

## Enhancing the Mechanical and Interfacial Properties of Hybrid Jute-Ramie-Carbon Fibre Composites Through Low-Concentration Microcrystalline Cellulose Modification



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### ABSTRACT

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*hybrid natural fibre composite, interfacial shear strength, jute-ramie-carbon hybrid, low-concentration microcrystalline cellulose*

This study investigates the synergistic effect of low-concentration microcrystalline cellulose (MCC) on the mechanical performance of a hybrid jute-ramie-carbon fibre composite in epoxy matrix. The composites were fabricated using vacuum bagging method, incorporating varying MCC concentrations of 0%, 0.25%, 0.50%, and 0.75% by weight. Triplicate measurement of tensile properties based on ASTM D3039 and interfacial shear stress measurements according to ASTM D5379 were used to characterize the resulting composites. Moreover, scanning electron microscopy is used to characterize the failure characteristics of the hybrid natural composite. Tensile strength and Young's modulus of the hybrid jute-ramie-carbon fibre composite peaked at 0.75% MCC loading, reaching 98.32 MPa and 1353.88 MPa, respectively. Interfacial shear strength (IFSS) similarly improved by 28.4% at the optimal 0.75% MCC loading level. Scanning electron microscopy (SEM) analysis confirmed that MCC acted as a bridging agent, mitigating the formation of macro-voids and promoting mechanical interlocking, which transitioned the failure mode from extensive fiber pull-out to more efficient load transfer and synchronized matrix-fiber fracture. These results identify 0.75% MCC as an optimal minimum threshold for maximizing load-transfer efficiency in hybrid natural-synthetic laminates that can be used as high-performance, lightweight, and sustainable materials for structural uses.

## 1. INTRODUCTION

Fibre-reinforced polymers (FRPs) have replaced other types of materials in numerous high-performance sectors, such as aerospace, automotive, and sporting goods, among others. The defining advantage of FRPs lies in their tailorable properties, enabling designers to prioritize specific characteristics—such as ductility or strength—for a given application. Their primary appeal stems from the ability to tailor their properties, allowing engineers to emphasise particular traits, such as toughness or load-bearing capacity, according to the intended use [1-3]. The growing demands of modern prosthetic design have accelerated the need for materials that offer superior strength, adjustable rigidity, and low mass, establishing FRPs as a fundamental component in current artificial limb technology [4, 5]. Currently, carbon-fibre reinforced polymer (CFRP) has become the mainstay material for prosthetic limbs owing to its well-established manufacturing technology and superior strength-to-weight ratio [6, 7]. Moreover, the pronounced stiffness of CFRP that reflected in its high Young's modulus have a potential to cause discomfort for the patients, especially among older individuals. This issue has

been linked to secondary health issues, including lower back pain and degeneration of joints in the unaffected limb [8-10].

These shortcomings, coupled with the considerable environmental burden of carbon fibre production, have spurred interest in hybrid natural fibre-reinforced polymers (HNFRPs). This strategy involves substituting a proportion of the carbon reinforcement with sustainable plant-based fibres, such as ramie, jute, or pineapple leaf [11-13]. The aim is to reduce expense, ecological impact, and brittleness while also tempering the overall stiffness of the composite to improve user comfort [14]. Irrespective of the proportion of carbon fibre substituted, the fabrication methods for HNFRPs align closely with those employed for conventional composites, commonly involving hand layup, vacuum bagging, or compression moulding techniques [15, 16].

Among available natural reinforcements, jute and ramie stand out owing to their mature, large-scale supply networks. Jute, in particular, benefits from a substantial global market, with annual output exceeding three million tonnes, making it one of the most cost-effective natural fibres available [17, 18]. Ramie, meanwhile, offers a notably broad range of specific modulus, reported to vary between 18 GPa (g/cm<sup>3</sup>) and 140

GPa ( $\text{g}/\text{cm}^3$ ) [18].

