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Structural Performance of Coir Fiber Crash Barriers: An Engineering Analysis of Safety and Sustainability

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Abstract: The coir industry, a traditional sector with deep socio-economic roots in India, is undergoing a critical transformation towards sustainable and value-added applications. As India aims for net-zero carbon emissions by 2050, the transportation sector's environmental impact necessitates sustainable infrastructure solutions. This study explores natural coir fiber, a biodegradable byproduct of coconut husks, as an eco-friendly alternative to conventional steel and concrete crash barriers. Focusing on the National Highway Authority of India's NH66 project, the research evaluates coir's mechanical properties, including tensile strength and energy absorption, alongside its durability and safety performance through prototype testing and ANSYS crash simulations. Results demonstrate that coir-based barriers offer comparable safety standards to traditional materials while significantly reducing carbon emissions (0.83 kg CO_2e/kg versus 1.4–1.85 t CO_2/t for steel and 0.93 lb CO_2/lb for concrete). Economically, coir barriers are cost-effective at ₹410/m compared to ₹1586.86–8604.72/m for conventional options, promoting rural livelihoods through coconut industry byproducts. This approach aligns with circular economy principles offering a scalable, low-carbon solution for road safety infrastructure. The findings advocate for further research into coir's long-term durability and standardized implementation to support sustainable development and climate goals.
Keywords: Coir fiber, crash barriers, sustainability, zero carbon emissions, road safety.

I. INTRODUCTION

The accelerating impact of climate change—manifested through rising global temperatures, extreme weather events, and ecosystem disruptions—has brought the sustainability of human development activities under intense scrutiny. One of the most critical sectors requiring transformation is infrastructure development, particularly transportation networks, which are expanding rapidly to meet the demands of urbanization, economic growth, and mobility in emerging economies like India. This expansion, however, comes at a significant environmental cost. The transportation sector is a major emitter of greenhouse gases (GHGs), accounting for nearly 10% of India's total emissions and contributing substantially to global carbon output through fuel consumption, material extraction, and infrastructure construction. In line with India's commitment to achieving net-zero emissions by 2050, as outlined in national policies such as the "Panchamrit" strategy announced at COP26, there is a compelling need to transition from conventional construction practices toward greener, more resource-efficient alternatives. Road safety systems, which constitute a vital component of transportation infrastructure, represent an impactful intervention point due to their ubiquity, material intensity, and direct interaction with both vehicular systems and public safety outcomes.

Currently, crash barriers are predominantly constructed using galvanized steel and reinforced concrete. While these materials provide proven mechanical performance, their environmental implications are significant. Steel production alone emits approximately 1.4–1.85 metric tons of CO_2 per ton of output, while concrete contributes roughly 2.05 kg CO_2 per kilogram of material produced (equivalent to 0.93 lb/lb). The production processes for these materials are not only energy-intensive but also contribute to land degradation, dust pollution, water contamination, and depletion of non-renewable resources such as limestone and iron ore. Moreover, the long-term lifecycle of these barriers—encompassing manufacturing, installation, maintenance, and eventual disposal—adds to their environmental footprint. In rural or economically constrained regions, the high initial cost and recurring maintenance expenses of such systems pose logistical and financial challenges, often leading to delayed infrastructure rollouts or

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suboptimal safety provisions.

Against this backdrop, the present study investigates the feasibility of utilizing natural coir fiber—a lignocellulosic fiber derived from the husk of coconuts—as a sustainable alternative for crash barriers, particularly along India's National Highway 66 (NH66), which spans key coastal regions with high coconut production. Coir is a byproduct of the coconut industry and is abundantly available in states like Kerala, Tamil Nadu, and Karnataka. Its advantages extend beyond renewability to include biodegradability, low toxicity, low embodied carbon (~0.83 kg CO_2e/kg), and minimal processing requirements. Mechanical testing was conducted on coir ropes with diameters ranging from 10 to 20 mm. Using a calibrated Hounsfield Monsanto Universal Testing Machine (UTM, Model S/N8889), the ropes were subjected to uniaxial tensile loading under standard laboratory conditions. The results showed breaking loads between 102 and 214 kgf, corresponding to a tensile strength of approximately 5.9 MPa. These findings underscore coir's potential for energy absorption and resistance to impact—key attributes for crash barrier performance.

