RESEARCH PAPER

Experimental, Microstructural and Statistical Evaluation of Optimized Processed Sugarcane Bagasse Ash as a Partial Replacement Material for Cement in Mortar

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Abstract
Sugarcane bagasse ash (SBA) an agro-industrial by-product can be transformed into a reactive supplementary cementitious material through controlled thermal and mechanical processing. This study investigates the influence of calcination temperature (600–1000 °C), duration (1–5 hours) and grinding (2000 revolutions) on mortar properties incorporating SBA at 5–30% cement replacement. Standard consistency, setting times and compressive strength were evaluated at 7, 28, 90, 180 and 270 days. Results indicates that higher water demand at lower calcination temperatures due to porous structure and unburnt carbon while it decreases at higher temperatures owing to improved particle densification. The initial and final setting times decreased to 142 min and 432 min respectively at optimum processing conditions. Compressive strength was lower at early ages (7 and 28 days) but significantly increased at later ages (90,180 and 270 days) surpassing the control mix. The optimum condition (700 °C, 2 hours, 20% replacement) exhibited pronounced amorphous silica in XRD, refined morphology in FESEM and enhanced pozzolanic reactivity. ANOVA confirmed statistically comparable strength performance while regression models showed strong prediction ($R^2 > 0.90$). Sustainability analysis indicated reduced carbon footprint and cement consumption with notable economic benefits supporting SBA as an eco-efficient cement alternative.
Keywords: Sugarcane bagasse ash, Supplementary cementitious material, Statistical analysis, Sustainability, Carbon footprint, eco-efficient.
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Highlights

- Optimized calcination and grinding improved SBA pozzolanic reactivity
- Higher water demand at low calcination, reduced at higher temperatures
- Optimum SBA showed improved long-term strength beyond control mix
- XRD–FESEM–EDS confirmed amorphous silica and refined morphology
- SBA reduced CO_2 emissions, cement usage and overall cost

1 Introduction

Massive development in the infrastructure sector has given an unforeseen rise in the demand for cement and to accommodate this demand, the world expends 30 billion tons of cement concrete every year [1]. A lot of energy is consumed to produce cement as like required in the production of steel and aluminum [2]. During production of cement harmful greenhouse gases like carbon dioxide (CO_2) is produced and emitted in the atmosphere resulting into increase in global warming [3]. Studies showed that cement production is a major contributor for global warming as every ton of Portland cement produced releases approximately one ton of CO_2 into the atmosphere [4]. To minimize the emission of CO_2 gases, supplementary cementations material can be used. The supplementary cementations material involves use of agriculture waste ash produced by sugarcane [5-18] rice husk [19,20] etc. Now a days industrial waste products like fly ash [21], ground granulated blast furnace slag [22] and silica fume [23] are being partially employed for replacing cement. In India, agriculture byproduct like bagasse waste is produced up to 600 million tons annually, out of which 91.162 million tons is generated by sugarcane itself [24]. Each day around 44,000 tons of SBA is produced in India [25]. This SBA pollutes the environment as well as natural resources like groundwater and soil. The produced ash is stored on the land which again incurs increased cost in its disposal. There is need to employ corrective measures during the disposal of bagasse ash. Primary research analysis reveals that the ash generated by bagasse can be considered as a pozzolanic material [26]. Owing to its easy availability in large quantities as waste, the ash produced from sugarcane bagasse in cogeneration plants was collected, processed and utilized as a supplementary cementitious material throughout this study.

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2. Materials and Methods

2.1 Materials

2.1.1 Ordinary Portland Cement (OPC)

The OPC grade 53 was utilized in this study as the binding material adhered to the specifications outlined in the IS 12269:2013 [27]. The physical and chemical properties are presented in table 1 and table 2 respectively.

2.1.2 Sugarcane Bagasse Ash (SBA)

The SBA was obtained from the Mula Sahakari Sakhar Karkhana Ltd., Sonai, in the Ahilyanagar district of Maharashtra, India. The physical properties such as color, size, loose bulk density, specific gravity and Blaine's specific surface area have been examined and compared with OPC 53 grade as presented in Table 1. The chemical properties of raw SBA have a higher carbon content which can be negatively affect mortar performance. Consequently, raw SBA must undergo processing to be effectively utilized as a pozzolanic material in mortar.

2.1.3 Processing on raw SBA

In the present study, raw SBA was initially subjected to a 500-micron IS sieve to eliminate impurities including unburnt carbon and fibrous material. The sieved SBA underwent further processing via calcination in an electric furnace at temperatures of 600 °C, 700 °C, 800 °C, 900 °C and 1000 °C for durations of 1 hour, 2 hours, 3 hours, 4 hours and 5 hours. Following calcination, the samples were maintained in an electric furnace for up to 24 hours to prevent property alterations caused by a rapid temperature drop from elevated levels to room temperature. Calcinated SBA was ground in a ball mill for 2000 revolutions at a speed of 30 to 33 rpm to increase fineness and enhance the amorphous reactivity of the processed material. The calcinated and grinded processed SBA has been utilized throughout this study.

Table 1: Physical properties of raw SBA, optimum processed SBA and OPC 53 grade

Physical properties	Raw SBA	Optimum processed SBA	OPC 53 grade
Color	Blackish grey	Grey	Grey
Size (µm)	0.1 to 105	0.1 to 45	22.5 to 28
Loose Bulk density (kg/m^3)	790	920	1160
Specific gravity	2.30	2.57	3.15
Specific surface area by Blaine (m^2 /kg)	240	400.45	330

Table 2: Chemical properties of raw SBA, optimum processed SBA and OPC 53 grade

Chemical properties	Raw SBA	Optimum processed SBA	OPC 53 grade
Silica (SiO_2), %	63.57	60.74	16 – 26
Ferric Oxide (Fe_2O3), %	13.89	1.27	2 – 5
Aluminum Oxide (Al_2O_3), %	10.92	2.5	4 – 8
Calcium Oxide (CaO), %	0.31	4.87	58 – 68
Magnesia (MgO), %	0.13	5.27	1 – 4
Loss on Ignition, %	3.85	1.36	≤ 4
Total Sulphur content, (SO), %	0.35	0.82	≤ 2.5
Moisture, %	0.35	0.037	0.5

2.1.3 Ennore sand

Ennore refers to a location situated in Tamil Nadu, India. The sand sourced from that location has proven to be the most suitable for fulfilling the requirements of cement and cementitious testing as a fine aggregate in the mortar. The material is categorized into three grades: grade I, II and III with sizes ranging from 01 mm to 02 mm, 0.5 mm to 01 mm and 0.09 mm to 0.5 mm respectively. Each grade accounts for 33.333% of the total weight.

