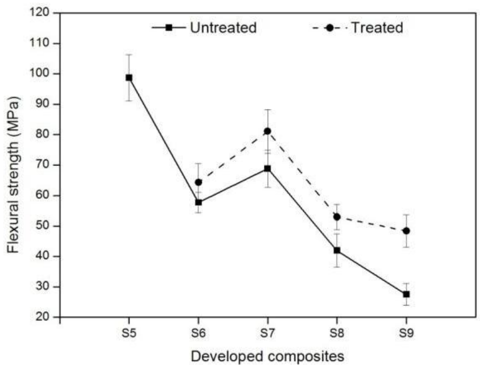
Figure 6: Flexural properties of untreated and alkali treated PALF/Glass fiber reinforced hybrid epoxy composites (a) Flexural strength, (b) Flexural modulus



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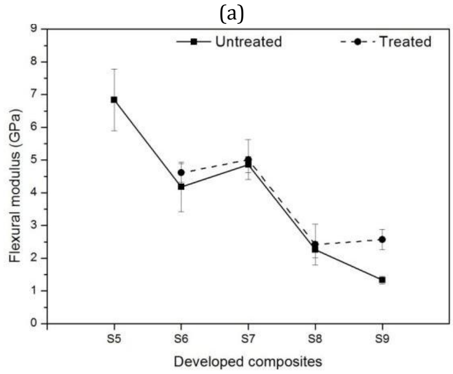


(b)

Figure 7: Flexural properties of untreated and alkali treated Coir/Glass fiber reinforced hybrid epoxy composites (a) Flexural strength, (b) Flexural modulus

and 68.21% higher bending strength as compared to the Glass/Epoxy, treated PALF/Epoxy, and Coir/Epoxy composite respectively. Moreover, it can be observed that the alkali treated pineapple leaf fiber exert a great impact on tensile and flexural properties of hybrid composites. Ultimately, we can conclude that the 15/15 PALF/Glass hybrid material with treated pineapple leaf fiber is the optimum one which displays better mechanical properties (tensile strength, flexural strength, and flexural modulus) amongst the other hybrid formulations.

Impact strength

The impact strength of developed PALF/Glass and Coir/Glass hybrid composites is shown in Figure 8 and 9 respectively. After the examination of test results, we can easily state that the alkaline treated (4% NaOH) fiber reinforced composites depicts higher values of strength during impact loading as compared to the untreated single and hybrid composite materials. In both cases (PALF/Glass and Coir/Glass), the mercerized 15/15 (v/v) hybrid composites [Sample S3 and S7] exhibit greater impact toughness amongst all the reinforced materials. The treated 15/15 (v/v) PALF/Glass and Coir/Glass hybrid specimens possess 18.24% and 38.84% higher impact strength than the single Glass/Epoxy composite respectively.

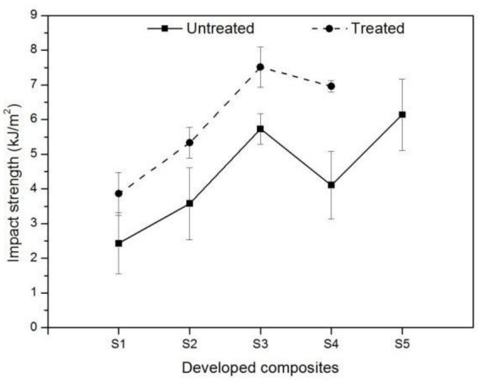


Figure 8: Impact strength of untreated and alkali treated PALF/Glass fiber reinforced hybrid epoxy composites

