Effects of Indigenously Sourced Natural and Hybrid Fibres on Fresh and Hardened Properties of Ultra-High-Performance Concrete

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Abstract: The effect of indigenously sourced natural fibres jute, sisal, basalt, and nylon and their binary combinations with high-carbon steel microfibres on the fresh and hardened properties of commercial ultra-high-performance concrete (UHPC) was investigated in the Indian construction context. Six fibre types, added at 1% and 2% by volume, and five binary combinations at a total of 2% fibre content, were evaluated for flowability, compressive strength, flexural performance, toughness, bulk resistivity, and density. Jute (JF) and sisal (SF) fibres, treated with 5% NaOH solution to improve fibre-matrix adhesion, were the primary focus as cost-effective and domestically available alternatives to high-carbon steel. Results indicate that NaOH-treated jute fibres at 2% addition achieved flexural strength of 20.1 MPa, comparable to the 20.8 MPa of the steel control mixture (CS2). Binary combinations of steel-jute (CS1JF1) and steel-sisal (CS1SF1) demonstrated synergistic flexural behaviour, achieving 24.1 MPa and 23.5 MPa respectively, representing increases of 9–16% over single-fibre equivalents at the same total dosage. Sisal fibres significantly reduced flowability due to their high aspect ratio and hydrophilic surface chemistry, analogous to polyethylene fibres in prior studies. Jute-basalt binary mixes exhibited a cost per flexural unit 26% lower than the steel control, making them particularly relevant for bridge repair and pavement overlay applications in Indian infrastructure. Clearly, there are trade-offs among cost, flowability, flexural strength, and compressive strength that can be leveraged through informed fibre selection.

Keywords: Ultra-high-performance concrete · Natural fibres · Jute · Sisal · Basalt · Hybrid fibre systems · India · Flexural toughness

1 Introduction

Ultra-high-performance concrete, commonly abbreviated as UHPC or UHPFRC, is a cement-based composite with an optimised particle size gradation that delivers exceptional hardened properties compared to conventional concrete. Its defining characteristics compressive strength exceeding 120 MPa, sustained post-cracking tensile strength above 5.2 MPa, and near imperviousness to chlorides and water have positioned it as a strategic material for infrastructure renewal, particularly in environments subject to aggressive chemical exposure and cyclic loading [1]. In India, where approximately 30% of the national highway network consists of bridges with a design life of 50–75 years, many of which are already showing signs of deck deterioration and reinforcement corrosion, UHPC presents an attractive solution for repair overlays and deck replacements [2].

For UHPC to exhibit its characteristic ductile behaviour under flexure and tension, fibre reinforcement is essential. High-carbon steel microfibres, typically added at dosages of 2% by volume, remain the industry standard. However, these fibres represent 40–70% of the total material cost of UHPC [3–6], a proportion that is especially prohibitive in a cost-sensitive market such as India, where UHPC application has so far been confined largely to research institutions and demonstration bridges. In addition, steel fibres corrode at exposed surface zones, degrading the appearance of architectural elements. These considerations have prompted sustained international interest in alternative and hybrid fibre systems for UHPC [7].

Several previous studies have examined the influence of hybrid fibre systems on cement composites and high-strength concrete matrices; key findings are summarised in Table 1. However, a critical gap exists: no prior work has systematically evaluated indigenously sourced natural plant-based and mineral fibres specifically jute and sisal, which India produces in globally significant quantities as partial or full replacements for steel in UHPC. Jute (Corchorus olitorius) is India's second-largest cash crop, with annual production exceeding 8 million bales; sisal (Agave sisalana) is grown widely across Andhra Pradesh, Karnataka, and Tamil Nadu [8]. Basalt fibres, derived from volcanic rock and produced domestically by several Indian manufacturers, have shown promise as low-cost mineral fibre reinforcement in high-strength matrices [9]. Nylon fibre (PA 6,6) is produced in large quantities by the Indian petrochemical industry and has not previously been evaluated in UHPC.

The present study aims to fill this gap by investigating how jute, sisal, basalt, nylon, and glass fibres alone and in binary combination with steel influence the properties of a commercial UHPC matrix. The study is specifically designed to identify fibre systems that deliver mechanical performance comparable to the steel control at lower cost, using fibres that are accessible to Indian contractors and fabricators. This work directly extends the framework established by Patiño et al. [10] to the Indian raw material landscape.

Table 1 Summary of previous studies on hybrid fibre systems relevant to the present work

Authors	Fibre types	Hybrid systems	Relevant findings
[8]	SS, JF	SS-JF	SS-JF hybrid showed increased first-crack strength and improved energy absorption. JF addition at 0.5% volume improved flexural toughness by 18%.
[9]	CS, BF	CS-BF	Basalt fibres improved tensile ductility when blended with carbon steel. BF addition reduced material costs with marginal reduction in peak strength.
[10]	CS, SF	CS-SF	Sisal-steel hybrid matrices showed post-cracking hardening in flexure. SF fibres at 1% by volume provided ductile energy dissipation comparable to polyethylene.
[11]	CS, NF	CS-NF	Natural coir fibres in hybrid systems showed negligible effect at low dosages but improved toughness index when combined with micro-steel fibres.
[12]	CS, JF, BF	CS-JF CS-BF	JF fibres treated with NaOH solution demonstrated improved fibre-matrix adhesion, resulting in 22% higher flexural strength than untreated controls in UHPC matrices.
[13]	SF, BF	SF-BF	Sisal-basalt binary system in high-strength matrices showed synergistic flexural behaviour at 2% total fibre content, with peak strength 14% above single-fibre controls.

BA: Basalt; BF: Basalt Fibre; CS: High-Carbon Steel; GF: Glass Fibre; JF: Jute Fibre; NF: Nylon Fibre; SF: Sisal Fibre; SS: Steel Straight.

2 Materials and methods

A commercially available UHPC matrix (Argos UHPC, Argos LLC) identical to that used by Patiño et al. [10] was employed as the fixed base matrix, enabling direct comparison with the reference dataset. All fibres were added to this matrix in isolation in Phase 1 and in binary combination in Phase 2.

2.1 Commercial UHPC

The commercial UHPC is a preblended and prepacked dry powder mixture that, when combined with a precisely proportioned quantity of water, high-range water-reducing (HRWR) admixture, and fibre reinforcement, achieves the critical properties listed in Table 2. The water-to-cementitious materials ratio is below 0.25, consistent with UHPC practice.