Numerous studies have explored the incorporation of these fibres into HNFRRP with variable success rates. Kharshiduzzaman et al. [19] fabricated a polyester-based composite by interweaving jute and carbon fibre mats in a jute/carbon/jute/carbon stacking sequence with an 80:20 mass ratio of jute to carbon. The resulting laminate achieved a Young's modulus of 6.05 GPa and a tensile strength of 108.8 MPa. However, the inclusion of carbon fibre also led to a reduction in tensile strength compared to expectations, a phenomenon ascribed to the inherently greater load-bearing capability of carbon relative to jute. Alvy et al. [20] tested a hybrid Jute/Carbon composite with carbon fibre as skin layer (Carbon/Jute/Jute/Carbon) in epoxy matrix. They reported a 361% increase in tensile strength and 258% increase in flexural strength compared to plain jute fibre composites. These findings were attributed to the presence of carbon fibre as the principal load-bearing material at the outermost surfaces. The higher load-bearing capacity of carbon fibre delayed failure initiation and propagation to the inner jute layers, which possess lower load-bearing capacity. Dabholkar and Harikumar hybridized ramie fibre with carbon fibre composite in an epoxy matrix, with carbon fibre layers sandwiching ramie plies. They found that increasing the number of carbon fibre layers correlated with higher tensile strength. However, at higher stress levels, delamination was observed at the interface between the carbon and ramie fibre layers [21].

Although researchers have extensively investigated HNFRRPs, several challenges persist, including poor fibre wettability, high moisture absorption, and inherent variability in individual fibre quality. Moreover, the primary obstacle in developing natural-synthetic hybrid composites is interlaminar delamination [22, 23]. Relative deformation between neighbouring plies causes this failure mode, which is usually brought on by cyclic loads or flaws in the manufacturing process. Fibres give little reinforcement in the through-thickness direction because they are arranged to provide strength inside the laminate's plane [24]. Consequently, the composite relies heavily on the relatively weak polymer matrix for interlaminar load transfer, rendering it particularly susceptible to interlaminar stresses [25].

Delamination significantly undermines structural integrity, as split layers are prone to buckling when subjected to compressive loads [22]. This issue is compounded in hybrid systems by non-uniform permeability at the fibre-matrix interfaces. Variations in the surface characteristics of natural and synthetic fibres induce capillary effects, leading to inconsistent resin flow [26]. Such uneven wetting compromises interfacial bonding and promotes the formation of voids and defect-nucleation sites. Additionally, the inherent chemical incompatibility between hydrophilic natural fibres and hydrophobic polymer matrices presents a considerable challenge. Constituents like lignin, hemicellulose, and waxes present in natural fibres can hinder effective interfacial adhesion. In particular, the hydroxyl groups in cellulose confer a strong hydrophilic nature to the fibre, contrasting sharply with the hydrophobic tendencies of most polymer matrices [27].

The common approach to this problem is to apply chemical surface treatments to remove inhibitory substances and modify the cellulose structure, thereby enhancing interfacial bonding and reducing the high moisture sensitivity of the natural fibre components [28-30]. However, excessive chemical treatment

can also lead to hydrolysis of cellulose fibre, thereby reducing its strength [31, 32].

Recently, a different approach utilizing micro-filler such as microcrystalline cellulose (MCC) to impart a mechanical interlocking between fibres has been explored to reduce delamination [33, 34]. MCC acts as a high-surface-area bridging agent, adhering to the surface of natural fibres within the composite and thereby enhancing mechanical interlocking between the fibres and the matrix [34]. This modification increases interlaminar shear strength (ILSS) and reduces fibre pull-out by facilitating more effective load transfer across the fibre-matrix interface. Additionally, by reducing the non-uniform permeability and irregular capillary effects frequently seen in hybrid layups, the addition of MCC stabilizes the resin infusion process [26, 35]. By promoting more uniform resin wetting on the surfaces of synthetic and natural fibres, MCC particles prevent gas bubble entrapment and reduce the formation of micro-voids [36]. The wettability-altering mechanism of MCC was attributed to the pronounced hydrophilicity of its particles, arising from the abundance of hydroxyl groups in the cellulose molecular structure [37]. By bridging the interface and improving compatibility between the natural fibres and the epoxy matrix, the addition of these hydroxyl groups mitigates the polarity mismatch between the matrix and the natural fibre reinforcement [38]. MCC successfully converts hydrophilic natural fibres that are intrinsically incompatible into high-performance reinforcements that can compete with their synthetic equivalents by balancing interfacial polarity and promoting stronger physical interactions [39, 40].

