Comparative Study on Mechanical Properties of Treated and Untreated Sisal-Jute Hybrid Lignocellulosic Fibre Composites

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***Abstract*—Natural lingnocellulosic hybrid fibers like sisal and jute are receiving notable research focus as environmentally sustainable reinforcements for polymer composites. This experimental study focuses on a comparative evaluation between untreated and NaOH-treated jute-sisal hybrid composites, fabricated through the hand lay-up technique using a hybrid ratio of 60% sisal and 40% jute fibres. To enhance the fibre matrix interfacial bonding, the fibres were subjected to sodium hydroxide (NaOH) surface treatment prior to composite preparation. Samples were prepared in accordance with ASTM standards and evaluated for tensile, flexural, and bond strength. Further analysis of bond behaviour was conducted using Nitobond and Nitowrap epoxy systems to compare their adhesive performance and interaction with the natural fibre composites. Experimental findings indicated that the alkali-treated composites possessed superior tensile and flexural performance, resulting from improved interfacial bonding and reduced fibre detachment. Among the adhesives tested, Nitowrap provided greater bond strength and lower slippage. Overall, the findings confirm that chemical surface modification and adhesive selection significantly enhance the mechanical and bonding performance of hybrid natural fibre composites (HNFRP).**

***Index Terms*—HNFRP, pull-out, matrix, Hand layup**

I. INTRODUCTION

Growing environmental consciousness and environmental conservation has accelerated the demand for eco-friendly sustainable composite substitutes developed to replace traditional synthetic fibre-reinforced polymers in structural applications. Among various natural fibres, jute and sisal have emerged as potential reinforcements in polymer composites owing to their affordability, renewability, biodegradability, and superior strength-to-weight efficiency [1], [3]. Being readily available in tropical areas, these fibres present considerable scope for substituting synthetic counterparts such as glass and carbon fibres in low- to medium-load structural applications [4]. In the past few years, considerable attention has been directed by researchers toward improving the performance and durability of the hybridization of natural fibers in composite research. Hybridization entails the incorporation of multiple fibre types within a single matrix to enhance mechanical behaviour, improve durability, and maintain economic feasibility. The hybrid approach overcomes the limitations of single-fibre composites, where certain mechanical properties such as impact strength or stiffness may be inadequate [5]. In the case of jute-sisal hybrid composites, the inherent stiffness of jute complements the toughness of sisal, resulting in improved mechanical synergy. Hybrid composites of this type have yielded favourable and consistent results in various studies in automotive panels, lightweight structures, and civil engineering applications where cost and sustainability are key considerations [6]. However, the practical utilization of natural fibres in composites faces a major challenge: the limited compatibility between natural fibres and hydrophobic polymer matrices. This weak adhesion primarily arises from the hydrophilic characteristics of ligno-cellulosic fibres and the existence of non-cellulosic elements like waxes, lignin, and hemicellulose that hinder proper bonding with resin systems. Several studies have demonstrated the positive influence of alkali treatment regarding the mechanical performance and thermal response of natural fibre-reinforced composites. Archana et al. (2022) reported significant improvement in tensile, flexural, and the impact performance of 4% NaOH-treated jute/sisal composites manufactured through the conventional hand lay-up technique [10]. Similarly, Ramesh et al. (2018) and Joseph et al. (2019) observed that alkali-treated fibres exhibited enhanced interfacial bonding with epoxy matrices and recorded a significant reduction in moisture uptake relative to the untreated specimens. These results collectively suggest that surface modification is crucial for attaining consistent and reliable mechanical performance in natural fibre composites. Despite the availability of several detailed investigations on the mechanical performance of natural fibre composites, limited research exists on the bond behaviour of hybrid natural fibre laminates, especially when bonded to concrete or other structural substrates. In civil engineering applications, such as the Externally Bonded Reinforcement (EBR) technique, bond strength between the composite and substrate has a significant influence on determining load transfer efficiency and overall structural behaviour. Epoxy type selection considerably affects on interfacial bonding. Commercial epoxies such as Nitobond and Nitowrap are frequently employed in FRP-based retrofitting and reinforcement of concrete elements, yet their compatibility and adhesion efficiency with hybrid natural fibre composites remain inadequately studied [7], [11]. The present investigation aims to fill this research gap by conducting a comparative experimental evaluation of the mechanical performance and adhesion behaviour of alkali-treated and untreated jute-sisal hybrid composites fabricated by the hand lay-up technique. For the chosen hybrid ratio, the composites were examined for mechanical behaviour using tensile and flexural testing, and the bonding characteristics were analysed through bond strength tests employing Nitobond and Nitowrap epoxy adhesives. The results derived from this investigation are expected to provide valuable insights into optimizing natural fibre-based hybrid composites for structural strengthening and sustainable engineering applications. Hence, this investigation contributes to the current body of knowledge by integrating both material-level characterization and bond interface evaluation, highlighting the influence of surface modification and epoxy selection on improving the properties of hybrid lignocellulosic composites.

