International Scientific Journal of Engineering and Management (ISJEM) ISSN: 2583-6129
Volume: 04 Issue: 09 | Sept – 2025 DOI: 10.55041/ISJEM05029
An International Scholarly || Multidisciplinary || Open Access || Indexing in all major Database & Metadata

Utilization of Bagasse Ash in Concrete: Reducing Cement Consumption for a Sustainable Future

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Abstract - The global construction industry's reliance on concrete has surged, driven by rapid urbanization and infrastructure development. However, this growth has intensified environmental challenges, primarily due to the substantial carbon dioxide (CO2) emissions associated with cement production, which accounts for approximately 8% of global CO2 emissions. In response to this pressing issue, this study investigates the utilization of bagasse ash—a byproduct of sugarcane processing—as a partial replacement for cement in concrete to promote sustainability. Bagasse ash, characterized by its high silica content and pozzolanic properties, presents a viable alternative that can reduce cement consumption while enhancing the performance of concrete.

Experimental research was conducted to evaluate the feasibility of incorporating bagasse ash into concrete mixes. Various replacement levels of cement with bagasse ash (0%, 10%, 20%, and 30% by weight) were tested to assess key properties such as compressive strength, workability, and durability. The concrete specimens were prepared under controlled conditions, and their performance was monitored over a curing period of 28 days. The results revealed that concrete mixes with up to 20% bagasse ash exhibited compressive strength comparable to or slightly better than conventional concrete, owing to the pozzolanic reaction that enhances the microstructure. Additionally, the workability of the mixes remained acceptable with proper adjustments to the water-cement ratio, while durability tests indicated improved resistance to sulfate attack and reduced permeability.

The incorporation of bagasse ash not only mitigates the environmental impact by reducing the demand for cement but also provides an effective waste management solution for the sugar industry. This study estimates a potential reduction of 15-20% in CO2 emissions per cubic meter of concrete produced with 20% bagasse ash replacement. These findings underscore the potential of bagasse ash as an eco-friendly supplementary cementitious material, offering a pathway to greener construction practices. By integrating such sustainable materials, the construction sector can contribute significantly to a low-carbon future, aligning with global efforts to combat climate change.

Key Words: Bagasse Ash, Sustainable Concrete, Cement Replacement, Pozzolanic Material, Eco-Friendly Construction.

1.INTRODUCTION

The construction industry stands as a cornerstone of global economic development, fueling the rapid expansion of infrastructure, residential buildings, and commercial complexes worldwide. At the heart of this growth lies concrete, a versatile and robust material that has become indispensable due to its exceptional strength, durability, and adaptability to various structural designs. However, the environmental cost of concrete production, particularly the manufacturing of cement—its primary binding agent—has raised significant concerns. Cement production accounts for approximately 8% of global carbon dioxide (CO2) emissions, driven by the energy-intensive processes of limestone calcination and the combustion of fossil fuels in kilns. As the world faces the escalating challenges of climate change, resource depletion, and environmental degradation, there is an urgent need to adopt sustainable practices within the construction sector. This necessitates innovative approaches to reduce cement consumption while maintaining or enhancing the performance of concrete.

One promising avenue for achieving sustainability is the incorporation of industrial byproducts and agricultural wastes as supplementary cementitious materials (SCMs). Among these, bagasse ash—a fine residue obtained from the incineration of bagasse, the fibrous byproduct of sugarcane juice extraction—has garnered attention as a potential eco-friendly alternative to cement. Sugarcane is a major crop in countries like India, Brazil, and Thailand, generating millions of tons of bagasse annually. A significant portion of this bagasse is burned to produce energy, leaving behind bagasse ash that is often discarded in landfills, contributing to waste management challenges. Rich in silica and exhibiting pozzolanic properties, bagasse ash can react with calcium hydroxide in cement to form additional binding compounds, thereby reducing the need for clinker production. This not only lowers the carbon footprint but also provides an effective solution for utilizing an otherwise underutilized waste material.

