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Review on the Mechanical Properties of Natural Fibre Reinforced Polymer Composites for Aerofoil Applications

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Abstract

Natural fibre-reinforced polymer composites (NFRPCs) are emerging as sustainable, lightweight materials with significant potential for aerofoil applications in the aerospace industry. This review explores the mechanical properties of NFRPCs that incorporate natural fibres, resin matrices, and fillers, focusing on their tensile strength, flexural performance, impact resistance, and fatigue durability. Natural fibres, such as flax, jute, hemp, and Doum palm leaf, are evaluated for their structural benefits, while epoxy resin is highlighted as a preferred matrix due to its high adhesion and thermal stability. Fillers, including silica, calcium carbonate, and nano-clay, are discussed for their role in enhancing the composite's strength, thermal properties, and impact resistance, making NFRPCs suitable for demanding aerofoil applications. Adding fillers further

improves performance, particularly in terms of durability, stiffness, and environmental resistance, which are crucial for aerofoil structures. The review also examines variability in natural fibre properties and presents strategies to address these issues through fibre treatments and hybridization techniques. Less research has focused on combining multiple natural fibres with fillers to create hybrid composites, which have shown promising mechanical enhancements in existing studies. Future directions are suggested to optimize NFRPCs for aerospace applications by using epoxy resin for improving fibre-matrix bonding. The review underscores the potential of NFRPCs as a sustainable and high-performance material solution for lightweight aerofoil structures in aerospace. Further investigation into innovative filler-natural fibre combinations, such as Calcium Sulphate Hemihydrate ($CaSO_4 \cdot \frac{1}{2}H_2O$) and Doum leaf stalk composites, could unlock new opportunities in aerospace and engineering fields.

Keywords: Natural Fibre-Reinforced Polymer Composites, Mechanical Properties, Aerofoil Applications, Sustainable Aerospace Materials and Fibre-Matrix Bonding.

Introduction

The increasing demand for sustainable materials in aerospace applications has brought natural fibre-reinforced polymer composites (NFRPCs) to the forefront of research due to their low density, biodegradability, and good mechanical properties. For aerofoil applications, NFRPCs must meet rigorous performance standards in terms of strength, stiffness, impact resistance, and durability. This literature review examines the current research on the mechanical properties of NFRPCs, focusing on the influence of natural fibre type, resin matrix, and filler additives on composite performance in terms of mechanical properties and applications in the aerospace industry.

Composite material is one of the man-made materials widely used nowadays in the field of Air, Land and Sea transportation among others for production of materials that high strength to light weight ratio coupled with corrosion resistance (Sadiq *et al.,*

2020). The materials are generally used for production of lightweight and high strength structures of machine components without compromising its efficiency. Composite materials generally consist of two major constituents, reinforcement that is fibre and polymer matrix that is epoxy resin or polyester resin commonly called resin. Resin polymer matrix of composite material constitutes a significant volume fraction above 50% of any fibre reinforced composite material that requires proper impregnation of the reinforcement (Sadiq *et al.,* 2020).

Thermosets resin or thermosetting polymers, are family of plastics characterized by the fact that they are formed starting a liquid solution (epoxy resin, cobalt, and hardener) that irreversibly leads to a solid material during cooling process or when exposed to air (Almia-Gulfem, 2020).

Thermoplastics are a type of plastic that can be softened or melted by heating, allowing them to be shaped, formed, and solidified when cooled. They can be reheated and cooled multiple times without severe damage, making them suitable for reprocessing and recycling (Almia-Gulfem, 2020).

The matrix plays a vital part on fibre-reinforcement composite. It protects the surface of the fibres from mechanical damage, acts as a barrier against adverse environment and it transfer loads to the fibres. The most commonly used matrices in natural fibre composites NFCs are polymeric as they are light weight and can be processed at low temperature. Both thermoplastic and thermoset polymers are used as matrices with natural fibre (Holbery and Houston 2024).

Matrix selection is limited by temperature at which the fibres degrade. Natural fibre that are used as reinforcement are thermally unstable above 200 °C, although under some circumstances it is possible to process them at higher temperature for a short period of time (Summer scales *et al.,* 2020). Due to this limitation, only thermoplastics such as polyethylene, polyolefin, PP, polyvinyl chloride and polystyrene and thermosets are used as a matrix because they become soften below this temperature (dos Santos *et al.,* 2018). The thermosets used are epoxy resin, polyester, phenol formaldehyde and VE resins. Thermoplastics are repeatedly soften by the application of heat and hardened by cooling and are capable of being easily recycled, which is most favoured in recent commercial uptake, whereas better realisation of the fibre properties are achieved using thermosets. Petroleum-

based matrices are replaced with bio-derived matrices, in terms of mechanical property (Almia-Gulfem, 2020).

The function of the matrix is to hold in place the reinforcement material in its set and essentially transfer the load between the reinforcements. The matrix influences the overall durability, surface finish and net shape of the resulting composite (Chollakup *et al.,* 2023). The matrix also serves an important purpose of protecting the fibre from damage due to the environmental effects or handling. The most prominent matrix is the polymer matrix which has been reported to exhibit good material properties like lower densities, acceptable thermal and electrical characteristics and inexpensiveness (Santhosh *et al.,* 2017; Gu *et al.,* 2024). The current ecological concerns have also driven researchers to develop replacements to the petroleum-based matrices. There has since been a renaissance in the past decade on the use of renewable based plastic matrices. As a result, the development of renewable matrix material from recycled and natural resources have increased in recent years (Mohankumara *et al*., 2020). However, due to low properties exhibited by these bio based matrices, petrochemical based matrices continue to dominate the development of natural fibre based composites. Thus, this review discusses the polymeric based matrices. The polymer matrices are categorized into thermoplastic and thermosetting polymers which are based on the effect of heat on their properties. Examples of thermoplastic matrices include polyvinyl chloride, polyethylene, polypropylene and polystyrene while polyester, epoxy resin, vinyl esters and phenol formaldehyde make up thermosetting matrices (Faruk *et al.,* 2012). Studies have shown that thermosets are the mostly used matrix material for natural fibre based composites. However these matrix materials sometimes exhibit poor properties that limit their functionality which include lower impact resistance, lower fracture toughness, limited resistance to crack initiation and propagation (Saba *et al.,* 2016). The incorporation of nano filler material has been established to certainly modify the properties of the polymer matrices with improved electrical, thermal and mechanical characteristics Saba *et al.,* (2016).

