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Sustainable Concrete Production Using Agricultural Waste Ash in Pakistan's Construction Industry

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Abstract

Pakistan's construction sector, contributing ~5.3% to GDP and driven by a cement industry with an installed capacity exceeding 86 million tons annually, faces mounting sustainability pressures from high energy consumption, coal dependency, substantial CO_2 emissions (~8–10% of national total), and depletion of conventional aggregates. This review evaluates the incorporation of agricultural waste ashes rice husk ash (RHA), sugarcane bagasse ash (SCBA), wheat straw ash, corn cob ash, and cotton stalk ash as supplementary cementitious materials (SCMs) and partial fine aggregate replacements in concrete production. Pozzolanic reactivity, particularly of RHA and SCBA (SiO_2 content 70–90%, fineness 20–40 m^2/g), enables 10–30% cement replacement while improving compressive strength (5–25% gain at 28–90 days), durability (reduced chloride permeability, sulfate resistance, water absorption), and workability when optimally processed (controlled burning at 600–700 °C, grinding to <45 µm). Life cycle assessment (LCA) studies indicate 15–40% reductions in global warming potential, fossil energy demand, and embodied carbon compared to ordinary Portland cement (OPC) concrete, alongside waste diversion from open burning (reducing ~1.2–2.0 t CO_2-eq per ton of ash utilized). Field and lab trials in Punjab and Sindh demonstrate structural feasibility for non-load-bearing elements, pavements, and low-to-medium strength concrete (20–40 MPa), with cost savings of 8–20% from lower cement and disposal expenses. Challenges variable ash composition, seasonal supply, grinding energy, alkali-silica reaction risk, and limited standardization are addressed through preprocessing protocols, mix optimization, and policy recommendations (incentives for ash utilization, inclusion in building codes). Agricultural waste ash emerges as a regionally abundant, low-cost, circular solution to enhance sustainability and resilience in Pakistan's rapidly urbanizing construction industry.

Keywords: Sustainable Concrete, Agricultural Waste Ash, Rice Husk Ash, Sugarcane Bagasse Ash, Supplementary Cementitious Materials, Life Cycle Assessment, Embodied Carbon, Pozzolanic Activity, Circular Economy, Pakistan Construction

1. Executive Overview of the Pakistani Cement and Construction Landscape

The construction industry in Pakistan occupies a pivotal role in the national economy, acting as a primary driver of infrastructure development and urbanization. Statistical assessments indicate that the sector holds a 5.3% share of the national GDP as of 2020, while the cement industry alone contributes approximately 1% to the GDP annually (GOP, 2020). This sector is characterized by a significant industrial footprint, comprising 16 operational companies and 27 plants with a cumulative production capacity that reached 77 million tons in fiscal year 2023 and expanded toward 86.7 million tons by 2024 (APCMA, 2024). Despite this robust capacity, the industry faces a complex array of macroeconomic challenges, including domestic sales declines and a precarious reliance on coal-based energy (SBOP, 2023).

The industrial operation is geographically divided into two major zones: the North and the South. The northern region hosts approximately 71% to 80% of the production capacity, while the southern region accounts for the remainder (Giljum et al., 2025). In the first nine months of the 2024 financial year, the industry produced 34.5 million tons of cement, representing a 3% year-on-year increase (BPOS, 2024). This discrepancy highlights an increasing pivot toward export markets, where Pakistani cement has found significant traction in regions like the United Kingdom and Africa (Trade Development Authority of Pakistan, 2024).

Table 1: Cement Industry Infrastructure and Economic Impact (2023-2024)

Parameter	**Industrial Statistics (2023-2024)**	**Regional Concentration (North/South)**	**Key Industry Players**
Operational Plants	27	80% North / 20% South	Lucky Cement, Fauji Cement, Bestway
Annual Capacity	77.0 - 86.7 million Tons	~66.4 Mt/a (North) / ~20.3 Mt/a (South)	DG Khan Cement, Kohat Cement
Direct Employment	~0.1 million People	Distributed	Attock Cement, Maple Leaf
GDP Share	~1% (Cement) / 5.3% (Construction)	National Impact	Dewan Cement, Cherat Cement
Energy Intensity	3.9 GJ/tonne of clinker	National Average	Lucky (Karachi/Pezu), Fauji (WHR Focus)

The environmental cost of this industrial activity is substantial. Cement manufacturing in Pakistan accounts for an estimated 25% of all industrial primary energy consumption and 65-70% of industrial coal consumption. Consequently, the sector is responsible for at least 49% of the country's coal emissions (World Bank, 2023). Globally, cement and concrete production are responsible for approximately 10% of total energy-related CO_2 emissions, a figure mirrored in Pakistan’s industrial profile. The carbon intensity is primarily driven by the calcination of limestone and high-temperature combustion in the kiln (Antunes et al., 2021). The integration of agricultural residues into concrete production follows a systematic processing pathway. This sustainable workflow, from biomass generation to concrete application, is illustrated in Figure 1.