2.1.4 Water

Water is an essential component of mortar as it significantly affects the mix design. This study employs potable tap water for the mixing of mortar ingredients.

2.2 Mortar Preparation

The mortar was composed by mixing OPC 53 grade, Ennore sand, processed SBA and water. Each sample of processed SBA was utilized as a partial substitute for cement at varying proportions of 5%, 10%, 15%, 20%, 25% and 30% by weight. Furthermore, the control mixture was examined for comparative analysis. The ratio of Cement to Ennore sand was established at 1:3 for all the mixtures.

2.3 Test procedure

2.3.1 Standard consistency

To complete the chemical reaction between water, cement and processed SBA, a certain minimum quantity of water has required to be determined. The standard consistency test was performed on Vicat's apparatus with plunger 10 mm diameter and test procedure followed as per IS 4031-1996 part 4 [28]. The results obtained in percentage by weight of dry OPC and processed SBA blended paste.

2.3.2 Setting time

To assess the hardening process, the initial (IST) and final (FST) setting times of processed SBA paste mixed with OPC 53 were measured using the Vicat needle apparatus according to IS 4031 part 5 [29]. The results are obtained in minutes.

2.3.3 Compressive strength

The compressive strength of mortar cubes blended with processed SBA was assessed using a standard mould measuring 70.60 mm x 70.60 mm x 70.60 mm in accordance with IS 4031 (part 6):1988 [30]. Specimens were subsequently kept at room temperature for 24 hours covered with wet jute bags. Following this period mould were demolded and placed in a water curing tank until testing at designated intervals (7, 28, 90, 180 and 270 curing days). The compressive strength reported was derived from the average of three cubic samples measured in MPa.

2.3.4 Microstructural analysis

An X-ray diffraction (XRD) analysis was performed using cu-k radiation across a 2θ range of 20 to 80^0 focusing specifically on the amorphous silica hump observed between 20 to 30^0. FESEM was employed to analyze particle morphology and the micro structure of optimized processed SBA whereas EDS offered semiquantitative data on elemental composition and Ca/Si ratios of the hydration products.

2.3.5 Mathematical modelling of strength evolution

The evolution of compressive strength of optimized processed SBA blended mortar was analyzed using regression modelling and statistical analysis. The relationship between compressive strength and curing age was modeled using a logarithmic regression function which is widely adopted for cementitious materials due to its ability to capture nonlinear strength gain over time. The model is expressed as:

$$f_c = a + b\ln(t)$$

where f_c is the compressive strength (MPa), t is the curing age (days) and a and b are regression coefficients determined using the least squares method. The goodness-of-fit of the regression model was evaluated using the coefficient of determination (R^2) ensuring the accuracy of prediction for both control and SBA mixes. The regression analysis was performed using experimental strength data obtained at curing ages of 7, 28, 90, 180 and 270 days. In addition to regression modelling, one-way analysis of variance (ANOVA) was conducted to assess the statistical significance of differences in compressive strength between control and SBA mixes. The total variation in strength data was partitioned into between-group (SSB) and within-group (SSW) components. The F-statistic was calculated as:

$$F = \frac{MSB}{MSW}$$

where MSB and MSW represent mean square between groups and within groups respectively. The corresponding p-value was used to determine statistical significance at a 95% confidence level. This combined approach enables both predictive modelling of strength development and validation of experimental results

2.3.6 Carbon footprint evaluation

The carbon footprint of cement and processed SBA was evaluated to quantify the environmental benefits of partial cement replacement. The assessment was based on a cradle-to-gate approach considering CO_2 emissions associated with raw material processing and manufacturing. A reference emission factor of 1 kg CO_2 per kg of cement was adopted for ordinary Portland cement. For processed SBA, a significantly lower emission factor was considered, accounting for energy consumption during calcination and grinding processes. The emission factor for SBA was calculated based on energy input during thermal treatment (600–1000 °C) and mechanical grinding (2000 revolutions) and was taken as 0.314 kg CO_2 per kg of SBA. The total carbon footprint of the blended system was calculated using the following relationship

CO_2 total = (Wc × EFc) + (W_{SBA} ×EF_{SBA})

Where, Wc = mass of cement (kg), W_{SBA} = mass of optimized processed SBA (kg), EFc = emission factor of cement (1 kg CO_2/kg), EF_{SBA} = emission factor of optimized processed SBA (0.314 kg CO_2/kg). The percentage reduction in CO_2 emissions was determined by comparing the emissions of SBA-blended mixes with that of the control mix.

2.3.7 Economic evaluation

The economic evaluation of SBA incorporation in mortar was carried out by estimating material cost savings and carbon credit benefits. The cost of OPC was considered as ₹6.6–₹7.6 per kg, while SBA was assumed to have minimal cost accounting only for processing. Based on a binder content of approximately 500 kg/m³, the reduction in cement consumption at different replacement levels was used to calculate cost savings per cubic meter. Additionally, carbon credit benefits were estimated from CO_2 emission reductions using prevailing carbon market rates (₹800–₹1500 per ton CO_2). The combined economic benefit was evaluated to assess the feasibility of SBA-based mortar systems.