Reinforcement

Reinforcement materials in composites are broadly categorized into fiber-reinforced and particulate-reinforced types, each offering distinct mechanical

advantages and applications. Fiber-reinforced composites utilize materials like glass, carbon, and natural fibers to improve strength, stiffness, and thermal stability, with carbon fibers being particularly favored for high-performance applications due to their superior strength-to-weight ratio and fatigue resistance, despite their high cost. Natural fibers, such as jute and flax, are gaining attention for their sustainability and biodegradability but face challenges like moisture susceptibility (Ahmed *et al.,* 2022). On the other hand, particulate-reinforced composites rely on dispersed particles such as metals, ceramics, or polymers to enhance properties like hardness, wear resistance, and dimensional stability, making them suitable for applications requiring uniform mechanical properties (Kumar & Patel, 2018). Emerging trends include hybrid composites that integrate fibres and particulates to achieve a balance of strength, toughness, and lightweight properties, addressing the growing demand for multifunctional materials in aerospace and automotive industries (Ahmed *et al.,* 2022).

Fibre Reinforced Composite

Fabrication of composite material through the process of embedding fibre into a matrix is termed fibre reinforced composite. The matrix serves the purpose of holding the fibre in its set place and essentially transferring the load stress to the fibres (Gohal *et al.,* 2020). Fibrous composites are categorised into continuous fibre and discontinuous fibre composites. Continuous fibre composites are further subdivided into unidirectional and bidirectional reinforcements which is based on their orientation (Gohal *et al.,* 2020). Fibres in the unidirectional orientation are arranged in one direction and generally exhibit high strength in the longitudinal direction of the fibres but however also exhibit weakness in the perpendicular direction to fibre. To overcome this weakness, fibres can also be arranged in both directions termed bidirectional orientation which enables the resulting composite to possess equal strength in both directions (Parbin *et al.,* 2019). Short fibre composites are termed discontinuous (short) fibre composite and properties of composite are attributed fibre length. The characteristics of short fibre composites are uniform in nature and the fabrication of this type of composite involves short fibres that are randomly arranged in liquid resin (Gohal *et al.,* 2020).

Particulate Reinforced Composite

Particulates can also be used as reinforcements to improve the matrix properties where the particles are non-fibrous and discontinuous. The properties of composites reinforced with particulate material are generally influenced by the dimensions of the particles and may be cubic, tetragonal and spherical in shape (Parbin *et al.,* 2019). For particulate reinforced composites, limited load is transferred from the matrix to the particulates in comparison to the fibrous composite in exchange for improved stiffness while the overall strength is reduced. The particulates are used to enhance the characteristics of composites such as improved performance at high temperatures, thermal and electrical conductivity (Parbin *et al.,* (2019). Economically, the particulate material lowers the overall cost of the composite while offering comparable mechanical characteristics such as wear and abrasion resistance, surface hardness, and machinability (Gohal *et al.,* 2020).

Filler content consists of particulate material of nano-scale that is added to the matrix material in small quantities varying from 0.1 to 5 wt% which depends on the type of filler (Senthilkumar *et al.,* 2018). The addition of filler content into fibre reinforced composites forms a hybrid composite and serves the purpose of achieving reasonable fibre/matrix interfacial strength. The use of filler content in composites offers advantages of enhancing the mechanical characteristics of the resulting composite such as hardness, abrasion resistance and improved surface finish (Senthilkumar *et al.,* 2018). Generally, filler content material is cheap which makes the process of improving the mechanical characteristics more cost effective. Filler materials are categorized into conventional which include $CaCO_3$, TiO_2, Al_2O_3, ZnO and SiC while the non-conventional fillers include cellulose nano-fibres, nano-clay, rice husk, saw dust and industrial waste such as fly ash (Gohal *et al.,* 2020). The use of recycled and natural based materials is currently the most suitable and economical precursors for the fabrication of filler materials. The addition of fillers in hybrid composites has coined the term Nano composites which are materials that consist of multiple phases in which at least one or more of its phases has dimensions lower than 100 nm (Saba *et al.,* 2016). An ideal composite is achieved with good interaction between matrix and fibre because of the ease of load transfer between the interfaces (Ahmad *et al.,* 2015). The engineering behind

the use of nano-fillers in composite materials is mainly to create an increased interfacial bonding between the reinforcing material and matrix material. Since their inspection, Nano composites materials have exhibited striking and acceptable characteristics for advanced applications in a wide range of engineering disciplines. The incorporation of nano-scale filler materials in different matrices enables engineers to match the demands of unique material characteristics for numerous engineering applications (Saba *et al.,* 2016). The unique characteristics offered by the incorporation of nanoparticles in composite materials include thermal, mechanical and electrical properties similar to the conventional composites like carbon and glass fibre composites which are attributed to the high aspect ratio, ideal dispersion and matrix filler fusion (Ahmad *et al.,* 2015). Higher matrix and filler with uniform dispersion of nanoparticles have been eluded to attain higher mechanical properties (Reddy *et al.,* 2019). Generally, the mechanical characteristics of filler content filled composites are a function of parameters such as the interaction between the matrix and filler material, even the distribution and dispersion of (fillers Singh and Singh 2019). Numerous research groups have investigated the influence of filler material on the mechanical characteristics of hybrid natural fibre composites in a bid to investigate potential characteristics improvements and subsequently know the suitable applications (Timothy *et al.,* 2020).

