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Effect of Sisal and Jute Fibre Addition on Mechanical Strength, Toughness, and Durability Properties of M25 Concrete

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ABSTRACT

Natural fibre reinforced concrete (NFRC) presents a sustainable alternative to synthetic fibre systems, leveraging India's abundant agricultural biomass as structural reinforcement [25],[26]. This paper investigates the mechanical and durability properties of M25 grade concrete reinforced with sisal fibre and jute fibre at four volume fractions (0%, 0.5%, 1.0%, 1.5%), using an M25 base mix designed per IS 10262: 2019 [8]. Both fibres were alkali pre-treated with 5% NaOH per Mwaikambo and Ansell [22]). Fresh properties, 28-day compressive strength [7]), split tensile strength [16]), flexural strength and toughness index (I_5 per ASTM C1018 [28])), impact resistance per ACI 544 [1]), and water absorption are evaluated. The study establishes that sisal at 1.0% achieves the best overall performance: 31.6 MPa compressive strength (IS 456 M30 [6] compliant), split tensile 3.84 MPa (+23.5%), flexural strength 4.62 MPa (+22.9%), toughness index $I_5 = 4.82$, and impact resistance $N_2 =$ 38 blows (+171% over reference). Jute at 0.5% achieves the highest compressive strength improvement (+6.4%, 32.1 MPa) with excellent workability and the lowest water absorption (3.4%, −19% vs. reference). Both sisal-1.0% and jute-0.5% satisfy IS 456: 2000 [6] M30 requirements. An IS 456-based compliance assessment is provided for all mixes, and a sustainability comparison quantifies the embodied CO_2 advantage of natural fibres over polypropylene [20],[11].

Keywords Natural Fibre Concrete [25], Sisal [29],[4], Jute [27],[19], IS 456 [6], Compressive Strength [7], Toughness [28], Impact Resistance [1], NaOH Treatment [22], Sustainability [20],[11].

INTRODUCTION

Concrete is the world's most consumed construction material, with India's construction sector placing it at the centre of a growing tension between infrastructure development and environmental sustainability **[21]**. The fundamental brittleness of plain concrete tensile strength typically 8–12% of compressive strength **[24]**) and negligible energy absorption after first crack has long been addressed through fibre reinforcement. Fibre-reinforced concrete (FRC) transforms the failure mode from brittle to pseudo-ductile by providing crack bridging resistance through fibre pullout **[23],[28]**.

Steel fibres and polypropylene (PP) fibres dominate commercial FRC practice, but both carry significant environmental and economic costs **[25]**). Steel fibre production has high CO_2 intensity; PP fibre is petrochemical-derived at approximately 3.0 kg CO_2/kg **[20]**). For a developing country like India, with a large rural construction sector and aggressive affordable housing targets, the cost of synthetic FRC is a significant barrier **[25]**). Natural plant-based fibres particularly sisal and jute, which India produces in abundance **[26]** offer a compelling alternative: comparable crack-bridging performance, 10–19× lower embodied CO_2 per kilogram **[20]**), and 2–4× lower material cost per cubic metre of concrete **[25]**.

Sisal fibre (from Agave sisalana) has the highest tensile strength of Indian natural fibres (400–700 MPa **[4],[29]**)) and has been studied internationally for cement composites, most notably by Toledo Filho et al. **[29]**). Jute fibre (from Corchorus capsularis) is India's most produced bast fibre at 1.1 million tonnes annually **[26]**), with moderate tensile strength (200–450 MPa **[22],[27]**)) and established use in mortar and concrete by Ramakrishna and Sundararajan **[27]**) and Islam et al. **[19]**). Despite this body of research, a direct comparative study of sisal and jute fibres under identical IS 10262: 2019 **[8]** M25 mix design conditions, with comprehensive mechanical and toughness evaluation, IS 456: 2000 **[6]** compliance assessment, and sustainability quantification, has not been published. This paper addresses this gap.

The specific contributions are: (i) controlled comparative characterisation of sisal and jute FRC at 0%, 0.5%, 1.0%, and 1.5% V_f under identical conditions; (ii) toughness index and ACI 544 impact evaluation **[1],[28]**); (iii) IS 456: 2000 **[6]**) compliance assessment; and (iv) embodied CO_2 and cost comparison with PP fibre FRC **[20],[11]**.

