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## A Comprehensive Review of Sustainable Concrete with Ceramic Waste: Performance, Challenges and Future Directions

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### Abstract

The objective of this review is to evaluate the potential of ceramic waste as a sustainable alternative material in concrete, addressing environmental, technical, and economic considerations. The analysis synthesizes findings from experimental studies, microstructural investigations, and life cycle assessments to examine ceramic waste used as both aggregate and supplementary cementitious material. Key performance indicators such as compressive, tensile, and flexural strengths, durability under aggressive conditions, thermal resistance, and workability are assessed. Advanced modeling tools, including finite element analysis and machine learning, are also reviewed for their role in predicting performance and optimizing mix design. Findings indicate that ceramic waste enhances strength and durability when used at optimal replacement levels (typically 10–20%), with improvements in resistance to chloride penetration, freeze-thaw cycles, and high-temperature exposure. Environmental and economic benefits include reduced carbon emissions, diversion of landfill waste, and material cost savings. However, variability in ceramic waste composition, reduced early-age strength, and lack of standardization remain significant barriers. This review improves on earlier studies by consolidating both technical and sustainability evidence, highlighting performance trends across different replacement levels, and emphasizing pathways for standardization and field-scale adoption.

*Keywords:* Aggregate Substitution; Life Cycle Assessment; Mechanical Properties; Structural Applications; Thermal Performance.

### 1. Introduction

The increasing demand for sustainable construction materials has driven significant interest in the valorization of industrial by-products and waste streams, particularly ceramic waste, as alternative constituents in concrete. Ceramic waste, generated from various sources such as tile manufacturing, demolition debris, and polishing residues, presents a promising avenue for reducing the environmental footprint of concrete production while simultaneously addressing waste management challenges [1, 2]. The integration of ceramic waste into concrete formulations is motivated by the dual objectives of enhancing resource efficiency and minimizing the reliance on natural aggregates and cement, both of which are associated with high energy consumption and carbon dioxide emissions [2, 3]. Research has demonstrated that ceramic waste can be utilized as a partial or complete replacement for both fine and coarse aggregates, as well as a supplementary cementitious material, depending on its physical and chemical characteristics [4, 5]. The composition of ceramic waste typically includes natural minerals such as plastic clay, feldspar, montmorillonite, and glass sand, which can impart beneficial properties to the resulting concrete matrix [4]. The use of ceramic waste as aggregate has been shown to influence the microstructure of concrete, particularly through the formation of mechanical interlocks at the

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interface between the cement paste and the porous ceramic particles. This phenomenon, often described as the creation of "mechanical hooks," enhances the adhesion between the matrix and the aggregate, potentially improving the mechanical performance of the composite [6].

The mechanical properties of concrete incorporating ceramic waste are of particular interest, because they determine the material's suitability for structural applications. Studies employing finite element analysis (FEA) have provided valuable insights into the effects of ceramic waste on compressive, tensile, and flexural strengths, revealing that the introduction of ceramic waste can maintain or even enhance these properties under certain conditions. The specific impact depends on factors such as the type and proportion of ceramic waste used, the particle size distribution, and the interaction with other supplementary materials like blast furnace slag [3]. In some cases, the replacement of natural coarse aggregate with ceramic tile waste has resulted in improved workability and comparable or increased compressive strength, while the substitution of fine aggregate may lead to a slight reduction in strength but still offers improved workability [5]. Durability is another critical aspect when evaluating the performance of ceramic waste-based concrete. The porosity and permeability of the concrete, which are closely linked to its long-term durability, can be assessed through water absorption measurements. These parameters provide insights into the material's resistance to aggressive environmental conditions and its expected service life [7].