Rationale for Hybridization and Fibre Ratio Selection

Hybridization of plant-based fibres is a proven strategy to optimize the overall mechanical efficiency of polymer composites by combining the complementary properties of different reinforcements. In the present study, sisal and jute fibres were selected owing to their distinct but compatible characteristics—sisal offers higher tensile strength, stiffness, and structural rigidity, while jute contributes improved interfacial adhesion, flexibility, and impact resistance. Many previous investigations have explored sisal-jute hybrid composites fabricated using different fibre ratios for the assessment of their mechanical and thermal characteristics.; however, the specific combination of 60 % sisal and 40 % jute has not been reported in the available literature. This novel ratio was deliberately chosen to achieve an optimized synergy between strength and ductility, ensuring efficient stress transfer through the sisal component and enhanced energy absorption via the jute phase. The sisal-dominant proportion improves load-carrying capacity and modulus, while the controlled jute content minimizes delamination and brittleness, thereby producing a composite with superior tensile, flexural, and inter-laminar bonding performance compared to conventional single-fibre or equal-ratio hybrids.

II. MATERIALS AND METHODS

2.1. Woven sisal-jute hybrid mat

The woven jute–sisal hybrid fabric utilized in this research was sourced from Extra Weave Pvt. Ltd., Kerala, India, a commercial producer of natural fibre reinforcements. It was manufactured in a plain weave configuration, with sisal yarns placed along the warp and jute yarns along the weft, maintaining a weight proportion of 60% sisal to 40% jute.

