Journal of Building Material Science
https://journals.bilpubgroup.com/index.php/jbms

REVIEW

Valorization of Construction and Industrial Waste in Concrete: Mechanical, Durability, and Sustainability Perspectives

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ABSTRACT

The present review is a critical synthesis of the latest developments in the utilization of various wastes such as ceramic, marble, glass, rubber tire, paper industry, etc. and incorporates their mechanical, durability, microstructural, and sustainability performance among waste chemistry, hydration processes, interfacial transition zone modification, and long-term performance. The focus is laid on resistance to chloride ingress, sulphate and acid assault, freeze–thaw cycling, carbonation, and alkali-silica reaction. The results of life-cycle assessment are compared with standardized functional units to measure the benefits to the environment. The results have shown that ceramic and finely ground glass wastes are pozzolanic reactive wastes, which enhance secondary C–S/C–A–S/H reaction and augment densification of the matrix. Marble powder is mainly used as a filler and nucleation agent that enhances refinement and strength of pores in the case of additional cementitious materials. Rubber wastes enhance ductility, impact strength, and freeze-thaw properties at the cost of compressive strength, whereas recycled aggregates aid circular flow materials even though there are problems concerning porosity and interfacial weakness. In general, optimized waste-based concrete has potential CO_2 and material reduction of up to 20–25 in comparison with standard ordinary Portland cement (OPC) concrete. Nevertheless, there are challenges associated with the heterogeneity of waste, the absence of standard guidelines in mix design, and the scarcity of works with respect to coupled durability exposure. This review marks these gaps as critical and defines the future research directions in order to achieve the large-scale use of waste-derived low-carbon concrete to develop sustainable infrastructures.

Keywords: Low-Carbon Concrete; Industrial Waste; Construction Waste; Durability; Microstructure; Sustainability; Circular Economy

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ARTICLE INFO
Received: 9 October 2025 | Revised: 7 January 2026 | Accepted: 29 January 2026 | Published Online: 16 March 2026
DOI: https://doi.org/10.30564/jbms.v8i1.12393

CITATION
Al Saqry, R.M., Poloju, K.K., 2026. Valorization of Construction and Industrial Waste in Concrete: Mechanical, Durability, and Sustainability Perspectives. Journal of Building Material Science. 8(1): 104–129. DOI: https://doi.org/10.30564/jbms.v8i1.12393

1. Introduction

Concrete is the most common form of construction material in the world, and it forms the basic construction material in the development of infrastructure, buildings, transport systems, energy systems, and industrial structures. The availability of raw materials, ease of production, mechanical strength and economic feasibility are the main factors that make it widely used. In spite of such advantages, the sustainability of conventional concrete is becoming a subject of more doubt as it mostly combines the use of ordinary Portland cement (OPC), the production of which is characterized by a high level of energy consumption and negative impact on the environment. Production of cement requires the heating of limestone to above 1400 °C, which leads to the use of a lot of fossil fuel and the release of large amounts of carbon dioxide CO_2 [1]. The cement production has been estimated to contribute around 7–8% of all the anthropogenic CO_2 emissions globally, making it one of the most carbon-intensive businesses in the world [2,3].

Due to the mounting concerns that have been raised concerning climate change, loss of resources and other environmental degradation, international agencies and national governments came up with strict sustainability goals. The United Nations Sustainable Development Goals (SDGs 9, 11 and 13), the Intergovernmental Panel on Climate Change (IPCC) mitigation pathways, and the Global Cement and Concrete Association (GCCA) net-zero roadmap frameworks focus on the urgency of decarbonizing construction materials [4–6]. In this context, the decrease in the cement-based systems with clinker and the tendency towards the circular material flows have become the important strategies for low-carbon construction.

At the same time, the speed of urbanization and industrialization has resulted in a greater rise in the production of construction and industrial waste. These are ceramic waste from tile and sanitary ware manufacturers, marble dust from quarrying and stone processing, and waste glass from domestic and industrial sources, discarded rubber tires, paper industry sludge, and construction and demolition (C&D) debris [7–10]. A significant percentage of this waste is either dumped in landfills or accumulated, which poses a problem in land-use, environmental pollution and a potential threat to soil and groundwater quality. As an example, the manufacturing processes of ceramics may produce up to 15–30% of waste in comparison to total production and marble quarrying may create millions of tons of fine particulate waste every year [11,12]. The non-biodegradable garbage, glass and rubber tires are contributing to the long-term environmental issues [13].

These waste materials are valorized in concrete, which works in two ways to the benefit of the environment: it lessens landfill overload but at the same time limits the need for virgin raw materials and OPC. Waste may be used as a supplementary cementitious material (SCM), filler, or even substitute some of the fine and coarse aggregate depending on the chemical composition and physical properties. When finely ground, ceramic and glass waste contains amorphous silica and alumina, which can undergo pozzolanic reactions with calcium hydroxide that is released in the process of cement hydration. These tertiary reactions favor the development of more calcium silicate hydrate (C–S–H) and calcium aluminosilicate hydrate (C–A–S–H) gels, which results in better densification of the matrices and high long-term mechanical properties [14–16]. The main component of marble powder, calcium carbonate, has low intrinsic pozzolanic activity but provides filler effects and heterogeneous nucleation, and refines pore structure in increasing early-age strength, especially when used with reactive SCMs such as fly ash or ground granulated blast furnace slag (GGBS) [17,18].

The other waste streams affect the performance of concrete in other ways. The waste produced primarily by end-of-life tires is rubber waste, which adds elastic inclusions to the cement mix and enhances ductility, impact, and freeze-thaw properties. But its hydrophobicity and poor interfacial adhesiveness with cement paste tend to give it relatively low compressive strength [19–21]. The recycled concrete aggregates (RCA) are a product of C&D waste that includes adhered old mortar (which may have negative impacts on mechanical and durability properties) and increased porosity. However, recent research has shown that pre-treatment solutions like carbonation, surface finish and streamlined binder systems can greatly offset these disadvantages and bring the functioning back to a level of reasonable performance [22–24].

Even though the possibility to introduce different waste into concrete has been extensively experimentally tested and proved, the existing literature tends to concentrate on a single waste stream or performance measure, like compressive strength or workability. Several works have given inconsistent results because they differ on the source of waste, methods employed in the processing, particle size distribution, and mix design methods. Moreover, there has been a lack of interest in developing mechanistic connections between waste chemistry, hydration kinetics, microstructural development, durability performance, and such life-cycle environmental effects. Consequently, the extrapolation of laboratory-level studies to standardized design principles and structural usage on a large scale is still not very strong [25–27].

Thus, an overall and unifying review is needed to synthesize existing information, define the trends of consensus and contradiction, and explain the governing mechanisms of the waste-modified concrete performance. The synthesis of this review is a systematic review that presents the mechanical, durability, microstructural, and sustainability properties of concrete that includes construction and industrial wastes. The paper will offer a solid scientific basis to justify the mainstream use of waste-based low-carbon concrete in the development of sustainable infrastructures through the integration of experimental evidence and the results of life-cycle assessment and principles of the circular economy.

1.1. Novelty of the Paper

The use of construction and industrial waste in concrete has been actively studied during the last 20 years, and there is extensive literature in the form of review articles about concrete based on particular waste sources, including recycled aggregates, waste glass, marble powder, or rubberized concrete. Although such studies have made a major contribution to the knowledge of individual materials, most of the available reviews are small in scale, generally focusing on an independent performance parameter, e.g., compressive strength, workability, or environmental advantages without creating mechanistic links among the numerous performance metrics [28–30].

