

Industrial and Agricultural Waste-Based Sustainable Concrete: A Review of Performance, Durability, and Applications in Pavement and Precast Construction

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Abstract

The cement industry's contribution to anthropogenic CO₂ emissions, combined with the growing volume of industrial and agricultural residues requiring disposal, has positioned waste-valorized concrete as a central theme in sustainable construction research. This review synthesizes the published literature on concrete systems incorporating industrial by-products such as fly ash, ground granulated blast furnace slag, steel slag, copper slag, silica fume, marble dust, quarry dust, and red mud alongside agricultural residues, including rice husk ash, sugarcane bagasse ash, palm oil fuel ash, coconut shell ash, bamboo leaf ash, and wheat straw ash. Drawing on mechanical, durability, microstructural, and life-cycle assessment (LCA) studies published largely between 2020 and 2026, the review consolidates reported trends in compressive, tensile, and flexural strength development; chloride, sulfate, and acid resistance; and the microstructural mechanisms (N-A-S-H/C-A-S-H gel formation, interfacial transition zone densification, pore refinement) that published authors have used to explain these trends. Particular attention is given to application-specific performance requirements for rigid pavement (IRC:58, AASHTO) and precast manufacturing (early-strength demoulding thresholds, heat-curing compatibility). A bibliometric synthesis of the field is presented, summarizing publication growth, leading contributing countries, and thematic evolution as reported in recent scientometric studies. A structured research-gap analysis identifies underexplored hybrid combinations, the scarcity of unified mechanical-durability-LCA frameworks, and the persistent gap between laboratory-scale findings and field-validated, codified design guidance. The review concludes that while individual waste streams are each reasonably well characterized in isolation, ternary and quaternary industrial-agricultural hybrid systems, standardized LCA reporting protocols, and low-carbon activator alternatives represent the highest-priority directions for future research aimed at pavement and precast infrastructure deployment.

Categories: Advanced Materials, Structural Engineering, Environmental and Sustainable Engineering

Keywords: industrial waste concrete, agricultural waste ash, sustainable concrete, supplementary cementitious materials, geopolymers concrete, concrete durability, sustainable pavement, precast construction, circular economy, waste valorization

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Introduction And Background

Ordinary Portland Cement (OPC) production is widely reported to account for approximately 5-8% of global anthropogenic CO₂ emissions, arising from limestone calcination and high-temperature clinker pyroprocessing [1,2]. At the same time, large industrial operations, coal-fired power generation, steel manufacturing, copper smelting, aluminum refining, and dimension-stone quarrying, and agricultural processing industries generate enormous volumes of by-products that are frequently landfilled or stockpiled, creating parallel environmental management challenges [3-5].

The convergence of these two pressures has motivated more than two decades of research into waste-valorized concrete [4]. Published reviews indicate that fly ash (FA) and ground granulated blast furnace slag (GGBS) can be incorporated either as supplementary cementitious materials (SCMs) in OPC blends or as aluminosilicate precursors in alkali-activated geopolymer concrete (GPC), with reported mechanical performance comparable to or exceeding OPC under appropriate mix design and curing [5,6]. Parallel literature streams document steel slag and copper slag as aggregate replacements, silica fume as a high-reactivity pozzolan, and marble dust, quarry dust, and red mud as fine-aggregate or precursor substitutes [7,8]. Agricultural ashes, rice husk ash, sugarcane bagasse ash, palm oil fuel ash, coconut shell ash, bamboo leaf ash, and wheat straw ash, have each been investigated as pozzolanic cement replacements, with reviews noting their high amorphous silica content as the common mechanistic basis for reactivity [6,7].

Despite this body of single-material literature, several gaps are repeatedly noted. First, hybrid systems combining multiple industrial and/or agricultural precursors simultaneously remain underexplored relative to single-precursor studies, despite indications that complementary chemistries (e.g., calcium-rich GGBS with silica-rich agricultural ash) yield synergistic gel networks. Second, application-specific evaluation against rigid pavement (IRC:58, AASHTO T97) or precast demoulding thresholds is less common than generic cube-cylinder testing. Third, integration of mechanical/durability performance with quantitative life-cycle assessment (LCA) within a single study is comparatively rare. This review addresses these gaps by consolidating findings across the fourteen waste streams named above, mapping them onto pavement and precast requirements, and presenting a bibliometric overview and structured gap analysis.

