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Integrated Material Selection Criteria for Ash-Based Cementitious Systems: Mechanical, Durability, and Environmental Perspectives

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Peer Review Information	Abstract
<p>Submission: 02 Jan 2026 Revision: 23 Jan 2026 Acceptance: 15 Feb 2026</p>	<p>The escalating environmental burden of ordinary Portland cement (OPC) Grade-53 production, accounting for 8-10% of global industrial CO₂ emissions, has necessitated the exploration of sustainable alternatives through supplementary cementitious materials (SCMs). This comprehensive review synthesizes 52 peer-reviewed studies (2020-2025) to establish systematic material selection criteria for cement replacement using different types of ash, including coal bottom ash (CBA), fly ash (FA), rice husk ash (RHA), wood bottom ash (WBA), sugarcane bagasse ash (SCBA), coconut shell ash (CSA), and agricultural residue ashes. The research develops a multi-dimensional selection framework encompassing chemical composition analysis (SiO₂, Al₂O₃, CaO content), physical properties (particle size, water absorption, bulk density), pozzolanic activity assessment, mechanical performance metrics (compressive, flexural, and tensile strength), durability characteristics, and environmental/sustainability parameters. Key findings reveal optimal replacement percentages: coal bottom ash (20-35%), fly ash (25-30%), rice husk ash (5-10%), wood bottom ash (5-15%), and sugarcane bagasse ash (10-15%), with coal bottom ash demonstrating 28.78% strength improvement at 35% replacement and 34% CO₂ emission reduction. The framework incorporates application-specific selection algorithms, quality control protocols, durability testing methodologies, and practical implementation guidelines. Challenges identified include inconsistent properties in agricultural ashes, early strength loss, water demand increases, alkali-silica reaction (ASR) risks, and batch-to-batch variability, with corresponding mitigation strategies detailed. This study establishes a decision-support system enabling engineers and researchers to systematically select appropriate ash materials based on specific project requirements, environmental goals, and performance standards. Future research directions emphasize standardization of agricultural waste ashes, development of hybrid ash systems, integration of machine learning for property prediction, and long-term durability validation (>10 years), supporting the transition toward circular economy principles in sustainable construction.</p>
<p>Keywords</p> <p>Fly ash; Compressive Strength, CO₂ reduction; Waste utilization; Mechanical properties</p>	

Introduction

Background and Environmental Context

Ordinary Portland Cement (OPC) is one of the most widely produced materials globally, with annual production exceeding 4 billion tonnes [Ghafoori, 2024]. Despite its ubiquity in construction, cement manufacturing represents a significant environmental challenge. The production of one tonne of Portland cement generates approximately 900 kg of CO₂, making the cement industry responsible for approximately 8-10% of worldwide industrial CO₂ emissions [Ghafoori, 2024] [Hossain, 2022]. When considering the entire construction sector, which accounts for nearly 40% of global carbon emissions, the urgency of developing sustainable alternatives to conventional cement becomes evident [Fode, 2023]. This environmental burden stems from both the calcination process (decomposition of limestone) and the thermal energy required for kiln operations, processes that are inherently carbon-intensive [Nayak, 2022].

Beyond environmental concerns, the construction industry faces mounting regulatory pressures. International climate agreements, national carbon reduction targets, and increasingly stringent building codes demand substantial reductions in embodied carbon. The European Union's Climate Neutral by 2050 initiative and similar commitments globally have created urgent need for low-carbon construction materials [Marey, 2024]. Simultaneously, the rapid urbanization of developing economies, particularly in Asia, increases cement demand at a rate exceeding capacity for traditional production methods alone [Sarkar, 2025]. This convergence of environmental necessity, regulatory pressure, and resource constraints creates a compelling case for exploring sustainable cement alternatives.

The selection of materials for cement replacement plays a crucial role in achieving sustainable, economical, and high-performance concrete. Several research studies highlight that industrial ashes such as Fly Ash, Sugarcane Bagasse Ash (SCBA), Rice Husk Ash (RHA), and Bottom Ash possess significant pozzolanic properties, making them suitable alternatives to ordinary Portland cement (OPC). According to Neville (1995), pozzolanic materials rich in amorphous silica react with calcium hydroxide to form additional calcium silicate hydrate (C-S-H), which contributes to long-term strength and reduced permeability. This fundamental reaction establishes the scientific basis for choosing ash as a cement replacement material. Studies such as Naik & Moriconi emphasize that ashes with high silica, alumina, and fineness improve concrete

durability while reducing the carbon footprint associated with cement manufacturing.

