

MECHANICAL PERFORMANCE OF SUSTAINABLE CONCRETE INCORPORATING BAGASSE ASH, STEEL FIBERS, AND POLYPROPYLENE FIBERS

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Abstract

The construction industry is increasingly focusing on sustainable and high-performance materials to reduce environmental impacts while enhancing structural performance. This study investigates the mechanical performance of sustainable concrete incorporating bagasse ash (BA), steel fibers (SF), and polypropylene fibers (PPF) as partial replacements and reinforcement additives. Bagasse ash, an agricultural by-product obtained from sugarcane processing, was utilized as a supplementary cementitious material to improve sustainability and reduce cement consumption. Steel fibers and polypropylene fibers were introduced to enhance the tensile strength, crack resistance, and ductility of concrete. Various concrete mixes were prepared with different proportions of bagasse ash and hybrid fiber combinations, and their fresh and hardened properties were evaluated through comprehensive experimental testing. Mechanical properties including compressive strength, split tensile strength, flexural strength, and modulus of elasticity were assessed at different curing periods.

The experimental results demonstrated that the incorporation of bagasse ash improved the microstructural characteristics of concrete through pozzolanic reactions, resulting in enhanced long-term strength development. The addition of hybrid fibers significantly improved tensile and flexural performance by controlling crack propagation and increasing energy absorption capacity. An optimum combination of bagasse ash, steel fibers, and polypropylene

fibers exhibited superior mechanical behavior compared to conventional concrete, achieving higher compressive strength, improved ductility, and better durability characteristics. The findings indicate that sustainable fiber-reinforced bagasse ash concrete can serve as an eco-friendly alternative for structural applications, contributing to waste utilization, reduction of carbon emissions, and improved structural performance in modern construction practices.

Keywords: Sustainable Concrete, Bagasse Ash, Steel Fibers, Polypropylene Fibers, Hybrid Fiber Reinforcement, Compressive Strength, Split Tensile Strength, Flexural Strength, Mechanical Performance, Green Construction Materials.

1 INTRODUCTION

Concrete is the most widely used construction material worldwide due to its versatility, durability, and cost-effectiveness. However, the extensive use of ordinary Portland cement (OPC) in concrete production contributes significantly to carbon dioxide emissions and environmental degradation. With increasing concerns regarding sustainable development and resource conservation, researchers have focused on incorporating industrial and agricultural waste materials into concrete as partial replacements for cement. Such practices not only reduce the environmental burden associated with waste disposal but also promote the development of eco-friendly construction materials capable of meeting modern engineering requirements.

Bagasse ash (BA), a by-product generated from the combustion of sugarcane bagasse in sugar industries, has emerged as a promising

supplementary cementitious material. Large quantities of bagasse ash are produced annually, and improper disposal of this waste can create environmental challenges. Due to its high silica content and pozzolanic characteristics, finely processed bagasse ash can react with calcium hydroxide released during cement hydration, forming additional calcium silicate hydrate (C-S-H) gel. This reaction contributes to improved concrete strength, reduced permeability, and enhanced durability. Consequently, the utilization of bagasse ash in concrete offers both environmental and technical benefits, making it an attractive material for sustainable construction practices.

Despite the advantages of bagasse ash, concrete containing supplementary cementitious materials often exhibits reduced tensile strength and increased brittleness. To overcome these limitations, fiber reinforcement has gained considerable attention in recent years. Steel fibers are known for their ability to enhance crack resistance, impact strength, toughness, and post-cracking behavior of concrete. They improve the load-carrying capacity by bridging cracks and delaying crack propagation under mechanical loading. However, the use of steel fibers alone may not effectively control microcrack formation during the early stages of loading.

Polypropylene fibers (PPF), on the other hand, are lightweight synthetic fibers that possess excellent resistance to chemical attack and corrosion. These fibers are highly effective in controlling plastic shrinkage cracks and improving the ductility of concrete. The combined use of steel fibers and polypropylene fibers, commonly referred to as hybrid fiber reinforcement, can provide synergistic benefits by controlling both microcracks and macrocracks. This hybrid approach enhances the overall mechanical performance of concrete by improving strength, toughness, energy absorption capacity, and crack resistance.