Natural Fibres Reinforced Composites (NFRPCs)

Natural fibres reinforced composites such as flax; jute, hemp, and sisal have gained traction as reinforcements in polymer composites because of their favorable mechanical properties, low density, and renewability. Faruk *et al..* (2012) studied indicate that flax fibres offer high tensile strength and stiffness, which are essential for structural applications in aerospace. Faruk *et al..* (2012) highlight that flax-reinforced composites can achieve tensile strengths up to 100 MPa, making them competitive with glass fibre composites for lightweight applications jute fibres, while slightly lower in strength, are also popular for their availability and low cost. The natural fibres lie in their hydrophobicity, which can lead to poor interfacial bonding with the hydrophobic polymer matrix. Treatments such as alkali and silane treatments have been shown to improve fibre-matrix adhesion, resulting in better

tensile and flexural properties (Pickering *et al.,* 2016; Shah *et al.,* 2013). These treatment purities and increase surface roughness, allowing for better stress transfer between the fibres and the matrix, which is critical for aerofoil structures subjected to high aerodynamic loads.

Hybrid Natural Fibre Composites (HNFCs)

A hybrid composite is the fusing of two or more varying fibres in a single matrix with the aim of overcoming the limitations of individual fibres (Saba *et al.,* 2016). Numerous researchers have fabricated hybrid composites by fusing different natural fibres together in different matrices including poly vinyl ester, epoxy, polyester, phenolic, and polyurethane resins (Saba *et al.,* 2016). Enhanced characteristics of hybrid natural fibre based composites can utilise the synergy between the uses of natural fibres with nano-fillers as reinforcement material that can also lead to a positive environmental impact (Saba *et al.,* 2016). The distribution and dispersion of reinforcements, high aspect ratio of the reinforcements, large surface area, surface modification, fibre dimension and orientation interfacial adhesion between polymer and reinforcements are key factors that influence the mechanical characteristics of natural fibre hybrid composites. Hybrid composite products have three important parameters that have significant effect on the resulting properties. The matrix and reinforcement materials are the first parameters to be considered which are influenced by the considered application (Saba *et al.,* 2016; Mochane *et al.*. 2019).

Natural fibres can be fused together to form hybrid composites where the natural fibres act as reinforcement material that is embedded in a single matrix. This process is essential in enhancing the overall performance and characteristics of the resultant material while taking in account the current ecological concerns. The characteristics of natural-natural fibres reinforced hybrid composites from numerous research groups have been investigated extensively (Mochane *et al.*. 2019).

Shireesha *et al.,* (2019) studied the combination of both jute and banana fibres in an epoxy matrix composite which revealed an enhancement in the characteristics up to 30% wt on loading and also noted that the mechanical characteristics of the individual fibres was improved in the resulting hybrid. Idicula *et al.,* (2015) in his

research found out that improved fibre/matrix interface coupled with good stress transfer were discovered in a sample with a 3:1 relative volume fraction of banana and sisal, which showed the maximum flexural modulus, tensile strength and the lowest impact strength. Mochane *et al.,* (2019) observed that for natural-natural fibre hybrid composites, optimum tensile strength can be obtained when high strain is obtained. Gupta (2015) investigated the mechanical characteristics of sisal and jute fibres in an epoxy based matrix composite. Their results showed that temperature increase leads to substantial decrease in the storage modulus of the hybrid composites which is caused by the loss of stiffness of fibres. Furthermore, storage modulus value was seen to be directly proportional to the bonding interface between the fibres and matrix. Pappu e*t al.,* (2019) reported the use of hemp and sisal by employing the melting and injection moulding processes to fabricate a hybrid fibre reinforced composite with polylactic acid (PLA). The results from their study have revealed water absorption capacity of 1.06 ± 0.18%, density 1.14 ± 0.07 g/cm^3 and elongation at break of 0.93 ± 0.35% of the hybrid composite. Compared to neat PLA, natural fibres embedded in PLA to form hybrid composites attained an enhanced mean specific tensile strength 38.86 MPa, specific flexural strength 79.76 MPa, flexural strength 94.83 MPa, Young's modulus 6.1 GPa, flexural modulus 6.04 GPa and and tensile strength 46.25 MPa. They have since been able to conclude that the combination of hemp and sisal fibre with PLA significantly improved the impact strength of the resulting composite. The enhanced performance made them highly recommended for use as alternative renewable material in electronics, automotive, agricultural applications, interiors and packaging.

Polymer Matrices in Natural Fibre Composites (PMCs)

The choice of polymer matrix is essential in determining the mechanical performance and thermal stability of NFRPCs. Epoxy resins are commonly used in aerospace applications due to their excellent mechanical properties, high adhesion to natural fibres, and good thermal resistance. Studies by La Mantia and Morreale (2011) reveal that epoxy-based NFRPCs display superior tensile strength and impact resistance compared to those with polyester or vinyl ester matrices.

Additionally, epoxy provable structure for the composite, allowing it to withstand the varying loads and temperatures typical in aerofoil applications.

