© SEP 2026 | IRE Journals | Volume 10 Issue 3 | ISSN: 2456-8880
DOI: https://doi.org/10.64388/IREV10I3-1723549

Recycled Materials and Sustainable Construction Chemicals for Low-Carbon Industrial Development in Saudi Arabia

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Abstract- Saudi Arabia's industrial growth offers two key materials challenges: reducing the embodied carbon of construction and diverting mineral, glass, polymeric, metallurgical, and construction-and-demolition waste from disposal. This review analyzes how recycled materials and sustainable construction chemicals can be integrated as a unified low-carbon strategy, rather than as separate innovations. It synthesizes 2020–2025 literature on recycled aggregates, recycled powders and glass, supplementary cementitious materials, alkali-activated binders, limestone-calcined-clay systems, and performance-enhancing chemicals such as polycarboxylate superplasticizers and corrosion inhibitors. The review focuses on the Saudi context, where high temperatures, chloride-rich coastal environments, long transport distances, rapid project schedules, and evolving circular-economy goals influence the balance between the laboratory results and real-world implementation. Results show that carbon reduction is greatest when high-volume mineral substitution is combined with admixtures that maintain workability, reduce water demand, manage durability risks, and extend service life. While recycled aggregate reduces demand for natural resources, it can increase porosity and binder requirements; therefore, effective treatment, grading, and use of low-clinker binders are essential. Waste glass and finely processed demolition powders can serve as aggregates or reactive components, but particle size, alkali-silica reaction control, and source consistency are critical. Alkali-activated and limestone-calcined-clay binders enable further clinker reduction, making chemical compatibility increasingly important as binder chemistry differs from ordinary Portland cement. A successful Saudi transition ought to prioritize performance-based specifications, regional material passports, verified life-cycle assessments, local beneficiation infrastructure, and procurement policies that reward whole-life carbon reduction rather than nominal recycled content. The paper concludes with a governance framework that links waste streams, binder design, chemical admixtures, durability qualification, and industrial-scale deployment.

Keywords: Recycled materials; sustainable construction chemicals; low-carbon concrete; circular economy; Saudi Arabia; construction and demolition waste; supplementary cementitious materials; Vision 2030

I. INTRODUCTION

Concrete-intensive infrastructure is central to industrial development, yet its material system concentrates two environmental burdens: extracting large quantities of virgin aggregates and the carbon intensity of Portland-cement clinker. Circular responses have often focused on replacing natural aggregate with construction and demolition waste. Meanwhile, decarbonization research has examined supplementary cementitious materials, alkali-activated binders, and clinker-efficient cements. Recent reviews show that these streams should not be managed independently. Recycled aggregate concrete can conserve quarry resources and reduce landfill demand. Still, adhered mortar, higher absorption, heterogeneous contaminants, and additional interfacial transition zones can compromise workability and durability unless mixture design is adjusted [1–5]. Likewise, many waste-derived aggregates and powders are technically viable only within bounded replacement ranges and with adequate pretreatment [6–8].

The Saudi case makes integration especially important. Industrial cities, giga-projects, housing expansion, roads, ports, and energy infrastructure create large material flows and substantial future demolition stocks. At the same time, concrete faces severe thermal cycles, aridity, sulfate-bearing soils, and chloride exposure in coastal zones. These conditions mean that "recycled" cannot be treated as synonymous with "low carbon" or "durable." Life-cycle studies repeatedly show that cement content and transport can dominate environmental impacts, so recycling strategies that inadvertently require more binder or long-haul processing may lose part of their expected benefit [9–11]. Regional evidence from the Gulf also indicates that recycled aggregate can become environmentally and economically attractive when transport, landfill avoidance, and local supply chains are explicitly included [11].

A second limitation in conventional sustainability discussions is the under-treatment of construction chemicals. Modern low-carbon concretes are not simply mixtures with less cement. They depend on controlled rheology, dispersion, setting, curing, corrosion protection, and sometimes surface or aggregate treatment. Polycarboxylate superplasticizers can reduce water demand and enable lower binder intensity, but their adsorption and dispersion behavior changes with sulfate content, clay contamination, calcined clays, and alkali-activated precursors [25]. Corrosion inhibitors can extend reinforced-concrete service life in chloride exposure and thereby reduce replacement-related carbon, although environmental and compatibility considerations have to be assessed [26,27]. Sustainable chemistry therefore concerns both the additive's embodied footprint and the system-level carbon avoided through performance.