The integration of bagasse ash with hybrid fiber reinforcement represents a sustainable and innovative approach to producing high-performance concrete. By simultaneously utilizing agricultural waste and advanced reinforcement techniques, it is possible to develop concrete mixtures that are environmentally friendly while maintaining superior structural characteristics. Such sustainable concrete can contribute to reducing cement consumption, minimizing waste disposal problems, and extending the service life of concrete structures.

Although several studies have investigated the individual effects of bagasse ash, steel fibers, and polypropylene fibers on concrete performance, comprehensive evaluations of their combined influence remain limited. The interaction between pozzolanic materials and hybrid fibers can significantly affect the mechanical properties of concrete, necessitating detailed experimental investigations. Understanding these interactions is essential for optimizing mix proportions and achieving the desired balance between sustainability and structural performance.

Therefore, the present study aims to evaluate the mechanical performance of sustainable concrete incorporating bagasse ash, steel fibers, and polypropylene fibers. The research focuses on assessing compressive strength, split tensile strength, flexural strength, and elastic behavior of various concrete mixtures containing different proportions of bagasse ash and hybrid fibers. The outcomes of this study are expected to provide valuable insights into the development of sustainable and durable concrete materials suitable for modern infrastructure applications while supporting environmental conservation and resource efficiency.

2 RELATED WORK

The growing demand for sustainable construction materials has encouraged researchers to investigate the utilization of agricultural by-

products and fiber-reinforced composites in concrete production. Among various waste materials, bagasse ash has attracted considerable attention due to its abundance, pozzolanic properties, and potential to reduce cement consumption. Simultaneously, fiber reinforcement techniques have been widely explored to enhance the mechanical and durability characteristics of concrete. This section reviews previous studies related to bagasse ash incorporation, steel fiber reinforcement, polypropylene fiber reinforcement, and hybrid fiber-reinforced sustainable concrete.

2.1 Bagasse Ash as a Supplementary Cementitious Material

Cordeiro et al. reported that finely ground sugarcane bagasse ash possesses significant pozzolanic activity and can effectively replace a portion of cement in concrete mixtures. Their study demonstrated improved long-term compressive strength and reduced permeability due to the formation of additional calcium silicate hydrate (C-S-H) gel. Similarly, Ganesan, Rajagopal, and Thangavel investigated the influence of bagasse ash on concrete properties and observed that replacement levels up to 20% resulted in enhanced compressive strength and durability performance.

Sales and Lima evaluated the microstructural characteristics of bagasse ash concrete and concluded that the high silica content of the ash contributed to improved particle packing and pore refinement. Their findings indicated that properly processed bagasse ash could significantly improve the sustainability of concrete while maintaining satisfactory mechanical properties. Researchers have also emphasized that the effectiveness of bagasse ash depends on factors such as fineness, burning temperature, and replacement percentage.

2.2 Steel Fiber Reinforced Concrete

Steel fibers have been extensively used to improve the tensile and flexural performance of

concrete. Banthia and Trottier demonstrated that steel fibers effectively bridge cracks and increase the energy absorption capacity of concrete under loading. Their experimental investigations revealed substantial improvements in post-cracking behavior and toughness compared to conventional concrete.

Nataraja, Dhang, and Gupta studied the mechanical properties of steel fiber reinforced concrete and found significant increases in split tensile strength and flexural strength with increasing fiber content. The presence of steel fibers improved crack control and delayed crack propagation, resulting in enhanced structural performance. Several studies have further reported that steel fibers contribute to improved impact resistance, fatigue performance, and overall durability of concrete structures.