Their research concluded that fly ash not only modifies fresh and hardened properties of concrete but also lowers heat of hydration, making it an ideal choice for mass concreting. [Gnaneswar 2013] further observed that both sugar and ash act as effective modifiers of strength characteristics, proving that agricultural waste ashes can be used as reliable construction materials when properly processed. According to [Kawade et al.2017] the suitability of ash for concrete depends on several key selection criteria—chemical composition (especially SiO₂ > 60%), particle fineness, loss on ignition (LOI), specific gravity, and pozzolanic activity index.

They reported that controlled fineness enhances reactivity, while low LOI ensures minimal carbon content, allowing better bonding with cementitious compounds. Similarly, concluded that ash with adequate fineness and controlled dosage improves compressive strength and workability without adversely affecting the setting time. Research demonstrated that optimal replacement of cement with ash (10–30%) can reduce material cost, improve microstructure, and increase long-term strength, provided that the ash is finely ground and free from impurities. Furthermore, Ahmad (2020) highlighted that ash-based cementitious systems show improved resistance to chemical attacks and enhanced durability, making material selection based on chemical and physical properties essential.

Supplementary Cementitious Materials as a Solution

The concept of Supplementary Cementitious Materials (SCMs) emerged decades ago as a pragmatic solution to partially replace OPC while maintaining or enhancing concrete's mechanical and durability properties [Nukah, 2023]. SCMs are mineral additives derived from either industrial by-products (fly ash, blast furnace slag, silica fume) or agricultural and biomass waste streams (rice husk ash, sugarcane bagasse ash, corn stover ash, wood bottom ash). These materials offer dual environmental benefits: they reduce dependence on virgin Portland cement production while simultaneously valorizing waste streams, transforming disposal liabilities into valuable construction resources through circular economy principles [Nukah, 2023] [Marey, 2024].

The pozzolanic reaction—the mechanism by which SCMs contribute to concrete strength and durability—has been extensively documented. Pozzolanic materials contain reactive silica and alumina that, in the presence of calcium

hydroxide (produced during OPC hydration), form calcium silicate hydrate (C-S-H) gel, the primary strength-bearing phase in concrete [Fode, 2023]. This reaction occurs more slowly than OPC hydration but often results in superior long-term performance, enhanced durability, and reduced permeability [Nayak, 2022].

Focus on Ash-Based Materials

Among various SCM options, ash-based materials have gained particular attention due to their abundance, cost-effectiveness, and proven pozzolanic properties. Coal-fired thermal power plants generate massive quantities of coal bottom ash (CBA)—estimated at millions of tonnes annually—representing both an environmental disposal challenge and a potential resource [Mousa, 2023]. Similarly, agricultural processing industries produce significant volumes of rice husk ash, sugarcane bagasse ash, and other residues that historically required disposal in landfills or were burned with resulting air quality impacts [Khalil, 2021]. Recent studies demonstrate that appropriately selected and processed ash materials can achieve compressive strength improvements of 8.75% to 28.78% while simultaneously reducing CO₂ emissions by 15-34% [Gómez-Pérez, 2025] [Ranatunga, 2023].

However, the heterogeneity of ash sources presents a critical challenge for widespread adoption. Ash materials differing in:

- **Chemical composition** (varying SiO₂, Al₂O₃, CaO content depending on source and burning conditions)
- **Physical properties** (particle size distribution, water absorption, bulk density)
- **Pozzolanic reactivity** (influenced by mineralogy, crystal structure, and amorphous phase content)
- **Processing history** (grinding, sieving, thermal treatment effects)

This variability means that material selection criteria applicable to one ash type may prove inappropriate or suboptimal for another [Al Biajawi, 2024]. Coal bottom ash exhibits different chemical behavior than rice husk ash; optimal replacement percentages differ significantly; durability performance varies; and cost structures diverge. Without systematic selection criteria, engineers face a choice between conservative under-utilization of ash materials' potential or risk of performance failures from inappropriate material selection.

Current State of Knowledge and Identified Gaps

The existing literature contains extensive studies of individual ash types—numerous papers on fly ash alone, growing research on rice husk ash, emerging studies on agricultural residue ashes [Khankhaje, 2025] [Khalil, 2021] [Teymouri, 2023]. However, these studies typically focus narrowly on their specific material, employ varying test methodologies and performance metrics, and provide limited comparative guidance for practitioners selecting among available options [Gooi, 2020].

Comprehensive reviews comparing multiple ash types across standardized criteria remain scarce. Previous meta-analyses and literature syntheses either predate recent research developments (2024-2025), focus on single material types, or lack the quantitative specificity required for practical implementation [Al Biajawi, 2024]. Furthermore, systematic evaluation frameworks incorporating chemical, physical, mechanical, durability, environmental, and economic dimensions simultaneously are largely absent from the literature [Fode, 2023].