Literature reviews have consistently highlighted the potential of ceramic waste to enhance the durability of concrete, particularly in terms of resistance to chloride penetration and other forms of chemical attack [1, 3]. However, the long-term performance of such materials under real-world conditions remains an area requiring further investigation. From a sustainability perspective, the incorporation of ceramic waste into concrete aligns with the principles of circular economy and resource conservation. By diverting waste from landfills and reducing the extraction of virgin materials, this approach contributes to lower environmental impacts and supports the development of greener construction practices [2, 3]. Collaboration among research institutions and industry stakeholders is essential for advancing knowledge sharing, standardizing best practices, and promoting the widespread adoption of sustainable manufacturing techniques. Continuous monitoring of sustainability metrics and investment in research are necessary to drive ongoing improvements in the production and application of ceramic waste-based concrete [8]. Despite the promising findings, several research gaps persist. Notably, there is a need for comprehensive studies on the long-term durability and optimal replacement levels of ceramic waste in various concrete types, ranging from conventional to ultra-high-performance concrete [1]. Additionally, the development of robust predictive models, supported by advanced techniques such as FEA and artificial intelligence, can enhance the reliability of sustainability assessments and guide the optimization of concrete formulations [3]. Addressing these gaps will be crucial for realizing the full potential of ceramic waste in sustainable concrete development and for informing future standards and guidelines in the construction industry.

Recent investigations have demonstrated that ceramic waste can significantly enhance the microstructural characteristics of concrete through advanced pozzolanic reactions. The incorporation of ceramic waste powder as a supplementary cementitious material has been shown to increase compressive strength by up to 41% when used at optimal replacement levels [9]. These improvements are primarily attributed to the formation of additional calcium silicate hydrate (C-S-H) gel through the reaction of reactive silica in ceramic waste with calcium hydroxide produced during cement hydration [10]. The microstructural densification achieved through ceramic waste incorporation has been confirmed through scanning electron microscopy (SEM) and energy dispersive X-ray analysis (EDS), revealing enhanced interfacial transition zones and reduced porosity in the concrete matrix [11].

The mechanical performance of ceramic waste concrete exhibits a complex relationship with replacement levels and curing time. Ultra-high-performance concrete incorporating ceramic waste has demonstrated remarkable strength gains, with compressive strengths reaching 171.3 MPa and 176.7 MPa at 56 days when 20% of cement was replaced with ceramic waste powder [12]. However, beyond optimal replacement levels, typically ranging from 15% to 20%, mechanical properties begin to deteriorate due to the dilution effect of cement content and increased porosity [13]. The split tensile strength of ceramic waste concrete has shown improvements of up to 26.32% at 28 days when ceramic waste was used to replace 20% of coarse aggregate, indicating enhanced crack resistance and improved load distribution within the concrete matrix [14].

Workability characteristics of ceramic waste concrete present both challenges and opportunities for practical implementation. The incorporation of ceramic waste typically results in reduced slump values due to the angular nature and increased surface area of ceramic particles, which increases water demand and internal friction within the mix [11]. Slump flow diameter decreases significantly with increasing ceramic waste content, dropping from 770 mm to 685 mm when 50% of cement is replaced with ceramic waste powder [12]. Despite these workability challenges, the smooth surface texture of certain ceramic wastes, particularly ceramic tiles, can enhance flowability and reduce segregation in concrete mixtures [14].

The durability aspects of ceramic waste concrete have been extensively investigated, revealing promising results for long-term performance. Water absorption studies indicate that ceramic waste concrete can achieve comparable or superior impermeability compared to conventional concrete when replacement levels are optimized [15]. Chloride

penetration resistance, a critical durability parameter, shows improvements at moderate ceramic waste content due to microstructural refinement and pore structure modification [16]. However, at higher replacement levels, the increased porosity can compromise chloride resistance, emphasizing the importance of optimal dosage determination [11].

Fire resistance properties of ceramic waste concrete represent a significant advancement in high-temperature applications. Research has demonstrated that ceramic waste concrete maintains superior mechanical properties under elevated temperatures compared to conventional concrete [16]. When subjected to temperatures up to 750°C, concrete containing 5% ceramic waste exhibited enhanced fire resistance, with improved thermal stability attributed to the refractory nature of ceramic materials [16]. The formation of beneficial compounds such as Gehlenite ( $\text{Ca}_2\text{Al}_2\text{SiO}_7$ ) during high-temperature exposure contributes to the material's thermal performance, making it suitable for fire-resistant construction applications [17].