The effectiveness of this approach was first illustrated by Jamasri and Yudhanto [40], who introduced 8% MCC into a hybrid composite reinforced with jute and glass fibres. Their findings revealed that the inclusion of MCC doubled both the flexural strength and deflection in composites featuring alternating jute and glass layers, suggesting that MCC plays a key role in delaying delamination failure. In a related investigation, Yudhanto et al. [39] incorporated 0.5% MCC into an unsaturated polyester matrix reinforced with a combination of carbon, glass, and ramie fibres. This addition led to notable increases of 47% and 16% in flexural strength and flexural modulus, respectively, although it also resulted in a 0.9% rise in water absorption relative to the MCC-free composite. When MCC is used in short FRPs, the improvements are less pronounced than those seen in long-fibre systems. This trend was observed by Maulana Al-Farizy et al., who combined MCC with short water hyacinth fibre in an HDPE matrix and documented only a modest 4.6% enhancement in tensile strength [41].

Despite various studies investigating the effects of MCC in FRPs, no research has yet examined its influence in HNFRRPs at low concentrations. In natural fibre-only composites, the addition of MCC at low concentrations has been shown to improve fibre wettability. Żelaziński et al. [42] demonstrated this by incorporating 1–8% MCC into a rape pomace/PLA composite. Similarly, Khairunnisa et al. [43] found that MCC dispersion stability in deionized water peaked at a concentration of 0.4%. Incorporating MCC at this optimal dispersion concentration can prevent agglomeration within the composite matrix, a common issue at higher MCC loadings [44]. Furthermore, existing studies on MCC addition have predominantly focused on composites in which synthetic fibres constitute an equal or greater proportion of the reinforcement. Therefore, this study aims to investigate the

effect of near-zero MCC concentrations (<0.75%) in a predominantly natural FRP (jute/ramie/carbon) with high fibre loading.

## 2. MATERIAL AND METHODS

### 2.1 Materials

Plain-woven carbon fibre mats (240 gsm) and epoxy resin were obtained from NJK (Surabaya, Indonesia). The epoxy system employed was Lycal 1011, a low-viscosity rigid epoxy resin with a 3:1 weight ratio of resin to hardener. The epoxy system requires a minimum curing schedule of 8 hours at ambient temperature or 1.5 hours at 80°C. A local supplier in Surabaya, Indonesia, provided woven ramie and jute mats. Sigma-Aldrich (USA) supplied the MCC powder (Sigmacell 50, average particle size: 50 µm).

### 2.2 Composite fabrication

The vacuum-bagging method was used to fabricate a hybrid jute-ramie-carbon fibre composite. The reinforcement stacking sequence, applied over a glass mould, consisted of alternating layers in the order: jute, ramie, carbon, ramie, and jute. After placing the final reinforcement layer, a peel ply and a flannel breather cloth were positioned atop the laminate. The breather cloth absorbs excess resin during curing, thereby increasing the fibre volume fraction, while the peel ply ensures clean separation between the composite and the breather material. MCC is then incorporated into the resin after being uniformly mixed with hardener. The MCC content was added at weight percentages of 0%, 0.25%, 0.50% and 0.75% based on the total resin weight (resin plus hardener). Based on the MCC weight percentage, the samples were labeled as MCC-0, MCC-0.25, MCC-0.50, and MCC-0.75, corresponding to MCC weight fractions of 0%, 0.25%, 0.50%, and 0.75%, respectively.

After all layers were constructed, the resin was infused into the reinforcement under high vacuum (675 torr) and maintained for 24 hours to ensure complete hardening. Following the curing interval, the composite laminate was removed from the vacuum apparatus and cut to the specified test specimen dimensions using an abrasive cutter. Figure 1 illustrates the entire assembly sequence.