LITERATURE REVIEW

A. Sisal Fibre in Concrete

Sisal is a leaf fibre from Agave sisalana, with tensile strength 400–700 MPa, elastic modulus 9–22 GPa, and cellulose content 60–78% **[4],[22]**). Toledo Filho et al. **[29]**) demonstrated that sisal at 2% volume fraction in cement composites improves flexural toughness by 50–90%. Fidelis et al. **[4]**) characterised sisal's tensile failure modes fibre fracture at high strain rates vs. pullout at low rates establishing the micro-mechanical basis for toughness design. The primary durability concern is alkali degradation: the $Ca(OH)_2$-rich pore solution (pH 12.5–13.5 **[21]**)) attacks sisal's hemicellulose (8–11%) and lignin over time **[29],[30]**). NaOH pre-treatment mitigates this by removing hemicellulose and improving fibre-matrix bond **[22]**). Wei and Meyer **[30]**) confirmed that sisal-GGBS composites maintain 85% initial flexural strength after 150 wet-dry cycles versus 52% for sisal-OPC, motivating supplementary cementitious material use.

B. Jute Fibre in Concrete

Jute (Corchorus capsularis) is a bast fibre containing cellulose 58–71%, hemicellulose 12–20%, and lignin 12–15% **[22],[27]**). Its higher lignin content versus sisal provides better alkali resistance **[22]**). Ramakrishna and Sundararajan **[27]**) found jute at 0.5% volume fraction improves impact resistance by 38–62% in mortar. Islam et al. **[19]**) reported 5–12% compressive strength improvement at 0.5% jute in M20 concrete with 1.5–2.0% SP, consistent with the present study's 6.4% improvement. Key limitation: jute's high water absorption (≈200% **[22]**)) significantly reduces workability and requires admixture compensation **[25]**.

C. Alkali Pre-treatment of Natural Fibres

Mwaikambo and Ansell **[22]**) established that 5% NaOH treatment for 1 hour improves tensile strength of sisal and jute by 10–30% while improving fibre-matrix adhesion through: (i) removal of surface waxes and impurities; (ii) partial dissolution of hemicellulose, reducing the most alkali-vulnerable component; and (iii) surface roughening through microfibre separation, increasing mechanical interlocking with the cement paste **[22]**). The present study applies this protocol to both fibre types.

D. Toughness Assessment

ASTM C1018 toughness indices **[28]**) quantify post-crack energy absorption from the load-deflection curve as:

$I_5 = \text{Area}(0\to 3\delta_1) / \text{Area}(0\to\delta_1)$ (Eq. 1) [28]

where δ_1 = deflection at first crack. For plain concrete $I_5 = 1.0$; for ideal ductile material $I_5 = 5.0$ **[28]**). Natural fibres at optimal content typically achieve $I_5 = 2–5$ **[28],[25]**). The ACI 544 **[1]**) drop-weight impact test records blows to first crack (N_1) and failure (N_2), with N_2/N_1 as the ductility index.

E. Sustainability Context

Joshi et al. **[20]**) demonstrated that natural fibre composites have 50–75% lower global warming potential (GWP) than glass fibre equivalents. The embodied CO_2 of jute is ≈ 0.18 kg CO_2/kg and sisal ≈ 0.20 kg CO_2/kg **[20]**) versus PP at 3.0 kg CO_2/kg **[20]**) and steel fibre at 1.3–1.8 kg CO_2/kg. The IPCC **[11]**) identifies agricultural residue use in construction as a viable carbon mitigation pathway under its sixth assessment report, directly supporting the use of sisal and jute in Indian concrete construction.

EXPERIMENTAL METHODOLOGY

A. Materials

OPC 43-grade per IS 8112: 2013 **[17]**: specific gravity 3.14, Blaine fineness 318 m²/kg, 28-day mortar strength 48.4 MPa. River sand per IS 383: 2016 **[14]** Zone II: FM 2.78, specific gravity 2.62, WA 1.2%. Crushed granite 20 mm MSA per IS 383: 2016 **[13]**: specific gravity 2.65, WA 0.5%, LA abrasion 22%. All aggregate tests per IS 2386 **[9]**). PCE superplasticiser per IS 9103: 1999 **[18]**: 0.6% by cement mass in all fibred mixes. Sisal fibres: 25 mm, alkali-treated, tensile strength 400–700 MPa **[4],[22]**). Jute fibres: 25 mm, alkali-treated, tensile strength 200–450 MPa **[22],[27]**.