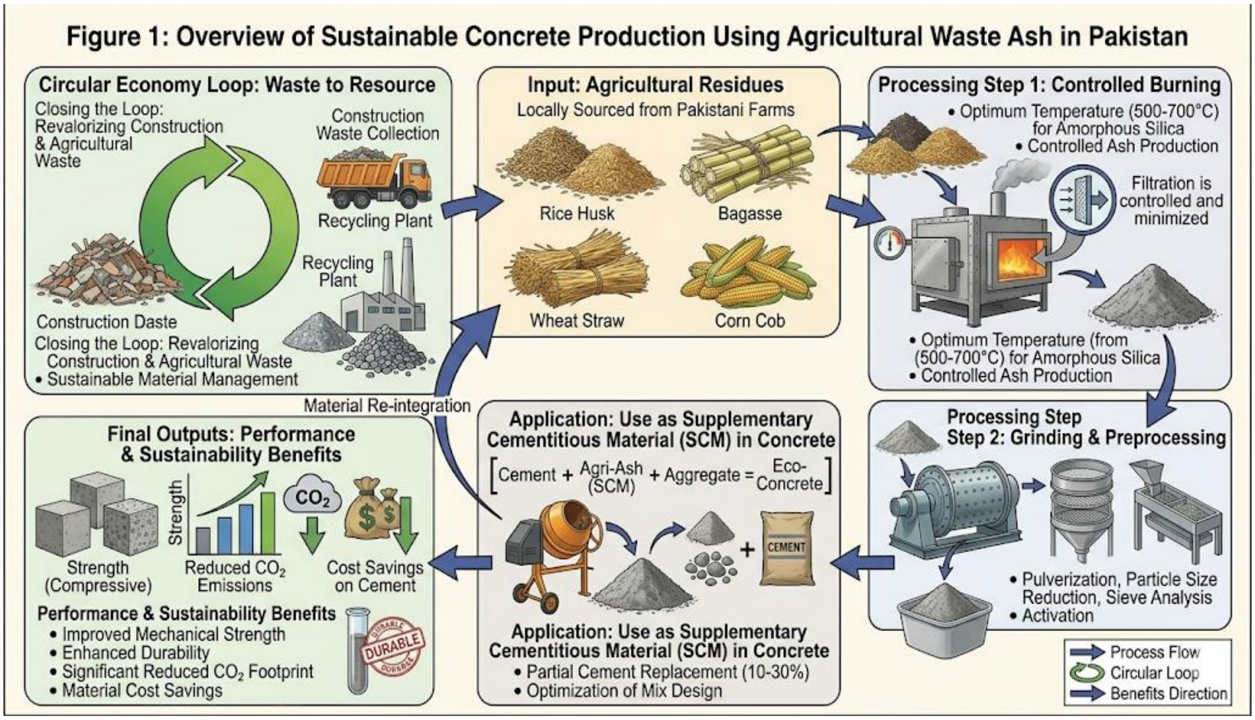


Figure 1: Overview of Sustainable Concrete Production Using Agricultural Waste Ash in Pakistan

2. Environmental Degradation and the Imperative for Sustainable Transition

The impact of the cement industry extends beyond atmospheric carbon. Proximity to cement manufacturing facilities in regions like Punjab has been linked to significant soil pollution. Investigations have identified elevated levels of heavy metals, including Lead (Pb), Zinc (Zn), Cadmium (Cd), and Chromium (Cr), in the surface soils within 500 meters of operational plants (Ismail et al., 2017). These contaminants impair plant growth by reducing chlorophyll content and altering soil physical properties, such as alkalinity and water retention capacity (Usman et al., 2023). This degradation underscores the urgent need for a transition toward the Circular Carbon Economy (CCE) framework, which seeks to balance growth with climate responsibility by incorporating "Reduce, Reuse, Recycle, and Remove" strategies (Munir et al., 2024).