Review

Review methodology

Search Strategy

This review was conducted following a structured search of the Scopus and Web of Science (Core Collection) databases. Searches were executed in March-April 2026 using the following keyword strings, applied to Title, Abstract, and Keywords fields:

- ("fly ash" OR "GGBS" OR "ground granulated blast furnace slag" OR "steel slag" OR "copper slag" OR "silica fume" OR "marble dust" OR "quarry dust" OR "red mud") AND ("concrete" OR "geopolymer" OR "supplementary cementitious material")
- ("rice husk ash" OR "sugarcane bagasse ash" OR "palm oil fuel ash" OR "coconut shell ash" OR "bamboo leaf ash" OR "wheat straw ash") AND ("concrete" OR "cementitious" OR "geopolymer")
- ("waste-based concrete" OR "industrial waste concrete" OR "agricultural waste concrete") AND ("pavement" OR "precast" OR "durability" OR "life cycle assessment")

The Google Scholar database was also searched to capture non-indexed grey literature and conference proceedings. Forward and backward citation chaining was applied to key review papers identified during primary screening.

Inclusion and Exclusion Criteria

Studies were included if they: (i) reported original experimental data or systematic review findings on one or more of the fourteen specified waste materials as a concrete constituent; (ii) reported at least one mechanical property (compressive, split-tensile, or flexural strength) or durability indicator (chloride ion penetrability, water absorption, acid resistance, sulfate resistance) or environmental indicator (global warming potential (GWP), embodied energy); and (iii) were

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published in English in a peer-reviewed journal or refereed conference proceeding, primarily between 2015 and 2026, with seminal studies from earlier years included where no more recent equivalent was identified. Studies were excluded if they: (i) reported only fresh-state properties without hardened-state data; (ii) concerned materials outside the fourteen specified waste streams; (iii) were not available in full text for verification; or (iv) were retracted at the time of this review.

Data Extraction and Synthesis

Data were extracted independently by the lead author into a structured spreadsheet recording: study reference, waste material(s) studied, replacement level(s), mix design parameters (w/b ratio, curing regime), key mechanical and durability results, and LCA system boundary and GWP outcome where reported. Where multiple studies reported the same performance indicator for the same material, qualitative synthesis (narrative, tabular comparison) was used rather than meta-analytic pooling, owing to the heterogeneity of mix designs and test conditions across studies. Quantitative values cited in the results sections are attributed to specific named studies throughout.

Literature review

Industrial Waste Precursors

Fly ash (FA). Class F fly ash is reported across multiple reviews as the most extensively studied geopolymer precursor, valued for its high silica-alumina content and capacity for long-term polycondensation into N-A-S-H gel. Reviews note slower early-age strength gain relative to calcium-rich alternatives, attributed to the comparatively low room-temperature reactivity of the glassy phase in Class F ash, with heat curing reported to substantially accelerate dissolution and strength development. Recent studies have also explored FA-based GPC incorporating recycled aggregates and its durability in marine and chloride-exposed environments, where the absence of a continuous capillary pore network is cited as the principal mechanism for improved chloride resistance relative to OPC [7,9-12].

GGBS. This is widely reported to contribute calcium-rich, rapidly forming C-A-S-H reaction products that accelerate early strength gain and densify the binder microstructure relative to FA-only systems. Multiple durability studies report that GGBS substitution reduces chloride ion penetrability and improves resistance to sulfate, acid, and seawater attack, attributing this to pore refinement and reduced capillary network connectivity [13-15].

Steel slag. Steel slag aggregate (SSA) is reported primarily as a coarse or fine aggregate replacement. Reviews note that untreated steel slag is prone to volumetric instability from free lime and magnesia content; however, once expansion is controlled, SSAC exhibits superior density, mechanical strength, and durability relative to natural aggregate concrete [16,17].

Copper slag. Copper slag, a glassy granular by-product of copper smelting, is reported to have low water absorption with particle morphology broadly comparable to sand. Reported optimal replacement levels vary by concrete grade, with peak compressive strength gains observed at approximately 40-60% fine-aggregate replacement [18,19].

Silica fume. Silica fume is consistently reported as a highly effective pozzolan, with reviews noting improvements in compressive strength, bond strength, abrasion resistance, and reduced permeability. Ternary blends combining silica fume with metakaolin or GGBS are reported to outperform binary blends in both strength and durability metrics [20,21].

Marble dust and quarry dust. Both are reported predominantly as fine-aggregate replacements. Compressive and flexural strength initially increase up to a moderate replacement threshold (commonly 10-25%) before declining at higher substitution. Scientometric reviews describe a rapidly growing publication base and call for more systematic evaluation of combined marble dust-quarry dust systems [22,23].

Red mud. Red mud (bauxite residue) is reported as a highly alkaline, iron- and aluminum-rich waste stream. Reviews report that red mud's inherent alkalinity assists in dissolving co-precursors such as FA or GGBS during geopolymerization, with ternary systems achieving structural-grade compressive strengths. Heavy-metal content requires leaching evaluation before large-scale deployment [24,25].