Environmental impact assessments through life cycle analysis (LCA) have revealed substantial sustainability benefits of ceramic waste utilization in concrete production. The replacement of cement with ceramic waste demonstrates significant reductions in environmental impacts including carbon dioxide emissions, which represent approximately 8% of global  $\text{CO}_2$  emissions from cement production [18]. Cost analysis has shown that replacing 15% of river sand with ceramic waste can reduce production costs by approximately 9%, from \$46/m<sup>3</sup> to \$42/m<sup>3</sup>, while simultaneously addressing waste disposal challenges [11].

Machine learning and artificial intelligence techniques are increasingly being employed to optimize ceramic waste concrete formulations and predict performance characteristics. Advanced predictive models using artificial neural networks (ANN) and Light Gradient Boosting Machine (LightGBM) have demonstrated exceptional accuracy in predicting mechanical properties of ceramic waste concrete, with correlation coefficients ( $R^2$ ) reaching 0.945 for compressive strength predictions [12]. These computational tools enable engineers to optimize mix designs without extensive experimental programs, significantly reducing development time and costs while ensuring optimal performance [19].

The synergistic effects of ceramic waste with other supplementary cementitious materials present opportunities for enhanced performance optimization. Combinations of ceramic waste with materials such as fly ash have demonstrated superior resistance to sulfate erosion under dry-wet cycling conditions compared to individual replacements. These hybrid systems leverage the complementary characteristics of different waste materials to achieve optimal concrete performance while maximizing waste utilization [20].

Processing techniques for ceramic waste preparation significantly influence the resulting concrete properties. Grinding ceramic waste to achieve specific surface areas, typically around 555 m<sup>2</sup>/kg, optimizes pozzolanic activity and enhances performance [12]. The particle size distribution and morphological characteristics of processed ceramic waste directly impact workability, strength development, and durability characteristics, emphasizing the importance of controlled preparation methods [13].

The interfacial transition zone (ITZ) between ceramic waste particles and cement paste plays a crucial role in determining the overall performance of ceramic waste concrete. The effectiveness of the bond between the cement paste and ceramic waste particles determines the quality of the ITZ, with larger surface areas of fine ceramic particles improving the bond and leading to better load transfer, reduced porosity, and higher mechanical strength [12]. Well-bonded ITZ can enhance the strength and durability of the concrete through improved microstructural characteristics [21].

Temperature sensitivity and thermal cycling effects on ceramic waste concrete performance require careful consideration for practical applications. While ceramic waste enhances high-temperature resistance, the material's response to freeze-thaw cycles influences long-term durability in harsh environmental conditions [16]. Understanding these temperature-dependent behaviors is crucial for establishing appropriate application guidelines and performance specifications [22].

Economic feasibility studies indicate that ceramic waste utilization in concrete production offers substantial cost benefits alongside environmental advantages. The widespread availability of ceramic waste, which can account for up to 30% of total production volume in ceramic industries, makes it readily accessible for concrete applications [11]. The economic viability is further enhanced by reduced landfill disposal costs and the potential for premium pricing in environmentally conscious markets [23].

Quality control and standardization efforts are crucial for widespread adoption of ceramic waste concrete technology. The establishment of robust predictive models and performance databases enables better quality assurance and facilitates the development of industry standards [19]. Continuous monitoring of sustainability metrics and systematic evaluation of long-term performance under various environmental conditions are essential for building confidence in ceramic waste concrete applications [24].

Microstructural investigations using advanced techniques such as SEM and energy dispersive spectroscopy (EDS) have revealed that ceramic waste incorporation leads to the formation of denser concrete matrices with refined pore structures. The pozzolanic activity of ceramic waste, though limited in early stages, improves over time, enabling enhanced crystalline formation and reduced macroporosity [11]. These microstructural improvements contribute directly to enhanced mechanical properties and durability characteristics [25].

The integration of ceramic waste as both aggregate and supplementary cementitious material presents unique opportunities for comprehensive waste utilization strategies. Studies have shown that simultaneous replacement of both cement and aggregate with ceramic waste can achieve optimal performance when replacement levels are carefully balanced [26]. This dual utilization approach maximizes waste consumption while maintaining or enhancing concrete performance characteristics [27].

