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Tensile Properties of Open Hole and Unhole Sugar Palm '*Ijuk*' (SPI) Fibre Composite Treated with Sodium Hydroxide (NaOH)

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ABSTRACT

This study evaluates the effects of sodium hydroxide (NaOH) treatment on tensile properties of sugar palm 'ijuk' (SPI) fibre-reinforced polymer (FRP) composites, with and without an open hole that acts as a stress concentrator. The NaOH treatment is aimed to improve the interfacial adhesion between SPI fibres and polymer matrix. Composite specimens were prepared using the hand lay-up method, incorporating SPI fibres in various orientations, and featuring a 6 mm diameter hole. Tensile tests were conducted to evaluate the mechanical performance of SPI FRP composite, including ultimate tensile strength, Young's modulus, and elongation at break. The research also compared the properties of SPI to those of synthetic glass fibre in fibre-reinforced polymer composites. The results showed that NaOH treatment significantly improves the fibre-matrix adhesion with 26% increase in tensile strength, leading to enhanced tensile properties in both samples, regardless of hole presence. The 0° orientation provides the highest strength and stiffness when the load is applied in the direction of the fibres. While for the 90° orientation, strength reduces by 14%. The impact of the hole on stress concentration and the subsequent mechanical behaviour of the open-hole specimens is substantial. The findings of this study offer insightful perspectives on the potential use of

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NaOH-treated SPI fibre in structural and other applications, demonstrating its ability to withstand tensile stresses, even with geometric discontinuities like holes.

Keywords: *Natural Fibre; Composites; Sugar Palm; 'Ijuk'; Open Hole; Tensile*

Introduction

An increasing number of studies are being conducted to advance the use of natural fibres in industry as alternatives to synthetic fibres. This shift, driven by environmental concerns, highlights materials from natural resources as viable substitutes for synthetic fibres [1]-[2]. Natural fibres offer several advantages: low cost, low density, comparable specific tensile properties, good thermal behaviour, non-abrasiveness to equipment, skin-friendliness, reduced energy consumption, lower health risks, renewability, recyclability, and biodegradability [3]. In response, researchers are showing significant interest in composites made of Natural Fibre-Reinforced Polymer (NFRP). In NFRP composites, natural fibres often serve as reinforcing elements, potentially enhancing the materials' mechanical properties. This trend towards natural fibre composites (NFC) aligns with the goal of maintaining ecologically friendly production practices. Replacing conventional materials with NFC in industrial applications has been the subject of various studies [4]-[5]. Known for their excellent corrosion resistance, resistance to chemical degradation, and moderate strength and durability, natural fibres are becoming a focal point of research [6]-[8].

One of the challenges in using natural fibres is their surface composition, which often includes a lignin and hemicellulose coating that acts as a wax barrier. This wax can impede the adhesion between the fibres and the matrix. Previous research suggests that chemically treating natural fibres surfaces enhances composite materials' physical and mechanical properties by facilitating effective fibre/matrix interfacial adhesion [9]-[10]. This process strengthens the interlocking between fibres and the matrix, enhancing adhesion strength and improving compatibility. Before fabrication, 'ijuk' fibres undergo surface treatment to improve their mechanical characteristics [11].

This research advocates the use of 'ijuk', or Arenga pinnata fibres, as a sustainable replacement for traditional synthetic fibres. Derived from the sugar palm or gomuti palm tree native to Southeast Asia, 'ijuk' fibres are known for their strength, longevity, and resistance to corrosion, especially in saltwater environments [12]. The environmental advantages of natural resources have spurred research into developing 'ijuk' fibres as an alternative to conventional fibres [13]-[15]. Modifications of the surface have been made by other researchers and these changes indicate increases in the mechanical properties of the samples. The surface treatment has been investigated by other researchers to improve the interfacial bonding between natural fibre and matrix resin [16]. It can increase the interaction of natural fibre and allow for better adhesion strength and increased compatibility by modifying the surface properties of natural fibres to promote adhesion between natural fibres and polymer matrices and enhance the overall performance of composite materials. Before fabricating the sample, surface treatment is performed on the 'ijuk' fibre to enhance its mechanical characteristics [17]. The surface of the untreated fibre reveals impurities and waxy substances at the surface while the treated fibre shows the pores that have removed the impurities of the hemicelluloses from the fibre [18].