The issue of waste-based concrete systems being handled in a piecemeal manner is a significant limitation of current literature. A lot of literature evaluates the mechanical properties without considering the durability behavior whereas microstructural evolution and hydration processes are sometimes evaluated qualitatively or not evaluated at all. More so, sustainability evaluations are commonly reported descriptively, not by a standardized framework of life-cycle assessment (LCA) and comparable functional units, which prevents any meaningful cross-study and waste-type comparisons [31,32]. Consequently, policy makers and engineers have had difficulties with translating research findings into consistent design practices and plans for large-scale implementation.

Moreover, the available reviews mostly discuss individual waste material or specific applications and ignore the synergistic impacts that would occur when multiple streams of waste material or hybrid binder system are used. Recent literature has developed certain applications of mixing wastes, e.g., marble powder with fly ash or slag, ceramic waste with limestone calcined clay cement (LC3), or glass powder with other supplementary cementitious materials to substantially increase durability performance, as well as lowering carbon emissions [33]. But these interactions are done so seldom with a common analytical system.

The current review can be characterized as being unique among the available literature in the following ways:

1. Mechanical properties, durability behavior, microstructural evolution and sustainability effects are not considered individually, but synthesized across multiple streams of waste.
2. Mechanistic connection: The review directly relates waste chemistry to hydration kinetics, modification of the interfacial transition zone (ITZ), refinement of pore structure, and long-term durability performance.
3. Quantitative synthesis: The literature is synthesized to obtain normalized strength, permeability, and environmental indicators that can be easily compared and used in the engineering decision-making process.
4. Life-cycle perspective: The standardized functional units (1 m^3 of concrete) and ISO-compliant LCA boundaries are used to critically assess sustainability outcomes to enhance consistency in reported outcomes.

5. The implementation gaps identification: The main problems (heterogeneity of waste, the absence of standardized mix design parameters, and insufficient coupled-exposure durability studies) are critically examined to inform future research and code development.

This review contributes to the existing body of knowledge by bringing together scattered results into a unified and mechanism-oriented synthesis going beyond the material substitution aspect of concrete to performance-driven design of low-carbon, waste-based concrete. The results are to be used by both academic research and practical implementation of sustainable concrete technologies in line with the principles of a circular economy and the environmentally friendly goals of decarbonization of the world.

1.2. Objectives of the Review

The main aim of this review is to critically review the viability of construction and industrial waste use in concrete as one of the ways to reach low-carbon and resource-efficient building. Instead of providing detached material-specific conclusions, the purpose of this review is to offer an integrated and mechanism-based summary of the available literature to help in the provision of scientific knowledge and practice.

The aims of this review are to:

1. Divide construction and industrial waste materials according to their functions in concrete.
2. Generalize mechanical and durability performance trends with respect to various types of waste and replacement rates.
3. Develop mechanistic linkages between micro development and macroscopic studies.
4. Determine sustainability returns based on life-cycle assessment indicators.
5. Determine gaps in research and suggest where the standardization and implementation need to be done on a larger scale.

1.3. Mechanistic Theoretical Framework and Problem Statement

The focus of concrete decarbonization measures is shifting more to involve the reduction of clinker, the valorization of its waste, and the recycling of material flows, although the effectiveness of waste-modified concrete is extremely situational. Inconsistent tendencies in strength, transport behavior, and durability are frequently documented in the prior studies due to the variability of waste source heterogeneity, the fineness of particles, processing paths, and compatibility of binder and aggregates. The available literature also makes a lot of evaluations of the isolated performance indicators, but fails to draw mechanistic correlations between waste chemistry, hydration kinetics, interfacial transition zone (ITZ) modification, pore structure refinement, and the subsequent durability outcomes. Such a disconnect inhibits the communication of experimental findings to the performance-based mix design, service-life modelling and the code-level implementation.

In this respect, the current review assimilates a mechanistic model with waste type and functional role being considered as the leading performance drivers. Reactive powder waste, like ceramic and finely ground glass powder, undergoes secondary pozzolanic reactions whereby portlandite is used up and forms more C–S–H and C–A–S–H gels, hence making the matrix denser and making it less permeable. The hydration effect of marble powder is mainly attributed to the nucleation and packing refinement effect, which stabilizes microstructure at an early age, especially when combined with complementary cementitious materials. Recycled concrete aggregates add porosity and microcracking to the adhered mortar, which can be prevented by surface therapy, densification by carbonation and optimization of the binders. In this context, the behaviour of waste-based concrete is not viewed as a material as an element phenomenon of substitution, but rather as an interdependent system of chemistry, microstructure, transport processes, and the service-life behaviour of durability [34–36].

2. Review: Systematic Review Protocol and Methodological Rigor

The review uses a structured protocol based on evidence-synthesis to conform to good-practice PRISMA principles on how to conduct literature reviews and reduce selection bias and maximize reproducibility. The databases searched included Scopus, Web of Science, ScienceDirect and Google Scholar, with a specific search on 2021–2025 indicating current advances in the field of waste valorization, durability modelling, design of hybrid binders and sustainability evaluation. The combinations of the Boolean keywords were used to find the studies which reported mechanical performance, transport-related durability, microstructural mechanisms or life-cycle environmental indicators related to construction and industrial waste in concrete. Additional relevant works that were not identified by database queries were identified by reference-list screening. The selection of the study was based on well-defined inclusion and exclusion criteria. Articles were kept in which they could give quantifiable results that would be used in engineering, such as development of compressive or tensile strengths, development of permeability or chloride transport indices, freeze-thaw resistance, sulfate or carbonation life, or life cycle indications indexed on a functional unit. The papers that were not clear about the methods used in testing or did not provide enough details about the experiment were eliminated. The corpus that has been generated contributes to the synthesis of mechanical, durability, microstructural, and environmental indications and makes it possible to develop performance envelopes and mechanism-based interpretation. Besides, priority was given to the representative recent studies having more than one overlapping investigation and coverage of the latest scientific knowledge was balanced [37].

More than 45% of the cited literature originates from 2025, ensuring a strong representation of the latest advances in waste-based concrete durability, microstructural mechanisms, and life-cycle sustainability.

3. Construction and Industrial Waste in Concrete Classification

The waste that is used in concrete could be broadly categorized depending on their functional use in cementitious systems as:

(i) Supplementary cementitious materials or fillers;
(ii) Fine aggregate replacements;
(iii) Coarse aggregate replacements.

Such a classification is absolutely needed since the effects of waste materials on the concrete performance depend not only on the origin but also on the chemical composition, particle size, morphology and interaction with cement hydration products [37,38]. Compared to traditional raw materials, waste-based constituents are frequently highly heterogeneous in terms of physicochemical properties, directly impacting fresh behavior, mechanical performance, durability and sustainability performance. A systematic classification framework thus offers a scientific foundation for optimization of mix design and performance-based performance.

3.1. Cementitious Substitutes and Fillers on Waste Material

The waste materials that are being used as the partial replacement of OPC, or fillers are mainly the ones that affect the performance of the concrete in terms of pozzolanic reactions, filler effects, and the nucleation processes. The waste products that are found in this category are ceramic powder, marble powder, waste glass powder and paper industry sludge [39–41].