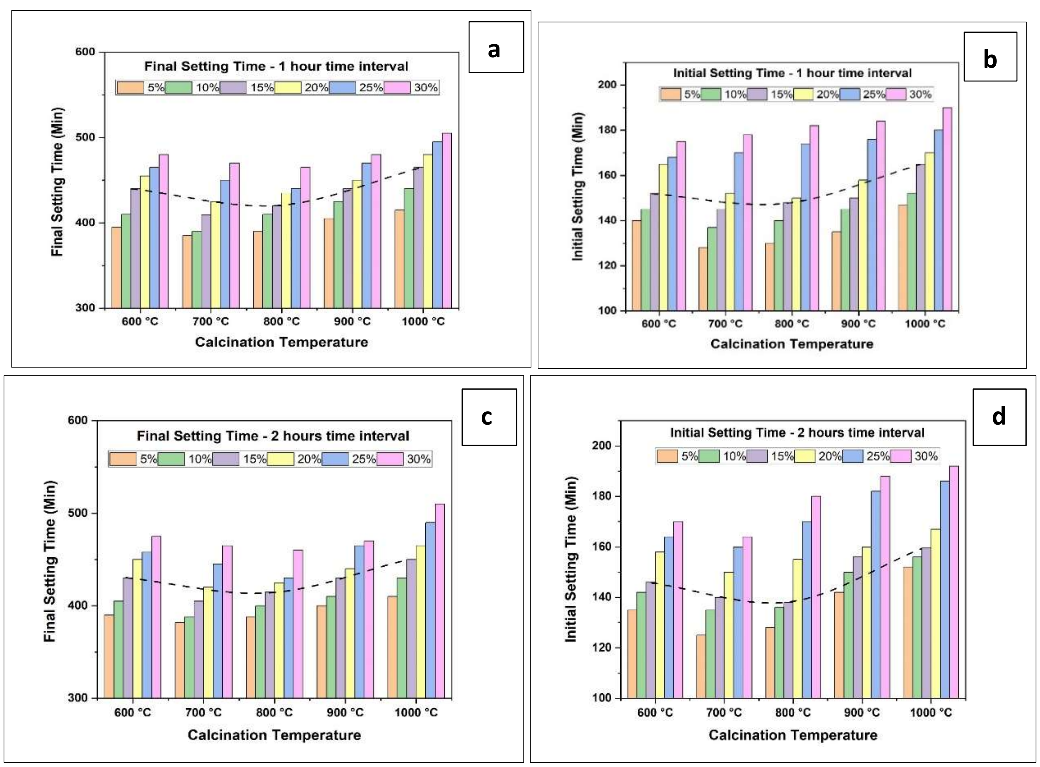
3. Result and discussion

3.1 Standard Consistency

The standard consistency showed notable variation with changes in SBA calcination conditions. At lower calcination temperatures (600–700°C), SBA exhibited higher water demand (standard consistency around 32.5–38%) attributable to increased particle porosity and residual carbon content. As calcination temperatures increased (800–1000°C) a reduction in porosity and carbon residue significantly lowered the water demand (standard consistency approaching 28.5–30%) nearing that of OPC 53 grade cement (28.5%). Calcination duration also influenced consistency at lower temperatures (600–700°C) and shorter durations (up to 2 hours) resulted in higher water demand (approximately 32–38%) due to incomplete combustion and residual carbon. However, extending the calcination period (3–5 hours) at these temperatures gradually reduced water demand to around 29.5% reflecting improved particle densification and reduced carbon content. Conversely, at higher temperatures (≥800°C) prolonged durations consistently decreased standard consistency from about 33.5% down toward 28.5–30% approaching the lower water requirement similar to OPC cement due to enhanced particle densification and reduced porosity.

3.2 Setting Time

The setting behavior of SBA-blended cement paste evaluated through IST and FST was found to be influenced by both the percentage replacement of cement and the calcination conditions of the ash. Increasing the SBA dosage led to a gradual delay in both IST and FST due to clinker dilution increased water demand and the slower pozzolanic reaction of the ash. However, this trend was also significantly affected by the calcination temperature. At lower calcination temperatures (600°C) the presence of residual carbon and unburnt organics caused substantial delays with IST extending up to 135–192 minutes and FST reaching 390–490 minutes at dosages (5–30%). As the calcination temperature increased to 700°C both IST and FST decreased notably due to improved combustion and removal of organic matter yielding IST in the range of 125–182 minutes and FST around 382–475 minutes. Beyond 800°C, setting times began to rise slightly again attributed to the reduction in pozzolanic reactivity due to the formation of crystalline phases and particle sintering. As calcination time increases from 1 to 5 hours, residual carbon decreases improving ash quality. Initially setting times and water demand reduce but beyond 3 hours prolonged heating may cause particle sintering and crystallization, slightly lowering pozzolanic reactivity and increasing setting times and reducing surface area. These trends emphasize that both setting times remain within the acceptable limits prescribed by IS:4031 (Part 5:1988), which requires a minimum IST of 30 minutes and a maximum FST of 600 minutes for standard cementitious materials. Thus, while increased SBA content tends to prolong setting times, the effect can be controlled by maintaining calcination temperature at 700°C and limiting the replacement level to 10–15%, which ensures practical and acceptable setting behavior in line with standard cementitious materials.



