Experimental Investigation of Bi-Directional Flax with Ramie Fibre- Reinforced Phenol-Formaldehyde Hybrid Composites

[1] H. Raghavendra Rao, [2] G. Sankaraiah & [3]P.Harishankar.

[2] Professor Department of Mechanical Engineering, G Pulla Reddy Engineering College Kurnool,
Andhra Pradesh, India.

[1,3] Associate professor Department of Mechanical Engineering, G Pulla Reddy Engineering College
Kurnool, Andhra Pradesh, India.

Absract

Natural, sustainable, and green materials that can take the place of conventional materials are the subject of current study. Natural fibre composites are the subject of extensive research due to their advantageous characteristics. The development of a flax fibre reinforced with phenol-formaldehyde resin hybridization with ramie fibre by a vacuum infusion procedure is the main goal of this study. Using a core-sheath construction, eight alternative sequences were created and physically assessed in accordance with ASTM requirements. The adherence of the matrix with reinforcement is influenced by the production method. The findings also show that ramie-flax composites perform better mechanically than those made with flax as the core and ramie as the sheath layer. Of the eight laminates created for this study, laminate H had the best mechanical characteristics. It had 54 MPa of tensile strength, 0.98 Gpa of tensile modulus, 7.1% of elongation, 143 Mpa of flexural strength, and 63.65 Mpa of compressive strength. All of the laminates displayed ductile behaviour before failing during the tensile test and the flexural test, according to the stress strain curves. The mechanical characteristics displayed by the laminate H and its analogues were affected by the stacking order. A morphological analysis of the failure surfaces was done. Following the testing, morphological examination revealed only a few faults in the laminate. In comparison to commercial composites on the market, the newly created composites have higher mechanical properties and can be utilised in lightweight structural applications.

Keywords: flax; ramie; phenol formaldehyde resin; vacuum infusion process; mechanical testing; scanning electron microscope.

1.Introduction

The usage of synthetic fibres (such carbon and glass) for strengthening or reinforcing engineering constructions has increased during the last few years. The fire resistance performance of synthetic fibres in this application is a serious problem and degrades abnormally when exposed to high temperatures. An approach that provides good mechanical enactment is the hybridization of a composite comprised of polymeric matrix reinforced with synthetic and natural fibres. Compared to synthetic fibres, natural fibres have a lower specific gravity and are biodegradable. Natural fibres, however, frequently show issues with compatibility between fibre and polymer matrixes. The hydrophobic properties of the fibre and the incompatibility of the matrix are to blame, and surface modification can help**.** Natural fibres, especially bast fibres, are a great alternative to conventional fibres since they are readily available, easy to extract, light weight, low density, biodegradable, and have a high specific strength. The characteristics of natural fibres vary depending on how they are harvested and cultivated. The development of natural fiber-based composites in the automobile industry is commonly thought to replace the use of synthetic fibres in a variety of industries, including aerospace. By enhancing toughness or impact resistance, hybridization provides a progression for expanding the function of composite materials, especially in advanced applications. In their study of the mechanical characteristics of a composite reinforced with cocos nucifera sheath and Kevlar, Naveen et al. found that cocos nucifera sheath has the potential to take the place of the Kevlar fibre polymer composite. Giridharan assessed the characteristics of a glass/ramie fibre-reinforced composite at various weight percentages. The addition of a small fraction of glass to the fibre resulted in increased properties of ramie, making it lowcost and eco-friendly . Yang et al. concentrated on the effects of unmodified ramie fibrereinforced polypropylene using melting hybrid technology to acquire good mechanical properties. Modified fibre thereby has more fibre reinforcement than unmodified ramie fibre. The thermal degradation temperature is reduced because of the polypropylene/ramie fibre . Composite laminate fabrication is shifting away from traditional hand layup processes and toward new techniques such as resin infusion, vacuum-assisted resin transfer moulding (VARTM), vacuum bagging, etc. It results from lower labour, material, and equipment costs, which increase the quality and affordability of producing parts. Natural fiber-reinforced composite laminate with a high fibre volume fraction and low processing costs is manufactured with bio-based epoxy resin. The created composite is designed for sectors of the economy that demand low costs, light weight, and low carbon footprints. Sanjeevi et al. investigated the impact of a hybrid natural fibre phenol-formaldehyde composite using the hand layup method. We looked at three alternative weight percentages: 25%, 35%, and 45%. The 35% fibre reinforcement composite outperformed the other two manufactured composites in terms of fiber-matrix bonding. The mechanical and thermal properties of ramie fibre are improved by grafting nano-silica to the surface, which increases surface roughness. To investigate the composites' load transfer process in nanohybrid shish-kebab structures, a shear lag model was created. It exhibits clear impacts on morphology and elastic modulus. Swamy et al. looked into how areca fibre affected its strength. Areca-treated phenol-formaldehyde is excellent for structural applications and the packaging industry since it quickly absorbs a substantial amount of moisture and degrades slowly. Phenol-formaldehyde strengthens the mechanical, moisture, and chemical resistance of pine needles, which is important for choosing applications in a variety of sectors. When banana fibre is soaked in phenol-formaldehyde, Joseph et al. found that it had better mechanical properties and interfacial shear strength than glass fibres. Sathyaseelan et al. investigated how the hybrid composite's stacking sequence affected the material's mechanical properties, which is crucial for improving composite laminate. Many academics have looked at the sustainability of natural fibre in a variety of applications due to growing environmental awareness and its excellent capacity to replace fossil fuel and non-renewable resources in reinforcing composite materials. Combining two or more elements to create a composite that can be entirely natural, entirely synthetic, or a mix of natural and synthetic materials is known as hybridization. Important components of composites include weight fraction, stacking order, volume fraction, chemical treatment, and environmental factors.

According to the reviewed literature, there hasn't been much research on the mechanical assessment of thermoset-based hybrid composite laminates created using constituent materials like flax, ramie, phenol, and formaldehyde. The hybridization technique was used to produce inexpensive composites. This study's primary goal is to look at how the order in which flax/ramie fiber-based hybrid composites are stacked affects the materials' tensile, flexural, compressive, impact, and hardness properties. A scanning electron microscope was used to do a morphological investigation on the cracked surface of the composite.

1. Materials and Methods

2.1. Flax Fibre

According to Figure 1a, the Linum Usitatissimum species of flowering plants are the source of flax fibre. The plant's flax fibre is slightly more durable than cotton fibre. It is a strong and durable fibre that is mostly used in the textile industry in Western nations. The advantages of flax fibre include its density, renewable status, less hazard when compared to glass fibres, and the fact that products created from flax fibre have a low tendency to deform. The supplier of the fibres was Go Green Products Pvt. Ltd. in Chennai, India.

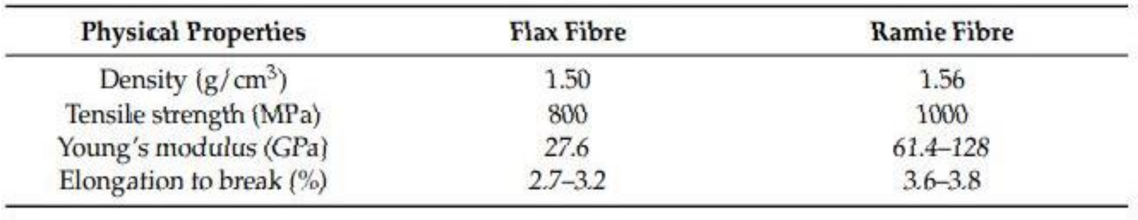
(a) (b)

Figure 1. Bidirectional woven sheet of (a) flax fibre (b) ramie fibre

1.2. Ramie Fibre

As shown in Figure 1b, ramie fibre is produced from a flowering plant belonging to the Urticaceae family. One of the strongest fibres, it keeps its strength even after being wet. Fishing nets and packing employ it, and to a lesser extent, garments and materials. Table 1 lists the physical characteristics of the fabrication material.