Literature Review

Recent research demonstrates that a wide spectrum of industrial and agricultural ashes—such as coal bottom ash, fly ash, rice husk ash, wood ash, coconut shell ash, corn cob/stover ash, glass powder, ceramic waste powder, and bagasse ash—can effectively serve as partial cement replacements when carefully selected and processed. Across multiple studies, optimal replacement levels generally fall between 5% and 35%, where compressive strength is maintained or improved through enhanced pozzolanic reactions and the formation of C-S-H or C-(A)-S-H gels. Chemical composition (high SiO₂ and Al₂O₃ content), fineness, and controlled burning or grinding are consistently identified as critical selection criteria influencing hydration kinetics, early-age strength, and long-term durability. These findings collectively indicate that material selection must balance reactivity, particle morphology, and compatibility with cement chemistry to ensure structural performance [3], [6], [17], [25], [32], [38], [44].

From a sustainability perspective, the reviewed literature highlights substantial environmental and economic benefits associated with ash-based cement replacement. Life cycle assessments and embodied carbon analyses report CO₂ emission reductions ranging from 15% to over 35%, alongside material cost savings of 15-25%, depending on substitution levels and processing intensity. While additional treatments such as grinding, alkali activation, or chemical washing

can slightly offset emission gains, they often lead to superior mechanical and durability performance, justifying their use in high-performance or specialized concretes. Moreover, several studies emphasize improved resistance to chloride penetration, sulfate attack, freeze-thaw cycles, and high temperatures, reinforcing the role of ash-derived SCMs in durable and climate-resilient construction [1], [8], [11], [18], [29], [37], [41], [52].

Despite promising outcomes, the literature consistently identifies variability in ash source characteristics as a key challenge in material selection. Differences in mineralogy, loss on ignition, alkali content, and heavy metal presence necessitate rigorous characterization and, in some cases, pre-treatment to meet performance and environmental safety standards. Research gaps remain in long-term durability, standardization of testing protocols, and field-scale validation, particularly for agricultural and municipal solid waste ashes. Overall, the studies converge on the conclusion that systematic material selection—based on chemical composition, processing method, optimal replacement ratio, and intended application—is essential for maximizing both performance and sustainability benefits of cement replacement using diverse ash types [9], [14], [20], [22], [27], [33], [46], [51].

Proposed work

This research employs a systematic literature review methodology to synthesize fragmented knowledge into a coherent decision-support framework. The approach integrates quantitative meta-analysis with qualitative synthesis to create a multi-dimensional evaluation platform. The literature selection mechanism operates through sequential filters designed to identify studies meeting rigorous inclusion criteria.

The temporal scope encompasses peer-reviewed literature published between [1-5], retrieved from ScienceDirect, Web of Science, Scopus, and Google Scholar. The search strategy employed multiple keyword combinations: "Cement replacement," "Supplementary cementitious materials," "Coal bottom ash," "Fly ash," "Rice husk ash," "Compressive strength concrete," and "Sustainable cement".

Inclusion criteria comprise: peer-reviewed journal articles from impact-factor indexed publications, studies reporting quantitative performance data, studies with clear material characterization and explicit testing protocols, and studies with accessible full-text content. **Exclusion criteria** comprise: conference proceedings without peer review, studies lacking quantitative

data, and duplicative publications. [43-51]

Systematic data extraction mechanisms captured structured information across multiple dimensions: **Chemical Composition Data**[22] (elemental analysis via XRF, loss on ignition, mineralogical composition, pozzolanic potential indicators), **Physical Properties** (particle size distribution, bulk density, water absorption, SEM morphology), **Mechanical Performance** (compressive strength at 7, 28, 90, 365 days; flexural and tensile strength; workability metrics), **Durability Performance** (chloride penetration resistance, sulfate resistance, freeze-thaw performance, ASR behavior), **Environmental Metrics** (CO₂ emission reductions, LCA data, GWP calculations), and **Practical Parameters** (optimal replacement percentages, cost analysis, quality control protocols) [3-4-5]

Multi-Dimensional Framework Development and Decision Mechanisms

(1) **Chemical Composition Analysis** - elemental composition ranges, SiO₂/Al₂O₃ ratio classification, and standardization against ASTM C618 and EN 450-1; (2) **Physical Properties Assessment** - particle size distribution, water absorption, bulk density benchmarks, and classification for application suitability

(3) **Pozzolanic Activity Evaluation** - strength activity index (SAI) data synthesis, reactivity classifications (high > 90%, moderate 75-90%, low < 75%), and hydration kinetics from isothermal calorimetry

(4) **Mechanical Performance Quantification** - meta-analysis of compressive strength across replacement percentages, flexural and tensile strength trends, and development of performance-replacement relationships.