Table I: Properties of Sisal and Jute Fibres After Alkali Treatment [22],[4],[27]

Property	Sisal Fibre [4],[22]	Jute Fibre [22],[27]
Fibre Length (chopped, mm)	25	25

Diameter (mm)	0.10–0.30	0.10–0.20
Aspect Ratio (L/d)	85–250	125–250
Tensile Strength (MPa)	400–700	200–450
Elastic Modulus (GPa)	9–22	10–30
Elongation at Break (%)	2–5	1.5–1.8
Specific Gravity	1.33–1.50	1.40–1.46
Cellulose Content (%)	60–78	58–71
Lignin Content (%)	8–11	12–15
Water Absorption (%)	~110	~200 (before treatment)
NaOH Treatment	5% NaOH, 2 hr [22]	5% NaOH, 2 hr [22]
Embodied CO_2 (kg/kg) [20]	0.20	0.18

B. Mix Design

M25 mix designed per IS 10262: 2019 **[8]**:
$f'cm = f'ck + 1.65\sigma = 25 + 1.65\times4 = 31.6$ MPa (Eq. 2) [8],[6]
OPC = 372 kg/m^3; sand = 614 kg/m^3; granite = 1,176 kg/m^3; water = 186 kg/m^3; w/c = 0.50 **[8]**). Fibres added as volumetric replacements at V_f = 0%, 0.5%, 1.0%, 1.5%:

$m\_fibre = V\_f\,(\%) \times 10 \times \rho\_fibre$ (kg/m^3) (Eq. 3) [25]
Sisal masses: 0, 7.0, 14.0, 21.0 kg/m^3 (ρ=1.40). Jute masses: 0, 7.15, 14.3, 21.45 kg/m^3 (ρ=1.43) **[22],[4]**. Superplasticiser at 0.6% by cement mass in all fibred mixes to compensate workability reduction without changing w/c **[18]**.

Table II: Mix Proportions All Eight Fibred Mixes + Reference (kg/m^3) [8],[6]

Mix ID	OPC	Sand	CA	Water	Sisal (kg)	Jute (kg)	SP (%)	V_f (%)
M0 (Control)	372	614	1176	186	—	—	—	0%
S-0.5	372	614	1176	186	7.0	—	0.6	0.5%
S-1.0	372	614	1176	186	14.0	—	0.6	1.0%
S-1.5	372	614	1176	186	21.0	—	0.6	1.5%
J-0.5	372	614	1176	186	—	7.15	0.6	0.5%
J-1.0	372	614	1176	186	—	14.3	0.6	1.0%
J-1.5	372	614	1176	186	—	21.45	0.6	1.5%
PP-1.0 (bench)	372	614	1176	186	—	—	0.6	1.0%

C. Specimen Details and Test Methods

Mixing: drum mixer; fibres added gradually over 3 min at slow speed **[27]**). Casting per IS 516: 2004 **[7]**). Moist curing at 27±2°C for 28 days.

- **Workability:** slump cone per IS 1199 **[12]**.
- **Compressive strength:** 150 mm cubes at 7, 28, 56 days per IS 516 **[7]**. Loading rate: 0.6 MPa/s **[7]**.
- **Split tensile strength:** 150×300 mm cylinders per IS 5816: 1999 **[16]**.
- **Flexural strength + toughness:** 100×100×500 mm prisms, two-point loading per IS 516 **[7]**). LVDT for deflection measurement; I_5, I_{10} per ASTM C1018 **[28]**.

- **Impact resistance:** ACI 544 **[1]**) drop-weight: 152 mm disc; 4.54 kg ball from 457 mm; N_1 = first crack; N_2 = failure.
- **Water absorption:** WA(%) = [(W_sat−W_dry)/W_dry]×100; 28-day cubes **[7]**.
- **RCPT:** ASTM C1202 **[3]**) at 28 days; 6 hours, 60 V DC.

FRESH PROPERTIES

Table III presents the workability (slump) results. The reference mix (M0) achieved 78 mm slump. Sisal fibre caused moderate slump reduction: S-0.5 = 58 mm, S-1.0 = 44 mm, S-1.5 = 28 mm **[29]**). Jute fibre caused greater reduction: J-0.5 = 62 mm, J-1.0 = 48 mm, J-1.5 = 36 mm **[27]**). The higher slump reduction per unit volume of jute versus sisal reflects jute's significantly higher water absorption (≈200% vs. ≈110% for sisal **[22]**)): jute fibres absorb free water from the mix, reducing the effective water available for paste lubrication and increasing viscosity. Despite the superplasticiser addition at 0.6% **[18]**), slump at 1.5% V_f falls below 30 mm for both fibres, indicating that further admixture increase would be needed for practical site placement at this volume fraction.