In this study, natural fibres from the sugar palm tree are alkali-treated before being woven into mats which are then used to create fibre-reinforced polymer composites. The production of these composites involves cutting them into standardized samples for material property evaluation. Figure 1 illustrates the sugar palm tree (a) and the 'ijuk' fibres located at the trunk of the tree (b).

Figure 1: (a) Sugar palm tree (b) 'Ijuk' at the trunk of the sugar palm tree

The study also examines the effects of hole formation in composite materials. The introduction of a hole can lead to a phenomenon known as delamination, which is a mode of failure where the layers of the composite material separate along their interfaces. Delamination is particularly detrimental as it significantly reduces the load-bearing capacity of the composite material, leading to premature failure. The extent of the reduction in mechanical properties due to the presence of a hole can depend on several factors, including the size and shape of the hole, the orientation of the fibres, and the type of composite material used. For instance, larger holes can result in a greater reduction in strength, and certain fibre orientations may be more susceptible to stress concentration and delamination. Composite materials, particularly fibre-reinforced composites, are widely used in various industries due to their high strength-to-weight ratio, corrosion resistance, and design flexibility. However, the introduction of a hole in a composite material, often necessary for assembly, can significantly affect its mechanical properties. Research on open hole tensile strength, as well as experimental and numerical simulations, has been conducted to assess the impact of holes on fibre properties, crack propagation, varying ply thicknesses, and different hole sizes [19]-[22]. Results indicate that the introduction of holes can initiate crack propagation from the hole, ultimately reducing the strength of the material. This information is essential for designing safe and reliable structures that use fasteners or other types of holes.

Methodology

Materials

This study utilised two types of fibres: synthetic and natural. The synthetic fibre used was unidirectional E-glass fibre, which is composed of alumina-calcium borosilicate and is known for its alkali-free nature and high electrical resistance. Specifically, the E-glass fibre used in this research was unidirectional continuous fibre with a diameter of 10 µm and a density of 2.04 g/cm^3. This synthetic glass fibre serves as the reference material.

For the natural fibre, sugar palm ‘ijuk’ (SPI) fibre was selected. This fibre is sourced from the trunk of the sugar palm tree, specifically from the eastern part of Indonesia. SPI fibre is notable for its unique properties and regional significance. The matrix material used in this research was WILLKAT® PL 2K Fast, belonging to the group of silicate-isocyanate resin systems. This resin is a non-foaming, elasticized two-component resin, distinguished by its excellent adherence to damp surfaces. It is primarily used for the reconstruction and sealing of conduit-type sewers and sewer lines in sewer repair, employing a quick liner technique. This choice of resin is integral to the study due to its compatibility with the selected fibres and its application in structural contexts.

Surface treatment of SPI fibre

Surface treatment is a process used to modify the surface properties of natural fibres. This process aims to enhance adhesion between the natural fibres and polymer matrices, thereby improving the overall performance of composite materials. In this study, SPI fibres underwent surface treatment before sample fabrication to enhance their mechanical characteristics. The treatment involves using chemicals to remove lignin and hemicellulose from the fibre's surface, facilitating better bonding between the fibre and the matrix.

To ensure effective adhesion between the matrix and the reinforcing material, the SPI fibre bundles were immersed in a 5% w/v Sodium Hydroxide

(NaOH) solution for two hours. Studies have shown that a 5% w/v alkali treatment effectively removes materials covering the surface of natural fibres [23]-[25].

Following this treatment, the fibres were thoroughly rinsed with distilled water multiple times until they achieved a neutral pH level of 7 using pH meter equipment. The final step in the treatment process involved drying the fibres in an oven at a temperature of 80 °C for eight hours. This preparation is crucial to optimize the use of fibres in composite material applications.

Fibre characterisation using SEM

The surface morphology of the SPI fibre before and after the treatment was examined using an analytical Scanning Electron Microscope (SEM), which operated at a voltage of 5.0 kV and a working distance of 10.5 mm. Microscopic images of the fibres were captured at magnifications of 200X, 500X, and 1000X. Before the samples were placed in the SEM for analysis, they were coated with a 5 nm-thick layer of gold. The coating is applied using an automated fine sputter coating machine to enhance the conductivity of the samples and improve image quality.

Fabrication of FRP composites

The vacuum bagging process and hand lay-up method were used to fabricate FRP composite laminates in creating the composite samples [26]. The laminate was constructed using eight layers of unidirectional glass and manually woven SPI fibres, combined with a silicate-isocyanate resin mixture in a specific ratio. Figure 2 displays the SPI yarn and glass fibre mat, each measuring 300 mm in length and 300 mm in width, utilized in making a composite plate. Figure 3 illustrates the vacuum bagging process and the resulting plate. These plates were then measured and cut following ASTM standards.