This review adopts a systems perspective in which recycled solids, alternative binders, and construction chemicals are co-designed around verified performance. Such integration is especially relevant to Saudi Arabia because infrastructure delivery must coexist with resource efficiency, industrial diversification, and long service lives amid demanding exposure. The analysis therefore treats carbon reduction as a life-cycle outcome rather than a single-material attribute. It connects waste beneficiation with mixture design, placement, durability, maintenance, and end-of-life recovery, allowing apparently competing goals—recycled content, clinker reduction, constructability, resilience, and industrial value—to be considered within a decision framework for low-carbon development.

II. AIM OF THE STUDY

This study intends to critically synthesize recent evidence on recycled construction materials and sustainable construction chemicals, and to develop an implementation framework for low-carbon industrial development in Saudi Arabia. It evaluates not only the potential of individual materials to replace conventional constituents, but also how preprocessing, binder chemistry, admixture compatibility, durability, logistics, and policy interact to influence net carbon and resource outcomes.

III. RESEARCH OBJECTIVES

The study pursues five objectives. First, it evaluates the technical and environmental roles of recycled aggregates, recycled fines, glass, plastics, metallurgical by-products, and other secondary materials in concrete. Second, it examines low-clinker and clinker-free binder routes, including supplementary cementitious materials, geopolymer or alkali-activated systems, and limestone-calcined-clay cement. Third, it analyzes how chemical admixtures and durability-enhancing chemicals enable or constrain recycled and low-carbon mixtures. Fourth, it identifies Saudi-specific deployment conditions related to climate, exposure, transport, industrial symbiosis, specification, and quality assurance. Fifth, it translates the evidence into research, managerial, and policy priorities for broad industrial adoption.

IV. RESEARCH QUESTIONS

Four questions guide the review: (RQ1) Which recycled material pathways offer the most credible combination of resource circularity, mechanical performance, durability, and carbon reduction? (RQ2) How do low-carbon binders and sustainable construction chemicals modify the performance limitations associated with recycled constituents? (RQ3) Which technical and institutional barriers are most consequential for Saudi Arabian deployment under hot-arid and coastal exposure conditions? (RQ4) What research, procurement, certification, and industrial infrastructure are needed to move from isolated laboratory mixtures to verified low-carbon construction systems?

V. REVIEW METHODOLOGY

An integrative structured-review method was selected because the research question spans materials engineering, durability, life-cycle assessment, and implementation policy. Searches were conducted in Scopus, Web of Science, ScienceDirect, SpringerLink, and publisher platforms, using Crossref or publisher records to verify bibliographic and DOI information. Core terms combined "recycled aggregate," "construction and demolition waste," "recycled powder," "waste glass," "steel slag," "supplementary cementitious material," "geopolymer," "alkali-activated," "limestone calcined clay cement," "superplasticizer," "corrosion inhibitor," "life cycle assessment," "low carbon concrete," and "Saudi Arabia" or "Gulf." The principal evidence window was 2020–2025, and older sources were considered only when indispensable for the interpretation of mechanisms; the final reference set was deliberately restricted to 30 peer-reviewed items, overwhelmingly from 2020 onward.

Inclusion criteria required direct relevance to concrete, cementitious materials, construction waste valorization, chemical admixture function, durability, or environmental assessment. Reviews were prioritized for broad synthesis, with selected experimental and life-cycle studies included when they clarified field performance or regional applicability. Excluded materials comprised trade articles, non-peer-reviewed webpages, unsupported market claims, patents, and papers with only tangential relevance. Fabricated PRISMA-style screening counts were not created, as the review was designed as an integrative evidence synthesis rather than a registered systematic review with a frozen database export. Transparency is provided through the stated search domains, eligibility rules, and complete reference set. Quality assessment considered journal peer-review status, methodological transparency, sample or evidence coverage, clarity of mixture variables, durability relevance, life-cycle boundary definition, and alignment between conclusions and reported evidence. Greater interpretive weight was assigned to comprehensive reviews in Resources, Conservation and Recycling, Cement and Concrete Research, Construction and Building Materials, Journal of Cleaner Production, and comparable journals, while regional life-cycle studies were used to contextualize logistics and economics. Cross-study synthesis followed five themes: secondary aggregates and powders; low-carbon binders; chemical enabling technologies; life-cycle and durability trade-offs; and Saudi implementation. Contradictory findings were treated as evidence of sensitivity to source quality, particle size, replacement ratio, curing, exposure, or functional unit, rather than being averaged into a single "optimal" percentage.

