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USE OF SUGARCANE BAGASSE ASH AS AN ADMIXTURE IN CONCRETE: A CENTURY-SCALE REVIEW WITH SPECIAL CONTEXT TO BRAZIL AND INDIA (1900–2025)

Engineering

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ABSTRACT

Sugarcane bagasse ash (SCBA), the finely divided residue from the combustion of sugarcane bagasse in cogeneration boilers, has emerged as a viable supplementary cementitious material (SCM) in concrete. This review synthesizes more than five decades of peer-reviewed research (with historical context since the early 1900s) focusing on SCBA's production, processing, chemistry, and its influence on fresh properties, strength development, durability, and microstructure of cementitious systems. A special emphasis is placed on Brazil and India—the world's largest sugarcane producers—covering ash availability, processing routes (controlled calcination, grinding, and classification), compliance with pozzolan standards (ABNT NBR 12653; IS 1727 as proxies), field-scale applications, environmental benefits (CO_2 reduction, landfill diversion), and techno-economics. Key findings highlight that low-carbon, high-reactivity SCBA is obtainable via controlled burn (≈500–700 °C), carbon removal (low LOI), and ultrafine grinding; optimized replacements of 10–25% (by mass of binder) generally improve 28–90-day strength, reduce chloride ingress and permeability, and densify the C–S–H nanostructure. Variability due to feedstock, boiler operation, and milling demands standardized beneficiation and certification protocols. The paper concludes with a research agenda on performance-based specifications, microstructural fingerprinting, and life-cycle/field validation to mainstream SCBA in civil infrastructure.

KEYWORDS

Sugarcane bagasse ash; supplementary cementitious material; pozzolanic activity; durability; chloride ingress; microstructure; Brazil; India; sustainability; life-cycle assessment.

1. INTRODUCTION

Sugarcane agro-industry produces vast amounts of bagasse, a fibrous by-product that is combusted for steam and power. The resulting sugarcane bagasse ash (SCBA) is rich in silica and, after beneficiation, can act as a pozzolan to partially replace Portland cement. Early technical mentions of plant-ash pozzolans date to the early 20th century, while systematic SCBA research accelerated from the late 1990s onward, led notably by Brazilian and Indian groups. This paper reviews the state-of-the-art on SCBA in concrete with a focus on Brazil and India, where supply chains and industrial interest make SCBA particularly relevant for decarbonizing cementitious materials.

2. Methodology Of The Review

A structured literature search (1995–2025) across Scopus, Web of Science, ScienceDirect, ASCE Library, and open repositories identified peer-reviewed journal articles and selected conference papers on SCBA processing, characterization, and performance in cementitious systems. Classic standards and handbooks provided historical and normative context. Inclusion criteria required reported experimental data (chemistry, mineralogy, fresh/hardened properties, or durability) or comprehensive reviews. Priority was given to studies from Brazil and India or those explicitly benchmarking SCBA against other SCMs.

3. SCBA Source, Processing, And Characterization

SCBA properties are governed by sugarcane cultivar, soil contamination (sand/soil), boiler type and temperature, air–fuel ratio, and post-combustion handling. High reactivity is associated with: (i) controlled calcination (≈500–700 °C) to convert biogenic silica to amorphous form while limiting crystallization; (ii) low loss on ignition (LOI), typically <6%; and (iii) fine particle size (median <10–20 µm) achieved by milling/classification or production of ultrafine ash. Beneficiation options include magnetic separation, floatation to remove unburnt carbon, acid washing to reduce alkalis, and blending strategies (e.g., SCBA with slag/fly ash). Mineralogical signatures (XRD), amorphous content (Rietveld/chemically combined SiO_2), and pozzolanic activity (Frattini, strength activity index, electrical conductivity) are used to screen suitability.

4. Standards And Compliance (Brazil & India)

Brazil applies ABNT NBR 12653 for pozzolanic materials, specifying chemical and physical requirements (e.g., reactive SiO_2, SO_3, LOI, strength index). While India's IS 3812 targets fly ash, IS 1727 provides general pozzolanic testing; SCBA can be qualified via performance-based criteria (strength activity index, Chapelle/Frattini) and durability indicators. Emerging practice adopts blended cements or binary/ternary binders using SCBA as a natural pozzolan analogue.