In response to these challenges, the industry has begun exploring new levers for decarbonization. These include reducing the clinker-to-cement ratio through the use of supplementary cementitious materials (SCMs), adopting alternative binders, and implementing waste-heat recovery (WHR) and solar power systems (Sherif et al., 2025). Major companies have already shifted toward captive power and renewable energy sources, with Lucky Cement operating a 42.8 MW solar plant at Pezu (Okeke et al., 2024). However, the most promising avenue for widespread impact lies in the utilization of Pakistan's vast agricultural residues as sustainable alternatives to traditional cement components (Khan et al., 2025).

3. Agricultural Biomass: An Abundant and Underutilized Resource

As a primarily agrarian economy, Pakistan generates an enormous quantity of biomass waste annually. The primary crops wheat, rice, sugarcane, and corn yield approximately 112.1 million tons of residue per year (Kashif et al., 2020). Historically, these residues have been treated as waste, often discarded in landfills or burned in open fields, a practice that contributes significantly to seasonal smog and environmental degradation (Doğruyol & Çetin, 2025).

The potential for utilizing these residues as supplementary cementitious materials is rooted in their chemical composition. When agricultural wastes are subjected to controlled incineration, they produce ash rich in amorphous silica (SiO_2), which acts as a highly reactive pozzolan (Sindhushree, 2025).

3.1 Rice Husk and Bagasse Production Dynamics

The availability of these materials is seasonal but centralized at processing mills, facilitating collection. Rice production in Pakistan has consistently exceeded 9 million tons, with forecasts for 2025/26 reaching 9.8 million tons (USDA, 2025). Since approximately 25% of the rice husk weight is converted to ash upon complete combustion, the potential for Rice Husk Ash (RHA) production is substantial (Rambabu et al., 2015). Similarly, Pakistan is a major global sugarcane producer, contributing 87.6 million tons of cane in the 2023-24 cycle. For every ton of sugarcane, approximately 6.6 kg of Sugarcane Bagasse Ash (SCBA) is produced, leading to a potential of 0.578 million tons of SCBA annually (Ullah et al., 2025).

Table 2: Regional Distribution and Annual Volume of Major Agricultural Residues

Agricultural Residue	Annual Production (Approx. Million Tons)	Derived Ash Product	Estimated Ash Volume (Mt)	Primary Regional Source
Rice Husk	1.15 - 2.4	Rice Husk Ash (RHA)	0.3 - 0.6	Punjab (North), Sindh
Sugarcane Bagasse	24.0 - 26.0	Bagasse Ash (BA/SCBA)	~0.578	Punjab, Sindh, KPK
Wheat Straw	27.5 - 31.5	Wheat Straw Ash (WSA)	Significant	Punjab (Barani/Irrigated)
Corn Stover	~9.5	Corn Cob Ash (CCA)	Unknown	Punjab, KPK

The regional distribution of these resources aligns with the high-demand construction zones in the North. Sugarcane production is concentrated in Punjab (67%) and Sindh (26%). This geographic proximity between agricultural production and cement clusters presents a unique logistical opportunity for a localized bio-waste-to-cement supply chain (Sitnicki et al., 2024).

4. The Chemical Kinetics of Agricultural Waste Ash (AWA)

The fundamental premise of using Agricultural Waste Ash (AWA) in concrete is the pozzolanic reaction. Unlike Ordinary Portland Cement (OPC), AWA acts as a pozzolan, containing high amounts of amorphous silica that react with calcium hydroxide (Ca(OH)_2), a byproduct of cement hydration, to form additional Calcium Silicate Hydrate (C-S-H) gel (Muneer et al., 2025).

4.1 Pozzolanic Reaction Mechanism

The reaction converts portlandite into dense C-S-H gel, which fills the capillary pores of the concrete matrix. This microstructural refinement leads to a reduction in permeability and a denser interfacial transition zone between the aggregate and the paste (Al-Saffar et al., 2023). The reactivity of the ash depends critically on the incineration process; for RHA, the optimal combustion temperature is around 600°C to 700°C to ensure the silica remains amorphous (Zhu, 2021).