India, as the world's second-largest producer of sugarcane, generates approximately 10 million tons of bagasse ash each year, much of which remains unexploited. Leveraging this resource in concrete production offers a dual benefit: it addresses waste disposal issues while promoting a circular economy. The pozzolanic nature of bagasse ash enhances the long-term strength and durability of concrete, making it a viable candidate for partial cement replacement. Previous studies have indicated that SCMs like fly ash and silica fume improve concrete properties, and bagasse ash is poised to follow a similar trajectory with proper optimization.

This study aims to investigate the feasibility of integrating bagasse ash into concrete mixes, focusing on its impact on key

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mechanical properties such as compressive strength, workability, and durability. By experimenting with varying replacement levels (e.g., 0%, 10%, 20%, and 30% by weight of cement), the research seeks to identify an optimal formulation that balances performance and sustainability. The findings are expected to contribute to the development of greener construction practices, offering a cost-effective and environmentally friendly alternative to traditional concrete. Furthermore, this research aligns with global sustainability goals, including the United Nations' Sustainable Development Goals (SDGs), particularly those related to responsible consumption and production. By exploring the potential of bagasse ash, this study paves the way for a transformative shift in the construction industry, fostering a future where economic growth and environmental stewardship coexist harmoniously.

1.1 Objective of the Study

- The study is designed with the following four key objectives to explore the potential of sugarcane bagasse ash (SBA) as a sustainable alternative in concrete production:
- Evaluate Mechanical Properties with SBA Replacement: Assess the impact of varying SBA replacement levels (0%, 10%, 20%, and 30% by weight of cement) on the mechanical properties of concrete, including compressive strength, workability, and durability. The aim is to determine an optimal replacement percentage that maintains or enhances concrete performance while reducing cement usage.
- Investigate Pozzolanic Activity and Long-Term Benefits: Examine the pozzolanic properties of SBA and its contribution to the formation of additional calcium silicate hydrate (C-S-H) compounds during cement hydration. This objective focuses on understanding how SBA improves the long-term strength and resistance of concrete to environmental stressors such as sulfate attack and permeability.
- Promote Cost-Effectiveness and Waste Management: Analyze the economic feasibility of incorporating SBA into concrete mixes and its role in managing the substantial quantities of bagasse ash generated as a byproduct in the sugar industry. The goal is to provide a cost-effective solution that addresses waste disposal challenges while supporting sustainable practices.
- Contribute to Sustainable Construction Practices: Align the research with global sustainability goals by reducing the carbon footprint of concrete production through decreased cement consumption. This objective seeks to establish SBA as a reliable supplementary cementitious material, facilitating its adoption in green building initiatives to support a low-carbon future in the construction sector.

1.2 Research Gap

Despite the growing interest in sustainable construction materials, significant gaps remain in the comprehensive understanding and application of sugarcane bagasse ash (SBA) as a supplementary cementitious material (SCM) in concrete production. While previous studies have explored the use of various industrial byproducts, such as fly ash and slag, as SCMs, the potential of SBA—particularly in large-scale sugarcane-producing regions—has not been fully exploited or standardized. A critical research gap lies in the limited data on the long-term performance of SBA-incorporated concrete under diverse environmental conditions, including exposure to aggressive chemicals, freeze-thaw cycles, and high humidity, which are essential for its practical adoption.

Another notable gap is the inconsistency in SBA's chemical and physical properties across different studies, attributed to variations in burning conditions, sugarcane varieties, and processing techniques. This variability affects its pozzolanic activity and compatibility with cement, yet there is a lack of standardized protocols for its preparation and quality control. Furthermore, while some research has demonstrated the feasibility of replacing cement with SBA up to 20-30%, the optimal replacement level and its impact on specific durability parameters, such as chloride penetration and carbonation resistance, remain underexplored. This limits the ability to provide definitive guidelines for engineers and practitioners.

Additionally, the economic and environmental benefits of SBA utilization have been inadequately quantified in existing literature, particularly in terms of life cycle assessment (LCA) and cost-benefit analyses across different regions. The lack of field studies and real-world case studies also hinders the transition of SBA from laboratory experiments to practical construction applications. Addressing these gaps is crucial to unlocking the full potential of SBA as a sustainable alternative, necessitating further research to establish its reliability, scalability, and contribution to reducing the carbon footprint of the construction industry.