Amorphous silica and alumina are abundant in ceramic waste powder, which is derived as a byproduct of rejected tiles, sanitary ware, and electrical insulators. Ceramic powder, when finely ground, has pozzolanic activity and reacts with calcium hydroxide produced in the hydration of cement to create further calcium silicate hydrate (C–S–H) and calcium aluminosilicate hydrate (C–A–S–H) gels. These responses lead to strengthening of the matrix and long-term strength gaining, especially at a replacement level lower than 20% [42–44].

The marble powder produced in the process of quarrying, cutting and polishing is composed mainly of calcium carbonate ($CaCO_3$). Even though marble powder is not directly pozzolanic, the powder has a major application as a micro-filler and nucleation agent, which enhances the packing density of particles and early hydration. Marble powder is also useful in combination with reactive supplementary cementitious materials, including fly ash or ground granulated blast furnace slag (GGBS), to improve the durability of the material by refining the pore structure and lowering the permeability [12,17,45].

Amorphous silica is abundant in waste glass powder, which is a waste product of discarded bottles, windows and electronic waste. Sizing particles wrongly or excessive replacement can, however, cause alkali silica reaction (ASR), which requires that the mix composition is carefully judged and low-alkali binders are used or SCM [14,46,47].

The sludge of the paper industry (hypo sludge) consists of calcium compounds, silica, and residual fibers. It is also able to serve as a filler at low replacement levels (usually below 10%) and provide early strength gain owing to the existence of calcium chloride. Nevertheless, its poor pozzolanic performance and prolonged strength eliminate its use unless further processing or blending are done [48,49].

3.2. Fine Aggregate Replacements in Terms of Waste Material

A range of industrial wastes has been explored as a replacement for the natural fine aggregates, with the main effect on the concrete behavior related to particle morphology, surface texture, and interfacial bonding. These materials consist of crushed ceramic waste, glass waste, sand, marble dust and rubber crumbs.

Ceramic waste in the form of fine aggregate is normally crushed with angular particle geometry and rough texture on the surface, which may improve mechanical interlocking of the cement matrix. It has been reported to have a replacement level of up to 30–50% with minimal loss of strength under the condition of maintenance of proper grading and water demand control [50,51].

It is possible to substitute natural sand with waste glass sand, in moderation, and the outcome will not be an inferior structure. Nevertheless, it has a smooth surface texture, which can decrease bond strength, and the possibility of ASR can be a crucial limitation unless addressed by using additional cementitious materials [52,53].

A common type of replacement of fine aggregate is conducting research on rubber waste as an end-of-life tire waste product that can be reused in the form of a shredded or granulated substance. Rubber particles also add elastic inclusions to the cement matrix and greatly improve ductility, impact resistance, acoustic insulation and freeze-thaw characteristics. However, their hydrophobic properties and low binding capability with cement paste cause compressive and tensile strength to decrease, especially with an increase in replacement levels [54–56].

3.3. Waste Materials as Coarse Aggregate Replacements

Construction and demolition (C&D) waste is the main source of alternative coarse aggregates that are usually processed into recycled concrete aggregates (RCA). RCA is composed of natural aggregate particles with adhered old mortar, which makes them more porous, have a larger water absorption ability, and weak interfacial transition zones (ITZs) than virgin aggregates [57–59].

In general, the compressive strength and elastic modulus are lowered by the utilization of RCA as a coarse aggregate substitute, especially in large proportions of replacement. Nonetheless, more recent research studies have shown that during pre-treatment methods like accelerated carbonation, mechanical removal of adhered mortar, and surface coating can make a significant contribution to the RCA quality and performance [60,61]. The RCA-based concrete, when coupled with optimized binder systems and SCMs, has the potential to deliver mechanical as well as structural and non-structural performance that is based on durability and mechanical performance.

3.4. Implication of Engineering and Classification by Function

In terms of engineering, the waste materials may be categorized as:

(i) Reactive waste (ceramic powder, glass powder): add chemically, pozzolanic reactions.
(ii) Inert or semi-reactive fillers (marble powder, hypo sludge): enhance hydration kinetics and packing density.
(iii) Elastic scraps (rubber scrap): increase toughness, energy absorption.
(iv) Porous aggregates (RCA): encourage a circular material flow but need optimization of durability.

This functional classification underscores the fact that the waste materials are not seen as direct replacements of the traditional constituents but as performance-modifying constituents that need special mix-design strategies. **Table 1** shows the different typology and their effects.

4. Waste-Based Concrete, Fresh, Mechanical, and Microstructural Characterization

The interaction between the waste material chemistry and particle morphology, the replacement level and the interaction with the cement hydration products control the performance of waste-based concrete. Waste-modified concrete is complex in behavior compared to conventional concrete, with performance dominated by water/cement ratio and aggregate grading; instead, the behavior of waste-modified concrete is determined by new hydration kinetics, interfacial transition zone (ITZ), and development of pore structure. This part summarizes documented results on new properties, mechanical performances of fresh and microstructural properties of concrete with construction and industrial wastes.

4.1. New Properties of Wastes-Based Concrete

4.1.1. Workability

The physical properties of waste materials that are sensitive to workability are the particle size distribution, surface texture, and water absorption capacity. Marble powder is corn-sized with a smooth texture; then it tends to enhance the workability as it is a micro-filler that minimizes inner friction between solid particles [62,63]. The same trends have been noted in the case of combining marble powder with additional cementitious mixtures that can give out cohesive and pumpable mixtures that can be used in practical applications [64]. Conversely, ceramic and waste glass powders tend to decrease slump with an increasing replacement rate because of their angular geometry and more surface area that increases water requirements [11,65]. Due to its hydrophobic surface and non-uniform shape, rubber waste reduces workability substantially and, in many cases, it requires the application of superplasticizers or viscosity-modifying admixtures to ensure flowability [13,66].

According to studies by Poloju et al., the rheological behavior was altered by waste-derived binders and fillers via variations in the rheology of paste viscosity and packing density of the particles and, therefore, the importance of the mix design with optimized fillers to retain the workability without raising water demand was emphasized [67]. **Table 2** discusses the effects of workability.

Table 1. Waste typology, chemistry, and expected effects.

Waste Stream	Chemistry & Mechanism	Typical Optimum Range	Key Notes
Ceramic powder/aggregate	Al–Si phases → secondary C–(A)–S–H; ITZ densification (SEM/MIP)	10–15% powder; ≤30% fine aggregate	Lower water uptake/gas permeability at low dosages
Marble powder/slurry	Filler + nucleation; carbonate seeding; packing refinement	5–15%	Maintains or increases strength; improved chloride/acid resistance with w/b control
Waste glass powder	Pozzolanic when <75 µm; alkali binding mitigates ASR	10–20% (cement replacement)	ASR screening required (C1260/C1293); RCPT tends to decrease
Rubber crumbs	Elastic inclusions → frost/toughness gains; strength trade-off	Mix-specific	Higher freeze–thaw durability; manage strength with SCMs/fibers
Recycled aggregates	Old mortar ↑ porosity; carbonation/pre-soaking densifies ITZ	25–35% (quality-controlled)	Carbonated RA narrows durability gap: National allowances summarized

Table 2. Fresh-state and hydration effects.