2.3 Polypropylene Fiber Reinforced Concrete

Polypropylene fibers have gained popularity due to their lightweight nature, chemical stability, and effectiveness in controlling microcracks. Bentur and Mindess reported that polypropylene fibers significantly reduce plastic shrinkage cracking and improve the ductility of cement-based materials. These fibers act as crack arresters during the early stages of concrete hardening, thereby minimizing crack development.

Research conducted by Alhozaimy et al. indicated that the inclusion of polypropylene fibers enhances tensile properties and reduces permeability by limiting crack widths. The study also showed improvements in resistance to thermal stresses and durability-related deterioration. Due to their corrosion resistance and low cost, polypropylene fibers have become an attractive option for sustainable concrete applications.

2.4 Hybrid Fiber Reinforcement in Concrete

The concept of hybrid fiber reinforcement combines two or more types of fibers to exploit their individual advantages and achieve superior overall performance. Yao, Li, and Wu

investigated concrete reinforced with steel and polypropylene fibers and reported notable improvements in compressive strength, tensile strength, flexural strength, and toughness. Steel fibers primarily contributed to macrocrack control, whereas polypropylene fibers effectively restrained microcrack formation.

Sivakumar and Santhanam evaluated hybrid fiber reinforced concrete under various loading conditions and observed enhanced ductility, impact resistance, and crack resistance compared to single-fiber systems. Their findings highlighted the synergistic interaction between steel fibers and polypropylene fibers, resulting in improved mechanical performance and structural reliability.

2.5 Sustainable Concrete Incorporating Bagasse Ash and Fibers

Recent studies have focused on combining supplementary cementitious materials with fiber reinforcement to develop sustainable high-performance concrete. Researchers have reported that the incorporation of bagasse ash alongside fibers enhances both environmental sustainability and structural performance. The pozzolanic reaction of bagasse ash improves the matrix density, while fibers compensate for the reduction in tensile capacity typically associated with cement replacement materials.

Experimental investigations by several researchers have shown that hybrid fiber-reinforced bagasse ash concrete exhibits superior compressive strength, flexural strength, and durability characteristics compared to conventional concrete. The combination of bagasse ash, steel fibers, and polypropylene fibers has been found to improve crack resistance, energy absorption capacity, and long-term performance. However, the optimum proportions of these materials vary depending on mix design parameters and material characteristics.

2.6 Research Gap

The reviewed literature confirms that bagasse ash can serve as an effective supplementary cementitious material, while steel fibers and polypropylene fibers significantly enhance the mechanical behavior of concrete. Although numerous studies have investigated the individual effects of bagasse ash and fiber reinforcement, limited research has comprehensively examined the combined influence of bagasse ash, steel fibers, and polypropylene fibers within a single concrete system. Furthermore, the interaction between pozzolanic reactions and hybrid fiber mechanisms requires deeper investigation to establish optimum mix proportions and performance characteristics. Therefore, the present study focuses on evaluating the mechanical performance of sustainable concrete incorporating bagasse ash, steel fibers, and polypropylene fibers, providing a comprehensive assessment of strength enhancement and structural efficiency for sustainable construction applications.

3 PROPOSED METHODOLOGY

This study proposes a sustainable concrete development framework that integrates bagasse ash (BA) as a supplementary cementitious material and a hybrid fiber reinforcement system consisting of steel fibers (SF) and polypropylene fibers (PPF). The methodology is designed to evaluate the influence of these materials on the mechanical performance of concrete through systematic mix preparation, specimen casting, curing, and laboratory testing. The proposed framework consists of six interconnected stages: material characterization, mix design development, concrete preparation, specimen casting and curing, mechanical testing, and performance evaluation.

Initially, the constituent materials including Ordinary Portland Cement (OPC), fine aggregate, coarse aggregate, bagasse ash, steel fibers, and polypropylene fibers are collected and

characterized according to relevant Indian Standards. Physical and chemical properties such as specific gravity, fineness, particle size distribution, and chemical composition are determined to ensure material suitability. Bagasse ash is processed through drying and grinding to achieve the required fineness and pozzolanic activity. The properties of steel fibers and polypropylene fibers, including aspect ratio, tensile strength, and dimensions, are also examined before incorporation into the concrete mixes.