5. Fresh Properties And Hydration

SCBA's fineness and carbon content influence water demand and workability. Properly processed SCBA can maintain or slightly reduce slump, while unprocessed, high-LOI ash can increase superplasticizer demand. Isothermal calorimetry shows reduced early heat release at 10–25% replacement and enhanced later-age hydration via nucleation and pozzolanic reactions, refining pore structure.

6. Mechanical Performance

Across numerous studies, optimum cement replacement levels of ~10–25% (by mass) yield comparable or higher compressive strength at 28–90 days, with notable gains in split tensile and flexural strengths in well-processed ashes. Ultrafine SCBA particularly enhances later-age strength through improved packing and accelerated C–S–H formation.

7. Durability

SCBA reduces permeability, sorptivity, and chloride ion penetration due to pore refinement; it also improves electrical resistivity. Sulfate resistance, acid resistance, alkali–silica mitigation, and carbonation behaviors depend on replacement level, mixture alkalinity, and curing. Chloride transport reduction is consistently reported for 15–30% SCBA in binary/ternary systems. Carbonation depth may increase at high replacement or low curing, suggesting the need for curing protocols in performance specifications.

8. Microstructure And Nanostructure

SEM/TEM, XRD, TGA/DTG, FTIR, and 29Si NMR evidence denser C–S–H, lower portlandite, and increased aluminosilicate hydrates in SCBA blends. Ultrafine SCBA acts as nucleation sites, modifies C–S–H chain length/Al-substitution, and reduces capillary connectivity—correlating with transport properties. Ash bearing residual quartz or high LOI demonstrates weaker pozzolanicity.

9. Brazil: Supply, Standards, And Applications

Brazil's ethanol–sugar sector generates large SCBA volumes. Seminal Brazilian research established processing windows (calcination 500–700 °C), demonstrated ultrafine grinding benefits, and reported industrial-scale cement replacement with associated CO_2 savings. Compliance with ABNT NBR 12653 and integration with national concrete design practices (e.g., ABNT NBR 6118) are increasingly documented. Case studies report structural and pavement concretes incorporating SCBA at 10–20% with maintained performance and improved durability.

10. India: Availability, Processing, And Field Practice

India's sugar industry enables SCBA availability near cogeneration plants. Indian studies quantified national availability, mapped logistics, and demonstrated SCBA as an alternative SCM with 10–25% replacement improving strength and transport properties in concretes and mortars. Processing recommendations emphasize beneficiation to meet pozzolan criteria, along with adoption of performance-based evaluation (IS 1727 tests, strength index) for specification and quality control.

11. Sustainability, LCA, And Techno-Economics

SCBA utilization diverts ash from landfills and reduces clinker content, cutting embodied CO_2 and cumulative energy demand. Life-cycle studies indicate meaningful CO_2 reductions proportional to replacement level and processing energy (milling, calcination). Cost models must account for beneficiation (screening, grinding, carbon removal) and quality assurance; proximity to mills minimizes transport impacts.

12. Mix Design Guidance (Performance-Based)

- Start with 10–20% cement replacement by mass for structural concretes; adjust to 25–30% for low-heat/durability-oriented mixes.
- Ensure LOI control (<6%), Blaine fineness comparable to or higher than cement, and amorphous silica confirmation.
- Use water-reducing admixtures to balance workability if needed; enforce moist curing (≥7 days) to mitigate carbonation.
- **Verify Performance:** strength (7/28/56/90 d), RCPT/RCM, sorptivity, rapid resistivity, sulfate attack, and ASR mitigation where relevant.
- For Brazil, qualify against ABNT NBR 12653; for India, use IS 1727/IS 4031 test suites and project-specific performance criteria.

13. Research Gaps And Future Work

Priority Topics Include: standardized beneficiation protocols; correlations between amorphous content, nanostructure, and transport; field monitoring of chloride/carbonation performance; synergy in ternary blends (SCBA+slag/fly ash/limestone); alkali balance and shrinkage control; adoption of performance-based specifications informed by resistivity/RCM; and region-specific LCAs for Brazil and India.

14. CONCLUSIONS

Properly processed SCBA is a technically sound, sustainability-aligned SCM for civil infrastructure. Brazilian and Indian studies demonstrate that 10–25% replacement can maintain or enhance mechanical performance and significantly improve durability through pore refinement. Transition from laboratory to mainstream practice requires beneficiation QA/QC, performance-based acceptance, and supply-chain integration. Given the magnitude of sugarcane industries in Brazil and India, SCBA presents a credible pathway to lower-carbon concretes at scale.

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