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Sustainable Utilization of Sugarcane Bagasse Ash in Concrete: Experimental Insights into Mechanical Performance

Md. Zakir Hossain Khan[1], Md. Rokonuzzaman[2], Rejwana Haque Riya[3], Tanvir Hasan[4] and Md. Taky Hasan[5]

[1] Assistant Professor, Department of Civil Engineering, Bangladesh Army University of Engineering and Technology, Natore-6431

[2] Lecturer, Department of Civil Engineering, Bangladesh Army University of Engineering and Technology, Natore-6431

[3, 4, 5] Graduate Student, Department of Civil Engineering, Bangladesh Army University of Engineering and Technology, Natore-6431

email engr.zakir@yahoo.com

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Abstract

This study evaluates the potential of Sugarcane Bagasse Ash (SBA) as a partial substitute for Ordinary Portland Cement (OPC) to enhance the sustainability and mechanical performance of concrete. Given that cement production is a significant contributor to global CO_2 emissions, the investigation focuses on the valorization of agricultural residue as a supplementary cementitious material. Concrete mixtures were prepared with SBA replacement levels of 0%, 5%, 10%, 15%, and 20%, and the resulting specimens were subjected to compressive and tensile strength testing at curing ages of 7, 14, and 28 days. The experimental results indicate that SBA replacement in the range of 5–10% leads to notable improvements in both compressive and tensile strengths, particularly at extended curing periods. This enhancement is attributed to the pozzolanic activity of SBA, wherein its amorphous silica content reacts with calcium hydroxide released during cement hydration to produce additional calcium silicate hydrate (C–S–H) gel, thereby refining the microstructure and enhancing matrix densification. Conversely, higher replacement levels (15–20%) resulted in strength reduction, likely due to the dilution of cementitious phases and insufficient pozzolanic contribution. Overall, the findings demonstrate that SBA, when used at optimal substitution levels, serves as a viable and environmentally responsible alternative to reduce cement consumption, lower construction costs, and promote effective waste utilization, contributing to more sustainable and resilient construction practices.

Introduction

Since the inception of human civilization, a wide range of materials has been utilized in building construction. Among these, concrete has emerged as the most prevalent construction material globally. Over time, it has evolved from a rudimentary mixture of cement, water, and aggregates into a sophisticated composite system incorporating mineral admixtures, chemical additives, and reinforcing fibers to enhance its mechanical and durability properties [1, 2]. Beginning with the Industrial Revolution, the widespread adoption of cement as a binding material significantly enhanced the strength and durability of constructed structures [3]. Cement serves as a fundamental binding component in the production of both concrete and mortar, playing a critical role in determining their mechanical and durability characteristics [4, 5]. The demand for cement continues to increase with the progression of modern society and infrastructure development. Among the various types of cement, Ordinary Portland Cement (OPC) remains the most widely utilized binder in construction practices across the world due to its favorable mechanical and durability characteristics [6, 7, 8]. Cement production experienced substantial expansion throughout the 20th century. Approximately a decade ago, global cement output was estimated at around 3 billion tons, reflecting an average annual growth rate of nearly 6.3% [9]. The manufacture of one metric ton of Portland cement typically consumes approximately 4–5 GJ of thermal and electrical energy, reflecting the energy-intensive nature of the production process [10]. The production of one metric ton of cement generally requires approximately 60–130 kg of fuel oil (or an equivalent energy source) along with about 110 kW·h of electrical power. The exact energy demand varies depending on the specific cement type and the technological efficiency of the manufacturing process [11]. The manufacture of one ton of cement typically results in the release of approximately 800–1000 kg of CO_2, highlighting the sector's significant contribution to global greenhouse gas emissions [9, 12, 13] . Cement manufacturing is estimated to contribute approximately 5%–8% of total anthropogenic CO_2 emissions globally, positioning it among the most carbon-intensive industrial activities [9, 13, 14, 15].