4.2 Comparative Physio-chemical Analysis

Table 3: Chemical and Physical Properties of Selected Supplementary Cementitious Materials

Chemical/Physical Property	Rice Husk Ash (RHA)	Sugarcane Bagasse Ash (SCBA)	Wheat Straw Ash (WSA)	Ordinary Portland Cement
Silica (SiO_2) Content	85% - 95%	60% - 75%	65% - 67%	~20%
Alumina (Al_2O_3)	~10%	~12%	~5%	~5%
Calcium Oxide (CaO)	~12.5%	~2% - 5%	~8%	~63%
Specific Gravity	2.44	1.99 - 2.1	~2.0	3.15

Particle Size (Avg)	~25 microns	Variable	~25 microns	~10 - 15 microns
Reactivity Index	Very High	High	Moderate-High	Hydraulic (Direct)

Research has emphasized that controlled burning in simple incinerators could produce ash with only 4% loss on ignition, indicating high carbon burnout and excellent pozzolanic quality. Optimized concrete mixes often focus on specific environmental goals, such as reducing the carbon footprint of materials during the initial construction phase (Beyer, 2025).

5. Mechanical Performance and Structural Integrity of AWA Concrete

The integration of AWA as a partial replacement for cement has demonstrated significant impacts on mechanical properties, ranging from standard M30 grade to Ultra-High-Performance Concrete (UHPC). Research suggests that replacement levels between 10% and 20% are optimal (Mangi et al., 2017).

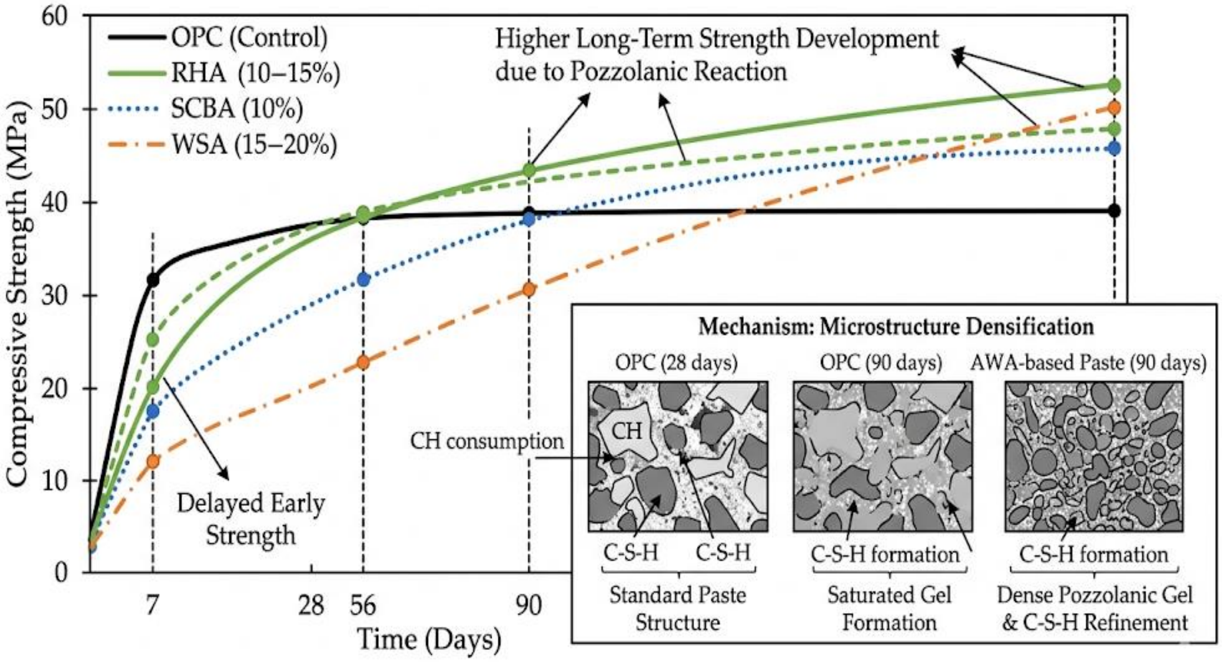
5.1 Strength Development Curves

Concrete containing AWA typically exhibits a different gain profile compared to conventional OPC concrete.

- **RHA Concrete:** Studies indicate that a 10% replacement can increase 28-day compressive strength by 16.14% and indirect tensile strength by 15.20% (Ali et al., 2024).
- **SCBA Concrete:** The incorporation of 10% SCBA has been confirmed as a favorable option, providing enhanced strength while reducing CO_2 emissions (Ullah et al., 2025).
- **WSA Concrete:** Substituting 15% of cement with WSA has shown to increase compressive strength at 28 and 91 days; even at 20% replacement, the strength of WSA concrete eventually exceeds that of the control at the 91-day mark (Doğruyol & Çetin, 2025).