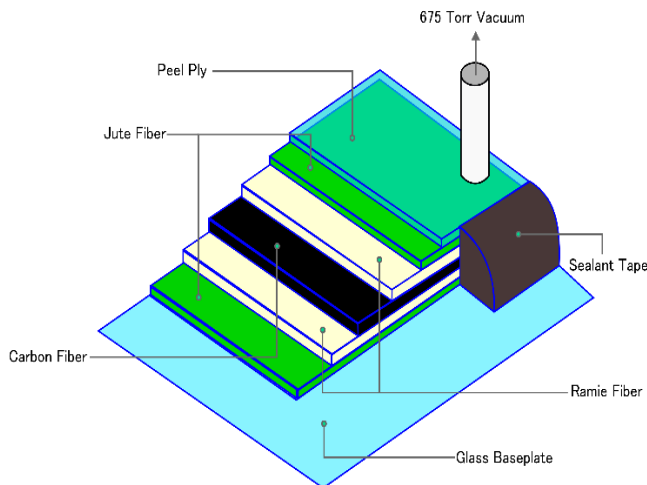


Figure 1. Composite lay-up assembly sequence

### 2.3 Tensile strength measurement

For fibre-reinforced composites, the predominant loading condition anticipated during service involves stresses applied parallel to the fibre orientation. Accordingly, tensile characteristics were assessed using a universal testing rig following the procedures outlined in ASTM D3039. Testing was performed under standard environmental conditions (25 °C and ambient pressure) at a fixed crosshead speed of 0.01 mm/s. To ensure statistical validity of the results, five replicate tests were undertaken for each specimen configuration. From the recorded data, key mechanical parameters—including tensile strength, elastic modulus, and failure strain—were determined for the composite samples.

### 2.4 Shear strength measurement

In FRPs, shear strength is routinely evaluated as an indicator of the bonding quality between the matrix and the reinforcing phase. A higher value of interfacial shear strength (IFSS) typically signifies more proficient transfer of stress from the matrix to the fibres [40]. Experimental determination of the V-notched shear strength was carried out in compliance with the ASTM D5379 standard. From these measurements, the IFSS of the hybrid composite was derived using the expression presented in Eq. (1).

$$IFSS = \frac{P}{t_{eff}h} \quad (1)$$

where,  $P$  corresponds to the load recorded at the point of fracture,  $t_{eff}$  denotes the effective thickness of the test specimen, and  $h$  is the effective gauge length spanning the notches [41].

### 2.5 Scanning electron microscopy analysis

Scanning electron microscopy (SEM) was performed to examine the fibre-matrix interface following composite failure. Micrographs of the fracture surfaces were obtained using a JEOL JSM-IT210 microscope equipped with a 15 kV electron gun. A secondary electron detector operated in high vacuum mode was employed to characterise the fracture surface morphology.