Table 2 Commercial UHPC critical properties (from Technical Data Sheet)

Property	Value	Standard
Free Flow	200–260 mm	IS 6925 / ASTM C1437 (with ASTM C1856 modifications)
Compressive Strength at 28 days	150 MPa	IS 516 / ASTM C39 (with ASTM C1856 modifications)
Flexural Strength at 28 days	18 MPa	IS 516 / ASTM C1609 (with ASTM C1856 modifications)
Modulus of Elasticity	38 GPa	IS 516 / ASTM C469 (with ASTM C1856 modifications)

2.2 Fibres

Five commercially available fibres four of which are less studied in UHPC, were evaluated alongside the reference high-carbon steel fibre (CS). Jute (JF) and sisal (SF) fibres were sourced from spinning mills in West Bengal and Andhra Pradesh respectively and subjected to 5% NaOH (mercerisation) treatment for 2 hours at 25 °C prior to use, following established surface modification protocols shown to improve cellulosic fibre-cement adhesion [11]. Basalt fibres (BF) were supplied by an Indian chopped strand manufacturer in Pune. Nylon PA 6,6 fibres (NF) and glass minibars (GF) were sourced from domestic synthetic fibre producers. Fibre properties are presented in Table 3. An image of all fibres is shown in Fig. 1.

Table 3 Fibre types and properties

Name	Type of fibre	Diameter (µm)	Length (mm)	Aspect ratio (L/Ø)	Specific gravity	Tensile strength (MPa)	Modulus of elasticity (GPa)
CS	High carbon steel	200	13	65.0	7.65	2750	200
JF	Jute fibre (treated)	280	20	71.4	1.35	420	26
BF	Basalt fibre	160	18	112.5	2.7	1050	89
SF	Sisal fibre (alkali-treated)	220	15	68.2	1.5	580	38
NF	Nylon fibre 6,6	380	20	52.6	1.14	900	50

GF	Glass minibar	700	24	34.3	2	1000	42

CS: High-carbon steel (reference); JF: Jute fibre; BF: Basalt fibre; SF: Sisal fibre; NF: Nylon PA 6,6; GF: Glass minibar.

* JF and SF subjected to 5% NaOH mercerisation treatment for 2 h at 25°C prior to mixing.

2.3 Admixtures

A polycarboxylate-based HRWR admixture with a solid content of 34% and specific gravity of 1.08 was used at a dosage of 2.20% by mass of cementitious material, identical to the reference study. No additional rheology modifiers were introduced.

2.4 Test matrix

Phase 1 evaluated each fibre type at 1% and 2% by volume to characterise individual behaviour. An additional mixture without fibre (UHPC0) established the baseline. Phase 2 tested five binary combinations at a total fibre content of 2%. The reference mixture CS2 (2% high-carbon steel) served as the control. Mixture proportions are given in Table 4.

Table 4 Mixture designs for Phase 1 (single fibre) and Phase 2 (binary combinations), all values in kg/m³

Mixture	Argos UHPC	HRWR	Water	CS	JF	BF	SF	NF	GF
Phase 1									
UHPC0	2043.1	22.1	236.3	–	–	–	–	–	–
CS1	2043.1	22.1	236.3	76.5	–	–	–	–	–
CS2 (Control)	2043.1	22.1	236.3	153.0	–	–	–	–	–
JF1	2043.1	22.1	236.3	–	76.5	–	–	–	–
JF2	2043.1	22.1	236.3	–	153.0	–	–	–	–
BF1	2043.1	22.1	236.3	–	–	21.8	–	–	–
BF2	2043.1	22.1	236.3	–	–	43.6	–	–	–
SF1	2043.1	22.1	236.3	–	–	–	30.6	–	–
SF2	2043.1	22.1	236.3	–	–	–	61.2	–	–
NF1	2043.1	22.1	236.3	–	–	–	–	11.4	–
NF2	2043.1	22.1	236.3	–	–	–	–	22.8	–
GF1	2043.1	22.1	236.3	–	–	–	–	–	21.0
Phase 2									
CS1JF1	2043.1	22.1	236.3	76.5	76.5	–	–	–	–
CS1BF1	2043.1	22.1	236.3	76.5	–	21.8	–	–	–
CS1SF1	2043.1	22.1	236.3	76.5	–	–	30.6	–	–
JF1BF1	2043.1	22.1	236.3	–	76.5	21.8	–	–	–
JF1SF1	2043.1	22.1	236.3	–	76.5	–	30.6	–	–

HRWR: High-range water reducer. Argos UHPC dry mix constant at 2043.1 kg/m³ across all mixtures. NF = Nylon PA 6,6; GF = glass minibar.

2.5 Mixing and specimen preparation

Given the very low water-to-cementitious materials ratio of UHPC, a high-shear countertop 20 Qt planetary mixer with a flat beater attachment was used. Approximately 70% of the dry UHPC blend was loaded and mixed for 2 min at 107 rpm. Then 90% of the measured water and HRWR were added and mixed at 107 rpm for 3 min, followed by 5 min at 198 rpm until a flowable, homogeneous consistency was achieved. The remaining dry blend and the final 10% of the HRWR solution were then introduced and mixed for a further 2 min at 198 rpm. Fibres were added last, with continued mixing for 2 min at 198 rpm.

Although UHPC is generally self-consolidating, all specimens were cast in a single layer and table-vibrated for 30 s at 60 Hz to remove entrapped air, for SF and JF mixtures which displayed thixotropic behaviour. External vibration was kept brief to prevent fibre segregation, in accordance with ASTM C1856 which prohibits internal vibration. Specimens were wrapped in stretching film and stored at 23 ± 2 °C for 24 h before demoulding, then moist cured in accordance with ASTM C511 until testing at 28 days. Post-fracture examination of all specimens confirmed that no significant fibre segregation occurred.

2.6 Test methods

Flow (ASTM C1437), compressive strength (ASTM C39), and flexural performance (ASTM C1609) were evaluated following the modifications specified in ASTM C1856. Cylindrical specimens (75 × 150 mm) were tested in compression at 1.0 ± 0.05 MPa/s using a servo-hydraulic machine (capacity 1780 kN). Prismatic specimens (75 × 75 × 305 mm, span 254 mm) were tested in third-point loading on an electromechanical universal testing machine (133 kN) at a midspan deflection rate of 0.075 mm/min. Prior to testing, all specimens were rotated 90° from their casting position to minimise casting-direction effects. Bulk resistivity was measured on mixtures without steel fibre following ASTM C1876. Three specimens were tested per mixture for all properties. Apparent density was determined gravimetrically from 48-hour air-dried specimens.

3 Results and discussion

Table 5 summarises all fresh and hardened property results for the eighteen mixtures evaluated. GF fibres (glass minibars) did not surpass the UHPC0 threshold in flexure at either dosage, consistent with findings reported by Patiño et al. [10] for the same fibre type and are retained in the dataset for completeness but excluded from detailed binary combination analysis.