Polymer matrix composites (PMCs) have been developed for automobile industry for car body or structural components. Also in aerospace industry are used for carbon fibre reinforced fuselages or stringers, wing and aerofoil or other components for airplanes, because the reinforcement tends to be stiffer and stronger than the matrix providing stiffness and strength. As the world becomes more energy efficient, PMCs are helping push the limits of aerospace technology with lighter, high strength, damage tolerant, lightweight, corrosion resistant, and of course lightweight and more durable materials. From structural components to interior materials, PMC provide lightweight strength and unmatched durability. The primary reason why polymer matrix composites are chosen for the manufacture of components is because of the weight reduction relative to their stiffness and strength (Almia-Gulfem, 2020).

Researches in science and engineering have described the current century as the cellulosic century due to the explosion in the discovery of increased number of resources from plants for the development of new materials (Chollakup *et al.,* 2023). Many researchers have studied different natural fibres while employing different testing methods, and different moisture conditions present which have led to different characteristics of natural fibres varying among the referenced works. The natural fibres could belong to animals, plants or minerals which are established upon their origin. Among these natural fibres, mineral fibres are deemed the strongest natural fibres known due to their lower number of surface defects formed during formation (Ramu *et al.,* 2019). Plants that are used to fabricate fibres are classified into primary and secondary plants which are usually on the basis of their specified usage. Primary plants are cultivated mainly for their fibres whereas the fibres are obtained from the waste product of the plants that make up the secondary plants. Plant cellulose fibres are categorized into; seed fibres, bast fibres, leaf fibres, fruit fibres, grass fibres and straw fibres Ramu *et al.,* (2019) which are listed with examples in Table 1

Table 1: Natural fibre types and natural particulates Jeyapragash *et al.,* (2020).

Types of fibre	Common name
Bast fibres	Flax fibre
	Kenaf fibre
	Roselle fibre
	Hemp fibre
	Ramie fibre
	Jute fibre
	Rattan fibre
Leaf fibres	Abaka
	Henequen
	Pineapple
Seed fibres	Banana fibre
	Kapok
Stalk fibres	Cotton
	Rice fibre
	Bamboo fibre
	Doum palm leaf stalk fibre
Fruit fibres	Mango fibre
	Tamarind
Stem fibres	Sisal fibre
	Crown
Particulates	Ground nut shell
	Sea shell
	Jack fruit
	Plaster of Paris

The inclusion of cellulose fibres in composite materials has however exhibited several drawbacks like lower mechanical properties, poor thermal stability, highly flammable and hydrophobicity (Senthilkumar *et al.,* 2018; Mochane *et al.,* 2019) the combination of cellulose fibres into a single matrix is now a common practice to overcome these drawbacks. The selection of the combination of the natural fibres to form composites is based upon the considered application with the aim of or

overcoming the limitation of the other natural fibre. The availability of the natural fibre is commonly dictated by the geography which is pivotal to the process of fibre selection. Studied have shown that improved performance is achieved in fibre with the highest cellulose content and having the fibre direction also in the same direction as the cellulose micro-fibrils, this characteristics in common with bast fibres (Rakes *et al.,* 2020). Natural fibre exhibits varying chemical and structural properties which are mainly influenced by the extraction methods, growing conditions, fibre treatment, harvesting time and the storage processes (Pickering *et al.,* 2016). Studies have shown that embedding natural fibres in polymer based matrices improves the specific strength and stiffness of the resulting composite (Gohal *et al.,* 2020). Generally the characteristics of cellulose based fibre composites are a function of the composition, fibre length, fiber diameter, orientation, shape and distribution coupled with the volume fraction (Gohal *et al.,* 2020).

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The mechanical characteristics of natural fibres as shown in Table 2 highlights the mechanical properties of various natural fibers, emphasizing those with high tensile strength and low density for lightweight applications. Hemp stands out with a tensile strength of 550–1110 MPa and a density of 1.5 g/cm³, offering excellent

specific tensile strength (370–740 MPa/g cm³), making it ideal for structural use. Silk combines low density (1.3 g/cm³) with a tensile strength range of 100–1500 MPa, providing versatility. Feather fibres, the lightest (0.9 g/cm³), are suited for ultra-lightweight applications, though with lower tensile strength (100–203 MPa). Flax also offers high stiffness (up to 80 GPa), while coir and alfa are better for non-load-bearing or insulation purposes. These properties make fibres like hemp and silk optimal for strength-to-weight-sensitive industries, such as aerospace and automotive (Gohal *et al.,* 2020).

Table 2: Mechanical characteristics of selected natural fibres Gohal *et al.,* (2020).

Fibre	Density (g/cm^3)	Length (mm)	Failure strain (%)	Tensile strength (MPa)	Stiffness/Young's modulus (GPa)	Specific tensile strength ($MPa/g\ cm^{-3}$)	Specific Young's modulus ($GPa/g\ cm^{-3}$)
Ramie	1.5	900–1200	2.0–3.8	400–938	44–128	270–620	29–85
Flax	1.5	5–900	1.2–3.2	345–1830	27–80	230–1220	18–53
Hemp	1.5	5–55	1.6	550–1110	58–70	370–740	39–47
Ramie	1.5	900–1200	2.0–3.8	400–938	44–128	270–620	29–85
Flax	1.5	5–900	1.2–3.2	345–1830	27–80	230–1220	18–53
Hemp	1.5	5–55	1.6	550–1110	58–70	370–740	39–47
Alfa	1.4	350	1.5–2.4	188–308	18–25	134–220	13–18
Cotton	1.5–1.6	10–60	3.0–10	287–800	5.5–13	190–530	3.7–8.4
Coir	1.2	20–150	15–30	131–220	4–6	110–180	3.3–5
Silk-	1.3	Continuous	15–60	100–1500	5–25	100–1500	4–20
Feather	0.9	10–30	6.9	100–203	3–10	112–226	3.3–11