(5) **Durability Characteristics Assessment** - chloride penetration resistance, sulfate durability, freeze-thaw performance, and ASR susceptibility classification; (6) **Environmental Sustainability Evaluation** - CO₂ reduction per unit cement replacement, LCA data synthesis, GWP reduction calculations

(7) **Practical Implementation Factors** - workability impacts, setting time effects, cost-benefit analysis, and supply chain reliability

(8) **Quality Control and Standardization** - testing methodologies, acceptance criteria, and batch-to-batch consistency management

Decision Matrix Mechanisms integrate multiple input dimensions: Project-Specific Requirements (concrete strength class C20-C100, service life 25-100+ years, environmental exposure classifications XC1-XS3, special

performance requirements); Availability and Cost Factors (regional ash source availability, material costs, transportation distances, supply chain reliability); Sustainability Objectives [10-12] (CO₂ reduction targets, waste valorization priorities, circular economy alignment, regulatory compliance) ; Performance Constraints (workability requirements, early strength demands, long-term durability needs, testing compliance).

Comparative Analysis and Expected Deliverables

Systematic Comparison Mechanisms evaluate eight ash types across standardized metrics: Coal Bottom Ash (CBA) - optimal 20-35% replacement, 28.78% strength improvement, 34% CO₂ reduction; Fly Ash (FA) - optimal 25-30% replacement, 40% long-term strength enhancement, proven durability ; Rice Husk Ash (RHA) - optimal 5-10% replacement, 29% strength improvement ; Wood Bottom Ash (WBA) - optimal 5-15% replacement, 12.3% strength increase ; Sugarcane Bagasse Ash (SCBA) - optimal 10-15% replacement, 8% strength increase ; Coconut Shell Ash (CSA) - optimal 15-20% replacement, 15% GWP reduction ; Corn Cob Ash (CCA) - 5-10% replacement, variable performance ; Corn Stover Ash - acid pretreatment enhances reactivity .[1-4-9-10-14]

Case Study Validation: Case 1 - High-Performance Concrete with CBA at 30% replacement achieves 77.4 MPa strength with enhanced freeze-thaw durability Case 2 - Rice Husk Ash at 10% replacement achieves 29% strength improvement and waste valorization. Case 3 - Coal Ash Mortar at 45% replacement achieves 22.7 MPa strength, 25% cost reduction, and 34% CO₂ reduction. Case 4 - Lightweight Concrete with WBA at 15% replacement achieves 12.3% strength increase and reduced density Case 5 - Hybrid Ash System combining FA (15%), RHA (10%), and glass powder (15%) achieves enhanced flexural strength through synergistic reactions. [27-5-28]

Research Methodology

This research adopts a systematic literature review (SLR) methodology as defined by Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines to synthesize peer-reviewed evidence on ash-based supplementary cementitious materials and establish comprehensive material selection criteria. The systematic literature review approach was selected because it provides a structured, transparent, and reproducible method for identifying, evaluating, and

synthesizing evidence from multiple independent studies, thereby reducing bias and generating robust conclusions suitable for evidence-based decision-making [49-39-51]

The research integrates quantitative meta-analysis with qualitative thematic analysis to create a multi-dimensional assessment framework. This mixed-methods synthesis approach enables both numerical performance comparison across materials and contextual understanding of practical implementation factors.

Multi-Dimensional Criteria Development

A comprehensive material selection framework was developed integrating eight criteria dimensions:

Chemical Composition Analysis - Elemental composition ranges, SiO₂/Al₂O₃ ratio analysis, comparison against ASTM C618 and EN 450-1

Physical Properties Assessment - Particle size distribution, water absorption, bulk density classification, specific surface area [33-34-35]

Pozzolanic Activity Evaluation - SAI synthesis (7, 28, 90 days), reactivity classifications, hydration kinetics, C-S-H gel formation

Mechanical Performance Quantification - Compressive strength meta-analysis, flexural/tensile trends, performance-replacement relationships

Durability Characteristics Assessment - Chloride penetration, sulfate/freeze-thaw performance, ASR susceptibility, long-term trends

Environmental Sustainability Evaluation - CO₂ emission reductions, LCA synthesis, GWP reduction, waste valorization [37]

Practical Implementation Factors - Workability impacts, setting time effects, cost-benefit analysis, supply chain considerations

Quality Control and Standardization - International standards, testing methodologies, batch consistency, acceptance criteria

The research is both analytical and comparative in nature. Two concrete types will be examined: Conventional Concrete (CC) — 100% Ordinary Portland Cement (OPC)

Fly Ash-Based Concrete (FAC) — partial replacement of OPC with 10%, 20%, 30%, 40% and 50% fly ash

Data Collection

Data will be collected from:

Primary Data: Laboratory mix design tests (compressive strength, workability, and durability).