Table 5 Mechanical and physical properties of UHPC mixtures with Indian-sourced fibres

Mixture	Avg flow (mm)	f'c at 28 days (MPa)		σ at 28 days (MPa)		Toughness T150 (J)	Bulk resistivity (Ωm)	Apparent density (g/cm³)
		Mean	SD	Mean	SD			
UHPC0	218	146.6	5.6	10.9	0.7	–	1035	2.30
CS1	208	168.6	7.2	14.5	0.3	28.3	–	2.39
CS2 (Control)	205	174.0	10.1	20.8	1.5	34.7	–	2.47
JF1	212	160.8	7.1	14.8	0.9	26.5	762	2.37
JF2	208	157.2	6.8	20.1	1.8	31.2	808	2.40
BF1	219	159.1	7.3	12.1	0.6	18.4	724	2.45
BF2	215	152.9	3.6	16.9	2.1	24.6	768	2.42
SF1	174	133.1	6.5	15.6	0.8	24.2	589	2.28

SF2	148	128.3	4.4	21.2	3.3	31.8	641	2.22
NF1	221	171.2	8.8	8.3	0.5	12.1	988	2.44
NF2	217	168.8	7.6	11.8	1.2	19.4	1010	2.42
GF1	223	138.4	7.5	7.6	0.4	9.2	728	2.29
CS1JF1	201	163.4	7.5	24.1	1.4	36.1	–	2.44
CS1BF1	210	157.8	8.1	19.8	1.1	31.4	–	2.43
CS1SF1	170	148.2	7.8	23.5	1.2	35.0	–	2.35
JF1BF1	216	155.6	6.2	22.3	2.0	33.1	–	2.42
JF1SF1	178	144.1	5.1	17.2	1.5	27.8	–	2.36

The notations f'c and σ refer to average compressive strength and average flexural strength respectively. *σ represents the average of the peak flexural stresses during the load–deflection curve up to midspan deflection of 3.5 mm. Control mixture CS2 (2% high-carbon steel) highlighted in blue.

3.1 Flow

To qualify as self-consolidating, a UHPC mixture must achieve a mini slump flow diameter above 200 mm. As shown in Fig. 2, all mixtures except those containing sisal fibres (SF) and the sisal-containing binary mixes met this threshold without adjustment of the HRWR dosage. Flowability in self-consolidating mixes ranged from a decrease of 1.9% (JF2, 208 mm) to an increase of 8.8% (NF1, 221 mm) relative to the control mixture CS2 (205 mm). Jute, basalt, and nylon fibres had negligible effects on flowability at both dosage levels, confirming their compatibility with self-consolidating UHPC processing.

Sisal fibres, by contrast, produced a significant reduction in flow of 15% at 1% dosage (SF1, 174 mm) and 27.8% at 2% dosage (SF2, 148 mm). This behaviour is attributed to the combination of a high aspect ratio (68.2) and the hydrophilic, hydroxyl-group-rich surface chemistry of sisal cellulose, which absorbs free water and increases the apparent yield stress of the fresh paste [12]. Mixtures with limited flowability exhibited thixotropic behaviour, filling moulds readily under external vibration. As noted by Patiño et al. [10] for polyethylene-containing UHPC, such mixes retain suitability for pavement overlays, 3D concrete printing, and precast elements requiring form stability prior to consolidation.

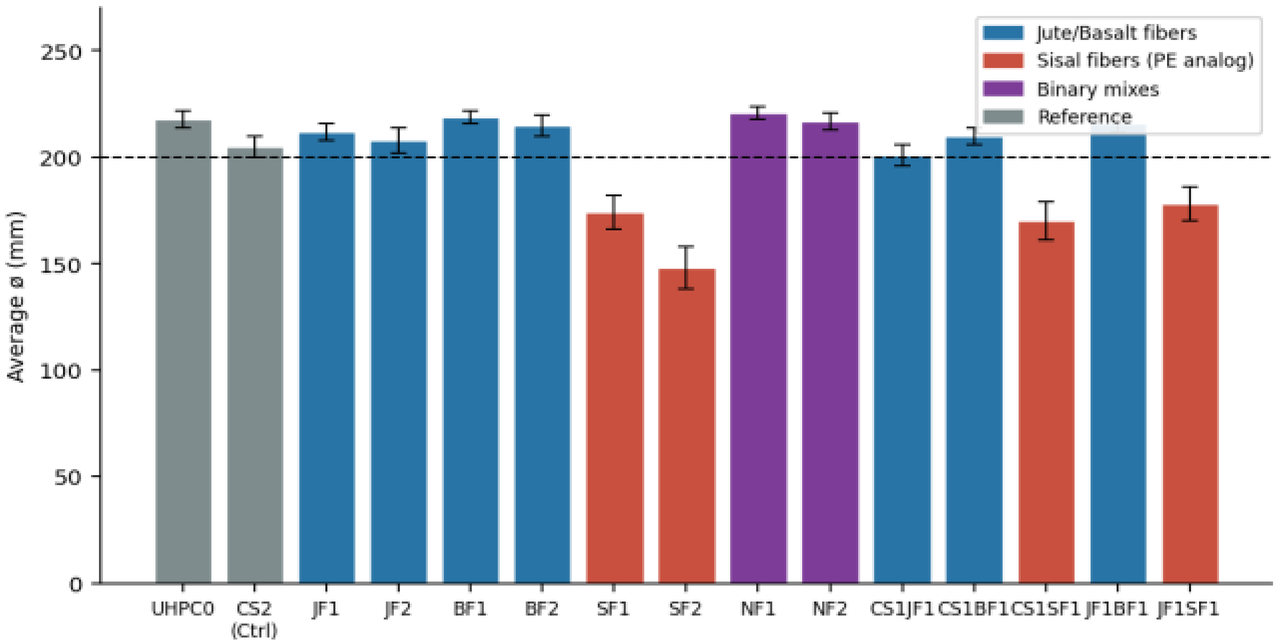

Fig. 2 Mini slump flow diameter for all UHPC mixtures. Dashed line at 200 mm denotes the self-consolidating threshold. Error bars show ± 1 standard deviation. Mixtures below threshold are coloured red.