Currently, considerable research efforts are directed toward the utilization of agricultural and industrial wastes as alternative raw materials in manufacturing processes. In this context, incorporating cementitious or pozzolanic by-products and waste materials as partial replacements for cement presents a promising strategy, offering both environmental and economic benefits [3]. The disposal of substantial quantities of waste generated from municipal activities, agricultural practices, and various industrial processes has become a significant environmental concern. Many of these waste materials possess inherent pozzolanic or cementitious properties, making them suitable for incorporation into cement-based composites. Their use as partial replacements for cement not only offers a viable waste management solution but also contributes to reducing production costs and mitigating the environmental impacts associated with conventional cement manufacturing [3]. Various Supplementary Cementitious Materials (SCMs) influence the properties of cement-based systems differently due to their distinct chemical compositions and physical characteristics. Furthermore, the availability and nature of any specific SCM are inherently tied to the particular industrial, agricultural, or municipal process from which it is derived [3, 16, 17]. Significant quantities of bagasse ash, generated as a residue from sugar production and from bagasse-based biomass fuel combustion, have been explored for potential utilization in the power generation sector [18]. A wide range of waste materials, including those originating from industrial processes, municipal activities, agricultural residues, and even certain naturally occurring by-products, can be processed and utilized as supplementary cementitious materials (SCMs) [3, 19, 20]. A diverse range of SCMs originates from both industrial and agro-industrial waste streams. Industrial by-product SCMs, such as fly ash, ground granulated blast furnace slag, bottom ash, silica fume, and finely ground limestone, have been widely incorporated into construction materials research and practice. Similarly, agricultural residues including palm oil fuel ash (POFA), rice husk ash (RHA), and

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sugarcane bagasse ash (BA) have also emerged as effective pozzolanic materials for partial cement substitution [3, 18].

Several countries, including Bangladesh and India, cultivate sugarcane for sugar production. In Bangladesh alone, sugar-cane output in 2019 reached approximately 3.20 million tonnes [21]. The combustion of dried bagasse is often considered carbon-neutral because the CO_2 emitted during burning is approximately equal to the amount absorbed by the sugarcane plant during its growth through photosynthesis. Thus, from a biogenic carbon cycle perspective, bagasse does not contribute additional fossil-based CO_2 to the atmosphere [3, 22, 23].

Extensive research has been undertaken to evaluate the mechanical behavior and pozzolanic performance of concrete in which Sugarcane Bagasse Ash (SBA) is used as a partial replacement for cement. The pozzolanic reactivity of SBA is strongly influenced by the calcination temperature applied during ash production as well as by the fineness of the resulting particles. These factors, in turn, have a direct impact on the mechanical properties and overall performance of SBA-modified concrete [24, 25]. This study focuses on evaluating the physical and chemical characteristics of Sugarcane Bagasse Ash (SBA) and examining the mechanical performance of concrete incorporating SBA as a partial cement replacement. Through these investigations, the research aims to promote the sustainable conversion of sugarcane processing waste into viable construction materials.

Methodology

This study investigates the use of Sugarcane Bagasse Ash (SBA) as a supplementary cementitious material (SCM) for the partial replacement of Ordinary Portland Cement (OPC) in concrete. The primary materials employed include OPC, natural Domar sand conforming to ASTM C128 as the fine aggregate, and crushed stone aggregates conforming to ASTM C33 as the coarse aggregate. SBA was obtained from locally incinerated sugarcane bagasse, oven-dried at approximately 110 °C, and subsequently sieved through a 0.075 mm sieve to obtain fine ash. Concrete mixes were prepared using a fixed proportion of 1:2:4 (cement:sand:coarse aggregate) with a water-cement ratio of 0.5. In these mixes, OPC was partially replaced by SBA at varying replacement levels of 0%, 5%, 10%, 15%, and 20%, alongside a control mix containing no SBA. The detailed mix proportions corresponding to each replacement level are presented in Table 1 and Table 2.