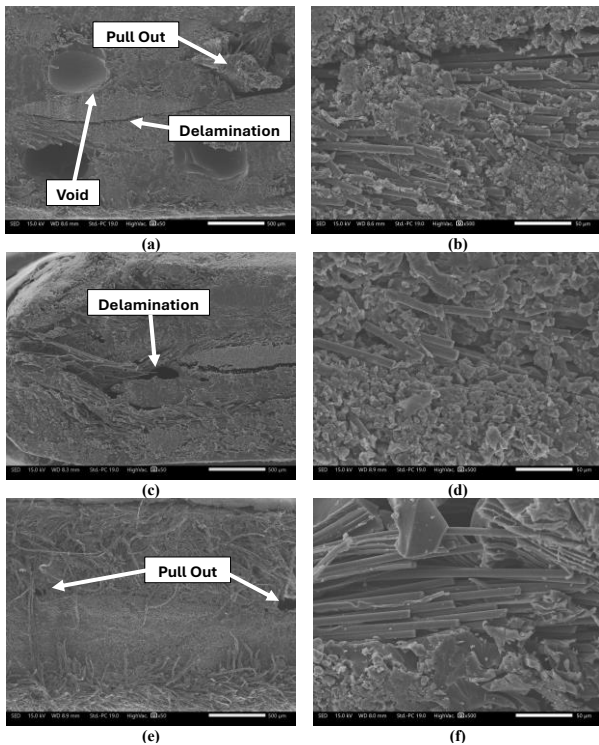
## 3. RESULTS AND DISCUSSION

### 3.1 Fracture morphology

Figure 2(a) shows the fracture morphology of unmodified hybrid jute-ramie-carbon fibre reinforced polymer. The fracture surface is characterised by macroscopic defects and poor interfacial integrity. Specifically, the presence of large, smooth-walled circular voids indicates significant air entrapment during the vacuum bagging process, likely attributable to insufficient viscosity control of epoxy resin. Furthermore, the observation of empty sockets within the matrix and protruding fibre bundles confirms extensive fibre pull-out, evidencing weak interfacial bonding between the hydrophilic jute fibres and the hydrophobic epoxy matrix. This inadequate adhesion impedes effective stress transfer, causing the fibres to debond and slide out rather than fracture under load. Moreover, a delamination was observed at the interface

between the natural fibre and carbon fibre layers, that caused by the strength difference between natural fibre and carbon fibre in withstanding loading. This failure mode arises from the disparity in load-bearing capacity between the natural and synthetic fibres, which induced matrix cracking along the fibre boundary [22].

The introduction of 0.25% MCC depicted in Figure 2(b) marks a transition toward improved structural homogeneity. The SEM micrograph of MCC-0.25 reveals a noticeable reduction in both the frequency and size of macro-voids relative to the unmodified composite. This finding aligns with a previous study demonstrating that even at low concentrations, MCC particles can enhance matrix distribution and fill microscopic gaps between fibre layers, thereby improving material homogeneity [40, 41]. The fracture surface reveals that the resin successfully coated a greater proportion of individual fibres, reducing the extent of debonding. This improvement is attributed to the MCC particles acting as a physical bridge at the interface, which begins to mitigate the natural incompatibility between the different fibre types (natural fibre and carbon). However, at this lower concentration, evidence of delamination persists, particularly at the boundaries where the stiffness mismatch between the high-modulus carbon and the lower-modulus jute is most pronounced.



**Figure 2.** SEM micrograph of hybrid jute-ramie-carbon fibre-reinforced polymer (a) MCC-0, 50x; (b) MCC-0, 500x; (c) MCC-0.25, 50x; (d) MCC-0.25, 500x; (e) MCC-0.75, 50x; (f) MCC-0.75, 500x

Note: SEM = Scanning electron microscopy, MCC = microcrystalline cellulose

Figure 2(c) presents the fracture surface of the MCC-0.75 specimen, where the morphology reflects a marked enhancement in both interlaminar and interfacial bonding. The SEM micrograph shows a compact, uneven matrix surface, suggesting effective stress transmission between the matrix and the reinforcing phase. At a concentration of 0.75%, the micrometre-scale MCC particles act to hinder crack growth

