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Comparative Performance Study of Concrete Incorporating Ceramic and Recycled Concrete Waste: Strength, Durability, and Sustainability

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Abstract

Construction and demolition waste, especially ceramic and concrete debris, is a byproduct that has been increasingly amassed over time and causes environmental pollutants. Valorizing these wastes as raw materials to produce sustainable construction materials represents an alternative option to minimize waste, conserve resources, and reduce CO_2 emissions. This paper aims to review the performance and environmental advantages of using ceramic and recycled concrete as an alternative fine aggregate in new concrete mixes, along with their innovative potential. The research assesses mechanical performance, durability, and sustainability implications as well as optimization options. The results indicate that the addition of ceramic and recycled aggregate concrete (RAC) from concrete waste yields a partial loss in strength but greatly improves durability, thermal stability, and green performance. The paper provides a conclusion that these waste-derived concretes will be an important direction for sustainable construction and circular economy development.

Keywords: Ceramic waste, circular economy, durability, recycled concrete aggregate, sustainable construction

INTRODUCTION

Concrete is the most commonly used construction material globally, although it has high environmental costs. Production of ordinary Portland cement (OPC), an essential building material for concrete, contributes directly to approximately 8% global CO_2 emissions and extreme stripping of natural aggregates through quarrying and mining. In contrast, construction and demolition (C&D) activities produce millions of tons of waste annually, and C&D debris, such as ceramics, occupies a large portion of these materials. The mismanagement of these wastes results in land pollution, resource depletion, and increasing pressure on landfills. Therefore, it is necessary to find available pathways for the reuse and recycling of such materials to promote eco-efficient and circular construction [1–3].

The ceramic waste used in this study originates from the tile, sanitary ware, and brick industries and is essentially composed of silicate (SiO_2) and alumina (Al_2O_3). When powdered, it has pozzolanic properties, analogous to other industrial byproducts used as partial cement replacements. In contrast, when demolished concrete structures are crushed and transformed into recycled concrete aggregates (RCA), these materials can be used as alternatives to natural aggregates. Both act as a cure-all for saving the environment, and open universities to new income streams that save on virgin resources.

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However, challenges remain. Ceramic and RCAs generally exhibit higher porosity and water absorption values than natural aggregates, which can have detrimental effects on the strength and durability of concrete. To date, it has been demonstrated that the mechanical performance of WWRHI depends largely on waste grain size, replacement percentage, and surface treatment techniques. Pretreatment methods, such as acid washing, carbonation, and coating with supplementary cementitious materials (SCMs) such as fly ash or silica fume, are designed to improve the bond strength at the interfacial transition zone (ITZ) and aid in microstructural connectivity [4–7].

The use of ceramic and recycled concrete waste is also in close agreement with global sustainability goals. The potential for reducing embodied energy, circular material flows, and low-carbon construction systems is also presented. Similar to the development of paste replacements, as research continues to optimize processing and mix designs, these materials also have potential for achieving mechanical and durability properties similar to or superior to those of traditional concrete (Figure 1).