Table 1. Physical properties of the reinforcement materials.



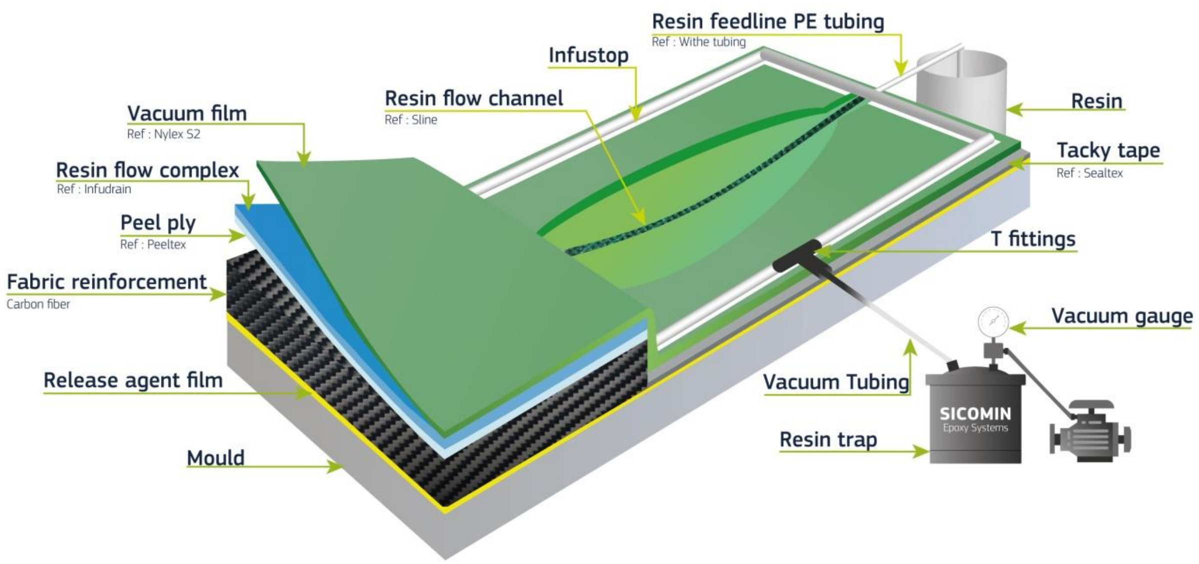
Physical Properties	Flax Fibre	Ramie Fibre
Density (g/cm^3)	1.50	1.56
Tensile strength (MPa)	800	1000
Young's modulus (GPa)	27.6	61.4–128
Elongation to break (%)	2.7–3.2	3.6–3.8

1.3. Phenol-Formaldehyde

Phenol-formaldehyde, also known as phenolic resin, is replacing other resins in popularity due to its superior surface smoothness, strength, affordability, and great fire resistance. These resins are synthetic polymers created by combining formaldehyde and phenol. Circuit boards are usually made with phenol-formaldehyde resin. A hardener and resin are combined in a 12.5:1 ratio. To apply the combined catalyst for 30 minutes, resin and hardener are continually swirled for 5 minutes. To achieve the best mechanical qualities, composite materials should be cured and then post-cured. At normal temperature, the manufactured composite laminate is cured. Phenol-formaldehyde resins and the hardener are supplied by ABR Organics Limited Telangana in Hyderabad, India.

Vacuum Infusion Process

Vacuum infusion was used in the current investigation to create composite laminate. It is affordable to produce high-strength composite parts similar to composite laminates made using prepreg, the autoclave method, etc. The vacuum infusion procedure is typically carried out in a closed system. During this procedure, dried fibre and release film are placed on top of the mould surface and sealed within a vacuum bag with a perforated film. The vacuum bag arrangement was made at home. Figure 2 shows how the vacuum force transports resin from the resin container into the vacuum bag along a symmetry line. The impregnation time is delayed when there is more fibre present.



Vacuum infusion process

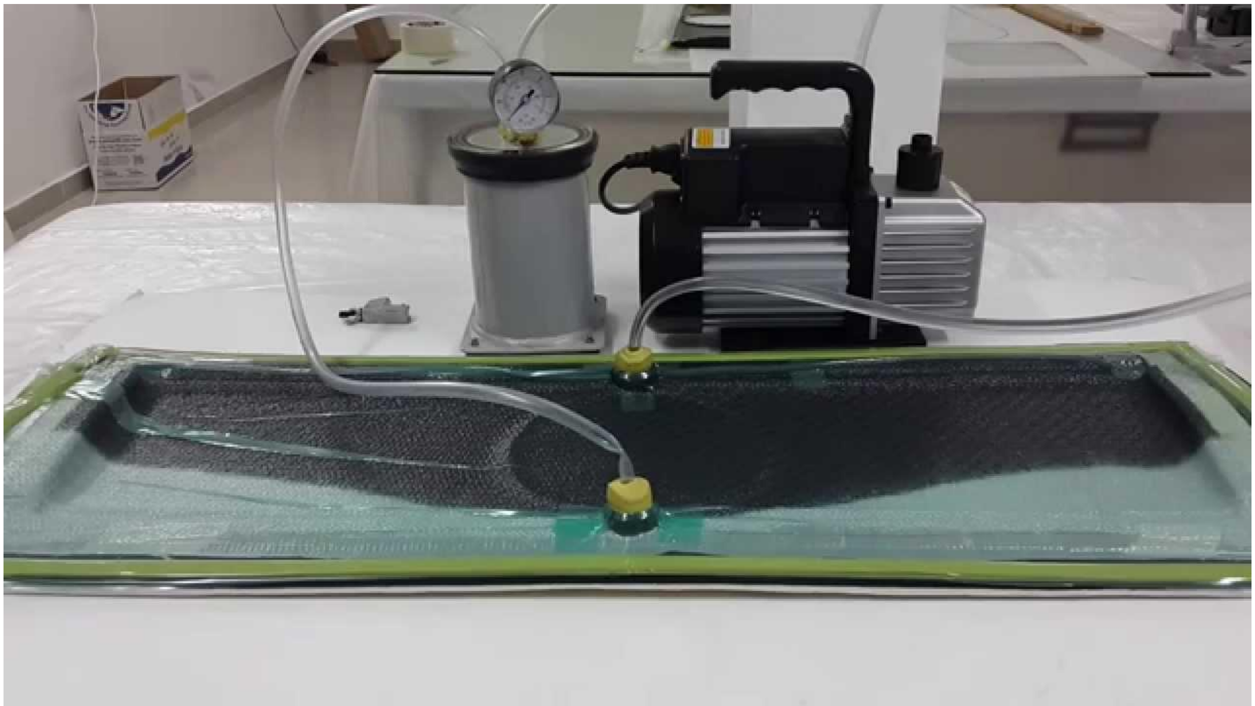
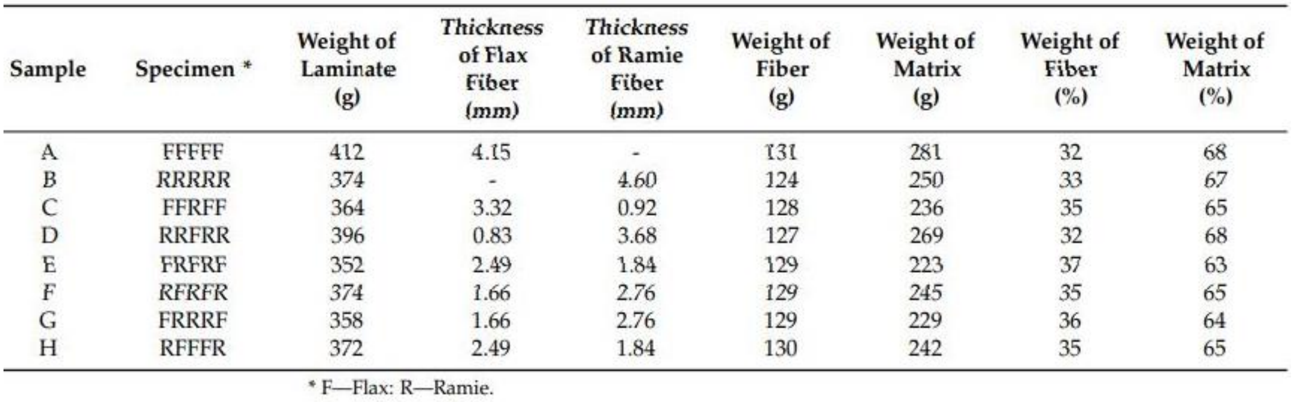