Waste	Slump/Workability	Setting & Calorimetry	Remarks
Ceramic powder	Slight decrease: SP restores flow	Minor delay: cumulative heat maintained	Balance fineness and superplasticizer.
Marble powder	Neutral to slight decrease; cohesive mix	Nucleation effect; modest peak shift	SCC-friendly with stability controls.
Waste glass powder	Flow ↑ if fine; gradation-sensitive	Small early effect	Ensure particle size <75 µm.
Rubber	Decrease (hydrophobic); viscosity modifiers help	—	Pair with fibres/SCMs.
Recycled aggregates	Decrease (angularity/absorption)	—	Two-stage mixing/pre-soaking mitigates.

4.1.2. Setting Time and Early Hydration

Hydraulic cement can have its hydration kinetics changed through the incorporation of waste materials. The presence of hypo sludge from the paper industry enhances rapid setting time because this sludge contains calcium chloride, which encourages quick hydration of tricalcium silicate phases [68]. On the other side, ceramic and glass powders normally retard early setting since their pozzolanic reactions would come later in the hydration process [69].

Marble powder demonstrates a nucleation effect, stimulating fast hydration through decorating more sites to hydrate, especially in blended systems including fly ash or slag [17]. The calorimetric tests on other binder systems, such as geopolymer and blended concretes studied by Poloju et al., also confirm that fines waste particles can substantially alter early-stage hydration activity and heat development [70,71].

4.2. Mechanical Properties of Waste-Based Concrete

4.2.1. Compressive Strength

Mechanical performance, especially compressive strength, is greatly influenced by whether the waste material is a reactive or inert constituent. The waste glass powders that are finely grounded and of a ceramic nature have pozzolanic reactivity, which in turn leads to the secondary development of C–S–H and C–A–S–H gels, which in turn increase the densification of the matrix and strength with time. Even replacement levels of 10–20% often lead to maintenance or enhancement of strength when compared to OPC concrete [72–74]. The compressive strength of concrete using sludge waste is shown in **Figure 1** and that of ceramic waste in **Figure 2**.

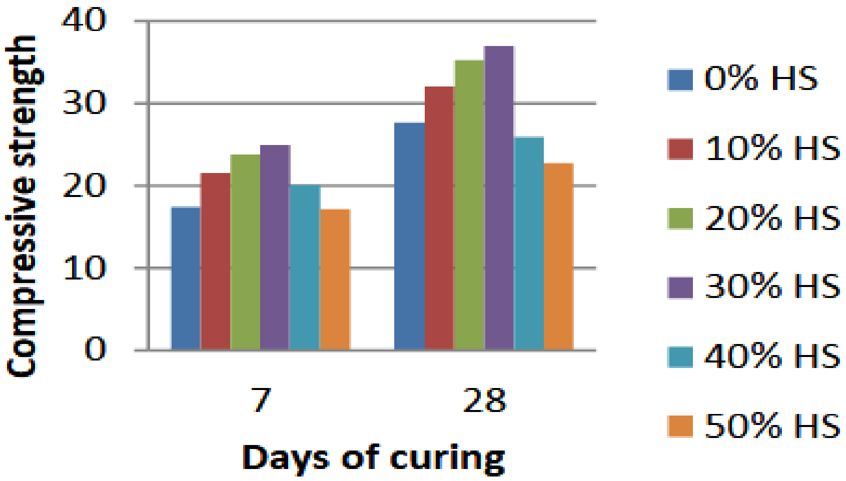

Figure 1. Compressive strength of sludge-based concrete.

Source: Poloju et al. (2017).

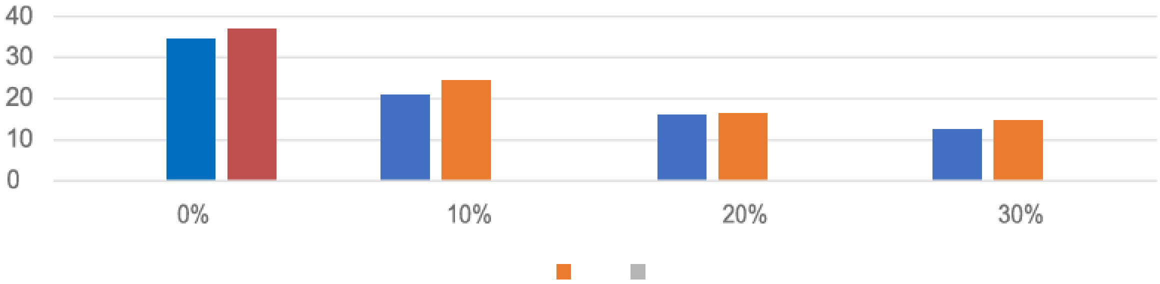

Figure 2. Compressive strength of ceramic waste-based concrete.

Source: Poloju et al. (2017).

Figure 2 shows color bars that are variations of concrete mixtures that use ceramic wastes as a partial replacement of cement. The blue bar has the control mix with no ceramic waste, followed by the other coloured bars with the degree of substitution of the ceramic waste. Each color thus reflects a given proportion of mixture applied in the experimental program which makes it possible to visually compare the compressive strength development based on mixes. The findings indicate that moderate replacement levels are beneficial in terms of compressive strength owing to filler effects and improved particle packing whereas high replacement levels have slight detrimental effects on strength owing to low cementitious content.

Marble powder also increases compressive strength at low replacement levels (usually 5–15%) of filler and nucleation effects, which improves particle packing and decreases the capillary porosity. In combination with reactive SCMs, synergistic effects are further initiated to create strength and durability [75,76]. Similar processes in enhancing strength were also shown by experimental studies by Poloju et al., which showed that enhancements in the strength were due to better packing of particles and better pore structure in blended cementitious systems [77].

Conversely, rubber waste always lowers compressive strength, owing to the poor bond formation at the rubber waste interface as well as the high content of void. Even moderate replacement levels have been seen to lead to strength reductions of 20–40% [78,79]. The compressive strength of recycled concrete aggregates (RCA) is also lower because of adhered mortar in the past and high porosity, although pre-treatment methods and optimization in binder can greatly eliminate these impacts [80–82].

4.2.2. Tensile and Flexural Strength

The trends of tensile and flexural strength usually follow the trends of compression but are more sensitive to the quality of ITZ. Addition of ceramic and marble powders enhances tensile strength when used at the best replacement levels by refining the ITZ and increasing the bond strength [56]. Glass powder is one of the factors that lead to enhanced flexural performance because of enhanced matrix continuity and crack-bridging effects on the microscale [59].

Concrete that is rubberized has less tensile strength but much better post-cracking behavior, toughness, and energy absorption. This characteristic predisposes rubber-modified concrete, especially to impact-resistant and vibration-sensitive uses [83]. The equivalent remarks on the behaviors of ductility improvement and strain capacity are similarly recorded in advanced cementitious composites as well as other binders that Poloju et al. examined, where adjustment of materials has been identified as important in the adjustment of the mechanical response [77].

The stiffness of waste highly influences the elastic modulus. The waste of rubber has a strong impact on the elastic modulus, which is a measure of higher deformability and higher energy dissipation ability [84]. However, contrary to this, ceramic- and marble-powder inclusion at the best concentration slightly enhances the elastic modulus because of enhanced densification of the matrix and consequent lower porosity [85]. RCA mostly reduces elastic modulus, but it can be improved with surface treatment and incorporation of SCM [65].