Table 1: Proportioning of Sugarcane Bagasse Ash (SBA) Concrete: Five Cubic Specimens

Mix Designation	Quantities						
	SBA (%)	Cement (gm)	Sand (gm)	Stone (gm)	SBA Mass (gm)	W/C ratio	Water (ml)
Cy 1	0%	512	1177.52	2121.58	0	0.5	256
Cy 2	5%	486.4	1177.52	2121.58	25.6	0.5	256
Cy 3	10%	460.8	1177.52	2121.58	51.2	0.5	256
Cy 4	15%	435.2	1177.52	2121.58	76.8	0.5	256
Cy 5	20%	409.6	1177.52	2121.58	102.4	0.5	256

The mixture designs for Sugarcane Bagasse Ash (SBA) concrete involved preparing five-cylinder specimens with different SBA replacement levels. For each mixing ratio, three samples were prepared and tested at curing ages of 7, 14, and 28 days; therefore, the total number of samples was

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45. This allowed evaluation of how SBA affects concrete strength and helped determine the most effective and sustainable mix proportion.

Table 2: Mixture Designs for Sugarcane Bagasse Ash (SBA) Concrete: Five Cylinder Specimens

Mix Designation	Quantities						
	SBA (%)	Cement (gm)	Sand (gm)	Stone (gm)	SBA in Replacement of cement (gm)	W/C	Water (ml)
Cu 1	0%	326	749.63	1350.64	0	0.5	163
Cu 2	5%	309.7	749.63	1350.64	16.3	0.5	163
Cu 3	10%	293.4	749.63	1350.64	32.6	0.5	163
Cu 4	15%	277.1	749.63	1350.64	48.9	0.5	163
Cu 5	20%	260.8	749.63	1350.64	65.2	0.5	163

Standard cube specimens measuring 4 in × 4 in × 4 in were cast for compressive strength testing, while cylindrical specimens with a diameter of 4 in and a height of 8 in were prepared for tensile strength testing. Following casting, all specimens were subjected to water curing for periods of 7, 14, and 28 days. The procedures for casting, molding, and curing of the specimens are illustrated in Fig. 1.

Figure 1: Preparation, Casting, and Curing of Specimens

The mechanical performance of the concrete mixtures was evaluated using compressive strength (see Fig. 2) and split tensile strength (see Fig. 3) tests, conducted in accordance with ASTM C39 and ASTM C496, respectively.

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Figure 2: Compressive Strength Test

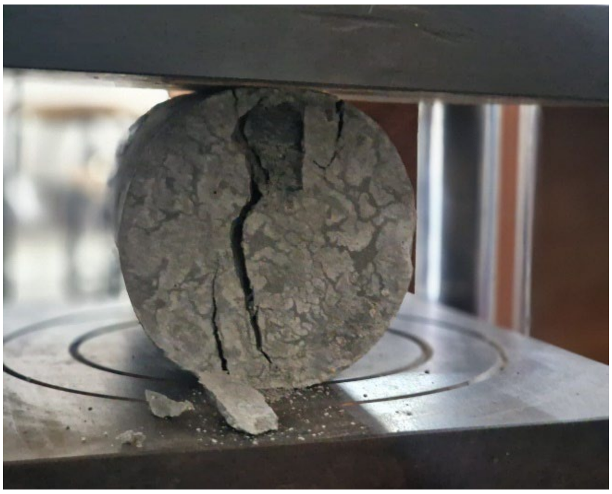

Figure 3: Tensile Strength Test

Additionally, the chemical composition and microstructural characteristics of the Sugarcane Bagasse Ash (SBA) were analyzed using X-ray Diffraction (XRD) and Scanning Electron Microscopy (SEM), following ASTM C1365, ASTM C114, and ASTM C1723-16 (2022). To evaluate the pavement performance, slab specimens were tested after 28 days of curing. This comprehensive experimental approach was undertaken to assess the durability and mechanical performance of SBA-incorporated concrete under varying conditions.

