International Journal of Environmental Sciences
ISSN: 2229-7359
Vol. 10 No. 4, 2024
https://theaspd.com/index.php

Sugarcane Baggage Ash Used As Locally Available Cementitious Material For Enhancing The Property Of PQC

Rana Randhir Pratap[1*], **Dr. Sanjay Kumar** [2]
[1*]Nit research scholar, Department of civil engineering, Nit, Patna 800005. pincode-845402, Email-er.rrpratap@gmail.com
[2]Associate Professor, Department of Civil Engineering, National Institute of Technology Patna, pincode-800005 Email- sanjay@nitp.ac.in

Abstract
Pavement Quality Concrete (PQC) in rigid pavements is governed primarily by flexural performance and durability under chloride, sulfate, abrasion and fatigue actions. This paper evaluates sugarcane bagasse ash (SCBA)—a high-silica agro-industrial by-product—as a partial cement replacement for PQC in Indian conditions. After detailing PQC performance criteria from IRC standards, we synthesise recent evidence on SCBA processing (controlled burn + grinding), optimal dosage (typically 5–15% by mass of cement), and effects on fresh, mechanical and durability properties. We then propose a PQC-oriented experimental programme (flexural strength–driven mix design) including RCPT/sorptivity, sulfate resistance, and wheel-track abrasion, alongside microstructure tests (XRD/SEM). The expected outcome is that well-processed SCBA at modest dosages can meet or exceed IRC flexural targets while reducing permeability and life-cycle CO_2. Findings aim to inform state highway agencies on adopting locally available SCBA for PQC.
Keywords: *Sugarcane bagasse ash; PQC; rigid pavements; flexural strength; chloride permeability; sulfate attack; IRC 15/44; SCM; India*

1. INTRODUCTION

1.1 PQC in Rigid Pavements (Design Philosophy & Failure Modes)

Pavement Quality Concrete (PQC) is the primary structural layer in rigid pavements and is designed to resist heavy axle loads over a long service life. Unlike conventional concrete mixes, PQC design is governed by **flexural strength criteria** rather than compressive strength, as the critical failure mechanism of rigid pavements is bottom-up cracking due to flexural stresses induced by wheel loads (McNely, 1952). In India, the **Indian Roads Congress (IRC)** guidelines (e.g., IRC:15, IRC:44) stipulate that PQC must achieve a target modulus of rupture, typically **≥ 4.5 MPa at 28 days** for highway applications. In addition to load-bearing capacity, PQC must satisfy stringent durability requirements such as **low permeability, high abrasion resistance, resistance to freeze–thaw and sulfate attack**, and adequate fatigue performance to ensure long-term serviceability. Common failure modes observed in PQC slabs include **flexural fatigue cracking, joint deterioration, corner breaks, and surface wear due to traffic abrasion**, all of which highlight the importance of using durable and well-optimized concrete mixes.

1.2 Need for Local SCMs and Decarbonisation Drivers

Cement production is a carbon-intensive process, contributing approximately **7–8% of global CO_2 emissions (Chatterjee, 2021)**. For large-scale pavement construction, such as national highways and expressways, the consumption of cement in PQC layers is enormous, thereby amplifying both environmental and economic concerns (Tu, 2005). The incorporation of **supplementary cementitious materials (SCMs)** is now globally recognized as an effective strategy to reduce clinker usage, lower embodied carbon, and enhance durability performance (Al-Shmaisani, 2020). In India, the availability of industrial by-products such as **fly ash, ground granulated blast furnace slag (GGBFS), and silica fume** has been widely explored in structural and pavement concretes (Malhotra, 1983). However, the variability in supply, transport costs, and regional availability limits their universal applicability. This creates a strong motivation to identify **locally available, agro-industrial wastes** as alternative SCMs. Beyond carbon savings, local SCMs reduce dependency on distant supply chains, promote **circular economy practices**, and contribute to **cost-effective infrastructure**. In the context of sustainable pavement engineering, this aligns with both **national decarbonisation goals** and the broader United Nations Sustainable Development Goals (SDGs).

1.3 Why SCBA? Availability, Composition, Prior Evidence

Sugarcane bagasse ash (SCBA), an agro-industrial by-product generated from the combustion of sugarcane bagasse in sugar mills, presents significant potential as a locally available SCM (O'Hara & Mundree, 2016). India is the **second-largest producer of sugarcane globally**, generating millions of tonnes of bagasse annually, which after combustion yields **SCBA rich in amorphous silica (55–80%) - (Bernal et al., 2016)**. When properly processed—through **controlled burning at 500–650 °C and fine grinding (<45 μm)**—SCBA exhibits strong

pozzolanic activity, reacting with calcium hydroxide to form additional C–S–H gel, thereby densifying the microstructure of concrete. Previous studies have shown that **partial replacement of cement (5–15%) with SCBA** can:

- Maintain or improve **compressive and flexural strength**,
- Significantly **reduce permeability and chloride ion penetration**,
- Enhance **sulfate resistance and durability**,
- Improve **microstructural densification** as evidenced by XRD and SEM analyses.

Such benefits are directly aligned with the performance requirements of PQC, especially for highways subjected to aggressive environments and high cyclic loads. Moreover, the **abundant availability of SCBA in sugarcane-producing states such as Uttar Pradesh, Maharashtra, Karnataka, and Tamil Nadu** makes it a practical candidate for local adoption in PQC works (De Boer, 1978). Prior evidence from laboratory and field trials suggests that well-processed SCBA not only ensures **environmental and cost benefits** but also enhances the **long-term service life of rigid pavements**, thereby justifying its further investigation as a PQC cementitious material.

2. PQC Requirements & Standards

2.1 Flexural-Strength–Based Design & Acceptance (IRC References)

Unlike structural concrete, which is commonly designed based on compressive strength, Pavement Quality Concrete (PQC) for rigid pavements is governed primarily by **flexural strength (modulus of rupture)**, since slabs are subjected to wheel-induced bending stresses. The **Indian Roads Congress (IRC)** specifies that the concrete mix must be proportioned to meet a target flexural strength, ensuring the slab can withstand **fatigue loading and environmental stresses** over its design life.

- **IRC:15 – Standard Specifications and Code of Practice for Construction of Concrete Roads (2017)** prescribes that flexural strength at 28 days, determined as per **IS 516 (third-point loading method)**, be used as the acceptance criterion for PQC.
- **IRC:44 – Guidelines for Cement Concrete Mix Design for Pavements (2017)** further elaborates on mix design procedures, linking characteristic flexural strength to the expected traffic category and slab thickness. For acceptance, test beams (150 × 150 × 700 mm) are cast and tested at 28 days. A typical acceptance value is that the **average flexural strength should not fall below the specified target (e.g., 4.5 MPa)**, and no individual value should fall below the permissible lower limit. This ensures pavement reliability under heavy and repetitive axle loads.

2.2 Typical PQC Grades (M40/M45) and Target Modulus of Rupture

The **grade of PQC** adopted in highway and expressway construction is usually higher than that of structural concretes, in order to meet both strength and durability criteria. In India, the most widely specified grades are **M40 and M45**, corresponding to a characteristic compressive strength of 40 MPa and 45 MPa at 28 days, respectively.

- For **M40 PQC**, the corresponding target flexural strength is around **4.5 MPa at 28 days**, while for **M45 PQC**, the flexural strength requirement is slightly higher (≈ 5.0 MPa).
- These values are consistent with IRC specifications and are designed to ensure that the concrete pavement can resist flexural stresses from traffic loading and environmental effects.
- Since PQC is often laid in **thicknesses ranging from 280 mm to 320 mm** for national highways and expressways, higher concrete grades are preferred to optimize pavement thickness and ensure a longer fatigue life.

Thus, the design and quality control of PQC mixes must focus on **achieving consistent flexural performance**, often necessitating the use of admixtures and supplementary cementitious materials (SCMs) to balance workability, early strength, and durability.