(a) (b) (c)

Figure 1: (a) SPI fibre, (b) unidirectional SPI fibre in one layer mat form, and (c) unidirectional glass fibre mat

Tensile test

The mechanical properties of the specimens were assessed by subjecting them to uniaxial tensile testing using a Universal Testing Machine (UTM). The tensile test for samples without holes followed ASTM D3039, whereas samples with centrally located 6 mm diameter holes were tested according to ASTM D5766. Each standard was tested with five samples, each measuring 200 x 40 x 2.5 mm and featuring varying fibre orientations at angles of 0º and 90º. To prevent the coupons from being crushed in the grips of the testing machine, aluminum tabs were affixed to the ends of each FRP coupon before testing. The tests measured ultimate tensile strength, elongation, modulus, and yield strength. The purpose of these tests is to evaluate the significant impact of a hole on the samples' properties.

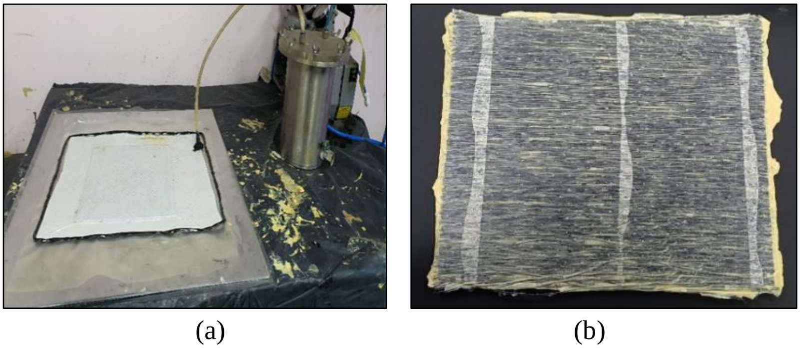
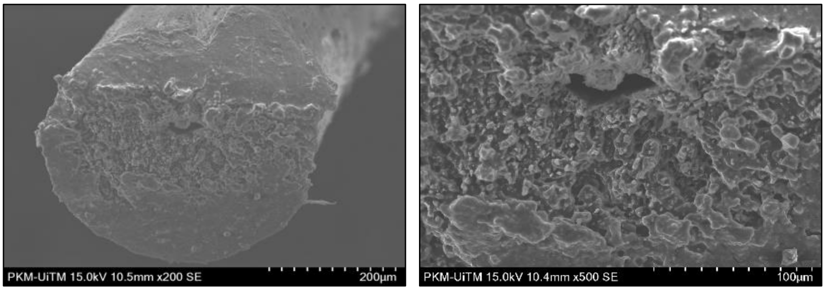

(a) (b)

Figure 3: (a) Set up of vacuum bagging process and (b) fabricated SPI fibre composite plate

Results and Discussion

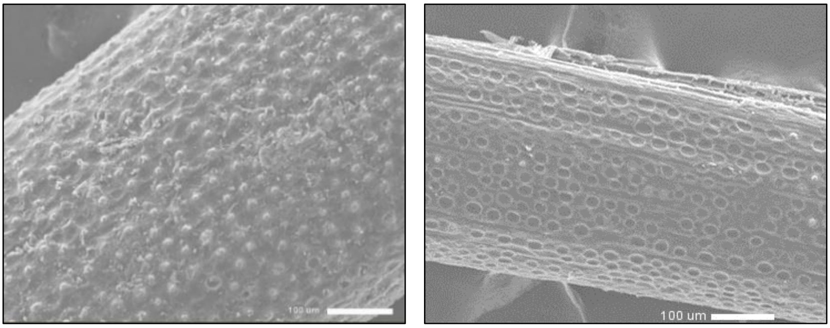
SEM characterization

Figures 4(a) and 4(b) show the cross-section of the SPI fibres where the vascular tissues can be observed on the fibrous surface of the plant. The SPI fibre has thick cell walls, resulting in a rough and long-lasting texture [27]. The effect of alkali treatment and the morphology of the surface of the fibre before and after treatment with an alkaline sodium hydroxide (NaOH) solution is presented in Figures 5(a) and 5(b). The fibre's surface morphology changes significantly after surface treatment. This change is necessary because the sole use of the alkalinization method has proven to be insufficient in eliminating all contaminants. The treatment process involved using various chemicals and stages to extract lignin, wax, and hemicellulose from the fibre's cell wall, which was successfully achieved. The primary aim is to enhance the bonding between the matrix and the fibre, ultimately leading to polymer matrix composites with improved physical and mechanical properties [28]-[29]. The surface of the untreated fibre reveals impurities and waxy substances, while the treated fibre shows pores that have removed the impurities of the hemicelluloses from the fibre [30]-[31].