Following material characterization, a control concrete mix is designed based on IS 10262 guidelines for the target compressive strength. Bagasse ash is introduced as a partial replacement for cement at varying percentages, while steel fibers and polypropylene fibers are incorporated in predetermined volume fractions. Several trial mixtures are prepared to identify the optimum combination of bagasse ash and hybrid fibers. The water-to-binder ratio, aggregate content, and admixture dosage are maintained within acceptable limits to ensure consistency among all mixes.

The prepared concrete ingredients are mixed in a laboratory concrete mixer to achieve a homogeneous mixture. Dry materials are first blended thoroughly, followed by the gradual addition of water and chemical admixtures. The fibers are introduced carefully to prevent balling and ensure uniform dispersion throughout the concrete matrix. Fresh concrete properties such as workability are evaluated immediately after mixing using slump tests to assess the influence of bagasse ash and fiber reinforcement on the consistency of the concrete.

After achieving the desired workability, concrete specimens are cast in standard molds for mechanical testing. Cube specimens are prepared for compressive strength evaluation, cylindrical specimens for split tensile strength assessment, and prism specimens for flexural strength testing.

The specimens are compacted using a vibration table to eliminate entrapped air and ensure proper consolidation. Following casting, the specimens are allowed to set for 24 hours before demolding and subsequently cured in water tanks under controlled conditions for 7, 14, and 28 days.

Mechanical performance evaluation is carried out after the designated curing periods. Compressive strength tests are conducted using a compression testing machine to determine the load-bearing capacity of the concrete. Split tensile strength tests are performed on cylindrical specimens to assess resistance against indirect tensile stresses, while flexural strength tests are conducted on prism specimens to evaluate bending performance. The modulus of elasticity and crack propagation characteristics are also examined to understand the structural behavior of the hybrid fiber-reinforced bagasse ash concrete.

Finally, the experimental results are analyzed and compared with those of conventional concrete. Statistical evaluation is performed to determine the significance of strength improvements achieved through the incorporation of bagasse ash, steel fibers, and polypropylene fibers. The optimum mix proportion is identified based on mechanical performance, sustainability benefits, and overall structural efficiency. The proposed methodology provides a comprehensive framework for developing eco-friendly high-performance concrete that promotes waste utilization, reduces cement consumption, and enhances the durability and strength characteristics of concrete structures.

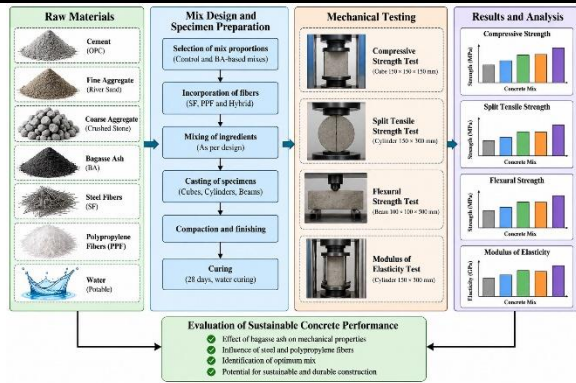


Fig. 1. Proposed experimental framework for evaluating the mechanical performance of sustainable concrete incorporating bagasse ash, steel fibers, and polypropylene fibers.

4 EXPERIMENTAL RESULTS

The mechanical performance of sustainable concrete incorporating bagasse ash (BA), steel fibers (SF), and polypropylene fibers (PPF) was evaluated through compressive strength, split tensile strength, flexural strength, and modulus of elasticity tests conducted after 28 days of curing. The experimental findings indicate that the incorporation of bagasse ash improved the pozzolanic activity within the concrete matrix, while the hybrid fiber system enhanced crack resistance and load-carrying capacity. Among all mixtures, the concrete containing 10% bagasse ash with combined steel and polypropylene fibers exhibited the best overall performance, demonstrating significant improvements in strength and ductility compared to conventional concrete.