The water absorption behavior of the concrete was evaluated by exposing a single surface of each specimen to water and measuring the corresponding mass gain over time, thereby determining the rate of capillary absorption.

Result and Discussions

Compressive strength is a critical parameter in determining the load-bearing capacity, safety, stability, and long-term durability of concrete structures. It reflects the material's ability to withstand compressive stresses prior to failure or significant deformation. The compressive strength of concrete is typically evaluated by applying a gradually increasing load to cube or cylinder specimens until failure occurs. In this study, the primary objective of the compressive strength test was to assess the influence of Sugarcane Bagasse Ash (SBA) as a partial replacement for Ordinary Portland Cement (OPC). Four SBA replacement levels were incorporated into the concrete mix design, 5%, 10%, 15%, and 20%, alongside a control mix containing no SBA. The compressive strength results obtained at curing ages of 7, 14, and 28 days are presented in Fig. 4, illustrating the strength development across the different replacement levels.

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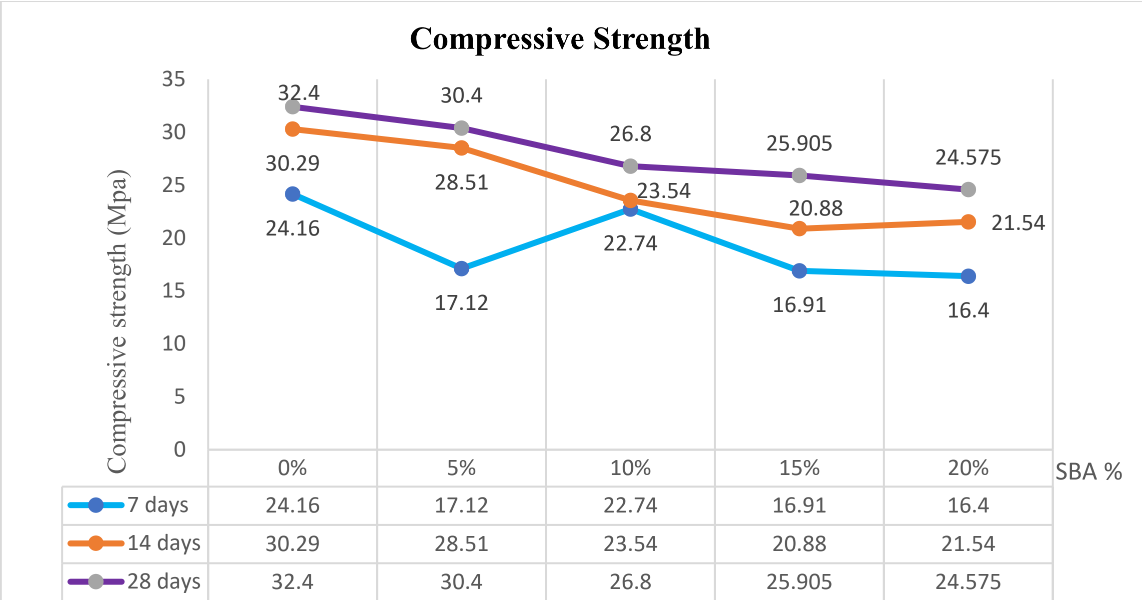

Figure 4: Average Compressive Strength at 7, 14, and 28 Days for Different SBA Replacement Levels

From Figure 4, it can be observed that the control mix (0% SBA) developed the highest compressive strength across all curing durations. Among the SBA-blended mixes, the concrete containing 10% SBA exhibited the highest strength at 7 days, while the 5% SBA mix demonstrated superior strength at both 14 and 28 days, indicating a continued improvement in strength with extended curing. Conversely, mixes incorporating 15% and 20% SBA showed noticeable reductions in compressive strength relative to the control, implying diminished performance at higher levels of cement replacement. The results indicate that incorporating SBA as a partial cement replacement at levels of 5–10% enhances long-term compressive strength, whereas higher replacement levels (15–20%) lead to reduced performance. This reduction may be attributed to the diminished pozzolanic contribution and the dilution of the cementitious matrix at elevated SBA contents. Overall, the findings suggest that an SBA replacement level within the range of 5–10% provides an optimal balance between mechanical performance and sustainability benefits in concrete production.