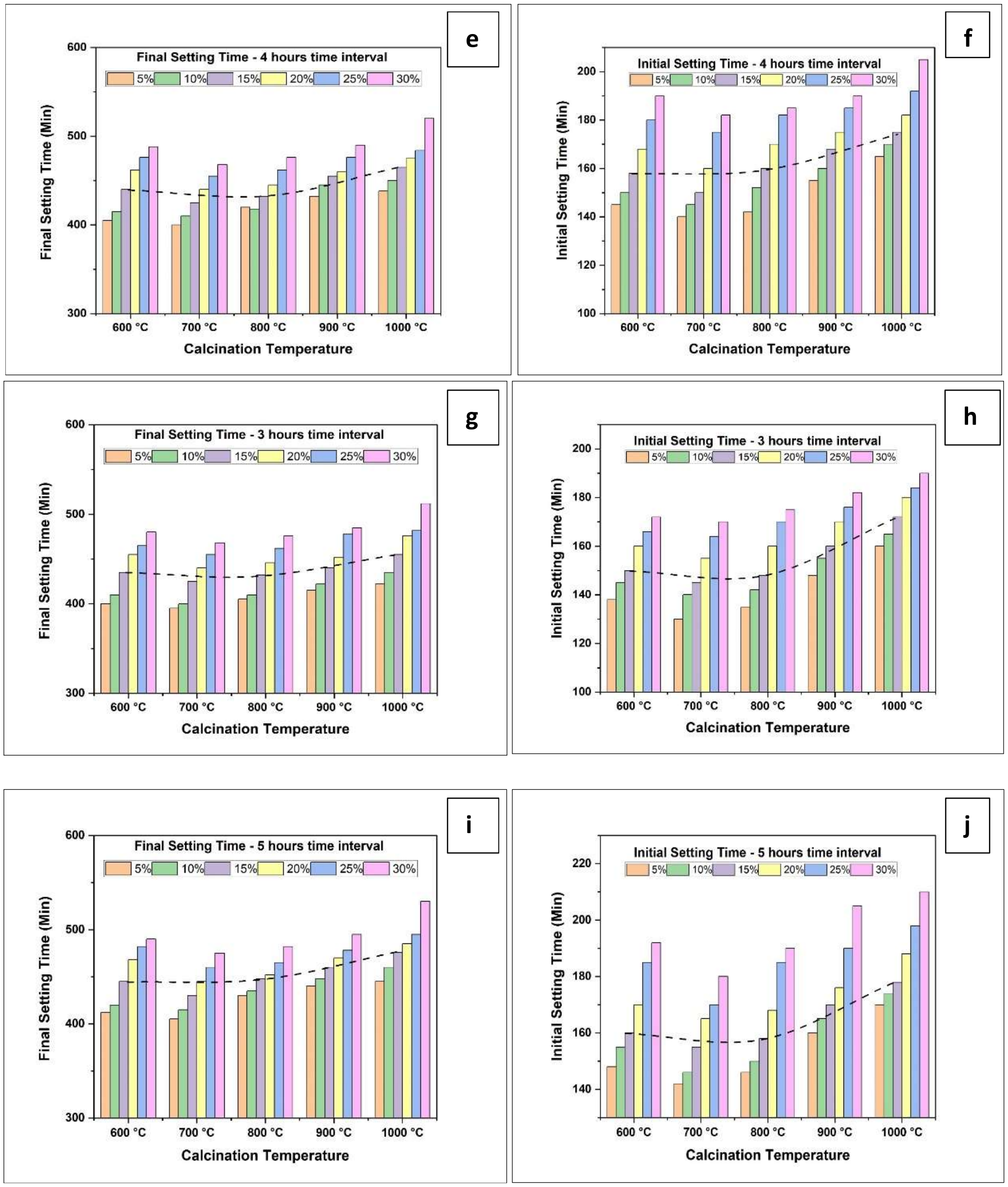


Figure 1: Variation of IST and FST of SBA-blended mortar with calcination temperature (600–1000 °C) at varying durations (1–5 h)

3.3 Compressive Strength

The compressive strength of mortar incorporating processed SBA varied significantly based on calcination conditions, grinding and replacement levels observed at curing ages of 7, 28, 56, 90, 180 and 270 days having replacement levels (5–30%). Early-age strengths at 7 days ranged from 34-20 MPa for the percentage dosage 5% to 30% slightly lower than OPC (35 MPa) primarily due to dilution effects and delayed pozzolanic reaction. By 28 days, SBA mortar strengths increased notably to 44.2-30.2 MPa approaching OPC (45 MPa) reflecting the beginning of pozzolanic activity converting calcium hydroxide into additional calcium silicate hydrate (C–S–H). At intermediate curing periods (56–90 days) mortars containing optimally calcined SBA (700°C, 2 hours, finely ground at 2000 revolutions with 15% to 20 % dosage) exhibited significantly enhanced compressive strengths of approximately 44.8–41.2 MPa at 56 days and 48.4–52.8 MPa at 90 days, surpassing or closely matching OPC values (approximately 48 MPa at 56 days and 50 MPa at 90 days). Long-term curing (180–270 days) clearly highlighted SBA's advantage achieving superior strength values of 54–58 MPa at 180 days and 56–60 MPa at 270 days compared to OPC's typical strengths of 53 MPa (180 days) and 55 MPa (270 days). Higher calcination temperatures (≥900°C) showed reduced long-term strength (45–50 MPa at 180–270 days) due to decreased pozzolanic reactivity and lower specific surface area. Therefore, optimal calcination (700°C, 2 hours) controlled grinding and moderate SBA dosage (15–20%) effectively improve long-term mortar performance confirming SBA's suitability as a sustainable cement alternative.