Concrete incorporating agricultural waste ash exhibits a distinct strength development pattern compared to conventional mixes. A comparative trend of strength gain over time is presented in Figure 2.

Figure 2: Compressive Strength Development of AWA-Based Concrete Compared to OPC



5.2 Stress-Strain Behavior and Ductility

The use of agricultural ashes has been linked to improvements in concrete's toughness and ductility. For WSA-based concrete, mixes with 15% to 20% replacement levels exhibited stiffness and toughness comparable to control samples, with notable improvements in ductility at 91 days (Amin et al., 2019).

Table 4: Summary of Mechanical Enhancements by AWA Type

Replacement Material	Optimal Substitution	Strength Outcome (at 28+ Days)	Additional Benefit	Source
RHA	10% - 15%	16% Increase	Refined Pore Structure	(Ali et al., 2020)
SCBA	10%	Significant Increase	Reduced Alkali-Silica Reaction	(Ullah et al., 2025)
WSA	15% - 20%	Surpasses Control at 91d	Higher Ductility/Toughness	(Amin et al., 2019)
POA (Palm Oil Ash)	30%	17.5 MPa vs 15 MPa (Control)	Waste Diversion	(Asif et al., 2025)

The workability of fresh AWA concrete is generally reduced because the high specific surface area and porous nature of the ash increase water demand. SCBA pushes initial setting times from 97 minutes to 114–187 minutes as replacement increases (Memon et al., 2022).

6. Durability in Aggressive Environments

Agricultural waste ashes significantly enhance the durability of concrete through microstructural densification and chemical stabilization (Sindhushree, 2025).

6.1 Resistance to Chloride Ingress and Sulfate Attack

One of the most critical durability enhancements is the reduction in chloride ion permeability. Sustainable UHPC mixes developed in Pakistan have shown a 93% reduction in chloride permeability (Akbar et al., 2025). Specifically, SCBA replacement at 10% can reduce chloride penetration by up to 45% compared to OPC. This improvement is attributed to the formation of secondary hydrates that block capillary pores. Similarly, AWA-based concrete demonstrates superior resistance to scaling and leaching from acids due to the reduction in portlandite content (Sohail et al., 2021).

6.2 Alkali-Silica Reaction (ASR) Mitigation

Pakistani research has confirmed that locally available SCBA effectively reduces expansion resulting from the alkali-silica reaction by binding alkalies within the hydration products. This allows for the safer use of certain local aggregates that might otherwise be deemed reactive (Amjad et al., 2025).

6.3 The "Sponge Effect" and Carbonation Resistance

An emerging area of research is natural carbonation, or the "sponge effect," where concrete acts as a passive CO_2 sink. Research indicates this could eliminate up to 30% of total cumulative cement effects for the years 2020–2030 (Cao et al., 2025). However, SCMs like SCBA must be balanced; high replacement levels can initially lead to higher carbonation depths due to reduced calcium hydroxide, although long-term resistance improves through matrix densification (Chen, 2025).

7. Economic Assessment and Life-Cycle Efficiency

The economic viability of transitioning to AWA concrete is underpinned by the rising cost of cement and the low cost of agricultural residues. As of 2026, the price of a standard 50kg bag of cement in Pakistan ranges from Rs. 1,405 to Rs. 1,490 (Knudsen, 2026).

7.1 Cost-Analysis of Cement Alternatives

Substitution offers direct savings; a 10% SCBA replacement level provides a 3.96% reduction in volumetric cost, while 15% offers a 6.05% reduction. In specialized applications, replacing 10% of cement or aggregates with processed agro-waste can reduce overall costs by as much as 35% (Khan et al., 2025).

Table 5: Market Comparison of Construction Materials (2025-2026 Projections)

Material Component	Average Rate (PKR) / Potential Saving	Unit	Updated Status
DG Khan Cement	1,415 - 1,425	50kg Bag	2026 Projections
Lucky Cement	1,380 - 1,390	50kg Bag	2026 Projections
Maple Leaf White	2,150 - 2,250	40kg Bag	2026 Projections
Margalla Crush	120.00	Cubic Ft	Feb 2025
RHA (Gardening Ref)	136.00 - 350.00	1kg	Retail Base
SCBA Replacement (10%)	~4% Net Saving	m^3 Concrete	(Ullah et al., 2025)

7.2 Life-Cycle Cost Analysis (LCCA)

While the initial cost of sustainable UHPC may be 2.2 times higher than conventional concrete, UHPC becomes more economical after 35 years due to reduced repair cycles. The overall cost saving over 100 years is estimated at 24% for Pakistan’s infrastructure (Issa & Afolabi, 2023).