Figure 2. Vacuum infusion process

Composite Specimen Preparation

Vacuum infusion was used to prepare composite specimen fabrication. Among moulding procedures, it is one of the most economically efficient manufacturing processes. A 12.5:1 mixture of phenol-formaldehyde resin and hardener was utilised as the matrix. For simple specimen removal, the bottom of the mould was coated with a releasing agent, and when the releasing agent dried, the initial layer of fibre was retained on top of the coated surface. The resin was then forced through the laminate using vacuum pressure as the other four layers of fibres were kept in place one after the other. Following the creation of a complete vacuum, the resin was carefully sucked into the laminate using the tube. This experiment used eight alternative stacking sequences, as indicated in Figure 3. The 300 mm3 manufactured composite laminate measured 300 mm3 in size. At room temperature, it was allowed to cure for 24 hours. The laminate was taken out of the vacuum setup after the curing process was finished and cut in accordance with ASTM specifications. Table 2 displays the configuration of the manufactured hybrid laminate and the order in which it was stacked.

Table 2. Sequence of prepared specimen



Sample	Specimen *	Weight of Laminate (g)	*Thickness of Flax Fiber (mm)*	*Thickness of Ramie Fiber (mm)*	Weight of Fiber (g)	Weight of Matrix (g)	Weight of Fiber (%)	Weight of Matrix (%)
A	FFFFF	412	4.15	-	131	281	32	68
B	RRRRR	374	-	4.60	124	250	33	67
C	FFRFF	364	3.32	0.92	128	236	35	65
D	RRFRR	396	0.83	3.68	127	269	32	68
E	FRFRF	352	2.49	1.84	129	223	37	63
F	RFRFR	374	1.66	2.76	129	245	35	65
G	FRRRF	358	1.66	2.76	129	229	36	64
H	RFFFR	372	2.49	1.84	130	242	35	65

* F—Flax: R—Ramie.

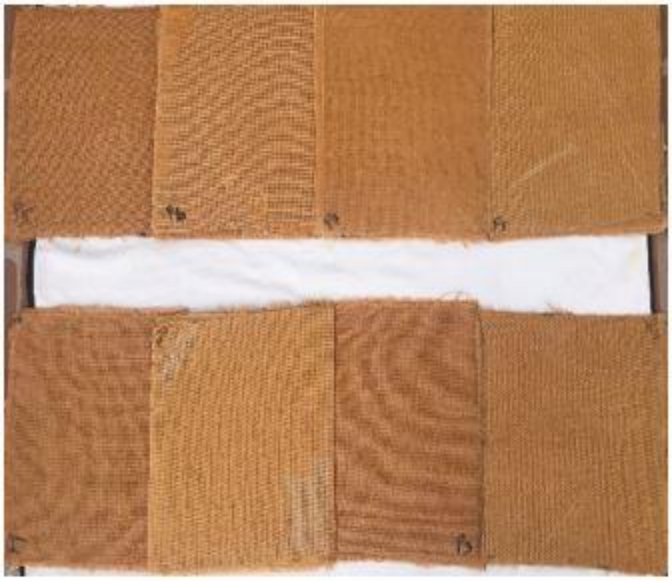


Figure 3. Fabricated laminate

Composite Characterization

The FMI Universal Testing Machine (UTM) (Perfect Enterprises, New Delhi, India), which has dimensions of 165 mm 19 mm and a crosshead speed of 2.5 mm/min, was used to conduct the tensile test in accordance with ASTM: D638. When establishing a material's capacity to support a load under stress in a UTM, tensile strength is crucial. The resulting composite material was frail because both the reinforcement and the matrix material were brittle. The flexural specimens were produced in accordance with ASTM D790 specifications, with dimensions of 127 mm 12.7 mm and a crosshead speed of 2.5 mm/min. For composite flexural testing, the three-point bending test was employed, and the load was applied under specific circumstances. The deflection was measured using the gauge at the specimen's base. The impact testing machine model XJJU 5 with dimensions of 65.5 mm 12.7 mm was used to perform the Izod impact test in accordance with ASTM standard D256. The device consists of a loaded striker that, when released, has a fixed amount of kinetic energy. The dial shows how much energy has been absorbed. The compression test was performed in an FMI universal testing machine that complied with ASTM: D695 and had dimensions of 70 mm 19 mm. It controls how the material reacts when the specimen is crushed while being loaded. The Shore D device then conducted the ASTM standard D2240 hardness test. By using a normal presser foot to apply the necessary force continuously without shock, it measures the depth of an indentation in a material. SEM was used to analyse the morphological examination of composites that had been generated. The photograph was taken using a F E I Quanta FEG 200 camera. In order to increase conductivity, samples were gold sputtered before the microstructure research was conducted on polymeric-based specimens. A minimum of three samples were prepared to test the mechanical characteristics of the composite laminate, and the average of the three values was chosen for discussion.

Results and Discussion

Tensile Strength

The tensile strength of eight different manufactured laminates is shown in Figure 4. Such events occur during tensile testing under constant stress conditions emerging at the gauge region; the specimens fractured between the tensile grips and at the gauge region. Additionally, in every instance the entire specimen failed brittle, and the same can be seen in the stress-strain behaviour. Due to its strong attachment to the matrix and reinforcement from the vacuum infusion process, laminate H, which featured an exterior layer of ramie fibre and a flax fibre core, displayed the highest strength of all eight laminates at 54 MPa. The tensile strength of hybrid laminates D and F, which contained an outer and alternating layer of ramie fibre, was, however, 48.16% and 20.39% lower than that of laminate H. Laminate E, which featured layers of ramie and flax fibres alternately, had a lower tensile strength of 21.99 MPa. On the other hand, laminates A and B had tensile strengths that were, respectively, 38.89% and 42.61% lower than those of laminate H. Since Raja et al. made the laminates utilising the hand layup approach, the maximum tensile strength of the banyan/ramie fiber-reinforced hybrid composite they presented was 24.63% lower than laminate H. . This demonstrates how fabrication methods have a significant impact on hybrid composites. Similar to this, Mohanavel et al. found that the tensile strength of laminate H was 35.18% lower for the jute and ramie fibre combination. The tensile characteristics of natural fibre regulate chemical compositions such cellulose, wax content, and fibre angle. Thus, it was determined after looking at the tensile strength of hybrid laminates that reinforcement and hybridization have a favourable effect on the tensile properties.