II. SELECTION OF RAW MATERIAL

Natural coir fiber, extracted from the husk of coconuts (*Cocos nucifera*), was selected as the primary material owing to its abundant availability in India, renewable nature, and environmentally sustainable characteristics. As a biodegradable agricultural byproduct, coir is broadly categorized into two types: brown fiber, obtained from mature coconuts, which exhibits high tensile strength and durability; and white fiber, derived from immature (green) coconuts, known for its greater flexibility but lower strength. For this study, brown coir was selected due to its superior mechanical properties, including a tensile strength of approximately 5.9 MPa, high elongation capacity, and efficient energy absorption. Additionally, its relatively low density (~1200 kg/m³) makes it suitable for lightweight structural applications such as crash barriers. Coir also demonstrates a low carbon footprint (approximately 0.83 kg CO_2e/kg) and requires minimal processing energy, aligning well with sustainable development objectives. Its inherent resistance to microbial degradation and the potential for chemical or physical treatments to enhance durability further support its application in infrastructure-related impact mitigation systems.

Sl. No	Property	Coir Rope
1	Density (kg/m³)	1200
2	Tensile Strength (MPa)	5.9
3	Breaking Load (kgf)	102–214 (10–20 mm diameter)
4	Maximum Tensile Stress (MPa)	5.9
5	Maximum Shear Stress (kPa)	200
6	Youngs Modulus (GPa)	5.0
7	Poisson's Ratio	0.3
8	Bulk Modulus (GPa)	4.167
9	Shear Modulus (GPa)	1.923
10	Maximum Deformation (m)	0.26314 (under impact)
11	Equivalent Elastic Strain (m/m)	1.7311 (under impact)
12	Equivalent von-Mises Stress (MPa)	24.891 (under impact)

Table:2.1 Mechanical Properties of coir rope for Crash Barrier Application

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III. EXPERIMENTAL TESTING

The experimental evaluation commenced with the preparation of coir ropes, 10–20 mm in diameter, procured from the Kerala State Coir Corporation Limited. Tensile testing was performed using a Hounsfield Monsanto Universal Testing Machine (Model S/N8889) to determine the breaking load and tensile strength. The ropes were securely clamped and subjected to uniaxial tension at a controlled loading rate. The tests yielded breaking loads ranging from 102 to 214 kgf, corresponding to an average tensile strength of approximately 5.9 MPa. Flexibility and energy absorption characteristics were further investigated by analyzing elongation under load, demonstrating the material's capability for impact mitigation. Diameter measurements were conducted using digital calipers, while force was precisely monitored using a calibrated load cell. All tests were conducted under standardized laboratory conditions (22 ± 1 °C, 65 ± 5% relative humidity) to ensure data consistency. The results indicate that coir ropes possess commendable tensile strength and energy dissipation properties, affirming their potential for structural and protective applications..

Fig 3.1 Rubberized coir

Fig 3.2 Breaking Load Test of Coir On UTM

IV. PROTOTYPE DEVELOPMENT

The prototype was constructed along National Highway 66 (NH66) in Kerala, India, a region with high coconut cultivation, ensuring local coir availability. Materials included brown coir ropes (10–20 mm diameter, sourced from Kerala State Coir Cooperation Limited), C-section steel posts (IS 2062 grade, 100 mm × 50 mm × 5 mm), and galvanized steel stay rods (12 mm diameter) for structural support. The construction sequence was as follows: (1) site clearance to remove debris and vegetation; (2) ground leveling to ensure a stable base; (3) insertion of stay rods into pre-dug holes at 2 m intervals; (4) tamping C-section steel posts into the ground at 1.5 m spacing using a manual tamper; (5) threading coir ropes horizontally through pre-drilled holes in the posts; and (6) securing ropes with steel clamps to maintain tension. Minimal machinery (hand tools and a manual tamper) was used, reducing installation costs and emissions. The prototype, spanning 10 m, demonstrated structural stability and resilience under environmental conditions, with no degradation observed during the testing period.

Figure 4.1

Figure 4.2

V.FINITE ELEMENT ANALYSIS (FEA) AND DISCUSSION

Finite element analysis (FEA) was performed using ANSYS 2025 R1 Explicit Dynamics to evaluate the coir-based crash barrier's performance under a simulated vehicle impact at 100 km/h. The model geometry replicated the NH66 prototype, comprising coir ropes (10–20 mm diameter, modeled as flexible cylindrical elements), C-section steel posts, and stay rods. Material properties for coir included a density of 1200 kg/m³, tensile strength of 5.9 MPa, Young's modulus of 5.0 GPa, Poisson's ratio of 0.3, bulk modulus of 4.167 GPa, and shear modulus of 1.923 GPa. The steel components used IS 2062 grade properties (Young's modulus: 200 GPa, Poisson's ratio: 0.3).

