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Original Research Paper

Experimental Investigation on Sustainable Concrete Incorporating Fly Ash, Manufactured Sand and Sisal Fiber

Nallagondla Venkata Sai Lokesh[1]*, D. Leela Durga[2], M. Rama Manikantha[3]

1PG Student, 2&3 Assistant Professor

School of Engineering, Department of Civil Engineering, Godavari Global University, Rajamahendravaram, Andhra Pradesh, India

*Corresponding author: lokesh@ggu.edu.in

Abstract. This study presents an experimental investigation on sustainable M30-grade concrete incorporating fly ash, manufactured sand (M-Sand) and sisal fiber. The objective is to reduce dependence on ordinary Portland cement and river sand while improving mechanical performance through natural fiber reinforcement. Four mixes were evaluated: a conventional control mix (CM), and three sustainable mixes containing 100% M-Sand, 10-30% fly ash as partial cement replacement and 0.5-1.5% sisal fiber by weight of cementitious material. The available experimental data include compressive strength at 7, 14 and 28 days, and split tensile and flexural strength at 28 days. Mix M1, containing 10% fly ash and 0.5% sisal fiber, achieved the highest 28-day compressive strength of 44.7 MPa, representing a 7.71% improvement over the control mix. Mix M2, containing 20% fly ash and 1.0% sisal fiber, achieved the highest split tensile strength of 4.10 MPa and flexural strength of 6.05 MPa, corresponding to improvements of 17.14% and 16.35%, respectively. The improvement is attributed to the combined contribution of fly ash pozzolanic activity, better particle packing provided by M-Sand, and crack-bridging action of sisal fibers. Higher replacement/fiber content in M3 reduced strength, likely because of lower workability, fiber clustering and delayed hydration. The results indicate that M2 provides the best overall balance between tensile performance, flexural performance and sustainability, whereas M1 gives the maximum compressive strength. The findings support the feasibility of fly ash-M-Sand-sisal fiber concrete as an eco-efficient cementitious composite for structural applications, subject to further durability and microstructural validation.

Keywords: Sustainable concrete; Fly ash; Manufactured sand; Sisal fiber; Natural fiber reinforced concrete; Mechanical properties; Low-carbon construction.

Introduction

Concrete is the most widely used construction material because of its versatility, compressive strength, availability and cost-effectiveness. However, the production of ordinary Portland cement (OPC) is energy intensive and contributes substantially to global carbon dioxide emissions. In addition, the continuous extraction of river sand has disturbed river ecosystems, altered sediment balance and increased the cost and scarcity of natural fine aggregates. These environmental and economic concerns have created a need for sustainable concrete technologies that reduce cement consumption, minimize natural sand use and improve long-term material performance.

The use of supplementary cementitious materials and alternative fine aggregates is one of the practical approaches for reducing the environmental footprint of concrete. Fly ash, an industrial by-product from thermal power plants, can partially replace cement and contribute to secondary calcium silicate hydrate (C-S-H) formation through pozzolanic reactions. Manufactured sand (M-Sand), produced by crushing hard rock, offers a controlled particle size distribution and reduces dependence on river sand. Natural fibers such as sisal fiber are renewable, biodegradable and capable of improving tensile resistance, ductility and crack control in cementitious composites.

Conventional concrete is strong in compression but weak in tension and susceptible to brittle cracking. Therefore, fiber reinforcement is often introduced to control crack propagation and improve post-cracking behavior. Sisal fiber, obtained from the Agave sisalana plant, has good tensile capacity, low density and wide availability in tropical regions. When properly dispersed in concrete, sisal fibers can bridge microcracks and delay crack propagation, thereby improving split tensile and flexural performance.

The present study investigates the combined use of fly ash, 100% M-Sand and sisal fiber in M30 concrete. The research is positioned as a mechanical performance and sustainability-oriented study based only on the available experimental data. Claims related to durability and microstructure are treated as mechanistic interpretations and not as direct experimental evidence, because no durability or microstructural test data were available in the submitted dataset.

