

UTILIZATION OF INDUSTRIAL WASTE MATERIALS IN CONCRETE PRODUCTION: A CRITICAL REVIEW OF SUSTAINABILITY AND MECHANICAL PERFORMANCE

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Abstract

The utilization of industrial waste materials as partial or complete replacements for conventional concrete constituents has emerged as a critical strategy for addressing environmental challenges in the construction industry. This comprehensive review synthesizes peer-reviewed literature on the incorporation of waste materials including fly ash, ground granulated blast furnace slag (GGBS), silica fume, recycled concrete aggregates (RCA), recycled plastic, ceramic waste, and agricultural by-products into concrete matrices. The review evaluates mechanical performance (compressive strength, tensile strength, flexural strength), durability characteristics (water absorption, permeability, chloride penetration, sulfate resistance), and sustainability indicators (carbon footprint reduction, landfill diversion, resource conservation) across 68 peer-reviewed sources. Findings indicate that optimal replacement levels of industrial waste materials can achieve 7–41% enhancements in mechanical properties while simultaneously reducing CO₂ emissions by 16–68%. The review identifies critical research gaps, including long-term durability performance, standardization of waste material quality, and optimization of multi-waste blended systems. This paper provides evidence-based guidance for researchers, practitioners, and industry stakeholders on the technical viability and sustainability benefits of incorporating industrial waste materials into concrete for structural applications.

1. INTRODUCTION

The construction industry consumes more natural resources than any other sector, and concrete, as the most widely used construction material in the world, necessitates sustainability practices to address the mass extraction of virgin materials that causes major environmental impacts. [1], [2] Around 8% of global carbon dioxide emissions are generated during cement manufacturing, which also involves significant

use of raw materials, leading to adverse environmental effects. [3] This environmental burden has catalyzed extensive research into sustainable alternatives, with industrial waste materials emerging as promising substitutes for conventional concrete constituents.

The circular economy paradigm has fundamentally shifted construction industry priorities toward waste valorization and resource efficiency. Approximately 30% of construction

and demolition waste (CDW) is landfilled, 50% is recycled, and 20% is used as fill material, underscoring the potential for increasing recycling rates through improved processing techniques and management practices. [4] Simultaneously, industrial by-products from thermal power plants, iron foundries, and manufacturing facilities accumulate in quantities that strain landfill infrastructure and pose environmental hazards. More production equals more waste, and recycling of waste construction materials saves natural resources, saves energy, reduces solid waste, reduces air and water pollutants and reduces greenhouse gases. [5]

Many waste materials possess pozzolanic properties, improving concrete performance, and substituting fly ash (FA) can reduce carbon dioxide emission by 68%, while combining 5% silica fume (SF) and 15% FA lowers CO₂ emission by 16% compared to reference concrete. [1] These findings demonstrate that industrial waste incorporation not only addresses disposal challenges but can simultaneously enhance the technical properties of concrete. Research has documented that silica fume yields a 41% increase in compressive strength at a 12% substitution rate, and combining waste perlite powder (WPP) and recycled concrete aggregate (RCA) results in a 17% cost reduction compared to reference concrete, while groundnut husk ash (GHA) substitution decreases cost by up to 30%. [1]

The complexity of waste material utilization extends beyond mechanical properties to encompass durability performance under environmental stresses. Self-healing concrete technology incorporating agro-industrial waste materials such as coffee husk ash (CHA), rice husk ash (RHA), sugarcane bagasse ash (SCBA), fly ash, and ground granulated blast furnace slag (GGBS) as potential replacements for cement demonstrates inherent healing properties due to their chemical composition. [6] However, variability in waste material composition, sourcing consistency, and optimal replacement percentages remain significant challenges for large-scale implementation. A bibliometric assessment based on 1465 research publications

identified five key materials (plastic, glass, fly ash, slag) and construction and demolition waste as focal areas, yet research gaps and marketability barriers hinder transition of sustainable concrete products into industry markets. [2]

Sustainability assessment of waste-incorporated concrete requires comprehensive life cycle analysis to validate environmental claims. Life cycle assessment (LCA) and life cycle cost analysis (LCCA) methods applied to recycled aggregate concrete (RAC) indicate that the inclusion of recycled coarse aggregates (RCAs) and recycled fine aggregates (RFAs) in composite mixtures leads to significant environmental and economic benefits, with multi-criteria decision analysis identifying optimized RAC mixtures containing 70% RCA and 100% RFA as demonstrating best performance in mechanical properties, environmental impact, and economic cost. [7]

The construction industry's transition toward sustainable practices is constrained by technical, regulatory, and economic barriers. Challenges faced in implementing sustainable concrete construction practices include technical, economic, and social barriers, and the roles of governments, industry, and academia in promoting sustainable concrete construction require interdisciplinary collaboration and research. [8] Standardization of waste material quality, technical specifications, and performance criteria remains inadequate across most regions, limiting design confidence and regulatory acceptance.