Tensile strength is a key mechanical property that defines the maximum stress a material can sustain when subjected to tension before cracking or failure occurs. It indicates the material's resistance to fracture and deformation under tensile or flexural loading conditions. In concrete, tensile strength plays a critical role in assessing structural performance, particularly for members subjected to bending and flexural stresses, and is therefore essential for evaluating durability, serviceability, and overall suitability for construction applications.

In this study, the tensile characteristics of concrete incorporating various proportions of Sugarcane Bagasse Ash (SBA) as a partial replacement for Ordinary Portland Cement (OPC) were examined to determine its influence on mechanical integrity and long-term performance. Concrete mixes with SBA replacement levels of 0% (control), 5%, 10%, 15%, and 20% were tested at curing ages of 7 and 28 days. The corresponding results are presented in Fig. 5.

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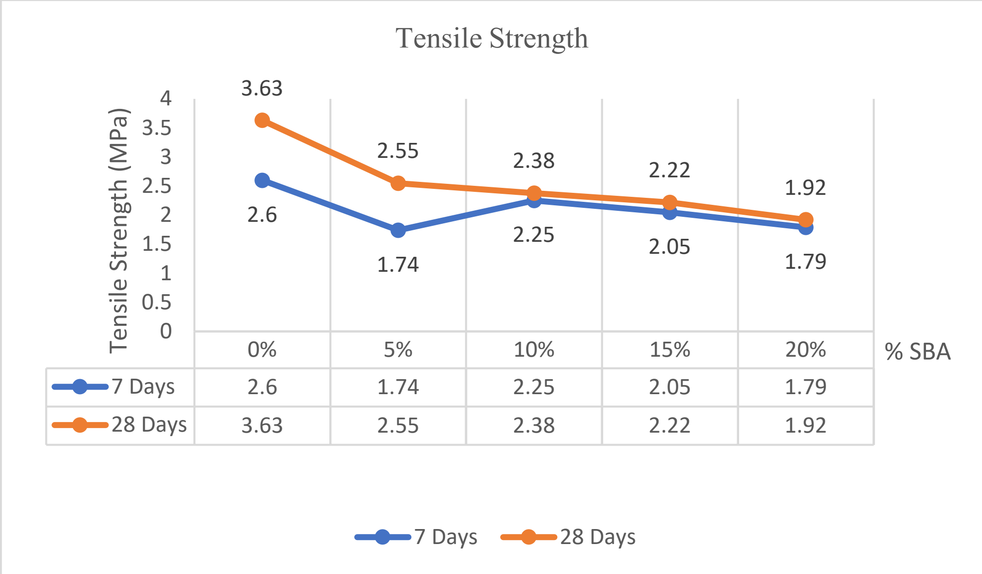
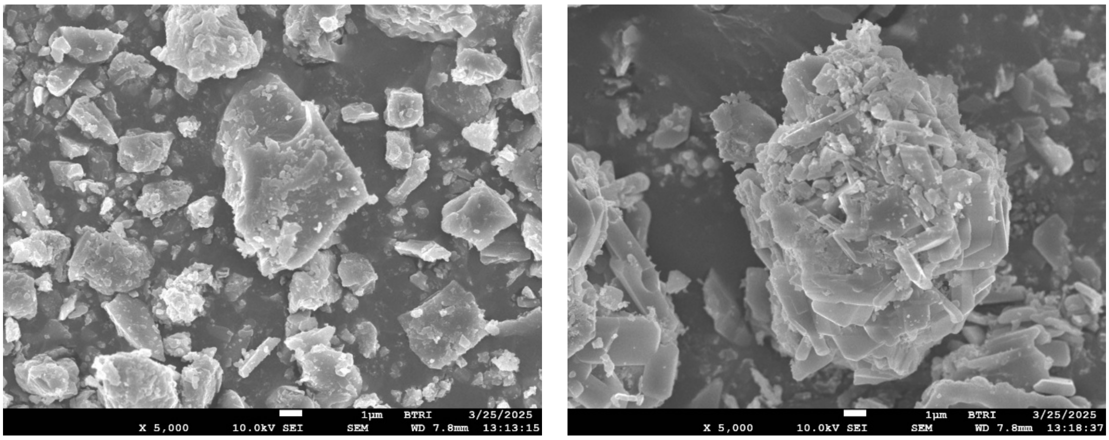