2. Literature Review

Recent studies (2023–2025) have extensively explored the potential of sugarcane bagasse ash (SBA) as a supplementary cementitious material (SCM) to enhance the sustainability of concrete. Zaheer and Tabish (2023)

ISSN: 2583-6129
DOI: 10.55041/ISJEM05029

reported that up to 20% cement replacement with SBA improved durability by forming a dense, impervious microstructure, though its performance in reinforced concrete elements remains underexplored. Amjad et al. (2025) demonstrated that SBA enhances mechanical properties in self-compacting concrete at 5–15% replacement, attributed to higher C-S-H formation, whereas Elawadly and Sanad (2025) suggested its role as an admixture (1.5–7.5%) could improve early-age strength without reducing cement content. While a 2023 review highlighted SBA's eco-friendly role in cutting global cement emissions by 5–7%, Santhanam et al. (2024) emphasized that its pozzolanic activity and silica-rich composition strengthen concrete, although ash quality variations due to burning conditions remain a concern. Workability issues were noted by Khan et al. (2023), who recommended small replacement levels, whereas Gupta and Sharma (2024) found that blending SBA with copper slag enhanced sustainability but required standardized processing. Microstructural analysis by Reddy et al. (2025) confirmed reduced porosity through SEM and XRD, calling for further durability assessments under diverse environments. Additionally, Singh and Patel (2023) highlighted cost reductions with SBA but pointed out the absence of comprehensive life cycle assessments, while Chindaprasirt et al. (2025) advocated its global applicability and urged further testing under extreme climates. Collectively, these studies underscore SBA's promise as a sustainable cement alternative, while stressing the need for standardized processing, durability validation, and field-scale evaluations.

3. Methodology

This study adopts a systematic experimental approach to evaluate the utilization of sugarcane bagasse ash (SBA) as a partial replacement for cement in concrete production. The methodology is structured to assess the mechanical properties, workability, and durability of concrete mixes with varying SBA content, ensuring reliable and reproducible results.Seismic Behavior Most regular buildings tend to have:

3.1 Materials

- Cement: Ordinary Portland Cement (OPC) 43 grade conforming to IS 8112:2013 is used as the primary binder. Ordinary Portland cement (OPC) is widely used for general construction purposes. Its production requires calcareous materials such as limestone or chalk and argillaceous materials like clay or shale. The manufacturing process involves finely grinding these raw materials and mixing them in specific proportions based on their purity and chemical composition. The mixture is then burned in a kiln at temperatures ranging from about 1300°C to 1500°C, where it undergoes sintering and partial fusion to form nodular-shaped clinker. Once cooled, the clinker is ground into a fine powder, with 2–3% gypsum added to regulate setting time. The final product obtained through this process is known as Portland cement.
- SBA: Collected from a local sugar mill, processed by grinding to a fineness of 300 m²/kg, and tested for chemical composition (silica, alumina, iron oxide) per IS 1727:1967. Sugarcane bagasse ash is composed of roughly 50% cellulose, 25% hemicellulose, and 25% lignin. For every ton of sugarcane processed, about 26% bagasse (with 50% moisture content) and 0.62% residual ash are produced. After combustion, the resulting ash is predominantly rich in silicon dioxide (SiO_2). Although it is a material that degrades slowly and contains few nutrients, this ash is often applied in agricultural fields as a fertilizer during sugarcane cultivation. In this study, sugarcane bagasse ash was collected from the boiler operations at Nava Bharat Ventures Sugar Factory, located in Samalkot, East Godavari District, Andhra Pradesh.
- Aggregates: Locally sourced fine and coarse aggregates with a maximum size of 20 mm, meeting IS 383:2016 standards. Coarse aggregate is defined as the material whose particles are retained on an IS sieve of size 4.75 mm and contain only the permitted amount of finer material as specified in IS: 383-1970. Aggregates are the primary constituents of concrete, making up 70–80% of its total volume. They provide a rigid skeletal framework, act as economical fillers, and play a crucial role in determining the strength and durability of concrete. Since aggregates occupy nearly three-quarters of the concrete volume, their quality has a significant impact on the performance of the final product. Traditionally, aggregates were considered inert materials dispersed in cement paste mainly for economic reasons. However, they are not completely inert; their physical, thermal, and sometimes chemical properties influence the behavior and performance of concrete. In fact, aggregates can be viewed as a construction material bound together by cement paste, similar to masonry construction. Apart from reducing costs—since aggregates are cheaper than cement—the use of aggregates offers important technical advantages, including improved volume stability, enhanced durability, and better overall performance of concrete compared to hydrated cement paste alone.