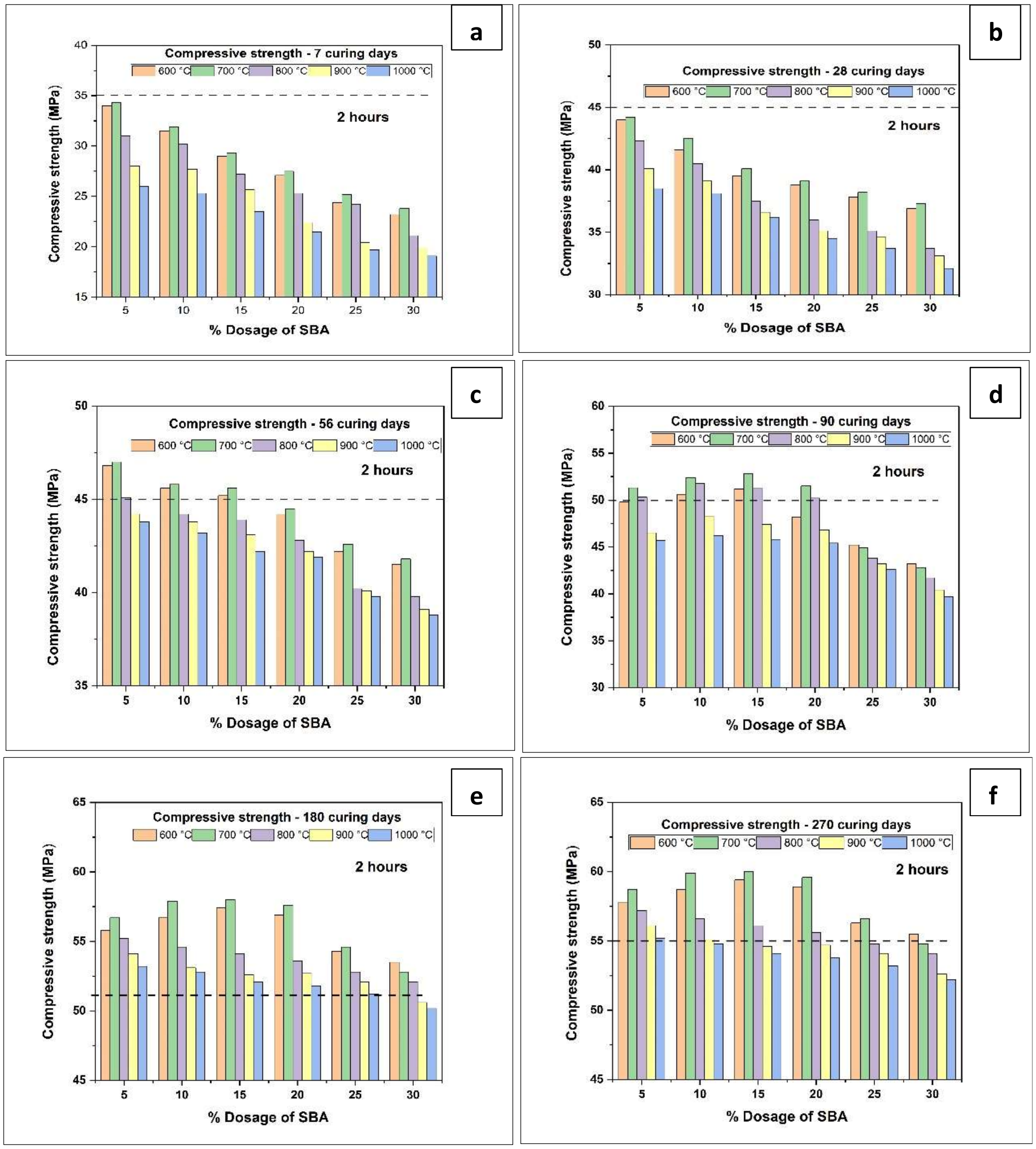


Figure 2: Compressive strength of SBA blended mortar at replacement level of 5% to 30 % at curing ages a) 7, b) 28, c) 56, d) 90, e) 180, f) 270 days.

3.4 Microstructural analysis

The characterization of optimized processed SBA was conducted through microstructural, mineralogical and elemental analyses using XRD, FESEM and EDS techniques to assess its potential as a supplementary cementitious material.

3.4.1 XRD analysis of optimized SBA

The XRD pattern of optimized SBA prominently features a broad diffuse hump within the range of 20°–30° (2θ), demonstrating a substantial amorphous silica phase is present. The amorphous nature plays a vital role in pozzolanic reactivity as amorphous silica easily interacts with calcium hydroxide produced during cement hydration. A slight sharp peak noted at approximately 26° (2θ) is indicative of crystalline quartz however its comparatively low intensity suggests that excessive crystallization was successfully prevented during the calcination process. The dominance of the amorphous phase indicates that the refined thermal treatment successfully maintained reactive silica which is a crucial factor for the development of long-term strength.

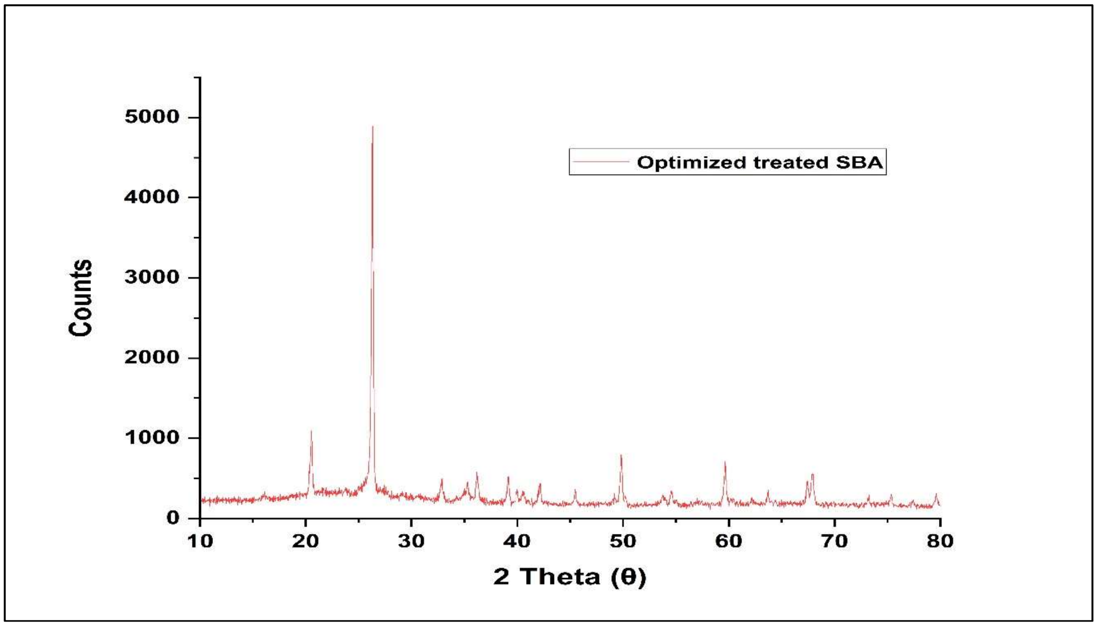


Figure 3: X-ray diffraction analysis of optimized treated SBA

3.4.2 FESEM analysis of optimized SBA

The FESEM micrograph of optimized SBA displays a highly refined morphology characterized by irregular, angular and partially agglomerated particles featuring a rough surface texture. The particle size varies from approximately 18.89 nm to 53.96 nm with an average size of approximately 32.51 nm indicating successful particle size reduction achieved through optimized calcination and grinding processes. The small particle size at the nanoscale greatly increases the specific surface area supporting improved interaction with hydration products.

