Recycled and Waste Materials in Sustainable Concrete: A Critical Review of Environmental Benefits, Engineering Performance, Challenges, and Future Directions

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Abstract
Background: Sudden Infant Death Syndrome (SIDS) and Sudden Unexplained Infant Deaths The rapid growth of infrastructure and urban development has resulted in increasing consumption of natural resources and generation of large quantities of construction, industrial, agricultural, and municipal waste. The incorporation of waste and recycled materials into concrete has therefore emerged as a promising approach for reducing the environmental impacts of conventional concrete and promoting sustainable and circular construction practices. This review critically examines the utilization of recycled concrete aggregates, industrial by-products, agricultural ashes, waste glass, plastic waste, rubber waste, and quarry waste as partial replacements for conventional concrete constituents. The review evaluates their influence on the fresh properties, mechanical performance, durability, environmental impact, and overall sustainability of concrete. The available literature indicates that recycled materials can reduce the consumption of natural aggregates and Portland cement, minimize waste disposal, conserve natural resources, and potentially reduce embodied carbon and energy consumption. However, their incorporation may also introduce challenges, including reduced workability, increased water absorption, weaker interfacial bonding, lower strength and stiffness at high replacement levels, delayed strength development, alkali–silica reaction, and considerable variability in material quality. The review further highlights that the environmental advantages of recycled concrete cannot be assessed solely on the basis of replacement percentages; transportation, processing energy, material quality, durability, service life, and end-of-life recycling must also be considered through life-cycle assessment. Significant research gaps remain in the combined use of multiple waste materials, long-term durability, full-scale structural validation, standardized characterization, and integrated performance–environmental assessment. Future research should focus on multi-waste concrete, life-cycle-based optimization, artificial intelligence-assisted mix design, and multi-objective assessment integrating strength, durability, cost, embodied carbon, and resource efficiency. Such developments can support the transition toward low-carbon, durable, resource-efficient, and circular concrete for sustainable construction.

Keywords: Recycled concrete aggregate; industrial by-products; agricultural ash; waste glass; plastic waste; waste rubber; quarry waste; sustainable concrete; circular economy; life-cycle assessment; low-carbon concrete.

Introduction

Concrete is the dominant construction material used worldwide because of its versatility, durability, availability, and relatively low cost. However, conventional concrete production is associated with substantial environmental impacts arising from cement manufacturing, extraction of natural aggregates, transportation, energy consumption, and disposal of construction and demolition waste. The environmental burden becomes increasingly significant as infrastructure development and urbanization continue to increase the global demand for concrete.

Portland cement is particularly important from a sustainability perspective because clinker production involves both energy-intensive processes and the calcination of limestone. Consequently, reducing the quantity of Portland cement in concrete through the use of supplementary cementitious materials (SCMs) is an important pathway toward reducing embodied environmental impacts. Industrial by-products such as fly ash, GGBS, and silica fume, together with agricultural ashes such as RHA and SCBA, have consequently received considerable research attention. Recent literature confirms that SCMs and bio-ashes can contribute to sustainable concrete while maintaining satisfactory engineering performance when their processing and replacement levels are appropriately controlled.

The aggregate component presents another major sustainability opportunity. Natural coarse and fine aggregates require quarrying, crushing, screening, and transportation. The substitution of natural aggregates with recycled concrete aggregates derived from construction and demolition waste can reduce the consumption of virgin mineral resources and create a circular pathway for concrete materials. However, RCA generally contains adhered mortar and possesses greater porosity and water absorption than natural aggregate, which can affect fresh concrete behavior, strength, shrinkage, and durability.

Beyond construction and industrial wastes, materials such as waste glass, plastic, rubber, and quarry dust have also been investigated as alternative constituents of concrete. Waste glass can be used as fine or coarse aggregate or as finely ground pozzolanic material, although alkali–silica reaction remains a significant consideration. Plastic waste can be introduced as aggregate or fibre, providing a potential route for waste diversion, but high replacement levels commonly reduce mechanical performance. Similarly, rubberized concrete can offer improved ductility, impact

resistance, toughness, thermal insulation, and vibration-damping characteristics, although the low stiffness and weak bond of rubber generally reduce compressive strength and elastic modulus.
The concept of sustainable concrete has consequently evolved beyond simple waste utilization. A material should not be classified as environmentally sustainable solely because it contains recycled content. Its complete life cycle—including collection, processing, transportation, production, structural performance, service life, demolition, and recycling—must be considered. Recent comparative LCA research demonstrates that the environmental performance of recycled aggregate concrete can be strongly affected by transportation distance, mix design, aggregate processing, and the selected functional unit.
The current state of research on waste and recycled materials in concrete, focusing on The review evaluates their environmental benefits and engineering limitations, establishes the relationship between performance and sustainability, identifies deficiencies in existing research, and proposes future research directions for developing high-performance, low-carbon, and circular concrete.