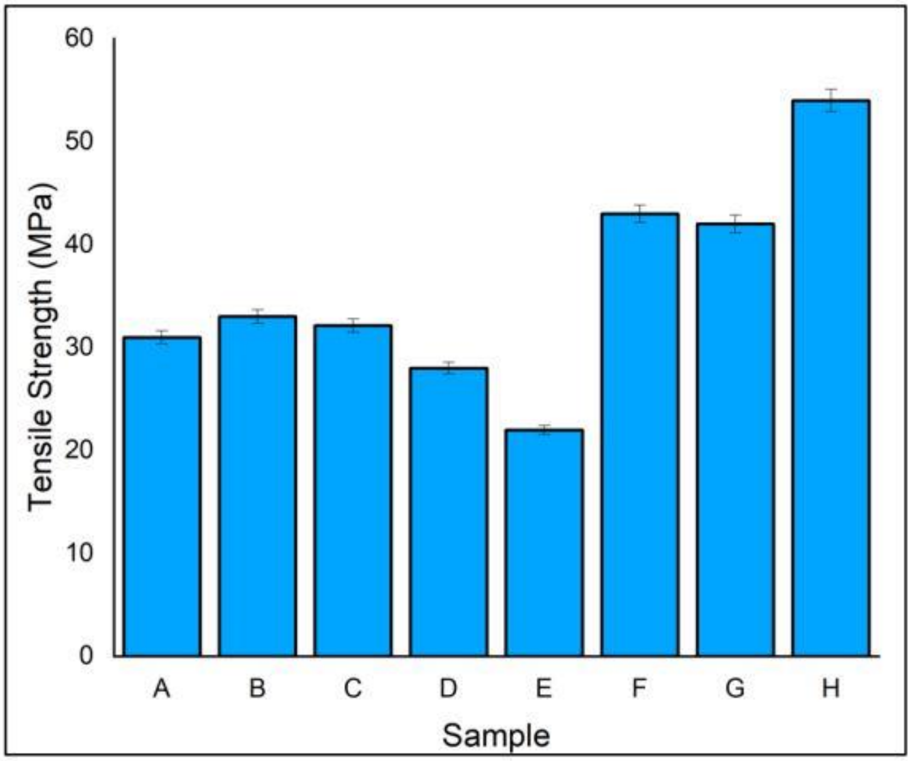


Figure 4. Tensile strength of specimen

Compressive Strength

The matrix material has an important influence on the compressive strength of laminates. The length of the compressive test specimen is designed to eliminate global buckling and to develop pure compressive stress at the gauge section. In Figure 5, the compressive strength of laminate H with ramie as the outer layer and flax as the core is 69.65 MPa, the highest among the fabricated laminates. On the other hand, the compressive strength of laminate E with alternate layers of flax and ramie is 34.20 MPa, the lowest of the eight laminates. The hybrid laminates' initial capacity to absorb compressive force improved. Laminate B, which had all five layers of ramie fibre, had a compressive strength of 51.95 MPa, 9.86% more than that of its counterpart, which had all five layers of flax fibre. When ramie is used as the outer layer, a strong fibre resistance to breakout is displayed. Plotting the compressive strength for the eight laminates revealed a pattern like the tensile test. It may be concluded that the laminates' compressive behaviour and the tensile test were compatible.

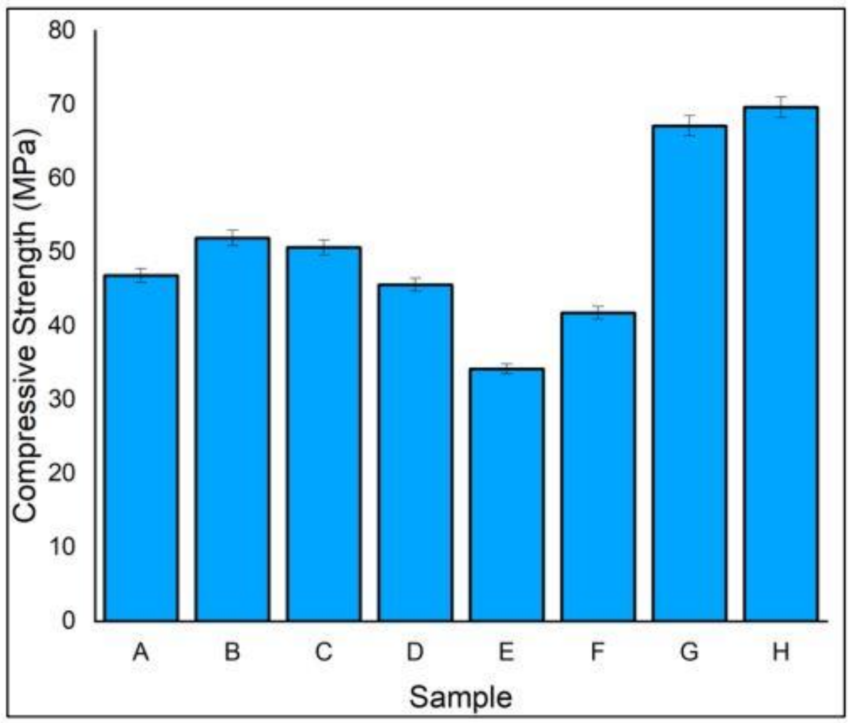


Figure 5 . Compressive strength of specimen

Hardness

A material's ability to tolerate constant deformation is referred to as hardness. The hardness of the manufactured laminates was evaluated using Shore D dness values. The outcomes are displayed in Figure 6. Due to the reduced mechanical strength of flax fibre in comparison to ramie fibre, Laminate A, which contained all five layers of flax, had a lower hardness value of 54. Due to the presence and the tight bonding of ramie with flax fibre, Laminate H demonstrated the greatest hardness rating of 88.20. In comparison to laminate A, hybrid laminates C, D, E, F, G, and H shown greater hardness. The hybrid composite's hardness was increased by the addition of ramie fibre, according to the results. . Due to the stacking of ramie and flax fibres, laminate H had a hardness that was 27.40% higher than laminate E's. Conclusion: Laminates with ramie fibre as the skin material resist more penetration and aberrations than laminates made of flax fibre. A high resistance to indentation by the indenter is provided by the stiffer flax and ramie fibres as well as greater interaction between the reinforcement fibres and phenol formaldehyde matrix. Figure 11 shows the specimen's impact strength. Hardness, a. A material's ability to tolerate constant deformation is referred to as hardness. The hardness of the manufactured laminates was evaluated using Shore D hardness measurements. The outcomes are displayed in Figure 12. Due to the reduced mechanical strength of flax fibre in comparison to ramie fibre, Laminate A, which contained all five layers of flax, had a lower hardness value of 54. Due to the presence and the tight bonding of ramie with flax fibre, Laminate H demonstrated the greatest hardness rating of 88.20. In comparison to laminate A, hybrid laminates C, D, E, F, G, and H shown greater hardness. The hybrid composite's hardness was increased by the addition of ramie fibre, according to the results. Due to the stacking of ramie and flax fibres, laminate H had a hardness that was 27.40% higher than laminate E's. Conclusion: Laminates with ramie fibre as the skin material resist more penetration and aberrations than laminates made of flax fibre. A high resistance to indentation by the indenter is provided by the stiffer flax and ramie fibres as well as greater interaction between the reinforcement fibres and phenol formaldehyde matrix.

