

Mechanical Behaviour and Water Absorption Properties Investigation of Hybrid Natural Fiber Reinforced Composites

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ABSTRACT

The present world scenario demands for the utilization of natural fiber-reinforced polymeric composites as opposed to synthetic fiber-reinforced composites mainly due to their environmental friendly behavior, availability in abundance, cost-effectiveness, and lightweight and moderately high-strength properties. Along with the above said advantages, the ease of manufacturing of natural fibers has made the researchers around the globe to exploit several locally available natural fibers to understand their feasibility as reinforcement phases in different polymeric composites and their suitability in various commercial and engineering applications. From the research concluded the more areca fiber and silicon carbide percentage of exhibits the maximum Tensile, compressive load, hardness & Impact load and maximum percentage of water absorption. The Maximum flexural strength and medium water absorption rate exhibits the medium areca and pineapple fiber and medium silicon carbide in the natural fiber composites.

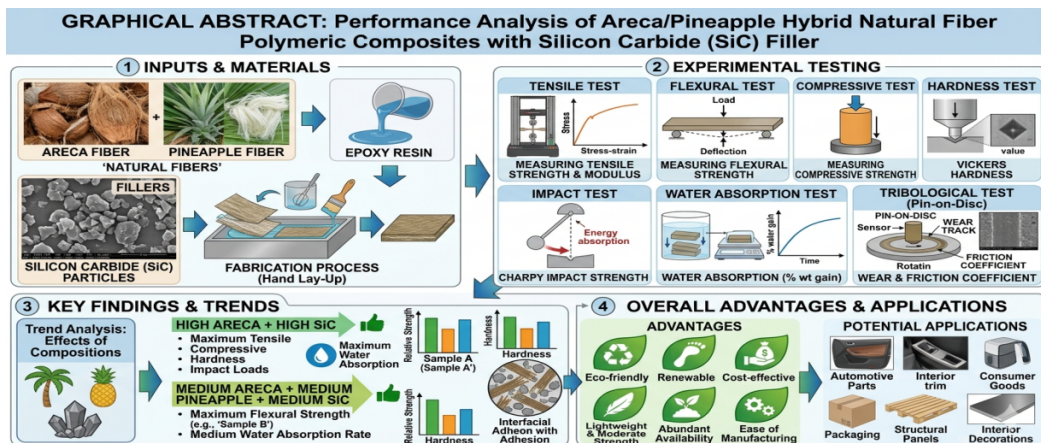
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GRAPHICAL ABSTRACT



HIGHLIGHTS

- Strength Optimization through Hybrid Loading
- The Water Absorption Trade-off
- Flexural Performance and Fiber Blending

1. INTRODUCTION

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In the quest for improved performance defined by reduced weight, more strength, and lower cost, traditional materials frequently reach the limit of their utility. This has led to the rise of composites, which are material systems consisting of a combination of two or more distinctly differing materials—a reinforcing phase and a matrix phase—that are insoluble in each other. Over the last thirty

years, these materials have moved from niche aerospace applications into the broader transportation and building sectors. In India, there is a specific focus on natural fiber composites using materials like Bamboo, Jute, and Coir, which serve as sustainable wood substitutes and help prevent the depletion of forest resources while supporting the rural economy.

A composite material is essentially designed to exploit the useful properties of its constituents while minimizing their flaws. For example, glass-fiber reinforced plastic (GRP) combines strong but brittle glass fibers with flexible plastic to create a tough, resilient material. The matrix acts as a binder that protects the fibers from environmental damage and transfers applied loads through shear stress, while the fibers provide the necessary stiffness and strength to resist cracks. This relationship is often governed by the principle that "smaller is stronger," as high-stiffness fibers are manufactured in small diameters to minimize internal flaws typically found in bulk materials.

However, composites face specific mechanical challenges such as punching, which is localized damage from a concentrated force, and buckling. These are managed by optimizing fiber orientation within the matrix. The constituents of these systems often include coupling agents to improve bonding and fillers like calcium carbonate to reduce cost and improve dimensional stability. The fibers themselves, occupying the largest volume fraction, are the primary load-bearing elements, while the polymeric matrix—either thermoplastic (reshapable by heat) or thermoset (chemically cross-linked and heat-stable)—determines the material's thermal stability and chemical resistance.