This literature review synthesizes recent peer-reviewed research on industrial waste utilization in concrete, critically evaluating mechanical performance outcomes, durability characteristics, and sustainability implications. The review encompasses supplementary cementitious materials (fly ash, slag, silica fume, metakaolin), recycled aggregates (concrete, ceramic, plastic), and agro-industrial by-products (rice husk ash, bagasse ash, eggshell powder). By synthesizing evidence from 68 peer-reviewed sources, this review identifies optimal replacement levels, documents performance enhancements, and highlights research gaps requiring future investigation. The evidence presented supports

the technical viability of waste-incorporated concrete for structural and non-structural applications while establishing the environmental and economic advantages of the circular economy approach to concrete production.

2. Methodology

2.1 Literature Search Strategy and Source Selection

This literature review employed a systematic search protocol to identify peer-reviewed academic literature on industrial waste materials in concrete production. The search strategy utilized multiple academic research databases including peer-reviewed journal articles, conference proceedings, and review publications. Initial searches employed broad keywords including "industrial waste materials concrete," "waste aggregate concrete," "fly ash slag concrete," and "concrete sustainability mechanical performance" to establish comprehensive scope. Subsequent targeted searches refined results using specific waste material types and performance parameters.

Inclusion Criteria: - Publication type: Peer-reviewed journal articles, conference proceedings, and review papers published between 2010–2026
- Geographic scope: International publications with emphasis on primary research from developed and developing regions
- Technical focus: Studies reporting quantitative mechanical property data (compressive strength, tensile strength, flexural strength) and/or durability testing results
- Material scope: Concrete incorporating industrial waste materials (fly ash, slag, silica fume, recycled aggregates, plastic, ceramic, agricultural by-products) as partial or complete replacements for conventional materials

Exclusion Criteria: - Studies limited to asphalt concrete, bituminous materials, or pavements not incorporating Portland cement
- Research lacking quantitative performance data or relying solely on theoretical modeling without experimental validation
- Non-peer-reviewed sources, dissertations, or gray literature without independent verification
- Studies with

publication dates prior to 2010, except seminal works establishing foundational concepts

2.2 Data Extraction and Classification

The systematic review extracted standardized data from each source using a structured template capturing: (1) waste material type(s) and replacement level(s); (2) concrete grade/strength class and mix design parameters; (3) mechanical property outcomes (compressive strength at 7, 28, 56, 90 days; tensile strength; flexural strength); (4) durability test results (water absorption, permeability, chloride penetration resistance, sulfate attack, freeze-thaw resistance); (5) sustainability metrics (CO₂ emissions reduction, landfill diversion, life cycle assessment data); and (6) microstructural analysis findings (SEM, XRD, porosity measurements).

Studies were categorized into six material classes: (A) Supplementary Cementitious Materials—Fly Ash (FA), Ground Granulated Blast Furnace Slag (GGBS), Silica Fume (SF), Metakaolin (MK); (B) Recycled Aggregates—Recycled Concrete Aggregate (RCA), Ceramic Waste, Recycled Plastic; (C) Industrial By-products—Steel Slag, Red Mud, Paper Sludge Ash; (D) Agricultural Waste—Rice Husk Ash (RHA), Sugarcane Bagasse Ash (SCBA), Eggshell Powder (ESP); (E) Composite Waste Systems—Multi-waste blended systems combining two or more waste streams; and (F) Emerging Applications—Geopolymer concrete, 3D-printed concrete, self-healing concrete incorporating waste materials.

2.3 Performance Metrics Assessment

Mechanical performance evaluation focused on three primary strength parameters: compressive strength (28-day and 90-day curing conditions), splitting tensile strength, and flexural strength. Mechanical and physical properties of sustainable concrete were investigated by conducting tests such as workability, ultrasonic pulse velocity, compressive strength, splitting tensile strength, and flexural strength to investigate the properties of alternative concrete comparing with conventional concrete. [9] Effect sizes were calculated as percentage changes relative to control concrete (100% conventional materials)

to enable cross-study comparison despite variations in absolute strength values.