1.1 Objectives of the Study

- To develop sustainable concrete mixes incorporating fly ash as partial cement replacement, M-Sand as complete fine aggregate replacement and sisal fiber as natural reinforcement.

*Corresponding Author:

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- To evaluate compressive strength at 7, 14 and 28 days for control and sustainable mixes.
- To evaluate 28-day split tensile strength and flexural strength of the proposed mixes.
- To identify the best-performing mix based on available mechanical strength data.
- To discuss the sustainability benefits and limitations of fly ash-M-Sand-sisal fiber concrete without adding unverified data.

2. Literature Review and Research Gap

Sustainable concrete research has increasingly focused on the partial replacement of cement and natural aggregates with industrial by-products and alternative construction materials. Fly ash is one of the most widely used pozzolanic materials in concrete. Its fine particles improve packing density, reduce permeability and enhance long-term strength through reactions with calcium hydroxide. However, high-volume fly ash replacement can reduce early-age strength because pozzolanic reactions are slower than cement hydration.

Manufactured sand has emerged as a feasible substitute for river sand. Compared with natural river sand, M-Sand generally provides angular particles, controlled grading and fewer deleterious impurities when properly processed. The angularity and rough surface texture of M-Sand can improve bond strength and particle interlock, although excessive fines may affect workability if not controlled.

Natural fibers such as sisal, jute, coir and banana fiber are being explored as environmentally friendly reinforcement materials in cementitious composites. Sisal fiber is particularly promising because of its tensile strength, low density and renewable origin. Fibers improve tensile and flexural performance mainly through crack bridging, stress redistribution and enhanced energy absorption. Nevertheless, excessive fiber dosage can reduce workability, cause fiber balling and create voids that weaken the concrete matrix.

Previous studies commonly investigated fly ash concrete, M-Sand concrete or sisal fiber reinforced concrete separately. The novelty of the present work lies in examining the combined use of fly ash, complete M-Sand replacement and sisal fiber in one sustainable concrete system. This combination attempts to address three sustainability concerns simultaneously: reduction of cement use, elimination of river sand use and replacement of synthetic fibers with a renewable natural fiber. The research gap addressed is the need for simple, practically applicable mix combinations that improve tensile/flexural response while maintaining acceptable compressive strength.

3. Materials and Methods

3.1 Materials

OPC 53 grade cement was used as the primary binder. Fly ash was used as a partial replacement for cement. The manuscript describes the fly ash as Class F type with pozzolanic compounds such as silica, alumina and iron oxide. Natural river sand was used only in the control mix, while M-Sand was used as the fine aggregate in the sustainable mixes. Coarse aggregate was obtained from crushed stone, retained on the 4.75 mm IS sieve. Sisal fibers were obtained from the Agave sisalana plant, manually cleaned and cut into approximately 30 mm lengths before mixing.

Table 1. Materials used in the experimental program

Material	Role in mix	Available information from submitted manuscript
OPC 53 grade cement	Primary binder	Used for M30 concrete; detailed physical properties not reported.
Fly ash	Partial cement replacement	Used at 10%, 20% and 30%; described as Class F pozzolanic material.
M-Sand	Fine aggregate replacement	Used as 100% replacement of river sand in sustainable mixes.
River sand	Fine aggregate in control mix	Used only in conventional control mix.
Coarse aggregate	Coarse aggregate skeleton	Crushed stone aggregate; detailed grading not reported.
Sisal fiber	Natural reinforcement	Used at 0.5%, 1.0% and 1.5%; cut length approximately 30 mm.

3.2 Mix Proportions

Concrete was designed for M30 grade with a constant water-cement ratio of 0.45. Four mixes were considered: one conventional control mix and three sustainable mixes. In all sustainable mixes, river sand was completely replaced with M-Sand. Fly ash was incorporated at 10%, 20% and 30%, while sisal fiber was incorporated at 0.5%, 1.0% and 1.5% by weight of cementitious material. The selected replacement levels follow the available experimental program and were retained without modification.