The method has three limitations. Publication bias favors successful laboratory formulations; many studies do not report comparable functional units or long-term exposure; and Saudi-specific peer-reviewed field data remain thinner than global laboratory evidence. Consequently, the review distinguishes mature findings, transferable principles, and Saudi-specific propositions that require local validation.

VI. THEMATIC LITERATURE REVIEW/CRITICAL ANALYSIS

Recycled aggregates are the most direct circular route because they replace large volumes of virgin stone while diverting demolition waste. Reviews consistently identify residual mortar as the governing weakness of recycled concrete aggregate: it increases porosity and water absorption. It creates old and new interfacial transition zones that influence stiffness, shrinkage, and transport properties [1,2,5]. Pretreatment can improve aggregate quality, but thermal, mechanical, chemical, carbonation, and microbial methods carry different energy and process burdens [1]. A better industrial strategy is therefore not "maximum treatment" but treatment proportional to end-use performance. High-grade structural concrete may justify selective demolition, source separation, advanced crushing, and beneficiation; lower-grade applications can accept broader variability.

Fine recycled aggregate and recycled powder require separate consideration. Fine fractions possess high surface area and often contain paste-rich particles, making water demand and variability more severe than for coarse fractions [3,8]. However, their environmental value can be substantial because fines are otherwise difficult to market. Carbon accounting should capture avoided disposal and reduced quarrying but also additional grinding, washing, and binder demand [9,10]. Gulf-region life-cycle evidence reinforces the importance of transport distance and local processing: regional recycling can be competitive when virgin aggregates and landfill routes involve longer logistics [11]. For Saudi Arabia, this supports decentralized or project-adjacent recycling hubs linked to demolition inventories rather than a single national processing model.

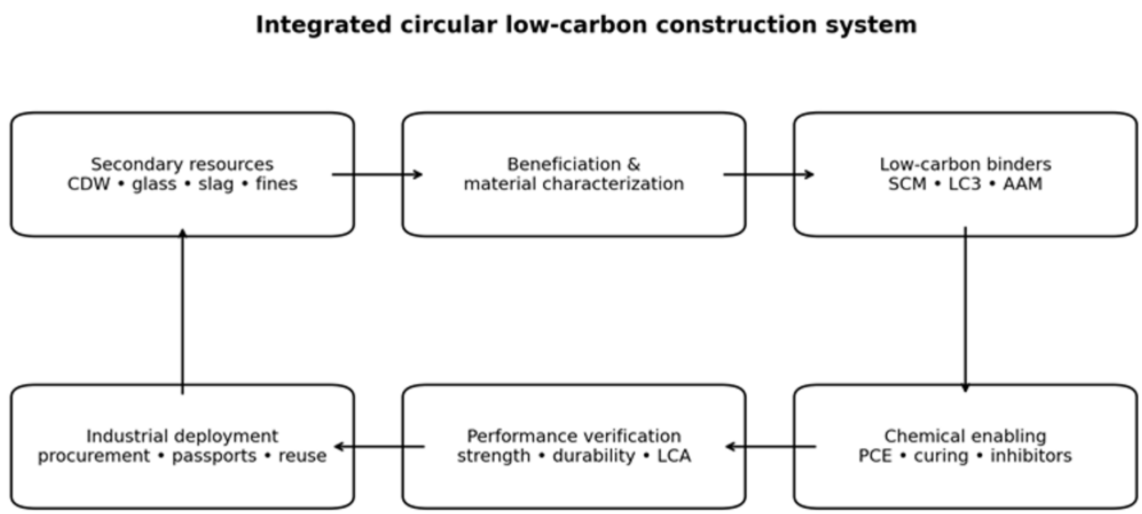

Figure 1. Integrated circular low-carbon construction system linking secondary resources, low-carbon binders, construction chemicals, performance verification, and deployment.