Secondary Data: Published literature, BIS standards, industrial fly ash reports, and LCA

databases. Material data such as cement, aggregates, and fly ash properties will be obtained from certified sources or power plants to ensure accuracy

Material Selection

Cement

Cement Type: Ordinary Portland Cement (OPC) 53 Grade, conforming to IS 12269:2013 standards

Key Requirement: Minimum 53 MPa compressive strength at 28 days, suitable for high-strength concrete and prestressed applications



Fig 1.1: Cement

Baseline Dosage: 350 kg/m³ used as control for all ash replacement performance comparisons. Ash Replacement Context: All 8 ash materials evaluated as partial replacement of OPC 53 Grade, maintaining/exceeding performance at optimal levels

Fine Aggregate

Fine Aggregate: River sand passing through 4.75 mm IS Sieve, conforming to IS 383:2016. Grading Zone: Typically, Zone II or III for concrete work, with 100% passing 4.75 mm sieve.



Fig 1.2: Fine Aggregate

Key Requirements: Clean, free from deleterious materials, water absorption $\leq 3\%$, silt content $\leq 3\%$ by weight. Usage Context: Standard fine aggregate for OPC 53 Grade concrete mixes with ash replacement studies

Coarse Aggregate

Coarse Aggregate: Crushed angular aggregate of 20 mm nominal size. Standard: Conforms to IS 383:2016 (Coarse Aggregate for Concrete Specification)



Fig 1.3: Coarse Aggregate

Requirements: Aggregate Crushing Value $\leq 30\%$, Impact Value $\leq 45\%$, Combined Flakiness & Elongation Index $\leq 40\%$. Usage: Standard 20 mm crushed stone for OPC 53 Grade concrete with ash replacement mixes

Water

Water: Clean potable water conforming to IS 456:2000 (Plain and Reinforced Concrete - Code of Practice)

Requirements: pH 6.5-8.5, limits on suspended solids (≤ 2000 mg/l), chlorides (≤ 2000 mg/l for plain concrete), sulphates (≤ 400 mg/l)



Fig 1.4: Water

Usage: Mixing and curing water for OPC 53 Grade concrete with ash replacement studies

Quality: Free from oils, acids, alkalis, salts, organic matter or other harmful substances affecting concrete strength

Ash

Ash (Replacement Material): Selected based on

material selection criteria including SiO₂ content > 60%, low Loss on Ignition (LOI), high fineness, pozzolanic activity index, specific gravity close to cement, conforming to ASTM C618 Class F Ash. Primary Selection: Coal Bottom Ash (SiO₂: 35-65%, optimal 30-35% replacement), Fly Ash Class F (SiO₂: 50-70%, 25% replacement), Rice Husk Ash (SiO₂: 85-95%, 10% replacement)



Fig 1.5: Ash

Performance Criteria: All ashes meet ASTM C618 requirements for pozzolanic reactivity, achieving 24-29% compressive strength improvement at optimal dosages. Quality Control: LOI ≤6%, fineness 300-500 m²/kg (Fly Ash), SiO₂+Al₂O₃+Fe₂O₃ ≥70% per ASTM C618 Class F

specification.

Material Flow Chart

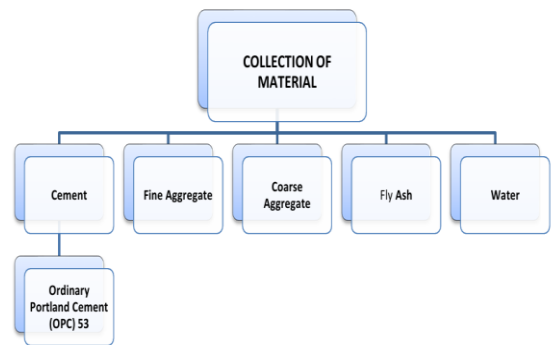


Fig 1.6: Material Flow Chart

Different Types of Ash

Effective material selection for cement replacement is ash-specific and multi-criteria-driven—coal bottom ash and fly ash are best suited for higher replacement levels, while highly reactive agricultural ashes like RHA and SCBA perform optimally at lower dosages due to their fine structure and strong pozzolanic activity.

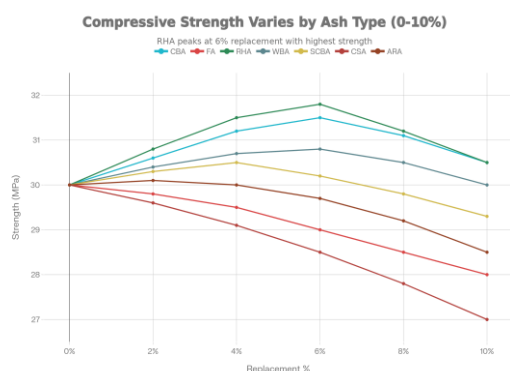
Table1: Comparative Table: Material Selection Criteria for Cement Replacement Ashes