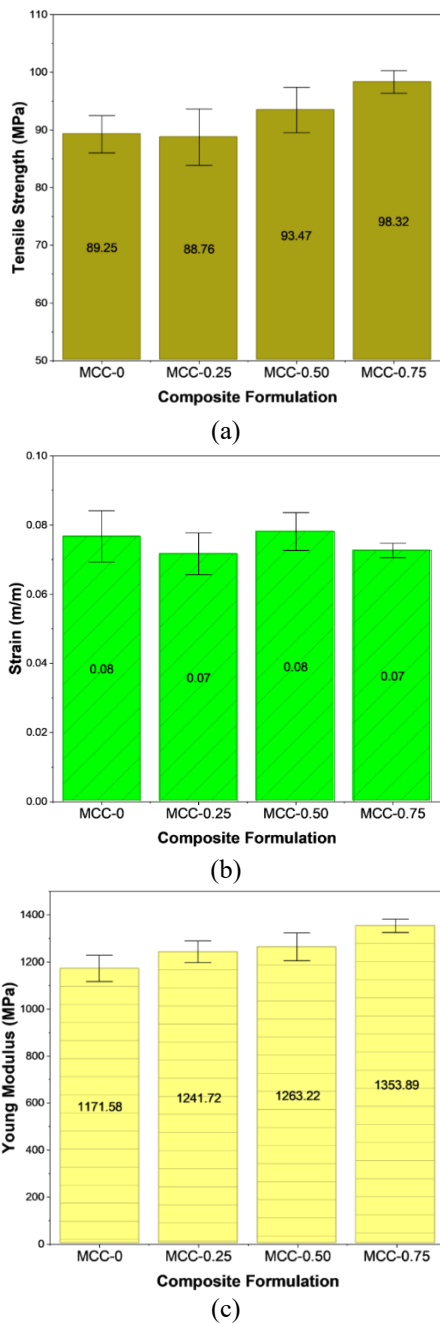
through deflection mechanisms, channelling cracks around the stiff cellulosic structures—a process commonly referred to as crack bridging. The interface between fibre and matrix appears considerably more cohesive, with limited evidence of fibre pull-out and an absence of wide delamination zones. Rather than exhibiting extended, exposed fibres, the image reveals broken fibre ends lying level with the matrix surface. This indicates that IFSS has been sufficiently enhanced such that failure occurs concurrently in both constituents, confirming efficient load transfer across the interface. At this loading level, MCC contributes to improved mechanical interlocking and increases the effective reinforcement volume fraction by partially displacing the epoxy matrix during vacuum processing. These factors collectively account for the superior mechanical behaviour observed relative to the MCC-0 and MCC-0.25 formulations.

### 3.2 Tensile strength of microcrystalline cellulose-modified hybrid natural composites

Figure 3 reveals the tensile test result of MCC-modified jute/carbon ramie FRP. The unmodified control sample recorded a tensile strength of 89.25 MPa, a value consistent with the typical range of 70–90 MPa reported for other hybrid natural fibre composites [45–47]. With the introduction of MCC, a progressive improvement in tensile strength was observed, the most pronounced being for the MCC-0.75 formulation, which reached 98.32 MPa—an increase of 10.15% relative to the unmodified material. A modest improvement rate of 0.25%–0.50% MCC loading was observed, although MCC addition generally improved mechanical properties. This behaviour can be attributed to suboptimal dispersion at this concentration. As a result, many interfacial sites remain unmodified, creating stress concentrations that initiate premature micro-cracking and delamination. SEM results in Figure 2(c) support this finding, revealing matrix delamination at low MCC concentrations. Comparison of the interfacial regions shown in Figures 2(b), 2(d), and 2(f) strengthens the evidence. The interfacial area of MCC-0 and MCC-0.25 exhibits similar segregation and fracture patterns, whereas the MCC-0.75 interface appears denser with fewer fractures. This positive trend indicates that the MCC particles have reached an effective distribution threshold, enabling them to enhance IFSS actively. By acting as a mechanical bridge between the hydrophilic natural fibres and the hydrophobic epoxy matrix, the MCC particles promote crack deflection, compelling propagating cracks to deviate around the cellulosic filler and thus raising the energy required for complete fracture [34].

The progressive rise in Young’s modulus across all MCC-containing samples further confirms the stiffening influence of the micro-particles. The unmodified composite exhibited 1171.57 MPa Young’s modulus, while the variations with the highest amount of MCC gained an increase in Young’s modulus to 1353.88 MPa (1.35 GPa), which is on the same order of magnitude as other hybrid fibre-reinforced composites [19, 39]. Owing to its highly crystalline structure and elevated elastic modulus, MCC effectively restricts the movement of epoxy polymer chains when embedded within the matrix, resulting in a more rigid overall composite. This stiffening follows the shear-lag principle, whereby stress is transmitted from the more compliant epoxy to the rigid MCC particles via interfacial shear forces [48, 49]. As the MCC occupies microscopic voids between the larger carbon and

natural fibre bundles, it creates a more continuous and dense material architecture, as seen in Figure 2(e). By eliminating these voids, the MCC reduces the spacing between reinforcing elements and optimises the shear-lag mechanism, facilitating more uniform stress transfer and limiting the presence of unreinforced resin zones that could otherwise act as sites for crack initiation. Consequently, very little voiding or delamination occurred when 0.75% MCC was added. This structural refinement is visible in the transition from MCC-0 to MCC-0.75, where the synergy between the diverse fibre constituents and the cellulose filler, facilitated by effective interfacial shear transfer, optimises the overall load-bearing capacity of the laminate.