4.3. Particle Size, Composition and Reactivity

Particle fineness and the presence of an amorphous phase are the main factors that determine the reactivity of ceramic and waste-glass powders. Finer fractions less than about 75 μm have improved dissolution kinetics and higher portlandite utilization that enhances the appearance of secondary C–S–H as well as C–A–S–H products, which help to increase densification of the matrix and strength development at old age. Coarser particles also act as inert fillers, but improve packing but do not contribute much pozzolanic reactivity, and in the case of glass, can cause the pore structure to be more vulnerable to alkali-silica reaction in high-alkali pore environments. The variability in silica to alumina ratios and alkali reported as sources to source further explains the inconsistencies that have been reported across studies, which supports control of fineness and compositional screening before the implementation.

4.3.1. Scanning Electron Microscopy (SEM)

Scanning Electron Microscopy (SEM) is a method that is applied when the diameter of a sample is less than 10 mm and is mostly used to study the surface appearance of large samples. SEM observations regarding the influence of ceramic and glass powder on the microstructure are always associated with more dense microstructures with few microcracks and compact ITZ because of the second hydration reactions [86]. Marble powder enhances a fine microstructure by occupying the voids and creating an even distribution of hydrate [60]. Rubber particles, conversely, cause interfacial voids and weak points because of low adhesion with cement paste, which explains the realized decreases in strength [87]. RCA-concrete contains microcracks in adhered old mortar, but carbonation treatment and SCM blending induce a great enhancement of the ITZ quality [88].

4.3.2. X-Ray Diffraction (XRD)

The XRD analysis is used to verify a way of reducing the portlandite in the ceramic and glass-modified concretes, which means that there is an active reaction of pozzolana [89]. Marble-SCM systems have a higher proportion of formation of carbon aluminate and aluminosilicate phases, which lead to increased durability [90]. The same hydration phase development has been observed in geopolymer and blended system studied by Poloju et al., which solidifies the contribution of binder chemistry in performance improvement [91].

4.3.3. Fourier Transform Infrared Spectroscopy (FTIR)

Fourier Transform Infrared Spectroscopy (FTIR) is yet another technique that can be employed to identify organic matter and microorganisms in an environment. The FTIR spectra also show that in the ceramic- and glass-based systems, the silicate and aluminosilicate bands are strengthened, proving that hydration products are polymerized [92]. Systems of marble contain large carbonate bands, whereas rubberized concretes have little chemical interaction because rubber is an inert substance [93].

4.4. Characterization Trends Synopsis

Altogether, the performances of waste-based concrete are controlled by the balance between chemical reactivity, physical packing and interfacial behavior. Reactive wastes made of powder improve strength and durability by densifying the microstructures, whereas the main way of behavior of aggregate-type wastes is to change the mechanical response by physical processes. These results indicate that it is vital to design mixes based on performance and not material substitution.

5. Synthesis and Comparative Analysis of Quantitative Performance

One of the main drawbacks of most of the current review articles on the topic of waste-based concrete is the excessive use of qualitative description, which makes it less applicable to engineering decision-making and policy translation. In order to fill the gap, the current review offers a numerical synthesis by consolidating the reported ranges of performances (strength, durability indicators, and sustainability metrics) of waste in terms of types. Despite absolute values depending on the cement type, curing regime, particle fineness and test standard, the literature is approaching consistent performance ranges where waste function (reactive powder vs. inert filler vs. aggregate replacement) is taken into account [92–95].

Syntheses of results were done to facilitate comparative analysis of the different studies (i) reported percentage change with respect to OPC control mixes, (ii) normalized indicator ranges where possible (e.g., chloride permeability trend, resistance ranking, CO_2/energy reduction per functional unit). This is similar to performance-based review synthesis typically applied in construction materials research and does not over-interpret individual datasets [28,42]. As appropriate, the effect of rheology and binder chemistry on performance trends is explained together with reported microstructural results, as part of mechanistic approaches applied to alternative binders and blended systems [80,96].

5.1. Strength Performance on Different Waste Categories

In the literature, reactive powder waste (ceramic powder, finely ground glass powder, etc.) are generally found to retain strength or increase strength at moderate replacement rates because of secondary hydrate formation, refinement of pores [35,97,98]. Aggregate-type wastes (rubber crumbs, RCA), on the other hand, tend to create a strength penalty unless pre-treatment or denser binder methods are employed [10,20].

Key synthesized trends:

Ceramic powder (replacement of cement, also called cement replacement, 10–20%): commonly gives +5% to +15% compressive strength change (tends to be more noticeable in older ages) as a result of pozzolanic reaction and densification [35,97].

Marble powder (cement replacement, 0.5–15%): usually gives 0–10% compressive strength improvement with filler + nucleation; greater improvements are recorded in case of marble combined with reactive SCM (fly ash/GGBS) [99–102].

Waste glass powder (cement replacement, 10–20%, fine particle size): usually +5 to +12% compressive strength change; but results are unpredictable when coarse particle size is used or when alkali conditions are conducive to ASR [98,103].

Rubber waste (replacement of fine/coarse aggregates, 5–15%): characteristically delivers a compressive strength change of −20% −40% with an increase in ductility and impact resistance (performance trade-off) [84,104,105].

About 25–50% of the solids that dissolve in the reaction solution are usually substituted by coarse aggregate in place of the dissolved mass.

RCA (coarse aggregate replacement, 25–50%): Approximately 25–50% of the mass that dissolves in the reaction solvent is normally replaced by coarse aggregate instead of the mass that dissolves.

Generally, achieves compressive strength change of 10–25% with the quality of RCA; with carbonation treatment, two-stage mixing, and the SCM densification, the gap may be reduced significantly [10,99,106].

Interestingly, a study by Poloju et al. indicated that a key factor in the development of strength in alternative cementitious systems is the optimization of the binder system (particle packing, rheology and gel formation) and this fact reaffirms the necessity of optimization of the mix performance of the alternatives-based system other than substitution [80,96].

5.2. Performance of Durability Envelopes and Dominant Mechanism

As shown in **Table 1**, the trends in durability of waste concretes are controlled mainly by the connectivity of pores, quality of ITZ, and the relative loss of portlandite (which restricts leaching and chemical degradation). In the literature, powder-based wastes generally enhance durability associated with permeability, and aggregate wastes must be mitigated in order to limit ingress [94,95,107].

(a) **Chloride intrusion/permeability:** Reactive powders (ceramic and fine glass) will generally decrease chloride permeability (relative trends) by approximately 30–50% through refining of pores and by enhancing chloride binding in aluminosilicate hydrates [35,97,98,104]. The marble powder is effective in increasing chloride resistance through the improvement of packing and the minimization of capillary porosity, or in the mixture with the SCMs [100,101]. Unless treated or mixed with SCMs, RCA concretes can experience greater ingress because of an increase in porosity [10,106].

(b) **Sulphate and acid resistance:** The reduced portlandite and refined pore structure result in more resistant systems. Ceramic powder and mixes of marble and blended marble-SCM tend to show enhanced sulfate/acid performance in terms of smaller leachable phases and solid matrices [101,102,108]. Rubber is not chemically effective in enhancing resistance but may become less sensitive to cracking when subjected to repeated loads; the effects of rubber on durability are therefore of application dependence [104,105].