Waste glass illustrates the boundary between recycled aggregate and reactive construction chemical/mineral functionality. Finely ground glass can contribute pozzolanic silica, while coarser particles can replace sand or aggregate. Performance depends strongly upon particle size, glass type, replacement level, and curing [21–24]. Reviews report that fine glass powder can densify microstructure and improve selected durability indicators, whereas poorly controlled particle size can increase alkali-silica reaction risk [22,23]. Field evidence using powder waste glass has shown that carefully designed mixtures can remain constructible and durable over multi-year exposure, strengthening the case for moving beyond short cube tests [24]. Saudi deployment would require source sorting, chloride and contaminant control, fineness specification, and enhanced expansion testing customized to local aggregates.

Other waste streams should be evaluated through performance niches rather than universal substitution targets. Iron and steel slags can function as aggregates or cementitious constituents but require attention to volumetric stability and chemistry [7]. Plastic waste can reduce density and divert persistent waste, yet many studies report trade-offs in stiffness, strength, bonding, and fire or durability behavior as replacement levels increase [28]. Fiber reinforcement may recover tensile and crack-control performance in recycled aggregate systems [29,30], but fiber production impacts and end-of-life implications must be considered. Agricultural and industrial by-products can be transformed into artificial aggregates, although sintering can erode carbon benefits and cold-bonded routes may be preferable where suitable [6]. The decision criterion should therefore balance clinker avoidance, virgin extraction avoidance, service-life performance, and processing energy.

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Table 1. Comparative roles and constraints of recycled and low-carbon material pathways

Pathway	Primary low-carbon/circular function	Key technical constraint	Saudi qualification priority
Recycled concrete aggregate	Avoids virgin aggregate and landfill	Absorption, residual mortar, variability	Moisture correction, chloride/sulfate limits, grading
Recycled fines / powders	Valorizes difficult fine fractions; filler/reactive potential	High surface area and variable reactivity	Fineness, chemistry, water/admixture demand
Waste glass	Aggregate or pozzolanic replacement	ASR risk and source contamination	Particle size, expansion testing, sorting
Slag / industrial by-products	Aggregate or SCM; reduces virgin extraction/clinker	Chemistry and dimensional stability	Source certification and volumetric stability
LC3 / SCM blends	Direct clinker reduction	Raw-material variability and admixture demand	Clay mapping, sulfate balance, durability
Alkali-activated binders	Deep clinker displacement and waste utilization	Activator footprint, curing, standardization	Ambient-curing validation and transparent LCA

Binder decarbonization generally offers a larger carbon lever than aggregate substitution because clinker production dominates conventional concrete emissions. Supplementary cementitious materials can lower clinker factor while improving later-age microstructure and selected durability properties; nevertheless, each SCM has distinct reactivity, curing sensitivity, and availability constraints [18–20]. As power and steel sectors decarbonize, traditional fly ash and blast-furnace slag supplies may become constrained, increasing the importance of calcined clays, natural pozzolans, recycled glass, and processed demolition fines. The design problem is thus shifting from selecting a named by-product to characterizing local materials by chemistry, fineness, amorphous content, and performance.

Limestone-calcined-clay cement is particularly relevant to zones with abundant limestone and clay because it can achieve major clinker reduction without relying on scarce industrial by-products. The LC3 literature explains the cooperation between reactive alumina from calcined clay and limestone, which promotes carboaluminate formation as well as microstructural refinement [17,18]. Mixture design nevertheless requires sulfate balance, clay characterization, and compatibility with chemical admixtures. For Saudi Arabia, a mineral-resource mapping program could identify low-grade kaolinitic clays near cement plants and industrial corridors, reducing transport and creating a domestic low-carbon binder pathway. Such localization may be strategically more robust than long-term dependence on imported SCMs.