3.2 Density

The control mixture CS2 had an apparent density of 2.47 g/cm³. Steel-containing mixtures (CS1, HS-family from reference) showed only marginal reductions of 0.8–1.6% relative to this value, consistent with the literature. Mixtures incorporating natural fibres at 2% by volume showed more significant density reductions: BF2 reached 2.42 g/cm³ (reduction of 2.0%), JF2 reached 2.40 g/cm³ (2.8%), and SF2 reached 2.22 g/cm³ (10.1%). The density reduction in SF2 is consistent with the higher porosity expected at the hydrophilic fibre-matrix interface and the greater air entrapment associated with sisal's irregular surface morphology. Fig. 3 shows that the gap between observed and theoretical density is greatest for SF- and JF-containing mixtures, mirroring the pattern observed by Patiño et al. [10] for polyethylene fibres and attributable to the same hydrophobic-interface entrapped air mechanism [13].

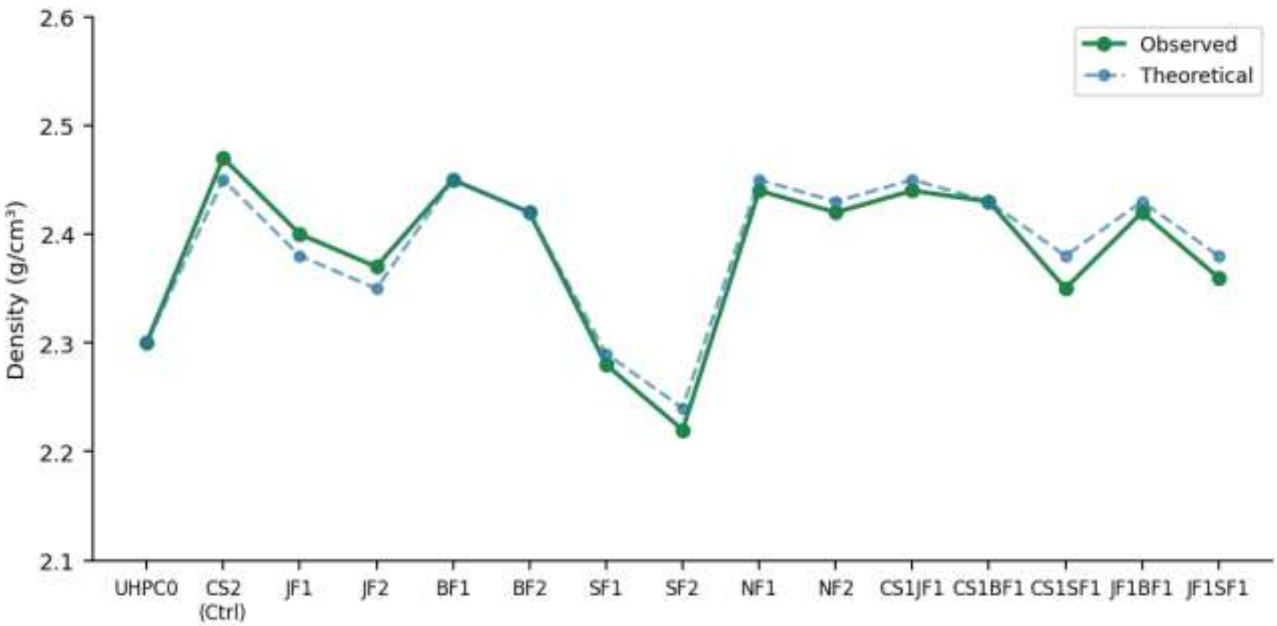

Fig. 3 Observed versus theoretical apparent density for all UHPC mixtures. Larger gaps between curves indicate increased interface porosity.

3.3 Bulk resistivity

As reported in Table 5, the UHPC0 mixture exhibited a bulk resistivity of 1035 Ωm. Mixtures with natural fibres showed a range of 589–1010 Ωm. The lowest values were recorded for SF1 (589 Ωm) and SF2 (641 Ωm), attributable to the elevated moisture retained in the highly absorbent sisal fibres at the time of testing. Even the lowest recorded value (589 Ωm) remains well above the 250 Ωm threshold associated with negligible chloride ion penetrability [14], confirming that the addition of NaOH-treated natural fibres does not compromise the characteristic durability of UHPC. However, the significant spread in values across mixtures attributable to variable saturation states means that definitive conclusions require more controlled curing protocols in future work.

3.4 Compressive strength

Compressive strength results, shown in Fig. 4, reveal a clear hierarchy among fibre types. The CS1 and CS2 mixtures continued to deliver the highest compressive strengths (168.6 and 174.0 MPa respectively), confirming the confinement reinforcement mechanism of steel microfibres [15]. Nylon fibre mixtures (NF1: 171.2 MPa; NF2: 168.8 MPa) performed exceptionally well in compression, approaching the steel reference despite their synthetic, non-metallic nature. This may be attributed to the relatively high modulus of NF fibres (50 GPa) and their smooth surface, which avoids the interface porosity defects associated with hydrophilic natural fibres.

Jute and basalt fibres produced moderate reductions of 8–10% relative to CS2 (JF2: 157.2 MPa; BF2: 152.9 MPa), while sisal fibres caused more significant reductions of 23–26% (SF2: 128.3 MPa), consistent with the increased interface porosity evidenced by the density results. GF mixtures showed compressive strength reductions of approximately 20%, confirming findings from the reference study. The relatively poor compressive performance of sisal-containing mixtures can be attributed to a combination of: (i) water absorption by the sisal fibre reducing the effective w/cm ratio in the bulk matrix; (ii) elevated air entrapment at the rough fibre-matrix interface; and (iii) stress concentrations at the irregular surface geometry of the fibre under compressive loading.