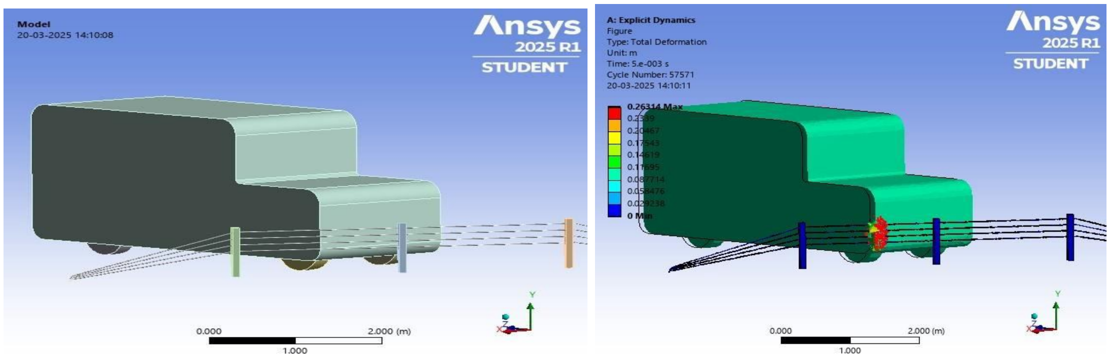

Figure 5.1 FEA Models

The mesh consisted of tetrahedral elements with a refined size of 5 mm near contact zones to ensure accuracy. Boundary conditions fixed the base of the posts, and a frontal impact load was applied using a rigid body (representing a 1500 kg vehicle). The simulation ran for 0.1 seconds to capture dynamic response. Results showed a maximum deformation of 0.26314 m, equivalent elastic strain of 1.7311 m/m, and equivalent von-Mises stress of 24.891 MPa, indicating effective energy dissipation and structural integrity. Lateral deflection remained within acceptable limits for flexible barriers, ensuring safe vehicle redirection. These results, corroborated by experimental data, confirm coir barriers' safety performance is comparable to steel systems. However, further research on moisture resistance and long-term durability is needed to enhance coir's viability for widespread adoption.

VI. CARBON EMISSION AND COST ANALYSIS

A detailed carbon footprint analysis was conducted to evaluate the environmental impact of coir fibre crash barriers compared to conventional materials, focusing on lifecycle emissions from raw material extraction, processing, and installation. Coir fiber exhibited a significantly lower carbon footprint of 0.83 kg CO_2e/kg, derived from its status as a renewable, biodegradable byproduct of the coconut industry, requiring minimal energy for retting, fiber extraction, and rope production. In contrast, steel crash barriers (W-beam systems) have a carbon footprint of 1.4–1.85 t CO_2/t, driven by energy-intensive mining, smelting, and galvanization processes. Concrete barriers emit approximately 0.93 lb CO_2/lb (2.05 kg CO_2/kg), primarily due to cement production, which contributes significantly to global emissions. The coir-based system's emissions are further reduced by its low-energy installation process, which relies on manual tools rather than heavy machinery. This results in up to a 50% reduction in greenhouse gas emissions compared to steel-based systems, aligning with India's net-zero carbon emission target by 2050. Cost analysis revealed coir barriers at 410 INR/m are highly economical compared to W-beam steel barriers (2568.96 INR/m³), cable barriers (1586.86 INR/m), and concrete barriers (6489.39–8604.72 INR/m³), attributed to coir's availability as an agricultural byproduct and low processing costs.

VII. RESULTS

The mechanical properties of coir fibre-based crash barriers were rigorously evaluated through experimental testing and computational simulations, focusing on tensile strength, energy absorption, and structural integrity under impact conditions. Tensile tests conducted on coir ropes of varying diameters (10 mm to 20 mm) revealed breaking loads ranging from 102 kgf to 214 kgf, corresponding to tensile strengths of approximately 5.9 MPa. These results indicate that coir fibre possesses sufficient tensile capacity to withstand significant impact forces, a critical requirement for crash barrier applications. The flexibility and high energy absorption of coir ropes were further validated, with the material demonstrating a maximum deformation of 0.26314 m under simulated impact conditions, as analyzed using ANSYS 2025 R1 Explicit Dynamics.