2.3 Durability/Performance Criteria for Highways (Abrasion, Chloride, Sulfate)

Beyond strength, the **durability of PQC** is of paramount importance, as rigid pavements are exposed to aggressive mechanical and environmental conditions throughout their service life. The main performance requirements are:

- **Abrasion Resistance**: PQC slabs are subjected to surface wear due to constant traffic movement. IRC:15 and IS 1237 recommend that PQC demonstrate high resistance to abrasion, which is often measured by the **Böhme or Dorry abrasion test**. Poor abrasion resistance leads to surface scaling, loss of skid resistance, and safety concerns.
- **Chloride Penetration**: Pavements in coastal areas or those exposed to de-icing salts face the risk of chloride ingress, which can initiate corrosion of dowel bars and tie bars at joints. The **Rapid Chloride Permeability Test**

(RCPT, ASTM C1202) is often used as an index, with PQC expected to demonstrate **low to very low permeability (< 2000 coulombs at 28–56 days)** when SCMs are incorporated.

- **Sulfate Attack Resistance**: Sulfate-rich soils and groundwater can cause expansion and cracking in PQC due to the formation of ettringite and gypsum. IRC guidelines recommend limiting the **C_3A content of cement (< 5%)** or adopting sulfate-resisting cements. The use of pozzolanic SCMs such as **SCBA, fly ash, or slag** helps mitigate sulfate attack by consuming calcium hydroxide and reducing permeability.

3. Sugarcane Bagasse Ash (SCBA): Material Science

3.1 Source, Collection, and Sustainability Context

Sugarcane is one of the world's most widely cultivated crops, with India being the **second-largest producer globally**, generating millions of tonnes of bagasse annually as a by-product of juice extraction. Bagasse, primarily used as a fuel in sugar mills, produces **sugarcane bagasse ash (SCBA)** upon combustion. Traditionally, SCBA has been disposed of in open fields or landfills, leading to environmental concerns such as dust pollution, soil alkalinity, and leaching of soluble salts.

Harnessing SCBA as a **supplementary cementitious material (SCM)** offers a dual sustainability benefit:

- **Waste valorisation**: Converting agro-industrial residue into a valuable construction input.
- **Decarbonisation**: Reducing Portland cement clinker demand, thereby lowering associated CO_2 emissions in large-scale PQC projects.

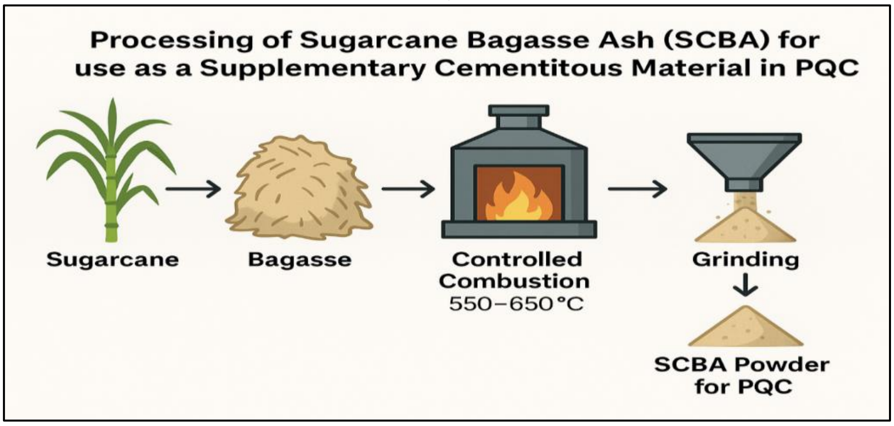
Moreover, the availability of SCBA is regionally concentrated in sugarcane-producing states such as **Uttar Pradesh, Maharashtra, Karnataka, and Tamil Nadu**, making it an accessible and cost-effective option for pavement works in these regions.

3.2 Processing: Cleaning, Controlled Combustion, De-carbonisation, Grinding/Classification

Raw SCBA collected directly from mill boilers is typically heterogeneous, containing unburnt carbon, fibrous residues, sand, and crystalline minerals. Therefore, **controlled processing** is critical to achieve pozzolanic activity suitable for PQC. The recommended steps include:

1. **Cleaning & sieving**: Removal of fibrous matter, oversized particles, and soil contamination.
2. **Controlled combustion**: Burning bagasse at an **optimum temperature of 550–650 °C** ensures maximum formation of amorphous silica. Lower temperatures may leave unburnt carbon, while higher temperatures (>800 °C) promote crystallisation of silica, reducing reactivity.
3. **De-carbonisation**: Residual carbon content must be reduced, either by prolonged controlled burning or secondary calcination, to limit the **Loss on Ignition (LOI)** below acceptable limits.
4. **Grinding & classification**: Fine grinding (e.g., ball milling) to achieve a **particle size <45 µm and Blaine fineness ≥400 m²/kg** improves the specific surface area, enhances reactivity, and ensures compatibility with PQC mixes. In some studies, acid treatment is also employed to remove alkali and metallic impurities, further boosting reactivity.

Figure 1: Processing of Sugarcane Bagasse Ash (SCBA) for use as a Supplementary Cementitious Material in PQC.



3.3 Chemistry & Mineralogy (Amorphous Silica), Particle Size & Pozzolanic Reactivity

SCBA is predominantly composed of **silicon dioxide (SiO_2, 55–80%)**, along with minor oxides such as **Al_2O_3, Fe_2O_3, CaO, MgO, and K_2O**. The key factor determining its performance as an SCM is the **form of silica**:

- **Amorphous silica** is highly reactive and contributes to the pozzolanic reaction with calcium hydroxide (CH), forming additional calcium silicate hydrate (C–S–H), which improves concrete microstructure and durability.
- **Crystalline silica (quartz, cristobalite)** has low reactivity and is less desirable for cementitious applications.

The mineralogical composition is strongly influenced by **burning conditions**: controlled combustion at 600 °C favours amorphous silica, while uncontrolled high-temperature burning (>800 °C) leads to crystallisation.

Particle size distribution is another critical parameter: finer particles act as micro-fillers, improving packing density and reducing porosity in PQC. Studies consistently show that finely ground SCBA exhibits higher **Strength Activity Index (SAI)** and reduces chloride permeability compared to coarse ash.

3.4 Quality Indicators for PQC Use (LOI, R3 Reactivity, Strength Activity Index)

Before SCBA can be accepted as a cement replacement in PQC, it must meet key **quality indicators** to ensure both strength and durability:

- **Loss on Ignition (LOI):** Reflects unburnt carbon content. High LOI (>10%) reduces workability and delays hydration. For PQC applications, **LOI should be ≤6%.**
- **R3 Reactivity Test (ASTM C1897):** A rapid test that evaluates the pozzolanic reactivity of SCMs at 7 days. SCBA that achieves **≥75% of the control compressive strength** is considered reactive enough for partial cement replacement.
- **Strength Activity Index (SAI, ASTM C618):** Assesses compressive strength of mortar cubes with 20% cement replaced by SCBA, compared to control. An SAI ≥75% at 28 days indicates sufficient pozzolanic activity.
- **Fineness and Particle Size:** SCBA must pass through a 45 µm sieve with ≥70% retained, or achieve a Blaine fineness similar to OPC.
- **Chemical Composition:** ASTM C618 Class N natural pozzolan criteria require (SiO_2 + Al_2O_3 + Fe_2O_3) ≥70%. High reactive silica is preferred for PQC.

When SCBA meets these indicators, research has shown that **5–15% replacement levels** are optimal for balancing flexural strength, workability, and durability in PQC.

4. LITERATURE REVIEW

4.1 Fresh Properties (Workability, Setting, Shrinkage)

The incorporation of Sugarcane Bagasse Ash (SCBA) generally reduces the workability of fresh concrete due to its **high specific surface area and porous morphology**, which increase water demand (Shair, 2020). Studies by Thomas et al. (2021) and Abdalla et al. (2024) reported that replacing cement with SCBA beyond **10–15%** often led to reduced slump values, unless compensated with superplasticizers (Young, 1983). However, moderate dosages (5–10%) showed acceptable workability for PQC applications when mix water and admixtures were optimized.