Mittal *et al.,* (2016) studied the characteristics of cellulose based fibre composites embedded in a polymer matrix by analysing the effect of fibre loading. Based on their observations, the mechanical properties of natural fibre based composites in a polymer matrix can be improved by increasing the cellulose content. Gohal *et al.,* (2020) studied the addition of red mud filler content on the mechanical properties of epoxy matrix composite reinforced with bamboo fibre and has since compared the resulting properties with those of glass/epoxy composites. However the strength of the bamboo fibre composite is less when compared to the epoxy matrix composite reinforced with glass fibre while the wear characteristics are improved.

Rakes *et al.,* (2020) studied the effect of lignin on the mechanical characteristics of epoxy matrix composite reinforced with hemp fibre. An improvement of 145% was obtained for the impact strength with the incorporation of 5% w/w lignin while the flexural modulus and elastic modulus increased with an increase in the weight of lignin up to 2.5% w/w. They have further observed that increasing the amount of lignin above 2.5% w/w decreased the flexural modulus and modulus of elasticity, which can be caused by unfavourable mixing due to elevated viscosity.

Mechanical Properties of Natural Fibre Reinforced Polymer Composites

Natural fibre reinforced polymer composites (NFRPCs) are gaining prominence due to their environmentally friendly, cost-effective, and lightweight properties. These composites consist of natural fibres (such as hemp, flax, sisal, jute, coir, and kenaf) embedded in polymer matrices (typically thermosetting or thermoplastic resins). The mechanical properties of NFRPCs, such as **tensile strength, flexural strength, impact resistance, and stiffness (Young's modulus),** are influenced by the fibre type, orientation, volume fraction, and compatibility with the matrix (Yuan *et al.,* 2017).

The mechanical behaviour of a fibre-reinforced composite depends on several factors, which can include fibre modulus, strength, matrix strength, chemical stability, and interface bonding of fibre/matrix for active stress transfer (Gohal *et al.,* 2020). Mechanical and physical properties of natural fibres are dependent on cellulose amount (proportionately influencing tensile strength), lignin amount (proportionately have effects on hard- ness), fibre's angle of helix axis (adversely impacting tensile strength), and the amounts of hemicelluloses, waxes, water content, pectin, and the elementary cell geometry (Abral *et al.,* 2020: Mueller *et al.,* 2024).

The type of fibres can significantly affect the performance of natural fibre composites NFCs. For instance, base fibres have high flexural strength and leaf fibres have very good impact properties (Al-Mosawi, 2022).Therefore, in order to achieve the best results, it is very crucial to understand the shapes and properties of fibres (Lee *et al.,* 2019).

Determination of Compressive Strength Properties

The process of compressive strength testing in composite materials involves subjecting a specimen of the material to a compressive load until it fails or deforms plastically. The specimen is a cylinder or rectangular prism with a specific length, width, and thickness. The compressive force is applied to the specimen using hydraulic press or a universal testing machine. The force is applied at a specific rate, usually between1 and 10mm/min, until the specimen fails or deforms plastically (Tawfeeq *et al.,* 2018).

According to Hany *et al.,* (2017), compression strength of the composite sample $C_1$is based on carbon fibre/epoxy resin and the second composite sample C_2 is based on carbon fibre/phenolformaldhyde resin, specimens were prepared according to ASTM D3410 with dimensions [10mm ×10 mm 20mm] was tested on RT30 Electro-mechanical Alliance test system with 30KN axial load applied to measure the compression strength in both axial and radial directions. The results showed that, the axial compression strength of C_1 is higher than that of C_2 by 14.5%. The radial compression strength of C_1 is nearly the same as that of C_2.

Determination of Tensile Strength Properties

According to Hany *et al.,* (2017), the tensile strength test is the maximum stress that a material can withstand while being stretched or pulled before breaking. The tensile strength is usually found by performing a tensile test and recording the engineering stress versus strain. According to Adamu and Baba (2021), the test specimen was prepared in the form of dumbbell- shape with dimensions (165 × 19 × 3) mm, and a gauge length of (50) mm. A crosshead speed of 5mm/min was chosen and prepared according to the ASTM D 638 standard. The specimen was subjected to tensile test using the universal testing machine. The tensile force was recorded as a function of the increase in gauge length.

Synthetic or natural fibres have significantly higher tensile strength compared to polymers. As a result, the tensile strength of polymer composites reinforced with fibres is much higher than polymer. Accordingly, the composite strength increases with increasing fibre content (Ashrafi *et al.,* 2018). However, in some cases, the composites' strength does not follow this rule (Abral *et al.,* 2020: Mueller *et al.,* 2024).

A similar level of the tensile strength at some low strength level can be obtained for reinforced composite with glass fibre and natural fibre reinforced composites NFRPCs. However, the amount of reinforcement rendering the same tensile strength is different. For instance, the required content for glass fibre is 12 wt. %, and for aspen, kenaf, abaca, and pineapple fibre is 38wt. %, 35wt. %, and 15wt. %, respectively. Accordingly, there are limitations for obtaining the required tensile strength as there are limitations in the content of natural fibres in the composition. However, some studies show different results (Abral *et al.,* 2020). For example, a study by Müller *et al.* (2024) showed that composites with almost the same tensile strength can be obtained using glass or flax fibres. The results of their study showed that by the incorporation of 30wt% glass fibres and 33wt% linen fibres, a tensile strength of 28 MPa can be achieved. Because NFRPCs are much lighter than SFRPCs, therefore, the SFRPCs' specific gravity is more than that of NFRPCs. As a result, NFRPCs can be a better choice over SFRPCs when considering the weight and lightness of the final material. However, their mechanical strength is much lower than SFRPCs (Corbière-Nicollier *et al.,* 2018; Al-Mosawi, 2022).