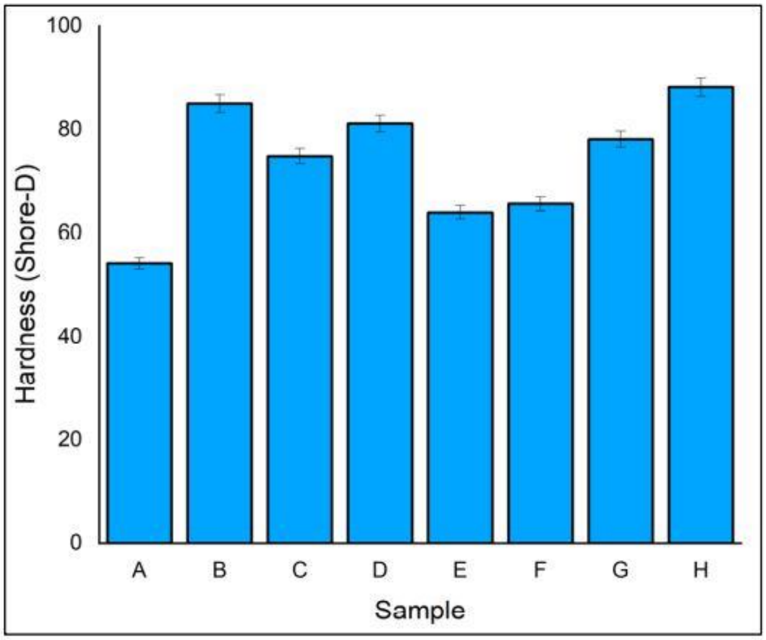
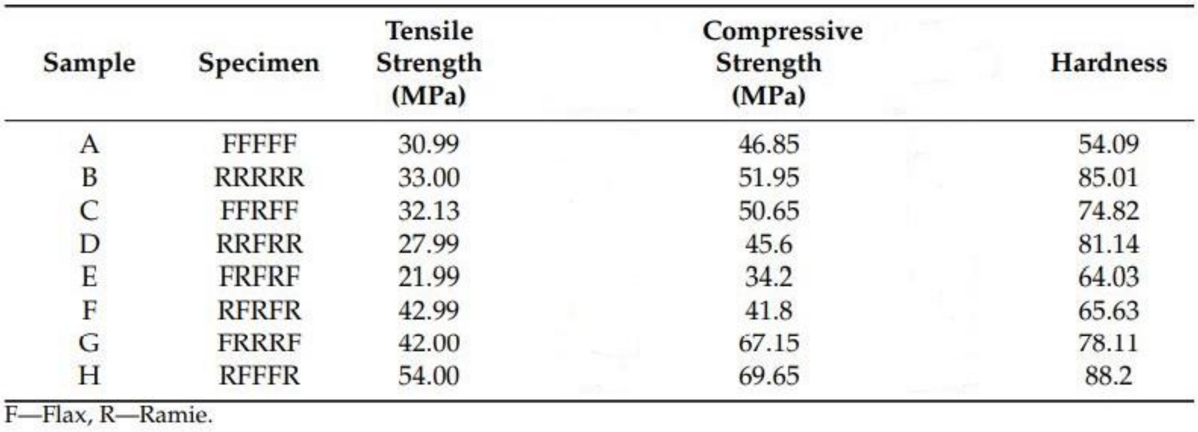


Figure 6. Hardness of specimen

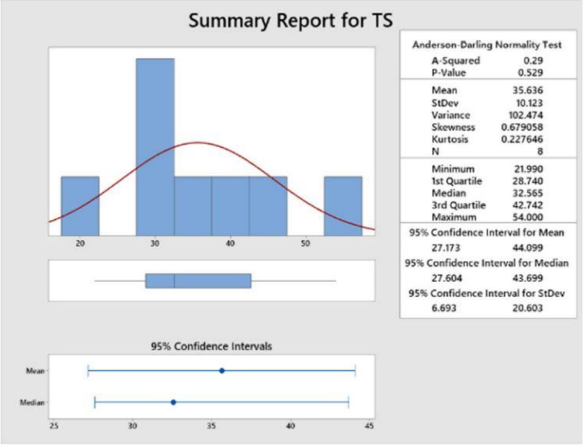
Table 3 displays the composites' experimental results. Tensile, flexural, compressive, impact, and hardness values acquired from Minitab 19 software (Minitab, LLC, USA) are statistically analysed in Figure 13 and are provided below. All of the p-values are larger than 0.05, which indicates that the experimentally measured values were normally distributed.

Table 3. Experimental result of Composite

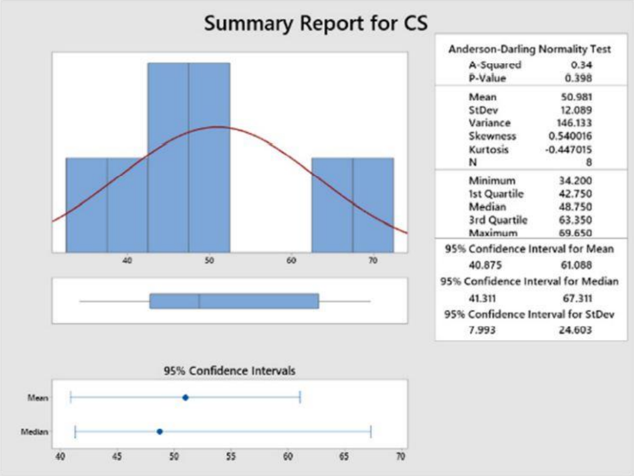


Sample	Specimen	Tensile Strength (MPa)	Compressive Strength (MPa)	Hardness
A	FFFFF	30.99	46.85	54.09
B	RRRRR	33.00	51.95	85.01
C	FFRFF	32.13	50.65	74.82
D	RRFRR	27.99	45.6	81.14
E	FRFRF	21.99	34.2	64.03
F	RFRFR	42.99	41.8	65.63
G	FRRRF	42.00	67.15	78.11
H	RFFFR	54.00	69.65	88.2

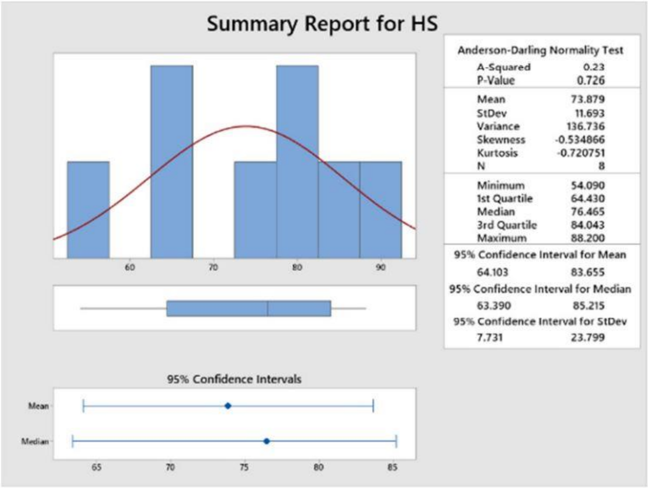
F—Flax, R—Ramie.