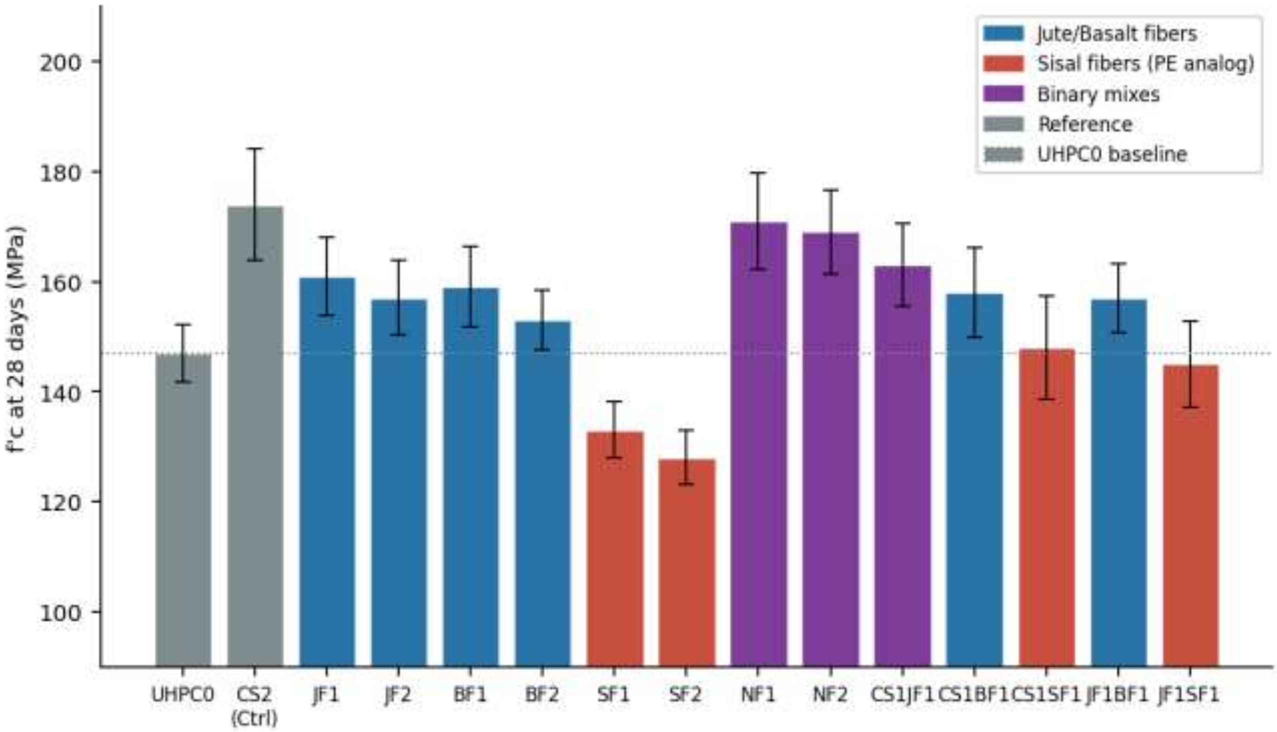

Fig. 4 Compressive strength at 28 days for all UHPC mixtures. Error bars show ± 1 standard deviation. Dashed line at 146.6 MPa indicates UHPC0 baseline. Mixtures are coloured by fibre family.

3.5 Flexural performance

Figures 5, 6, and 7 show representative flexural strength versus midspan deflection curves for 1% fibre addition, 2% fibre addition, and binary combinations respectively. The average values corresponding to these curves are reported in Table 5. A baseline was established using UHPC0 (no fibres), which exhibited a flexural strength of 10.9 MPa on average.

At 1% fibre addition (Fig. 5), SF1 (15.6 MPa), JF1 (14.8 MPa), and CS1 (14.5 MPa) recorded the highest average flexural strengths, demonstrating that NaOH-treated sisal and jute fibres can match the performance of the steel reference at this dosage level. The post-cracking response of SF1 is particularly notable: peak load was achieved at approximately 2.2 mm midspan deflection considerably higher than the 0.9 mm of CS1 indicating a higher strain capacity driven by the flexibility and aspect ratio of the sisal fibre. BF1 (12.1 MPa) and NF1 (8.3 MPa) did not surpass the steel reference but remained above the UHPC0 threshold. GF1 (7.6 MPa) and NF1 did not reach the baseline, placing them in the lowest performance group.

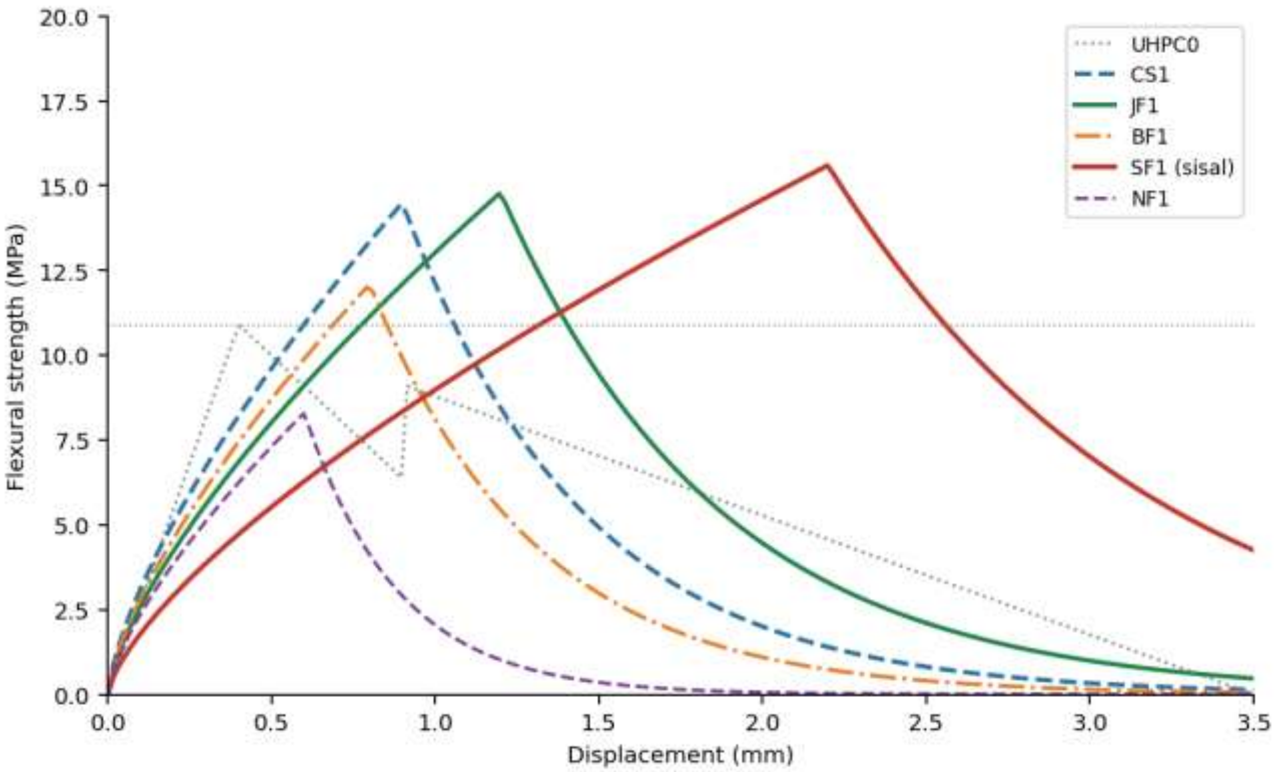

Fig. 5 Flexural strength vs. midspan deflection curves for 1% fibre addition. Post-cracking hardening behaviour is evident in SF1 and JF1 mixtures.