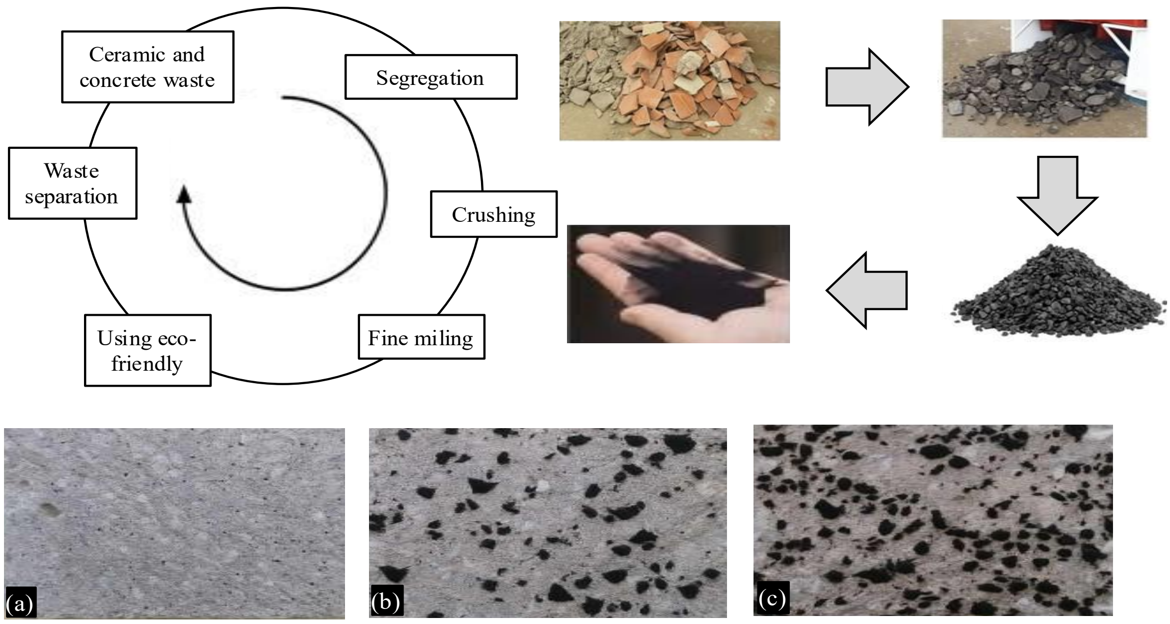
LITERATURE REVIEW

Ray et al. (2021)

- *Focus area:* Review of concrete incorporating ceramic waste as aggregates.
- *Key results:* The mechanical and durability properties of ceramic waste aggregate concrete are similar to those of conventional concrete. The compressive strength and bond strength values of ceramic waste concretes generally satisfy code requirements, even though they have higher water absorption than plain concrete because of the porosity created by the ceramic [8–10].

Omnia F. Youssef et al. (2025)

- *Focus area:* Performance evaluation of sustainable concrete with recycled brick and ceramic aggregates.
- *Key results:* Summarization demonstrates that the mechanical and durability properties of ceramic waste aggregate concrete are similar to those of conventional concrete. The compressive strength and bond strength values of ceramic waste concretes generally satisfy code requirements, even though they have higher water absorption than plain concrete because of the porosity created by the ceramic [8–10].



Ceramic and concrete waste in impacturale agregade

Figure 1. Materials.

Elemam, Agwa, and Tahwia (2023)

- *Focus area:* Concrete with ceramic waste as fine aggregate and supplemental cementitious material.
- The compressive and flexural strengths were increased up to a maximum of 50% fine replacement and 10% powder replacement. The mechanical properties improved at the best ratios; however, workability deteriorated. Ceramic and powder composites are effective for enhancing high-temperature capability.

Geng et al. (Fiber-Reinforced Review) (2025)

- *Focus area:* Systematic review of fiber-reinforced recycled ceramic waste concrete.
- *Findings:* Unique Physical Foamed ceramic waste incorporation of 20% coarse and 50% fine aggregate enhanced compressive strength to about 32.98–35.83 MPa, and CO_2 release significantly decreased (≈40% dependent on porosity). The use of fibers increased both crack resistance and frost durability, improving sustainability indicators.
- *Key findings:* The compressive strength of high-strength concrete increased (by ~12%) with 20% ceramic coarse aggregate replacement compared to the control mix, and the durability was similar to that of a normal concrete mix, which performed as well as that with conventional coarse aggregates in terms of durability.
- The increase in pH value is observed when 20% ceramic waste aggregate is used.

Medina et al. (~2010)

- *Focus area:* Concrete with ceramic tile waste as coarse aggregate.
- *Key findings:* The compressive strength of high-strength concrete increased (by ~12%) with 20% ceramic coarse aggregate replacement compared to the control mix, and the durability was similar to that of a normal concrete mix, which performed as well as that with conventional coarse aggregates in terms of durability.
- The increase in pH value is observed when 20% ceramic waste aggregate is used.

Siddique et al. (~2017)

- *Focus area:* Ceramic waste aggregate concrete strength performance.
- *Key findings:* Mixtures containing recycled ceramic waste aggregates exhibited strengths that reached 80–95% of the strength achieved by conventional mixes; the behavior was highly dependent on both replacement level and interactions developed at the aggregate particle scale.

METHODOLOGY

To cover all, this review followed a systematic study method, and the following keywords were further adopted to perform research: “ceramic waste concrete,” “recycled concrete aggregate,” “construction and demolition waste (CDW);” mechanical performance,” durability,” and sustainability.”