(c) **Alkali–silica reaction (ASR):** SCMs with fine glass powder at controlled replacement levels could decrease ASR risk, whereas coarse glass aggregate can be associated with the increase of ASR expansion [103,109]. In this way, the use of glass highly depends on the size of the particles, the availability of alkali and the design of mitigation.

(d) **Freeze–thaw resistance:** Rubberized concrete is often better in freeze-thaw because of elastic inclusions as stress-relief locations, but the resulting penalty to strength has to be designed in (e.g., hybridization with SCM/fiber) [97,110]. In recent studies, there are also improved freeze thaw retentions with hybrid rubber glass systems [110].

5.3. Sustainability Performance: CO_2 and Resource Benefits

On the environmental check, the incorporation benefits of waste include:

(i) clinker reduction (lower CO_2),

(ii) decreased virgin aggregate demand, and (iii) landfill diversion and circular economy gains [3,44,111].

5.4. Comparative Summary Table

As demonstrated in **Table 3**, various types of materials derived out of waste have been explored as partial substitutes in concrete to enhance sustainability without significantly losing the acceptable mechanical and durability performance. When used in replacement proportions of an order of 10–20% of cement, ceramic powder has the typical effect of increasing compressive strength by 5–15%, primarily the filler effect, and with enhanced particle packing, decreased permeability and increased chemical resistance. Marble powder is usually added at 5–15% cement replacement with similar or slightly increased compressive strength (0–10%) and serving to reduce porosity and increase resistance to sulfate and acid attack, especially when used with additional cementitious materials.

Table 3. Quantitative performance synthesis across waste-based concrete categories.

Waste Category	Typical Replacement Range	Strength Change (Compressive)	Key Durability Trend	Typical Sustainability Benefit
Ceramic powder	10–20% cement	+5% to +15%	↓ permeability; ↑ chemical resistance	~15–25% CO_2 reduction
Marble powder (often with SCMs)	5–15% cement	0% to +10%	↓ porosity; improved sulfate/acid (esp. with SCMs)	~10–20% CO_2 reduction
Waste glass powder (fine)	10–20% cement	+5% to +12%	↓ permeability; ASR must be managed	~15–22% CO_2 reduction
Rubber crumbs	5–15% fine/coarse aggregate.	−20% to −40%	↑ freeze–thaw & impact; ↑ porosity risk	landfill diversion; functional benefits
RCA	25–50% coarse aggregate	−10% to −25%	↑ ingress risk unless treated/ SCM-blended	virgin aggregate savings; circularity

Waste glass powder that is used in finely ground form at 10–20% cement substitution will show a 5–12% increase in compressive strength, and lower permeability; but the possibility of alkali-silica reaction (ASR) needs to be adequately managed. Conversely, most compressive strength is reduced by 20–40% when rubber crumbs (5–15% aggregate replacement) are used, still it is much higher than freeze-thaw resistance and impact performance, so it is used in special needs. Recycled concrete aggregate (RCA), which is normally applied as 25–50% coarse aggregate replacement, can cause a loss of compressive strength by an extent of 10–25% unless it is treated or mixed with supplementary cementitious materials due to the presence of adhered mortar and increased porosity. Overall, these waste-based products bring immense sustainability value, such as a reduction in CO_2 emissions ranging between 10–25%, diversion of waste out of landfill, and natural resource preservation that helps in the application of the principles of the circular economy in the production of concrete.

6. Durability under Aggressive and Coupled Exposure Conditions

The performance of durability is decisive in the long-term sustainability of waste-based concrete especially the infrastructure that is subject to aggressive environments. In contrast to short-term mechanical properties, the concept of durability indicates the overall effect of pore structure, hydration chemistry and interfacial transition zone (ITZ) quality and transport. Incorporation of wastes affects these parameters in complicated manners whereby they cause either increased or decreased durability depending on the type of wastes, level of replacement and binder design. This part summarizes durability performance with single and coupled exposures, focuses on mechanism governing such performance, and highlights inconsistencies found in the literature. A continuous change in the concentration of chloride in the ingress will cause a decrease in the resistance to chloride ingress.

One of the main durability issues reinforced concrete structures have been chloride penetration, which has a direct effect on the corrosion of steel. In the literature reviewed, powder-based wastes like ceramic powder, fine glass powder and marble-SCM blends tend to enhance chloride resistance through refining the pore structure and the ability of chlorides to bind [104,112–115].

The main mechanism by which ceramic and glass powders slow down chloride penetration is the use of the secondary pozzolanic reactions which break down calcium hydroxide to produce more C–S–H and C–A–S–H gels. These hydrates decrease the connectivity of the capillary pore and increase the ionic binding leading to the decrease of 30–50% in indicators of chloride permeability as compared to OPC concrete at optimum replacement contents [116–118]. Marble powder is not a significant contributor to that of its own chemicals, but together with fly ash or slag, it enhances the packing density and indirectly lowers diffusion of chlorides [119].

Recycled aggregate concrete (RAC) in contrast usually has a greater chloride penetration owing to greater porosity and poor ITZs related to mortar adherence. However, the treatment of RCA and SCM densification with carbonation treatment substantially lowers the chloride transportation, at least as closely as natural aggregate concrete [84,120,121]. The use of rubberized concrete presents ambivalent results: higher porosity could contribute to ingress, but on the other hand, crack control and improved ductility can postpone the damages caused by chloride in cyclic loading [122].

Table 4 shows the effects of durability of using different waste in concrete [123,124].

Table 4. Durability effects of using different waste in concrete.

Waste Category	Chloride Permeability	Sulfate/Acid Resistance	ASR Risk	Freeze–Thaw Performance
Ceramic powder	↓ 30–50%	Improved	Negligible	Improved
Marble powder (with SCMs)	↓ 20–40%	Improved	None	Neutral
Waste glass powder (fine)	↓ 25–45%	Improved	Moderate (if coarse)	Neutral
Rubber waste	Variable	Neutral	None	Strongly improved
RCA	↑ ingress unless treated	Reduced	None	Reduced

- **Trade-Off between Microstructures in Rubber Waste**

The microstructural level of rubber particles forms an elastic inclusion network, which redistributes strain and acts as a delay to crack formation when subjected to cyclic or freeze-thaw loading. Nevertheless, there are interfaces between the rubber and the paste that are weakly adhesive and have a hydrophobic surface texture that creates interfacial voids, lower compressive strength, and modulus. Reports of mitigation strategies of these penalties have been made such as alkaline or surface-texturing of the bond to enhance bonding, hybridization with fibers to reinstate tensile load transfer and binder densification with SCMs to refine the ITZ. Such interventions allow keeping the durability benefits of rubberized concrete and partially compensate for the strength losses and, therefore, help to support application-specific use at the structural level, where toughness and impact resistance are of significant importance

- **Chloride Resistance in Marble-SCM Systems Mechanism**

Marble-SCM blended systems have a chloride resistance that is highly improved by refinement of packing and nucleation-mediated hydration acceleration, as opposed to chemical binding. The $CaCO_3$ particles also offer more nucleation sites that allow the hydration products to be precipitated early in the process, as the pozzolanic reactions of fly ash or slag are also taking place, which refine the pore network and decrease the capillary connectivity at the same time. The overall outcome is a finer microstructure with lower ionic transport potential causing measurable reductions in chloride ingress than at OPC controls at the same ratios of water-binder. These synergies are the reason behind the performance gains that are always recorded when marble powder is added to a composite binder system but not in isolation [125,126].