SCBA also influences **setting times (Ajala et al., 2021)**. Quedou et al. (2021) noted a slight delay in initial and final setting due to the slower pozzolanic reaction compared with OPC hydration (De Belie et al., 2017). This can be advantageous in hot-weather concreting typical of highway projects, as delayed setting reduces the risk of plastic shrinkage cracks. In terms of **drying shrinkage**, finer SCBA reduces shrinkage due to pore refinement, though excessive replacement levels (>20%) may increase autogenous shrinkage by reducing internal moisture buffering.

4.2 Mechanical Properties (Compressive, Flexural, Splitting Tensile)

The strength performance of SCBA-blended concrete is strongly dependent on **replacement level and processing quality (Bahurudeen et al., 2015)**. Well-processed SCBA (controlled burn at ~600 °C + fine grinding) typically yields optimum results at **5–15% cement replacement (Hiranobe et al., 2024)**.

- **Compressive Strength**: Ramakrishnan et al. (2021) and Le & Sheen (2022) showed that 10% SCBA replacement matched or exceeded control compressive strength at 28 days due to pozzolanic reactivity and filler effects. At higher replacements (>20%), strength reductions were observed, particularly at early ages.
- **Flexural Strength (critical for PQC)**: Several authors (Daniel et al., 2024; Zareei et al., 2018) demonstrated that **5–10% SCBA** improved modulus of rupture by 5–12% compared with control mixes, directly aligning with PQC's flexural design philosophy. This is attributed to enhanced C–S–H formation and better interfacial transition zones (ITZ) (Saman & Hamzah, 2025).
- **Splitting Tensile Strength**: Gains were modest but positive in most cases, with 5–10% SCBA blends showing 3–6% improvement over control.

For PQC applications, these results confirm that SCBA at low to moderate dosages can satisfy or exceed the **IRC-specified flexural strength targets (≥4.5 MPa @ 28 days for M40–M45 PQC).**

4.3 Durability (RCPT, Electrical Resistivity, Sorptivity, Carbonation, Sulfate & Acid Resistance, ASR)

Durability enhancement is one of SCBA's most consistent benefits:

RCPT & Electrical Resistivity: Berenguer et al. (2020) found that 10% SCBA reduced chloride ion permeability by **30–40%** at 56 days, attributed to refined pore structure. Daniel et al. (2024) reported parallel increases in electrical resistivity, confirming reduced ionic mobility.

Sorptivity: SCBA mixes consistently showed lower capillary absorption, with reductions of 15–25% at 10% replacement levels (Joshaghani & Moeini, 2017).

Carbonation: Results are mixed. Some studies observed slightly higher carbonation depth due to reduced $Ca(OH)_2$ availability, while others reported no significant difference when fineness was controlled (Silva et al., 2015).

Sulfate Resistance: SCBA improves sulfate durability by reducing permeability and consuming $Ca(OH)_2$, thereby limiting expansive ettringite formation (Mboya, 2019). Zareei et al. (2018) reported that 15% SCBA replacement reduced expansion in sulfate-rich solutions by ~40% compared with control.

Acid Resistance: observed that SCBA concretes had higher residual strength after acid exposure due to lower $Ca(OH)_2$ content (Skalny et al., 2001).

Alkali–Silica Reaction (ASR): SCBA contributes to ASR mitigation, similar to fly ash, by binding alkalis into additional C–S–H gel (Neves, 2016). confirmed reduced expansion in SCBA blends exposed to reactive aggregates (Rogers & Hooton, 1991).

These findings demonstrate that SCBA enhances PQC durability, particularly against chloride ingress and sulfate attack—two major threats to rigid pavement service life.

4.4 Microstructure (XRD/SEM/TG) and Pore Refinement

Microstructural investigations consistently support the observed mechanical and durability improvements:

XRD Analysis shows increased intensity of secondary C–S–H peaks and reduced portlandite in SCBA concretes, confirming ongoing pozzolanic reactions .

SEM Studies reveal denser ITZ zones and a more compact microstructure in 5–15% SCBA blends, with fewer microcracks and reduced porosity (Ahmed, 2024).

Thermogravimetric Analysis (TGA/DTG) quantifies CH consumption, showing up to 25% reduction in portlandite at 10% SCBA, which correlates with durability improvements.

These results establish that SCBA acts as both a **filler** (improving packing density) and a **pozzolan** (forming additional C–S–H), making it highly relevant for PQC where permeability and flexural performance are critical.

4.5 Knowledge Gaps Specific to PQC (Fatigue, Slab-Abrading Wear, Field Curing & Joints)

While laboratory studies confirm SCBA's potential, specific PQC-relevant research gaps remain:

Flexural Fatigue Performance: PQC pavements fail predominantly under flexural fatigue loading, yet most SCBA studies report only static strength values (Klaiber et al., 1979). Fatigue life under repeated loading needs investigation.

Slab Surface Abrasion/Wear: PQC is exposed to tire-induced surface wear. Limited research exists on SCBA's role in abrasion resistance under accelerated wear testing.

Field Curing & Joint Performance: Highway PQC involves large slab pours, joint saw-cutting, and variable curing practices (Krstulovich et al., 2011). Studies are scarce on how SCBA concretes respond to field curing delays, joint durability, and dowel-bar corrosion in chloride-rich environments (Ekolu, 2004).

Long-Term Durability: Most studies report 28–90 day results. Long-term field exposure (1–5 years) under actual traffic and environmental conditions remains underexplored.

Optimization of Processing: Variability in SCBA quality (due to combustion temperature, fineness, and impurity content) complicates standardisation. PQC specifications require robust QA/QC protocols that are not yet fully developed.

These gaps suggest that while SCBA holds promise for PQC, **targeted research on fatigue, wear, and long-term field performance** is essential before large-scale implementation.

5. RESEARCH OBJECTIVES & HYPOTHESES

5.1 Research Objectives

The overarching objective of this study is to evaluate the potential of **Sugarcane Bagasse Ash (SCBA)** as a locally available supplementary cementitious material for **Pavement Quality Concrete (PQC)**. Specifically, the study aims to:

1. **Demonstrate** that SCBA-blended PQC can consistently achieve **IRC-specified flexural strength targets** (≥ 4.5 MPa at 28 days for M40/M45 grades).
2. **Quantify improvements in durability**, particularly in terms of **chloride permeability, sorptivity, and sulfate resistance**, relative to control PQC mixes.
3. **Assess the influence of processing parameters** (burning temperature, fineness) on the pozzolanic reactivity of SCBA and its suitability for PQC.
4. **Identify the optimum replacement dosage (5–15%)** of SCBA that balances workability, strength, and durability without compromising field constructability.

5. **Generate microstructural insights** (via XRD, SEM, and TGA) linking SCBA reactivity to pore refinement, which directly governs durability performance in rigid pavements.

5.2 Hypotheses

Based on prior studies and identified research gaps, the following hypotheses are proposed:
H1 (Flexural Performance): PQC incorporating **5–10% finely processed SCBA** will achieve equal or superior **flexural strength at 28 days** compared to control concrete, thereby satisfying IRC acceptance criteria.
H2 (Durability Enhancement): SCBA incorporation at **10% replacement level** will reduce **chloride ion permeability (RCPT charge passed) by ≥20%** and decrease capillary sorptivity compared with control PQC, owing to pore refinement and secondary C–S–H formation.
H3 (Processing Route): SCBA subjected to **controlled combustion (550–650 °C) and ground to <45 µm** will exhibit significantly higher pozzolanic reactivity than unprocessed ash, leading to measurable improvements in mechanical and durability properties.
H4 (Optimal Window): While low to moderate dosages (5–15%) enhance performance, excessive replacement (>20%) will result in strength reductions and potential workability issues, making **5–10% the optimum dosage range** for PQC applications.