Alkali-activated and geopolymer systems can displace Portland clinker more fully and incorporate fly ash, slag, glass, and other aluminosilicate wastes [12–16]. Recycled aggregate can also be combined with geopolymer binders, integrating two circular strategies [13]. Yet the environmental superiority of these systems is not automatic. Activator production, curing energy, precursor transport, and durability assumptions affect life-cycle outcomes. Reviews also show that the curing regime strongly changes strength and durability [15]. Saudi hot weather may benefit some ambient or warm-curing reactions, but rapid moisture loss and limited site control remain concerns. Standardization should therefore focus on performance classes and precursor-activator transparency rather than labeling all geopolymer concrete as inherently green.

Construction chemicals are the enabling layer connecting high-solid-replacement mixtures to practical concrete production. Polycarboxylate superplasticizers achieve high water reduction through adsorption and steric dispersion, however their effectiveness depends on molecular configuration and cementitious surface chemistry [25]. Recycled fines, clay-bearing aggregates, calcined clays, and high-alkali binders can change adsorption demand and slump retention. In low-carbon design, an admixture that permits lower water-binder ratio, lower paste volume, or higher SCM content can have a favorable system effect even if the chemical itself has an embodied footprint. Procurement should therefore compare "carbon per delivered performance" rather than rejecting chemicals merely because they are manufactured products.

Durability-enhancing chemicals create a second system effect. Chloride-induced reinforcement corrosion is a central service-life risk in marine and salt-exposed concrete, and corrosion inhibitors can delay initiation or reduce corrosion rate [26,27]. Their sustainability value is strongest where service-life extension avoids repair, replacement, traffic disruption, and additional cement consumption. However, inhibitors must be compatible with alternative binders, reinforcement systems, and local exposure. Nitrite-based products have established performance, but environmental and health concerns motivate research into organic and alternative inhibitors [26]. Saudi coastal infrastructure therefore needs comparative testing that combines electrochemical performance, concrete transport properties, leaching, and whole-life carbon.

The central finding across these themes is that recycled solids and chemicals are interdependent. A porous recycled aggregate may require water compensation that raises binder demand; a superplasticizer can avoid that penalty. A high-SCM binder may improve chloride resistance but alter carbonation behavior; curing and inhibitor strategies may then become important. Fine glass may increase reactivity, but also alkali risk; particle-size control and binder alkalinity determine the outcome. Accordingly, material selection should proceed through coupled mixture optimization rather than single-variable replacement percentages.

Another issue is distinguishing between circularity and decarbonization at the material-processing stage. Crushing concrete into aggregate is usually less energy intensive than manufacturing clinker, yet washing, repeated crushing, thermal treatment, and fine grinding can grow important when pursuing high-quality recycled products. Current applications reviews emphasize that construction and demolition waste can serve in concrete, road bases, masonry products, and other applications, suggesting that the highest-value outlet is not always the lowest-carbon outlet [3]. Cascaded use may be preferable: clean concrete fractions can return to structural concrete, mixed mineral fractions can enter road layers or blocks, and very fine fractions can be investigated as fillers or reactive powders. This hierarchy can minimize processing intensity while retaining material value.

The interaction between recycled aggregates and low-carbon binders also merits closer attention. Recycled aggregate concrete research commonly uses conventional Portland cement, while geopolymer studies frequently use natural aggregates. Combining both strategies can magnify circular benefits, but the resulting system has more interfaces, more variable pore solution chemistry, and greater curing sensitivity [12–16]. Recycled aggregate may internally cure some binders because of its stored moisture, but uncontrolled absorption might also disrupt effective activator concentration or the water-to-binder ratio. Research on geopolymer recycled-aggregate concrete indicates technical feasibility, but scalable practice requires moisture-state specifications, activator handling protocols, and robust acceptance tests [13]. In Saudi conditions, these controls must remain workable at high ambient temperatures and during long haul times.

Chemical admixtures should also be evaluated according to compatibility windows rather than single recommended dosages. PCE performance results from anchoring groups, backbone chemistry, side-chain length, charge density, and molecular topology [25]. Calcined clay, recycled powder, and clay contamination may increase surface area or compete for adsorption, which can sharply change slump retention. This explains why a dosage optimized for ordinary cement may underperform in a low-clinker mixture even when compressive strength potential is high. A sustainable admixture strategy therefore includes raw-material acceptance limits, simple plant-scale rheology tests, and feedback between chemical supplier and concrete producer. Quantify the avoided carbon from reduced cement or water demand alongside the additive footprint.