Table III: Workability (Slump) and IS 456 Classification [6],[12]

Mix ID	Slump (mm)	Reduction (mm)	IS 456 Class [6]	Remarks
M0 (Control)	78	—	Medium (50–100 mm) [6]	Baseline
S-0.5%	58	−20	Medium	Good; IS 456 compliant [6]
S-1.0%	44	−34	Low (25–50 mm) [6]	Acceptable; vibration needed
S-1.5%	28	−50	Low	Near limit; SP increase advised
J-0.5%	62	−16	Medium	Best workability + strength
J-1.0%	48	−30	Low	Acceptable for structural
J-1.5%	36	−42	Low	SP increase for site use
PP-1.0% (ref)	52	−26	Medium	Synthetic benchmark [25]

COMPRESSIVE STRENGTH RESULTS

Table IV and Figure 1 present compressive strength at 7, 28, and 56 days for all mixes. The reference M0 achieves 22.8 MPa (7-day) and 30.2 MPa (28-day) satisfying IS 456 M25 requirements **[6]**. The characteristic strength f'ck = f'cm − 1.65σ = 30.2 − 1.65×2.8 = 25.6 MPa ≥ 25 MPa **[6],[8]**.

Sisal series: S-0.5 achieves 31.4 MPa (+4.0%); S-1.0 achieves 31.6 MPa (+4.6%) the highest sisal compressive strength; S-1.5 slightly lower at 29.8 MPa (−1.3%). The optimum is clearly 1.0% for sisal, where the fibre's tensile stiffness provides maximum micro-crack arrest without introducing excessive matrix defects **[29],[4]**). At 56 days, S-1.0 reaches 37.2 MPa the highest of all mixes, confirming continued strength development through ongoing pozzolanic interaction **[21]**.

Jute series: J-0.5 achieves 32.1 MPa the highest 28-day compressive strength of the entire programme (+6.4% over M0), consistent with Islam et al. **[19]**) who reported 5–12% improvement at 0.5% jute. This early optimum reflects jute's moderate aspect ratio providing effective micro-crack diversion at low volume fractions, before excessive fibre-induced voids and workability reduction dominate at higher fractions **[27]**). J-1.5 drops to 28.4 MPa (−6.0%), confirming the practical limit of 1.0% for jute in M25 concrete.

Table IV: Compressive Strength Results All Mixes at 7, 28, and 56 Days [7]

Mix ID	f'c 7d (MPa)	f'c 28d (MPa)	f'c 56d (MPa)	% vs M0 (28d)	IS Grade [6]	Notes
M0 (Control)	22.8	30.2	34.8	100%	M25 ✓ [6]	Reference [8]
S-0.5%	23.2	31.4	36.2	+4.0%	M30 ✓	Good [29]

S-1.0%	23.8	31.6	37.2	+4.6% ★	M30 ✓ [6]	Optimal sisal [4]
S-1.5%	22.0	29.8	34.6	−1.3%	M25 ✓	Slight decline
J-0.5%	23.6	32.1	36.4	+6.4% ★	M30 ✓ [6]	Best 28d [19]
J-1.0%	22.4	30.8	35.2	+2.0%	M25 ✓	Good
J-1.5%	19.8	28.4	32.8	−6.0%	M25 ✓	Workability effect
PP-1.0% (ref)	24.2	32.4	37.0	+7.3%	M30 ✓	Benchmark [25]

Figure 1: 28-Day Compressive Strength Sisal and Jute Series [7],[6]
(IS 456 [6] M25 = 25 MPa and M30 = 30 MPa limits shown as dashed lines)

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f'c 28d (MPa)
 32.4 ┤  ◆ PP-1.0% = 32.4 MPa (synthetic benchmark) [25]
 32.1 ┤  ■ J-0.5% = 32.1 MPa ← HIGHEST of both natural fibres [19]
 31.6 ┤  ○ S-1.0% = 31.6 MPa ← OPTIMAL sisal [4],[29]
 31.4 ┤  ○ S-0.5% = 31.4 MPa
 30.8 ┤  ■ J-1.0% = 30.8 MPa
 30.2 ┤ ─── M0 Reference = 30.2 MPa ──────────────────────────
 30 ┤ ─── IS 456 M30 lower limit ─ ─ ─ ─ ─ ─ ─ ─ ─ ─ ─ ─ [6]
 29.8 ┤  ○ S-1.5% = 29.8 MPa
 28.4 ┤  ■ J-1.5% = 28.4 MPa
 25 ┤ ─── IS 456 M25 minimum = 25 MPa [6] ─ ─ ─ ─ ─ ─ ─ ─ ─
    └──────────────────────────────────────────── Mix ID
     M0   S-0.5  S-1.0  S-1.5  J-0.5  J-1.0  J-1.5  PP-1.0
■ = Jute  ○ = Sisal  ◆ = PP benchmark
All mixes satisfy IS 456 M25 [6]; optimal mixes satisfy M30 [6]
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Figure 1: ***28-Day Compressive Strength Sisal and Jute FRC Mixes vs. Reference [7],[6]***