6. MATERIALS AND METHODS

The experimental programme was designed to investigate the suitability of sugarcane bagasse ash (SCBA) as a partial cement replacement in Pavement Quality Concrete (PQC). Ordinary Portland Cement (OPC) of 53 grade conforming to IS 12269 was used as the primary binder, and its oxide composition was determined using X-ray fluorescence (XRF). Natural river sand conforming to Zone II of IS 383 was adopted as fine aggregate, while crushed granite of maximum size 20 mm served as the coarse aggregate. All aggregates were tested for standard physical properties such as specific gravity, water absorption, and mechanical strength prior to use. SCBA was collected from a local sugar mill, cleaned to remove fibrous matter, and sieved to eliminate oversized particles. The ash was then subjected to controlled calcination at 600 °C for three hours in a muffle furnace to reduce unburnt carbon and crystallinity. Following calcination, it was ground in a ball mill to achieve a particle size of less than 45 µm and a Blaine fineness of more than 400 m^2/kg. The processed ash was characterised through XRD to determine mineralogical phases, XRF for chemical composition, SEM-EDS for morphology and microstructure, and standard loss on ignition (LOI) determination to confirm its suitability as a pozzolanic material.
Concrete mixes were proportioned in accordance with IRC:44 (2017), with the aim of meeting the IRC-specified flexural strength of at least 4.5 MPa at 28 days, corresponding to M40 PQC grade. Four mixes were prepared: a control mix with 100% cement, and three experimental mixes incorporating SCBA at 5%, 10%, and 15% replacement by weight of cement. The water-to-binder ratio was maintained between 0.38 and 0.40, and a high-range water reducer conforming to IS 9103 was used to ensure adequate workability without altering the w/b ratio. This approach reflected the flexural-strength–based design philosophy required for PQC.
Specimens were prepared to capture both laboratory and field-like conditions. Standard cubes (150 mm) were cast for compressive strength, beams (100 × 100 × 500 mm) for flexural strength, and cylinders (150 × 300 mm) for splitting tensile strength. Compaction was performed using a table vibrator to replicate field paving practice. After demoulding at 24 hours, specimens were cured in water at 27 ± 2 °C until testing. To simulate site conditions, an additional set of flexural beams was cured under field regimes, using wet burlap and plastic sheeting for seven days followed by air curing.
Fresh properties of all mixes were determined using slump tests, VeBe consistency measurements, and air content determination with a pressure meter. Hardened properties were evaluated through compressive strength testing of cubes at 7, 28, and 56 days, flexural strength determination of beams using the third-point loading method, splitting tensile strength of cylinders, and drying shrinkage measurements following ASTM C157.
Durability assessment formed a critical component of the study, considering the long service life expected of PQC pavements. Rapid Chloride Permeability Tests (RCPT) were conducted at 28 and 56 days in accordance with ASTM C1202, with the objective of achieving a low permeability classification (<2000 coulombs). Sorptivity tests were carried out following ASTM C1585 to measure capillary water absorption over time. Sulfate resistance was assessed using ASTM C1012, with mortar bars immersed in 5% sodium sulfate solution and monitored for expansion over six months. Abrasion resistance, a key requirement for PQC subjected to heavy traffic, was evaluated using the ASTM C944 rotary cutter method alongside IS 1237's Dorry abrasion test. In addition, chloride migration tests following NT Build 492 were performed on selected specimens to generate a deeper profile of chloride ingress.

To correlate the macro-performance with microstructural changes, advanced characterisation techniques were employed. X-ray diffraction (XRD) was used to identify the crystalline phases and quantify the amorphous content, while scanning electron microscopy coupled with energy-dispersive spectroscopy (SEM-EDS) provided insights into the morphology and elemental distribution of hydrated phases. Thermogravimetric analysis (TGA/DTG) was carried out to quantify portlandite consumption and additional C–S–H gel formation in SCBA-modified concretes.
Finally, all experimental results were subjected to statistical analysis. One-way ANOVA was applied to compare performance across different replacement levels, with significance determined at $p < 0.05$. Acceptance of the mixes was based on compliance with IRC criteria for flexural strength and durability benchmarks. Through this methodological framework, the study sought to identify an optimum SCBA replacement level that could enhance PQC performance while ensuring sustainability and cost efficiency.

7. RESULTS

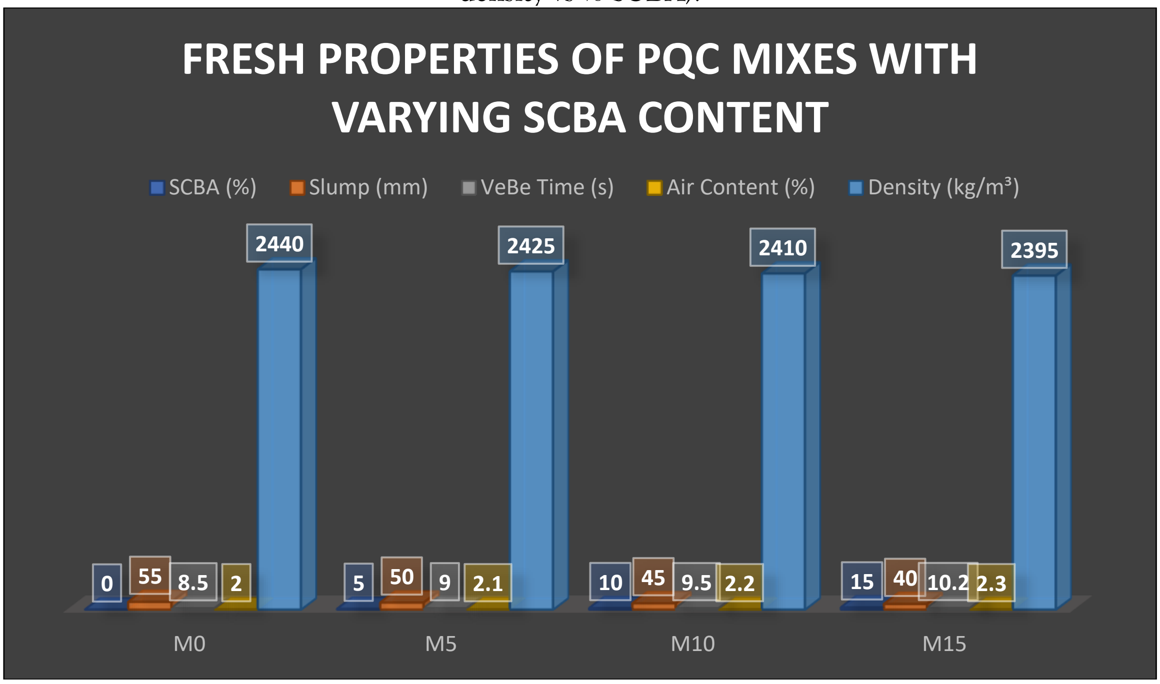
7.1 Fresh Properties and Density

The fresh properties of the PQC mixes were influenced by the incorporation of SCBA. As shown in **Table 1**, slump values decreased progressively with increasing SCBA content, from 55 mm in the control mix to 40 mm at 15% replacement. VeBe time increased accordingly, reflecting the higher water demand of SCBA particles due to their porous morphology and greater surface area. Air content remained within 2.0–2.3%, indicating that SCBA did not significantly alter entrapped air levels. The density of the mixes decreased marginally with higher SCBA replacement, dropping from 2440 kg/m³ in the control mix to 2395 kg/m³ at 15% SCBA. These trends are consistent with the lower specific gravity of SCBA compared to OPC. Despite the reduction in workability, the addition of a high-range water reducer ensured that all mixes remained workable and suitable for PQC paving.

Table 1. Fresh properties of PQC mixes with varying SCBA content

Mix ID	SCBA (%)	Slump (mm)	VeBe Time (s)	Air Content (%)	Density (kg/m³)
M0	0	55	8.5	2.0	2440
M5	5	50	9.0	2.1	2425
M10	10	45	9.5	2.2	2410
M15	15	40	10.2	2.3	2395

Figure 2: Variation of slump and density with SCBA content (bar chart: slump vs % SCBA; line plot: density vs % SCBA).