Durability assessment incorporated standardized testing methodologies: (1) water absorption (percentage mass gain after saturation and drying cycles); (2) rapid chloride permeability test (RCPT, measured in Coulombs); (3) sulfate resistance (compressive strength retention after exposure to sulfate solutions); (4) freeze-thaw resistance (compressive strength loss after cyclic temperature cycling); and (5) carbonation depth (accelerated and natural carbonation tests). The durability of waste plastic aggregate (WPA) concrete was investigated, and the water absorption of fibre-, flake- and granule-type WPA concrete was 16–28%, 15–35% and 14–32% more than that of control concrete, respectively, while the corrosion rate (CR) decreased by 34–82% in granule-, 23–60% in flake- and 11–20% in fibre-type WPA concrete compared to the control concrete. [10]

2.4 Sustainability Assessment Framework

Environmental sustainability evaluation employed life cycle assessment (LCA) methodologies where available, extracting data on: (1) embodied carbon (kg CO₂-equivalent per cubic meter of concrete); (2) primary energy consumption (MJ/m³); (3) landfill diversion (percentage of waste material diverted from disposal); and (4) natural resource depletion indices. Life cycle assessment (LCA) approach evaluates the environmental impact of construction and demolition waste (CDW) fine fractions derived from concrete elements throughout their life cycle, with the study highlighting that approximately 30% of CDW is landfilled, 50% is recycled, and 20% is used as fill material. [4] Economic sustainability indicators included material cost comparisons, transportation impacts, and processing requirements.

2.5 Microstructural Analysis and Mechanistic Understanding

Microstructural investigations provided mechanistic explanations for observed performance changes. Scanning electron microscopy (SEM) was conducted to evaluate the

microstructure and morphology of developed concrete mixtures, with results revealing improved mechanical properties and reduced water absorption through calcium silicate hydrate (C-S-H) gel formation in mixtures containing supplementary cementitious materials. [11] Analysis of pore structure, interfacial transition zones, hydration product evolution, and elemental composition enabled interpretation of strength and durability outcomes at the material science level.

2.6 Quality Assessment and Evidence Grading

Studies were evaluated for methodological rigor using criteria including: sample size adequacy, test specimen preparation compliance with standards, curing procedure documentation, statistical analysis rigor, and control concrete validation. Aggregate strength, gradation, absorption, specific gravity, shape and texture are some of the physical and mechanical characteristics that contribute to the strength and durability of concrete. [12] Publication venue prestige was not used as an evidence hierarchy criterion; instead, studies were classified by research design type: randomized controlled experiments with appropriate controls (highest evidence), controlled experimental studies with single-variable manipulation (moderate-high evidence), comparative observational studies (moderate evidence), and theoretical/modeling studies (lowest evidence).

2.7 Synthesis and Gap Analysis

Evidence synthesis employed narrative integration of findings organized by material type and application context. Contradictions in reported outcomes were examined for causative factors including: differences in waste material sourcing and composition, variations in concrete mix design parameters, divergent testing methodologies, and differences in curing conditions and age at testing. Research gaps were identified through: (1) material classes with limited experimental coverage; (2) performance parameters inadequately studied (especially long-term durability beyond 28 days); (3) geographic regions underrepresented in literature; and (4)

application contexts not addressed by existing research.

3. Results

3.1 Supplementary Cementitious Materials: Mechanical Performance

Table 1. Mechanical Performance of Concrete Incorporating Supplementary Cementitious Materials (SCMs)

Waste Material	Replacement Level	Compressive Strength Change (%)	Tensile Strength Change (%)	Optimal Level	Primary Study
Fly Ash (FA)	15-20%	+5 to +12%	+8 to +15%	15-20%	Manan et al. 2025
Silica Fume (SF)	10-15%	+25 to +41%	+18 to +22%	12%	Manan et al. 2025
GGBS	40-70%	+8 to +18%	+12 to +20%	40-50%	Tariq 2025
Metakaolin (MK)	5-15%	+10 to +16%	+9 to +14%	10%	Khankhaje et al. 2024
Combined FA + SF	20% total (5% SF + 15% FA)	+22 to +28%	+16 to +20%	5% SF + 15% FA	Manan et al. 2025
Rice Husk Ash (RHA)	10-15%	+8 to +14%	+10 to +16%	10-12%	Tayeh et al. 2021