Table 2. Mix proportions used in the study

Mix ID	Sisal fiber (%)	M-Sand (%)	Fly ash (%)	Water-cement ratio	Description
CM	0	0	0	0.45	Conventional mix with river sand
M1	0.5	100	10	0.45	Sustainable mix 1
M2	1.0	100	20	0.45	Sustainable mix 2

M3	1.5	100	30	0.45	Sustainable mix 3

3.3 Specimen Preparation and Testing

Concrete ingredients were mixed using a tilting drum mixer. Dry materials were mixed first, followed by the addition of water to obtain a uniform consistency. Fresh concrete was placed in moulds in layers and compacted using a vibrating table. Specimens were demoulded after 24 hours and cured in clean water at approximately 27 +/- 2 deg C until testing. The available data include compressive strength of cube specimens at 7, 14 and 28 days, and split tensile and flexural strength at 28 days.

Table 3. Test program based on available data

Test	Specimen type	Testing age	Reported data status
Compressive strength	Cube specimens	7, 14 and 28 days	Available for all mixes
Split tensile strength	Cylinder specimens	28 days	Available for all mixes
Flexural strength	Prism/beam specimens	28 days	Available for all mixes
Slump/workability	Fresh concrete	Immediately after mixing	Test mentioned; numerical values not available
Durability/microstructure	Not reported	Not reported	No data available

4. Results and Discussion

4.1 Workability Observation

Based on the mix composition and the observed reduction in strength at the highest fiber/fly ash content, workability is expected to decrease as sisal fiber dosage increases. Natural fibers absorb water and may interlock or cluster at higher contents, reducing flowability and compaction efficiency. Therefore, the reduction in strength observed in M3 may be partly associated with lower workability and fiber balling. Quantitative slump values should be added in the final version if available from laboratory records.

4.2 Compressive Strength

Table 4 and Figure 1 present compressive strength results at 7, 14 and 28 days. The control mix achieved 41.5 MPa at 28 days. M1 achieved the maximum 28-day compressive strength of 44.7 MPa, corresponding to a 7.71% improvement over the control mix. M2 achieved 43.8 MPa, which is 5.54% higher than the control mix. M3 recorded 39.2 MPa, showing a 5.54% reduction compared with the control.

Table 4. Compressive strength results

Mix ID	Fly ash (%)	Sisal fiber (%)	7 days (MPa)	14 days (MPa)	28 days (MPa)
CM	0	0	28.6	34.2	41.5
M1	10	0.5	30.1	36.8	44.7
M2	20	1	29.5	35.6	43.8
M3	30	1.5	26.8	32.5	39.2

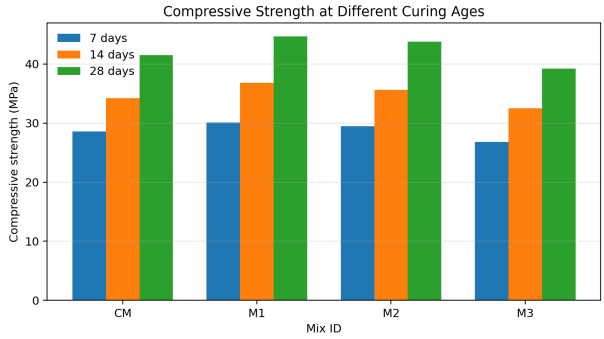


Figure 1. Compressive strength of CM, M1, M2 and M3 at 7, 14 and 28 days.

The strength improvement in M1 and M2 can be explained by the pozzolanic activity of fly ash, which reacts with calcium hydroxide to form additional C-S-H gel. This secondary hydration product refines the pore structure and improves matrix density. M-Sand may also contribute through angularity and improved interlocking. However, when fly ash increased to 30% and sisal fiber to 1.5% in M3, compressive strength decreased. This reduction may be due to delayed hydration at higher fly ash content, reduced early calcium hydroxide availability, lower workability and possible fiber clustering.