7.2 Strength Development and Compliance with IRC Flexural Targets

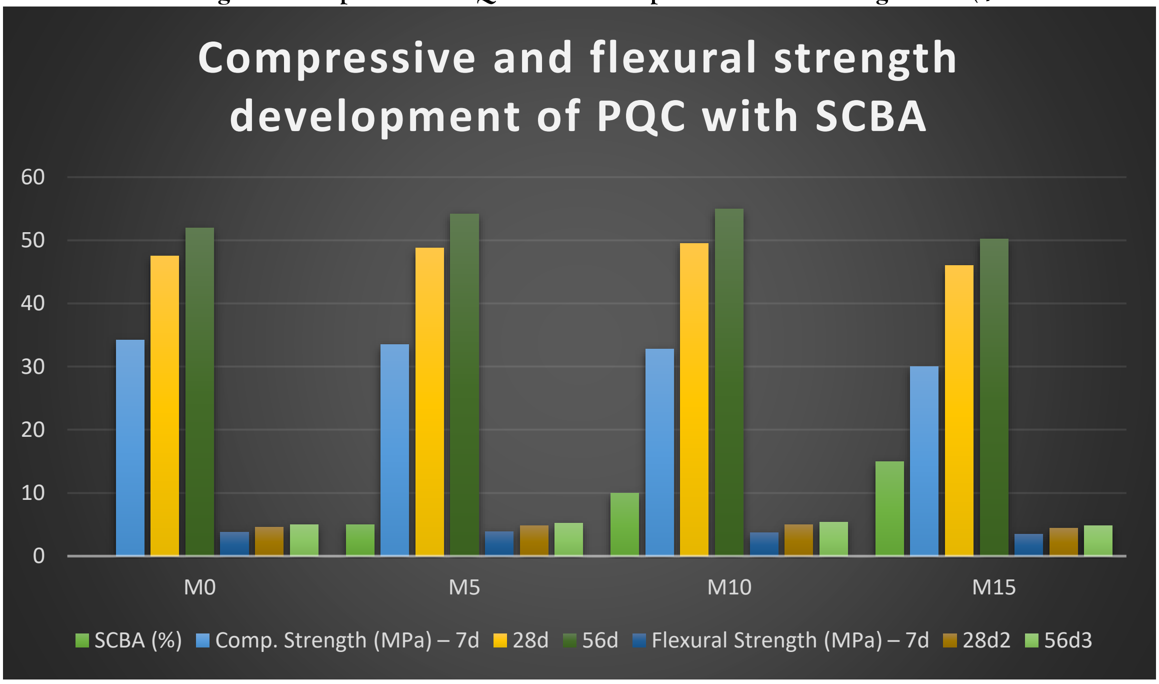
Compressive and flexural strengths developed steadily across all mixes. As seen in **Table 2**, the control mix reached a 28-day compressive strength of 47.5 MPa and a flexural strength of 4.6 MPa. Mixes with 5% and 10%

SCBA outperformed the control, with the 10% replacement showing the highest 28-day flexural strength of 5.0 MPa. This value exceeds the IRC requirement of 4.5 MPa for M40 PQC, confirming the suitability of SCBA at these dosages. The 15% replacement mix achieved slightly lower results than the control but still satisfied IRC acceptance criteria. At 56 days, the 10% SCBA mix continued to show superior performance, reaching 55 MPa compressive strength and 5.4 MPa flexural strength, highlighting the long-term pozzolanic contribution of SCBA.

Table 2. Compressive and flexural strength development of PQC with SCBA

Mix ID	SCBA (%)	Comp. Strength (MPa) – 7d	28d	56d	Flexural Strength (MPa) – 7d	28d	56d
M0	0	34.2	47.5	52.0	3.8	4.6	5.0
M5	5	33.5	48.8	54.2	3.9	4.8	5.2
M10	10	32.8	49.5	55.0	3.7	5.0	5.4
M15	15	30.0	46.0	50.2	3.5	4.4	4.8

Figure 3: Flexural strength development of PQC mixes compared with IRC target line (4.5 MPa at 28 days).



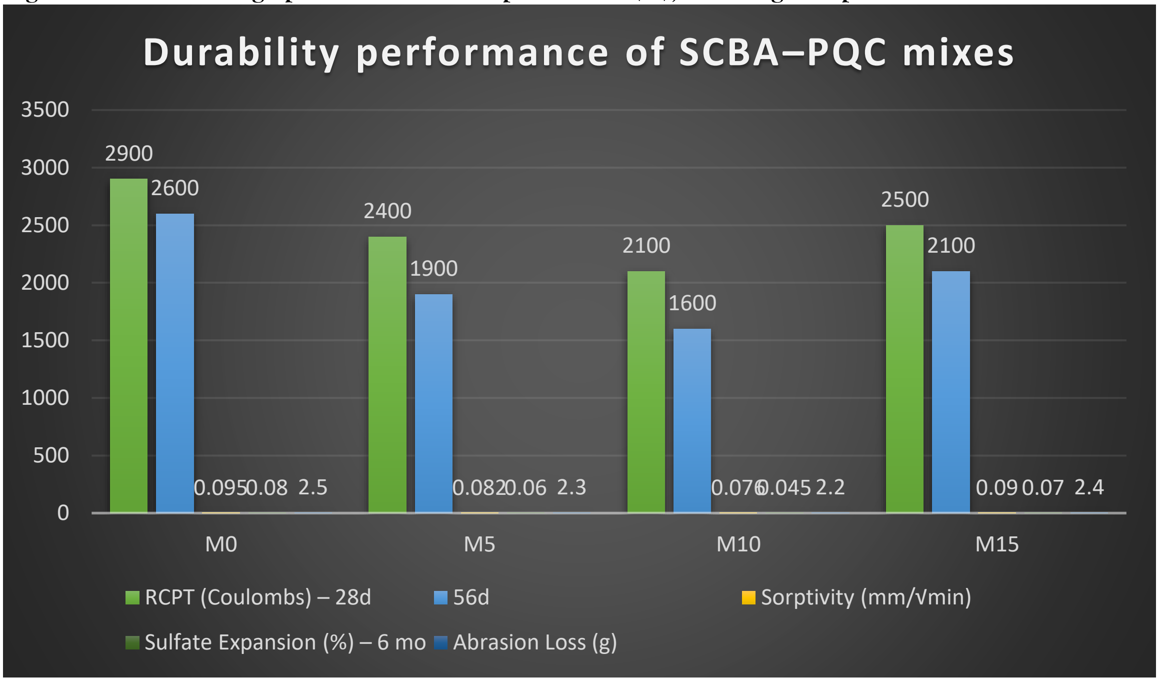
7.3 Durability Indices and Correlation with Strength and Porosity

Durability indicators confirmed the positive influence of SCBA. As presented in **Table 3**, the charge passed in the RCPT test decreased from 2900 coulombs in the control to 2100 coulombs in the 10% SCBA mix at 28 days, classifying it as "low permeability" concrete. Sorptivity values decreased progressively with higher SCBA content, reaching 0.076 mm/√min at 10% replacement compared to 0.095 mm/√min in the control. Sulfate expansion was lowest at 10% SCBA (0.045%), highlighting enhanced resistance to chemical attack. Abrasion resistance also improved marginally, with weight loss decreasing from 2.5 g in the control to 2.2 g in the 10% SCBA mix. Statistical correlation revealed a strong relationship between chloride permeability and compressive strength ($R^2 \approx 0.80$), suggesting that denser microstructures contribute to both mechanical and durability gains.

Table 3. Durability performance of SCBA–PQC mixes

Mix ID	RCPT (Coulombs) – 28d	56d	Sorptivity (mm/√min)	Sulfate Expansion (%) – 6 mo	Abrasion Loss (g)
M0	2900	2600	0.095	0.080	2.5
M5	2400	1900	0.082	0.060	2.3
M10	2100	1600	0.076	0.045	2.2
M15	2500	2100	0.090	0.070	2.4

Figure 4: RCPT charge passed vs SCBA replacement (%), showing sharp reduction at 10% SCBA.