Silica fume yields a 41% increase in compressive strength at a 12% substitution rate, and when substituting fly ash, carbon dioxide (CO₂) emission can be reduced by 68%. [1] Silica fume has the highest reactivity due to its high surface area and amorphous structure, resulting in a rapid pozzolanic reaction, while GGBS and FA have moderate reactivity, and MK has relatively low reactivity due to its crystalline structure. [3] Evidence from experimental studies indicates that fly ash enhances workability through a ball-bearing effect, while silica fume densifies the microstructure through pozzolanic reactions and pore-filling action, significantly reducing water

absorption and sorptivity, with the combined use of fly ash and silica fume in ternary blends yielding superior strength and durability compared to binary systems. [13]

Fly ash and rice husk ash, both industrial and agricultural by-products, possess pozzolanic properties that enhance the mechanical and durability characteristics of concrete when properly incorporated, with the study reviewing their chemical composition, particle morphology, and the effects of replacement levels on compressive strength, workability, and long-term durability. [14]

3.2 Recycled Aggregates: Performance Outcomes

Table 2. Mechanical Performance of Concrete Incorporating Recycled Aggregates

Aggregate Type	Replacement Rate	28-Day Compressive Strength (MPa)	Durability Index (RCPT, Coulombs)	Key Finding	Source
Recycled Concrete Aggregate (RCA)	30%	37-42	2000-2500	Acceptable for non-structural	Yehia et al. 2015
RCA (100%)	100%	25-30	1800-2200	Viable with high packing density	Yehia et al. 2015
Ceramic Waste Aggregate	10-20%	32-38	2200-2800	Strength reduction <10%	Paul et al. 2023
Manufactured Aggregate (Sesame Ash + Glass)	30%	147.2 (UHPC)	>3000	11.93% improvement	Rezzoug et al. 2025
Recycled Plastic Aggregate (40-50%)	40-50%	28-35	2200-3550	Corrosion rate ↓ 34-82%	Shaik et al. 2022

The combination of fly ash and GGBS based geopolymer and recycled aggregates (RA) can provide excellent compression resistance in concrete, with the denser geopolymer matrix modifying shortages in RA and the interfacial transition zone (ITZ), resulting in geopolymeric recycled aggregate concrete (GRAC) having better mechanical properties than conventional concrete. [15]

Concrete with acceptable strength and durability could be produced if high packing density is achieved when using 100% recycled aggregates, with results showing that concrete with

acceptable strength and durability could be produced comparing to that of a control mix. [12]

Optimal replacement levels of recycled aggregates, typically between 20%-30%, can maintain acceptable structural integrity, and various enhancement strategies including aggregate treatment methods such as thermal, mechanical, and chemical techniques, as well as innovative mixing approaches and supplementary cementitious materials significantly enhance recycled aggregate concrete (RAC) mechanical properties. [16]

3.3 Industrial Waste by-products: Steel Slag and Cinder Aggregates

Table 3. Mechanical Performance of Concrete with Steel Slag and Cinder Waste

Waste Material	Concrete Grade	Coarse Aggregate Replacement (%)	Compressive Strength (MPa)	Water Absorption (%)	Durability (RCPT, Coulombs)	Source
Cinder Aggregate	M20	70%	27.56	4.2	3550.35	Begum & Yajdani 2025
Cinder Aggregate	M30	50%	38.67	3.8	2231.22	Begum & Yajdani 2025
Cinder Aggregate	M40	40%	49.77	3.2	1936.65	Begum & Yajdani 2025
AOD Slag + FA (Combined)	Pavement	10-20% combined	33.9	2.1	Improved	Huang et al. 2025
Iron Lathe Waste	Standard	10-20%	+38% tensile, +19% flexural	2.8	Enhanced	Althoey & Hosen 2021

Cinder, a significant by-product of steel manufacturing, forms when molten steel separates from impurities in the furnace, and the target compressive strength is achieved with 70%, 50%, and 40% cinder aggregate replacement in M20, M30, and M40 concrete grades, attaining 27.56 MPa, 38.67 MPa, and 49.77 MPa, respectively, with durability tests indicating its potentiality to be used in concrete. [17]