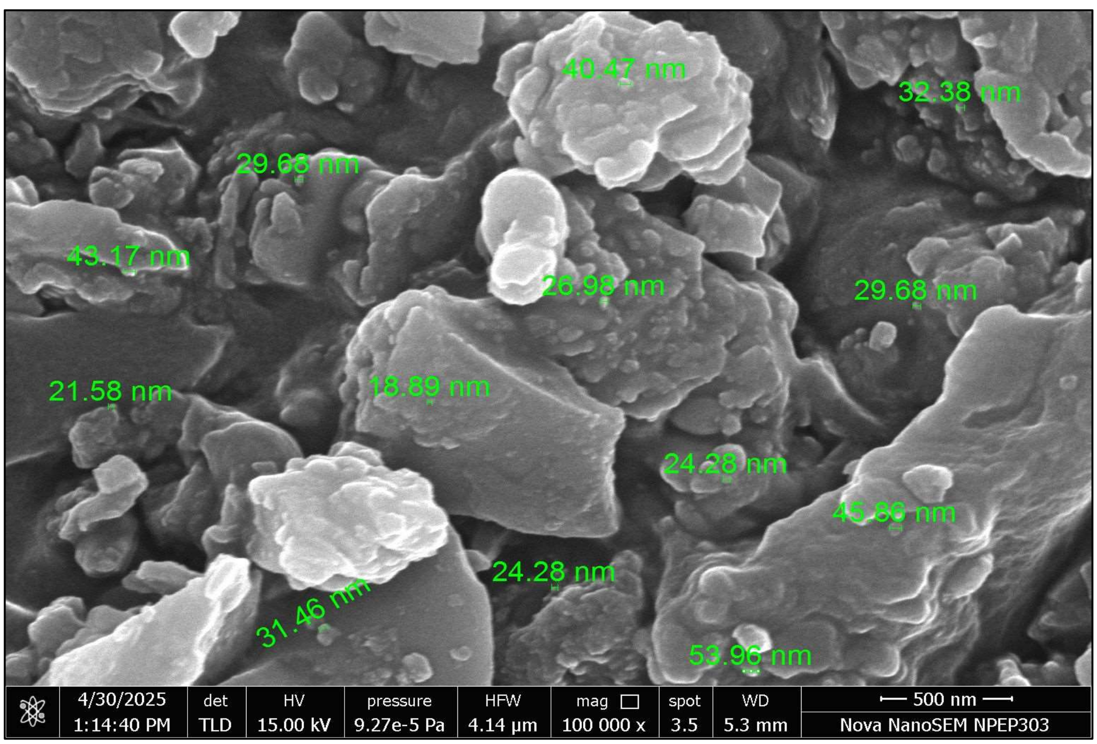


Figure 4: FESEM analysis of optimized treated SBA at 500 nm magnification

3.4.3 EDS analysis of optimized SBA

The EDS analysis reveals that the optimized SBA primarily consists of silicon (Si), oxygen (O) and aluminum (Al) with smaller amounts of iron, calcium and various trace elements present. The elevated levels of silicon and oxygen validate the silica rich characteristics of the material whereas the finding of aluminum indicates the potential for the development of supplementary aluminosilicate hydration products (C–A–S–H). The comparatively low calcium content suggests that SBA functions mainly as a pozzolanic material instead of a self-cementing binder. The elemental composition aligns with the XRD results, thereby reinforcing the existence of reactive oxides essential for pozzolanic reactions.