Table 1. Compressive Strength of Concrete Mixes

Mix ID	Bagasse Ash (%)	Fiber Combination	Compressive Strength (MPa)
CM	0	None	32.4
BA10	10	None	35.8
BA10-SF	10	Steel Fiber	39.6
BA10-PPF	10	Polypropylene Fiber	37.9

BA10-HF	10	SF + PPF	43.8
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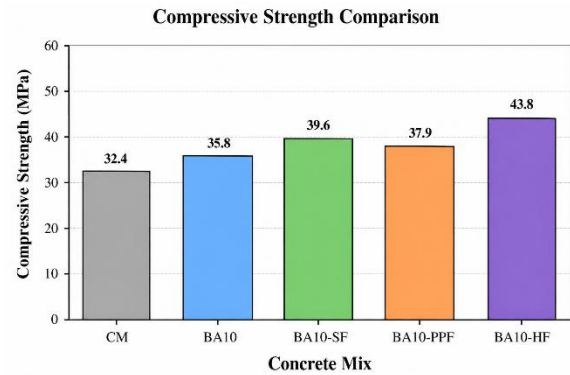


Fig. 2. Comparison of 28-day compressive strength of conventional concrete and sustainable concrete mixes incorporating bagasse ash, steel fibers, and polypropylene fibers

Table 2. Split Tensile Strength of Concrete Mixes

Mix ID	Split Tensile Strength (MPa)
CM	3.25
BA10	3.78
BA10-SF	4.46
BA10-PPF	4.18
BA10-HF	5.12

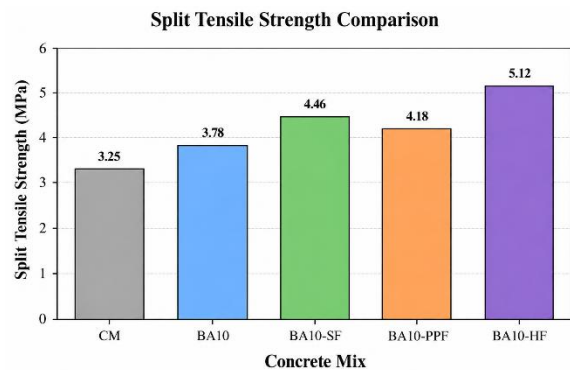


Fig. 3. Comparison of 28-day split tensile strength of various concrete mixes containing bagasse ash and hybrid fiber reinforcement.

Table 3. Flexural Strength of Concrete Mixes

Mix ID	Flexural Strength (MPa)
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CM	4.48
BA10	5.02
BA10-SF	5.81
BA10-PPF	5.46
BA10-HF	6.72

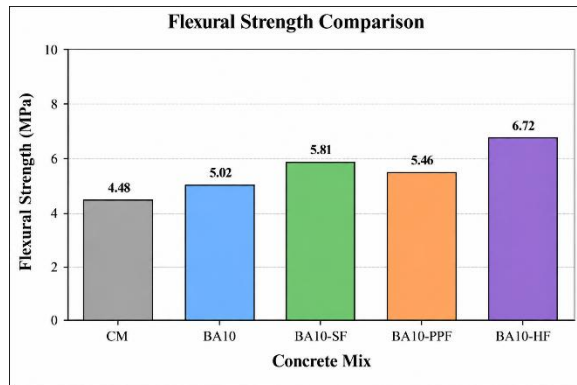


Fig. 4. Comparison of 28-day flexural strength of concrete mixes reinforced with steel fibers and polypropylene fibers in the presence of bagasse ash.