Within the realm of resins, polyesters are common due to low cost, while epoxies are used for high-performance aerospace needs because of their superior covalent bonding and cross-linking. Vinyl esters offer a middle ground with better water resistance than polyesters. For high-temperature environments, phenolic resins are preferred for their fire resistance and low toxic gas emission. Beyond polymers, composites can also feature metal or ceramic matrices. Ceramic Matrix Composites (CMCs) are particularly valued in aerospace turbine blades and high-performance automotive brakes for their ability to withstand extreme heat, though they remain expensive to manufacture through processes like chemical vapor infiltration.

The focus is increasingly shifting toward "green composites," where natural plant fibers like flax, hemp, ramie, and jute are used as reinforcements. These fibers are comprised of crystalline cellulose microfibrils embedded in a lignin or hemicellulose matrix. While they offer high specific strength and low density, they are hygroscopic, meaning they absorb moisture which can lead to swelling and biological decay if not treated. Despite these challenges, natural fibers are a renewable resource with a low carbon footprint. Truly green

composites utilize these fibers within a bio-polymer matrix, ensuring that the CO₂ released during end-of-life incineration equals the amount consumed by the crop during growth, achieving a neutral impact on global warming.

The mechanical performance of these composites is heavily influenced by fiber selection, aspect ratio, and manufacturing processes. Bast fibers like flax and hemp generally offer the highest stiffness because their microfibrils are aligned with the fiber direction. While their absolute strength and stiffness are lower than synthetic E-glass, their specific properties (property divided by density) are highly competitive. By carefully balancing fiber dispersion, orientation, and interfacial strength, engineers can create sustainable, lightweight materials that meet the rigorous requirements of modern industrial and domestic applications.

2. THE OBJECTIVES OF THE PRESENT WORK:

Fabrication of Epoxy resin-based hybrid composites reinforced with various fibers such as areca and pine apple fibers with various ratio percentages. Evaluate the mechanical properties like that tensile, Flexural compressive and Hardness. Evaluate the Water absorption characteristics. To identify the applications of hybrid composite developed and implementation.

2.1. Pine Apple Fiber

Pineapple leaf fibers represent a biodegradable raw material sourced from renewable resources whose use contributes to reducing the carbon footprint and limiting the amount of waste generated. Their potential applications can effectively decrease the industry's dependence on plastics and support sustainable development, which should accompany the production of modern materials. Pineapple leaf fiber (PALF), an undervalued byproduct of pineapple cultivation, has gained attention for its renewable, cost-effective, and biodegradable properties. Despite being a waste material, PALF has potential as a reinforcement agent in composite materials, particularly in replacing pure resin to improve mechanical properties. PALF has diverse applications in textiles, cosmetics, medicine, and biopolymer coatings, and further research could unlock its potential for use in other products. However, challenges such as improving PALFs' compatibility with polymer matrices remain to be addressed. One of the main drawbacks of PALF is that, particularly at high temperatures, its hydrophilic nature makes it challenging to bond with hydrophobic materials. Chemical treatments such as sodium hydroxide treatment onto dewaxed PALF improve the adhesion between PALF and polymer. One example of a green composite is a bioplastic reinforced with natural fibers that is readily broken down by bacteria and enzymes.

2.2. Areca Fiber

Areca fiber is chiefly obtained from the fruit areca, frond, and stalk leaf. The world today is facing the problem of growing new and propelled innovations and methods to eliminate or utilize solid wastes, particularly with

polymers that are non-reversible in nature. The methods adopted in splitting up the wastes do not seem economical and tend to generate chemicals that prove harmful. Taking into account these factors, reinforcing polymers using natural fibers seems the only option that could result in solving the issue. Regular strands are easily available and reusable, have less thickness, and are ecofriendly. They possess high tensile properties and can be used to substitute the customary strands. The strong demerit of using characteristic strands for strengthening plastics is the contrariness, causing weak bondage between normal filaments and lattice gums and thus leading to low pliable characteristics. A number of theories and surface modification methods have been evolved to improve fiber-network interfacial holding and enhance malleable characteristics of the composites. Further, it is proved that the loading of fiber mainly influences the strength and stiffness of the natural fiber polymer composites. Up to a particular extent, there is a rise in mechanical properties with increasing fiber weight ratio. In order to evaluate the tensile properties of natural fiber reinforced composites, mathematical models/finite element models are being adopted as a necessity.