Despite increasing interest in sustainable construction, several gaps hinder the practical adoption of ceramic waste in concrete. These include the absence of standardized guidelines, limited insights into long-term durability, and inconsistent results on mechanical performance. This study addresses these gaps by reviewing existing research on the use of ceramic waste as both aggregate and cement replacement. Emphasis is placed on its pozzolanic activity, contribution to strength and durability, environmental and economic benefits, and optimization through advanced tools such as finite element analysis and machine learning, paving the way for future standardization and application.

The article is organized to provide a comprehensive review of ceramic waste utilization in concrete. It first outlines the background, motivation, and environmental implications of ceramic waste, followed by an examination of its sources, properties, and forms. Subsequent sections address its incorporation into concrete, including mix design considerations and the influence on mechanical and durability performance. The discussion then extends to sustainability benefits and potential applications across conventional and advanced concretes. Finally, the paper identifies key challenges and research gaps, before presenting future directions to facilitate standardization and large-scale implementation.

## 2. Background and Motivation

### 2.1. Global Issues in Construction and Sustainability

The construction sector contributes significantly to environmental challenges through concrete use and resource consumption. Cement production accounts for approximately 7% of global CO<sub>2</sub> emissions, while natural aggregate extraction causes environmental degradation, and resource depletion [3, 28]. Rising infrastructure demand intensifies pressure on natural resources, making alternative materials critical [28, 29].

Sustainability involves both emission reduction and waste minimization through circular material use. Construction and demolition waste accumulation presents challenges as materials often end up in landfills [29]. Reusing ceramic waste offers dual benefits: waste diversion and reduced natural aggregate demand [28]. Research shows 10% replacement of natural fine aggregates with ceramic waste powder can optimize properties while supporting sustainability goals [3]. Challenges persist due to material variability affecting concrete consistency. The industry's sustainability transition is driven by climate awareness, regulatory pressures, and resource scarcity concerns [28, 29].

### 2.2. Waste Management Challenges in the Construction Industry

Construction faces significant ceramic waste management challenges from manufacturing and demolition activities. Ceramic waste disposal occupies landfill space and contributes to environmental degradation due to ceramics' inert, non-decomposing nature [14, 30]. Growing volumes pressure industries toward sustainable disposal strategies as traditional landfilling becomes unsustainable [30].

Natural resource reliance, particularly fine aggregates, exacerbates concerns through depletion, habitat destruction, and increased costs [3]. While ceramic waste integration offers promising solutions, adoption faces barriers including lack of standardized processing methods and property variability [8].

Despite research demonstrating improved properties through pozzolanic reactivity, limited industry awareness and acceptance continue to hinder widespread adoption [31]. The conservative construction sector prioritizes proven performance over innovation, while logistical challenges in waste collection and processing persist [14, 30]. Long-term durability research remains insufficient [32].

### 2.3. Need for Alternative and Sustainable Materials

Mounting pressure exists to address traditional concrete production's environmental consequences, particularly cement manufacturing's 7% contribution to global CO<sub>2</sub> emissions. Natural aggregate depletion and costs intensify demand for materials that maintain performance while reducing environmental impact [3].

Ceramic waste emerges as a promising candidate addressing multiple challenges: waste diversion, reduced resource consumption, and potential performance improvements [32]. Integration aligns with circular economy principles emphasizing resource efficiency and waste minimization. Ceramic materials' unique properties, including pozzolanic activity and cement hydration inertness, contribute to durability [33].

Economic benefits include lower production costs and potential sustainable construction incentives [32]. Advanced analytical tools like FEA enable better understanding of material substitution implications, enhancing performance prediction reliability [3].