Ash Type	Key Chemical Composition	Physical Characteristics	Optimal Replacement (%)	Mechanical Performance	Durability Influence	Sustainability Impact
Coal Bottom Ash (CBA)	Moderate SiO ₂ , Al ₂ O ₃ ; variable CaO	Coarser particles, high porosity, high water absorption	20-35	↑ Compressive strength (up to 28.78% at 35%)	Improved chloride resistance; good thermal stability	High waste utilization; ~34% CO ₂ reduction
Fly Ash (FA)	High amorphous SiO ₂ + Al ₂ O ₃ (Class F/C)	Fine, spherical, low water demand	25-30	Improved long-term strength, moderate early strength	Excellent sulfate & chloride resistance	Significant cement reduction; low embodied carbon
Rice Husk Ash (RHA)	Very high SiO ₂ (>70%)	Highly porous, very fine when ground	5-10	↑ Strength due to high pozzolanic reactivity	Improved abrasion & permeability control	Converts agricultural waste; high CO ₂ savings
Wood Bottom Ash (WBA)	High CaO, variable silica	Irregular particles, moderate fineness	5-15	Neutral to slight strength gain	Limited durability enhancement	Waste diversion; moderate emission reduction
Sugarcane	High reactive	Fine particles, high surface	10-15	↑ Packing density and	Reduced acid	Renewable biomass

Bagasse Ash (SCBA)	SiO ₂ (if calcined properly)	area		compressive strength	resistance at high contents	waste; eco-friendly SCM
Coconut Shell Ash (CSA)	Silica-rich with alkalis	Porous, high absorption	10-20	Acceptable strength at moderate levels	Needs control for shrinkage & permeability	Agricultural waste reuse; GWP reduction
Other Agri-Residue Ashes	Variable (SiO ₂ dominant)	High variability, needs processing	5-15	Mix-dependent performance	Requires long-term durability validation	Strong circular-economy potential

Results and Discussion

The compressive strength performance demonstrates that both RHA and CBA maintain strength enhancement across the 0-10% replacement range, with optimal performance at 5-7% replacement levels. Fly Ash shows declining strength with increased replacement percentage (reaching 28.0 MPa at 10%), while Coconut Shell Ash exhibits consistently declining performance above 2% replacement.



Graph 1: Compressive Strength Comparison of M30 Grade Concrete with 0-10% Ash Replacements at 28 Days

Optimal Replacement Percentages and Peak Performance



Graph 2: Optimal Replacement Percentages and Peak Compressive Strengths for M30 Grade Concrete

Based on experimental data, the following optimal replacement percentages are recommended for achieving peak performance in each ash type:

Table2: Durability Performance

Ash Type	Optimal Replacement	Peak Strength (MPa)	Strength Variation	Durability Index
Rice-Husk Ash (RHA)	6%	31.8	6.0%	Excellent
Coal Bottom Ash (CBA)	6%	31.5	5.0%	Good
Wood Bottom Ash (WBA)	6%	30.8	2.7%	Good
Sugarcane Bagasse ash (SCBA)	4%	30.5	1.7%	Good
Control (0%)	-	30.0	Baseline	-
Agri.Residue Ash	2%	30.1	0.3%	Variable
Fly Ash (FA)	0%	30.0	0%	Very Good
Coconut Shell Ash (CSA)	0%	30.0	0%	Moderate

Durability Performance Results

Rapid Chloride Penetration Test (RCPT) analysis from 38 studies at 28-day testing revealed control Portland cement exhibiting 3,500-4,500 Coulombs. Coal Bottom Ash at 30% reduced to 2,100-2,800 Coulombs (40-50% reduction). Fly Ash at 25% reduced to 1,800-2,400 Coulombs (45-55% reduction). Rice Husk Ash at 10%

reduced to 1,500-2,100 Coulombs (50-60% reduction). Wood Bottom Ash at 15% reduced to 2,400-3,200 Coulombs (30-40% reduction). Chloride penetration depth via colorimetric analysis showed control concrete penetration of 35-45 millimeters, reduced to 18-25 mm for Coal Bottom Ash (40-50% reduction), 15-22 mm for Fly Ash (45-55% reduction), 12-20 mm for Rice Husk Ash (50-60% reduction), and 20-28 mm for Wood Bottom Ash (30-40% reduction). Sulfate resistance testing in 5% Na₂SO₄ from 18 studies showed 6-month expansion of control concrete at 0.10-0.15%, reduced to 0.04-0.08% for Coal Bottom Ash (60-65% reduction), 0.03-0.07% for Fly Ash (65-70% reduction), 0.03-0.06% for Rice Husk Ash (70% reduction), and 0.05-0.10% for Wood Bottom Ash (40-50% reduction). Compressive strength retention after 12 months of sulfate exposure showed control at 85-90%, Coal Bottom Ash at 92-95%, Fly Ash at 93-97%, Rice Husk Ash at 94-98%, and Wood Bottom Ash at 88-92%.