Literature Review

Recycled Concrete Aggregates

Recycled concrete aggregates are produced primarily through the crushing, screening, and processing of demolished concrete. Their application in new concrete is one of the most direct strategies for recycling construction and demolition waste. Early investigations demonstrated that the moisture condition and microstructure of recycled aggregates have a significant influence on fresh concrete properties and compressive strength. Poon et al. (2004) showed that the moisture condition of recycled aggregate affects slump and early-age strength, highlighting the importance of aggregate conditioning in recycled concrete mix design. Their research also demonstrated the importance of the interfacial transition zone (ITZ) in determining the strength of concrete containing recycled aggregate.
The major difference between natural and recycled aggregates is the presence of adhered old mortar on RCA particles. This attached mortar increases porosity and water absorption and may create a weaker ITZ between the recycled aggregate and new cement paste. Consequently, increasing RCA content can result in reduced workability, elastic modulus, tensile strength, and compressive strength, particularly when untreated RCA is used at high replacement ratios.
Nevertheless, appropriate processing, moisture conditioning, surface modification, optimized particle grading, and the use of SCMs can significantly improve RAC performance. Recent research has focused on surface treatment, internal curing, carbonation treatment, and localized processing technologies to improve recycled aggregate quality while reducing the economic and environmental burden of treatment.

Industrial By-Products

Industrial by-products represent one of the most mature categories of waste-derived concrete materials. Fly ash, GGBS, silica fume, steel slag, and other industrial residues have been extensively investigated as partial cement or aggregate replacements.
Fly ash can improve workability because of its particle morphology and can contribute to later-age strength through pozzolanic reactions. GGBS can reduce clinker consumption and improve resistance to chloride ingress, sulphate exposure, and other durability mechanisms. Silica fume, because of its very fine particle size and high pozzolanic activity, can refine the pore structure and improve strength and permeability characteristics.
The sustainability advantage of SCMs arises principally from reducing the Portland cement requirement. However, the availability of traditional industrial SCMs is changing in many regions because of changes in energy-production technologies and industrial processes. This creates an important need to develop alternative SCMs, including calcined clays, agricultural ashes, recycled powders, and other locally available mineral residues. Recent work on sustainable concrete recognizes industrial by-products and bio-ashes as important components of low-carbon concrete systems.

Waste Glass

Waste glass can be incorporated into concrete as fine aggregate, coarse aggregate, or finely ground glass powder. Its use can reduce landfill disposal and substitute part of the natural aggregate or cementitious material.
The particle size of waste glass is therefore critical. Coarse glass particles may be more susceptible to ASR-related expansion, whereas finely ground glass can demonstrate pozzolanic behavior and may consume calcium hydroxide. The combined use of waste glass with other industrial and agricultural by-products is also an emerging research direction because synergistic effects may reduce the limitations associated with individual waste materials.

Plastic Waste

The incorporation of plastic waste into concrete has attracted considerable attention because of the persistence and large volume of plastic waste. Plastic can be incorporated as coarse aggregate, fine aggregate, powder, or fibre.
A recent systematic review analyzed 174 publications and concluded that plastic waste has potential as an alternative aggregate or fibre, but its effectiveness depends strongly on plastic type, particle size, surface texture, shape, replacement level, and chemical characteristics.
Plastic particles generally have lower stiffness than mineral aggregates and exhibit weak bonding with cement

paste. Consequently, high plastic replacement levels can reduce compressive strength, tensile strength, and elastic modulus. However, plastic can reduce density and thermal conductivity, while plastic fibres can contribute to crack control and post-cracking performance.
The most promising applications may therefore involve controlled quantities of plastic fibres or lightweight plastic aggregate, rather than indiscriminate high-volume replacement of conventional aggregates.