Anderson-Darling Normality Test	
A-Squared	0.29
P-Value	0.529
Mean	35.636
StDev	10.123
Variance	102.474
Skewness	0.679058
Kurtosis	0.227646
N	8
Minimum	21.990
1st Quartile	28.740
Median	32.565
3rd Quartile	42.742
Maximum	54.000
95% Confidence Interval for Mean	
27.173	44.099
95% Confidence Interval for Median	
27.604	43.699
95% Confidence Interval for StDev	
6.693	20.603



Anderson-Darling Normality Test	
A-Squared	0.34
P-Value	0.398
Mean	50.981
StDev	12.089
Variance	146.133
Skewness	0.540016
Kurtosis	-0.447015
N	8
Minimum	34.200
1st Quartile	42.750
Median	48.750
3rd Quartile	63.350
Maximum	69.650
95% Confidence Interval for Mean	
40.875	61.088
95% Confidence Interval for Median	
41.311	67.311
95% Confidence Interval for StDev	
7.993	24.603



Morphological analysis

Using a scanning electron microscope, the morphological investigation of ramie and flax fiber-reinforced hybrid composite at its maximum condition was carried out. The morphological study of laminate H under tensile loading revealed the strong adherence of the fibre and resin. Figure 17a provides a vivid illustration of this. Despite using the vacuum infusion method to create the laminate, there were observable flaws such tiny holes. These could have contributed to certain failures. The final failure of laminate H was caused by matrix cracking and fibre pull-out, according to a thorough investigation of the failure zone of the laminate. It was discovered that the matrix and the fibre reinforcement bonded well. Due to this, the laminate was able to withstand a heavy load before breaking. The failure zone of laminate E was thoroughly examined during the flexural test. The flexural test demonstrates that matrix cracking was the actual cause of failure. The matrix material continued to contain the reinforcing fibres, according to the SEM from the flexural test specimen. The matrix, however, was stretched to the limit before brittle fracture. The morphological characterization of laminate G after a compression test is shown in Figure 7b. After the compression test, defects including delamination and kinking of the fibres were found. Compression of the reinforcement fibres caused the matrix material to become brittle. Under the impact of the compressive force, the fibres that emerged from the matrix element were twisted and distorted. The matrix material displayed fracture properties that were both brittle and ductile

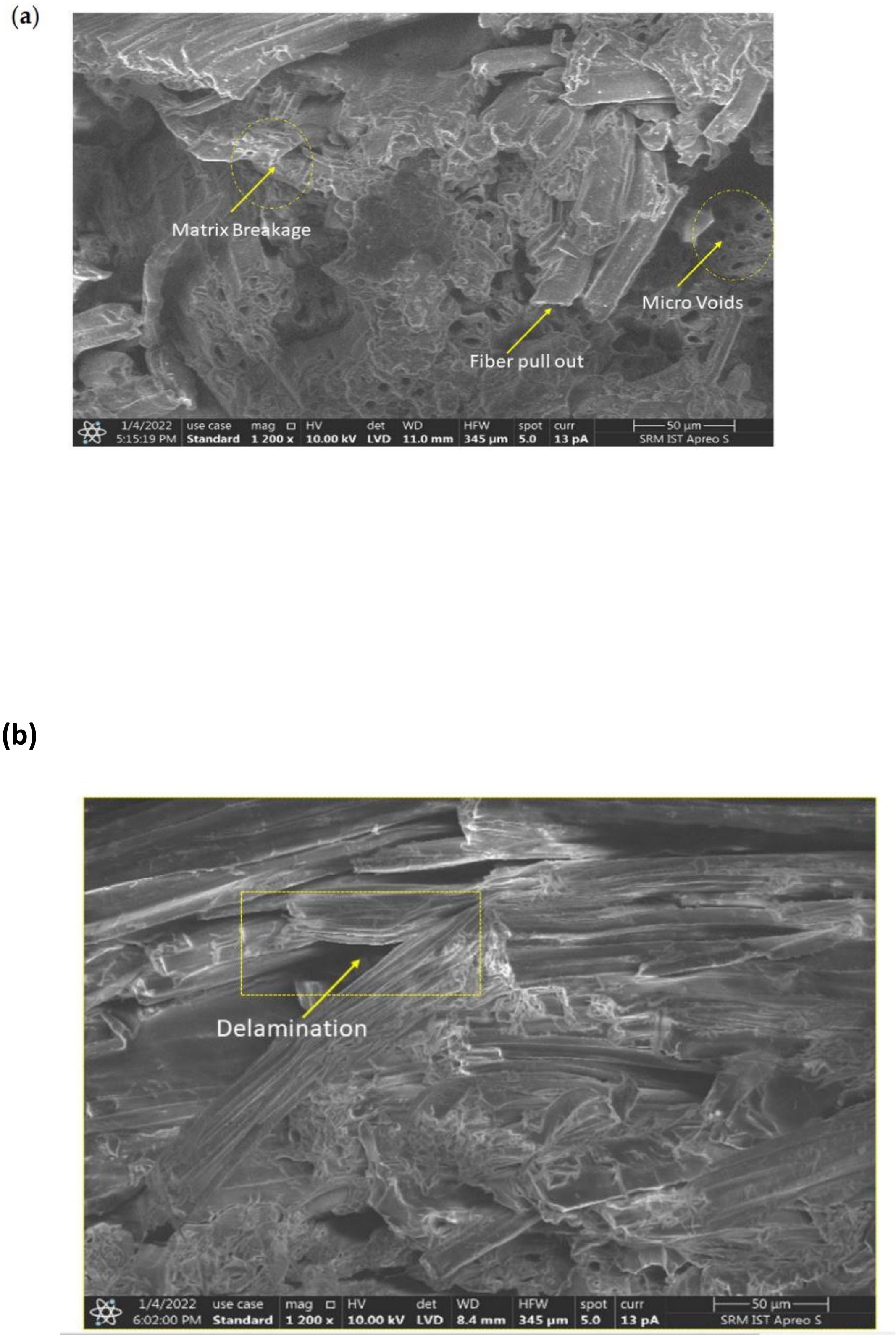


Figure .7. A morphological study of (a) tensile (b) compressive

Conclusions

In this study, experimental work has been done in accordance with ASTM standards to produce and evaluate the hybridization effect on bidirectional flax fibre with ramie fibre reinforced with phenol-formaldehyde polymer composites made by a vacuum infusion technique. Below is a list of the study's findings.

- When compared to all other laminates, Laminate H exhibited a stronger flexural strength of 143 MPa and a stronger tensile strength of 54 MPa. The interfacial adhesion of ramie and flax fibres with phenol-formaldehyde was the primary root cause. The secondary factor in getting the better value was the vacuum infusion method's process capability.
- Laminate H had the highest compressive strength measurement, measuring 69.65 MPa, compared to other laminates. The usage of ramie fibres as outer layers, which were employed to absorb the imposed compressive load, was the cause of this.
- The highest hardness value for laminate H according to the Shore D hardness scale was 88.2. Furthermore, all of the laminates except for the one with all five layers of flax fibre exhibited higher hardness ratings.