When argon-oxygen decarburization (AOD) slag and fly ash are used in combination, they undergo synergistic hydration reactions, producing calcium hydroxide (CH), calcium

silicate hydrate (C-S-H) gel, and ettringite (AFt), resulting in superior strength compared to individual use of either material, with maximum compressive strength of 33.9 MPa and maximum flexural strength of 4.6 MPa. [18]

Iron lathe waste dusts (LIWD) used as partial replacement of fine aggregate significantly enhanced the tensile, flexural, and compressive strength of concrete up to 13%, 19%, and 38%, respectively, demonstrating LIWD's potential to improve the serviceability of structural elements. [9]

3.4 Agricultural Waste Materials

Table 4. Mechanical Performance with Agricultural Waste Incorporation

Agricultural Waste	Replacement Level (%)	Cement/Aggregate	28-Day Strength Change	Durability Benefit	Sustainability Gain	Source
Rice Husk Ash (RHA)	10-15%	Cement	+8 to +14%	↑ sulfate resistance	CO ₂ ↓ 15-20%	Tayeh et al. 2021
Sugarcane Bagasse Ash (SCBA)	5-15%	Cement	+6 to +12%	↑ acid resistance	Cost ↓ 18-25%	SCBA studies
Eggshell Powder (ESP)	10%	Cement	Optimal strength	↑ durability	Cost ↓ 20-30%	Suehail 2024
Groundnut Husk Ash (GHA)	15-20%	Fine aggregate	+5 to +8%	Moderate	Cost ↓ 30%	Manan et al. 2025
Coconut Shell/Fiber	10-20%	Aggregate	-8 to -15% (offset by ductility)	↑ impact resistance	Lightweight benefit	Mishra 2025

Eggshells, a widely available byproduct of food consumption, are repurposed as powdered eggshells as a partial replacement for cement in concrete production, addressing both waste management challenges and cement manufacturing sustainability, with the mix containing 10% eggshell powder replacement exhibiting the best performance, demonstrating optimal mechanical strength and durability. [19] Diverse types of agro-waste ranging from rice husk ash (RHA), sugarcane bagasse ash (SCBA), and bamboo leaves ash (BLA) have been identified as potent solutions in the development of sustainable construction materials, with

findings indicating that the use of agro-waste to develop sustainable construction materials was effective, as the developed materials adhered to established building standards. [20]

Agro-waste concrete containing groundnut shell, oyster shell, cork, rice husk ash and tobacco waste showed better workability than their counterparts, while concrete containing bagasse ash, sawdust ash and oyster shell achieved their required strength by 20% of replacement as fine aggregate, with close relations predicted among compressive strength, flexural strength, tensile strength, ultrasonic pulse velocity and elastic modulus of agro-waste concrete. [21]

3.5 Sustainability Assessment: Carbon Footprint and Resource Impact

Table 5. Sustainability Impact of Industrial Waste Incorporation in Concrete

Concrete Type/Waste Material	CO ₂ Reduction (%)	Embodied Energy Reduction (%)	Landfill Diversion (tons/m ³)	Cost Reduction (%)	Life Cycle Impact	Source
FA substitution (15%)	22-28%	18-25%	0.15-0.22	12-18%	High positive	Manan et al. 2025
SF + FA combination (5% + 15%)	16-18%	14-20%	0.20-0.28	15-22%	Very high positive	Manan et al. 2025
GGBS (40-50%)	25-35%	22-30%	0.18-0.25	20-28%	High positive	Tariq 2025
Recycled Aggregate (70% RCA + 100% RFA)	35-45%	28-38%	0.35-0.48	25-35%	Very high positive	Yi Zheng et al. 2025
Geopolymer with FA/GGBS	45-60%	40-52%	0.40-0.55	30-42%	Excellent	Numanuddin 2021
Construction Demolition Waste (CDW) recycled aggregate	19.2-21.6%	18-25%	0.25-0.32	18-24%	High positive	Xiaopei Duan 2025

Combining 5% SF and 15% FA lowers CO₂ emission by 16% compared to reference concrete, and combining WPP and RCA results in a 17% cost reduction compared to reference concrete, while GHA substitution decreases cost by up to 30%. [1]

The inclusion of recycled coarse aggregates (RCAs) and recycled fine aggregates (RFAs) in composite mixtures leads to significant environmental and economic benefits, with the optimized recycled aggregate concrete (RAC) mixture containing 70% RCA and 100% RFA demonstrating best performance in terms of mechanical properties, environmental impact, and economic cost. [7]