Agricultural Waste Precursors

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Agricultural residues considered suitable as concrete SCMs are typically evaluated against four criteria: (i) amorphous silica content, generally required above 70-85% under controlled combustion; (ii) combustion temperature and duration, which govern the crystalline-to-amorphous silica ratio; (iii) post-combustion fineness/grinding, necessary to achieve adequate pozzolanic reactivity; and (iv) consistent regional and seasonal availability to support supply-chain viability at scale.

Beyond agro-processing residues (RHA, SCBA, POFA), purpose-grown high-biomass-yielding crops such as Napier grass have been explored primarily as fiber reinforcement in other composite applications, but their ash remains largely unstudied as a concrete SCM. This represents a comparatively unexplored precursor category relative to established agricultural ashes.

Rice husk ash (RHA). RHA is widely reported as one of the most reactive agricultural pozzolans owing to its high amorphous silica content (commonly cited above 85-90% under controlled combustion). Particle fineness and combustion control are critical determinants of pozzolanic performance. RHA combined with GGBS is reported to improve pore structure and long-term durability [26].

Sugarcane bagasse ash (SCBA). SCBA is reported as a viable SCM when subjected to controlled combustion and grinding. Combined RHA-SCBA blends are reported to provide comparable or improved strength relative to single-ash systems. Performance variability linked to inconsistent combustion practices across sugar mills is consistently flagged in reviews [27,28].

Palm oil fuel ash (POFA). POFA exhibits high pozzolanic reactivity and effective micro-filling capability, with growing use in self-compacting and ultra-high-performance concrete formulations. Treated POFA consistently outperforms untreated material in published comparative studies [29,30].

Coconut shell ash, bamboo leaf ash, and wheat straw ash. These less extensively studied agricultural residues exhibit pozzolanic behavior linked to amorphous silica content, with comparatively smaller experimental datasets than the three more established agricultural ashes. Bamboo leaf ash is reported to improve compressive strength and reduce chloride penetration in select high-performance concrete studies. Wheat straw ash shows demonstrated pozzolanic activity and embodied-carbon reduction benefits, though dedicated durability datasets remain limited [30-34].

Materials and characterization

Published characterization studies report the following defining features for each waste stream: (i) fly ash (Class F) silica- and alumina-dominant oxide composition, spherical fine particle morphology, specific gravity 2.0-2.5; (ii) GGBS calcium-, silica-, and alumina-bearing off-white powder, angular irregular particle morphology, specific gravity 2.85-2.95; (iii) steel slag dense, angular aggregate particles with free lime and magnesia fractions responsible for volumetric expansion if untreated; (iv) copper slag glassy, dark, granular particles, iron-oxide dominant composition, low water absorption relative to natural sand; (v) silica fume ultra-fine, near-amorphous silica particles with very high specific surface area; (vi) marble dust/quarry dust calcium-carbonate-dominant (marble) or silicate-dominant (quarry) fine powders, marble dust notably fine and angular; (vii) red mud highly alkaline iron-oxide- and alumina-rich residue with trace heavy metals; (viii) agricultural ashes predominantly amorphous-silica-bearing biomass residues with reactivity dependent on combustion temperature and post-combustion grinding [17-19,21,24-27,29].

Mix Design Considerations

Published mix design literature converges on several recurring principles: (i) an optimum replacement window for each material beyond which mechanical performance declines, commonly attributed to dilution of reactive cement/precursor content, increased water demand, or particle packing disruption; (ii) for agricultural ashes, replacement beyond roughly 15-20% disproportionately increases water demand and reduces workability [35]; (iii) for alkali-activated systems, activator-to-binder ratio and alkali concentration are primary determinants of both workability and degree of reaction [5,36]; (iv) combining calcium-rich industrial precursors (GGBS, steel slag) with silica-rich precursors (FA, RHA, SCBA) can

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produce coexisting C-A-S-H and N-A-S-H gel networks, improving ITZ quality and reducing permeability [15,16]; and (v) ambient curing is appropriate for pavement-oriented mixes, while heat curing at 60-80°C substantially accelerates strength development in FA- and red-mud-dominant systems relevant to precast manufacturing [17,37,38].