(a) (b)

Figure 4: Scanning Electron Microscope (SEM) image of natural fibre (a) cross-section of single SPI fibre, and (b) surface of SPI fibre



(a) (b)

Figure 5: Surface of SPI fibre (a) before treatment, and (b) after treatment

Tensile properties of FRP composite

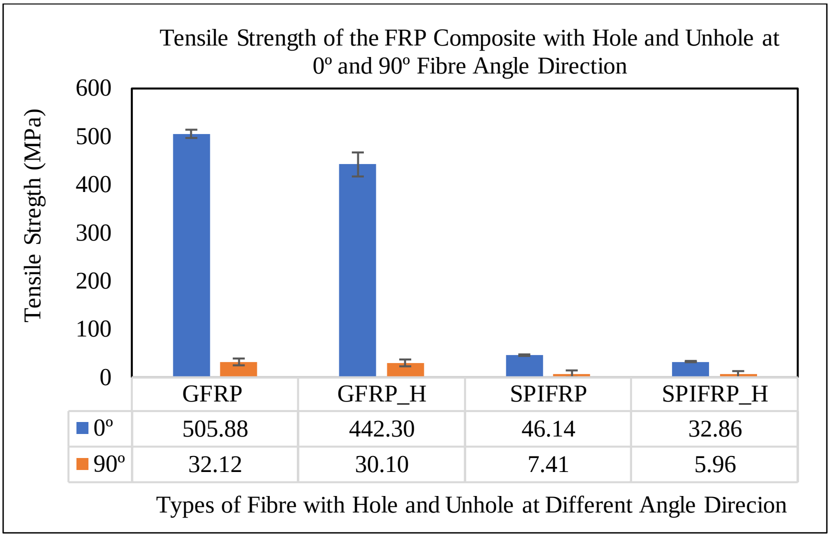
Tensile strength

Table 1 shows the tensile strength of the sample SPI before and after NaOH treatment. The value of tensile modulus and strength increased by about 78% and 26%, respectively. However, the value strain (%) decreased by 53%. After NaOH treatment, the tensile properties of the fibres can change. The treatment removes surface impurities and partially dissolves hemicellulose and lignin, non-cellulosic components of the fibre. This process exposes more cellulose, increases the roughness of the fibre surface, and results in better mechanical interlocking between the fibres and the matrix [32]-[34]. As a result, the tensile strength of the composite material can be improved due to the enhanced fibre-matrix adhesion.

Table 1: Tensile properties of SPI composite before and after NaOH treatment

Fibre type	Tensile modulus (GPa)	Tensile strength (MPa)	Tensile strain at break (%)
SPI before NaOH treatment	1.83 ± 0.08	36.6 ± 0.64	3.37 ± 0.31
SPI after NaOH treatment	3.26 ± 0.07	46.14 ± 1.08	2.20 ± 0.17

Figure 6 represents the ultimate tensile strength of different fibre reinforcements. In the results, the terms Glass fibre Reinforced Polymer (GFRP) and Sugar Palm ‘ijuk’ fibre-Reinforced Polymer (SPI FRP) indicate the outcomes of synthetic glass fibre and natural SPI fibre, respectively. The results illustrate the tensile strength of samples both with and without a central hole. Tensile testing conducted on specimens without holes assesses the material's ability to withstand external forces without undergoing catastrophic failure. Meanwhile, specimens with holes are used to evaluate the material's damage tolerance, referring to its capacity to continue bearing loads after the introduction of a hole or damage [35]. The graph exhibits a consistent pattern, with varying values. The highest ultimate tensile strength was recorded at 505.88 MPa for GFRP without a hole at 0° fibre orientation, and decreasing to 32.12 MPa at 90° fibre orientation. For SPI FRP fibre, the strength was 46.14 MPa at 0° and dropped to 7.41 MPa at 90° in the absence of a hole. In composite samples with a hole, the tensile strength was 442.30 MPa at 0° for GFRP and decreased to 30.10 MPa at 90° in the fibre orientation. SPI FRP composite exhibited a strength of 35.64 MPa at 0° and 5.96 MPa at 90° in the fibre orientation. Fibre orientation significantly affects the mechanical properties of FRPs. When fibres are aligned in the direction of the applied load (0° orientation), the material exhibits its maximum tensile strength. This is because the load is directly borne by the high-strength fibres, which are the primary load-carrying component in FRPs. The strength pattern shows a significant reduction corresponding to the fibre orientation, in which GFRP fibre experiences a greater difference compared to SPI FRP fibre with reductions of 13% and 2%, respectively, in strength according to the fibre direction [36]-[37]. Furthermore, GFRP fibre exhibits a higher percentage of overall strength compared to SPI FRP fibre.