SPLIT TENSILE AND FLEXURAL STRENGTH

A. Split Tensile Strength

Table V presents 28-day split tensile strength. The reference M0 achieves 3.11 MPa. Sisal at 1.0% achieves 3.84 MPa (+23.5%) the best result of the programme, driven by sisal's high tensile stiffness (9–22 GPa **[4]**)) providing effective crack bridging **[23]**). Jute at 0.5% achieves 3.48 MPa (+11.9%) **[27]**). As fibre content increases from 1.0% to 1.5%, both fibres show declining tensile strength sisal-1.5% = 3.44 MPa and jute-1.5% = 3.28 MPa indicating that matrix disruption from excess fibres outweighs the additional crack-bridging contribution **[24],[22]**.
The split tensile improvement is governed by the fibre pullout force per crack area:

$P_{pullout} = \tau_{bond} \times \pi \times d_f \times l_e$ (N per fibre) (Eq. 4) [23]
where τ_{bond} = interfacial shear bond strength, d_f = fibre diameter, l_e = embedded length **[23]**). Sisal's higher bond strength after NaOH treatment **[22]**) roughened surface and reduced surface wax gives higher $P_{pullout}$ per fibre, explaining the superior tensile improvement over jute **[4],[22]**.

B. Flexural Strength

Sisal at 1.0% achieves the highest flexural strength: 4.62 MPa (+22.9% over reference 3.76 MPa). Jute at 0.5% achieves 4.18 MPa (+11.2%). The IS 456: 2000 **[6]**) formula $f_r = 0.7\sqrt{f'ck}$ underestimates actual flexural strength of both fibre types by 10–23% at optimal content **[7],[28]**), because the IS formula does not capture post-crack fibre contribution **[28]**.

Table V: Tensile and Flexural Strength Results at 28 Days [7],[16],[28]

Mix ID	f_t (MPa) [16]	% vs M0	f_r (MPa) [7]	% vs M0	IS 456 Pred. f_r [6]
M0 (Control)	3.11	100%	3.76	100%	0.7×√30.2=3.85

S-0.5%	3.54	+13.8%	4.22	+12.2%	0.7×√31.4=3.92
S-1.0%	3.84	+23.5% ★	4.62	+22.9% ★	0.7×√31.6=3.94
S-1.5%	3.44	+10.6%	4.18	+11.2%	0.7×√29.8=3.82
J-0.5%	3.48	+11.9%	4.18	+11.2%	0.7×√32.1=3.97
J-1.0%	3.62	+16.4%	4.32	+14.9%	0.7×√30.8=3.89
J-1.5%	3.28	+5.5%	3.84	+2.1%	0.7×√28.4=3.73
PP-1.0%	3.72	+19.6%	4.52	+20.2%	0.7×√32.4=3.98

TOUGHNESS AND IMPACT RESISTANCE

A. Toughness Indices

Table VI presents toughness indices for the four optimal mixes and the PP reference. Sisal at 1.0% achieves $I_5 = 4.82$ and $I_{10} = 7.84$ the highest among natural fibres and approaching PP-1.0% ($I_5 = 5.24$). This high toughness reflects sisal's combination of adequate tensile stiffness enabling crack bridging and sufficient elongation (2–5% **[4]**)) allowing meaningful pullout displacement before fibre fracture **[29],[28]**).

Jute at 0.5% achieves $I_5 = 3.12$ a moderate toughness improvement, limited by jute's low elongation at break (1.5–1.8% **[22]**)). At this elongation, jute fibres fracture at relatively small crack opening displacements, limiting the available pullout energy **[23]**). The N_2/N_1 ductility ratios confirm the same pattern: S-1.0 = 2.53 vs J-0.5 = 1.56 sisal provides more than 60% higher post-first-crack impact ductility than jute **[1]**.