### 3. Overview of Ceramic Waste

#### 3.1. Sources and Types of Ceramic Waste

Ceramic waste is heterogeneous, arising from manufacturing processes, construction/demolition activities, and post-consumer products. Manufacturing generates waste from defects, breakage, or off-specification products in tiles, sanitary ware, porcelain, and stoneware production, representing consistent, pure waste streams [29]. Construction and demolition activities yield broken tiles, bricks, and ceramic components, often with attached mortar complicating direct reuse [33]. Ceramic wastes can be divided into two categories based on the origin of their raw materials. The first category includes all fired waste produced by structural ceramic manufacturers, who typically use only red pastes to create products like bricks, blocks, and roof tiles. The second category includes all fired waste generated in stoneware ceramic, such as wall tiles, floor tiles, and sanitary ware. Manufacturers in this category use both red and white pastes; however, white paste is used more frequently and in significantly larger quantities. In each category, the fired ceramic waste was categorized according to the production process as shown in Figure 1 which represents the classification of ceramic wastes according to their type and manufacturing method [34].

Types include porcelain, stoneware, earthenware, and various tiles with distinct compositions. Chemical composition is dominated by  $\text{SiO}_2$ ,  $\text{Al}_2\text{O}_3$ , and  $\text{MgO}$  oxides, with additional constituents affecting behavior in concrete applications [29]. Physical properties like fineness modulus (2.55), specific gravity (2.50), and bulk unit weight ( $1500 \text{ kg/m}^3$ ) differ from natural sand, influencing concrete characteristics [12]. Environmental implications are significant, with ceramics constituting 54% of global construction/demolition waste in 2014, and 68 million tons landfilled annually in the UK [35].

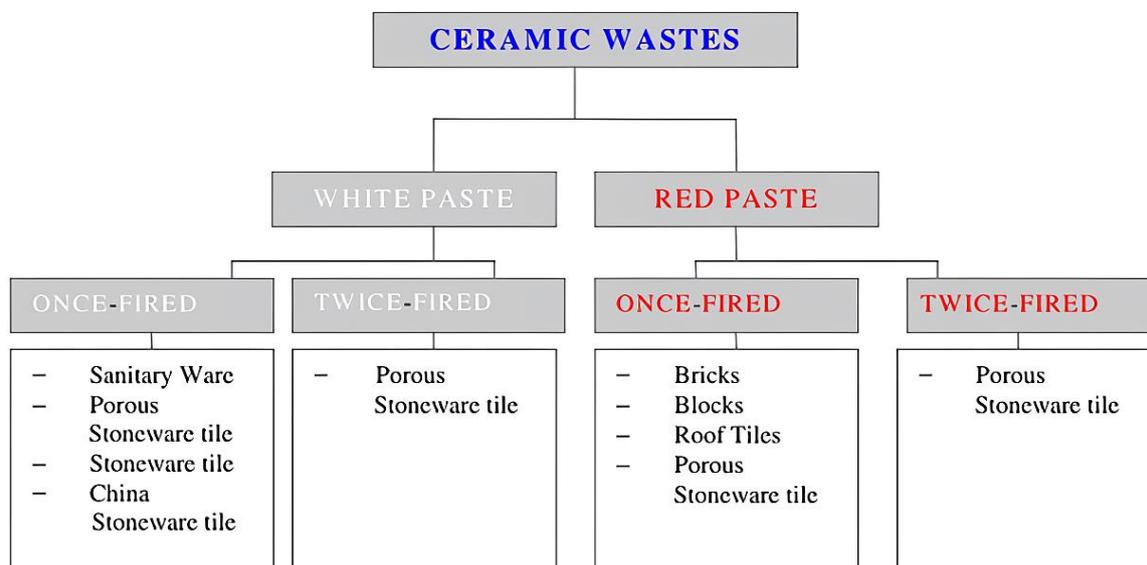


Figure 1. Classification of ceramic wastes according to their type and manufacturing method [34]

#### 3.2. Properties of Ceramic Waste

Ceramic waste's chemical composition includes  $\text{SiO}_2$ ,  $\text{Al}_2\text{O}_3$ , and  $\text{Fe}_2\text{O}_3$ , often reaching 90%, and surpasses minimum pozzolanic material thresholds per ASTM C618-15 [35]. High aluminosilicate content enables pozzolanic reactivity in cementitious systems [35, 36]. Silicon dioxide content can reach 66% versus 19% in Portland cement, suggesting strong potential for additional C-S-H gel formation [36].