Table 4. Modulus of Elasticity of Concrete Mixes

Mix ID	Modulus of Elasticity (GPa)
CM	26.8
BA10	28.4
BA10-SF	30.6
BA10-PPF	29.5
BA10-HF	33.2

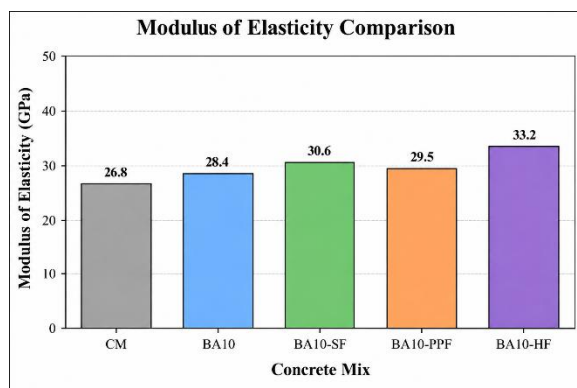


Fig. 5. Comparison of modulus of elasticity of sustainable concrete mixes showing the influence of bagasse ash and hybrid fiber reinforcement on stiffness characteristics.

4.2 Discussion

The experimental results clearly demonstrate that the incorporation of bagasse ash positively influenced the strength development of concrete. The pozzolanic reaction between the silica-rich bagasse ash and calcium hydroxide produced during cement hydration contributed to the formation of additional calcium silicate hydrate (C-S-H) gel, resulting in a denser and stronger concrete matrix. Compared with conventional concrete, the bagasse ash mixtures exhibited improved compressive strength and enhanced bonding between aggregate particles and the cementitious matrix. The increase in strength was particularly evident at 28 days, indicating the beneficial long-term contribution of bagasse ash to concrete performance.

The inclusion of steel fibers and polypropylene fibers further enhanced the mechanical behavior of the concrete by controlling crack initiation and propagation. Steel fibers improved load transfer and post-cracking resistance, while polypropylene fibers effectively minimized microcrack formation and shrinkage-related cracking. The hybrid fiber combination produced the highest values of compressive strength, split tensile strength, flexural strength, and modulus of elasticity among all tested mixtures. This synergistic interaction between bagasse ash and hybrid fibers resulted in a durable and high-performance concrete capable of withstanding greater mechanical stresses. The findings confirm that sustainable concrete incorporating bagasse ash, steel fibers, and polypropylene fibers offers an effective solution for reducing cement consumption while simultaneously improving structural performance and service life.

5 CONCLUSION

This study investigated the mechanical performance of sustainable concrete incorporating bagasse ash (BA), steel fibers (SF), and polypropylene fibers (PPF) as environmentally friendly alternatives to

conventional concrete constituents. The experimental results demonstrated that the partial replacement of cement with bagasse ash enhanced the strength development of concrete through pozzolanic reactions, leading to a denser microstructure and improved mechanical characteristics. Furthermore, the inclusion of steel fibers and polypropylene fibers significantly improved crack resistance, tensile behavior, flexural performance, and overall ductility of the concrete.

Among the various mixes evaluated, the hybrid fiber-reinforced concrete containing 10% bagasse ash exhibited the highest compressive strength, split tensile strength, flexural strength, and modulus of elasticity. The synergistic action of steel fibers and polypropylene fibers effectively controlled both microcracks and macrocracks, thereby enhancing load-carrying capacity and post-cracking behavior. Compared to conventional concrete, the optimum sustainable concrete mix achieved notable improvements in strength and structural performance while simultaneously reducing cement consumption.

The findings confirm that the combined utilization of bagasse ash, steel fibers, and polypropylene fibers provides a practical approach for developing high-performance sustainable concrete suitable for modern construction applications. In addition to improving mechanical properties, the proposed concrete contributes to environmental sustainability through agricultural waste utilization and reduction of carbon emissions associated with cement production. Therefore, hybrid fiber-reinforced bagasse ash concrete can be considered a promising material for durable and eco-friendly infrastructure development.

Future research may focus on evaluating the long-term durability performance of such concrete under aggressive environmental conditions, including sulfate attack, chloride penetration, freeze-thaw cycles, and elevated

temperatures. Further optimization of bagasse ash replacement levels and fiber contents may also help in developing cost-effective sustainable concrete mixtures for large-scale structural applications.

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