8. Policy, Standards, and Regulatory Frameworks

The Ministry of Climate Change and the Pakistan Engineering Council. have collaborated to establish the Green Building Code of Pakistan 2023 (Bashir et al., 2024).

8.1 Green Building Code of Pakistan 2023 (GBCP-2023)

The GBCP-2023 is modeled after the 2021 International Green Construction Code and provides benchmarks for resilient design. Salient features include the encouragement of sustainable materials and specific energy provisions modeled after the Energy Conservation Building Code 2023 (Murtagh et al., 2020).

9. Socio-Economic and Logistical Barriers to Adoption

Barriers include internal organizational resistance and structural logistical deficits (Carpejani et al., 2020).

9.1 Logistical and Data Deficits

The primary challenge is the lack of real-time data on waste generation. While mills produce massive quantities of ash, there is no standardized system for collection and distribution (Kabugo et al., 2020).

9.2 Market and Perceptual Barriers

Surveys highlight a lack of awareness regarding the advantages of green building practices. This is compounded by a reliance on antiquated techniques and high initial investment costs for smaller firms (Sherif et al., 2025).

Table 6: Summary of Barriers and Proposed Mitigation Strategies

Barrier Category	**Specific Challenge in Pakistan**	**Potential Mitigation Strategy**
Policy	Lack of mandatory codes & incentives	Enforcement of GBCP-2023 & tax rebates
Logistical	Weak supply chain & inconsistent data	Establishment of regional bio-waste hubs
Technical	Variability in ash quality/composition	Standardization of incineration & grinding
Awareness	Limited knowledge of SCM benefits	Public awareness campaigns & certifications
Economic	High initial processing/setup costs	Public-private partnerships & carbon credits

10. Innovative Applications: Sugarcrete® and Bio-Bricks

Beyond its role as a cement replacement in structural concrete, agricultural waste is being utilized to develop novel building components that further support the circular economy. This includes Sugarcrete®, a low-carbon alternative for semi-structural applications, and lightweight clay bricks incorporating RHA or SBA to reduce structural density by up to 77% (Amjad et al., 2025).

11. Recommendations for Industrial Scaling and Sustainable Practice

To realize the full potential of agricultural waste ash in Pakistan's construction industry, the establishment of a Regulatory Framework for Sustainable Agricultural Waste Management is recommended to restrict open burning while providing subsidies for residue collection (Okeke et al., 2024). Secondly, centralized "Bio-Processing Hubs" should be established near industrial clusters (Khan et al., 2025).

Conclusion

Incorporating agricultural waste ashes as supplementary cementitious materials and fine aggregate substitutes offers Pakistan a practical, regionally tailored pathway to decarbonize concrete production while addressing dual challenges of agricultural residue disposal and resource-intensive cement manufacturing. The high silica content and pozzolanic reactivity of RHA and SCBA, when properly processed, deliver concrete with enhanced mechanical properties, superior durability, and significantly lower environmental footprints achieving 15–40% reductions in GWP and energy demand per cubic meter compared to conventional mixes. These benefits are amplified by economic advantages: reduced cement consumption, lower disposal costs, and potential revenue from ash valorization, making the approach particularly viable in Punjab and Sindh where rice and sugarcane residues are abundant. Despite variability in ash quality, supply seasonality, and technical barriers (e.g., grinding requirements, ASR risk), controlled combustion, standardized preprocessing, and mix design optimization can ensure consistent performance suitable for structural and non-structural applications. Widespread adoption, however, hinges on policy enablers updating Pakistan Building Code to permit higher SCM levels, incentivizing ash collection and processing through subsidies or carbon credits, mandating green procurement in public projects, and establishing quality certification protocols. By scaling agricultural waste ash utilization, Pakistan can simultaneously reduce open-field burning emissions, conserve limestone and energy resources, lower construction costs, and align the cement/construction sector with national climate commitments and circular economy goals. This transition not only strengthens environmental sustainability and economic resilience but also positions the industry as a model of resource-efficient development in a resource-constrained, rapidly urbanizing emerging economy.

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