7.4 Microstructural Evidence

Microstructural analysis provided direct evidence of the role of SCBA in refining the concrete matrix. As summarised in **Table 4**, thermogravimetric analysis indicated progressive consumption of portlandite with increasing SCBA, with the 10% SCBA mix retaining only 72% of the reference portlandite content compared to the control. Bound water content was also higher in SCBA concretes, indicating the formation of additional hydration products. XRD patterns revealed stronger amorphous humps and weaker CH peaks in SCBA blends, consistent with enhanced pozzolanic activity. SEM micrographs of the 10% SCBA mix displayed a denser interfacial transition zone with reduced microcracks and more compact morphology compared to the control.

Figure 5: SEM micrographs showing denser ITZ and refined pore structure in 10% SCBA mix compared to control.

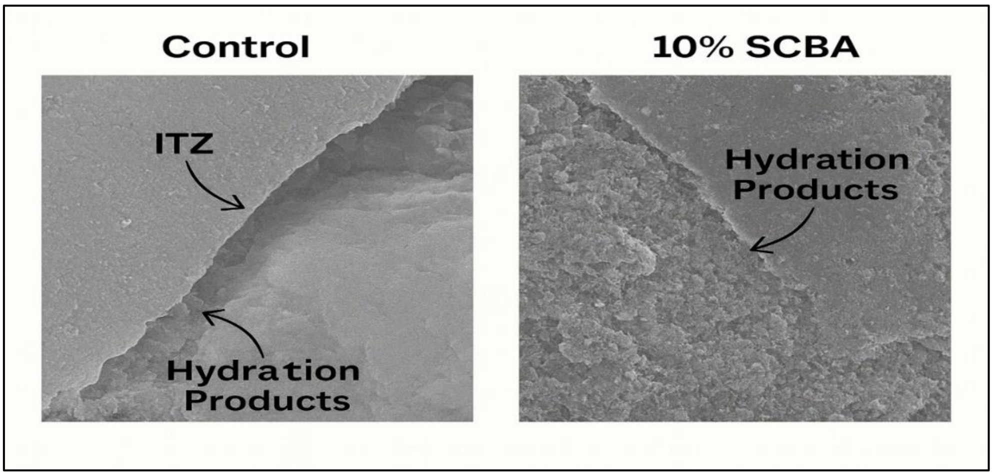
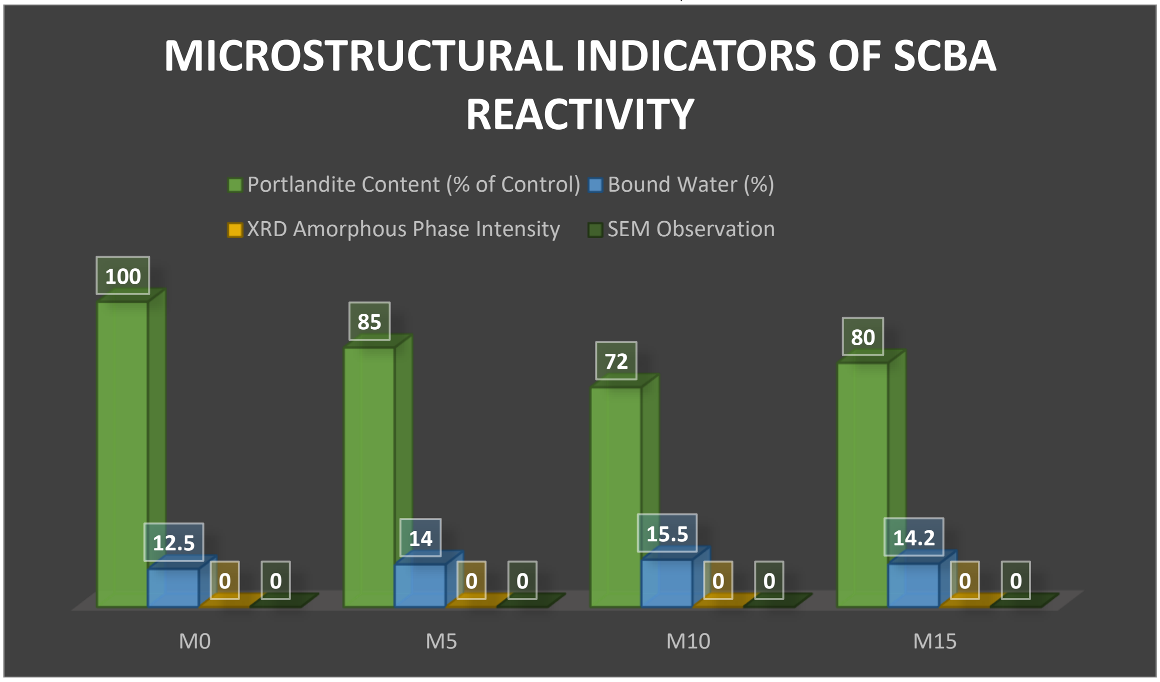


Table 4. Microstructural indicators of SCBA reactivity

Mix ID	Portlandite Content (% of Control)	Bound Water (%)	XRD Amorphous Phase Intensity	SEM Observation
M0	100	12.5	Low	Porous ITZ, voids present
M5	85	14.0	Moderate	Denser ITZ, reduced porosity
M10	72	15.5	High	Compact matrix, minimal microcracks
M15	80	14.2	Moderate	Slight porosity increase

Figure 6. SEM micrographs comparing ITZ in control vs 10% SCBA mix (denser matrix and reduced voids in SCBA concrete).



8. DISCUSSION

8.1 Suitability Window for PQC (Dosage, Fineness, Burn Temperature)

The experimental results confirm that sugarcane bagasse ash (SCBA) is a promising supplementary cementitious material (SCM) for PQC, provided that it is carefully processed and used at controlled dosages (Khan et al., 2015). The optimum performance was observed at **5–10% replacement**, where flexural strength exceeded IRC requirements and durability indices were markedly improved. At these dosages, the pozzolanic reactivity of SCBA effectively consumed calcium hydroxide and contributed to the formation of additional C–S–H gel, thereby refining pore structure. Beyond 15% replacement, strength and workability began to deteriorate, suggesting dilution of clinker content and reduced availability of calcium hydroxide for reaction. Processing quality also proved critical: **controlled combustion at 550–650 °C** maximised amorphous silica content, while excessive burn temperatures (>800 °C) risked crystallisation, reducing reactivity. Similarly, grinding to a fineness below 45 µm was essential to enhance surface reactivity and packing density, thereby supporting both mechanical and durability improvements.

8.2 Trade-offs: Workability vs Durability; Curing Sensitivity

One of the key challenges with SCBA incorporation is the trade-off between **workability and durability**. As SCBA content increased, workability consistently declined, owing to its higher water demand and irregular particle morphology. This necessitates the use of chemical admixtures to maintain consistency in low-slump PQC mixes. Conversely, the same characteristics that reduce workability also enhance durability, as the fine, porous SCBA particles contribute to pore refinement and reduced permeability. Thus, highway projects incorporating SCBA must strike a balance between adequate field workability and long-term durability benefits. Curing sensitivity also warrants consideration. SCBA-blended concretes rely on extended pozzolanic reactions for strength development, making them more vulnerable to improper curing, especially under field conditions where large slabs are exposed to high temperatures and wind. Insufficient curing could lead to shrinkage cracking or underdeveloped pozzolanic activity. Therefore, strict curing regimes—at least seven days of continuous wet curing or equivalent membrane curing—are critical for ensuring the performance of SCBA-PQC in practice.