Sl.No.	Parameter	Metal (Steel) Crash Barrier	Coir Fibre Crash Barrier
1	Material Composition	W-beam steel (galvanized, IS 2062 grade)	Brown coir fibre (from coconut husks)
2	Tensile Strength (MPa)	400–550	5.9
3	Breaking Load (kgf)	Not applicable (rigid structure)	102–214 (10–20 mm rope diameter)

4	Maximum Deformation (m)	Minimal (rigid, <0.1)	0.26314 (flexible, under impact)
5	Equivalent von-Mises Stress (MPa)	350–500 (under impact)	24.891 (under impact)
6	Energy Absorption	Moderate (relies on deformation of posts)	High (flexible ropes dissipate energy)
7	Carbon Footprint	1.4–1.85 t CO2/t	0.83 kg CO2e/kg
8	Cost (INR/m)	2568.96 (W-beam system)	410
9	Installation Complexity	High (requires heavy machinery, welding)	Low (manual tools, minimal machinery)
10	Environmental Impact	High (requires heavy machinery, welding)	Low (manual tools, minimal machinery)
11	Environmental Impact	High (non-renewable, energy-intensive)	Low (renewable, biodegradable)
12	Durability	High (resistant to weathering)	Moderate (requires moisture resistance treatment)
13	Sustainability	Low (non-recyclable in practice)	High (supports circular economy)

Table: 7.1 Comparative Analysis of Metal (Steel) and Coir Fiber Crash Barriers

A comparative carbon footprint analysis underscored the environmental advantages of coir fibre over traditional materials. Coir fiber exhibited a carbon footprint of 0.83 kg CO2e/kg, significantly lower than steel (1.4–1.85 tonnes CO2/tonne) and concrete (0.93 lb CO2/lb). This reduction is attributed to coir's status as a renewable, biodegradable byproduct of the coconut industry, requiring minimal energy for processing. The adoption of coir-based crash barriers could reduce greenhouse gas emissions associated with road infrastructure by up to 50% compared to steel-based systems, aligning with India's net-zero carbon emission target by 2050.

Cost analysis revealed that coir fiber crash barriers are economically viable, with a cost of 410 INR/m, compared to 2568.96 INR/m³ for W-beam steel barriers, 1586.86 INR/m for cable barriers, and 6489.39–8604.72 INR/m³ for concrete barriers. The low cost of coir, coupled with its availability as an agricultural byproduct, makes it an attractive option for large-scale infrastructure projects, particularly in resource-constrained regions. The prototype constructed along NH66 demonstrated practical feasibility, with coir ropes integrated into a flexible barrier system supported by C-section steel posts and stay rods. The construction process, including site clearance, leveling, and rope insertion, was straightforward and required minimal heavy machinery, reducing both cost and emissions associated with installation. Field observations confirmed that the prototype maintained structural stability under environmental conditions, with no significant degradation observed over the testing period.

VIII. CONCLUSION

This study establishes natural coir fiber as a viable, sustainable, and economically advantageous alternative to conventional materials for crash barriers in road infrastructure. Experimental evaluations—including tensile testing and computational simulations via ANSYS—demonstrate that coir-based barriers possess the requisite mechanical properties to effectively absorb impact energy, redirect vehicular motion, and maintain safety performance on par with traditional steel and concrete systems. With a measured tensile strength of approximately 5.9 MPa and significant energy absorption capacity, coir ropes exhibit favorable behavior under dynamic loading conditions, while their inherent flexibility mitigates damage to both vehicles and occupants during collisions.

From an environmental standpoint, coir's low carbon footprint (~0.83 kg CO_2e/kg), biodegradability, and minimal processing requirements position it as a critical material in the pursuit of low-impact infrastructure. Its utilization supports circular economy principles by valorizing agricultural waste, thereby diverting biomass from landfills and promoting sustainable waste management practices. The significantly lower unit cost of coir-based barriers (410 INR/m) enhances their feasibility for deployment in both urban and rural settings, making road safety improvements more accessible and equitable across socio-economic strata.

The successful prototype deployment along National Highway 66 (NH66) underscores the practical scalability of coir-based barrier systems, especially in regions with abundant coconut cultivation. However, technical challenges remain—particularly regarding moisture resistance, biological degradation, and long-term mechanical stability under varying environmental conditions.

Addressing these concerns will require focused research into fiber enhancement techniques, such as bio-based surface treatments, polymer impregnation, or integration into hybrid composite systems.

Looking ahead, the standardization and certification of coir-based crash barriers—through regulatory agencies such as the Bureau of Indian Standards (BIS)—will be crucial to ensuring consistent quality, safety, and public trust. Establishing performance benchmarks, conducting field trials across diverse climatic zones, and developing design guidelines tailored to natural fiber systems will further facilitate their adoption in mainstream infrastructure planning.