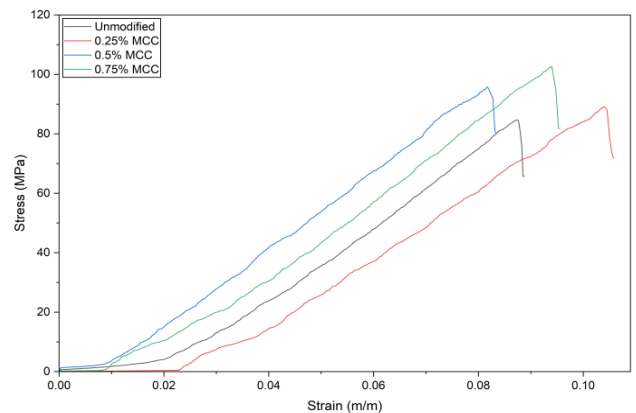


**Figure 3.** Graphical representation of the mechanical properties of a hybrid composite reinforced with jute, carbon, and ramie fibres, modified with microcrystalline cellulose (MCC) (a) ultimate tensile strength, (b) strain at failure, and (c) elastic modulus

Note: The error bars indicate the standard deviation derived from five repeated measurements.

The performance achieved in this work exceeds that of several comparable systems reported in the literature. For example, the maximum tensile strength of 98.32 MPa obtained here is markedly higher than the 73 MPa documented for jute/glass hybrid laminates modified with analogous MCC loadings [40]. Similarly, the current carbon-jute-ramie hybrid outperforms the 91.71 MPa peak tensile strength observed in studies of multi-fibre composites incorporating ramie, jute, and e-glass [50]. These comparisons highlight the benefits of the chosen stacking sequence and the combination of carbon fibre with affordable, widely available natural fibres processed via vacuum bagging. The resulting material not only offers improved sustainability but also delivers mechanical properties superior to those previously reported for similar natural fibre hybrids. The findings suggest that MCC-0.75 represents an optimal balance for maximizing structural integrity in high-performance hybrid applications.

While the tensile strength and Young's modulus of the MCC-modified composite increase alongside the addition of MCC, the strain value of the composite showed no significant change throughout the variations. MCC-0 managed to gain 7.66% strain, while MCC-0.75 had 7.27% strain before failure. The unaffected strain value suggests that the strengthening of the composite was done because of the increase in stiffness of the composite, not because of the increase in elongation. The stress-strain diagram of the hybrid composite produced is shown in Figure 4.



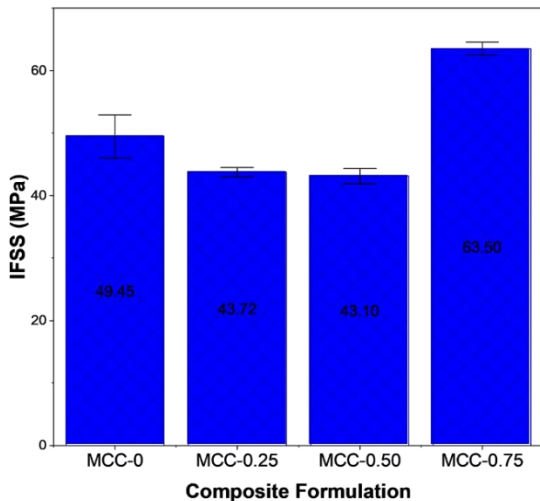
**Figure 4.** Stress-strain diagram of microcrystalline cellulose (MCC)-modified jute-carbon fibre-ramie reinforced polymer