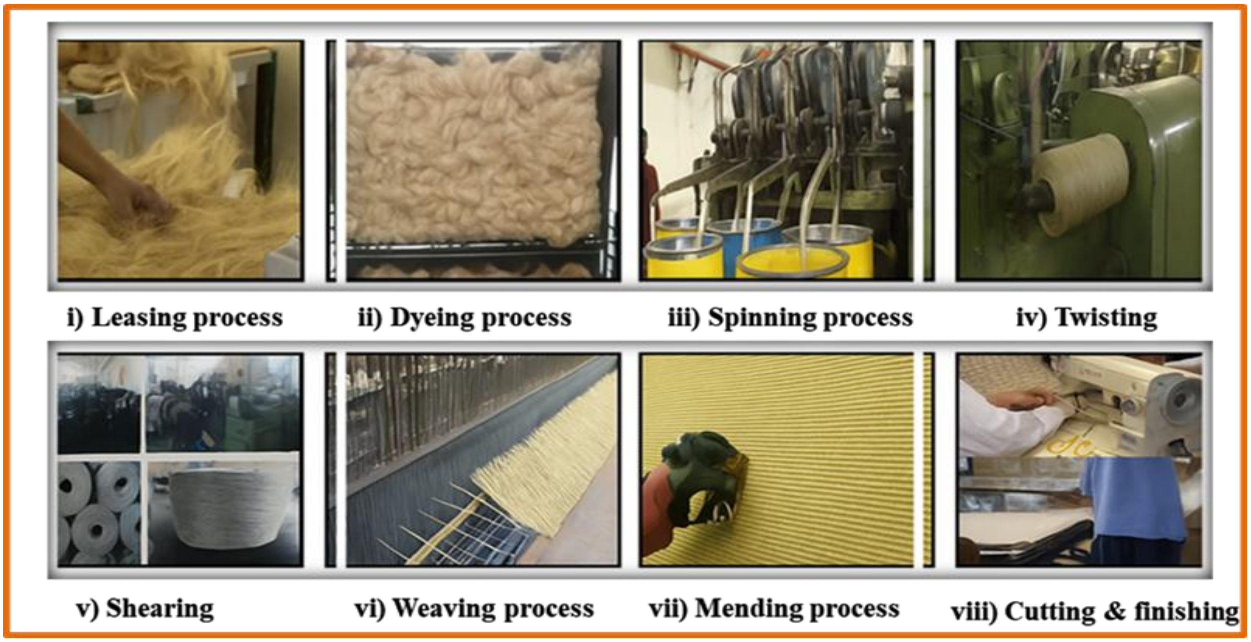


Fig 1: Manufacturing process of hybrid woven

The manufacturer provided data on the woven mat preparation along with the individual fibres' physical and chemical attributes, which are detailed in Table 1. The fibres exhibit good interlacing uniformity and mechanical stability, making the fabric suitable for composite fabrication. The production process included several sequential operations to ensure fibre uniformity, dimensional stability, and mechanical reliability. Initially, raw fibres underwent leasing and sorting to eliminate impurities and non-fibrous materials. The cleaned fibres were then washed and dyed in an automated dyeing unit to achieve uniform colour distribution and surface quality. Post dyeing, the fibres were subjected to radio frequency (RF) drying at approximately 75 °C for 1.5–2 hours, reducing the moisture content to below 5% by weight. The dried fibres were then spun into yarns with controlled fineness and twisted to form two-ply yarns to enhance tensile strength and minimize breakage during weaving. These yarns were sheared to remove surface hairiness and improve smoothness. The fabrication of the woven mat was undertaken on 4 m wide industrial looms, producing continuous woven rolls of jute–sisal hybrid fabric with uniform grammage (GSM) and alignment. After weaving, the fabric underwent mending and trimming to remove edge irregularities and ensure consistent surface quality. The finished woven mats, typically produced in 4 m × 30 m rolls, were cut to the required dimensions for hybrid composite fabrication and mechanical testing. This preparation process ensured the production of defect-free, dimensionally stable woven mats with uniform fibre orientation, suitable for epoxy-based hybrid composite development. Fig 2.1 shows the process of manufacturing hybrid mats.

Table 1: Properties of Sisal and jute Fibres

Property	Sisal Fibre	Jute Fibre
Length (m)	1.0 –1.80	1.5 –4.0
Diameter (µm)	50 – 300	17 – 20
Tensile Strength (GPa)	0.4 – 0.7	0.4 – 0.8
Elongation (%)	2.5 – 4.0	1.5 – 2.0
Moisture Regain (%)	13	12 – 14
Cellulose-(%)	55 – 65	58 – 63
Hemi-cellulose(%)	10 – 15	20 – 24
Lignin-(%)	10 – 20	12 – 14

2.2 Epoxy Resin

The matrix material used for bonding and impregnation of the fibre mats was a two-part epoxy system (Nitowrap 410) supplied by Fosroc Chemicals India Pvt. Ltd. The epoxy consists of a hardener and base, mixed in a 1 : 1.1 ratio by weight as per manufacturer specifications. This particular system was adopted owing to its high adhesion strength,.

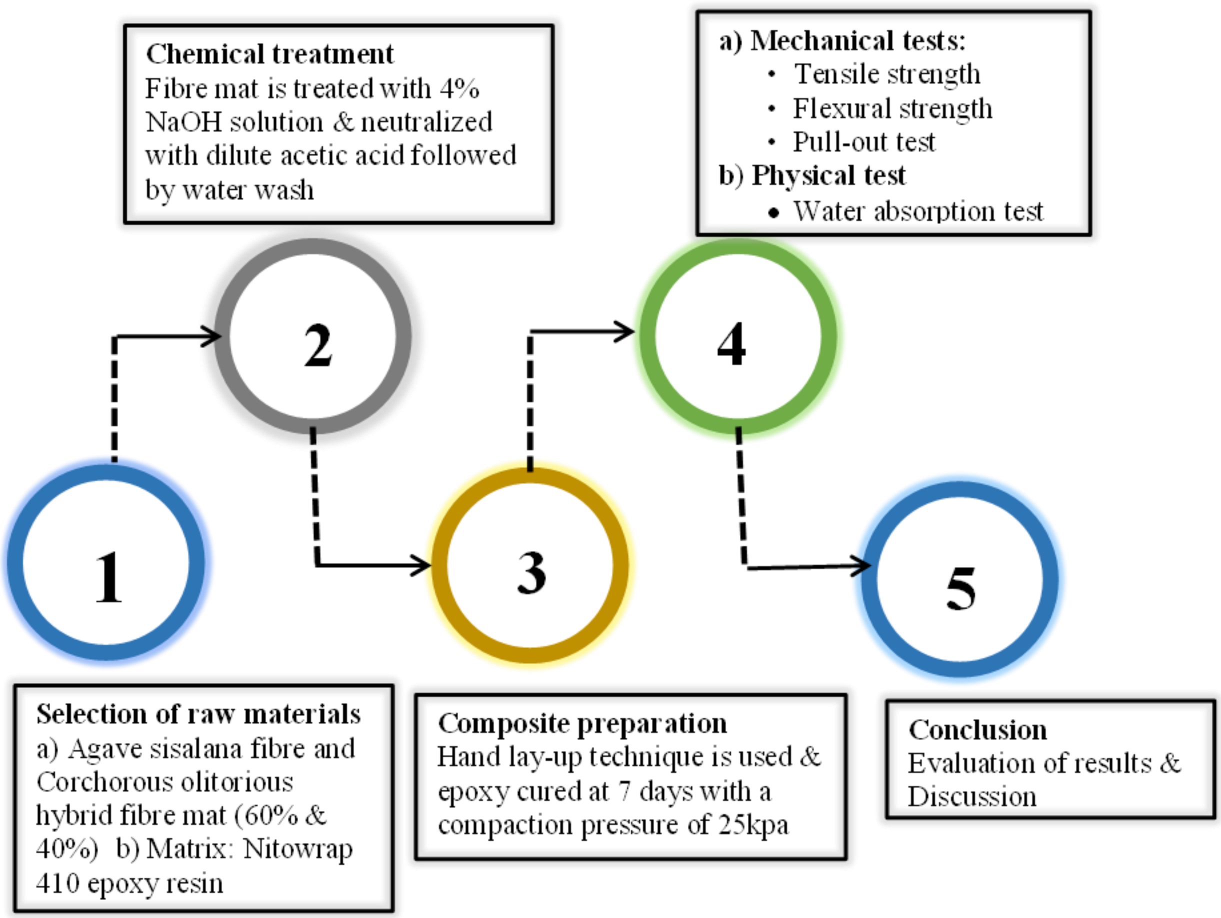


Fig 2: Flowchart for methodology

durability, and compatibility with natural fibre-reinforced composites. The mixed epoxy was applied uniformly during the hand lay-up process to ensure complete wetting of the fibres and void-free HNFRP strip formation