Mechanical Performance

Across the reviewed literature, several consistent qualitative trends emerge: (i) industrial waste materials used as cementitious precursors (FA, GGBS, red mud after activation) achieve 28-day compressive strengths broadly comparable to or exceeding OPC reference mixes, particularly where calcium- and silica-rich precursors are combined; (ii) aggregate-replacement materials (steel slag, copper slag, marble dust, quarry dust) enhance strength at low-to-moderate replacement levels, with strength declining beyond an optimum threshold; (iii) agricultural ashes contribute most strongly to longer-term strength gain via pozzolanic reaction; and (iv) hybrid binder systems produce interpenetrating N-A-S-H/C-A-S-H gel networks that densify the ITZ, a mechanism reported across FA-GGBS, GGBS-RHA, and red mud-FA-slag systems [7,8,15,16,38]. Figure 7 presents a comparative summary of the reported optimum replacement levels and peak compressive strength gains for the subset of materials where a single quantified value is available in Table 1. Table 2 provides a quantitative comparison of optimum replacement levels and reported strength changes across the fourteen industrial and agricultural waste materials reviewed. Where studies report a single quantified strength-gain value at a specific replacement level (Materials 2, 4, 5, 6, 7), this is shown explicitly; for materials where the literature reports only qualitative or range-based outcomes, this is noted accordingly.

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S. No.	Material	Category	Primary Role	Reported Optimum	Key Performance Outcome (cited)
1	Fly Ash (FA)	Industrial	SCM / Geopolymer precursor	Variable (up to 100% in single-precursor GPC); 15–30% in OPC blends	Comparable or superior 28-day strength to OPC under proper curing; improved chloride resistance attributed to N-A-S-H gel densification [11,13,14]
2	GGBS	Industrial	SCM / Cementitious binder	30–40% OPC replacement	+33.3% compressive strength at 30% GGBS + 1.5% steel fiber; improved sulfate and acid resistance through C-A-S-H densification [15,16]
3	Steel Slag	Industrial	Coarse/fine aggregate replacement	Up to 100%	Enhanced density, mechanical strength, and durability once volumetric expansion controlled; some studies report no strength compromise at 100% replacement [17,18]

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4	Copper Slag	Industrial	Fine aggregate replacement	40–60% (grade-dependent)	At 40% replacement (M30): +37.6% compressive, +40.7% flexural strength vs. control; optimum varies M20/M40/M60 = 60%/50%/40% [19]
5	Silica Fume	Industrial	High-reactivity pozzolan / SCM	5–12%	Ternary SF + metakaolin blends: +15% compression, +38% flexure over binary blends; reduced permeability and improved abrasion resistance [20,21]
6	Marble Dust	Industrial	Fine aggregate (sand) replacement	10–12.5%	At 12.5%: +25.9% compressive strength vs. control, declining beyond threshold; +11.8% at 10% MD + 1% recycled PP fiber [22,23]
7	Quarry Dust	Industrial	Fine aggregate (sand) replacement	12.50%	At 12.5%: +17.7% compressive strength vs. control; beyond 25%: –7.5% (below control) [22]
8	Red Mud	Industrial	Geopolymer precursor (ternary blends)	Blend-dependent (e.g., RM:FA:slag = 5:2:3 after 800°C activation)	Structural-grade compressive strengths (~54 MPa) reported for RM–BFS two-part geopolymer; thermal pre-activation significantly enhances reactivity [24,25]

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9	Rice Husk Ash (RHA)	Agricultural	Pozzolan SCM	10–20%*	Improved later-age strength and permeability reduction; combined with GGBS retains >90% residual strength after 6-month chloride/sulfate/acid exposure [26]
10	Sugarcane Bagasse Ash (SCBA)	Agricultural	Pozzolan SCM	10–20%*	Enhanced strength when combined with RHA; performance variability linked to inconsistent combustion practices across sugar mills [27,28]
11	Palm Oil Fuel Ash (POFA)	Agricultural	Pozzolan SCM	10–30%*	High pozzolanic reactivity; effective micro-filling in SCC and UHPC formulations; treated POFA consistently outperforms untreated [29,30]
12	Coconut Shell Ash	Agricultural	SCM / Lightweight aggregate (shell form)	5–15%*	Pozzolan behavior linked to amorphous silica; reviewed alongside RHA/SCBA/POFA with comparatively smaller dedicated dataset [31,32]
13	Bamboo Leaf Ash	Agricultural	Pozzolan SCM	5–15%*	Reported to improve compressive strength and reduce chloride penetration in select HPC studies [33,34]

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14	Wheat Straw Ash	Agricultural	Pozzolanic SCM	5–15%*	Demonstrated pozzolanic activity and embodied-carbon reduction benefits; dedicated durability datasets remain limited [30,34]
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TABLE 1: Summary of Industrial and Agricultural Waste Materials Used in Sustainable Concrete