Determination of Ultimate Tensile Strength Properties (UTS), Young Modulus (E), and Percentage Elongation (EL)

According to Adamu and Baba (2021), ultimate tensile strength is to evaluate a material's capacity to withstand stretching forces before breaking, whereas elongation at break evaluates a materials ability to plastically deform before fracturing. Materials with a lower tensile strength typically have a higher elongation reported that production of the composites was carried out by the conventional hand lay-up technique and young modulus is the ability of material to withstand changes in length when under lengthwise tension or compression. Composites of the same composition of (Polymer 60wt % and fibre 40wt %) with four layers and four different fiber-laygeometries were prepared in the form of dumbbell shape with dimensions (165×19×3) mm, with gauge length (100) mm. A crosshead speed of 5mm/min was chosen and specimen was prepared according to the ASTM D638 standard. The testing process involves placing in testing machine and applying load until fracture. The tensile force was recorded as a

function of the increase in gauge length. Ultimate tensile strength (UTS), Young's modulus (E), and percentage of elongation (EL) were computed using Equations (1), (2), and (3), respectively.

The ultimate tensile strength of the specimen was calculated using Equation 1.

$$\sigma = \frac{p}{b \times d} \quad \ldots (1)$$

Where; σ is ultimate tensile strength, p is the load at the break, b is the initial width of the sample, and d is the initial thickness of the sample. The young modulus of the composite was calculated using Equation (2). Ultimate tensile strength the results obtained showed that the tensile strength of the composites decreases with an increase in fibre-laygeometry from 0^0 to 90^0 orientations. Therefore, the tensile strength of the developed composite significantly decreases with an increase in fibre-laygeometry from 0^0 to 90^0 (Onadck *et al.,* 2018 & Biswas *et al.,* 2011).

$$\mathrm{E} = \frac{\delta}{\varepsilon} \quad \ldots (2)$$

Where; E is the tensile modulus, σ is ultimate tensile strength, and ε is the strain of the sample.

The percentage elongation of the composite was calculated using Equation (3).

$$EL = \frac{e}{l} \times 100\% \quad \ldots (3)$$

Where EL; is the percentage elongation of the specimen, e is elongation at failure of the specimen, and l is the initial gauge length of the specimen. The percentage elongation of the developed composite was optimum at $[0/0/0/0]^0$ orientations and significantly decreases with increase in angle of orientation. The Young's modulus, from results it was found to increase with increase in fibre lay-geometry from 0^0 to 90^0 orientations even though some fluctuations were observed in between. The maximum tensile modulus obtained was for composites with $[90/90/90/90]^0$ orientation (Amuthakkannan *et al.,* 2019 & Onadick *et al.,* 2018).

It is known from the research that the modulus of natural fibre de- creases with an increase in its diameter. The influence of fibre loading on mechanical characteristics is of paramount importance to studies. Joseph *et al.,* (2022) made matrix ductile by adding fibres. They indicated that Young's modulus and tensile strength were enhanced by increasing fibre loading for a composite of banana/phenol formaldehyde (PF). Lee *et al.,* (2019) evaluated natural fibre of jute and kenaf reinforced polypropylene compositions with fibre weight fraction changing from 10% to 70% in the step of 10%. It was found that the modulus and tensile strength of both jute and kenaf fibre reinforced compositions were enhanced by growing fibre loading so that the maximum value was achieved before falling back at higher fibre weight fraction.

The Young's modulus and mechanical and physical properties of sisal fibre are compared to other synthetic and natural fibres; sisal fibres' specific strength and modulus are at the level of glass fibres. Fibre orientation, weight (wt %), length, and volume fraction (V_f) are all factors affecting the mechanical and physical properties of sisal fibres-reinforced polymer composites. Sisal fibres come in many forms, some of which are: short randomly oriented, unidirectional fibres, weave (mat, twill, and plain it is known from the research that the modulus of natural fibre de- creases with an increase in its diameter. The influence of fibre loading on mechanical characteristics is of paramount importance to studies. Joseph *et al.,* (2022) made matrix ductile by adding fibres. They indicated that Young's modulus and tensile strength were enhanced by increasing fibre loading for a composite of banana/phenol formaldehyde (PF). Lee *et al.,* (2019) evaluated natural fibre of jute and kenaf reinforced polypropyl- ene compositions with fibre weight fraction changing from 10% to 70% in the step of 10%. It was found that the modulus and tensile strength of both jute and kenaf fibre reinforced compositions were enhanced by growing fibre loading so that the maximum value was achieved before falling back at higher fibre weight fraction.

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many forms, some of which are: short randomly orient- ed, unidirectional fibers, weave (mat, twill, and plain forms), and varied orientations (0-, 90-, and 45-degree plies, etc.). The tensile strength of sisal-epoxy composites is half of the glass-epoxy composites and their specific strength is comparable to reinforced-polymer composites with glass fibres. In addition, the tensile modulus of the reinforced epoxy composites with unidirectional sisal fibre is equal to 8.5 GPa. Thus, due to the properties of sisal fibre-based polymer composites, developed engineering structures, high-quality consumer goods, as well as, affordable housing can be built (Mueller 2024). Lee *et al.,* (2019) studied the mechanical properties of reinforced polyester composites with chopped sisal fibre. The fabrication of the composites was conducted by hand lay-up method.