Physical characteristics include substantial specific surface area ( $562 \text{ m}^2/\text{kg}$ ) enhancing reactivity and cement matrix integration. Ceramic aggregate porosity is lower than other recycled materials, affecting water absorption and autogenous shrinkage mitigation capabilities [37]. Mechanical incorporation influences reinforced concrete beam deflection behavior and overall performance [3]. Waste originates from diverse sources creating property variations

requiring careful mix design consideration [14, 38]. Ceramics constitute up to 54% of global construction waste in some regions [35].

### 3.3. Environmental Impact of Ceramic Waste Disposal

Ceramic waste constitutes significant portions of global solid waste streams, with improper landfill disposal creating major environmental concerns due to volume and persistent nature. Construction/demolition waste accounts for approximately 50% of landfilled waste, with ceramics as substantial fractions [31]. Impact is exacerbated by the scale of generation - ceramics were the single largest construction/demolition waste contributor globally at 54% in 2014, with 68 million tons landfilled annually in the UK [35]. Ceramics remain inert in landfills without breakdown, representing missed resource recovery opportunities [1].

Environmental burden includes land occupation and potential leachate composition influences, though ceramics are generally chemically stable. Co-disposal with other wastes may introduce risks, particularly with residual contaminants [33]. Absence of efficient recycling pathways results in linear waste management contrasting with sustainable development principles [35].

## 4. Use of Ceramic Waste in Concrete

### 4.1. Historical Development

Historical utilization development is rooted in sustainable construction needs and environmental impact concerns. Early efforts were motivated by significant quantities generated, particularly in high construction activity regions. In the EU, construction/demolition wastes account for one-third of all wastes, with ceramics as substantial fractions [39].

Initial research focused on feasibility of ceramic waste as concrete aggregate, examining physical and chemical compatibility. Mineralogical composition verification using X-ray diffraction confirmed suitability without introducing deleterious substances [4]. Understanding advanced to investigate interfacial transition zone influences and cement paste-ceramic aggregate adhesion [6].

Evolution paralleled concrete technology advancements, expanding from conventional concrete to self-compacting and high-performance applications. Studies showed ceramic waste in self-compacting concrete enhanced abrasion resistance beyond reference mixes [14]. Development of analytical tools like FEA and AI models accelerated adoption by enabling precise mix design optimization [3]. Scope broadened to include diverse ceramic industry by-products, with demonstrations of recovering up to 100% of materials including end-of-life geopolymers, aligning with circular economy principles [38]. Despite advances, challenges remain in standardized guidelines and long-term durability assessments [1, 33].

### 4.2. Forms of Ceramic Waste Used in Concrete

#### 4.2.1. Ceramic Waste Powder

Ceramic waste powder, produced by finely grinding waste ceramics, serves as a promising supplementary material with pozzolanic properties enabling reaction with calcium hydroxide to form additional calcium silicate hydrate, enhancing microstructure and mechanical performance [33]. Production involves crushing, grinding, and sieving waste ceramics for cement or fine aggregate partial replacement [3, 7].

As partial cement replacement, ceramic powder improves concrete properties. Up to 26% ceramic powder by cement weight in ultra-high-performance concrete enhances splitting tensile strength through improved interfacial bonding [8]. Fine-ground powder replacing 10-40% of cement in high-performance concrete, yields high strength and excellent durability, reducing chloride ion permeability [40]. Pozzolanic activity is confirmed at replacement levels up to 25% [33]. For fine aggregate substitution, ceramic powder maintains or enhances mechanical properties while offering environmental and economic benefits by reducing natural resource demand [3]. Pozzolanic nature contributes to improved workability and strength development, though effects depend on replacement level and source characteristics [33].

Challenges include potential strength reduction at excessive replacement levels due to poor interfacial bonding and increased porosity [7]. Optimizing particle size and replacement ratios is critical for performance-sustainability balance. Future research needs include long-term behavior studies, fire performance, and resistance to various attacks [39]. Standardizing processing and quality control remains challenging due to property dependence on original ceramic manufacturing conditions [5].