Values marked (*) represent commonly reported ranges in the literature; exact optimum values vary depending on ash quality, fineness, and concrete mix design. All cited performance outcomes are sourced from the specific references listed in each row. OPC, Ordinary Portland Cement; GPC, Geopolymer Concrete; SCM, Supplementary Cementitious Material; GGBS, Ground Granulated Blast Furnace Slag; SF, Silica Fume; MD, Marble Dust; PP, Polypropylene; RM, Red Mud; BFS, Blast Furnace Slag; SCC, Self-Compacting Concrete; UHPC, Ultra-High-Performance Concrete; HPC, High-Performance Concrete

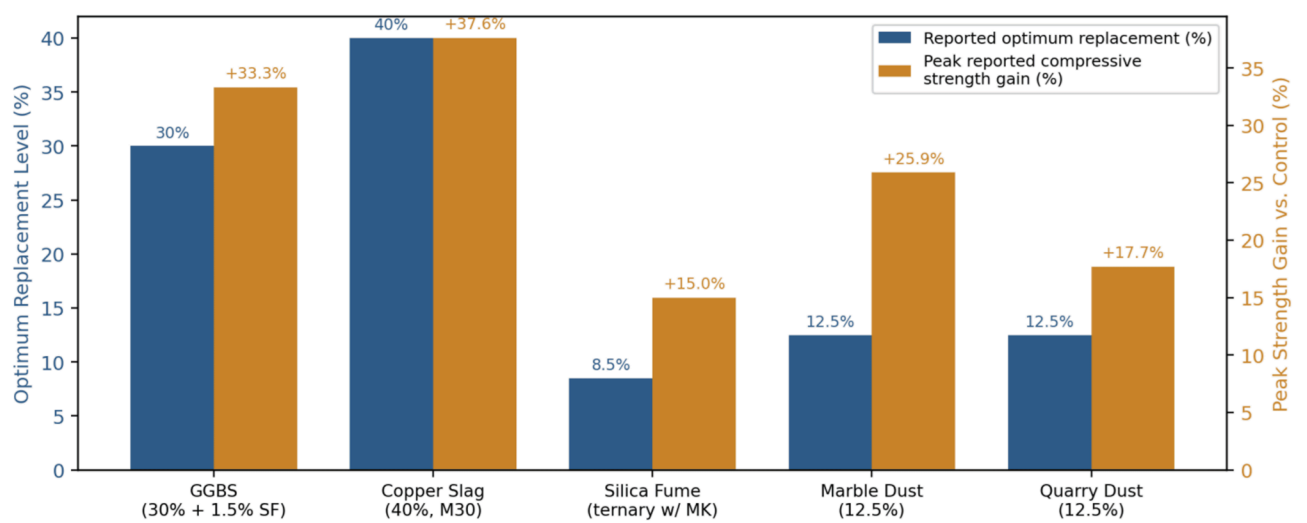


FIGURE 1: Strength Comparison Bar Chart

GGBS, ground granulated blast furnace slag

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Sl. No.	Material	Optimum Replacement (%)	Reported % Strength Change	Source
1	Fly Ash (FA)	15–30 (OPC blends); up to 100 (single-precursor GPC)	Comparable to or superior vs. OPC (no single % reported)	[11,13,14]
2	GGBS	30–40	+33.3% compressive (at 30% GGBS + 1.5% steel fiber)	[15,16]
3	Steel Slag	Up to 100	No strength compromise reported at 100% replacement (no % gain specified)	[17,18]
4	Copper Slag	40–60 (grade-dependent)	+37.6% compressive, +40.7% flexural (at 40%, M30 grade)	[19]
5	Silica Fume	5–12	+15% compressive, +38% flexural (ternary SF + metakaolin vs. binary blend)	[20,21]
6	Marble Dust	10–12.5	+25.9% compressive (at 12.5%); +11.8% (at 10% MD + 1% recycled PP fiber)	[22,23]
7	Quarry Dust	12.5	+17.7% compressive (at 12.5%); –7.5% (below control, beyond 25%)	[22]
8	Red Mud	Blend-dependent (e.g., RM:FA:slag = 5:2:3)	~54 MPa absolute compressive strength (structural-grade); no baseline % gain reported	[24,25]
9	Rice Husk Ash (RHA)	10–20	Improved later-age strength; >90% residual strength retained after 6-month chloride/sulfate/acid exposure (combined with GGBS)	[26]