The data were gathered through prestigious databases, such as Scopus, Web of Science, and Google Scholar, for peer-reviewed articles published between 2010 and 2025. The review is structured as follows:

- To assess the effect of the addition of ceramic and recycled concrete waste on the compressive, tensile, and flexural strengths of concrete.
- To analyze microstructural features causing performance differences (porosity, ITZ, and particle bonding).
- To review various treatment and reinforcement methods that enhance compatibility and performance.
- To evaluate the mechanical and durability properties, such as permeability, freeze–thaw, and thermal resistance.
- To evaluate aspects of potential sustainability, such as environmental impact, life cycle benefits, and application potential.

The investigation into ceramic and recycled aggregates shows an equilibrium in terms of sustainability advantages and mechanical strength sacrifices. These features are essentially related to the nature and amount of waste used, as well as the particle shape and pretreatment processes followed to enhance their surface adhesion with that of the cement matrix [1, 2, 5, 7].

Mechanical Strength (Compressive, Tensile, and Flexural)

Numerous studies have reported that replacing natural aggregates with ceramic fragments or recycled concrete particles typically results in a moderate decline in strength, depending on the replacement level and material quality [1, 3, 5, 8]. However, strength losses can often be mitigated through optimized mix designs and surface modification treatments.

Compressive Strength

The compressive strength (CS) was observed to fall with an increase in the ratio of replacement of natural aggregate with ceramic or RCA, even at a substitution ratio higher than 25–30% [5]. This decrease is attributed to the more porous and rough surface texture of recycled materials. However, it is possible to replace a part of the cement with fine ceramic powder owing to its pozzolanic activity, thus resuming or even improving the mechanical performance at an early stage. The Laboratory experiments' behavior usually demonstrates a nonlinear decline, but the strength remains constant up to 15–20% replacement, followed by a rapid reduction beyond this level (Figure 2) [1, 4, 6].

The tensile and flexural strengths also followed the same trend. Corrosion-resistant alloys (CRAs), as ceramic wastes, enhance crack resistance by accommodating micromechanical interlocking owing to their sharper horny particles, and CRAs, as RCA, improve strain capacity by generating microvoids that delay crack growth [3, 7]. These materials produce some decrease in ultimate strength but contribute to the increase of potential ductility, impact energy absorption, and fracture warning behavior over conventional concrete Figure 3.

Stress–Strain Behavior and Density

Ceramic or RCA-based concrete typically exhibits a more gradual stress–strain curve and less brittle failure characteristics. The lower densities of the recycled aggregates, which resulted from remained mortar and inherent pores in it, lead to a decrease in their unit weight by 5–12%, opening up a new possibility for using them as low-density concrete or nonstructural materials [5, 6].

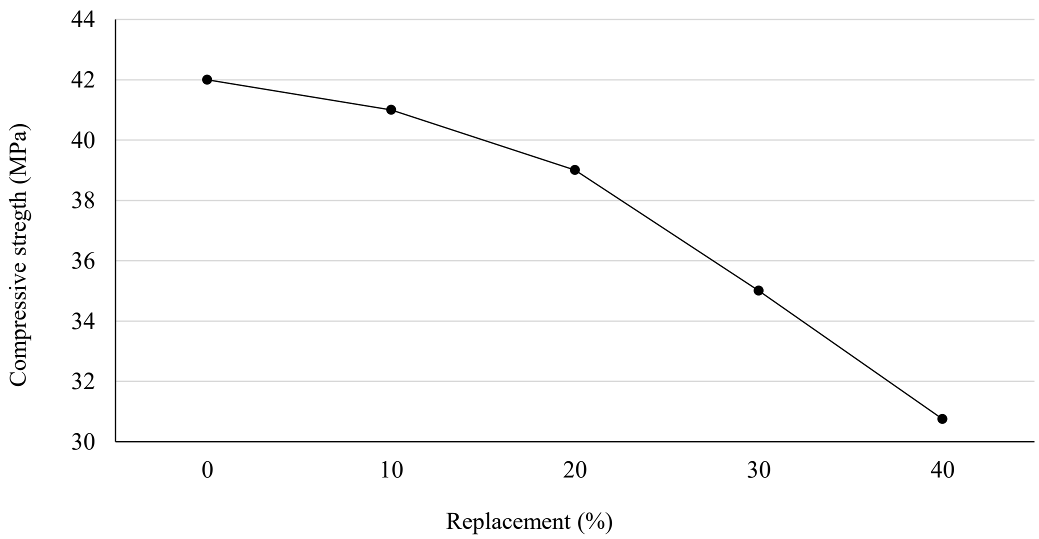


Figure 2. compressive strength versus waste replacement.