	GFRP	GFRP_H	SPIFRP	SPIFRP_H
🟦 0°	505.88	442.30	46.14	32.86
🟧 90°	32.12	30.10	7.41	5.96

Figure 6: Tensile strength of the FRP composite with different angles of fibre direction with hole and without hole at the centre

<u>Young's modulus</u>

Young's modulus quantifies a material's ability to resist elastic deformation caused by stretching or compression. It is measured by observing how much the material distorts when subjected to a specific load. Higher Young's Modulus values indicate stiffer materials that deform less under the same load, whereas less rigid materials deform more readily when exposed to a similar force. Various researchers have measured the Young's modulus of these materials as part of their studies [38]-[39]. Figure 7 illustrates the outcomes of Young's modulus for both composites with and without holes. The highest Young's modulus value was 20.34 GPa for GFRP fibre material at 0° orientation, and 3.26 GPa at 0° for SPI FRP fibre without holes. Conversely, for composites with holes, the modulus values were 17.88 GPa for GFRP and 2.55 GPa for SPI FRP at 0° fibre direction. When the fibres were oriented at 90°, the modulus yielded lower values, with 3.84 GPa for GFRP and 1.13 GPa for SPI FRP in samples without holes. For samples with holes, Young's modulus was 3.53 GPa for GFRP and 0.91 GPa for SPI FRP at 90° fibre direction. It shows that the young modulus is higher at 0° compared to 90° fibre direction with holes and without holes even in synthetic or natural fibre composites. Young's modulus, a measure of material stiffness, is significantly influenced by the orientation of fibres within composite materials. This aspect is fundamental to composites, which are inherently anisotropic, indicating that their mechanical properties vary with direction.

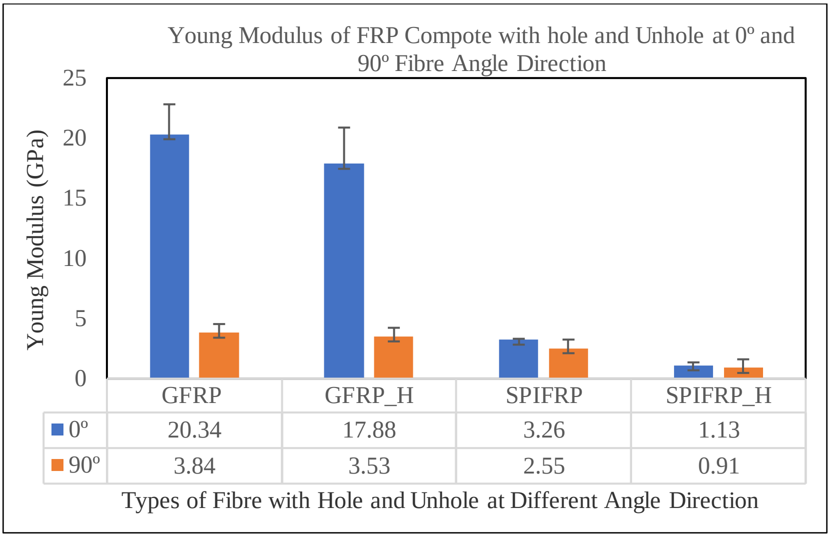


Figure 7: Young modulus of the FRP composite with different angles of fibre direction with hole and without hole at the centre

<u>Elongation at break</u>

When conducting a tensile test, the strain value is used to quantify the degree to which a material has been deformed or stretched because of the applied force. It is an essential measure for gaining an understanding of the mechanical behaviour of a substance, and it can supply important details regarding the substance's elasticity and ductility. Strain in a material is a measure of deformation representing the displacement between particles in the material body relative to a reference length. Figure 8 shows the results of deformation in a different direction of the fibre. The maximum value of strain can be attained by achieving a higher value of both the ultimate tensile strength and the young modulus of the fibre.