Service life is equally central to the environmental case. Carbon-efficient binders sometimes show slower early strength development or different carbonation and chloride-binding behavior, while recycled aggregates can increase transport routes if porosity is not controlled. These effects do not invalidate low-carbon materials; they shift attention toward performance-based durability design. Corrosion inhibitors are one possible intervention, but good curing, reduced permeability, cover depth, crack control, and binder chemistry generally remain the first line of defense [26,27]. Inhibitors should therefore be positioned as part of an exposure-management portfolio, particularly for marine assets where repair emissions and operational disruption may be substantial.

Industrial feasibility ultimately depends on quality consistency. Recycled streams are intrinsically variable because building age, original concrete strength, masonry content, gypsum, glass, and contaminants differ. The appropriate response is not to demand virgin-material uniformity but to define statistically defensible acceptance envelopes. Batch-level moisture, density, absorption, chloride, sulfate, and composition indicators can be connected to adaptive mix-design rules. This approach converts variability from an uncontrolled risk into a managed input and is compatible with digital quality systems progressively used in large construction programs.

VII. DISCUSSION

The evidence suggests three hierarchy levels for Saudi low-carbon construction. The first is "resource substitution," where recycled aggregates, glass, slags, plastics, and demolition fines replace virgin materials. This level is visible and politically attractive, but carbon savings can be modest if cement content is unchanged. The second is "binder transformation," where SCMs, LC3, and alkali-activated systems reduce clinker intensity. This generally offers larger embodied-carbon leverage but creates greater sensitivity to raw-material chemistry and curing. The third is "performance enabling," where admixtures, curing control, corrosion protection, and quality assurance allow the first two levels to operate without sacrificing constructability or service life. Low-carbon industrial development requires all three.

This hierarchy also explains why recycled content should not be used as the sole sustainability metric. A mixture with high recycled aggregate but excessive cement could have greater embodied carbon than a mixture with less recycled aggregate and a much lower clinker factor. Conversely, a low-clinker concrete that deteriorates early in chloride exposure may shift impacts into repair cycles. LCA studies of recycled aggregate warn that functional unit, transport, allocation, and mixture design can change conclusions [9–11]. Saudi procurement therefore needs project-specific environmental product data and whole-life performance assumptions rather than generic carbon factors imported from different electricity grids and transport systems.

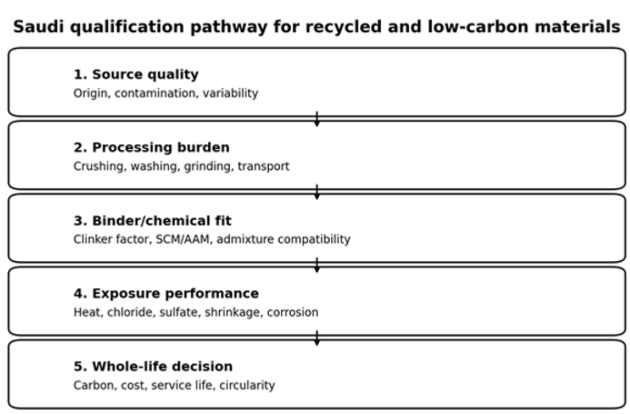

Figure 2. Performance-based qualification pathway for recycled and low-carbon construction systems in Saudi Arabia.

Geography matters. Riyadh and central industrial zones may prioritize demolition recycling, calcined-clay supply, and heat-resilient curing. Red Sea and Arabian Gulf developments require stronger chloride, sulfate, and corrosion qualification. Remote industrial projects may face transport distances that make local natural materials environmentally preferable to distant recycled products unless mobile beneficiation is available. Circularity should therefore be organized through regional material ecosystems linking demolition contractors, recyclers, cement plants, ready-mix producers, chemical suppliers, testing laboratories, and asset owners.

The most mature near-term route is likely blended cement or clinker-efficient concrete combined with quality-controlled recycled aggregate at moderate replacement, advanced water-reducing admixtures, and exposure-specific durability design. More disruptive geopolymer or high-recycled-content systems should progress through demonstration projects with instrumented field monitoring. This staged pathway avoids the false choice between conservative standards and rapid innovation: conventional projects can reduce carbon immediately, while higher-risk technologies build an evidence base for future specification.