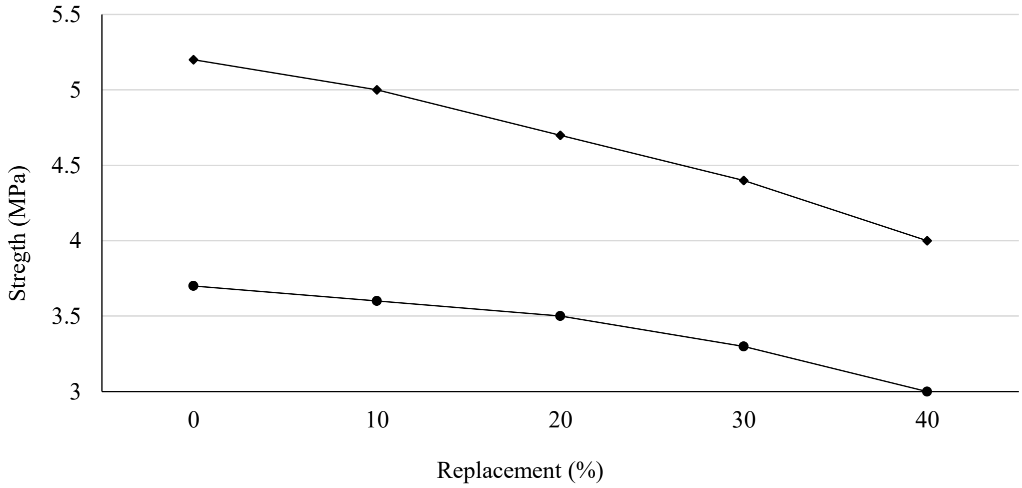


Figure 3. Tensile and flexural strength trends.

Mechanisms of Strength Reduction

The scatter observed in the mechanical response can be attributed to three main microstructural phenomena [6, 7]:

- *High porosity and absorption:* The presence of old mortar and microcracks in recycled concrete and ceramic particles absorbs additional water, resulting in reduced workability and poor bonding at the interface.
- *Weak interfacial transition zone:* The bond between the older mortar or ceramic surface and the new paste is weak due to the presence of residual cement dust and chemical inertness. This is the main cause of microcrack expansion.
- *Micropores and microcracks:* Generally, the waste-aggressive (crushing the waste aggregates and maneuvering) would create fine cracks and trapped air to reduce concrete compressive strength but enhance energy absorption, power, and damping performance.

The Interfacial Transition Zone Optimization and Treatment Methods

Enhancing the ITZ quality among waste particles with fresh cement paste is crucial for strength recovery. Typical improvement strategies include:

- *Surface cleaning and soaking:* Pre-soaking RCA or ceramic aggregates in water decreases their absorption, resulting in more uniform w/c ratios when mixing [9].
- *Chemical treatment:* Washing aggregates with weak acid and treatment with silica solutions increases the reactivity of the surface, resulting in more notable interfacial bonding [7].
- *SCMs use:* Materials such as fly ash, silica fume, or ground granulated blast-furnace slag (GGBFS), clog pores in the vicinity of waste grains, densifying the ITZ and increasing the long-term strength.
- *Hybrid blending:* Ceramic and RCA are mixed in optimal proportions to achieve a balanced performance, wherein ceramic fines enhance matrix density, whereas RCA reduces density and increases sustainability.

Durability and Resilience: The Key Advantages

Although certain mechanical characteristics may decrease, physical properties, such as durability and resistance, are usually enhanced by waste addition [5, 8]. Ceramic particles are chemically inert and thermally stable; the salad post-porosity of RCA would facilitate stress distribution.

- *Water and chloride penetrability:* Mixing with a well-designed ceramic powder lowers penetration because of the closure of pores and fewer capillary channels.

- *Freeze–thaw:* Owing to the porous nature of RCA, repeated loading from ice expansion develops cracking in aged concrete with less regularly structured natural aggregates.
- *Temperature and fire resistance:* Ceramic aggregates exhibit heat-resistant properties that reduce explosive spalling while increasing residual strength at high temperatures.
- *Effect on impact and abrasion resistance:* Concrete containing waste materials exhibited higher energy absorption and toughness owing to its better crack-bridging ability and heterogeneous structures.