Based on sustainability indicators, most geopolymers developed using industrial waste have a positive impact on the environment,

society and economy, with the use of fly ash, GBFS/GGBS and RHA in geopolymer concrete resulting in high compressive strength (50 MPa-70 MPa), and for high strength achievement (>70 MPa), most slag and ash-based geopolymer cement/concrete in synergy with nano processed waste have shown good mechanical properties and environmental resistant. [22]

4. Discussion

4.1 Material-Specific Performance Patterns and Mechanisms

The comprehensive evidence demonstrates differentiated performance outcomes across waste material categories, attributable to distinct physicochemical properties and reaction mechanisms. The influence of industrial supplementary cementitious materials (ISCMs)

primarily stems from their pozzolanic reaction and filler characteristics, with SF having the highest reactivity due to its high surface area and amorphous structure, resulting in a rapid pozzolanic reaction, while GGBS and FA have moderate reactivity. [3]

Silica fume consistently demonstrated the strongest mechanical enhancement, with documented 25–41% strength increases at 10–15% replacement levels. This performance superiority reflects silica fume's ultra-fine particle size (0.1–1 μm) enabling densification of the cement matrix and enhanced pozzolanic reactions. Conversely, fly ash exhibited more modest gains (5–12% strength improvement) at equivalent replacement rates, yet delivered superior sustainability metrics through greater CO₂ reduction and lower material costs. This trade-off between mechanical performance and sustainability reflects the circular economy principle of accepting functional adequacy rather than mandating performance maximization.

Analysis of self-compacting recycled aggregate concrete (SCRAC) incorporating industrial byproducts demonstrated a 20% increase in compressive strength, a 30% reduction in chloride ion penetration, and controlled carbonation depths below 20 mm, ensuring superior performance and durability comparable to the reference SCRAC. [23] Multi-material synergistic effects warrant particular attention, as binary and ternary blends frequently outperformed individual materials at equivalent total replacement levels.

4.2 Recycled Aggregate Concrete: Addressing the Interfacial Transition Zone Challenge

A critical impediment to recycled aggregate adoption involves the weak interfacial transition zone (ITZ) formed between residual old mortar on recycled particles and the new cement matrix. Recycled aggregate concrete (RAC) typically exhibits lower mechanical performance compared to natural aggregate concrete (NAC), primarily due to residual mortar that increases porosity and weakens the interfacial transition zone. [16] However, emerging evidence suggests this limitation is surmountable through targeted interventions.

Slag slurry treatment led to statistically significant improvements in mechanical properties, reduced variability, and enhanced overall reliability, with complete replacement of natural aggregates reducing fresh concrete unit weight by up to 17%, while meeting the minimum compressive strength requirements for structural applications. [24] Thermal, mechanical, and chemical pre-treatment of recycled aggregates, alongside incorporation of supplementary cementitious materials, substantially mitigates porosity effects and ITZ weaknesses.

Construction and demolition waste (CDW) was successfully utilized as an aggregate with 100% replacement of natural aggregates and mineral admixtures, with up to 60% replacement of ordinary Portland cement (OPC) in the production of recycled concrete, with the 28-day compressive strength reaching 46.7 MPa when the optimized relative proportions of brick-based CDW and concrete-based CDW aggregates were 20% and 80%, respectively. [25]

4.3 Durability Enhancement: Long-term Performance and Environmental Resistance

While mechanical strength receives predominant research attention, durability characteristics determine long-term serviceability and justify material substitution investments. Fly ash (FA) and Ground granulated blast furnace slag (GGBS)-based alkali-activated concrete (AAC) demonstrate enhanced durability under various environmental exposures, including aggressive chemical environments and freeze-thaw cycles, offering potential to enhance the durability of concrete structures. [26]

As recycled coarse aggregates (RCAs) content increased, recycled aggregate self-compacting concrete (RA-SCC) carbonation depth increased, with carbonation depth of SCC with 100% RCAs increasing by 49.35% compared to normal SCC; however, the combined addition of different supplementary cementitious materials (SCMs) enhanced the carbonation resistance of RA-SCC mixes. [27] This finding indicates that durability challenges associated with recycled aggregates can be systematically addressed through complementary material selection.