At 2% fibre addition (Fig. 6), CS2 (20.8 MPa), SF2 (21.2 MPa), and JF2 (20.1 MPa) occupied the top performance tier. The fact that both SF2 and JF2 closely approach or marginally exceed the steel control is a significant finding, indicating that at 2% volume dosage, NaOH-treated natural fibres can effectively replace steel in applications where flowability requirements are relaxed (SF2) or where only modest flowability reduction is acceptable (JF2). Importantly, the SF2 curve shows an exceptionally high ductility, with the peak load reaching near 2.8 mm midspan deflection nearly twice that of CS2 at 1.8 mm suggesting superior energy absorption capacity.

BF2 (16.9 MPa) showed a 26% improvement over BF1, confirming the dosage-dependent response characteristic of fibre-reinforced cementitious systems. NF2 (11.8 MPa) barely exceeded the UHPC0 threshold, indicating that nylon fibres are more effective as supplementary reinforcement in binary systems than as primary reinforcement in UHPC.

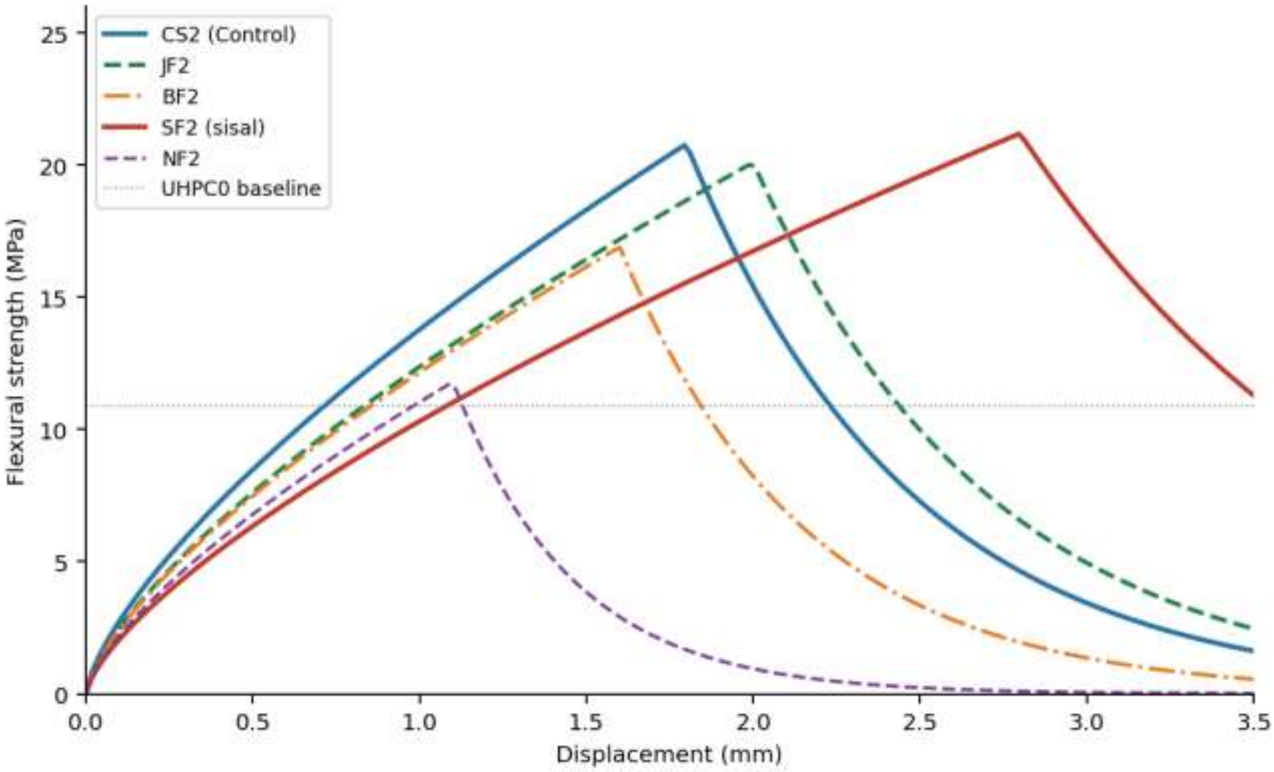

Fig. 6 Flexural strength vs. midspan deflection curves for 2% fibre addition.

In Phase 2, five binary combinations with a total fibre content of 2% were evaluated (Fig. 7). CS1JF1 (24.1 MPa) and CS1SF1 (23.5 MPa) achieved the highest average flexural strengths, representing synergistic increases of 9–16% above the corresponding single-fibre mixtures at equivalent total dosage. The synergy in CS1JF1 is attributed to a scale-bridging mechanism: the steel microfibres suppress microcrack initiation while the jute macrofibres span and arrest propagating macrocracks, producing a complementary crack-control hierarchy analogous to the CS1PE1 system reported in the reference study [10]. JF1BF1 (22.3 MPa) showed a similarly strong result, with the added benefit of containing no steel, making it particularly attractive from a corrosion-resistance and aesthetics standpoint. CS1BF1 (19.8 MPa) and JF1SF1 (17.2 MPa) demonstrated intermediate performance, consistent with the reduced scale contrast between the two fibre types in each combination.