2.3. Thermal properties of areca fiber

In the design of natural fiber composites, thermal stability is considered crucial. It can decide the selection of compatible processing techniques for fibers and composites. Hence, thermal properties act as a guideline during the entire design process and prevent the temperature from rising above the degradation temperature of the fiber, since it could decrease the performance of the fibers and the composites. The fiber is found to be thermally stable up to 230°C, as evinced by lack of weight loss after the minor loss caused by moisture evaporation. Beyond this point, there is occurrence of polymerization and degradation processes of hemicelluloses and cellulose up to 330°C. Analysis of the DTG curve shows small peaks at 273.4 and 325.8°C and reveals the pyrolysis, decomposition, and degradation of hemicelluloses and cellulose. It is found that the kinetic activation energy for areca fibers falls in the range set for natural materials.

The value is indicative of areca fibers possessing excellent thermal stability, which permits it to undergo the polymerization process in the production of composites. At a temperature of about 325°C, the burning of fiber has been evinced, which a reasonably high temperature for polymer is processing to manufacture composites.

3. MECHANICAL PROPERTIES OF ARCA FIBER

Single fiber tensile testing has been used to evaluate the mechanical properties and provide some basic information necessary for the design of the potential use of plant fibers. Areca fibers have been compared with coir and palm leaf fibers with regard to the mechanical properties, particularly tensile strength. This could be attributed to its high crystallinity index and spiral angle. Considering application in reinforcement, the greater strain and low modulus of areca husk fiber offer superior toughness. The results indicate that areca fiber can substitute reinforced

polymer composites, similar to other representatives from the family of Palmae/Arecaceae. On the other hand, chemical modification also determines the mechanical properties of the fiber. The untreated and alkali-treated fibers in selected concentration and weight have been characterized, and the changes undergone by the removal or minimization of non-cellulose components, like hemicellulose, lignin, and wax pectin, and other impurities from the fiber surface have been described. The modification results in surface roughness and fibrillation due to the exclusion of cementing materials that lead to improved mechanical properties of the fiber reinforced composite. 5% alkali-treated fiber has been found to exhibit the greatest tensile strength and modulus based on tensile characterization of untreated and treated areca leaf stalk fibers. This could be attributed to the disruption of hydrogen bonds in the fiber network. But a reduction in tensile strength has been observed with a rise in alkali concentration above the optimum. The tensile strength of individual fibers has been enabled by the increase in the pores and pits on the surface of fibers. Also, benzylation treatment is found to yield better tensile properties in comparison with the alkali-treated and untreated short areca sheath fibers. The FTIR studies reveal that the absorption of alkali and benzylation treatments have decreased the (–OH) groups compared to in the case of the untreated fiber, due to the removal of hemicelluloses. Further, the presence of phenyl nucleus has been noticed, while the C–H deformation from lignin confirmed its removal, and the aromatic ring associated with the C–O bond demonstrated the removal of hemicellulose and pectin.

3.1. Silicon carbide

Silicon carbide (SiC), also known as carborundum is a compound of silicon and carbon with chemical formula SiC. It occurs in nature as the extremely rare mineral moissanite. Silicon carbide powder has been mass-produced since 1893 for use as an abrasive. Grains of silicon carbide can be bonded together by sintering to form very hard ceramics which are widely used in applications requiring high endurance, such as car brakes, car clutches and ceramic plates in bulletproof vests. Electronic applications of silicon carbide as light emitting diodes (LEDs) and detectors in early radios were first demonstrated around 1907 and today SiC is widely used in high-temperature/high-voltage semiconductor electronics. Large single crystals of silicon carbide can be grown by the Lely method; they can be cut into gems known as synthetic moissanite. Silicon carbide with high surface area can be produced from SiO₂ contained in plant material

3.2. Epoxyresin

Polymers generally act as a good binder for fibers as observed from several references. Their carry availability coupled with their lower cost has provoked the selection of polymer as the binder for these fibers. Unsaturated polyester offers the advantage of easy mold ability, better handling, and better flow properties. Easy fabrication and

better mixing of polyester provoke their usage. They have a low density of 2.02g/cc adding to our main objective of fabricating a low weight composite.