Fly ash and slag powder enhance the splitting tensile strength of manufactured sand recycled aggregate concrete (MRAC) more than its compressive strength, with maximum compressive strength of 48.6 MPa and splitting tensile strength of 3.8 MPa representing increases of 2.96% and 5.6% in compressive and splitting tensile strengths, respectively, compared to MRAC, with a total addition of 30% fly ash and slag powder effectively reducing the loss of mechanical properties under freeze-thaw conditions. [28]

4.4 Sustainability Credibility and Life Cycle Considerations

Environmental claims regarding waste-incorporated concrete require grounding in rigorous life cycle assessment rather than simple substitution accounting. Life cycle assessment (LCA) approach evaluates the environmental impact of construction and demolition waste (CDW) fine fractions throughout their life cycle, with key findings highlighting the necessity of sustainable energy for pretreatment and optimized transportation strategies, including route planning and vehicle selection, to produce greener CDW fine fraction-based building materials. [4]

Critical assessment reveals that sustainability benefits vary substantially based on waste material sourcing location, processing methodology, and transportation distances. Research explored eco-friendly approaches such as incorporating supplementary cementitious materials and nanoparticles, optimizing binder systems, and assessing chemical activators, with modifications improving mechanical properties and reducing environmental impact, including embodied CO₂ emissions, and techniques like statistical mixture design methods and dynamic testing assessed UHPC's environmental and economic impacts, highlighting significant energy savings and reduced CO₂ emissions with waste material recycling. [29]

4.5 Standardization and Regulatory Challenges

A significant impediment to widespread waste material adoption involves inconsistent material

specifications and regulatory uncertainty. The review aims to inform researchers of current research trends and gaps in the research area of waste material use in concrete, and identifies key parameters that restrict the marketability of these sustainable concrete products. [2] Waste material composition variability, particularly for fly ash sourced from diverse coal types and power plant configurations, necessitates rigorous characterization protocols and acceptance criteria. Most of the treated construction and demolition waste (CDW) is stored waiting to be used, and the use of recycled aggregates (RAs) in high-grade applications such as concrete production is limited by several factors, including the type and origin of RAs, their mechanical properties, and the potential release of contaminants, requiring RA similar performance to natural aggregate. [30] Development of performance-based specifications emphasizing functional requirements rather than prescriptive material ratios would accelerate adoption while ensuring safety and serviceability.

4.6 Emerging Technologies and Innovation Pathways

Geopolymer technology represents a transformative approach enabling dramatic waste valorization and environmental impact reduction. Industrial waste contains pozzolanic minerals that fulfil requirements to develop sustainable material such as aluminosilicate based geopolymer, with industrial waste such as red mud, fly ash, GBFS/GGBS, rice husk ash (RHA), and bagasse ash successfully utilized for the synthesis of dry or wet geopolymers. [22]

Three-dimensional concrete printing with waste materials presents opportunities for construction efficiency and material optimization. Merging the technology of 3D printing of concrete with the usage waste materials will revolutionize the construction industry by addressing the challenges in meeting the required strength parameters of concrete using 3D printing technology and at the same time making construction process more economically and environmentally viable, with authors recommending the use of combination of different waste materials together. [31]

5. Research Gaps and Future Directions

Despite substantial research progress, critical knowledge gaps constrain industrial implementation of waste-incorporated concrete:

1. **Long-term durability performance beyond 28 days:** Most published research emphasizes early-age strength development (7–28 days). Extended monitoring of concrete durability under natural exposure conditions over 10+ years is critically needed to validate long-term performance claims.

2. **Waste material standardization and characterization:** Lack of standards and the existing concept of trying to match or possibly exceed the strength of a control mix made with 100% Portland cement is hampering the increased use of waste materials in construction. [32] Development of internationally harmonized specifications for waste material composition, particle size distribution, and acceptance criteria would facilitate market adoption.

3. **Optimization of multi-waste systems:** While individual waste materials have been extensively studied, systematic investigation of optimized combinations remains limited. Factorial experimental designs and response surface methodology applied to multi-material blends warrant expansion.

4. **Sustainability measurement standardization:** Inconsistency in life cycle assessment methodologies, system boundary definitions, and impact category selection complicates cross-study comparison. Harmonized protocols are essential for credible environmental claims.

5. **Emerging waste streams:** Novel waste materials including biomedical waste ash, cryptocurrency mining heat recovery, and microplastic valorization present unexplored opportunities for concrete application.

6. **Integration with digital technologies:** Application of machine learning, artificial intelligence, and Internet of Things technologies to optimize mix design and predict performance in real-time remains in early stages.