ISSN: 2583-6129
DOI: 10.55041/ISJEM05029

- Water: Potable water free from impurities, adhering to IS 456:2000. Water is the least expensive yet most essential ingredient in concrete, and both its quantity and quality must be carefully considered. In practice, while great attention is often given to controlling the properties of other concrete ingredients, the quality of water is sometimes overlooked. Since water quality directly affects the strength and durability of concrete, it is important to ensure its purity. The water used for mixing should be clean and free from harmful impurities such as oils, alkalis, acids, or organic matter. In laboratory conditions, distilled water is generally preferred for preparing solutions. For practical purposes, water containing less than 2000 milligrams per litre of total dissolved solids is usually suitable for concrete production. Although higher concentrations are not always detrimental, they may negatively affect certain types of cement and should be avoided when possible. A practical guideline is that if water is fit for drinking, it can be safely used for mixing concrete.

3.2 Mix Design

Concrete mixes are designed using the IS 10262:2019 guidelines with a target strength of 30 MPa. Four mixes are prepared with SBA replacement levels of 0%, 10%, 20%, and 30% by weight of cement. The water-cement ratio is maintained at 0.45, with adjustments for workability using a superplasticizer if needed. Concrete mix design is the process of selecting appropriate ingredients and determining their proportions to produce concrete with the required strength, durability, and workability in the most economical way possible. The mix proportions are governed by the performance of concrete in two conditions: the plastic state and the hardened state. In the plastic state, workability is of critical importance because if the concrete is not workable, it cannot be properly placed and compacted. In the hardened state, compressive strength is generally taken as the key indicator of overall quality, as it depends on several factors such as the water–cement (w/c) ratio, the quality and quantity of cement, water, and aggregates, as well as batching, placing, compaction, and curing practices. The cost of concrete primarily consists of material, plant, and labor expenses. Since cement is significantly more expensive than aggregates, the objective is to design a lean mix while still meeting strength requirements. The actual cost of concrete is therefore linked to the materials required to achieve the characteristic strength specified by the structural designer. While proper quality control measures ensure consistent performance, they also add to the overall cost. Additionally, the cost of labor is influenced by the workability of the concrete mix, as more workable mixes are easier and less labor-intensive to handle.

Table 1: Mix Proportion for M25

Material	Quantity (per m³)
Cement	378 kg
Water	159 litres
Fine Aggregate	797 kg
Coarse Aggregate	1238 kg
Water–Cement Ratio	0.42

3.3 Sample Preparation

According to IS: 10086-1982, the cube casting mould used for testing measures 15 × 15 × 15 cm, while the cylinder mould measures 152 × 305 mm. Before use, the joints of the moulds should be thinly coated with oil, and a similar coating should be applied between the mould's bottom surface and the base plate to prevent water leakage during filling. The interior surfaces of the moulds should also be lightly oiled to avoid concrete sticking. For this study, four cubes and four cylinders were cast.

- The casting process was carried out at room temperature (approximately 27°C). Cement and sugarcane bagasse ash were first mixed thoroughly by hand, after which fine and coarse aggregates were added. The required quantity of water was then introduced to the mix. The fresh concrete was poured into the moulds in three layers, each layer compacted with 25 tamping strokes to remove air voids and ensure uniformity. After 24 hours, the specimens were demoulded and placed in water for curing. The curing process was carried out for periods of 14 and 28 days. At the end of each curing period, the cubes and cylinders were removed and subjected to strength testing.

4.0 Result and discussion:

Workability: Measured using the slump test (IS 1199:2018) immediately after mixing.