The aforementioned conclusions led to the conclusion that laminates with flax fibre as the core and ramie fibre as the outer layer had improved mechanical characteristics in terms of tensile, compressive, and strength. The innovative aspect of the proposed work is the creation of composites with superior mechanical properties than currently available commercial composites, which can be applied to lightweight structural applications. The current study can be expanded by including filler materials made of natural fibres to increase the scope of applications for polymer composites.

References

1. Xian, G.; Guo, R.; Li, C.; Wang, Y. Mechanical performance evolution and life prediction of prestressed cfrp plate exposed to hygrothermal and freeze-thaw environments. Compos. Struct. 2022, 293, 115719. [CrossRef]

2. Kalita, K.; Mallick, P.K.; Bhoi, A.K.; Ghadai, K.R. Optimizing Drilling Induced Delamination in GFRP Composites using Genetic Algorithm & Particle Swarm Optimisation. Adv. Compos. Lett. 2018, 27, 096369351802700101.

3. Behera, R.R.; Ghadai, R.K.; Kalita, K.; Banerjee, S. Simultaneous prediction of delamination and surface roughness in drilling GFRP composite using ANN. Int. J. Plast. Technol. 2016, 20, 424–450. [CrossRef)

4. Mouritz, A.P.; Feih, S.; Kandare, E.; Mathys, Z.; Gibson, A.G.; Jardin, P.E.D.; Case, S.W.; Lattimer, B.Y. Review of Fire Structural Modelling of Polymer Composites. Compos. Part A Appl. Sci. Manuf. 2009, 40, 1800–1814. [CrossRef]

5. Dong, K.; Hu, K.; Gao, W. Fire Behavior of Full-Scale CFRP-Strengthened RC Beams Protected with Different Insulation Systems. J. Asian Arch. Build. Eng. 2016, 15, 581–588. [CrossRef]

6. Li, C.; Xian, G. Experimental and Modeling Study of the Evolution of Mechanical Properties of PAN-Based Carbon Fibers at Elevated Temperatures. Materials 2019, 12, 724. [CrossRef]

7. Chen, Z.; He, X.; Ge, J.; Fan, G.; Zhang, L.; Parvez, A.M.; Wang, G. Controllable fabrication of nanofibrillated cellulose supported HKUST-1 hierarchically porous membranes for highly efficient removal of formaldehyde in air. Ind. Crops Prod. 2022, 186, 115269. [CrossRef]

8. Wang, Z.; Zhao, X.L.; Xian, G.; Wu, G.; Raman, R.K.S.; Al-Saadi, S. Effect of Sustained Load and Seawater and Sea Sand Concrete Environment on Durability of Basalt- and Glass-Fibre Reinforced Polymer (B/GFRP) Bars. Corros. Sci. 2018, 138, 200–218. [CrossRef]

9. Fiore, V.; Calabrese, L. Effect of Glass Fiber Hybridization on the Durability in Salt-Fog Environment of Pinned Flax Composites. Polymers 2021, 13, 4201. [CrossRef]

10. Mochane, M.J.; Mokhena, T.C.; Mokhothu, T.H.; Mtibe, A.; Sadiku, E.R.; Ray, S.S.; Ibrahim, I.D.; Daramola, O.O. Recent Progress on Natural Fiber Hybrid Composites for Advanced Applications: A Review. Express Polym. Lett. 2019, 13, 159–198. [CrossRef]

11. Kabir, M.M.; Wang, H.; Lau, K.T.; Cardona, F. Chemical Treatments on Plant-Based Natural Fibre Reinforced Polymer Composites: An Overview. Compos. B Eng. 2012, 43, 2883–2892. [CrossRef]

12. Lubis, M.A.R.; Handika, S.O.; Sari, R.K.; Iswanto, A.H.; Antov, P.; Kristak, L.; Lee, S.H.; Pizzi, A. Modification of Ramie Fiber via Impregnation with Low Viscosity Bio-Polyurethane Resins Derived from Lignin. Polymers 2022, 14, 2165. [CrossRef] [PubMed]

13. Moghtadernejad, S.; Barjasteh, E.; Johnson, Z.; Stolpe, T.; Banuelos, J. Effect of thermo-oxidative aging on surface characteristics of benzoxazine and epoxy copolymer. J. Appl. Polym. Sci. 2021, 138, 50211. [CrossRef]

14. He, L.; Li, W.; Chen, D.; Zhou, D.; Lu, G.; Yuan, J. Effects of Amino Silicone Oil Modification on Properties of Ramie Fiber and Ramie Fiber/Polypropylene Composites. Mater. Eng. 2015, 77, 142–148. [CrossRef]

15. Aristri, M.A.; Lubis, M.A.R.; Laksana, R.P.B.; Sari, R.K.; Iswanto, A.H.; Kristak, L.; Antov, P.; Pizzi, A. Thermal and Mechanical Performance of Ramie Fibers Modified with Polyurethane Resins Derived from Acacia Mangium Bark Tannin. J. Mater. Res. Technol. 2022, 18, 2413–2427. [CrossRef]

16. Liu, Z.-T.; Yang, Y.; Zhang, L.; Liu, Z.W.; Xiong, H. Study on the Cationic Modification and Dyeing of Ramie Fiber. Cellulose 2007, 14, 337–345. [CrossRef]

17. Pandey, J.K.; Ahn, S.H.; Lee, C.S.; Mohanty, A.K.; Misra, M. Recent Advances in the Application of Natural Fibre Based Composites. Macromol. Mater. Eng. 2010, 295, 975–989. [CrossRef]

18. Ku, H.; Wang, H.; Pattarachaiyakoop, N.; Trada, M. A review on the tensile properties of natural fibre reinforced polymer composites. Compos. Part B Eng. 2011, 42, 856–873. [CrossRef]

19. Peças, P.; Carvalho, H.; Salman, H.; Leite, M. Natural fibre composites and their applications: A review. J. Compos. Sci. 2018, 2, 66. [CrossRef]

20. Luo, G.; Xie, J.; Liu, J.; Zhang, Q.; Luo, Y.; Li, M.; Jiang, Z. Highly conductive, stretchable, durable, breathable electrodes based on electrospun polyurethane mats superficially decorated with carbon nanotubes for multifunctional wearable electronics. Chem. Eng. J. 2023, 451, 138549. [CrossRef]

21. Naveen, J.; Jawaid, M.; Zainudin, E.S.; Sultan, M.T.H.; Yahaya, R. Mechanical and Moisture Diffusion Behaviour of Hybrid Kevlar/Cocos Nucifera Sheath Reinforced Epoxy Composites. J. Mater. Res. Technol. 2019, 8, 1308–1318. [CrossRef]

22. Giridharan, R. Preparation and property evaluation of Glass/Ramie fibres reinforced epoxy hybrid composites. Compos. Part B Eng. 2019, 167, 342–345. [CrossRef]

23. Zhang, Y.; Wen, B.; Cao, L.; Li, X.; Zhang, J. Preparation and properties of unmodified ramie fibre reinforced polypropylene composites. J. Wuhan Univ. Technol.-Mater. Sci. Ed. 2015, 30, 198–202. [CrossRef]