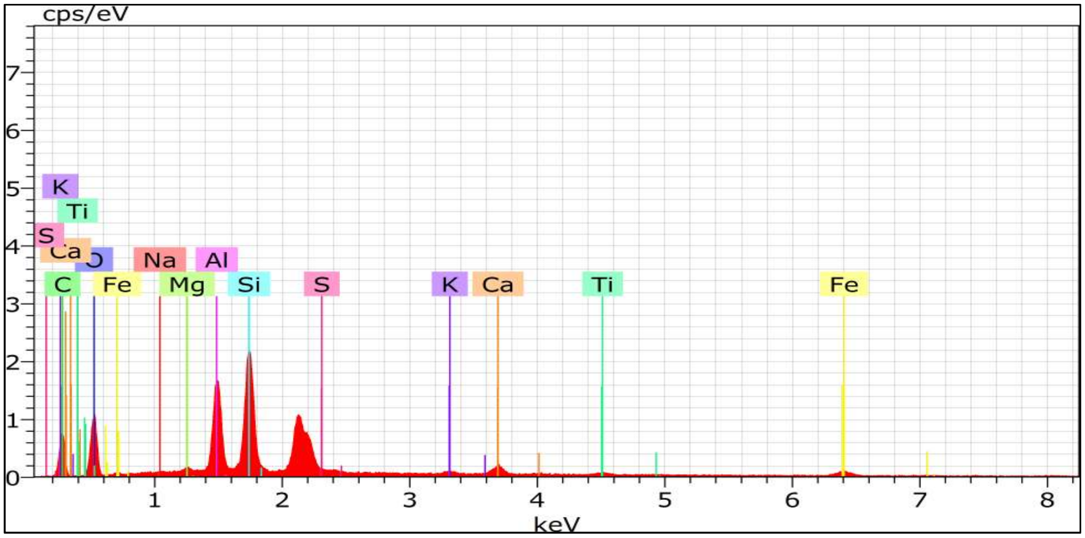


Figure 5: Energy Dispersive X-ray Spectroscopy (EDS) analysis

3.4.4 Correlation of Microstructural analysis with Compressive Strength

The compressive strength development of SBA-blended cementitious system is strongly influenced by its mineralogical, microstructural and chemical characteristics. At early curing ages (7–28 days) the strength is comparatively lower than the control mixes due to the dilution effect and the slow kinetics of the pozzolanic reaction. The amorphous silica present in SBA requires time to react with calcium hydroxide released during cement hydration. At later curing ages (90–270 days) a significant increase in compressive strength is observed. This improvement is primarily attributed to the presence of amorphous silica observed in XRD, which actively participates in secondary hydration reactions forming additional C–S–H gel. The FESEM analysis showing nanoscale particle size (32.5 nm) and irregular morphology indicate a high specific surface area which enhances reactivity and promotes better particle packing through filler effects. Furthermore, the EDS results confirm a silica-rich composition with the presence of Al_2O_3 contributing to the formation of additional C–A–S–H gel. These combined mechanisms result in microstructural densification, reduced porosity and improved interfacial bonding, ultimately leading to enhanced long-term compressive strength and overall performance of SBA-based cementitious materials.

3.5 Mathematical modelling of strength evolution

A logarithmic age dependent strength model provided excellent agreement with the assume dataset (R^2>0.97). Model parameters indicated slower early age kinetics but enhanced long term gain for processed SBA mortars consistent with microstructural observation.

$$y = 19.779\ln(x) + 28.582$$

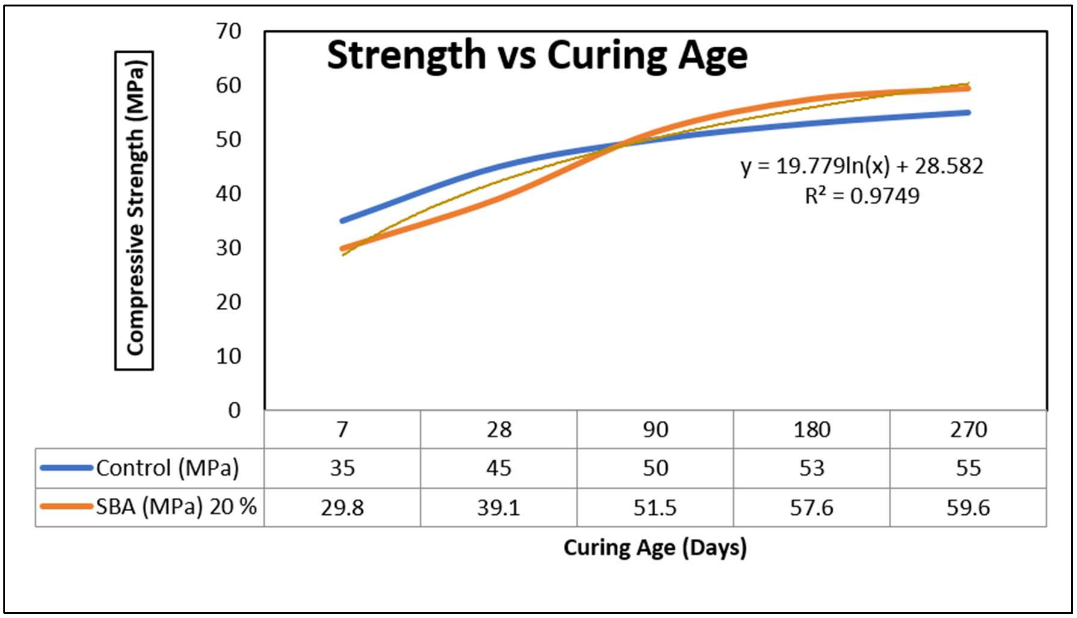


Figure 6: Compressive strength development of SBA blended mortar with curing age

The statistical significance of strength differences between control and SBA mixes was evaluated using one-way ANOVA. The procedure, including decomposition of total variation into between-group (SSB) and within-group (SSW) components. The ANOVA results yielded an F-value of 2.914317806 and a p-value of 0.105714832, indicating that the overall difference between control and SBA mixes is statistically insignificant ($p > 0.05$) at a 95% confidence level. This confirms that SBA achieves comparable overall performance to conventional cement when all curing ages are considered. Despite statistical similarity, the age-wise trend is distinct: SBA is lower at early ages but surpasses the control at later ages. This is consistent with the delayed but sustained pozzolanic reaction. In regression analysis, R^2 is 0.993636476 further shows that compressive strength follows a logarithmic relationship with curing time:

$$f_c = a + b\ln(t)$$

with high goodness-of-fit ($R^2 > 0.90$). The SBA mix exhibits a steeper growth trajectory at later ages, corroborating enhanced long-term reactivity. The SBA mix exhibits lower early-age strength (7–28 days) due to slower hydration kinetics while at later ages (90–270 days), it demonstrates superior strength compared to the control mix. This behavior is attributed to the gradual formation of secondary hydration products, primarily C–S–H gel. The combined use of regression modelling and ANOVA provides a comprehensive understanding of strength evolution, demonstrating both predictive reliability and statistical validation of SBA performance.