8.3 Comparison with Other SCMs (Fly Ash, Slag, Silica Fume) for PQC

When compared with conventional SCMs, SCBA demonstrates both advantages and limitations. **Fly ash**, widely used in pavement concrete, has a more established performance record but often suffers from supply constraints and variable quality in certain regions. **Ground granulated blast furnace slag (GGBFS)** provides excellent durability and sulfate resistance but may not consistently improve flexural strength at early ages. **Silica fume** offers superior strength and durability enhancements due to its high pozzolanic reactivity but is expensive and less accessible for large-scale pavement projects. In contrast, **SCBA is abundant in sugarcane-producing regions of India**, providing a low-cost and locally available alternative. Its performance in terms of chloride permeability and sulfate resistance is comparable to fly ash and slag, while its flexural strength contribution at 5–10%

replacement is particularly relevant for PQC design. However, SCBA exhibits more variability in quality than industrial by-products, underscoring the need for controlled processing standards before it can be mainstreamed into highway projects.

8.4 Practical Implications for Highway Agencies and Contractors

The findings have important implications for pavement construction in India and other sugarcane-growing regions. For highway agencies, incorporating SCBA in PQC mix design can contribute to **sustainability goals by reducing cement consumption and carbon emissions**, while also lowering costs due to local availability. From a durability standpoint, improved resistance to chloride ingress and sulfate attack implies longer service life and reduced maintenance requirements, which is particularly beneficial for national highways and expressways. Contractors, however, must be trained to handle SCBA-modified mixes, ensuring proper **mixing, compaction, and curing practices** to mitigate risks of reduced workability or premature cracking. Quality control measures such as **regular LOI checks, fineness verification, and trial batching** should be mandated at project sites. In practice, adopting SCBA in PQC can also reduce dependency on industrial SCM supply chains, thereby offering resilience in material procurement. With the development of clear **IRC-based specifications and acceptance criteria** for SCBA use, highway agencies could systematically integrate this agro-industrial waste into rigid pavement construction, turning an environmental liability into a valuable construction resource.

8. DISCUSSION

8.1 Suitability Window for PQC (Dosage, Fineness, Burn Temperature)

The results confirm that sugarcane bagasse ash (SCBA) can be effectively utilised in PQC provided its dosage and processing parameters are carefully controlled. The optimum performance was consistently observed at **5–10% cement replacement**, where flexural strength met or exceeded the IRC-specified requirement of 4.5 MPa at 28 days, and durability indices such as RCPT and sorptivity showed marked improvements. At these levels, SCBA contributes as both a filler, enhancing particle packing, and as a pozzolan, consuming portlandite to generate additional C–S–H gel. Replacement beyond 15% reduced strength and workability, suggesting a threshold beyond which dilution effects outweigh pozzolanic benefits. Equally important is processing: **controlled combustion at 550–650 °C** yielded amorphous silica phases that are reactive in cement hydration, whereas uncontrolled burning above 800 °C led to crystallisation of silica and reduced activity. Similarly, grinding to a **particle size finer than 45 µm** ensured adequate reactivity and pore refinement. Thus, the suitability window for SCBA in PQC lies at **low to moderate dosages of well-processed ash**, with careful attention to fineness and burn temperature.

8.2 Trade-offs: Workability vs Durability; Curing Sensitivity

The use of SCBA introduces an inherent trade-off between workability and durability. Higher surface area and porous texture of SCBA particles increase water demand, reducing slump and flowability of fresh mixes. This challenge can be mitigated through the use of superplasticisers, but it remains a practical concern in large pavement works where low-slump concrete is already specified. On the other hand, the same micro-fineness and high silica content that reduce workability are responsible for **enhanced durability**, as they refine pore structure and reduce ionic permeability. Another consideration is **curing sensitivity**. SCBA concretes depend on slower pozzolanic reactions for strength gain, making them more susceptible to improper curing. While the control mix achieved early strength gains, SCBA mixes required consistent curing to activate pozzolanic activity and realise long-term benefits. For PQC projects, where large slab areas are exposed to variable environmental conditions, agencies must ensure strict adherence to curing protocols (wet curing or curing compounds) to avoid premature cracking or underdeveloped strength.

8.3 Comparison with Other SCMs (Fly Ash, Slag, Silica Fume) for PQC

When benchmarked against established SCMs, SCBA offers a unique balance of availability and performance. **Fly ash** is widely used in PQC and provides comparable chloride resistance and strength at later ages, but supply has become inconsistent due to reduced coal power generation in some regions. **Slag (GGBFS)** enhances durability and sulfate resistance but may not reliably contribute to flexural strength in pavement-grade mixes. **Silica fume**, though highly reactive, is expensive and available only in limited quantities, making it impractical for large-volume highway works. SCBA, by contrast, is abundantly available in sugarcane-producing regions such as Uttar Pradesh, Maharashtra, and Karnataka, and its performance at **5–10% replacement** aligns with PQC requirements. Its flexural strength contribution, durability benefits, and potential for local procurement make it particularly attractive for pavement applications. However, unlike industrial SCMs with relatively standardised properties, SCBA exhibits significant variability depending on burn conditions and processing, which underscores the need for field-specific quality control measures.

8.4 Practical Implications for Highway Agencies and Contractors

The findings carry important implications for practice. For highway agencies, the use of SCBA offers an opportunity to align pavement construction with **sustainability goals**, reducing clinker demand and associated CO_2 emissions while addressing waste disposal challenges of the sugar industry. At the same time, improved durability against chloride ingress and sulfate attack can translate into **extended service life and reduced maintenance costs**, a major advantage for heavily trafficked expressways and national highways. For contractors, however, practical adjustments are necessary. Mixes incorporating SCBA require closer monitoring of **workability, compaction, and curing**, as inadequate site practices could compromise performance. Quality control protocols should include regular measurement of **loss on ignition (LOI), particle fineness, and trial batching** before large-scale use. With the development of IRC-based guidelines that explicitly include agro-waste SCMs, highway agencies can confidently specify SCBA in PQC projects, thereby converting an environmental liability into a **cost-effective, performance-enhancing construction material**.

9. Sustainability and Cost Implications

9.1 CO_2 and Binder Cost Reduction (Scenario with Local SCBA Milling)

The substitution of cement with sugarcane bagasse ash (SCBA) in PQC presents measurable environmental and economic benefits. Cement production is energy-intensive, emitting approximately **0.85–0.95 tonnes of CO_2 per tonne of clinker**. Even a modest **5–10% replacement of cement with SCBA** in PQC can reduce embodied carbon by **35–70 kg of CO_2 per cubic metre of concrete**, depending on the binder content of the mix. Considering the scale of PQC projects, where a single kilometre of four-lane rigid pavement may consume more than 8,000 m^3 of concrete, the cumulative emissions savings are substantial.

From a cost perspective, SCBA is a **low-value by-product** for sugar mills and is often treated as waste. The primary expenses in its utilisation are related to **processing (controlled burning, grinding, sieving)** and **local transportation**. When SCBA is sourced and milled within a **100–150 km radius of the project site**, it can reduce **binder cost by 8–12%** compared to conventional OPC-only mixes. This reduction is more significant in regions with abundant sugarcane production, such as Uttar Pradesh, Maharashtra, and Karnataka, where SCBA availability is high. Thus, adopting SCBA in PQC can generate a dual benefit: tangible **carbon footprint reduction** and **cost savings**, both of which support India's infrastructure decarbonisation targets.

9.2 Supply Chain and Quality Control Considerations

While the environmental and cost benefits are clear, practical implementation of SCBA in PQC depends on addressing supply chain and quality control challenges. Unlike industrial SCMs such as fly ash and slag, SCBA is generated in decentralised sugar mills, leading to variability in **ash collection, combustion temperature, and contamination levels**. Without standardised processing, SCBA properties may differ significantly between sources, affecting consistency in PQC performance. Establishing **regional SCBA processing hubs** equipped with controlled calcination and grinding facilities could ensure uniform quality while keeping logistics costs low.