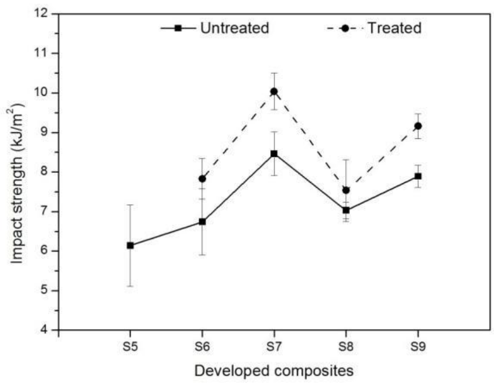
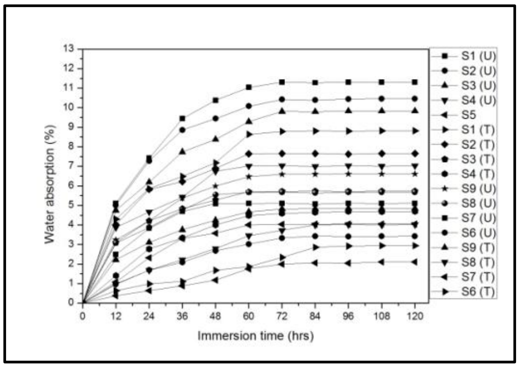


Figure 9: Impact strength of untreated and alkali treated Coir/Glass fiber reinforced hybrid epoxy composites

It was due to the synergistic hybridization between cellulosic and synthetic fiber; and positive attributes of alkaline treatment against the surface impurities, wax, pectin, and hemicellulose content which leads to the higher interfacial bond strength, less void content and higher restrictions to crack propagation along the interface between fiber and matrix. The overall impact strength of a polymer-based composite material mainly depends on the ability of the matrix to transfer load uniformly and efficiently to reinforcing fibers. It was observed that the coir fiber reinforced unhybridized and hybridized composites have a higher value of impact strength than that of pineapple leaf fiber reinforced composites. This was attributed to the greater value of the microfibrillar angle in COIR fiber (15-40^0). The impact strength of Glass/Epoxy composite was significantly improved by the addition of treated pineapple leaf or coir fiber up to 15% of total fiber volume content. The impact resistance of a hybrid fibrous material is greatly depends on the yarn geometry and structure, orientation and arrangement of each kind of fibers in a matrix material, inherent ability of fibers to dissipate or absorb energy, and their relative volume content in the same matrix system. The treated and untreated pure coir and pineapple leaf fiber reinforced composites absorbs less amount of energy or shows brittleness in comparison to 15/15 (v/v) hybrid specimen. From all the three crucial mechanical tests (Tensile, Flexural, and Impact), we can conclude that the alkaline treated hybrid composites (PALF/Glass, 15/15 v/v) and (Coir/Glass, 15/15 v/v) are the most appropriate material which shows substantial higher tensile, flexural and impact properties respectively.

Water absorption

The moisture sorption demeanour of untreated and alkali treated pineapple leaf fiber and coir fiber reinforced composites as a special reference of immersion time is depicted in Figure 10. It can be easily conclude that the composites consist of chemically treated fibers have better dimensional stability in a humid environment than that of untreated NFRC's. From the experimental test results reported in Figure 13, it was observed that the NaOH treated pineapple leaf fiber [S1 (T)] and coir fiber [S9 (T)] reinforced composites absorbs 22.01% and 26.62% less water than that of untreated pure PALF/Epoxy [S1 (U)] and Coir/Epoxy [S9 (U)] Composites. This was because of the removal of hydroxyl and polar functional groups as a result of mercerization which leads to the greater compatibility and adhesion between reinforcing fibers and matrix. Figure 11 clearly demonstrates that the dimensional stability of Glass/Epoxy composite [S5] in wet conditions was deteriorated with the incorporation of untreated and alkali treated pineapple leaf fiber. In all cases, the amount of water absorption increases linearly with the immersion time up to 72 hr and then becomes saturated (moisture equilibrium condition) at 120 hr. The composites reinforced with coconut husk fiber have better impedance to water molecules than that of pineapple leaf fiber reinforced composites. This was attributed to the presence of more hydrophobic lignin and waxy substances on the surface of COIR fiber. From Figure 10 and 12, we can finally conclude that the treated hybrid composite reinforced with equal volume content of coir and glass fibers [Coir: Glass = 15:15 v/v, S7 (T)] absorbs the least amount of water among all the developed composite specimens. The 15/15 (v/v) Coir/Glass hybrid composite was absorbed 47.91% less moisture as compared to the pure Glass/Epoxy composite. It was due to the presence of less void content, better interaction between fibers and matrix resin at the surface, high lignin content in coir fiber cell wall, the greater value of the microfibrillar angle, and synergistic hybrid effect of Coir and Glass fibers.