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10	Sugarcane Bagasse Ash (SCBA)	10–20	Enhanced strength when combined with RHA (no isolated % reported)	[27,28]
11	Palm Oil Fuel Ash (POFA)	10–30	High pozzolanic reactivity; treated POFA outperforms untreated (no isolated % reported)	[29,30]
12	Coconut Shell Ash	5–15	Pozzolanic behavior reported; comparatively smaller dataset (no isolated % reported)	[31,32]
13	Bamboo Leaf Ash	5–15	Improved compressive strength and reduced chloride penetration (select HPC studies; no isolated % reported)	[33,34]
14	Wheat Straw Ash	5–15	Demonstrated pozzolanic activity and embodied-carbon reduction (no isolated % reported)	[30,34]

TABLE 2: Comparative Summary of Optimum Replacement Levels and Reported Strength Changes

OPC, Ordinary Portland Cement; GPC, Geopolymer Concrete; GGBS, Ground Granulated Blast Furnace Slag; HPC, High-Performance Concrete; SF, Silica Fume; MD, Marble Dust; RM, Red Mud; PP, Polypropylene

Durability Performance

Chloride ingress. Multiple studies report that GGBS, FA-based geopolymer, and well-designed hybrid systems reduce chloride ion penetrability relative to OPC, attributed to pore structure refinement and, in geopolymer systems, the absence of a continuous capillary network associated with Portlandite leaching pathways [\[15,16\]](#). GGBS-RHA-LECA systems are reported to retain over 90% residual strength after extended exposure to chloride solution in select studies [\[26\]](#).

Sulfate and acid attack. GGBS is reported to improve sulfate resistance through reduced calcium hydroxide availability and altered hydration product chemistry. Geopolymer and red-mud-based systems show markedly improved acid resistance relative to OPC, mechanistically linked to the absence of free Portlandite [\[24,25\]](#).

Abrasion and freeze-thaw. Fiber-reinforced GGBS pavement-oriented mixes are reported to improve abrasion resistance in dedicated pavement studies [\[15\]](#). Silica fume and metakaolin are reported across reviews to improve freeze-thaw resistance through matrix densification and pore refinement [\[20,21\]](#).

Microstructural Analysis

How to cite this article:

X-ray Diffraction studies consistently report a broad amorphous diffraction hump (typically 20-40° 2θ) in well-reacted geopolymer and hybrid systems, interpreted as evidence of disordered aluminosilicate gel network formation, alongside absent or reduced Portlandite peaks relative to OPC diffractograms. Under ambient curing, unreacted quartz and mullite peaks from incompletely dissolved FA are commonly reported; heat curing reduces the intensity of these residual peaks, consistent with enhanced dissolution. SEM imaging of well-optimized hybrid mixes (GGBS-RHA, red mud-FA-slag) reveals dense, well-filled interfacial transition zones with minimal macro-porosity, in contrast to the more heterogeneous, micro-cracked morphology reported for OPC reference matrices [15,24-26].

Sustainability and Life Cycle Assessment

LCA studies consistently report substantial reductions in GWP for waste-incorporating concretes relative to OPC baselines. Multiple cradle-to-gate LCA studies identify elimination or reduction of OPC clinker as the single largest contributor to GWP reduction. Several LCA studies note that alkaline activator manufacturing (NaOH, Na₂SiO₃) becomes the new dominant emissions hotspot once clinker is eliminated, with some reviewers cautioning that activator-intensive geopolymer formulations partially offset sustainability gains [17]. Published cradle-to-gate assessments report GWP reductions for FA-based and hybrid geopolymer systems spanning roughly 40-80% relative to OPC baselines, depending on system boundary, activator dosage, and allocation method for waste-derived precursors. Multiple LCA papers note that industrial by-products are typically assigned burden-free or low-burden status under waste-allocation approaches, a methodological choice that materially affects comparative GWP results. Water demand comparisons between conventional and waste-based concrete are reported inconsistently across the literature. Agricultural ash-blended mixes generally exhibit increased water demand at replacement levels beyond approximately 15-20%, attributed to the high specific surface area and internal porosity of ash particles. In contrast, industrial precursors such as GGBS and Class F FA show comparatively neutral or reduced water demand relative to OPC at moderate replacement levels. Dedicated blue-water footprint assessments remain limited in the reviewed literature and are identified here as a research gap.

Economic Feasibility Considerations

Techno-economic evaluations of waste-based concrete remain comparatively limited in the reviewed literature. Alkaline activator cost, handling, and transport are consistently cited as economic barriers to geopolymer adoption, while industrial by-products such as FA, GGBS, and slag are typically assigned low or burden-free cost status under waste-allocation frameworks, improving relative cost competitiveness. Dedicated life-cycle costing studies integrating material, activation, and curing costs are scarce and represent a priority gap for future research.