In summary, the integration of coir fiber into road safety infrastructure offers a multifaceted opportunity to align India's transportation development with its climate mitigation goals. This research provides a robust foundation for policymakers, engineers, and infrastructure stakeholders to pursue a paradigm shift toward environmentally responsible, socially inclusive, and economically viable crash barrier solutions. As India accelerates its transition to a net-zero future, coir-based barriers represent a compelling innovation at the intersection of engineering, sustainability, and rural development.

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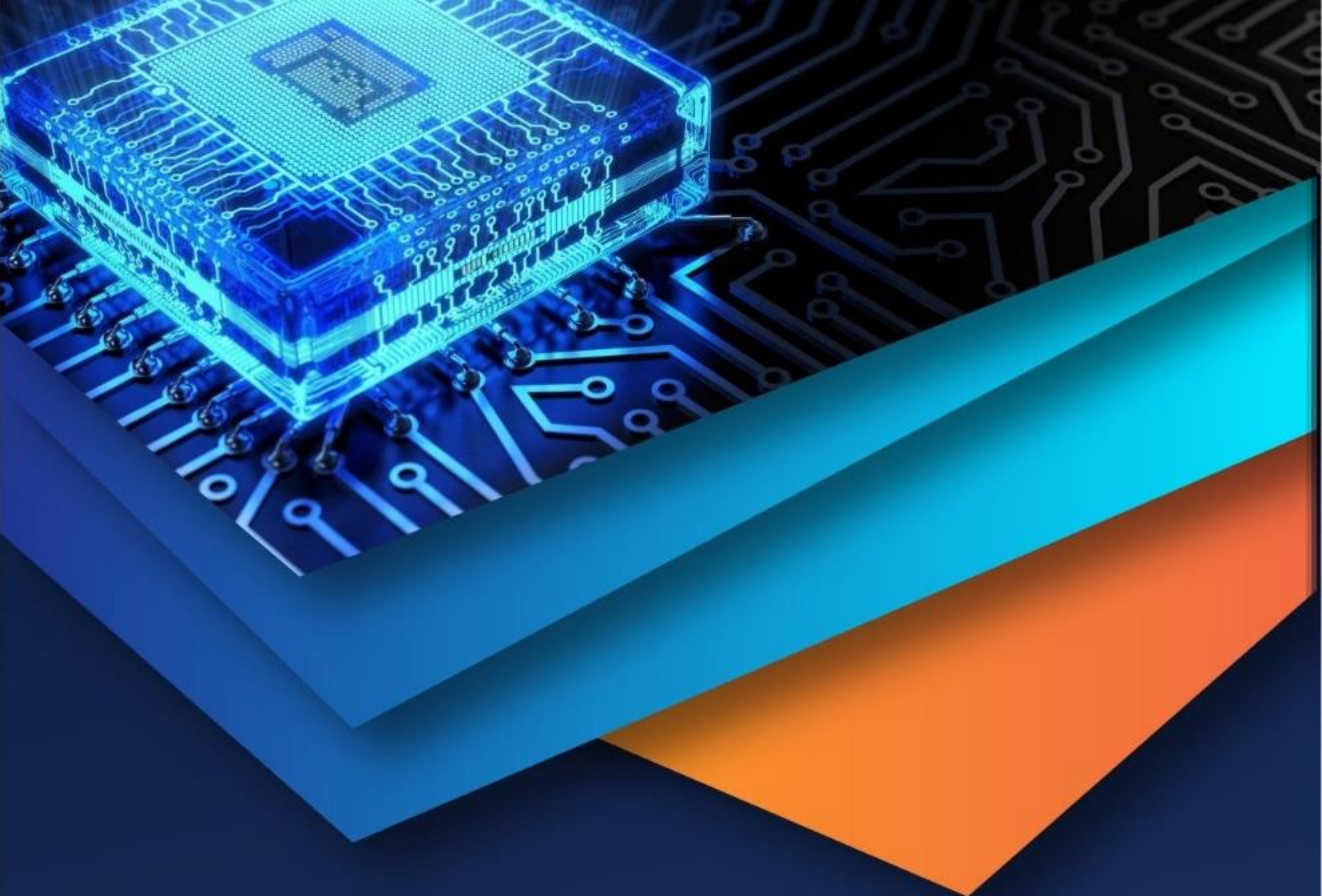

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