Epoxy resins, also known as poly epoxies, are a class of reactive polymer high mechanical properties, temperature,

and chemical resistance. Epoxy has a wide range of applications, including metal coatings, use in electronics/ electrical components, high tension electrical insulators, fiber-reinforced plastic materials and structural adhesives.

Table 1: Properties of major SiC polytypes

Polytype	3C (β)	4H	6H (α)
Crystal structure	Zinc blende (cubic)	Hexagonal	Hexagonal
Space group	T^2_d-F43m	$C^4_{6v}-P6_3mc$	$C^4_{6v}-P6_3mc$
Pearson symbol	cF8	hP8	hP12
Density (g/cm^3)	3.21	3.21	3.21
Bulk modulus (GPa)	250	220	220
Thermal conductivity ($W\ cm^{-1}K^{-1}$) @ 300K (see [28] for temp. dependence)	3.6	3.7	4.9

4. MECHANICAL TEST

There are three types of tests used with accuracy by the metals industry; they are the Brinell hardness test, the Rockwell hardness test, and the Vickers hardness test. Since the definitions of metallurgic ultimate strength and hardness are rather similar, it can generally be assumed that a strong metal is also a hard metal. The way the three

of these hardness tests measure a metal's hardness is to determine the metal's resistance to the penetration of a non-deformable ball or cone. The tests determine the depth which such a ball or cone will sink into the metal, under a given load, within a specific period. The followings are the most common hardness test methods used in today's technology



Figure 1: Shore-D Hardness Test

The Shore D Hardness test is also called Durometer Hardness Test. The letter "D" symbolizes the type of durometer used to measure the hardness of a material. It is a dimensionless quantity. It goes between 0 and 100. The higher number of hardness represents the harder

material. Durometer is the tool used to measure Shore D hardness. The hardness is determined by the penetration of the Durometer indenter foot into the sample under a defined spring force. The hardness value is read directly from the durometer scale

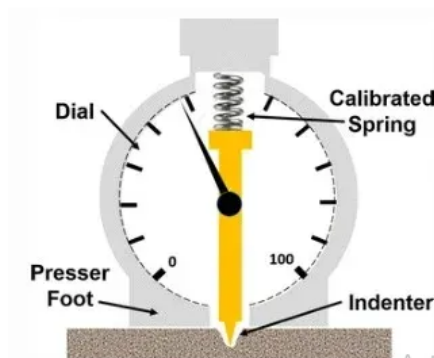


Figure 2: Nomenclatures of Shore D-Hardness test

5. IMPACT TEST

Izod impact strength testing is an ASTM standard method of determining impact strength. A notched sample is generally used to determine impact strength. Impact is a very important phenomenon in governing the life of a structure. In the case of aircraft, impact can take place by the bird hitting the plane while it is cruising, during take-off and landing there is impact by the debris present on the runway an arm held at a specific height (constant potential energy) is released. The arm hits the sample and breaks it. From the energy absorbed by the sample, its impact strength is determined. The North American standard for Izod Impact testing is ASTM D256. The results are expressed in energy lost per unit of thickness (such as ft-lb/in or J/cm) at the notch. Alternatively, the results may be reported as energy lost per unit cross-sectional area at the notch (J/m² or ft-lb/in²). In Europe, ISO 180 methods are used and results are based only on the cross-sectional area at the notch (J/m²). The dimensions of a standard specimen for ASTM D256 are 65 x13x3. The figure:4.2 shows low energy impact testing machine and all the ratio and impact testing specimens were evaluated with the help of this machine.