### 3.3 Interfacial shear strength of microcrystalline cellulose-modified hybrid natural composites

Iosipescu's shear testing according to ASTM D5379 Standard was performed to determine the IFSS of hybrid jute-carbon fibre-ramie reinforced polymer and displayed in Figure 5. The results reveal a characteristic non-linear response to the concentration of MCC, which closely parallels the macroscopic tensile behaviour observed in the carbon-jute-ramie hybrid composite. The initial reduction in IFSS from 49.45 MPa in MCC-0 to 43.72 MPa and 43.1 MPa at MCC-0.25 and MCC-0.50, respectively, suggests a transient disruption of the interfacial integrity. This decrease is likely a consequence of heterogeneous filler distribution at lower loadings, where isolated MCC particles or small agglomerates act as localized stress concentrators rather than reinforcing agents. At these low concentrations, the particles may disrupt the continuous chemical and mechanical bonding between the epoxy matrix and the fibres without providing sufficient

surface area for mechanical interlocking, resulting in poor bonding in the composite system and effectively weakening the boundary layer. This interfacial suppression directly correlates with the initial dip in tensile strength (from 89.25 MPa to 88.76 MPa), as a weaker interface limits the efficiency of stress transfer from the matrix to the load-bearing fibre constituents.

However, a significant transition occurs at MCC-0.75, where the IFSS increases sharply to 63.5 MPa, representing a 28.4% improvement over the unmodified specimen. This surge indicates that the composite has reached an interfacial toughening threshold. At this concentration, the MCC particles are sufficiently concentrated to form a dense reinforcing network at the fibre-matrix interface, facilitating superior mechanical interlocking and crack bridging.



**Figure 5.** Interfacial shear strength (IFSS) of microcrystalline cellulose (MCC)-modified jute-carbon FRP  
 Note: Error bars represent the standard deviation of five replicates.

Previous research supports this phenomenon, noting that optimal cellulose loading can enhance the surface roughness of natural fibres, thereby increasing the frictional resistance during fibre debonding [40, 41, 51]. The increase in IFSS value is qualitatively validated by the previous SEM observations. In MCC-0.75, the transition from empty sockets and extensive fibre pull-out (seen in the unmodified and low percentage MCC samples) to fractured fibre ends that are flush with the matrix surface is a direct morphological indicator of high interfacial strength. When the IFSS exceeds the fibre's longitudinal strength, the composite fails via fibre rupture rather than interfacial slipping. Consequently, this robust bond that creates a jump in IFSS value from 49.45 MPa observed in MCC-0 to 63.50 MPa observed in MCC-0.75 is the primary driver behind the peak tensile performance (98.32 MPa) and the elevated Young's modulus (1353.89 MPa) observed at this loading level, as it ensures that the high-stiffness carbon and natural fibres are utilised to their maximum capacity before the structural integrity of the laminate is compromised.

#### 4. CONCLUSIONS

Adding 0.75% MCC to a hybrid composite reinforced with jute, ramie, and carbon fibres yielded the most effective reinforcement level, delivering a maximum tensile strength of 98.32 MPa and a Young's modulus of 1353.88 MPa. This

improvement is supported by a 28.4% increase in IFSS, measured at 63.5 MPa, confirming that MCC serves as a high-surface-area coupling agent that strengthens mechanical interlocking among the distinct fibre types and the epoxy matrix. Examination via SEM showed that while specimens with 0.25% MCC formulation suffered from uneven dispersion and weaker mechanical properties compared the unmodified composites, higher MCC concentrations successfully removed large voids and shifted the dominant failure mode from interfacial debonding to clean fibre breakage. Since tensile strain values remained nearly unchanged across all samples, the enhanced strength can be attributed mainly to greater matrix stiffness and more efficient load transfer, rather than improved ductility. In comparison to conventional glass-fibre hybrids, this carbon-jute-ramie system demonstrates superior performance, indicating that low-level MCC incorporation offers a promising route toward developing high-performance, sustainable composites for structural uses, such as lightweight trusses and prosthetic devices. Nonetheless, further assessment of fatigue life, impact resistance, and swelling characteristics is required before these materials can be reliably adopted in service environments.

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