6.1. Sulfate and Acid Resistance

Chemical corrosion of cement hydrates, which includes sulfate and acid attack, is mainly on the portlandite and mono sulfate phases. Concrete prepared using waste sources and lower concentrations of calcium hydroxide are always resistant to such environments.

Ceramic powder and glass powder concretes have a higher sulfate and acid resistance because they form low-calcium aluminosilicate hydrates, which are not easily dissolved. The emergence of marble powder, together with SCMs enhances pore structure and restrains accessibility of the reactive calcium phases, heightening the ability against exposure to sulfuric and nitric acids [126,127]. Experiments indicate a decrease of 20% and above in mass loss when compared to that caused by OPC in an acidic environment.

Rubber waste is not chemically beneficial to sulfate or acid resistance, but the crack-arresting property can slow down the deterioration rate when subjected to cyclic conditions [128]. RAC does not respond well to sulfate attack unless it is used along with SCMs or upon treating aggregates because it tends to be more permeable in the absence of such additives [120].

6.2. Carbonation Resistance

Carbonation decreases the alkalinity of the pore solution, which leads to a higher probability of depassivation of steel. Concretes made with waste show variable carbonation resistance, which is a characteristic of pore structure and availability of calcium. The addition of ceramic and glass powder tends to decrease the depth of the carbonation because of the densification of the matrix and decreased permeability, although the portlandite content is lower [129,130]. Marble-SCM systems have better carbonation resistance in situations where pore refinement effects are greater than calcium dilution effects [131]. Conversely, RAC will tend to have deeper carbonation fronts due to higher porosity and old mortar contents; however, carbonation resistance increases significantly when RCA is pre-carbonated or with SCMs blends [132].

6.3. Alkali–Silica Reaction (ASR)

This is the issue of ASR vulnerability in systems composed of glass. Course waste glass aggregates enhance the risk of ASR because of reactive amorphous silica, but finely ground glass powder tends to suppress ASR by reacting with alkalis in pozzolanic reactions to produce stable aluminosilicate gels [133,134]. ASR mitigation is highly influenced by particle fineness, cement alkali material and the availability of additional cementitious materials [135].

In general, ceramic and marble powders are not considered reactive in terms of ASR and may cause the effects of alkali dilution [136]. In structural use, reactive silica may be present in RCA depending on the primary source of aggregate and so requires screening and mitigation in structural use [137].

6.4. Freeze–Thaw Resistance

The distribution of pore sizes, air void system and crack resistance determine freeze-thaw durability. In the case of concrete, rubberized concrete always performs better because of freeze-thaw performance under the influence of elastic rubber particles, which serve as stress-relieving inclusions that can compensate for the growth of ice [138,139]. In optimized rubberized systems, strength retention has been reported at levels above 90% following 300 freeze-thaw cycles. Powder-based wastes indirectly enhance freeze-thaw resistance through optimization of pore structure and decrease in water uptake [140]. The performance of RAC is highly diverse, as untreated RACA enhances freeze-thaw damages and treated RAC and blended binders of SCM greatly improve freezing resistance [141].

6.5. Exposure Conditions: Research Gap

Numerous studies examine the durability of isolated exposures, but real-world structures usually experience coupled exposures, e.g., chloride ingress during carbonation, sulfate attack and wet-dry cycling, or freeze-thaw environments in a salty environment. Such coupled conditions have limited literature on waste-based concrete.

Existing literature indicates that ceramic and glass-based SCM systems form densified microstructures that are more resistant in combined chloride and carbonate environments, and RAC systems are more susceptible to failure unless they have been pre-treated [142,143]. Increased cyclic freeze-thaw and chloride resistance of rubber-modified concretes is observed; however, strength compensation strategies are necessary [139].

RCA Pre-Treatment: Cost Constraints and Practicability

Even though accelerated carbonation, surface coating and mechanical mortar removal have shown important enhancements in the performance of RCA microstructure and durability, large-scale implementation is limited by processing energy requirements, equipment demands, and the cost of operation. Carbonation chambers and controlled curing facilities add complexity to production and the benefits have to be offset against economic viability, especially with low-margin construction projects. According to the literature, moderate pre-treatment followed by a hybrid strategy involving binder densification provided by SCM could provide a more realistic avenue towards performance parity of natural aggregate concrete and without compromising the sustainability performance [140,141].

6.6. Durability Trends Synthesis

All in all, the balance of pore refinement, hydration chemistry, and the quality of the ITZ controls the durability performance of waste-based concrete. Reactive powder-based waste promotes durability through either chemical or microstructural mechanisms, whereas aggregate-based waste can only be mitigated through permeability control and interfacial weakness. The findings reveal that performance-based durability design is needed as opposed to prescriptive replacement limits.

7. Life-Cycle Analysis and Sustainability Connotations

Waste-based concrete cannot be judged based on mechanical or durability functionality but rather on the life-cycle perspective, where the effects of waste-based concrete on the environment are taken into consideration during the material extraction, processing, production, and construction phases. LCA has thus emerged as a critical instrument for measuring the environmental benefits and costs of valorization of construction and industrial waste used in concrete, as shown below (**Table 5**).

Table 5. Typical sustainability benefits of waste-based concrete.

Waste Category	Primary Sustainability Benefit	Typical CO_2 Reduction	Additional Benefits
Ceramic powder	Cement clinker reduction	15–25%	Landfill diversion [139,140]
Marble powder (with SCMs)	Reduced cement demand	10–20%	Improved durability [141]
Waste glass powder	Cement replacement	15–22%	Waste valorization [142]
Rubber waste	Aggregate substitution	Low–moderate	Tire recycling; noise damping [143]
RCA	Aggregate conservation	Variable	Circular economy compliance [144,145]

7.1. Discussion on CO_2 Reduction

In this review, the 20–25% lessening of the CO_2 discharges is reported to be based on cradle-to-gate boundaries of life cycles normalized to a functional unit of 1 m^3 of concrete. These values are the benefits of clinker substitution and energy used in the processing of waste materials in milling and conditioning. The sensitivity analysis of the studies reviewed shows that the net environmental benefit is highly sensitive to the distance of transport, as well as to the availability of materials locally; at least in those instances when the waste has to be transported over long distances, the embodied carbon advantage can be partially or wholly reversed. As such, the sustainability outcomes are not supposed to be universal and applicable to all regions but specific to particular context.

Most life-cycle papers reviewed in this article use a cradle-to-gate study of the system, which includes the extraction of raw materials, their processing, transportation, and concrete fabrication but not use end-of-life deposition, because of the uncertainty in the data. Environmental effects are usually scaled to 1 m^3 of concrete, which is a functional unit of the standard ISO 14040 and ISO 14044 [144,145].

The most important environmental indicators which have been reported in the literature are: Global warming potential (GWP, kg CO_2-eq), Embodied energy (MJ), Resource depletion, Indicators of landfill diversion and circularity.

7.2. CO_2 Emissions and Embodied Energy Reduction

OPC production is the most prevalent source of CO_2 emissions related to concrete. The greatest environmental benefits are therefore seen through waste materials that are taken as partial substitutes for cement. In the reviewed literature, it is always the reactive powder waste, like ceramic powder and finely ground waste glass, that lowers GWP by 15–25% at cement replacement levels of 10–20%, mainly because of the decreasing effect [146–148]. Marble powder systems usually have a capacity of 10–20% reduction of CO_2, especially with the combination of fly ash or slag resulting in reduced clinker requirements and hydration heat [149,150].