5.1 Tensile Test & Comprssion Test

Tensile strength is the measure of strength of material against an axial pull. Determination of tensile strength is vital for any material because, it is the primary load to be satisfied by the material when applicable in a structural member. In this investigation, the tensile strength & compressive strength of composites was tested in universal testing machine of model INSTRON 3369. The test was conducted according to the standard ASTM 3039 (tensile test) and compressive strength ASTM-D 3410 the cross head speed was maintained as 5 mm/min.

5.2 Flexural strength

The flexural strength of a material is defined as the maximum bending stress that can be applied to that material before it yields. The most common way of obtaining the flexural strength of a material is by employing a transverse bending test using a three-point flexural test technique. Flexural strength is also known as bending strength, modulus of rupture or transverse rupture strength. For evaluation of the flexural Properties viz. strength and modulus, samples of the composites are mostly prepared according to ASTM D 790 standard. The three-point bending technique is a material testing method which evaluates modulus of elasticity in bending, flexural stress and flexural strain when the material sample is set up as a simply supported beam under two supports and a load is applied at a point. The figure no:4.5 shows flexural test images. Flexural strength is a critical property for materials used in beams, panels, and structural components, as it determines the material's ability to withstand bending loads without failure. In composite materials, flexural strength is highly influenced by the type of reinforcement (fibers), matrix material, and the bonding between them. The measured flexural strength depends on specimen dimensions such as thickness, width, and span length. Proper standardization (like ASTM D790) ensures accurate and comparable results. During a three-point bending test, failure may occur due to tensile cracking on the lower surface, compressive failure on the upper surface, or shear failure within the material, depending on its properties. Flexural strength data is widely used in selecting materials for applications such as automotive parts, aerospace structures, construction panels, and sports equipment where bending loads are common.



Figure 3: Flexural Test Image

5.3 Hardness Value

The Shore-D hardness testing machine was utilized to evaluate the hardness test. Higher hardness was

determined by the hardness evaluation Ratio-3. Maximum hardness 71.66 was caused by the percentages of maximum areca, and silicon carbide filler.

Table 2: Hardness value

RATIO	MATERIAL	SHORE-D			
B1	ARF30%+PAF7.5% +SIC 2% +ER125 g	72	65	65	67.33
B2	ARF35%+PAF.% +SIC3% +ER125 g	70	71	63	68
B3	ARF40%+PAF7.5% +SIC4% +ER125 g	74	72	69	71,66

5.4 Hardness Value Graphical Presentation

The Shore-D hardness testing machine was utilized to evaluate the hardness test. Higher hardness was

determined by the hardness evaluation Ratio-3. Maximum hardness 71.66 was caused by the percentages of maximum areca, and silicon carbide filler.

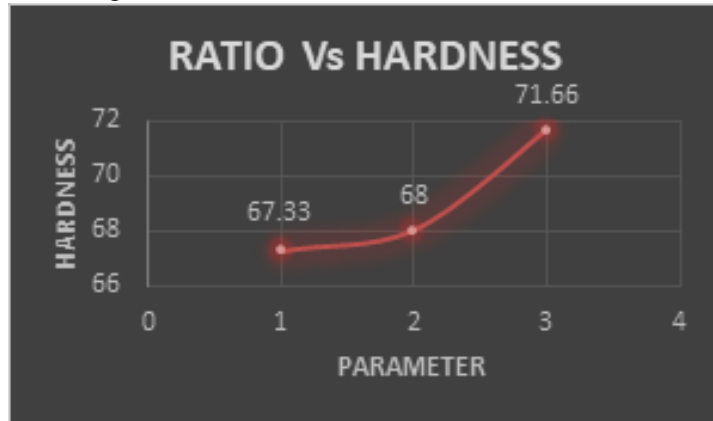


Figure 4: Hardness Strength Graph

6. TENSILE STRENGTH VALUES

The results of the tensile test indicate that a higher ratio of Areca fiber combined with Silicon carbide fillers yields the maximum tensile strength, measured at approximately

14.67 N/mm². This is followed by a second higher percentage of Areca fiber, which demonstrates a tensile strength of 10.40 N/mm².