24. Torres-Arellano, M.; Renteria-Rodríguez, V.; Franco-Urquiza, E. Mechanical Properties of Natural-Fibre-Reinforced Biobased Epoxy Resins Manufactured by Resin Infusion Process. Polymers 2020, 12, 2841. [CrossRef] [PubMed]

25. Li, W.; Krehl, J.; Gillespie, J.W.; Heider, D.; Endrulat, M.; Hochrein, K.; Dubois, C.J. Process and Performance Evaluation of the Vacuum-Assisted Process. J. Compos. Mater. 2004, 38, 1803–1814. [CrossRef]

26. Hsiao, K.-T.; Heider, D. Vacuum assisted resin transfer molding (VARTM) in polymer matrix composites. In Manufacturing Techniques for Polymer Matrix Composites (PMCs); Woodhead Publishing: Sawston, UK, 2012; pp. 310–347. [CrossRef]

27. Cicala, G.; Pergolizzi, E.; Piscopo, F.; Carbone, D.; Recca, G. Hybrid composites manufactured by resin infusion with a fully recyclable bioepoxy resin. Compos. Part B Eng. 2018, 132, 69–76. [CrossRef]

28. Sanjeevi, S.; Shanmugam, V.; Kumar, S.; Ganesan, V.; Sas, G.; Johnson, D.J.; Das, O. Effects of water absorption on the mechanical properties of hybrid natural fibre/phenol formaldehyde composites. Sci. Rep. 2021, 11, 13385. [CrossRef]

29. Dilfi, K.F.A.; Che, Z.J.; Xian, G.J. Grafting of Nano-Silica onto Ramie Fiber for Enhanced Mechanical and Interfacial Properties of Ramie/Epoxy Composite. J. Zhejiang Univ. Sci. A 2019, 20, 660–674. [CrossRef]

30. Chen, M.; Lu, Z. Load Transfer Mechanism of the Composites Incorporating Nanohybrid Shish-Kebab Structures. Compos. Struct. 2015, 121, 247–257. [CrossRef]

31. Swamy, R.P.; Kumar, G.C.M.; Vrushabhendrappa, Y.; Joseph, V. Study of Areca-Reinforced Phenol Formaldehyde Composites. J. Reinf. Plast. Compos. 2004, 23, 1373–1382. [CrossRef]

32. Thakur, V.K.; Singha, A.S. Mechanical and Water Absorption Properties of Natural Fibres/Polymer Biocom-posites. Polym. -Plast. Technol. Eng. 2010, 49, 694–700. [CrossRef]

33. Joseph, S.; Sreekala, M.S.; Oommen, Z.; Koshy, P.; Thomas, S. A comparison of the mechanical properties of phenol formaldehyde composites reinforced with banana fibres and glass fibres. Compos. Sci. Technol. 2002, 62, 1857–1868. [CrossRef]

34. Sathyaseelan, P.; Sellamuthu, P.; Palanimuthu, L. Influence of stacking sequence on mechanical properties of areca-kenaf fibre-reinforced polymer hybrid composite. J. Nat. Fibres 2020, 19, 369–381.

35. Dunne, R.; Desai, D.; Sadiku, R.; Jayaramudu, J. A review of natural fibres, their sustainability and automotive applications. J. Reinf. Plast. Compos. 2016, 35, 1041–1050. [CrossRef]

36. Lotfi, A.; Li, H.; Dao, D.V.; Prusty, G. Natural fibre-reinforced composites: A review on material, manufacturing, and machinability. J. Thermoplast. Compos. Mater. 2019, 34, 238–284. [CrossRef]

37. Sujon, M.A.S.; Habib, M.A.; Abedin, M.Z. Experimental investigation of the mechanical and water absorption properties on fibre stacking sequence and orientation of jute/carbon epoxy hybrid composites. J. Mater. Res. Technol. 2020, 9, 10970–10981. [CrossRef]

38. EL-Wazery, M.S.; El-Kelity, A.M.E.; Elsad, R.A. Effect of Water Absorption on the Tensile Characteristics of Natural/Synthetic Fabrics Reinforced Hybrid Composites. Int. J. Eng. 2020, 33, 2339–2446.

39. Da Silva, R.V.; Voltz, H.; Filho, A.I.; Milagre, M.X.; Machado, C.D.C. Hybrid composites with glass fibre and natural fibres of sisal, coir, and luffa sponge. J. Compos. Mater. 2020, 55, 717–728. [CrossRef]

40. Fabris, H.J.; Knauss, W.G. Comprehensive Polymer Science and Supplements. In Synthetic Polymer Adhesives; Elsevier: Amsterdam, The Netherlands, 1989; pp. 131–177. [CrossRef]

41. Roy, A.; Naskar, A.; Ghosh, A.; Adhikari, J.; Saha, P.; Ghosh, M. Hybrid Plastics and Natural Materials. Reference Module in Materials Science and Materials Engineering; Elsevier: Amsterdam, The Netherlands, 2021. [CrossRef]

42. Raja, T.; Ravi, S.; Karthick, A.; Afzal, A.; Saleh, B.; Arunkumar, M.; Prasath, S. Comparative Study of Mechanical Properties and Thermal Stability on Banyan/Ramie Fibre-Reinforced Hybrid Polymer Composite. Adv. Mater. Sci. Eng. 2021, 2021, 5835867. [CrossRef]

43. Mohanavel, V.; Raja, T.; Yadav, A.; Ravichandran, M.; Winczek, J. Evaluation of Mechanical and Thermal Properties of Jute and Ramie Reinforced Epoxy-based Hybrid Composites. J. Nat. Fibres 2021, 1–11. [CrossRef]

44. Herrera-Franco, P.J.; Valadez-González, A. A Study of the Mechanical Properties of Short Natural-Fiber Reinforced Composites. Compos. B Eng. 2005, 36, 597–608. [CrossRef]

45. Srinivasan, V.S.; Boopathy, S.R.; Sangeetha, D.; Ramnath, B.V. Evaluation of Mechanical and Thermal Properties of Banana–Flax Based Natural Fibre Composite. Mater. Eng. 2014, 60, 620–627. [CrossRef]

46. Sarwar, A.; Mahboob, Z.; Zdero, R.; Bougherara, H. Mechanical Characterization of a New Kevlar/Flax/Epoxy Hybrid Composite in a Sandwich Structure. Polym. Test. 2020, 90, 106680. [CrossRef]

47. Haameem, J.A.M.; Majid, M.S.A.; Afendi, M.; Marzuki, H.F.A.; Fahmi, I.; Gibson, A.G. Mechanical Properties of Napier Grass Fibre/Polyester Composites. Compos. Struct. 2016, 136, 1–10. [CrossRef]

48. Özturk, S. Effect of Fiber Loading on the Mechanical Properties of Kenaf and Fiberfrax Fiber-Reinforced Phenol-Formaldehyde Composites. J. Compos. Mater. 2010, 44, 2265–2288. [CrossRef]

49. Chaudhary, V.; Bajpai, P.K.; Maheshwari, S. Studies on Mechanical and Morphological Characterization of Developed Jute/Hemp/Flax Reinforced Hybrid Composites for Structural Applications. J. Nat. Fibers 2018, 15, 80–97. [CrossRef]

50. Zhong, J.B.; Lv, J.; Wei, C. Mechanical properties of sisal fibre reinforced Ureaformaldehyde resin composites. Express Polym. Lett. 2007, 10, 681–687. [CrossRef