Pavement Applications

Several studies report that GGBS-modified and hybrid geopolymer pavement mixes meet or exceed flexural strength thresholds specified under IRC:58 (minimum 4.5 MPa) and AASHTO T97 (4.1-4.8 MPa) for rigid pavement design, a finding reported as a key technical validation point in multiple papers targeting pavement applications [15,16]. Among the limited field-validated (as opposed to laboratory-scale) studies, reviews report early applications of GPC in footpaths, precast walkways, and cycle lanes, precast walkways, and cycle lanes (notably in Australia), with no reported signs of distress in the cited observation periods. Fiber-reinforced GGBS pavement mixes show measurable improvements in abrasion resistance relevant to wearing-surface performance [15]. GPC is also reported as a candidate repair material for highway infrastructure, though large-scale deployment remains limited relative to laboratory and pilot-scale validation.

Precast Construction Applications

Heat-cured geopolymer and hybrid mixes are reported across multiple studies to achieve early (1-3 day) compressive strengths sufficient for rapid formwork turnover, a critical operational requirement in precast manufacturing. Railway sleepers and sewer/drainage pipes represent the most mature precast geopolymer application category, owing to the compatibility of controlled factory curing with geopolymer reaction kinetics and the high chemical resistance required in sewer environments. Structural precast elements (beams, columns, slabs, tunnel segments) are reported as emerging but less mature application categories. Reviewers note that curing temperatures in the 50-75°C range are compatible with

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existing precast steam-curing infrastructure, lowering the capital barrier to adoption [38]. Figure 2 illustrates the distinct application pathways and performance requirements governing the deployment of waste-valORIZED concrete in pavement versus precast construction, as discussed in the following two sections.

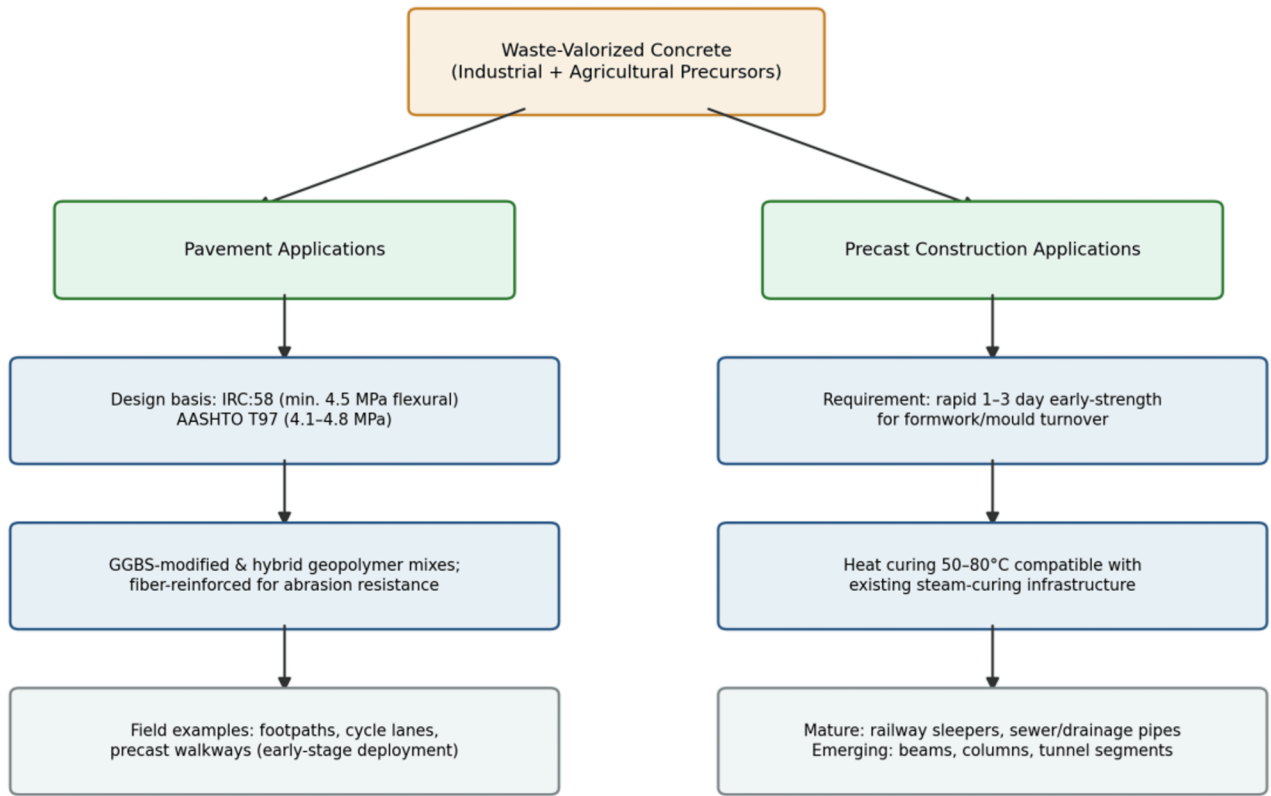


FIGURE 2: Application Pathway Diagram

Correlation discussion: compressive strength, durability, and sustainability indicators