Table 2. Proposed staged implementation priorities for Saudi industrial construction

Stage	Material strategy	Chemical/performance strategy	Evidence required
Near-term deployment	Moderate recycled aggregate + blended low-clinker cement	PCE optimization, curing control, exposure-specific durability	Plant trials, EPD/LCA, standard durability tests
Demonstration scale	High recycled content, glass powder, LC3	Compatibility mapping, shrinkage and corrosion control	Instrumented pilot projects and multi-year monitoring
Advanced transition	Alkali-activated / geopolymer systems with recycled inputs	Activator optimization, admixture compatibility, service-life design	Saudi-specific standards, field databases, whole-life carbon
System governance	Regional circular supply chains and material passports	Batch traceability and adaptive mix control	Accredited labs, procurement thresholds, verified datasets

A second implication concerns industrial symbiosis. Cement plants, precast factories, demolition contractors, glass processors, steel producers, and chemical manufacturers can exchange materials only when they coordinate specifications, quantities, and timing. A slag or glass stream may be technically suitable but commercially unusable if volumes fluctuate or transport requires long backhauls. Long-term offtake agreements and shared preprocessing facilities can reduce these transaction barriers. For major Saudi industrial zones, spatial planning of material flows could identify where waste sources, cement kilns, aggregate demand, and project pipelines overlap.

The evidence also supports a distinction between product certification and project qualification. A recycled aggregate may satisfy a generic material standard, but a specific low-carbon mixture still needs verification for its intended exposure and structural role. Conversely, requiring every project to repeat all foundational material testing would slow adoption. A tiered system can certify recurring feedstocks and production controls while reserving project-specific testing for mixture performance, exposure class, and unusual constituents. This balances innovation with construction risk management.

A final requirement is measurement discipline. Every demonstration should report a reference mixture, declared functional unit, cradle-to-gate and service-life assumptions, constituent transport distances, recycled-content definition, and relevant durability indicators. Without this information, apparently similar carbon claims cannot be compared, and procurement decisions may reward accounting choices rather than genuine reductions. Consistent reporting would also allow Saudi project data to accumulate into national benchmarks, enabling regulators and designers to tighten carbon thresholds safely over time while retaining flexibility for different regional materials, structural functions, and exposure conditions.

VIII. RESEARCH GAPS AND FUTURE RESEARCH

Five gaps warrant priority. First, Saudi material databases are incomplete. Research should characterize regional demolition waste, glass streams, slags, quarry fines, clays, and industrial by-products using standardized mineralogical, chemical, physical, and contamination metrics. Second, multi-variable mixture studies are needed. Most experiments vary one recycled constituent at a time, whereas industrial low-carbon concretes combine recycled aggregate, SCMs, admixtures, fibers, curing compounds, and inhibitors. Design-of-experiments and machine-learning approaches should optimize these interacting variables without replacing mechanistic validation.

Third, durability evidence must shift from short laboratory tests to exposure-specific service-life data. Chloride ingress, sulfate attack, carbonation, thermal cycling, drying shrinkage, and corrosion should be tested under Saudi-relevant temperatures and humidity. Fourth, construction-chemical compatibility needs dedicated study for LC3, recycled fines, and alkali-activated binders. PCE adsorption, retardation, air entrainment, curing compounds, inhibitors, and surface treatments may behave differently as pore-solution chemistry changes [25–27]. Fifth, comparative LCA should use Saudi electricity, fuel, desalinated water, transport, quarry, landfill, and recycling data. Studies should report sensitivity to functional unit and service life so that carbon claims remain auditable [9–11].

Future demonstration programs should publish mix composition, environmental data, quality-control limits, placement behavior, and multi-year field performance. Open data would reduce repeated laboratory work and accelerate code acceptance. Research should also quantify the carbon and economic value of avoided maintenance, particularly where chemical durability measures extend the life of coastal infrastructure.