*U = Untreated, T = Alkaline treated

Figure 10: Water absorption behavior of developed composites as a function of immersion time

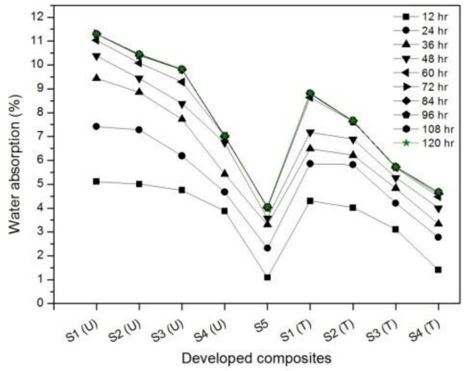


Figure 11: Water absorption of untreated and alkali treated PALF/Glass fiber reinforced hybrid epoxy composites

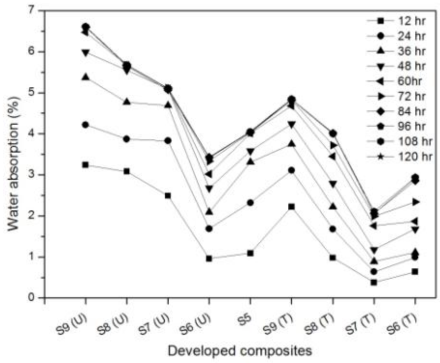


Figure 12: Water absorption of untreated and alkali treated Coir/Glass fiber reinforced hybrid epoxy composites

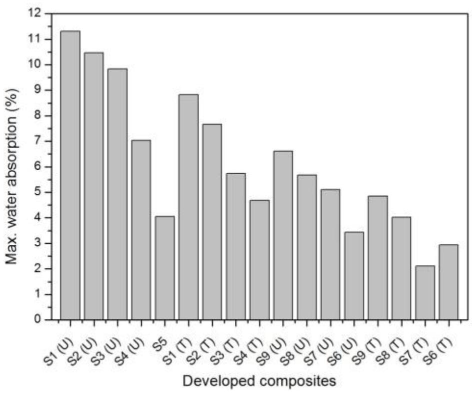


Figure 13: Maximum Water absorption of developed hybrid composites

The tensile, flexural, impact and water absorption properties of treated PG-EP and CG-EP composites (sample S3 and S7) were compared with the hybrid KP-PE (Kenaf/Pineapple-Polyethylene) composite [29] in Figure 14, 15, 16, and 17 respectively. It was observed that the alkaline treated 15/15 (v/v) PG-EP composite possess significantly higher tensile and flexural properties (strength and modulus) than that of KP-PE and CG-EP composites. However, the impact strength and moisture resistance properties of treated pineapple leaf fiber reinforced hybrid composite were slightly lower than the KP-PE composite. Therefore, it becomes necessary to improve the toughness and moisture sorption affinity of PALF/Glass hybrid material by the incorporation of high strain to failure COIR fiber which may results a high performance structural biocomposite material having an optimum combination of strength, stiffness, and ductility.

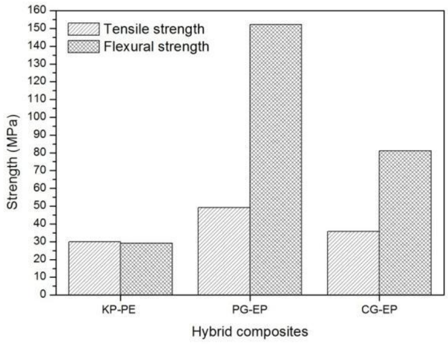


Figure 14: Comparison of tensile and flexural strength for KP-PE, PG-EP, and CG-EP hybrid composites