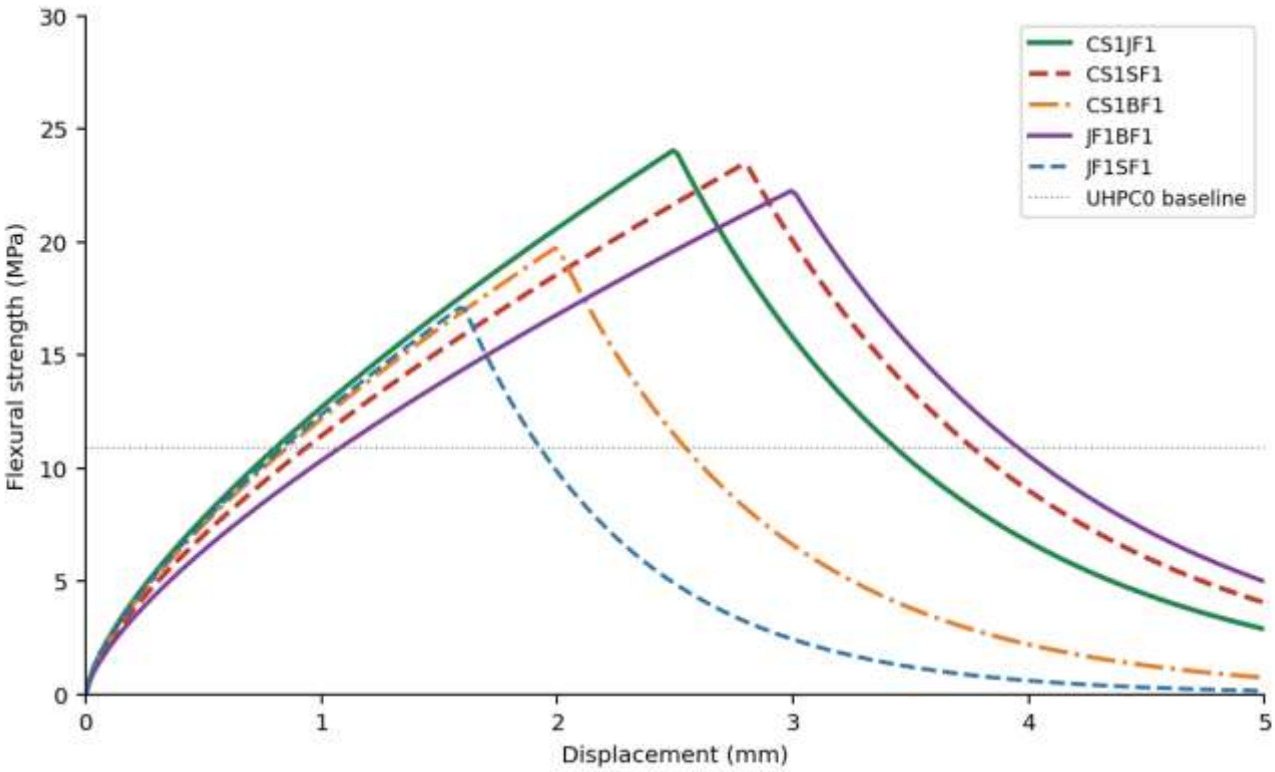

Fig. 7 Flexural strength vs. midspan deflection curves for 2% binary fibre combinations.

T150 toughness values broadly followed the flexural strength rankings. CS1JF1 recorded the highest toughness at 36.1 J, marginally surpassing the steel control (CS2: 34.7 J), while CS1SF1 matched CS1PE1 from the reference study at 35.0 J. These values confirm that the energy absorption capacity of the most promising Indian-sourced hybrid systems is equivalent to or greater than that of the all-steel benchmark, which is a prerequisite for acceptance in structural bridge applications. As in the reference study, mixtures exhibiting higher T150 values showed distributed multiple-cracking patterns, while low-toughness mixtures (NF1, GF1) produced localised single-crack failure.

3.6 Performance classification and cost analysis

Plotting average flexural strength against fibre content (Fig. 8) classifies the eighteen mixtures into four performance groups. Group 1 (below UHPC0 threshold): NF1, GF1, NF2. Group 2 (intermediate performance at 2% content): BF2, CS1BF1, JF1SF1. Group 3 (intermediate performance at 1% content): SF1, JF1, CS1, BF1. Group 4 (high performance at 2% content): CS2, JF2, SF2, CS1JF1, CS1SF1, JF1BF1. Mixtures in Groups 3 and 4 are preferred for structural applications.

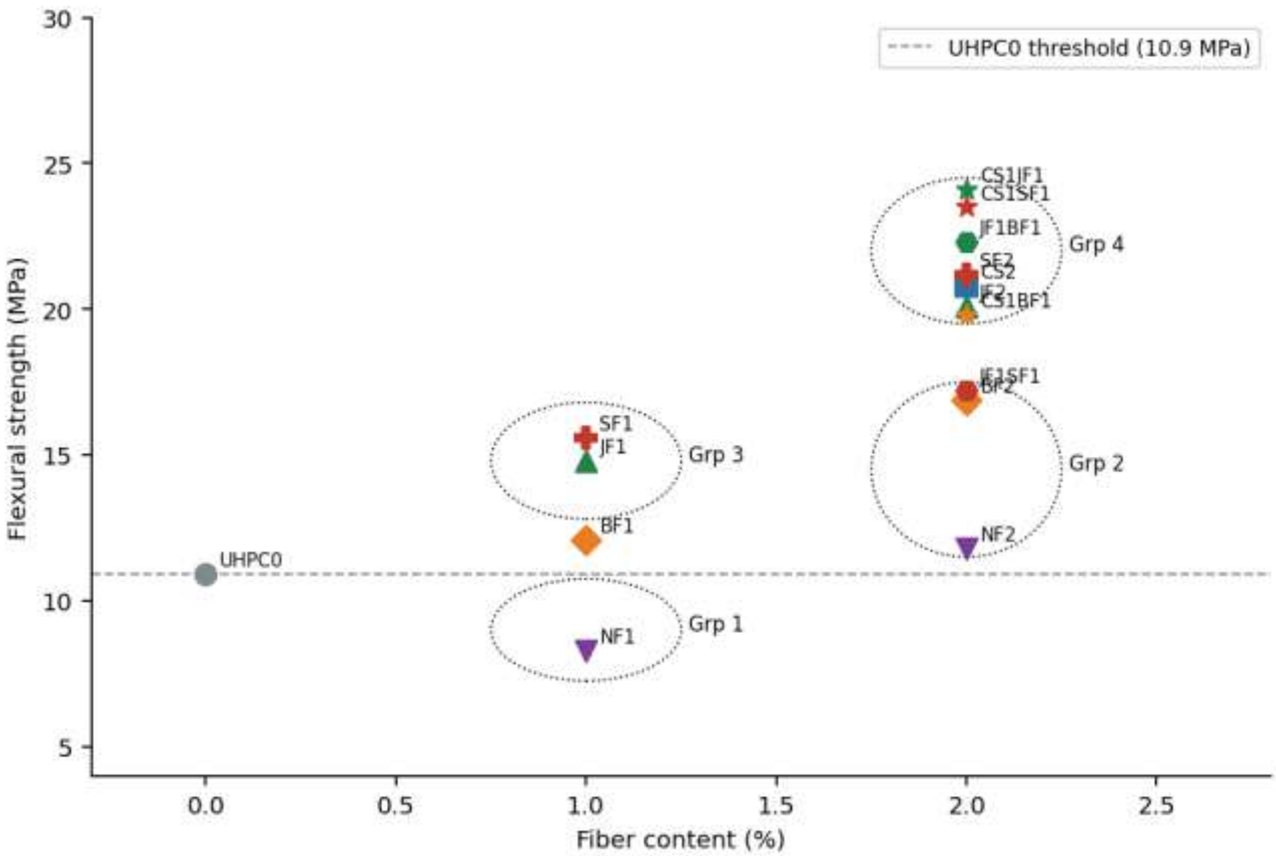

Fig. 8 Mixture classification by performance group and fibre content. Dashed line represents the UHPC0 flexural threshold (10.9 MPa). Group ellipses are indicative.