Figure 5: Development of Tensile Strength at 7-Day and 28-Day Curing Ages

The tensile strengths of the concrete mixes incorporating different proportions of SBA are illustrated in Figure 5. The control mix (0% SBA) recorded the highest tensile strength at both 7 days (2.60 MPa) and 28 days (3.63 MPa), representing the baseline performance of concrete without supplementary materials. Among the SBA-modified mixes, the 10% SBA replacement exhibited greater tensile strength at 7 days (2.25 MPa) compared to the 5% SBA mix (1.74 MPa). However, at 28 days, the 5% SBA mix achieved a slightly higher tensile strength (2.55 MPa) than the 10% SBA mix (2.38 MPa). This trend indicates that lower SBA replacement levels favor long-term tensile strength development, likely due to enhanced pozzolanic activity and improved densification of the cementitious matrix over time.

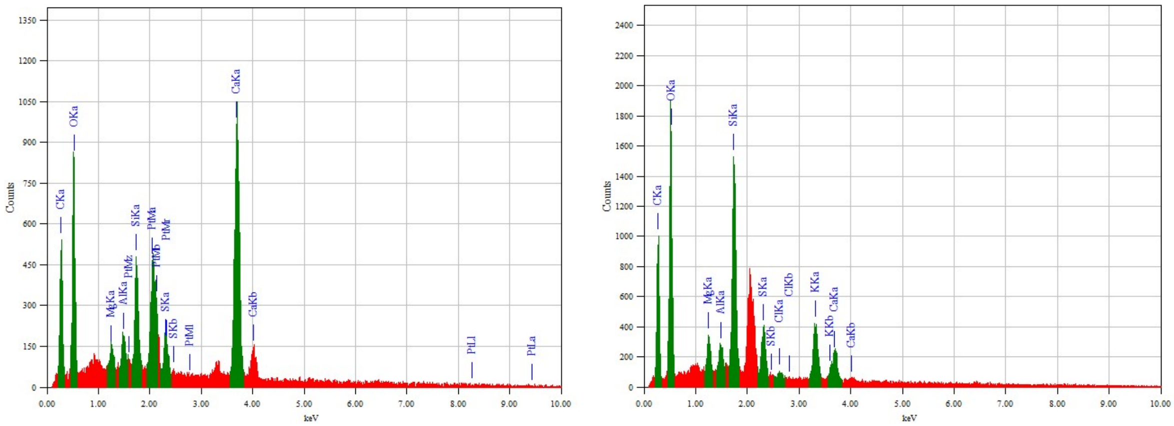
In contrast, higher SBA replacement levels (15% and 20%) resulted in significant reductions in tensile strength at both curing ages, with the 20% SBA mix exhibiting the lowest values (1.79 MPa at 7 days and 1.92 MPa at 28 days). This reduction is likely due to the dilution of the cementitious binder and the limited pozzolanic reactivity available at higher ash contents. Overall, the findings suggest that incorporating SBA at a replacement level of 5–10% provides the most favorable balance between sustainability and mechanical performance, improving tensile characteristics while maintaining structural integrity.