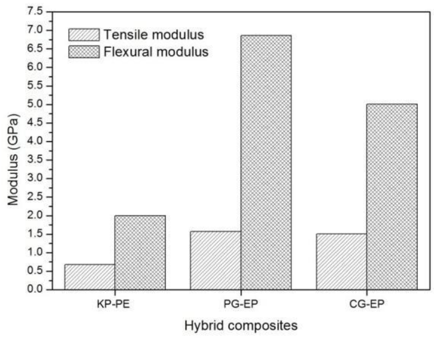


Figure 15: Comparison of tensile and flexural modulus for KP-PE, PG-EP, and CG-EP hybrid composites

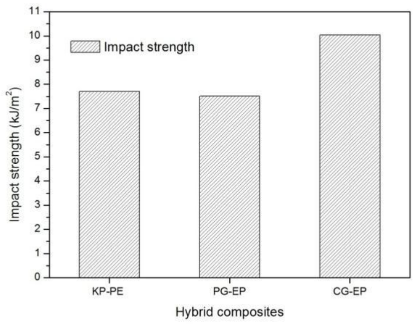


Figure 16: Comparison of impact strength for KP-PE, PG-EP, and CG-EP hybrid composites

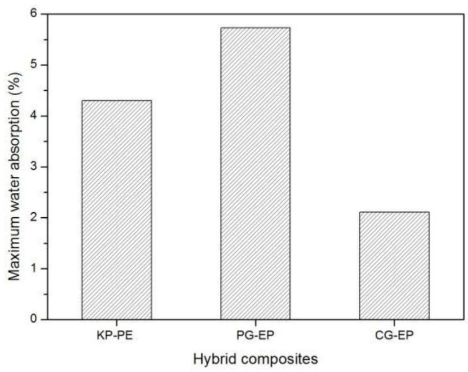


Figure 17: Comparison of maximum water absorption for KP-PE, PG-EP, and CG-EP hybrid composites

Conclusions

On the basis of the above experimental findings, the following conclusions can be made:

- The optimum fiber volume ratio of cellulosic and glass fiber is 15:15. The 15/15 (v/v) PALF/Glass hybrid composite exhibits higher tensile strength, flexural strength, and flexural modulus than that of other hybrid formulations.
- Alkali-treated composites have better mechanical and water resistance properties than that of untreated reinforced composites. This was because of the good interfacial adhesion between reinforcing fibers and polymer matrix. The 15/15 (v/v) hybrid composite reinforced with mercerized pineapple leaf fiber depicts 35.13% and 18.24% higher flexural and impact strength as compared to the pure Glass/Epoxy composite respectively. This was attributed to the synergistic hybridization between pineapple leaf fiber and glass fiber.
- Among all the developed composites, the alkali treated 15/15 (v/v) Coir/Glass fiber reinforced material possess the highest impact toughness and dimensional stability. The composite reinforced with equal volume content of NaOH treated coir and glass fiber [15/15 (v/v) Coir/Glass] exhibits 38.84% and 25.19% greater impact strength as compared to the Glass/Epoxy and treated 15/15 (v/v) PALF/Glass hybrid composite respectively.
- The alka1i treated 15/15 (v/v) Coir/Glass hybrid composite absorbs less amount of water than that of other hybrid formulations. It absorbs 47.90% less water than the pure synthetic Glass/Epoxy composite.

Overall, we can conclude that the hybrid composite developed by the combination of chemically treated cellulosic and glass fibers in an optimum volume ratio has better properties than that of single glass fiber reinforced material. From this significant and valuable research work, we have found that the alkaline treated 15/15 (v/v) PALF/Glass hybrid epoxy composite has better tensile and flexural properties. Whereas the 15/15 (v/v) Coir/Glass hybrid material possess highest impact toughness and impedance to moisture sorption. Therefore, to develop a high-performance structural cellular based material, it becomes necessary to optimally combine pineapple leaf fiber, coir fiber, and glass fiber in an epoxy thermoset matrix resin. It may produce a structural biocomposite material for load-bearing applications.

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