Table VI: Toughness Indices and Impact Resistance Results [28],[1]

Mix ID	I_5 [28]	I_{10} [28]	N_1 (blows) [1]	N_2 (blows) [1]	N_2/N_1	Assessment
M0 (Control)	1.00	1.00	12	14	1.17	Brittle [1]
S-0.5%	3.48	5.62	18	30	1.67	Good [29]
S-1.0%	4.82	7.84	15	38	2.53	BEST NF ★ [4],[29]
S-1.5%	3.84	6.12	14	28	2.00	Good
J-0.5%	3.12	4.86	18	28	1.56	Moderate [27]
J-1.0%	3.62	5.84	16	24	1.50	Moderate
PP-1.0% (ref)	5.24	8.46	18	44	2.44	Benchmark [25]

Figure 2: Toughness Index I_5 and Impact Resistance N_2 All Mixes [28],[1]

LEFT: Toughness Index I_5 [28] RIGHT: Impact Blows N_2 [1]
(I_5=1.0 = brittle plain concrete; higher = more ductile)

I_5 N_2 (failure blows)
5.24 ┤ ◆ PP-1.0% 44 ┤ ◆ PP-1.0% (best overall)
4.82 ┤ ○ S-1.0% ← BEST NF [4] 38 ┤ ○ S-1.0% ← BEST NF
3.84 ┤ ○ S-1.5% 30 ┤ ○ S-0.5%
3.62 ┤ ■ J-1.0% 28 ┤ ■ J-0.5%; ○ S-1.5%
3.48 ┤ ○ S-0.5% 24 ┤ ■ J-1.0%
3.12 ┤ ■ J-0.5% 14 ┤ ■ M0 (PLAIN brittle [1])
1.00 ┤ ■ M0 Reference

KEY: ■=Jute ○=Sisal ◆=PP
S-1.0%: I_5=4.82 = 91.9% of PP-1.0% (5.24) at 43% of PP cost [25]

S-1.0%: N_2=38 = 86.4% of PP-1.0% (44) → viable natural FRC [25]

Figure 2: ***Toughness Index I_5 and Impact Resistance (N_2) Comparison [28],[1]***

DURABILITY RESULTS

A. Water Absorption

Table VII presents water absorption (WA) at 28 days. The reference M0 absorbs 4.2%. Sisal-0.5% (3.6%, −14.3%) and jute-0.5% (3.4%, −19.0%) show reduced absorption relative to reference attributable to fibre-induced crack arrest limiting pore network connectivity **[27],[25]**). This finding is consistent with Ramakrishna and Sundararajan **[27]**) who reported 8–15% reduction in mortar absorption at 0.5% natural fibre content.

At 1.5% fibre content, WA increases above the IS 456: 2000 **[6]**) limit of 5% for all mixes: S-1.5% = 5.4% and J-1.5% = 5.2%. This reversal occurs because excessive fibre-matrix interfaces and local fibre bundling create preferential water pathways **[25],[22]**). Engineers should limit both sisal and jute to ≤ 1.0% volume fraction for IS 456 durability compliance **[6]**.

B. Rapid Chloride Permeability (RCPT)

RCPT results (Table VII) show that sisal-1.0% and jute-0.5% reduce charge passed by 18–22% relative to reference, falling into the 'Moderate' classification per ASTM C1202 **[3]**). The reference passes 3,820 C (Moderate); S-1.0 passes 3,120 C (still Moderate but lower), and J-0.5 passes 2,940 C. At 1.5% fibre, RCPT increases marginally above reference, consistent with the water absorption trend **[3],[22]**.

Table VII: Water Absorption and RCPT All Mixes [6],[3]

Mix ID	WA (%)	WA vs. Ref.	IS 456 WA [6]	RCPT (C) [3]	RCPT Class [3]
M0 (Control)	4.2	—	✓ ≤5%	3,820	Moderate [3]
S-0.5%	3.6	−14.3%	✓	3,380	Moderate
S-1.0%	4.2	0.0%	✓	3,120	Moderate (lower)
S-1.5%	5.4	+28.6%	✗ Fail [6]	4,080	Moderate-High
J-0.5%	3.4	−19.0% ★	✓	2,940	Moderate (best)
J-1.0%	4.0	−4.8%	✓	3,240	Moderate
J-1.5%	5.2	+23.8%	✗ Fail [6]	4,220	Moderate-High
PP-1.0% (ref)	3.8	−9.5%	✓	2,820	Moderate [25]

IS 456 COMPLIANCE AND SUSTAINABILITY ASSESSMENT

A. IS 456 Compliance

Table VIII presents the comprehensive IS 456: 2000 **[6]**) compliance assessment. Requirements for M25 concrete in Moderate Exposure (Table 5, IS 456 **[6]**)): f'ck ≥ 25 MPa; maximum w/c = 0.55; minimum cement content = 300 kg/m^3; maximum water absorption = 5%. The adopted w/c = 0.50 and cement = 372 kg/m^3 satisfy these requirements for all mixes. The binding IS 456 **[6]**) failure criterion is water absorption > 5% triggered at S-1.5% and J-1.5% only.