Under tensile loading, the strain exhibited by a GFRP composite in the 0º direction is influenced by the high load-bearing capacity of the aligned fibres. Since the fibres are much stiffer and stronger than the matrix, they do not deform as much under load, leading to lower strain values. However, the composite as a whole can exhibit higher strain values before failure due to the matrix material's contribution, which deforms more easily. In contrast, when the load is applied in the 90º direction, the mechanical load is primarily borne by the polymer matrix, as the fibres are oriented perpendicular to the applied load [40]. Meanwhile, for SPI FRP composite, relatively similar strain values were observed in Arenga Pinnata fibre-reinforced composites along both the 0º and 90º fibre directions which may be attributed to the unique properties of this natural fibre. Arenga Pinnata fibres, derived from the sugar palm tree, might possess an inherent isotropy or relatively uniform mechanical behaviour in multiple directions.

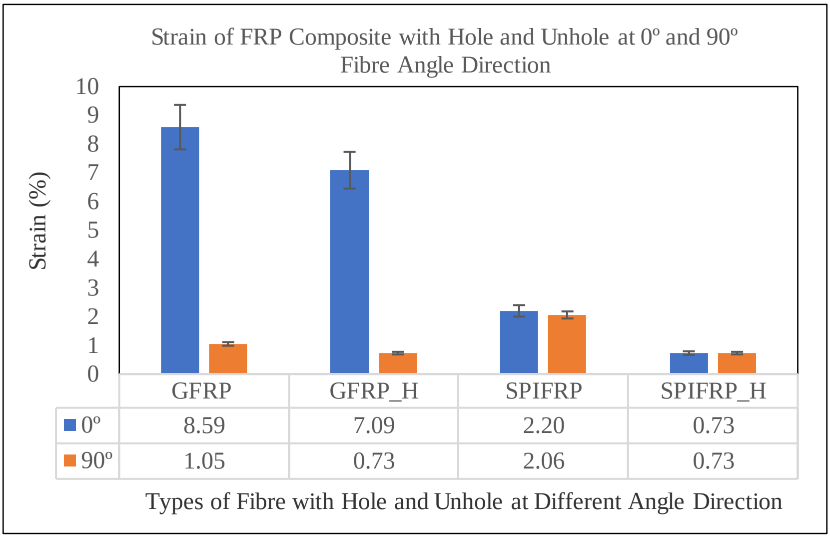


Figure 8: Strain (%) of the FRP composite with different angle of fibre direction with hole and without hole at the centre

Composite materials, particularly fibre-reinforced composites, are widely used in various industries due to their high strength-to-weight ratio, corrosion resistance, and design flexibility. However, the introduction of a hole in a composite material, often necessary for assembly, can significantly affect its mechanical properties [41]. The presence of a hole in a composite material can lead to a reduction in its strength. Results show that the introduction of the hole degrades the properties of the composite material. This reduction is primarily due to the interruption of fibre continuity, a key factor in the material's ability to bear loads. When a hole is introduced, the fibres around it are cut which disrupts the load path, leading to a concentration of stress. This stress concentration can significantly reduce the material's tensile and compressive strength, as the load is no longer evenly distributed across the material [42]-[43].

Conclusion

Treating natural fibres surface with an alkaline solution has been shown to effectively remove wax and hemicellulose, thereby enhancing the mechanical properties of the samples with a 26% increase in tensile strength. The utilization of synthetic fibres in the industry is gradually being supplanted by natural fibres due to their promising attributes. This transition is driven by factors such as biodegradability, sustainability, and cost-efficiency. The ultimate tensile strength reaches its peak when the fibres are oriented at 0º without holes, with the values of 505.88 MPa for GFRP and 46.14 MPa for SPI FRP composite, respectively. In contrast, for samples with holes, the ultimate tensile strength is reduced to 442.30 MPa for GFRP composite fibres and 35.64 MPa for SPI FRP composite fibres. Meanwhile, in the 90º angle direction, the value decreases by 14% in tensile strength. The resulting pattern clearly indicates that introducing holes reduces the strength of the composites. The presence of a hole creates a discontinuity in the material, leading to a stress concentration around the hole's edges during loading. This stress concentration can result in a reduction of the material's strength, as proven in the results.

Contributions of Authors

The authors affirm that they have contributed equally to all aspects of this research. All authors have reviewed and approved the final version of the manuscript.

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Conflict of Interests

All authors declare that they have no conflict of interest.

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