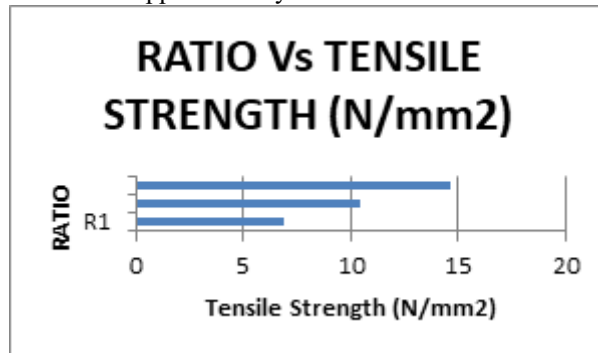


Figure 5: Tensile Strength Graph

Table 3: Tensile Strength

Identification	Thick mm	Width mm	CSA mm ²	TL KN	TS KN/mm ²
B1	2	25	75	0.52	6.93
B2	3	25	75	0.78	10.40
B3	3	25	75	1.10	14.67

6.1 Impact Test

During that investigation of impact test, the reading shows of more percentage contribution of Areca and Silicon

carbide fillers less percentages of Pineapple fiber exhibit maximum impact load 4.11 joules and followed by more pineapple fiber percentages result shows 4.102 joules

Table 4: Impact Energy

S.No	Sample	Impact value in(J)
B1	ARF30%+PAF7.5% +SIC 2% +ER125 g	4.02
B2	ARF35%+PAF.5% +SIC3% +ER125 g	3.82
B3	ARF40%+PAF7.5% +SIC4% +ER125 g	4.11

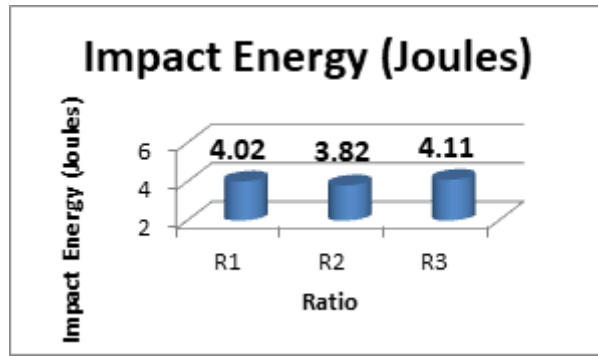


Figure 5: Impact Energy Graph

6.2 Flexural Strength

The mentioned formula was used to find the flexural strength- $((3/2) \times (WL/bd^2))$. Flexural strength test result shows that the reading medium Areca pineapple fiber and

silicon carbide filler percentages ratio exhibits maximum flexural strength of about 130.26 N/mm² and followed by maximum weight percentages of areca and SiC achieved 115.38 N/mm²

Table 5: Flexural Strength

Identification	Thickness (t) mm	Span length (l) mm	Flexural load (W) KN	Flexural Strength (N/mm ²)
B1	3.38	50	0.11	84.61
B2	3.24	50	0.17	130.26
B3	3.41	50	0.15	115.38

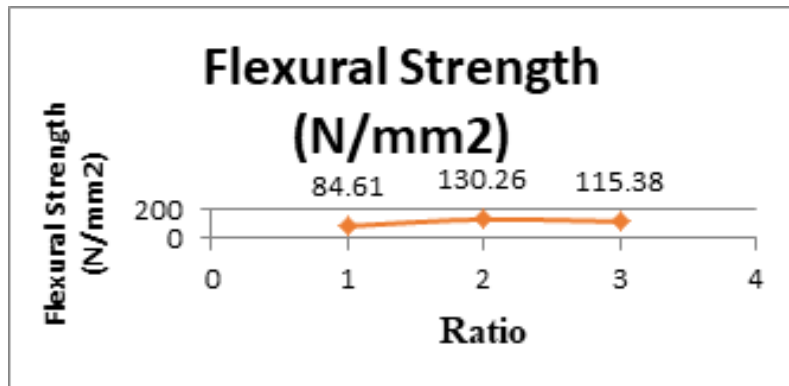


Figure 6: Flexural strength

7. COMPRESSION STRENGTH

The results of the compressive load test indicate that a higher ratio of Areca fiber combined with Silicon carbide filler leads to a maximum compressive strength of approximately 4.93 N/mm². In contrast, medium percentages of both fiber and fillers yield a compressive strength of 3.07 N/mm².