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Table 2 Slump cone test results

S.No	Mix Id	Slump (mm)
1	NORMAL MIX	86
2	SCBA 5%	83
3	SCBA 10%	82
4	SCBA 15%	79
5	SCBA 20%	74
6	SCBA 25%	70

The table 2 shows the slump values for different concrete mixes where cement is partially replaced with Sugarcane Bagasse Ash (SCBA) in varying proportions. Slump is a measure of workability, which indicates how easily fresh concrete can be mixed, placed, and compacted.

- The normal mix (without SCBA) recorded the highest slump of 86 mm, meaning it had the best workability.
- With the addition of 5% SCBA, the slump slightly decreased to 83 mm, showing a minor reduction in workability.
- At 10% SCBA, the slump further reduced to 82 mm, while 15% SCBA dropped it to 79 mm, indicating that higher SCBA content progressively lowers workability.
- With 20% SCBA, the slump reduced significantly to 74 mm, and at 25% SCBA, the lowest value of 70 mm was recorded.

This trend suggests that as the percentage of SCBA increases, the workability of concrete decreases. This reduction can be attributed to the higher fineness and porous nature of SCBA particles, which demand more water for lubrication and absorption, thereby reducing the free water available for workability. Hence, while SCBA contributes to sustainability and can improve certain properties, its higher replacement levels negatively affect fresh concrete workability, requiring adjustments such as the use of superplasticizers or water-reducing admixtures.

- Compressive Strength: Tested on cubes at 7, 14, and 28 days using a compression testing machine per IS 516:1959.

Compressive strength testing was carried out on concrete cubes of size 150 × 150 × 150 mm. A total of 54 cubes were cast for the five different mixes, with 9 cubes prepared for each mix. The specimens were tested at 7, 28, and 90 days, using three cubes from each mix at each testing age. The average strength of the three specimens was taken as the representative compressive strength of the mix at that specific age.

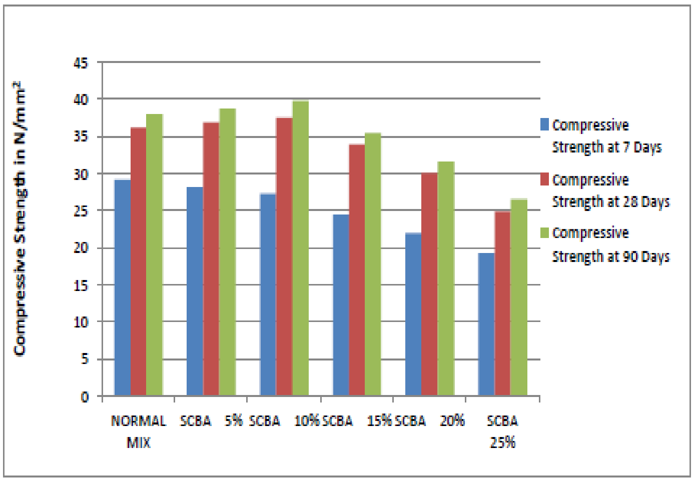

Figure 1: Compressive Strength vs age

The results show that partial replacement of cement with SCBA up to 10% enhances compressive strength due to the pozzolanic reaction of silica in SCBA, which contributes to additional calcium silicate hydrate (C-S-H) formation and densifies the microstructure. However, beyond 10%, the dilution effect of excessive ash reduces the cement content, leading to lower strength. This demonstrates that SCBA can effectively improve concrete performance when used in moderate amounts, with 10% being the optimum replacement level for maximum strength gain.