2.3. Chemical Treatment of Fibre mat

The hybrid sisal-jute hybrid mats were subjected to alkali treatment using a 4% sodium hydroxide (NaOH) solution to remove surface impurities, wax, and hemicellulosic content, thereby improving fibre–matrix adhesion. According to Sanjay et al. (2018), the fibre mats were immersed in a 4% NaOH solution for one hour at ambient temperature, followed by thorough rinsing with distilled water to remove residual alkali. Mild neutralization using dilute acetic acid was subsequently performed to eliminate traces of alkalinity. After neutralization, repeated washing with distilled water was carried out until the rinse water attained a neutral pH of approximately 7, as confirmed using pH indicator paper. The treated mats were subsequently oven-dried at 60 °C for 24 hours until mass equilibrium was attained. The alkali treatment roughened the fibre surface and partially removed non-cellulosic constituents, promoting improved interfacial bonding with the epoxy resin. Such controlled alkali modification has been reported in previous studies to enhance mechanical and bonding performance of natural fibre composites.

2.4 Composite Fabrication (Hand Lay-Up Process)

The jute–sisal hybrid composite strips were produced using the conventional hand lay-up technique. Two flat steel slabs measuring 200 cm × 150 cm were used as the mould surfaces to provide a smooth and uniform finish. Before lay-up, the steel surfaces were cleaned and covered with a uniform film of polyvinyl alcohol (PVA) releasing agent to facilitate easy demoulding. The epoxy hardener & base (Nitowrap 410) were mixed in a 1 : 1.1 ratio by weight, as recommended by the manufacturer. The prepared resin mixture was evenly applied over the surface of the sisal-jute hybrid mats, ensuring thorough wetting of the fibres. Manual rolling was performed to remove entrapped air and distribute the resin uniformly throughout the mat. To ensure adequate consolidation and matrix impregnation, a uniform pressure of approximately 25 kPa was applied by placing the steel slabs over the mat. The assembly was left undisturbed under ambient conditions for 24 hours to facilitate primary curing, followed by post-curing of seven days to achieve complete polymer cross-linking and dimensional stability. After curing, hybrid-matrix mat were carefully demoulded and cutted to the required specimen dimensions.

2.5 Testing of Composites

a) Tensile and flexural assessment

The tensile behaviour of the hybrid composites was determined in accordance with ASTM D3039 standards. Specimens measuring 250 mm × 25 mm × 3.8 mm and having a gauge length of 170 mm were subjected to testing on a Universal Testing Machine (UTM) at a crosshead speed of 2 mm/min. The bending strength and modulus of the hybrid sisal-jute composite specimens were determined under single-point loading as per ASTM D790. The specimen dimensions were maintained at 125 mm × 25 mm × 3.8 mm, with a support span of 116 mm.

b) Pull-out test

The bond performance between the alkali treated hybrid natural fibre-reinforced polymer (HNFRP) strip and concrete substrate was assessed by means of a pull-out test. A total of four concrete cube specimens, each having dimensions of 150 × 150 × 150 mm, were cast for the experimental program. The hybrid NFRP strips were fabricated with a uniform width of 50 mm, thickness of 3.8 mm, and an embedded bond length of 75 mm, ensuring uniform bonded areas for all specimens. Two epoxy-based adhesive systems were adopted for comparison one is Nitowrap 410 & Nitobond EP mixed in a 1:10 ratio (Hardener : base) by weight. Before bonding, the concrete surfaces were cleaned, roughened, and dried to remove dust and laitance. The mixed epoxy was applied uniformly on the bonding area, and the hybrid FRP strips were carefully positioned to ensure full contact and alignment. The specimens were maintained under ambient laboratory conditions for a curing period of seven days to ensure complete adhesive hardening. After curing, the pull-out test was conducted by applying a uniaxial tensile load at the unrestrained end of the FRP strip with the aid of a Universal Testing Machine (UTM) until failure occurred. The maximum load recorded during testing was used to calculate the bond stress, which represents the adhesive strength between the FRP and concrete surface.