In the higher ratio configuration, the Silicon Carbide (SiC) particles likely act as "structural pillars" within the polymeric matrix. At 4.93 N/mm², the high

concentration of Areca fibers works in tandem with these SiC fillers to resist crushing forces. The filler particles fill the microscopic voids between the fibers, creating a denser, more compact internal structure that prevents the matrix from collapsing under pressure.

The drop to 3.07 N/mm² at medium percentages suggests that there is a critical threshold for reinforcement. In the "medium" blend:

- Fiber-to-Fiber Proximity: There may be more "unreinforced" resin areas.

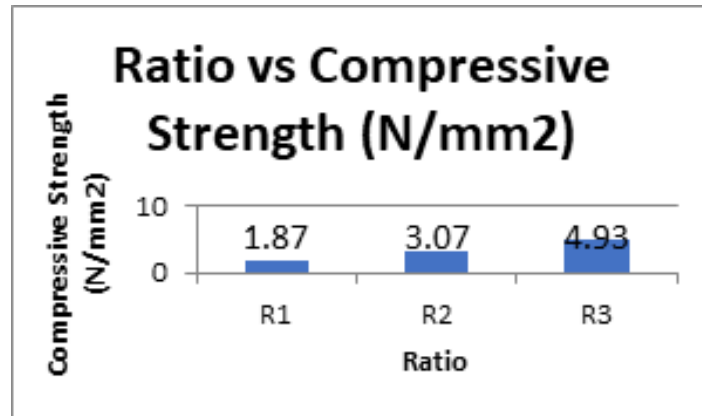


Figure 7: Compression Strength Graph

7.1 Water Absorption Evaluation

All hybrid fiber composites water absorption were evaluated with the periodical gap 24 hours for the 3 days. The water absorption test results indicate that the highest moisture absorption analysis for higher weight percentages

of silicon carbide and areca fibre is 14.07%, while the lowest water absorption is 10.8% for lower contributions of areca fibre and higher percentages of pineapple fibre percentages.

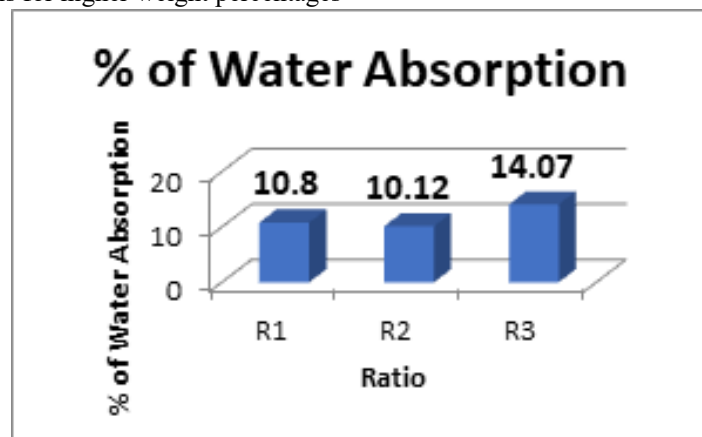


Figure 8: Water Absorption Graph

Hybrid natural fiber composites had been successfully developed in this project. The mechanical properties (Hardness, Tensile, impact, flexural & compression) of the composite has been studied and discussed here. The water absorption and wear properties were analyzed for each composite ratio. The following conclusions have been

drawn from this study. This work shows that successful fabrication of hybrid natural fiber reinforced composites by compression moulding method. Composite samples are suitable for analyze mechanical properties such as tensile bioplastics impede their use in load-bearing