Research should additionally investigate scale-up phenomena that small laboratory batches rarely capture: stockpile moisture gradients, recycled-aggregate dust, seasonal temperature, admixture dosing accuracy, pumping pressure, mixer energy, and prolonged delivery time. Pilot studies should compare laboratory and plant batches using the same acceptance metrics. Another gap concerns repairability and end-of-life behavior. Assess low-carbon mixtures for compatibility with repair mortars, future crushing, reinforcement recovery, and repeated recycling so today’s circular solution does not become tomorrow’s difficult waste stream.

IX. PRACTICAL/MANAGERIAL/POLICY IMPLICATIONS

For producers, the priority is controlled feedstock rather than nominal waste intake. Recyclers should implement selective demolition protocols, contamination thresholds, grading, moisture management, and traceable batch certificates. Ready-mix plants should pre-saturate or correct moisture in recycled aggregates and verify admixture demand for every major feedstock change. Cement and chemical suppliers should co-develop admixture packages for high-SCM, LC3, and alkali-activated systems rather than transferring conventional OPC dosage rules unchanged.

For asset owners and contractors, specifications should move from prescriptive exclusions to performance-based limits covering strength, permeability, shrinkage, chloride resistance, sulfate resistance, dimensional stability, and embodied carbon. Pilot projects should begin with noncritical, repetitive elements, then expand to structural and exposure-critical applications as evidence accumulates. Digital material passports can connect waste origin, processing history, laboratory results, mix design, and installed location, creating a basis for future reuse and forensic quality assessment.

Policy should align circularity and decarbonization incentives. Landfill charges can improve recycling economics, but recycled-content mandates alone may encourage low-value use. Public procurement should instead set declining whole-life carbon benchmarks while recognizing verified recycled content and local sourcing. The Saudi Building Code and related material standards can provide qualification routes for recycled aggregate, glass powder, LC3, geopolymer binders, and durability-enhancing chemicals. Certification laboratories should be equipped to test alkali-silica reactivity, chloride migration, sulfate resistance, shrinkage, and chemical compatibility. Finally, industrial clusters should be encouraged to exchange mineral by-products and waste heat, turning cement plants and recycling facilities into circular-material hubs rather than isolated supply chains.

X. LIMITATIONS

This review is limited by the heterogeneity of the available literature and by the uneven geographical distribution of field evidence. Many publications use laboratory materials with tightly controlled properties that may not represent mixed demolition streams. Reported replacement percentages are not directly comparable because water-binder ratio, cement chemistry, curing, aggregate source, and testing age differ. Environmental comparisons are similarly sensitive to system boundary, allocation, transport, electricity mix, and assumed service life. The paper therefore does not prescribe universal optimum replacement levels. Its Saudi recommendations are evidence-informed implementation propositions that require local pilot validation. In addition, the selected 30-reference set was intentionally focused to maintain verifiability and recent relevance; it does not constitute an exhaustive bibliometric inventory.

XI. CONCLUSION

Recycled materials can support low-carbon industrial development in Saudi Arabia, but their value emerges from system design rather than from recycled content alone. Recycled concrete aggregate, demolition fines, glass, slags, plastics, and other secondary materials reduce disposal and virgin-resource demand, yet some introduce absorption, variability, reactivity, or durability penalties. Binder transformation through SCMs, LC3, and alkali-activated systems offers a stronger route to embodied-carbon reduction because it directly lowers clinker demand. Construction chemicals provide the enabling bridge: superplasticizers can preserve rheology and lower water or paste demand, while corrosion inhibitors and related durability measures can protect service life in aggressive exposure.

The practical implication is a shift from material substitution to integrated performance engineering. Saudi Arabia should couple regional waste characterization with low-clinker binder development, admixture compatibility testing, durability qualification, and locally representative LCA. Performance-based codes, material passports, demonstration projects, and whole-life-carbon procurement can then convert laboratory options into bankable industrial practices. The most credible transition is staged: deploy mature blended and recycled systems now, monitor advanced binders in targeted pilots, and expand approval as field evidence grows. This approach aligns circular-resource management with industrial competitiveness and durable infrastructure, ensuring that carbon reductions are not purchased at the expense of constructability, resilience, or future maintenance.

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DOI: https://doi.org/10.64388/IREV10I3-1723549

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