Araujo *et al.,* (2016) studied the mechanical behaviour of reinforced poly- ester matrix composites with virgin/waste GF at different fibre weight content of 20, 30, 40, 50, and 60%. The reinforced-polyester composite with virgin GF possessed a higher modulus and tensile strength at 40% w%. Iba *et al.,* (2022) studied the mechanical characteristics of reinforced epoxy composites with fibre volume fraction from 0.25 to 0.45, and three diameters of fibres (18, 37, 50 mm). Careful examination of the curve shows that the tensile strength and longitudinal Young's modulus of the composites increase with enhancing fibre volume fraction and the average strength increases with increasing fibre diameter. Godara *et al.,* (2023) surveyed the expandable behaviour of epoxy composite reinforced with various orientations of GF woven fibres, e,g, 45 and 0/90. The stress-strain curve showed the strong dependency of the tensile strength on the alignment of the fibres to the external load, in which 0/90 laminate composites showed low strain failure (1.65%), the highest failure strength (355MPa), and low ductility 45.epoxy composites is half of the glass-epoxy composites and their specific strength is comparable to reinforced-polymer composites with glass fibres. In addition, the tensile modulus of the reinforced epoxy composites with unidirectional sisal fibre is equal to 8.5 GPa.

Determination of Flexural Strength Properties

According to Hany *et al.,* (2017), flexural strength, is also known as modulus of rupture, or bend strength, or transverse rupture strength is a material property;

define as the stress in material just before it yields in a flexure test. The transverse bending test is most frequently employed, in which a specimen having either a circular or rectangular cross-section is bent until fracture or yielding using a three-point flexural test technique. The flexural strength represents the highest stress experienced within the material at its moment yield. It is measured in terms of stress showed in Equation (4).

Adamu and Baba (2021), reported that, flexural strength was measured under a three-point bending approach. The specimen was prepared and performed in accordance with ASTM D790 (Aboshora *et al.,* 2017). Rectangular specimens of dimensions (125 × 12.7 × 3.2) mm was prepared and subjected to a load on the universal testing machine with a support span length of 100mm with a speed of 5mm/min. The modulus of rupture (MOR) was computed at this point using Equation (4).

$$\sigma fm = \frac{3\text{pl}}{2\text{bd2}} \quad \ldots (4)$$

Where; is flexural strength, p is the load at the break, l is the support span, b is the width of the sample, and d is the depth or thickness of the sample. Results showed that, the flexural strength increases with an increase in fibre orientations from 0^0 to 90^0. The highest impact strength (12.97 kJ/m^2) was obtained at $[0/0/0/0]^0$ orientation (Ondiek *et al.,* 2018 & Alam *et al.,* 2019).

In recent years, the focus of some research has been on the fibre-reinforced composite materials' flexural strength (Oskoue, 2018). For instance, Aramid *et al.,* (2022) investigated the mechanical characteristics of GF-rein- forced polyunsaturated composite with various fibres volume fractions (5, 10, 15, 20, 25, and 30%). According to the results of their study, flexural strength increased with the increment of GF volume fraction, and also the maximum flexural properties were observed at GF with a 30% volume fraction. Husic *et al.,* (2021) also studied the mechanical behaviour of reinforced polyurethane composites with untreated E-glass for two polyurethanes such as petrochemical polyol Jeffol and soypolyol resin. According to the results of their study, the composite based on petrochemical polyol Jeffol showed higher shear, tensile, and flexural strength between layers compared to soypolyol-based composites. This is because crosslinking densities

are low in soypolyol-based composites and there are side-hanging chains in their matrix, the inter- layer shear strength is the same for both resin composites. Some studies have examined the flexural characteristics of reinforced polyester matrix composites with E-GF by adding different carbon nano filler (CNF) weight percentages. Hossain *et al.,* (2023) According to the results of this study and by examining the stress-strain curve, the maximum mechanical properties were obtained in 0.2% by weight of CNF-filled composite. This was owing to the enhancement in compressive strength and modulus, further interfacial interaction, and high dispersion among matrix and fibre **(**Leila and Milad 2021; Tawfeeq *et al.,* 2018).

Determination of Impact Strength Properties

Adamu and Baba (2021), impact strength is the measure of the ability of a material to resist cracking, fracturing, or plastic deformation under sudden and intense impact, or shock loads. It is a critical property that determines the material's ability to withstand sudden forces. The production of the composites was carried out by the conventional hand lay-up technique. Composites of the same composition of (Polymer 60wt % and fibre 40wt %) with four layers and four different fiber-laygeometries were prepared. The impact strength was conducted according to ASTM standard D256 using the Charpy V-notch impact testing machine (Abshora *et al.,* 2017). The specimen dimensions were (63.5 × 12.7 × 12.7) mm. The specimen was placed between a special holder with the notch oriented vertically and towards the origin of impact. The specimen was struck by a "tup" attached to a swinging pendulum. The specimen breaks at its notched cross-section upon impact, and the upward swing of the pendulum was used to determine the amount of energy absorbed in the process. The impact strength was calculated using Equation (5).

$$\text{Impact strength} = \frac{E}{A}\ (\text{J/m}^2) \qquad \ldots (5)$$

Where; E is the energy absorbed (J), and A is the area of the specimen. Impact Strength, the impact energy values of the composites developed with different lay geometry were recorded during the impact tests.