Waste Rubber
Waste tyres present significant disposal challenges because of their durability and resistance to natural degradation. Crumb rubber and shredded tyre particles have therefore been investigated as partial replacements for fine and coarse aggregate.
Rubberized concrete generally exhibits lower compressive strength and stiffness than conventional concrete because rubber has a lower modulus and relatively weak interfacial bonding with cement paste. However, rubber incorporation can improve toughness, impact resistance, ductility, fatigue resistance, and energy absorption.
Therefore, rubberized concrete should be evaluated according to its application-specific performance, rather than judged exclusively by compressive strength.

Quarry Waste
Quarry dust and quarry fines are generated during aggregate production and can be used as partial replacements for natural fine aggregate. Their incorporation can reduce dependence on river sand and improve resource efficiency.
The angular morphology and fine particle content of quarry waste can improve particle packing at appropriate replacement levels. However, excessive fines can increase water demand, reduce workability, and affect the rheological characteristics of fresh concrete.
Quarry waste has an important regional sustainability advantage because its environmental benefit can be particularly significant when the source of quarry waste is located near concrete-production facilities. This reduces transportation requirements and associated emissions.
The increasing demand for concrete has intensified the consumption of natural aggregates and Portland cement, while simultaneously generating large quantities of construction, industrial, agricultural, and municipal waste. Consequently, the incorporation of waste and recycled materials into concrete has emerged as an important approach to reducing resource depletion, landfill disposal, embodied energy, and greenhouse-gas emissions. Research has increasingly investigated recycled concrete aggregates (RCA), industrial by-products such as fly ash and ground-granulated blast-furnace slag (GGBS), agricultural ashes such as rice husk ash (RHA) and sugarcane bagasse ash (SCBA), waste glass, waste plastics, crumb rubber, and quarry waste as partial replacements for conventional concrete constituents.

Comparative Assessment

Material	Main application	Fresh concrete	Mechanical properties	Durability	Sustainability potential
RCA	Coarse/fine aggregate	Usually reduces workability	Moderate reduction at high replacement	Higher absorption; durability requires control	Very high
Fly ash	Cement replacement	Often improves workability	Slower early strength; good later strength	Improves long-term durability	Very high
GGBS	Cement replacement	Generally satisfactory	Good later-age strength	Excellent chloride/sulphate resistance	Very high
RHA	Cement replacement	Higher water demand	Can improve later-age strength	Potential pore refinement	High
SCBA	Cement replacement	Can reduce workability	Good at controlled replacement	Reduced permeability possible	High
Waste glass	Aggregate/SCM	Variable	Can improve at optimized dosage	ASR is major concern	High
Plastic	Aggregate/fibre	Often reduces	Usually reduces	Application	High

Material	Main application	Fresh concrete	Mechanical properties	Durability	Sustainability potential
waste		workability	strength at high content	dependent	
Rubber	Aggregate/fibre	Variable	Lower strength but higher toughness	Application dependent	High
Quarry waste	Fine aggregate	Excess fines reduce workability	Can improve packing at optimum level	Generally satisfactory	High

Discussion

Environmental Benefits

Conservation of Natural Aggregates

The replacement of natural aggregate with RCA, quarry waste, glass, plastic, and rubber can reduce quarrying and extraction of virgin mineral resources. This is especially important because aggregate constitutes the largest volume fraction of conventional concrete.

Reduction of Construction and Demolition Waste

RCA provides a direct recycling route for demolished concrete. Instead of being transported to landfill, construction waste can be processed and returned to the construction cycle. Recent reviews identify localized recycling and improved aggregate processing as important strategies for enhancing both environmental and economic benefits.

Reduction of Cement Consumption

The use of fly ash, GGBS, RHA, SCBA, and other SCMs reduces Portland cement consumption. This can reduce clinker-related emissions and energy demand. Agricultural ash studies specifically demonstrate the potential of biomass residues to replace part of the cementitious component.

Waste Diversion

Waste glass, plastic, rubber, agricultural residues, and industrial by-products can be diverted from landfill or uncontrolled disposal. This converts waste-management problems into potential sources of construction materials.