(c) Water Absorption assessment

The moisture absorption characteristics of the hybrid composite was determined in accordance with ASTM D570. Rectangular specimens measuring 50 × 25 × 3.64 mm were oven-dried at 60 °C for a period of 24 hours and weighed to obtain the initial dry mass (W_1). Each specimen was Subsequently immersed in distilled water under controlled temperature conditions (27 ± 2 °C) for different exposure periods of 24 h, 48 h, and 72 h After each interval, the samples were surface-wiped with filter paper and immediately weighed to record the wet mass (W_2). Water uptake was quantified through the relation expressed in Equation (1):

Water Absorption (%) = $\frac{w2-w1}{w1} * 100$

III. RESULTS AND DISCUSSION

The results obtained from the experimental testing of HNFRP epoxy composites are presented and discussed in this section. The study primarily aimed at investigating the impact of alkali surface treatment on the mechanical performance and physical characteristics of the hybrid composites. Accordingly, the tensile, flexural, and analysis of water absorption behaviour was undertaken on both un-treated & treated specimens to assess

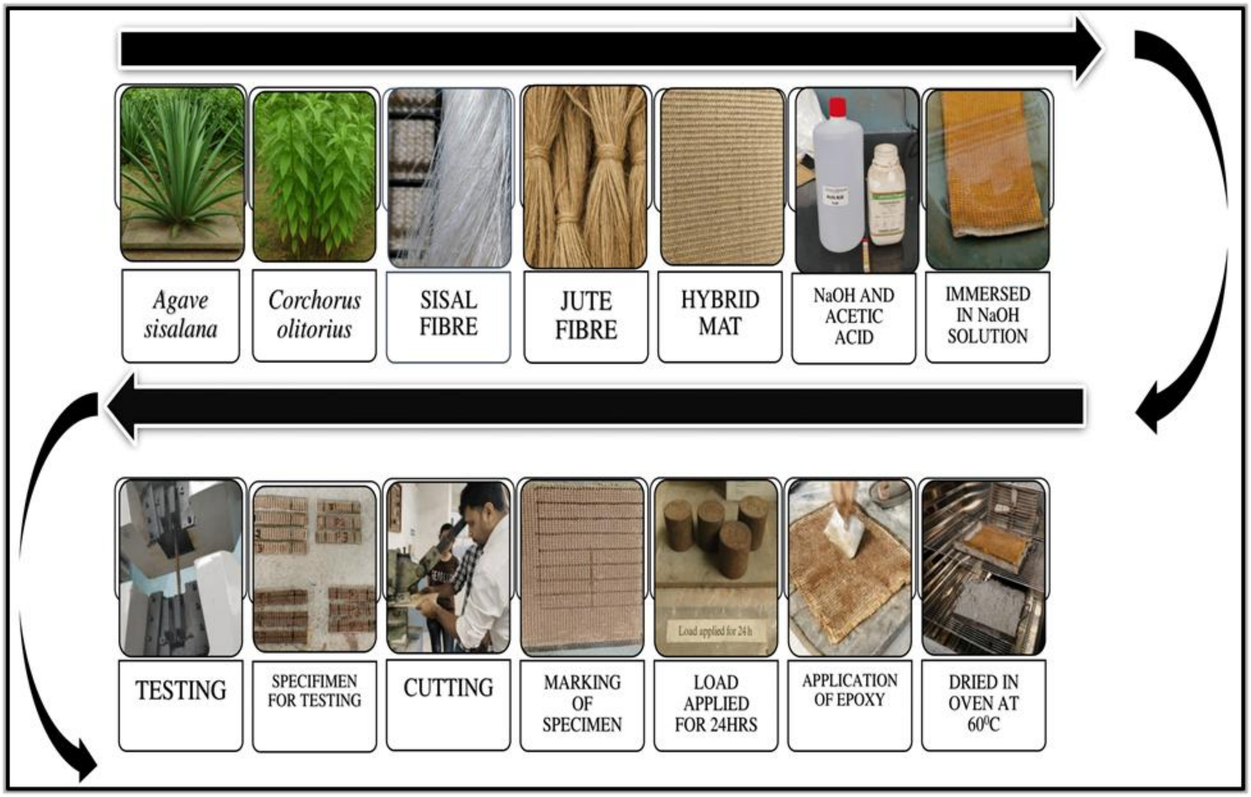


Fig 3: Preparation of HNFRP composite

the impact of surface treatment on fibre-matrix adhesion and overall performance. In addition, a interfacial adhesion behaviour was analysed between the the treated hybrid composite strip and the concrete substrate by pull-out test. For this evaluation, all specimens were prepared with alkali-treated hybrid fibre strips, and two distinct epoxy systems were employed to assess the bonding efficiency and adhesion behaviour.