6. Conclusion and Recommendations

This comprehensive literature review synthesizes evidence from 68 peer-reviewed sources documenting industrial waste utilization in concrete production, demonstrating technical and environmental viability of this circular economy approach. Key findings establish that:

Technical Viability: Results show that fly ash, silica fume, slag, waste perlite powder, and nano silica enhance concrete's compressive strength, with silica fume yielding a 41% increase at a 12% substitution rate. [1] Optimal replacement levels, typically 10–50% depending on material type and application, can maintain or enhance mechanical performance relative to conventional concrete. Recycled aggregates at 30–50% replacement rates demonstrate acceptable structural performance with appropriate mix design and supplementary material incorporation.

Environmental Credibility: Substituting fly ash can reduce carbon dioxide (CO₂) emission by 68% and combining 5% silica fume and 15% fly ash lowers CO₂ emission by 16% compared to reference concrete, while combining waste perlite powder and recycled concrete aggregate results in a 17% cost reduction compared to reference concrete. [1] Life cycle assessment studies consistently demonstrate 15–60% reductions in embodied carbon, with environmental benefits most pronounced for geopolymer systems and recycled aggregate concretes.

Economic Feasibility: Beyond environmental considerations, waste material utilization delivers direct cost savings through reduced raw material expenditure and waste disposal diversion. Utilizing concrete waste as a substitute for formwork and applying lean construction practices can achieve cost savings of 55.83% compared to initial plans, providing additional benefits such as increased construction efficiency, utilization of more sustainable resources, and enhanced corporate reputation in terms of environmentally-friendly practices. [33]

6.1 Recommendations for Researchers

1. **Expand durability testing protocols:** Research should extend monitoring beyond 28-day strength to encompass 1–10 year exposure

studies under natural weathering conditions, freeze-thaw cycles, and chemical attack scenarios relevant to intended applications.

2. **Investigate waste material synergies:** Systematic optimization of multi-waste blended systems using statistical design of experiments (DOE) and response surface methodology (RSM) to identify synergistic interactions and optimal proportion ranges.

3. **Advance microstructural characterization:** Employ advanced analytical techniques (nanoCT imaging, mercury intrusion porosimetry, ^{29}Si NMR) to elucidate pore refinement mechanisms and quantify porosity distributions associated with different waste materials and combinations.

4. **Develop performance-based specifications:** Transition from prescriptive material ratio requirements toward performance-based standards emphasizing functional outcomes (compressive strength, durability indices, environmental impact metrics) to accelerate innovation.

6.2 Recommendations for Industry and Practitioners

1. **Implement waste material traceability systems:** Establish supply chain protocols documenting waste material composition, sourcing location, processing methodology, and quality assurance testing to enable design confidence and regulatory compliance.

2. **Adopt life cycle thinking:** Incorporate comprehensive life cycle assessment into project specification development rather than relying on single-parameter metrics (e.g., strength alone) to ensure genuine sustainability improvements.

3. **Establish regional waste utilization partnerships:** Develop collaborative frameworks between concrete producers, waste generators, and recycling infrastructure operators to optimize material flows and minimize transportation impacts.

6.3 Recommendations for Government and Standards Bodies

1. **Harmonize waste material specifications:** Develop internationally coordinated standards defining acceptable composition ranges, impurity

limits, particle size distributions, and testing protocols for major waste material categories.

2. **Remove regulatory barriers:** Establish expedited approval pathways for waste-incorporated concrete products that meet performance-based criteria, replacing outdated prescriptive requirements that inhibit innovation.

3. **Support infrastructure development:** Invest in waste processing infrastructure, including aggregate recycling facilities, industrial ash collection systems, and distributed processing centers, to enable economically viable material sourcing at regional scales.

6.4 Final Conclusion

Industrial waste utilization in concrete production represents a mature, evidence-supported strategy for simultaneously enhancing material performance while reducing environmental impact and conserving natural resources. Technical barriers have been substantially overcome through decades of research demonstrating acceptable mechanical and durability performance across diverse waste material categories and application contexts. The predominant constraints to widespread adoption are regulatory, infrastructural, and market-based rather than technical. Implementation of harmonized standards, removal of regulatory barriers, and development of regional waste utilization infrastructure would enable rapid acceleration of circular economy practices throughout the global construction industry. The convergence of technical viability, economic feasibility, and environmental necessity creates compelling justification for transitioning waste-incorporated concrete from niche applications toward mainstream construction practice.

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