4.3 Split Tensile Strength

The 28-day split tensile strength results are presented in Table 5 and Figure 2. The control mix recorded 3.50 MPa, whereas M1, M2 and M3 recorded 3.85 MPa, 4.10 MPa and 3.75 MPa, respectively. The highest value was obtained by M2, giving a 17.14% improvement over the control mix.

Table 5. Split tensile strength results and percentage improvement

Mix ID	Fly ash (%)	Sisal fiber (%)	28-day split tensile strength (MPa)	Change vs. control (%)
CM	0	0	3.50	+0.00
M1	10	0.5	3.85	+10.00
M2	20	1	4.10	+17.14
M3	30	1.5	3.75	+7.14

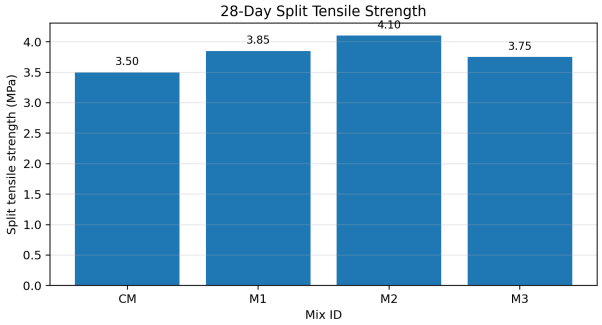


Figure 2. 28-day split tensile strength of the investigated mixes.

The improvement in split tensile strength is mainly attributed to fiber bridging. Sisal fibers act as micro-reinforcement within the cement matrix and transfer tensile stress across developing microcracks. This delays crack growth and improves the tensile load-bearing capacity of concrete. The reduction from M2 to M3 indicates that excessive fiber content may reduce homogeneity and introduce voids, reducing effective bonding between paste, aggregate and fiber.

4.4 Flexural Strength

Flexural strength results are shown in Table 6 and Figure 3. M2 achieved the maximum flexural strength of 6.05 MPa, representing a 16.35% improvement over the control mix. M1 also improved flexural strength by 7.69%, while M3 showed only 3.85% improvement.

Table 6. Flexural strength results and percentage improvement

Mix ID	Fly ash (%)	Sisal fiber (%)	28-day flexural strength (MPa)	Change vs. control (%)
CM	0	0	5.20	+0.00
M1	10	0.5	5.60	+7.69
M2	20	1	6.05	+16.35
M3	30	1.5	5.40	+3.85

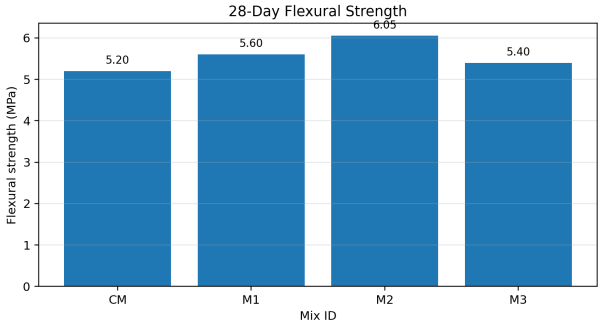


Figure 3. 28-day flexural strength of the investigated mixes.

The flexural strength improvement confirms the effectiveness of sisal fibers in controlling crack opening under bending. The fibers bridge cracks and help maintain post-cracking resistance, increasing toughness and deformation capacity. The best flexural result at 1.0% sisal fiber suggests that moderate fiber content gives effective stress transfer, while excessive fiber addition may reduce compaction and create weak zones.

4.5 Overall Performance Comparison

Table 7 summarizes the overall mechanical performance. M1 produced the maximum compressive strength, while M2 produced the best split tensile and flexural strength. Therefore, the optimum mix depends on the design priority. For compression-governed applications, M1 may be preferred; however, for overall mechanical performance, crack resistance, tensile behavior and sustainability, M2 is the most balanced mix.