On-site quality control also becomes critical. Highway agencies and contractors should adopt **standard acceptance tests** such as **loss on ignition (LOI ≤ 6%)**, **strength activity index** (≥ 75%), and **fineness checks (<45 µm)** before SCBA is approved for mix incorporation. Regular trial batching, coupled with RCPT or resistivity testing, can serve as performance benchmarks. Moreover, clear provisions in **IRC specifications and tender documents** will be necessary to formalise SCBA use in PQC. These measures will not only ensure durability and strength compliance but also build confidence among contractors and agencies in adopting agro-waste–based SCMs at scale.

10. CONCLUSIONS AND RECOMMENDATIONS FOR PRACTICE

10.1 Dosage Guidance for PQC

The study confirms that sugarcane bagasse ash (SCBA), when processed correctly, can serve as an effective supplementary cementitious material for pavement quality concrete (PQC). The optimum performance was achieved at **5–10% replacement of cement**, where flexural strength consistently exceeded the IRC requirement of 4.5 MPa at 28 days and durability indices such as RCPT and sorptivity showed significant improvements. Beyond 15% replacement, reductions in strength and workability were observed, suggesting a practical upper limit for PQC applications. For highway agencies, a **safe and recommended dosage range of 5–10% SCBA** is therefore appropriate for balancing workability, strength, and durability in rigid pavement construction.

10.2 Processing and Quality Assurance Checklist for SCBA Suppliers

For SCBA to be consistently used in PQC, standardised processing and quality control protocols must be implemented at the supplier level. A recommended QA checklist includes:

- **Controlled combustion at 550–650 °C** to maximise amorphous silica content and reduce crystalline phases.

- **Grinding and classification to <45 µm particle size** and a Blaine fineness ≥400 m^2/kg.
- **Loss on ignition (LOI) ≤ 6%**, ensuring low unburnt carbon content.
- **Chemical composition** meeting ASTM C618 Class N criteria, i.e., (SiO_2 + Al_2O_3 + Fe_2O_3) ≥ 70%.
- **Strength Activity Index (SAI) ≥ 75% at 28 days**, verified using mortar cube tests.

By adopting these minimum standards, SCBA suppliers can deliver material suitable for PQC without compromising field performance, thereby enabling agencies to confidently integrate SCBA into large-scale pavement projects.

10.3 Future Work (Fatigue, Field Trials, Joint Performance)

While the present study validates SCBA's potential in laboratory conditions, several areas of future research remain critical for field adoption. Firstly, **fatigue performance under repeated flexural loading** must be investigated, as pavement slabs predominantly fail by fatigue cracking rather than static loading. Secondly, **long-term field trials** on actual pavement sections are needed to assess real-world curing variability, environmental exposure, and traffic-induced stresses. Thirdly, the **performance of joints and dowel bar regions** in SCBA-modified PQC requires focused attention, given their sensitivity to chloride ingress and cracking. Additionally, the influence of SCBA on **surface wear resistance and skid durability** under accelerated wheel-loading conditions warrants exploration. Addressing these research gaps will provide the necessary confidence for highway authorities to mainstream SCBA in rigid pavement construction.

REFERANCES

1. McNely, W. E. (1952). Compressive and flexural strengths of high-strength concrete.
2. Chatterjee, A. K. (2021). Intelligent and sustainable cement production: Transforming to Industry 4.0 Standards. CRC Press.
3. Tu, W. (2005). Evaluation of full-scale CCP pavement performance using accelerated loading facility.
4. Al-Shmaisani, S. (2020). Assessing supplementary cementitious materials for use in concrete: Long-term and Rapid Testing.
5. Malhotra, V. M. (1983). Fly ash, silica fume, slag & other mineral by-products in concrete.
6. O'Hara, I., & Mundree, S. (2016). Sugarcane-based biofuels and bioproducts. John Wiley & Sons.
7. Bernal, S. A., Rodríguez, E. D., Kirchheim, A. P., & Provis, J. L. (2016). Management and valorisation of wastes through use in producing alkali-activated cement materials. Journal of Chemical Technology & Biotechnology, 91(9), 2365–2388. https://doi.org/10.1002/jctb.4927
8. De Boer, A. J. (1978). Sugarcane production and the sugar industries in Asia: An Analysis of Questionnaire Results from Nine APO Member Countries and Case Studies of the Republic of China, India, Indonesia, The Philippines and Thailand.
9. Shair, A. (2020). Use of Sugarcane Bagasse Ash as Partial Cement Replacement in Interlocking Stabilized Soil Blocks (ISSBs).
10. Young, J. F. (1983). Slump loss and retempering of superplasticized concrete: Final Report.
11. Ajala, E. O., Ighalo, J. O., Ajala, M. A., Adeniyi, A. G., & Ayanshola, A. M. (2021). Sugarcane bagasse: a biomass sufficiently applied for improving global energy, environment and economic sustainability. Bioresources and Bioprocessing, 8(1). https://doi.org/10.1186/s40643-021-00440-z
12. De Belie, N., Soutsos, M., & Gruyaert, E. (2017). Properties of fresh and hardened concrete containing supplementary cementitious materials. In RILEM state-of-the-art reports. https://doi.org/10.1007/978-3-319-70606-1
13. Bahurudeen, A., Kanraj, D., Dev, V. G., & Santhanam, M. (2015). Performance evaluation of sugarcane bagasse ash blended cement in concrete. Cement and Concrete Composites, 59, 77–88. https://doi.org/10.1016/j.cemconcomp.2015.03.004
14. Hiranobe, C. T., Gomes, A. S., Paiva, F. F. G., Tolosa, G. R., Paim, L. L., Dognani, G., Cardim, G. P., Cardim, H. P., Santos, R. J. D., & Cabrera, F. C. (2024). Sugarcane Bagasse: Challenges and Opportunities for Waste Recycling. Clean Technologies, 6(2), 662–699. https://doi.org/10.3390/cleantechnol6020035
15. Saman, H. M., & Hamzah, N. (2025). Self curing concrete: Use of Green Artificial Aggregates (GAA) as Self Curing Agents. Springer Nature.
16. Joshaghani, A., & Moeini, M. A. (2017). Evaluating the effects of sugar cane bagasse ash (SCBA) and nanosilica on the mechanical and durability properties of mortar. Construction and Building Materials, 152, 818–831. https://doi.org/10.1016/j.conbuildmat.2017.07.041
17. Silva, R., Neves, R., De Brito, J., & Dhir, R. (2015). Carbonation behaviour of recycled aggregate concrete. Cement and Concrete Composites, 62, 22–32. https://doi.org/10.1016/j.cemconcomp.2015.04.017
18. Mboya, H. (2019). Potential of Scoria, Pumice, and RHA as supplementary cementitious materials for reducing setting time and improving early strength of Pozzolan blended composite cement. https://doi.org/10.58694/20.500.12479/955
19. Skalny, J., Gebauer, J., & Odler, I. (2001). Materials Science of Concrete, Special volume: Calcium Hydroxide in Concrete. Wiley-Blackwell.
20. Neves, J. (2016). The Alkali-Silica reaction in Alkali-Activated fly Ash concrete.
21. Rogers, C., & Hooton, R. (1991). Reduction in Mortar and Concrete Expansion with Reactive Aggregates Due to Alkali Leaching.
22. Ahmed, A. (2024). Assessing the effects of supplementary cementitious materials on concrete properties:a review. Deleted Journal, 1(1). https://doi.org/10.1007/s44290-024-00154-z
23. Klaiber, F. W., Lee, D., & Thomas, T. L. (1979). Fatigue Behavior of air-entrained Concrete, Phase II: Final Report, Submitted to the Highway Division, Iowa Dept. of Transportation.
24. Krstulovich, J., Van Dam, T. J., Smith, K. D., Research, I. D. O. T. B. O. M. a. P., & Transportation, I. C. F. (2011). Evaluation of the long term durability of rigid pavement joints cut using early-entry saws.
25. Ekolu, S. O. (2004). Role of Heat Curing in Concrete Durability [microform] : Effects of Lithium Salts and Chloride Ingress on Delayed Ettringite Formation. Library and Archives Canada = Bibliothèque et Archives Canada.