Reviewed studies consistently report that mixes achieving higher compressive strength through gel-network densification also exhibit improved chloride and acid resistance, consistent with a shared underlying mechanism of pore structure refinement [15,16,24,25]. This correlation is reported most strongly for cementitious-precursor materials (FA, GGBS, RHA, red mud) and less consistently for aggregate-replacement materials (steel slag, copper slag, marble dust), where strength gains are more often attributed to particle packing or interfacial bonding effects. Several LCA studies report that the precursor combinations achieving the highest strength do not always correspond to the lowest GWP, since GGBS production and alkaline activator manufacturing carry non-trivial embodied emissions; reviewers note this trade-off as a key reason for integrating LCA directly into mix optimization. Conversely, durability improvements align positively with sustainability outcomes through extended service life and reduced maintenance-phase emissions, even where this extension is not always captured within cradle-to-gate LCA system boundaries [17].

Challenges and Limitations

Synthesizing the reviewed commercialization and adoption literature, recurring challenges include: (i) material property inconsistency, with variability in precursor source chemistry (especially FA and agricultural ashes) cited as the most frequent barrier to standardized specification; (ii) alkaline activator cost, safety, and carbon footprint, which represent both economic and environmental bottlenecks; (iii) regulatory and code gaps, with the absence of mature design codes

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and standardized testing protocols cited as a significant barrier to mainstream adoption; (iv) inconsistent regional availability of specific industrial by-products (particularly red mud and certain agricultural ashes); and (v) limited large-scale field demonstration data and conservative industry/regulatory attitudes toward unfamiliar binder systems [17,38].

Future Research Directions

Based on the gaps identified throughout this review, the following directions are recommended for future primary research: (i) systematic investigation of ternary and quaternary hybrid systems combining industrial and agricultural precursors (e.g., GGBS + RHA + red mud; steel slag aggregate + SCBA binder) remains comparatively underexplored relative to single-material studies; (ii) development of a harmonized LCA reporting framework specific to waste-based concrete, addressing system boundary, functional unit, and by-product allocation standardization; (iii) development and evaluation of low-carbon activator alternatives, including waste-derived sodium silicate, carbonate-based activators, and recycled-concrete-powder-based activators; (iv) long-term field trials in actual pavement and precast applications addressing creep, shrinkage, bond strength with reinforcement, freeze-thaw performance, and carbonation resistance beyond the 28-day laboratory window; (v) systematic heavy-metal leaching characterization for red mud and certain industrial slags as a prerequisite for expanded structural deployment; (vi) application of machine-learning-assisted mix optimization across the full set of materials reviewed; and (vii) systematic evaluation of high-biomass-yielding crop ashes (e.g., Napier grass) as novel agricultural SCM precursors [17,21,24,25,38].

Conclusions

This review synthesized the available literature on eight industrial waste materials (FA, GGBS, steel slag, copper slag, silica fume, marble dust, quarry dust, and red mud) and six agricultural waste materials (rice husk ash, sugarcane bagasse ash, palm oil fuel ash, coconut shell ash, bamboo leaf ash, and wheat straw ash) utilized in sustainable concrete for pavement and precast infrastructure applications. The reviewed studies demonstrate that these waste-derived materials can partially or fully replace conventional concrete constituents while maintaining or enhancing mechanical strength, durability, and long-term performance, with improvements attributed to pore refinement, microstructural densification, enhanced interfacial transition zones, and supplementary pozzolanic reactions. LCA studies consistently report substantial reductions in GWP compared with conventional concrete, although alkaline activator production remains a significant environmental hotspot in alkali-activated systems. Variability in waste material properties, the absence of standardized mix-design procedures, limited long-term field performance data, and inconsistencies in sustainability assessment methodologies continue to restrict broader adoption. Future research should therefore prioritize optimizing hybrid waste-material combinations, developing low-carbon activation systems, establishing standardized testing protocols, and conducting large-scale field validations for pavement and precast applications.

Additional Information

Author Contributions

All authors have reviewed the final version to be published and agreed to be accountable for all aspects of the work.

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Data Availability Statements

Data sharing is not applicable. This work is theoretical; no datasets were generated or analyzed.

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