The SEM and EDX analyses highlight clear distinctions between Sugarcane Bagasse Ash (SBA) and Ordinary Portland Cement in terms of particle morphology and elemental composition. The SEM micrographs show that SBA is characterized by highly porous, irregular, and in some cases, spheroidal particles, whereas cement particles appear denser, angular, and predominantly crystalline in structure. These morphological variations arise from the fundamentally different origins and processing methods of the two materials. The physical properties of SBA and cement are presented in Fig. 6, while their respective chemical compositions are shown in Fig. 7.



(1) (2)

Figure 6: Physical Properties of Cement (1) and Sugarcane Bagasse Ash (2)



(1) (2)

Figure 7: Chemical Composition of Cement (1) and Sugarcane Bagasse Ash (2)

The most notable distinction between the two materials lies in their chemical composition, as evidenced by the EDS analysis. Cement is predominantly calcareous, characterized by a high presence of calcium (Ca) and oxygen (O), which is fundamental to its role as a hydraulic binder. In contrast, Sugarcane Bagasse Ash (SBA) is primarily siliceous, exhibiting elevated concentrations of silicon (Si) and oxygen (O), reflecting its substantial silicon dioxide (SiO_2) content.

Microstructural characterization of raw materials revealed pronounced differences between SBA and cement. The SEM micrograph of Sugarcane Bagasse Ash (SBA) shows predominantly porous, highly irregular particle morphologies. Corresponding EDS analysis indicates that SBA is rich in silicon (Si) and oxygen (O), reflecting a high content of amorphous SiO_2, which contributes to its pozzolanic reactivity. In contrast, the SEM image of the cement sample exhibits a dense, microcrystalline structure composed of angular, block-like particles. Elemental analysis confirmed a high calcium (Ca) content, characteristic of calcium silicate phases that form the primary binding components in Ordinary Portland Cement.

The distinct chemical composition and particle morphology of SBA play a key role in its effectiveness as a supplementary cementitious material (SCM). During the hydration of Portland cement, the primary reaction products are calcium silicate hydrate (C–S–H) gel, which contributes to strength development, and calcium hydroxide [$Ca(OH)_2$], which remains as a secondary byproduct. The presence of $Ca(OH)_2$ in the hardened matrix can be detrimental to long-term

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durability because it is relatively soluble and may promote increased porosity, thereby facilitating the ingress of aggressive agents.

The role of SBA as a supplementary cementitious material is governed by its pozzolanic reactivity. The amorphous silica present in SBA reacts with the calcium hydroxide produced during cement hydration to form additional calcium silicate hydrate (C–S–H) gel, which contributes to strength development. This reaction can be represented as:

$$SiO_2 \text{ (from SBA)} + Ca(OH)_2 \text{ (from cement hydration)} \rightarrow \text{C−S−H gel}$$

Through this mechanism, SBA not only enhances the formation of the binding phase (C–S–H) but also reduces the amount of free $Ca(OH)_2$, thereby improving the durability and densification of the concrete matrix.

This reaction serves two critical functions:

1. By consuming soluble calcium hydroxide, the pozzolanic reaction enhances the chemical stability of the matrix, thereby improving the long-term resistance of concrete to degradation and aggressive environmental exposure.
2. The formation of additional C–S–H gel contributes to microstructural densification, refinement of the pore network, and a corresponding increase in mechanical strength, particularly noticeable at later curing ages.

The porous, high–surface area morphology of SBA particles further enhances their pozzolanic effectiveness by providing abundant reaction sites for the interaction between $Ca(OH)_2$ and amorphous silica. This increased reactivity promotes more efficient conversion of calcium hydroxide into additional C–S–H gel, contributing to improved microstructural densification and overall superior performance of SBA-blended cementitious systems [26, 27]. Therefore, while cement contributes predominantly to early strength development, SBA enhances the long-term performance of the composite by converting an otherwise weak and undesirable hydration byproduct into additional binding gel at the microstructural level. This confirms that SBA functions not simply as an inert filler, but as an active supplementary cementitious material, capable of improving both the mechanical properties and durability of cementitious systems.