3.1 Influence of alkali-treatment on tensile characteristics

The untreated specimens exhibited an average tensile strength of 102.4 MPa, where as the NaOH treated specimens achieved an average tensile strength of 145.3 MPa, representing an improvement of approximately 42%. The elastic modulus also increased from 6.5 GPa to 8.3 GPa, while the elongation at break slightly increased from 1.8% to 2.1%. Hybrid composite specimens subjected to tensile testing primarily exhibited progressive bending and partial delamination failure rather than a complete tensile rupture. As observed in Figure X, the specimens developed a distinct localized curvature at the mid-section accompanied by matrix cracking. None of the specimens showed evidence of total fibre breakage under the applied load.. The deformation pattern indicates that the woven fibre mat permitted load redistribution across the warp and weft directions, which delayed catastrophic failure. The slight bending observed after testing suggests that the matrix failed first, transferring the load to the fibres, which subsequently underwent layer separation. This behaviour is typical for woven hybrid fibre reinforced strips where inter-yarn slippage occur before total rupture. In the alkali-treated specimens, the extent of failure pattern was comparatively less, and the laminate retained its integrity with limited delamination. The outcome clearly demonstrates that chemical surface treatment enhanced the fibre–matrix bonding, reducing the chance of premature separation and improving load transfer efficiency.

b) Influence of alkali-treatment on bending characteristics

The post-failure appearance of the hybrid jute–sisal composite specimens after the flexural test is presented in Figure 9b). The untreated specimens (top) predominantly exhibited mid-span bending accompanied by partial surface cracking and delamination. The failure progressed gradually, characterized by matrix deformation and fibre separation, which indicates weak interfacial adhesion developed between the fibre and polymer matrix. The untreated specimens recorded an average flexural-strength of 46.5 MPa and a flexural -modulus of 2500 MPa. In contrast, the alkali-treated specimens (bottom) showed a distinct rupture along the tensile face with minimal delamination, suggesting more efficient stress transfer and stronger fibre-matrix adhesion. The treated specimens achieved an enhanced bending strength of 68.4 MPa and a flexural-modulus of 3150 MPa, reflecting an overall improvement of about 47%. Furthermore, the treated composites developed a clearly defined fracture zone near the mid-span, confirming their improved load-bearing capacity and reduced interfacial slippage.

c) Pull –out behaviour

The pull-out experimental outcomes are compiled in Table 4. Specimens bonded with Nitowrap 410 exhibited a higher average bond stress of 3.09 N/mm², while those bonded with Nitobond EP showed 1.37 N/mm², indicating superior adhesion performance of Nitowrap 410. No separation was observed at the epoxy–concrete interface within the 75 mm bonded length. Failure initiated within the hybrid FRP strip due to internal epoxy cracking and fibre–matrix debonding rather than adhesive detachment. This confirms that the interfacial bond strength exceeded the internal cohesive strength of the strip, ensuring efficient stress transfer between the FRP and the substrate.

d) Water Absorption Behaviour

The data presented in Table 5 indicate that the moisture uptake increased with longer immersion durations for both types of composites; however, the treated specimens exhibited considerably lower absorption values. After 72 hours, the alkali-treated composite showed approximately 45% less water uptake compared to the untreated counterpart, demonstrating that the alkali treatment effectively minimized hydrophilicity and enhanced fibre-matrix interfacial bonding.

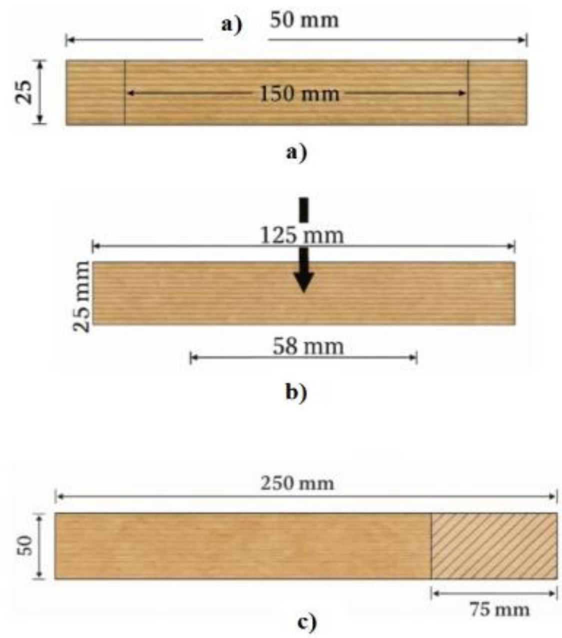


Fig 4: Specimen dimensions conform to the prescribed standards a) Tensile test specimen