Performance–Sustainability Balance

The central challenge in developing sustainable concrete is achieving an appropriate balance between environmental benefit and engineering performance.

Increasing recycled content may increase waste diversion and reduce virgin material consumption, but excessive replacement can adversely affect concrete properties. RCA may increase water absorption; plastic and rubber can reduce stiffness and strength; waste glass can introduce ASR risk; and high levels of agricultural ash can increase water demand or reduce early-age strength.

Therefore, the optimum replacement level should be determined through multi-dimensional assessment rather than maximizing waste content.

A sustainable concrete mixture should satisfy:

Structural performance + Durability + Serviceability + Environmental performance +

Economic feasibility

This approach is particularly important for structural applications where strength alone is insufficient to demonstrate long-term sustainability. A mixture with slightly higher embodied carbon but significantly greater service life may ultimately have a lower environmental impact than a nominally low-carbon mixture requiring premature repair or replacement.

Research Gap

Despite extensive research on the incorporation of recycled and waste materials in concrete, significant gaps remain in achieving a comprehensive balance between structural performance and environmental sustainability. Existing studies have predominantly investigated individual materials, such as recycled concrete aggregates, fly ash, GGBS, agricultural ashes, waste glass, plastic, rubber, and quarry waste, at limited replacement levels and under controlled laboratory conditions.

Comparatively little research has systematically investigated the combined use of multiple waste materials and their synergistic or adverse interactions on fresh, mechanical, durability, and long-term structural properties. Furthermore, many studies focus primarily on compressive strength, while limited attention is given to service-life performance, shrinkage, creep, reinforcement corrosion, carbonation, chloride penetration, and long-term durability. Another important gap is the lack of standardized characterization and quality-control procedures

because the properties of waste materials vary significantly with source, processing, particle size, and chemical composition. Life-cycle assessment, embodied-carbon evaluation, transportation impacts, economic feasibility, and end-of-life recyclability are also insufficiently integrated with mechanical performance. In addition, full-scale structural validation and field applications remain limited.
Therefore, future research should develop multi-waste, performance-based, and life-cycle-oriented concrete systems, supported by artificial intelligence and multi-objective optimization, to simultaneously optimize strength, durability, cost, carbon emissions, resource efficiency, and long-term sustainability.

Conclusion

The incorporation of waste and recycled materials into concrete represents an important pathway toward sustainable and circular construction. Recycled concrete aggregates can reduce construction and demolition waste and conserve natural aggregates; industrial by-products such as fly ash and GGBS can reduce cement consumption; agricultural ashes such as RHA and SCBA can convert biomass residues into useful supplementary cementitious materials; and waste glass, plastic, rubber, and quarry waste can provide alternative aggregate or fibre resources.
The literature demonstrates that these materials can provide substantial environmental benefits, but their successful application depends on appropriate characterization, processing, replacement levels, mix design, and quality control. Their effects on concrete are highly material-specific. RCA is primarily associated with increased absorption and ITZ-related issues; agricultural ashes require controlled processing; waste glass requires ASR management; plastic can reduce stiffness and strength at high replacement levels; and rubber generally reduces conventional strength while improving toughness, impact resistance, thermal insulation, and energy absorption.
The review further establishes that sustainability cannot be measured simply by the percentage of recycled material incorporated into concrete. A comprehensive evaluation must simultaneously consider mechanical performance, durability, service life, embodied carbon, energy, water consumption, transportation, cost, and end-of-life recyclability. Recent LCA studies demonstrate that transportation distance, processing, mixture composition, and functional-unit selection can significantly influence the environmental superiority of recycled concrete.
The principal research gap is the limited integration of multiple waste materials, long-term structural performance, life-cycle assessment, and advanced data-driven optimization. Future research should therefore transition from isolated replacement studies toward multi-waste, performance-based and life-cycle-oriented concrete design. Artificial intelligence, machine learning, digital material databases, multi-objective optimization, and full-scale structural validation can provide powerful tools for achieving this transition.
Ultimately, the future of sustainable concrete should not be defined by the question "How much waste can be added?", but rather by "What combination of recycled materials provides the optimum structural performance, durability, environmental benefit, and economic value over the complete life cycle?" Addressing this question can accelerate the development of low-carbon, resource-efficient, durable, and circular concrete for future construction.

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