Table VIII: IS 456: 2000 [6] Compliance Assessment All Mixes

Mix ID	f'ck≥25? [6]	WA≤5%? [6]	w/c≤0.55?	Cem.≥300?	IS 456 Status [6]
M0 Control	✓ 30.2	✓ 4.2%	✓ 0.50	✓ 372	M25 COMPLIANT [6]
S-0.5%	✓ 31.4	✓ 3.6%	✓	✓	M30 COMPLIANT ✓

S-1.0%	✓ 31.6	✓ 4.2%	✓	✓	M30 FULLY COMPLIANT ✓ ★
S-1.5%	✓ 29.8	✗ 5.4%	✓	✓	FAIL WA exceeds 5% [6]
J-0.5%	✓ 32.1	✓ 3.4%	✓	✓	M30 FULLY COMPLIANT ✓ ★
J-1.0%	✓ 30.8	✓ 4.0%	✓	✓	M25 COMPLIANT ✓
J-1.5%	✓ 28.4	✗ 5.2%	✓	✓	FAIL WA exceeds 5% [6]

B. Sustainability Comparison

Embodied CO_2 of each mix was computed per Joshi et al. **[20]** and IPCC **[11]**) coefficients. At 1.0% V_f: sisal adds 14.0 × 0.20 = 2.8 kg CO_2/m^3 and jute adds 14.3 × 0.18 = 2.6 kg CO_2/m^3 versus PP at 9.1 × 3.0 = 27.3 kg CO_2/m^3 **[20]**). The total embodied CO_2 of M25 concrete is approximately 317.8 kg CO_2/m^3 (dominated by OPC); natural fibre addition increases this by only 0.8–0.9% versus PP's 8.6% increase **[20],[11]**.

Cost analysis at Indian market prices: sisal-1.0% adds ≈ ₹196/m^3 and jute-1.0% adds ≈ ₹204/m^3 versus PP-1.0% ≈ ₹455/m^3 **[25]**). The cost-per-toughness-unit for sisal-1.0% (I_5=4.82): ₹196/(4.82−1.0) = ₹51/unit, versus PP-1.0% (I_5=5.24): ₹455/(5.24−1.0) = ₹107/unit sisal is 2.1× more cost-effective per unit of toughness **[25],[20]**.

Table IX: Sustainability Comparison Sisal, Jute vs. PP at 1.0% V_f [20],[11],[25]

Metric	Sisal-1.0%	Jute-1.0%	PP-1.0% (ref)
Fibre CO_2 added (kg/m^3) [20]	2.8	2.6	27.3
% increase in total concrete CO_2 [20]	0.88%	0.82%	8.58%
Fibre cost added (₹/m^3) [25]	₹196	₹204	₹455
Cost per toughness unit [25]	₹51/unit	N/A (I_5=3.62)	₹107/unit
IS 456 compliance [6]	✓ M30	✓ M25	✓ M30
f'c 28d improvement	+4.6%	+2.0%	+7.3%
Toughness I_5 [28]	4.82	3.62	5.24
CO_2 vs. PP [20],[11]	−89.7% lower	−90.5% lower	Baseline

DISCUSSION

The results reveal a clear performance hierarchy between sisal and jute, governed by their different fibre properties. Sisal's higher tensile stiffness (9–22 GPa vs. jute 10–30 GPa comparable, but sisal's longer crack bridging is more effective in the concrete grain structure **[4],[22]**)) combined with its moderate elongation at break (2–5% vs. jute 1.5–1.8% **[22]**)) produces superior toughness (I_5 = 4.82 vs. 3.12) and impact resistance (N_2 = 38 vs. 28). Jute's advantage lies in ambient compressive strength at 0.5% its lower aspect ratio and specific surface area introduce fewer matrix defects at low volume fractions, producing the highest 28-day compressive strength improvement (+6.4%) **[19],[27]**.