b) Flexural test specimen c **c)** ut test specimen

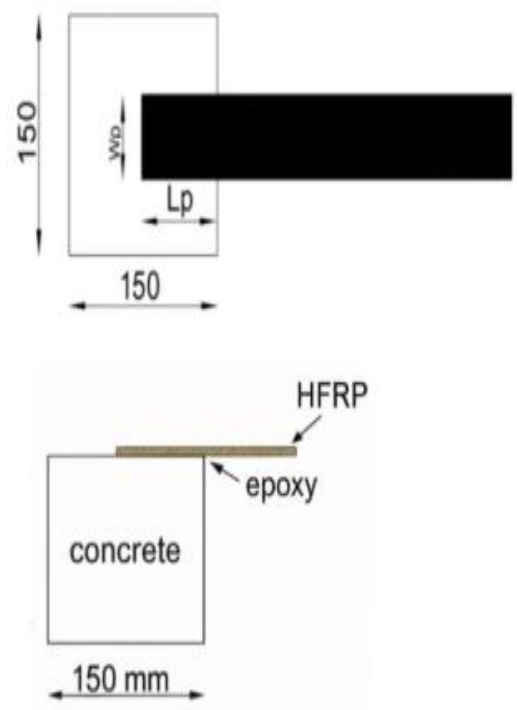


Fig 5 Schematic top & front -view of the pull-out test specimen

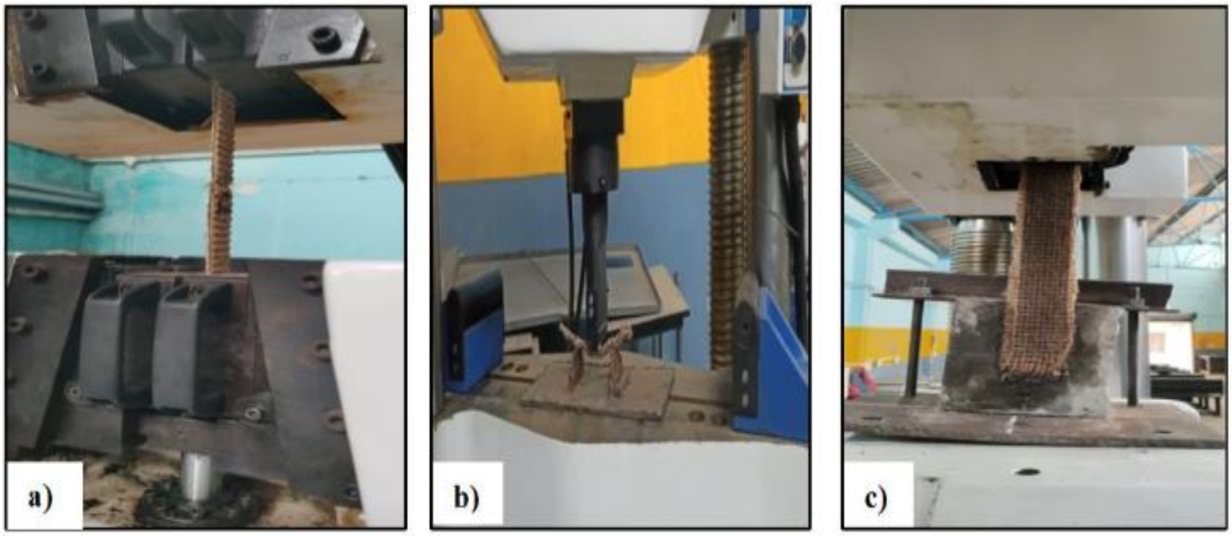


Fig 6: UTM-machine a) Tensile-test arrangement b) Flexural-test arrangement c) Pull-out-test arrangement

Table 2: pull-out test result

Batch No.	Type of Epoxy	Area of Contact (Ac)*(mm²)*	Failure Load (Pf) *(N)*	Bond stress	Average Pf *(N)*	Average Bond Stress (δb) *(N/mm²)*
1	Nitowrap 410	3750	12250	3.26	11605	3.094
2		3750	10960	2.92		
3	Nitobond EP	3750	5320	1.41	5150	1.373
4		3750	4980	1.328		

Table 3: Water Absorption test result

Exposure Duration (h)	Untreated Composite (%)	4 % NaOH Treated Composite (%)
24	3.42	2.15
48	4.76	2.84
72	5.58	3.09