Table 6: Water Absorption Evaluation

Identification	Duration				Weight difference gms	Percentage of water absorption
	Before weight	After 24 hrs weight	After 48 hrs Weiwei	After 72 hrs weight		
B1	3.31	3.56	3.61	3.67	0.36	10.8
B2	2.85	3.26	3.31	3.36	0.41	10.12
B3	4.05	4.43	4.57	4.62	0.57	14.07

skeletal applications. The addition of hydroxyapatite or β -tricalcium phosphate improves compressive strengths and elastic moduli, but mechanical properties achieved using these composites are typically within the lower range of cancellous bone. Furthermore, the mechanical requirements of cortical bone exceed the capabilities of these formulations (Zhang et al., 2021; Kumar and Sharma, 2023). However, unlike collagen-rich bone

extracellular matrix, the intrinsically globular albumin lacks a hierarchical fibrillar structure, which together with its intrinsic globularity, results in low tensile

The water absorption evaluation is a critical performance metric for natural fiber composites, as plant-derived reinforcements like Areca and Pineapple are inherently hygroscopic. This test measures the material's ability to

resist moisture, which directly affects its dimensional stability and mechanical longevity.

According to your data, the highest water absorption occurs in composites with the maximum percentage of Areca fiber and Silicon Carbide (SiC). This is often due to the increased surface area of the fibers and the potential for microscopic voids at the interface between the SiC particles and the matrix. When water penetrates these voids, it causes the fibers to swell, leading to micro-cracking and delamination (the separation of fiber from the resin).

The research shows that a "medium" ratio of fiber and filler provides a more balanced absorption rate. By optimizing this ratio, engineers can minimize the "wicking" effect—where water travels along the fiber length—ensuring the composite remains durable for engineering applications without significant loss of strength or biological decay.

8. CONCLUSION

Hybrid natural fiber composites had been successfully developed in this project. The mechanical properties (Hardness, Tensile, impact, flexural & compression) of the composite has been studied and discussed here. The water absorption and wear properties were analyzed for each composite ratio.

The following conclusions have been drawn from this study. This work shows that successful fabrication of hybrid natural fiber reinforced composites by compression moulding method. Composite samples are suitable for analyze mechanical properties such as tensile.

It has given information about the suitability of hybrid fiber as a source of reinforcement in epoxy matrix composites. NFR composites have higher fiber content for equivalent performance, which reduces the amount of more polluting base epoxy resin. Now a days many automobile field used instead of aluminium, natural fiber and synthetic fiber for interior components with extraordinary strength characteristics. The following results were obtained during the investigation of mechanical and tribological behaviors of natural hybrid fiber composites.

The Shore-D hardness testing machine was utilized to evaluate the hardness test. Higher hardness was determined by the hardness evaluation Ratio-3 the maximum percentages of areca fiber and silicon carbide fillers .

The results of the tensile test indicate that a higher ratio of Areca fiber combined with Silicon carbide fillers yields the maximum tensile strength, measured at approximately 14.67 N/mm². This is followed by a second higher percentage of Areca fiber, which demonstrates a tensile strength of 10.40 N/mm². During that investigation of impact test, the reading shows of more percentage contribution of Areca and Silicon carbide fillers less percentages of Pineapple fiber exhibit maximum impact

load 4.11 joules and followed by more pineapple fiber percentages result shows 4.102 joules. Flexural strength test result shows that the reading medium Areca pineapple fiber and silicon carbide filler percentages ratio exhibits maximum flexural strength of about 130.26 N/mm² and followed by maximum weight percentages of areca and SiC achieved 115.38 N/mm². The results of the compressive load test indicate that a higher ratio of Areca fiber combined with Silicon carbide filler leads to a maximum compressive strength of approximately 4.93 N/mm². The water absorption test results indicate that the highest moisture absorption analysis for higher weight percentages of silicon carbide and areca fibre is 14.07%, while the lowest water absorption is 10.8% for lower contributions of areca fibre and higher percentages of pineapple fibre percentages. In conclusion, it was found that, in addition to flexural strength characteristics, various mechanical properties exhibited a strong correlation with the percentage of areca fiber and silicon carbide fillers. In the hybrid natural fiber composites, the undesirable property of water absorption increases with a higher presence of areca fiber and silicon carbide particle.

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