#### 4.2.2. Crushed Ceramic Aggregates

Crushed ceramic aggregates offer significant ceramic waste valorization opportunities in concrete technology. The production process involves collecting ceramic waste (tiles, sanitary ware), crushing, and sieving to achieve appropriate

particle sizes [34]. These aggregates have specific gravity and water absorption characteristics comparable to conventional aggregates, enabling integration into standard concrete mixes without major modifications [2].

Ceramic aggregates as replacements for natural coarse aggregates can maintain or enhance mechanical properties. Their smoother surface texture improves workability by reducing internal friction during mixing, though a trade-off exists between workability and compressive strength at higher replacement levels due to pozzolanic activity [33]. The mineralogical composition (predominantly quartz and feldspars) ensures adequate hardness and chemical stability [34].

Mechanically, concrete with ceramic aggregates can surpass conventional concrete strength when optimal replacement ratios are used, due to dense microstructure and improved interfacial transition zones [2, 33]. Additional benefits include improved durability, high temperature resistance, and enhanced radiation shielding properties from heavy metal content [3, 41, 42]. Challenges include property variability affecting consistency and the need for long-term durability studies. Current research suggests ceramic aggregates are viable, sustainable alternatives supporting circular economy principles [3, 41].

#### 4.2.3. Other Derivatives of Ceramic Waste

Ceramic powder, produced by finely grinding waste materials, can partially replace cement or serve as filler. It refines pore networks, decreases porosity, and creates denser microstructures, enhancing strength and durability [32]. High-calcium ceramic powder (HCCP) improves recycled concrete aggregate microstructure and interfacial transition zone density [43].

Ceramic waste can be processed into lightweight aggregates or water storage bricks for thermal insulation and internal curing applications. These provide superior thermal insulation and serve as internal curing agents in high-performance concrete [44, 45]. Synergistic effects with other supplementary materials like rice husk ash can enhance pozzolanic activity [46].

Applications extend to high-temperature concretes, where ceramic aggregates with alumina cement achieve high strength parameters for demanding thermal environments [6]. These derivatives support sustainability by substituting traditional materials and reducing environmental impact [12]. Research gaps remain regarding long-term durability and optimal replacement levels for different ceramic waste forms [43, 45, 46].

### 4.3. Processing and Preparation of Ceramic Waste for Concrete

Processing involves collecting ceramic waste from various sources, followed by physical and chemical characterization to determine suitability as aggregates or supplementary materials [38]. Preparation requires crushing and grinding to achieve desired particle sizes, with grinding intensity depending on intended application - coarse aggregates need less processing while fine powders require intensive milling [36]. The transformation affects surface texture, porosity, and packing density. Finely ground ceramic waste enhances pozzolanic reactivity, contributing to matrix densification [14, 42]. Processing parameters including grinding degree, mixing duration, and thermal treatment depend on waste type and target application [47].

Ceramic waste can partially replace cement, requiring high fineness to maximize pozzolanic activity [32, 40]. Mineralogical composition variations influence reactivity and cementitious system compatibility [37]. Appropriate processing can achieve properties comparable to or better than conventional concrete, though higher absorption capacity may require mix design adjustments [48].

### 4.4. Mix Design Considerations

#### 4.4.1. Replacement Levels

Replacement levels critically influence fresh and hardened concrete properties. For aggregates, levels vary from 10-100% by weight depending on application and desired properties [2]. For cement replacement, typical levels are 5-30% by weight, with optimum levels determined by evaluating strength, durability, and workability [33, 36].

Jwaida et al. [33] found ceramic powders exhibit pozzolanic activity up to 25% replacement. Higher replacement levels may compromise durability parameters like water absorption [49], though specific ceramic types can enhance durability [43]. Economic and environmental considerations influence choices, with cement replacement yielding more significant CO<sub>2</sub> emission reductions [2]. Systematic experimentation is needed to identify optimal levels, balancing waste utilization with performance requirements [33, 49].

#### 4.4.2. Mix Proportion Adjustments

Mix adjustments are essential due to ceramic waste's different physical and chemical characteristics. Particle size distribution, water absorption, and pozzolanic activity directly influence concrete properties [6, 37]. Higher water absorption may require water content adjustments or water-reducing admixtures [37, 44].