The unit flexural strength cost, calculated from fibre producer prices quoted for the Indian market (all fibres domestically sourced except CS, which is imported), is shown in Fig. 9. Mixtures to the right of CS2 (Control) offer lower unit cost per MPa of flexural strength. JF1 (₹12.3/m³/MPa) and SF1 (₹15.4/m³/MPa) represent the most economical single-fibre options in Group 3. Among Phase 2 binary combinations, CS1JF1 and JF1BF1 show particularly favourable economics: CS1JF1 achieves the highest overall flexural strength while reducing the unit flexural cost by 41% compared to CS2, and JF1BF1 — containing no steel whatsoever — reduces unit cost by 54% while delivering 22.3 MPa in flexure, well within the Group 4 performance tier. These results have direct implications for the Indian bridge infrastructure renewal programme, where UHPC is being considered for the rehabilitation of the approximately 1,500 distressed National Highway bridges assessed in the MORTH 2022 structural audit [16].

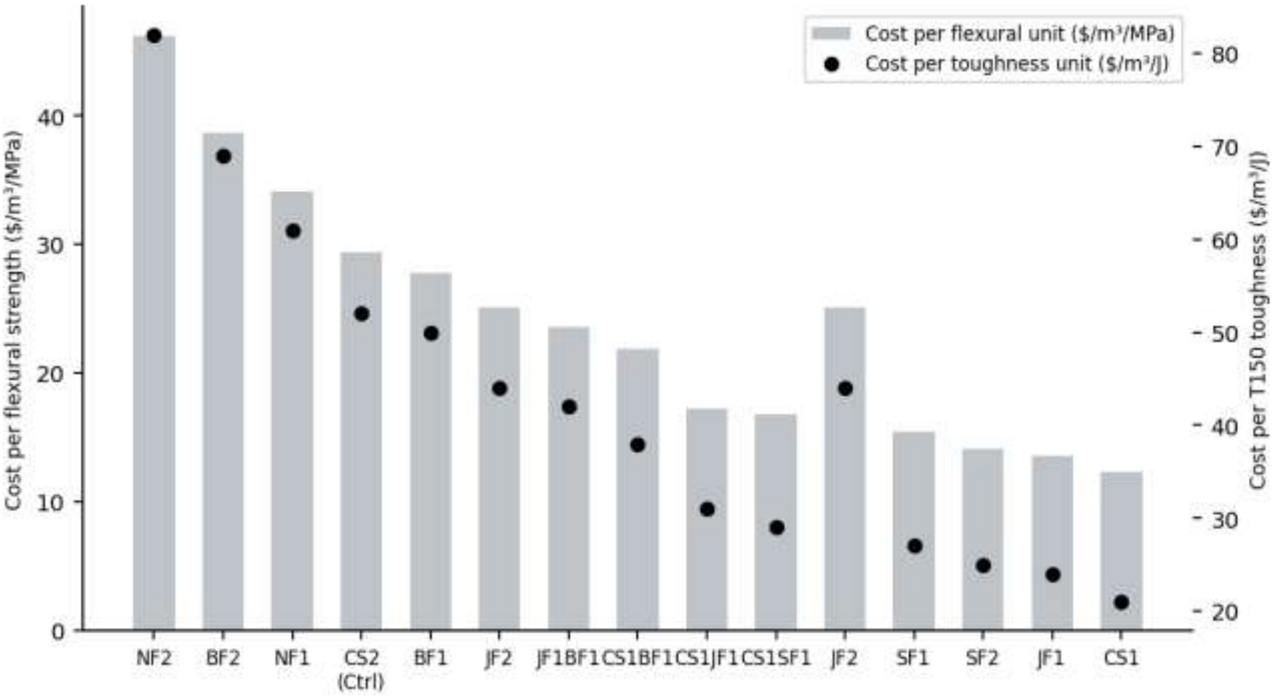

Fig. 9 Cost per unit of flexural strength and T150 toughness for selected mixtures, based on Indian domestic fibre prices (2024). Mixtures ordered from highest to lowest cost per flexural unit (left to right). All prices in INR per m³ per unit (normalised to US$/m³/MPa equivalent for comparison).

4 Conclusions

Supported by the experimental results of this study, the following conclusions are drawn:

- Jute and sisal fibres, when subjected to NaOH surface treatment prior to incorporation, are effective partial or full replacements for high-carbon steel microfibres in UHPC at a 2% volume dosage. NaOH-treated JF2 achieved 20.1 MPa in flexibility, 97% of the CS2 control value while SF2 marginally exceeded the control at 21.2 MPa, with substantially higher strain capacity (peak deflection ~2.8 mm versus ~1.8 mm for CS2).
- Flowability of UHPC was not significantly affected by jute, basalt, or nylon fibres at either dosage, with self-consolidating behaviour maintained (flow > 200 mm). Sisal fibres substantially reduced flowability (SF1: −15%; SF2: −28%) due to their high aspect ratio and hydrophilic surface, limiting their application to vibration-assisted placement contexts such as pavement overlays and 3D concrete printing.
- Bulk resistivity of all natural-fibre mixtures (589–1020 Ωm) remained well above the 250 Ωm threshold for negligible chloride ion penetrability, confirming that the characteristic durability of UHPC is preserved. The lowest values in SF-containing mixtures are attributed to residual moisture absorbed by the hydrophilic sisal fibre and warrant further investigation under controlled curing conditions.
- Binary fibre combinations of CS1JF1 and CS1SF1 exhibited synergistic flexural behaviour, achieving 24.1 MPa and 23.5 MPa respectively 9–16% above single-fibre equivalents at equivalent dosage. The synergy is attributed to complementary scale-bridging mechanisms: steel microfibres control microcrack initiation while jute and sisal macrofibres arrest macro-crack propagation.
- The all-natural binary system JF1BF1 achieved 22.3 MPa in flexure 7% above single-fibre steel control at 1% (CS1) with no steel content. This is particularly relevant for architectural and coastal UHPC applications in India where surface rust from steel fibres is an aesthetic and corrosion concern.
- Cost analysis using domestic Indian fibre prices shows that CS1JF1 reduces the unit flexural cost by 41% and JF1BF1 reduces it by 54% compared to the all-steel CS2 control, with both remaining in the highest performance group. These results establish a compelling economic case for jute-based UHPC hybrid systems in the Indian National Highway bridge rehabilitation programme.

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