Table 7. Overall comparison of mechanical performance

Mix ID	28-day compressive strength (MPa)	Comp. change (%)	Split tensile strength (MPa)	Split change (%)	Flexural strength (MPa)	Flex. change (%)
CM	41.50	+0.00	3.50	+0.00	5.20	+0.00
M1	44.70	+7.71	3.85	+10.00	5.60	+7.69
M2	43.80	+5.54	4.10	+17.14	6.05	+16.35
M3	39.20	-5.54	3.75	+7.14	5.40	+3.85

Based on the available results, M2 is recommended as the best overall sustainable concrete mix because it combines 20% fly ash replacement, 100% M-Sand and 1.0% sisal fiber. It improves split tensile strength by 17.14% and flexural strength by 16.35%, while still maintaining a 28-day compressive strength of 43.8 MPa, which is 5.54% higher than the control mix. This makes M2 suitable where crack control and flexural resistance are important.

4.6 Sustainability Considerations

The sustainable character of the proposed concrete is derived from three material substitutions. First, fly ash reduces cement demand and thereby reduces cement-related CO2 emissions. The available manuscript states that replacing 20% cement with fly ash can reduce CO2 emissions by approximately 15-20%. This should be treated as an indicative cement-related reduction rather than a full life-cycle assessment, because transportation, processing and curing impacts were not quantified. Second, 100% replacement of river sand with M-Sand reduces pressure on river ecosystems. Third, sisal fiber provides a renewable and biodegradable reinforcement alternative to synthetic fibers.

4.7 Limitations of the Present Study

- Numerical slump/workability values were not available, although the slump test was mentioned in the manuscript.
- The number of specimens tested per mix and replicate-level data were not available; hence mean values and standard deviations could not be reported.

- No durability tests such as water absorption, sorptivity, RCPT, acid attack or carbonation were available.
- No microstructural tests such as SEM, XRD, FTIR or TGA were available; microstructural discussion is therefore mechanistic rather than experimentally verified.
- A full life-cycle assessment and cost-benefit analysis were not available and should be performed before field-scale recommendation.

5. Conclusions

Based on the available experimental data, the following conclusions are drawn:

1. Sustainable concrete incorporating fly ash, 100% M-Sand and sisal fiber can achieve mechanical performance equal to or better than conventional concrete.
2. M1, containing 10% fly ash and 0.5% sisal fiber, achieved the highest 28-day compressive strength of 44.7 MPa, which is 7.71% higher than the control mix.
3. M2, containing 20% fly ash and 1.0% sisal fiber, achieved the best split tensile strength of 4.10 MPa and flexural strength of 6.05 MPa, representing improvements of 17.14% and 16.35%, respectively.
4. M3, containing 30% fly ash and 1.5% sisal fiber, showed reduced compressive strength and lower overall performance, indicating that excessive fly ash and fiber dosage may adversely affect workability and compaction.
5. The improved tensile and flexural performance is attributed to fiber bridging, crack arresting and improved stress transfer, while fly ash and M-Sand contribute to matrix densification and particle interlock.
6. M2 is recommended as the best overall mix from the available dataset because it provides the strongest balance of strength, crack resistance and sustainability benefits.
7. The study should be extended with quantitative workability, durability, microstructural, statistical, cost and carbon-footprint studies before large-scale implementation.

6. Future Scope

- Conduct durability tests such as water absorption, sorptivity, RCPT, sulphate resistance, acid resistance and carbonation depth.
- Perform SEM/XRD/FTIR studies to verify fiber-matrix bonding, C-S-H formation, pore refinement and the interfacial transition zone.
- Report replicate test results with mean, standard deviation and coefficient of variation.
- Measure slump, compaction factor or flow values to quantify fresh concrete behavior.
- Develop a full life-cycle carbon and cost assessment for fly ash-M-Sand-sisal fiber concrete.
- Investigate long-term performance, field casting behaviour and durability under aggressive environmental exposure.

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Author Note for Final Submission

This revised manuscript intentionally uses only the available data from the submitted paper. Before final journal upload, the authors should insert verified laboratory values for specimen count, slump, standard deviation, material properties and any durability/microstructural tests if such data exist. No missing experimental data have been invented in this revision.