Ceramic and RCA Concrete in Specialized Applications

The use of ceramic waste and RCA combines ease as sustainable materials with a minimum level of structural strength. These products are particularly helpful in nonstructural and semistructural applications where durability and ecological considerations are key.

- *Pavement and sidewalk:* Pavers, wastage in tiled pavements, cement pavers/checkered tiles outs.
- Overburden material from mines, such as checkered tiles, can be ‘partial’ or “full thickness” depending on the mix design (guidance from GRIHA); commonly used for making pathways within a building or inside a complex.
- *Precast and blockwork:* A medium-strength material with high dimensional stability, ideal for use in masonry blocks, floor tiles, and non-load-bearing walls.
- *Thermal and sound panel:* Ceramic matrix composites have inferior thermal conductivity but good sound-absorbing properties and can thus be utilized in interior wall panels.

Environmental and Economic Sustainability

Ceramic and RCA concrete are practical examples of the circular economy, transforming construction waste into new building materials.

- *Rubbish measures:* Reprocessing ceramic tiles and crushed concrete reduces landfill waste and the need for fresh aggregates.
- *Resource saving:* By substituting 20–30% of natural coarse aggregates with RCA, natural resource extraction can be reduced by over 25%, thereby prolonging quarry life.
- *Life cycle assessment (LCA):* Research indicates that including recycled content in construction materials can decrease the embodied carbon footprint by 15-40%, primarily because of reduced energy consumption and waste transport.
- *Thermal performance:* Ceramics have low thermal conductivity, which enhances the insulation performance of concrete members and subsequently lowers building operational energy consumption.
- *Economical:* Although more investment is required for subsequent crushing and cleaning processes, the cost can be offset by favorable savings in raw material purchasing, landfill disposal fees, and environmental levies.

In conclusion, the utilization of ceramic waste with recycled RCA is a two-way profit process that provides eco-friendly and cost-effective sustainable construction materials.

Future Scope

The routine use of RCA and ceramics as aggregates for concrete will rely on continued refinements in processing, testing, and regulations. Future research directions can be concluded with the following research agenda.

Enhanced Material Processing and Surface Finish

- *Innovative conditioning processes:* emitter designs can take advantage of alternative carbon and activation without chemical waste from sustainable cleaning gasification methods, such as carbonation, ultrasound, or plasma treatment.

- *Premixed particle size and grading:* Definition of particle size (fine or coarse) limits to promote consistent strength and durability performance.

Structural and Code Implementation

- *Application to load-bearing members:* Additional large-scale structural testing is necessary to demonstrate its use in beams, columns, and slabs.
- *Standards and recommendations:* Establishment of code provisions and acceptance criteria for the safe use of RCA and ceramic-based materials in conventional construction.

Hybrid and Multifunctional Composites

- *Mixing with SCMs and wastes:* incorporation of ceramic waste and RCA in the presence of fly ash, slag, or glass powder can increase strength recovery and durability owing to synergistic pozzolanic reactions.
- *Functionally integrated:* The aforementioned multifunctional concrete with self-healing, heat resistance, and electromagnetic shielding capabilities could be realized in the future.

Long-Term Durability and Environmental Assessments

- *Field validation:* Full-scale field testing under various climatic and loading conditions to evaluate freeze–thaw, carbonation, and fatigue behavior.
- *Leaching and environmental safety:* to assess the long-term effects of leachate and microparticles on RCAs in accordance with environmental regulations.

CONCLUSION

The recycling of ceramic and recycled concrete waste in construction materials is an efficient method for solving environmental and resource problems in the construction industry. Although the utilization of these waste materials may lead to a decrease in compressive and tensile strength to a certain extent at higher replacement levels, such drawbacks can be alleviated by selecting appropriate mix proportions, a reasonable particle size distribution, and the incorporation of SCMs, such as fly ash or silica fume. The high-performance concrete (HPC) composites exhibit better longevity, thermal resistance, and long-term performance owing to a more homogeneous microstructure and the development of ITZ pimples.

In addition, reusing ceramic and concrete waste remarkably reduces landfill space, hinders the extraction of more natural aggregates, and lowers CO_2 emissions caused by concrete production. These sustainability advantages deliver on circular economy principles and global targets to reduce construction waste and CO_2 emissions. Thus, the use of ceramics and rate analysis (RA) in concrete becomes a technically feasible alternative to produce sustainable future infrastructure, where performance, cost, and environmental balance are considered.

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