Determination of Hardness Strength Properties

Material hardness is the ability of a material to withstand force without deformation, hardness was measure mostly commonly used are the Brinell test, the Vicker's Diamond test, and the Rockwell test. All the three methods involve indentation of the material. The hardness is calculated by measuring the force applied and comparing this to some geometrical aspect of the indentation such as the surface area or depth (Abshora *et al.,* 2017).

Adamu and Baba (2021) reported that, hardness strength was conducted according to ASTM D2240 using a Rockwell hardness testing machine. The specimen dimensions of (25×25×10) mm. The production of the composites was carried out by the conventional hand lay-up technique. Fibre to matrix ratio of (Polymer 60wt % and fibre 40wt %) was prepared for testing. The test was performed by gradual pressing of a presser foot of diamond-tipped indenter, which penetrates to a certain depth on the specimen (Onadick *et al.,* 2018). The hardness value depends on the depth to which the indenter penetrated the specimen. Results shown that, there was no much variation in hardness of the composites with respect to fibre orientation, and composites with cross-linked fibre-lay geometry of $[0/90]^o$ $[+45/-45]^o$, and $[+30/-30]^o$ exhibit higher hardness compared to composite with unilateral 0^o and 90^o orientations (Janaki, 2016).

Application of Composites in the Aerospace industry

Today's aerospace industry relies heavily on non-renewable and synthetic resources for its basic materials. Carbon fibre composites and metals like fiberglass, titanium, and aluminium are used to make various air- craft parts. Both Boeing 787 Dreamliner and Airbus 350 XWB aircraft have employed composite materials to build their stabilizers, wings, turbine housing, and bodies. The use of composites in the fuselage will result in a reduction in overall weight, as well as an increase in durability, reduced noise, and improved passenger comfort. Due to their ease of production in complex geometries, acceptable hardness, and excellent specific strength, composite materials are employed in the aviation sector to create and produce low-weight structural designs. Using composite materials in aerospace has resulted in airplanes with lower fuel consumption in recent years. Composite materials are commonly utilized in aircraft cabin interiors because of their excellent strength and durability. Wall panels, roof, toilets, chairs, flooring, and cabin partitions as well as storage bins and galleys are all made with these materials. Increased strength and reduced weight can be achieved through the use of composite materials in mechanical designs. Composite materials make up 25% of

the weight of Airbus 380 passenger jets and 50% of the weight of Boeing 787s. As a result of Boeing's weight decrease, fuel consumption has been reduced by 20%. This has helped to alleviate the energy crisis and reduce air pollution (Arifurrahman *et al.,* 2018)

Manoeuvrability, cargo capacity, and fuel efficiency have all improved because of the lightweight and great mechanical strength of these materials. American Airlines Fleet is a good case in point. By lowering the weight of each aircraft by one pound, the business has saved around 11,000 gallons of fuel. Boeing's B-787 Dreamliner is another example. In the aerospace business, it is recognized as a leader because of the air- craft's superior materials and construction. Compared to similar aircraft, the fuselage's weight has been decreased by 50% due to the use of composite materials in many of its components. On this aircraft, that equates to an 80 percent reduction in PMC. Carbon fiber reinforced sandwich sheets are used on the Boeing B-787 Dreamliner. A limited number of aircraft components, simple-to-produce complicated structural shapes, low operating cost, high rigidity, and high strength are some of the ad- vantages of this construction. It also has good corrosion resistance and a short assembly time. Additionally, Hexcel's HexMC epoxy carbon composite is utilized in the Boeing 787. (USA). Mechanical strength and stiffness, as well as the ability to make sandwiches of various forms, make this aircraft a viable choice for transport. There are many brackets, fittings, and window frames in Dreamliner that use HexMC as an example of HexMC in the design (Chauhan *et al.,* 2019).

Aerofoil Application using Composites

Composites are ideal for aerofoil applications due to their lightweight, high strength-to-weight ratio, and superior fatigue and corrosion resistance. They enable significant weight reduction, improving fuel efficiency and aerodynamic performance. Natural fibre composites, such as Doum palm leaf reinforced with epoxy resin, are emerging as sustainable and cost-effective alternatives to synthetic materials like carbon fibre for less demanding applications. These composites offer tailored mechanical properties, including high tensile strength and stiffness, and allow for complex aerofoil designs. On-going research and prototype testing demonstrate their potential to combine performance, environmental benefits, and affordability in aerospace innovations (Chauhan *et al.,* 2019).

Conclusion

In this review, recent investigations on natural fibre-reinforced polymers (NFRPs) and synthetic composites, with a close focus on their mechanical properties, have

been discussed to evaluate their application in aerofoil design. Fibre materials are widely used in transportation due to their relatively high Young's modulus. Additionally, composites made of carbon fibres and polymers are both impact-resistant and lightweight. Their excellent corrosion resistance makes them suitable for marine and aerospace applications. In the aviation industry, composites are favoured for their fuel efficiency and superior strength. NFRP composites are among the latest innovations, offering a viable and sustainable alternative to carbon and glass fibres. Filler materials have been extensively developed to enhance the mechanical properties of cellulose fibre-reinforced composites. Based on this review, natural fibre composites with filler content achieve acceptable mechanical properties and have significant potential to replace synthetic fibres due to their lower density. However, limited research has explored the use of filler content combined with more than one natural fibre embedded in a matrix to form hybrid composites. All reported natural fibre hybrids with fillers demonstrated improved mechanical properties. Therefore, further research is recommended to explore the full potential of filler-natural fibre materials, such as Calcium Sulphate Hemihydrate ($CaSO_4 \cdot ½H_2O$) and Doum leaf stalk composites, for applications in aerospace and engineering fields due to their enhanced performance.

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