Both fibres confirm the fibre optimum principle **[24]**) performance improves up to an optimal V_f then declines. The decline is governed by two competing effects: (i) increasing fibre volume increases crack bridging area and toughness; (ii) beyond optimum, increased fibre-matrix interfaces reduce workability, increase voids, and disrupt matrix homogeneity **[25]**). For sisal, optimum is 1.0%; for jute, optimum is 0.5% for compressive strength and 1.0% for tensile performance.

The IS 456: 2000 **[6]**) compliance boundary at 1.5% volume fraction where water absorption exceeds 5% provides a regulatory upper limit that coincidentally aligns with the mechanical performance optimum. This convergence of mechanical and durability optima at ≤ 1.0% provides a clear, single specification recommendation: limit both sisal and jute to ≤ 1.0% in IS 456-governed structural concrete. Alkali pre-treatment per Mwaikambo and Ansell **[22]**) is essential for adequate fibre-matrix bond and should be specified as a mandatory step.

The sustainability case is compelling. Sisal-1.0% achieves 91.9% of PP-1.0% toughness performance at 43% of material cost and 10.3% of the embodied CO_2 impact **[20],[11]**). For Indian affordable housing, rural infrastructure, and impact-resistant industrial floor applications, sisal-1.0% concrete represents a technically adequate, economically superior, and environmentally responsible alternative to PP fibre concrete **[25],[26]**.

CONCLUSIONS

This paper has presented a controlled comparative investigation of sisal and jute fibre reinforced M25 concrete. The principal conclusions are:

1. Workability: Sisal reduces slump more moderately than jute at equivalent volume fractions (sisal-0.5%: 58 mm; jute-0.5%: 62 mm). Both fibres maintain acceptable workability at ≤ 1.0% with 0.6% PCE superplasticiser. V_f = 1.5% requires further admixture increase for site placement [18],[6].
2. Compressive strength: Jute-0.5% achieves the highest 28-day compressive strength (32.1 MPa, +6.4%, IS 456 M30 compliant [6]). Sisal-1.0% achieves 31.6 MPa (+4.6%, M30). Both surpass IS 456 M25 requirements at all volume fractions tested. Optimal content: jute 0.5%, sisal 1.0% [8],[6].
3. Split tensile and flexural strength: Sisal-1.0% achieves the best tensile improvement (f_t = 3.84 MPa, +23.5%; f_r = 4.62 MPa, +22.9%) due to high tensile stiffness and improved NaOH-treated bond [4],[22]. Jute at 0.5% achieves f_t = 3.48 MPa (+11.9%) and f_r = 4.18 MPa (+11.2%).
4. Toughness: Sisal-1.0% achieves I_5 = 4.82 91.9% of PP-1.0% (5.24) and approaching the lower range of steel FRC performance [28]. Jute-0.5% achieves I_5 = 3.12. The toughness advantage of sisal over jute arises from higher elongation at break (2–5% vs. 1.5–1.8% [22]) enabling larger crack opening displacement before fibre fracture.
5. Impact resistance: Sisal-1.0% achieves N_2 = 38 blows (+171%) and ductility ratio N_2/N_1 = 2.53. Jute-0.5% achieves N_2 = 28 blows (+100%), N_2/N_1 = 1.56 [1]. Both confirm genuine ductile impact failure behaviour suitable for seismic and impact-prone applications [2].
6. Durability: Jute-0.5% achieves the lowest water absorption (3.4%, −19%) and both sisal-1.0% and jute-0.5% satisfy IS 456: 2000 [6] water absorption limit (≤ 5%). V_f = 1.5% exceeds this limit for both fibres confirming ≤ 1.0% as the IS 456 compliant upper bound.
7. Sustainability: Sisal-1.0% and jute-1.0% add only 2.6–2.8 kg CO_2/m^3 versus PP's 27.3 kg CO_2/m^3 at equivalent dosage a 90% embodied CO_2 advantage [20],[11]. Cost-per-toughness-unit for sisal-1.0% is ₹51/unit versus ₹107/unit for PP-1.0% 2.1× more cost-effective [25].
8. RECOMMENDATION: Sisal-1.0% is recommended for structural applications requiring maximum performance (toughness, impact, flexural). Jute-0.5% is recommended for applications prioritising maximum compressive strength improvement, lowest water absorption, and cost-effectiveness. Both fibres should be alkali-treated with 5% NaOH for 2 hours before incorporation [22],[29].

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