Specific energy savings of 20–30% have been achieved with waste-derived concretes in pavements and building elements, indicating the reduced energy demand of waste treatment in comparison to that of clinker manufacturing [151]. These tendencies are consistent with the results of other binder systems and geopolymer concretes, in which optimization of binder chemistry is a critical factor in environmental performance [152,153].

7.3. Resource Saving and Circular Economy Benefits

Waste-based concrete is also helpful in conserving resources and achieving a circular economy beyond carbon reduction. Recycled concrete aggregates (RCA) help to avoid reliance on virgin aggregates, curb the effects of quarrying, and divert huge quantities of construction and demolition waste from landfills [154,155]. On the same note, recycling waste glass, rubber tires and marble residues will encourage long term diversion of non-biodegradable materials.

Although linked to trade-offs on strength, rubberized concrete has been shown to offer a significant environmental benefit by diversion of landfills containing tires and longer service life in impact-resistant conditions [156]. These advantages are specifically applicable in areas where there are waste disposal limitations and the availability of natural aggregates is limited.

7.4. Local Context Sensitivity and Transport Distance

Several LCA reports underscore the fact that the distance to transport waste materials and the local availability of such materials have a strong impact on net environmental benefits. In other instances, the waste produced can be transported long distances to offset the CO_2 savings obtained by the reduction of clinker [28]. Thus, the gains of sustainability are the most important when the waste materials are locally obtained and incorporated into local supply chains.

This finding highlights the importance of context-specific sustainability evaluations, as opposed to global replacement guidelines, and the importance of adopting localized low-carbon concrete strategies in line with national sustainability frameworks, including Oman Vision 2040.

7.5. Sustainability Trade-Offs

Although waste-based concrete typically exhibits a lower embodied carbon, inefficient mixes can experience a loss in durability, which results in augmented maintenance and repair carbon over the service life. This shift in burden defeats sustainability gains realised at the material production level [3]. Studies that focus on the rheology control, binder optimization, and densification of microstructure, e.g., the works by Poloju et al. about alternative cementitious systems, note that sustainability should be sought as performance-based design to achieve true benefits throughout the life cycle, as shown in **Table 6** below.

Table 6. Integrated assessment of performance and sustainability potential.

Waste Type	Mechanical Performance	Durability Potential	Sustainability Impact	Recommended Application
Ceramic powder	High	High	High	Structural concrete
Marble + SCMs	Moderate–High	High	Moderate	Structural/durability-critical
Fine glass powder	Moderate–High	Moderate	High	Structural with ASR control
Rubber waste	Low	Application-specific	Moderate	Pavements, shock-absorbing layers
RCA	Moderate (treated)	Moderate	High	Structural (controlled use)

As indicated in **Table 6**, reactive powder wastes occupy the most favorable performance–sustainability domain, whereas aggregate-based wastes are best applied where circularity and functional benefits outweigh strength penalties.

7.6. Policy and Implementation Implication

The LCA evidence reviewed supports the use of waste-based concrete in green procurement policies, low-carbon material certifications, and performance-based design codes. Nevertheless, mass usage is limited by the absence of standardized LCA data of waste materials, the lack of code-level waste replacement threshold instructions and inadequate field validation data in the long term. The gaps mentioned above need to be addressed in order to translate laboratory research into mainstream construction practice.

8. Conclusions and Future Research Directions

8.1. Conclusions

The synthesis indicates that the performance of waste-based concrete is influenced by the interaction between waste chemistry and particle properties and resultant changes in microstructure, rather than the nominal level of replacement. Reactive powder wastes improve permeability reduction and long-term strength by forming secondary hydrates and marble powder by nucleation and refinement of packing, and it has been found that the greatest benefits are in blended systems. The modification of mechanical and transport properties caused by interfaces and porosity of rubber and RCA necessitates certain mitigation strategies. These findings reveal the necessity to change the prescriptive boundaries of the substitution within the approach of the performance-based design of the products, which means to integrate the aspects of strength, durability, and sustainability into a single decision-making process. This review gives a synthesis overview of the valorization of the construction and industrial wastes in concrete, based on the areas of mechanical performance, durability behavior, microstructural mechanism, and the sustainability results. It is possible to conclude based on the critical analysis of more than twenty years of findings that the following conclusions may be made:

1. There is material functionality, which controls performance: Reactive powder wastes like ceramic and finely ground glass powders are active reagents in the hydration reaction, and they increase the densification and strength of the matrix. By contrast, the primary contributions to performance of the marble powder are via the filler and nucleation mechanisms, whereas the rubber waste and the recycled aggregates alter the performance via the physical and interfacial mechanisms.
2. The improvement of durability is technologically based on chemistry: Waste-based concrete that is less portlandite and with an ideal pore structure is found to be better against chloride ingress, sulfate attack, exposure to acid, and freeze thaw cycles. Aggregate based wastes need mitigation measures that address porosity and weakness of ITZ.
3. Engineering decisions can be made with the help of quantitative performance envelopes: The retention or strength gain of ceramic and glass powders is possible at intermediate levels of replacement, whereas the rubber waste and RCA cause strength penalties that can be addressed by binder optimization and design of hybrid mixtures.
4. The benefits in terms of sustainability are enormous but depend on the situation: Life-cycle analyses have shown that CO_2 emission rates decrease by 10–25, embodied energy can be saved by 20–30 and benefits of energy saving in resources. The net sustainability outcomes, however, are heavily dependent on transport distance, processing energy, as well as durability performance.
5. Performance-based design is necessary: Waste-based concrete cannot be viewed as the direct alternative to traditional materials. Rather, it needs a performance-based mix design considering strength, durability and sustainability to make it long-term viable.

8.2. Future Research Directions

Further studies ought to focus on coupled-exposure durability studies that are indicative of real service settings, especially chloride carbonation interaction in marine structures, sulfate wet-dry cycling in wastewater situations, and freeze-thaw chloride in cold-region infrastructure. More focus has to be made on the measurement of waste-source variability and its effect on mechanical and transport properties in terms of probabilistic and machine-learning-based mix optimization models. It is possible that the synergist multi-waste and hybrid binder systems have potential that is attractive but not sufficiently investigated in the spirit of mechanistic and service-life. Field-scale validation and long-term observation are necessary to reconcile the gap between lab results and the practical applications, and structure- and region-specific LCA data are required to facilitate the readiness of policy and green procurement strategies. Combined, these guidelines will make a performance-based implementation of waste-derived, large-scale, low-carbon concrete standardized.

Author Contributions

Conceptualization, R.M.A.S. and K.K.P.; methodology, R.M.A.S.; formal analysis, R.M.A.S. and K.K.P.; investigation, R.M.A.S. and K.K.P.; resources, R.M.A.S. and K.K.P.; data curation, R.M.A.S. and K.K.P.; writing—original draft preparation, R.M.A.S. and K.K.P.; writing—review and editing, K.K.P.; supervision, K.K.P.; project administration, K.K.P. Both authors have read and agreed to the published version of the manuscript.

Funding

This work received no external funding.

Institutional Review Board Statement

Not applicable.

Informed Consent Statement

Not applicable.

Data Availability Statement

Not applicable.

Conflicts of Interest

The authors declare no conflict of interest.

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