3.6 Carbon footprint evaluation

The carbon footprint analysis demonstrates the environmental advantage of incorporating SBA as a partial replacement for cement. Based on the calculated emission factors, ordinary Portland cement was considered to emit 1 kg CO_2/kg while processed SBA exhibited a significantly lower emission factor of 0.314 kg CO_2/kg, derived from energy consumption during calcination and grinding. The replacement of cement with SBA resulted in a proportional reduction in CO_2 emissions. At 20% replacement, the reduction in carbon emissions was found to be approximately 13.72% at the binder level, indicating a substantial environmental benefit. When expressed per unit volume, the CO_2 savings ranged from 34.3 to 68.6 kg CO_2/m^3 for mortar depending on the replacement level. The reduction in carbon footprint is primarily attributed to the lower embodied energy of SBA compared to cement and the utilization of agro-industrial waste material. Furthermore, optimized processing conditions ensured that SBA maintained high pozzolanic reactivity while minimizing additional energy consumption. These findings clearly indicate that the use of SBA not only enhances long-term mechanical performance but also significantly reduces greenhouse gas emissions. Therefore, SBA can be considered a viable low-carbon alternative to conventional cement contributing to sustainable construction and circular economy practices.

3.7 Economic Analysis

The economic feasibility of incorporating SBA in mortar was evaluated by considering both material cost savings and carbon credit benefits. The cost of ordinary Portland cement was taken as ₹6.6–₹7.6 per kg while SBA was assumed to be a low-cost material with minimal processing expenses. For mortar with a binder content of approximately 500 kg/m³, partial replacement of cement with SBA resulted in significant cost savings. At 20% replacement, the cement saving to 100 kg/m³, resulting in a cost saving of about ₹660–₹760 per m³. In addition to direct material savings, SBA incorporation also provides economic benefits through carbon credit potential. At 20% replacement, the CO_2 reduction was approximately 68.6 kg CO_2/m^3 (0.0686 t CO_2/m^3). Considering a carbon credit value of ₹800–₹1500 per ton of CO_2, this corresponds to an additional economic benefit of approximately ₹55–₹103 per m³. Therefore, the total economic benefit for mortar at 20% SBA replacement can reach up to ₹715–₹863 per m³, combining both cost savings and carbon credit gains. This highlights that SBA not only reduces construction costs but also provides additional financial incentives, making it a highly viable and sustainable alternative to conventional cement.

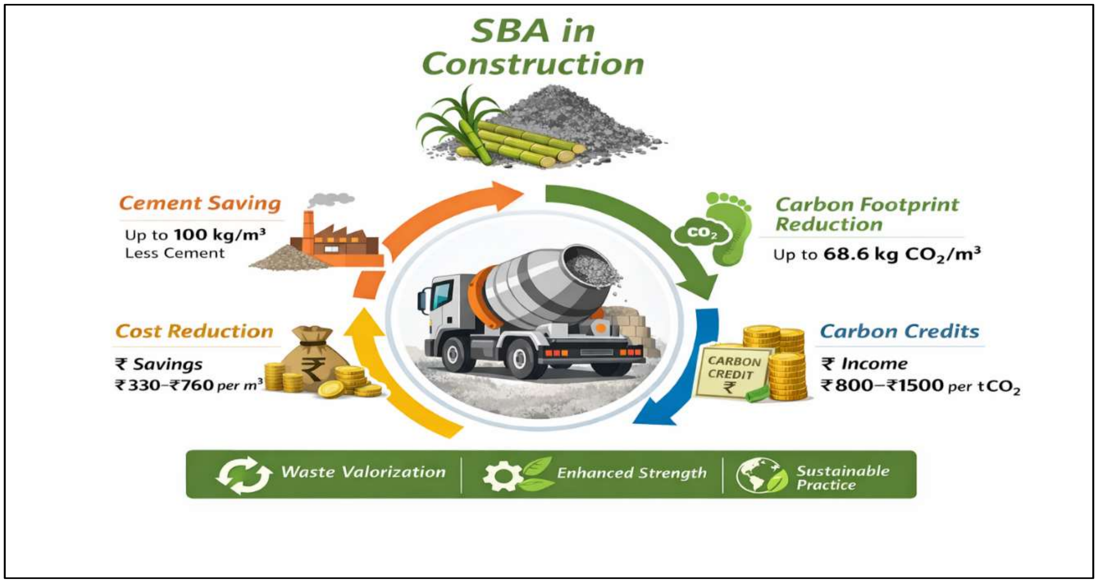


Figure 7: Integrated environmental and economic benefits of SBA in mortar for sustainable construction applications.

4. Conclusion

This study systematically evaluated the influence of controlled thermal and mechanical processing of SBA on its performance as a supplementary cementitious material in mortar. The key findings are summarized as follows:

- Optimized processing: The optimum condition was identified at 700 °C calcination for 2 hours with 2000 revolutions grinding producing highly reactive SBA.
- Fresh properties: Water demand was higher at lower calcination temperatures due to porous structure and unburnt carbon but decreased at higher temperatures due to particle densification. The initial and final setting times reduced to 142 min and 432 min respectively under optimum conditions.
- Mechanical performance: SBA mixes showed lower early-age strength but significant long-term strength enhancement (90–270 days) surpassing the control mix due to sustained pozzolanic reactions.
- Microstructural characteristics: XRD confirmed amorphous silica formation, FESEM showed refined nanoscale morphology and EDS indicated silica-rich composition, collectively contributing to improved performance.
- Statistical validation: Regression analysis demonstrated strong predictive capability ($R^2 > 0.90$), while ANOVA confirmed statistically comparable strength performance between control and SBA mixes.
- Sustainability and economy: SBA incorporation reduced carbon footprint, cement consumption and material cost with additional benefits from carbon credit potential.

Overall, the optimized SBA demonstrates a balanced improvement in mechanical performance, environmental sustainability and economic efficiency, making it a promising low-carbon alternative to conventional cement in mortar applications.

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Declaration of Competing Interest

The authors declare that there are no known competing financial interests or personal relationships that might have influenced the work presented in this paper.

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Author Contribution

Atul B. Jondhale: Developed the concept, designed the methodology, conducted experimental investigations, analyzed data, created models and prepared the manuscript. Sachin B Mulay and Pramod K. Kolase: supervision, examination, careful assessment and refinement of the manuscript. All contributors have reviewed and approved the final manuscript.

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