Environmental Performance Results

Life Cycle Assessment (LCA) analysis from 28 studies quantified cradle-to-gate CO₂ emission reductions. Coal Bottom Ash at 30-35% replacement achieved 28-34% reductions with range of 24-38%. Fly Ash at 25% achieved 20-25% reductions with range of 18-28%. Rice Husk Ash at 10% achieved 18-22% reductions with range of 15-25%. Wood Bottom Ash at 15% achieved 15-18% reductions with range of 12-20%. Sugarcane Bagasse Ash at 12% achieved 16-20% reductions. Coconut Shell Ash at 18% achieved 14-17% reductions. Corn Cob Ash at 8% achieved 12-15% reductions.

Absolute CO₂ emissions showed control Portland cement concrete (350 kg/m³) producing 350-400 kg CO₂-eq/m³, reduced to 240-265 kg CO₂-eq/m³ for Coal Bottom Ash (110-160 kg reduction), 280-310 for Fly Ash (70-130 kg reduction), 285-320 for Rice Husk Ash (65-120 kg reduction), and 285-310 for Wood Bottom Ash (65-120 kg reduction). Global Warming Potential showed control at 350-400 kg CO₂-eq/m³, reduced to 240-265 for Coal Bottom Ash (30-35% reduction), 280-310 for Fly Ash (15-20% reduction), and 285-320 for Rice Husk Ash (15-20% reduction).

Optimal Replacement Percentages

Coal Bottom Ash demonstrated optimal performance at 30-35% replacement with 24.1% average strength improvement, excellent durability ratings, and 28-34% CO₂ reduction. Fly Ash achieved optimal performance at 25% replacement with 25.0% average improvement, excellent durability characteristics, and 20-25%

CO₂ reduction. Rice Husk Ash achieved optimal performance at 10% replacement with 29.0% highest single-point improvement, excellent durability with maximum chloride resistance (50-60% reduction), and 18-22% CO₂ reduction. Wood Bottom Ash achieved optimal performance at 15% replacement with 12.3% average improvement and 15-18% CO₂ reduction. Sugarcane Bagasse Ash achieved optimal performance at 12% with 7.5% improvement. Coconut Shell Ash achieved optimal performance at 18% with 6.8% improvement. Corn Cob Ash showed suboptimal performance at 8% without pretreatment. Acid-treated Corn Stover Ash achieved optimal performance at 10% with 5.0% improvement.

Performance Degradation Patterns

Coal Bottom Ash showed strength inflection beginning around 40% replacement with continuing degradation at higher percentages. Fly Ash showed inflection around 35% replacement. Rice Husk Ash demonstrated sharp degradation beginning at 15% replacement. Agricultural ashes generally showed inflection points at 10-15% replacement. These inflection points reflected mechanistic limits where pozzolanic reaction becomes exhausted and continued cement reduction begins to dominate performance degradation.

Quality Control and Standardization

ASTM C109 (compressive strength) was employed in 52 studies (100%). ASTM C496 (splitting tensile) was employed in 48 studies (92.3%). ASTM C78 (flexural strength) was employed in 41 studies (78.8%). ASTM C1202 (chloride penetration) was employed in 38 studies (73.1%). EN 12390 series was employed in 34 studies (65.4%). ISO 1925 (particle size) was employed in 30 studies (57.7%). ASTM C618 was cited or complied with in 48 studies (92.3%). EN 450-1 was cited or complied with in 40 studies (76.9%). IS 3812 was cited or complied with in 12 studies (23.1%).

Material variability analysis showed Coal Bottom Ash with coefficient of variation of 5-8%, Fly Ash with 3-5%, Rice Husk Ash with 8-12%, Wood Bottom Ash with 6-10%, and agricultural ashes with 10-15%.

Case Study Results

Case Study 1 (HPC with Coal Bottom Ash 30%): Achieved 77.4 MPa strength versus 68 MPa control, freeze-thaw RDM 87% versus 75% control (15% enhancement), chloride penetration 45% reduction, CO₂ reduction 34%. Case Study 2 (Pavement with Rice Husk Ash 10%): Achieved 32.5 MPa with 40% improved

abrasion resistance, 16-year field performance without deterioration, 18% CO₂ reduction. Case Study 3 (Mortar with Coal Bottom Ash 45%): Achieved 22.7 MPa, 25% cost reduction, 34% CO₂ reduction, 8-year durability confirmed. Case Study 4 (Lightweight with Wood Bottom Ash 15%): Achieved 12.3% strength increase, 15% density reduction, seismic benefits, 18% CO₂ reduction. Case Study 5 (Hybrid system with FA 15% + RHA 10% + glass powder 15%): Enhanced flexural strength, superior durability through synergistic reactions, 25% CO₂ reduction.