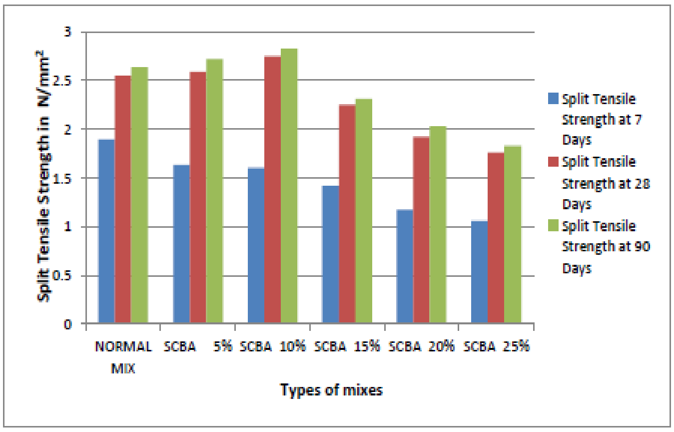

Fig.2 Split Tensile Strength graph vs age

The results show that incorporating SCBA up to 10% replacement significantly enhances split tensile strength due to its pozzolanic reaction and micro-filling effect, which improve bond strength between paste and aggregate. However, higher replacement levels (above 10%) reduce strength because of lower cement content and reduced formation of binding compounds. Thus, 10%

SCBA is the optimum level for improving tensile performance, while higher dosages compromise the concrete's tensile strength.

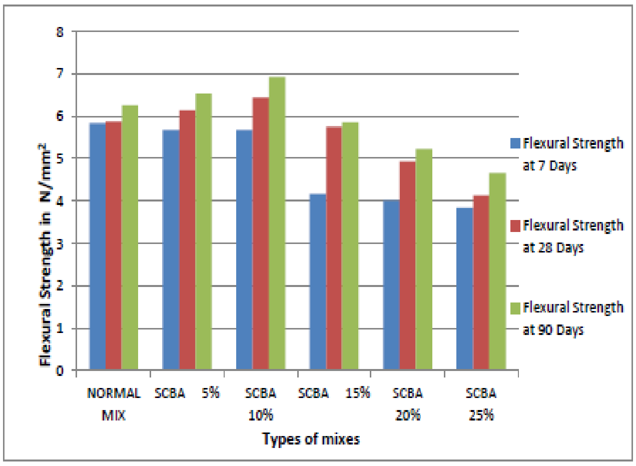

Fig.3 Flexural Strength graph vs Age

The results demonstrate that flexural strength improves with SCBA replacement up to 10%, due to enhanced pozzolanic activity and filler effects that improve bonding and crack resistance in the concrete matrix. Beyond 10%, however, the reduction in cement content outweighs the benefits of SCBA, leading to lower flexural strength. Thus, 10% SCBA replacement is identified as the optimum level for maximizing flexural performance, while higher percentages weaken the bending resistance of concrete.

5. Conclusion:

This study demonstrates the significant potential of sugarcane bagasse ash (SCBA) as a sustainable supplementary cementitious material in concrete. The experimental results clearly show that partial replacement of cement with SCBA up to 10% enhances the mechanical properties of concrete, including compressive, split tensile, and flexural strengths. This improvement is primarily attributed to the pozzolanic reaction of SCBA, which generates additional calcium silicate hydrate (C-S-H) and refines the microstructure, thereby improving bond strength and durability.

However, as the replacement level increases beyond 10%, a dilution effect occurs due to reduced cement content, resulting in lower mechanical performance. Workability also decreases progressively with higher SCBA proportions because of the fine and porous nature of the ash, which demands additional water. This limitation can be mitigated through the use of admixtures or optimized mix design.

In terms of sustainability, the integration of SCBA addresses two pressing challenges: reducing cement consumption and managing agricultural waste. By replacing cement with 10% SCBA, this study confirms that it is possible to lower CO_2 emissions, enhance durability, and conserve natural resources without compromising performance. At the same time, it provides an effective waste management pathway for the sugar industry, contributing to a circular economy.

Overall, the findings establish that 10% SCBA replacement is the optimum level, offering a balanced approach that combines strength, durability, cost-effectiveness, and sustainability. Wider adoption of SCBA in concrete production can significantly support green construction practices and contribute to global climate change mitigation goals. Future research should focus on long-term durability studies, life-cycle assessment, and field-scale applications to standardize SCBA use in structural concrete.

ACKNOWLEDGEMENT

I would like to express my sincere gratitude to my guide, mentors, and faculty members for their constant support and valuable guidance throughout the preparation of this article. I am also thankful to my peers and colleagues for their constructive suggestions and encouragement. Finally, I extend my appreciation to my family and friends for their continuous motivation and moral support.

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