The results of this study indicate that partial replacement of Ordinary Portland Cement (OPC) with Sugarcane Bagasse Ash (SBA) in the range of 5–10% provides the most effective balance between mechanical performance, durability, and environmental sustainability. The improvements in compressive and tensile strength observed at these levels are attributed to the pozzolanic reactivity of SBA, which facilitates the formation of additional calcium silicate hydrate (C–S–H) while consuming calcium hydroxide, thereby enhancing microstructural densification and long-term performance. Conversely, higher replacement levels (15–20%) resulted in noticeable reductions in strength, likely due to the dilution of cementitious constituents and reduced pozzolanic efficiency. These observations are consistent with findings from previous research, which similarly report enhanced performance at lower SBA substitution levels and a decline in strength with excessive replacement [28, 29, 30].

From a broader sustainability standpoint, the incorporation of SBA as a supplementary cementitious material directly supports several United Nations Sustainable Development Goals (SDGs). In particular, it contributes to SDG 9 (Industry, Innovation, and Infrastructure) by encouraging the development of resource-efficient and innovative construction materials; supports SDG 11 (Sustainable Cities and Communities) by enhancing the durability and resilience of the built environment; and advances SDG 12 (Responsible Consumption and Production) by transforming

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agricultural waste into valuable construction resources, thereby promoting circular material use and reducing environmental burdens [32, 33, 34]. Moreover, by reducing clinker consumption and the corresponding CO_2 emissions associated with cement production, the use of SBA also contributes to SDG 13 (Climate Action) through the mitigation of greenhouse gas emissions [35]. Collectively, these findings demonstrate that the judicious incorporation of SBA at optimal replacement levels not only improves the mechanical and durability performance of concrete but also provides a practical pathway toward more environmentally responsible construction practices. As cement is the most expensive component in concrete production, substituting a portion of it with an economical, naturally available, and locally sourced material such as Sugarcane Bagasse Ash (SBA) offers dual advantages: it facilitates the sustainable reutilization of agricultural waste and reduces the overall cost of concrete and housing construction [35, 36, 37].

Numerous studies have examined the incorporation of sugarcane bagasse ash (SBA) in concrete; however, these investigations have predominantly employed uncontrolled or non-standardized preparation methods, resulting in variability in the characteristics of SBA and the corresponding effects on concrete properties.

Conclusions

The present study demonstrates the potential of Sugarcane Bagasse Ash (SBA), an agro-industrial byproduct, as a sustainable partial replacement for Ordinary Portland Cement (OPC) in concrete. Experimental findings indicate that replacing 5–10% of OPC with SBA leads to notable improvements in both compressive and tensile strengths. This enhancement is primarily attributed to the pozzolanic reaction, whereby the amorphous silica in SBA reacts with the calcium hydroxide generated during cement hydration to form additional calcium silicate hydrate (C–S–H) gel. The formation of this supplementary C–S–H contributes to microstructural densification, improved internal cohesion, and increased resistance to deterioration. The beneficial effects become particularly pronounced at later curing ages, reflecting the gradual and sustained nature of the pozzolanic process.

Higher replacement levels (15–20%) were observed to result in reduced strength, indicating that there is an optimal substitution range beyond which the dilution of cementitious phases outweighs the benefits of pozzolanic activity. Overall, the incorporation of SBA at optimal levels provides an environmentally responsible strategy to reduce cement consumption, lower carbon emissions, and valorize agricultural waste, thereby producing concrete with improved durability while promoting sustainable construction practices and climate-conscious infrastructure development. This approach not only addresses the disposal challenges associated with sugarcane processing residues but also mitigates the environmental impact of cement production, which is a significant contributor to global CO_2 emissions. The present study therefore identifies unprocessed Sugarcane Bagasse Ash as a viable, cost-effective supplementary cementitious material that can reduce the cost of concrete and housing while advancing efficient waste management and greener construction solutions.

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