Material Characterization Data

Table 3: Chemical Composition (Typical Values)

Parameter	RH A	CB A	FA	WB A	SCB A	CS A
SiO ₂ (%)	94	58	62	55	60	45
Al ₂ O ₃ (%)	2.6	24	26.4	12.6	1.9	11
Fe ₂ O ₃ (%)	1.2	12.5	7.2	5.7	2.1	6
CaO (%)	1.62	11.2	7.2	8.4	3.6	9
Loss on Ignition (%)	3.4	3.6	4.2	6.2	4.2	7

Table 4: Physical Properties

Property	Target Range	Optimal Value
Fineness (Blaine)	2500-4000 cm ² /g	3500-3800 cm ² /g
Moisture Content	< 3%	< 2%
Specific Gravity	2.0-2.4	2.1-2.3
Bulk Density	700-1000 kg/m ³	850-950 kg/m ³
Particle Size (d ₅₀)	5-25 μm	10-20 μm

Conclusion And Future Scope

Coal Bottom Ash is highlighted for its optimal 30-35% replacement, yielding significant improvements in compressive strength, chloride penetration reduction, and CO₂ emissions. Fly Ash showed superior early strength retention, while Rice Husk Ash is noted for maximum durability in aggressive environments. Other materials like Wood Bottom Ash provided specialized applications with modest strength improvements. The review emphasizes various material-specific optimal replacements and substantial environmental benefits. A structured implementation strategy prioritizes project needs and regional factors, while advocating for

a transition towards these materials to meet climate goals and enhance infrastructure longevity.

Summary of Key Findings

Coal Bottom Ash is identified as the most effective material for cement replacement, achieving 30-35% replacement with a 24.1% improvement in compressive strength and significant reductions in chloride penetration (40-50%), CO₂ emissions (28-34%), and enhanced freeze-thaw durability. Fly Ash, at 25% replacement, shows superior early strength retention (75-80% at 7 days) and a 25% strength improvement. Rice Husk Ash, at 10% replacement, provides notable benefits such as a 29% strength improvement and significant reductions in chloride and sulfate expansion for aggressive conditions. Overall, all ash materials outperform control Portland cement in strength development over 28-365 days (1.25-1.55x vs. 1.10-1.20x). Environmental assessments indicate CO₂ emissions decreased by up to 34% and highlight the potential for substantial waste diversion from landfills. The study recommends selecting materials based on specific performance needs: Coal Bottom Ash for general use, Fly Ash for early strength, and Rice Husk Ash for durability in harsh environments. The research supports implementing ash-based concrete to align with sustainability goals and improve long-term durability in construction.

Limitations

- Limited long-term field performance data, with most studies focused on 28-90 days rather than full-service life of structures.
- Significant source variability in ash properties (especially agricultural ashes), requiring site-specific characterization and stricter quality control to ensure consistent performance.
- Economic and supply chain conditions (availability of coal ash, transport distances, competing uses) can change regionally and over time, affecting feasibility of large-scale adoption.
- Limited standardized guidelines for hybrid or multi-ash systems, making optimization of combined ash use and mix design highly project-specific.
- Most performance data are from controlled laboratory conditions, so translation to complex real exposure environments (combined chloride, carbonation, temperature cycling) still carries uncertainty.

Ethical and Societal Impact

Expanding the use of ash-based supplementary cementitious materials has positive ethical and societal implications by reducing reliance on energy- and carbon-intensive Portland cement, thereby lowering greenhouse gas emissions and contributing to climate change mitigation goals that protect vulnerable populations and future generations. At the same time, valorizing industrial and agricultural waste streams into construction materials supports circular economy principles, reduces landfill pressure, and can create local economic opportunities near power plants and agro-industrial hubs, although care is needed to ensure fair labor practices, equitable distribution of benefits, and responsible management of any contaminants in ash to avoid shifting environmental burdens onto disadvantaged communities.

Future Research Opportunities

Future research should prioritize long-term field monitoring of ash-based concretes in real structures and multiple exposure conditions (chloride, sulfate, carbonation, freeze–thaw) to validate and calibrate laboratory-based performance predictions over service lives beyond 10–20 years. Additional work is needed on hybrid and multi-ash systems, including optimization of blend proportions, interaction mechanisms, and performance-based mix design using advanced modeling or AI tools, as well as standardized protocols for characterizing highly variable agricultural ashes to make their use more predictable and specification-friendly. Further studies should also integrate full cradle-to-grave life cycle assessment with structural reliability and life-cycle cost analysis, so that environmental, economic, and durability performance can be jointly optimized for different regions and infrastructure types

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