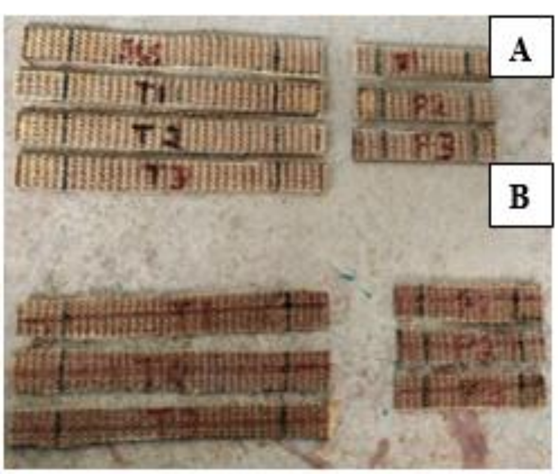


Fig 7: Specimens before Testing A) Untreated B) Treated

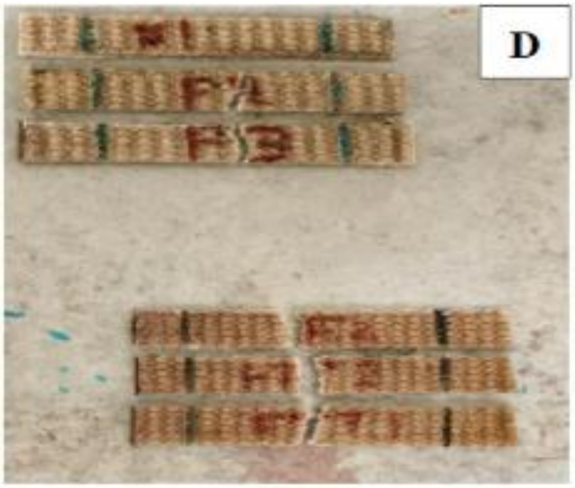
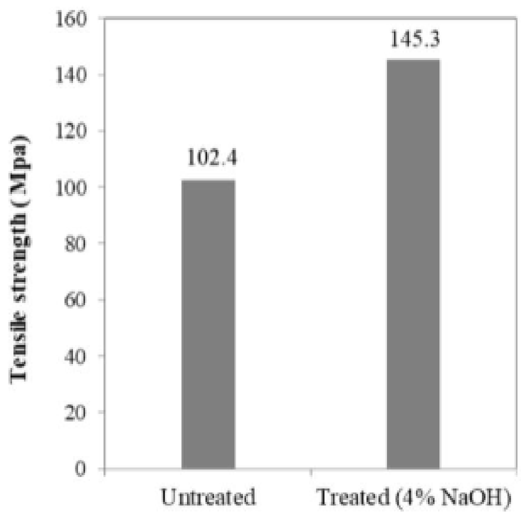
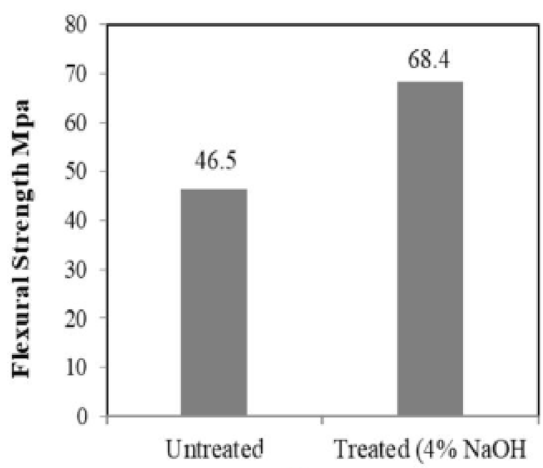


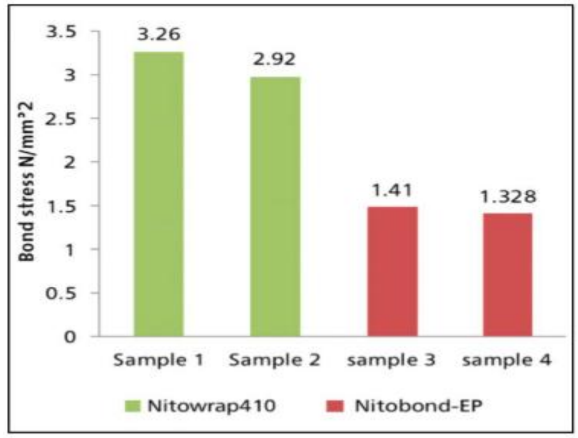
Fig 8: Specimens rupture after Testing a) Tensile b) bending



i)



ii)



iii)

Fig 9: Characteristics of HNFRP strips i) Tensile strength ii) flexural strength iii) Pull-out test

IV. CONCLUSION

1) The 4% NaOH treatment efficiently eliminated surface impurities and wax coatings from the jute–sisal hybrid fibres, resulting in enhanced interfacial adhesion between the fibres and the polymer matrix within the composite material.
2) The treated hybrid composite displayed a notable improvement in tensile and flexural performance in comparison to the un-treated composites, substantiating the favourable effect of chemical surface modification on fibre–matrix interaction
3) The enhancement in elastic modulus of treated composites indicates a more efficient stress transfer mechanism and better stiffness characteristics.
4) The alkali-treated specimens exhibited lower water absorption, demonstrating improved resistance to moisture and enhanced dimensional stability.
5) In the bond strength analysis, the composite bonded with Nitowrap410 epoxy showed superior interfacial adhesion compared to Nitobond EP, validating the suitability of Nitowrap410 for natural fibre composites.

V. SCOPE FOR FUTURE RESEARCH

1) The study can be extended to investigate the long-term durability of beams strengthened with hybrid natural fibres, particularly under

environmental effects such as moisture, temperature variation, and chemical exposure.

2) Different hybrid combinations and orientations of natural fibre composites may be explored to optimise flexural and shear strengthening.
3) Analytical and numerical modelling can be carried out to predict behaviour and validate experimental results for large-scale structural applications.
4) The influence of different bonding agents or resins on the effectiveness of natural fibre reinforcement can also be evaluated.

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