Optimal ceramic waste replacement can enhance properties through synergistic effects with supplementary materials. For example, 40% ceramic tile waste with 30% fly ash converted  $\text{Ca}(\text{OH})_2$  into additional C-S-H gel, increasing strength [50]. In ultra-high-performance concrete, optimal replacement was observed at 20% [12].

Mix design must account for waste interactions with other materials and source variability. Standardized procedures provide frameworks, but modifications are often required [38]. Future research should develop predictive models accounting for ceramic waste variability [2, 8].

#### 4.4.3. Workability and Fresh Properties

Ceramic waste incorporation generally reduces workability due to higher specific surface area and angular particle shape increasing internal friction [28, 51]. This can be mitigated using superplasticizers (0.2-0.4% by binder weight), which effectively restore workability by dispersing particles more efficiently [43, 51]. It was noted that the slump value declined with the increase in ceramic waste content, as shown in Figure 2. This suggests that adding ceramic waste (CW) to the mix affects its cohesiveness, to the extent of leading to shear or collapse slump [52].

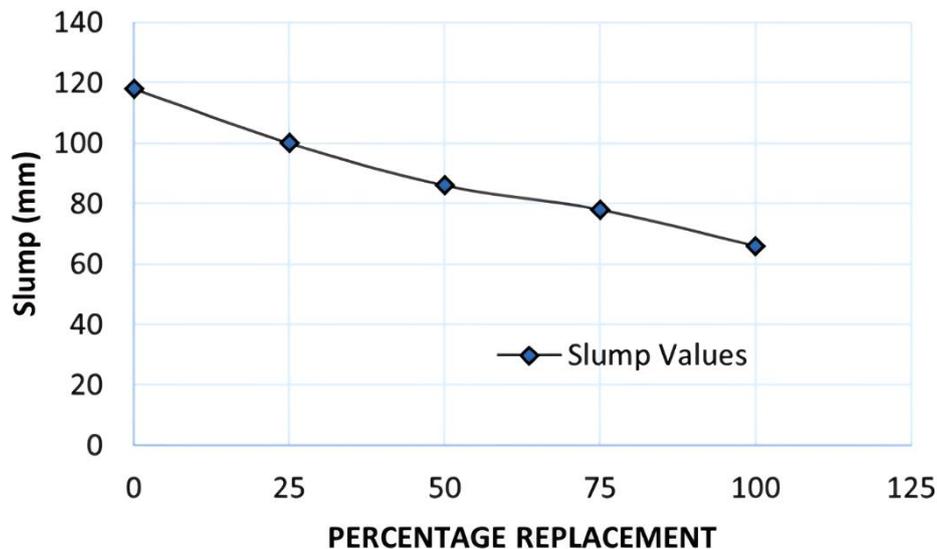


Figure 2. Change in workability with varying ceramic waste (CW) content [52]

In self-consolidating concrete, waste ceramic powders up to 15% replacement can benefit fresh properties when properly optimized [30]. However, the relationship between ceramic content and workability is non-linear, with higher levels causing pronounced flowability reductions [28].

Fresh property effects depend on incorporation method and physical characteristics. When used as fine aggregate replacement, specific gravity and absorption differences alter water demand and consistency [8]. Optimization of replacement levels, particle size, and admixture dosage is essential for maintaining desired fresh properties [30, 43, 51].

## 5. Properties of Ceramic Waste-Based Concrete

### 5.1. Mechanical Properties

#### 5.1.1. Compressive Strength

The compressive strength of concrete incorporating ceramic waste demonstrates varying outcomes depending on the type, proportion, and processing methods employed. Studies reveal that partial replacement of conventional aggregates or cement with ceramic waste can maintain or enhance compressive strength under optimal conditions. Finite element analysis of recycled aggregate concrete with ceramic waste powder shows higher strength compared to traditional mixes, supporting sustainable waste reuse [3]. The incorporation of ceramic waste fine aggregates at 20% replacement enhances compressive strength and significantly improves chloride-ion penetration resistance [47].

However, the relationship between ceramic waste content and compressive strength is non-linear; excessive ceramic waste beyond optimal levels leads to strength reduction. Jwaida et al. observed decreased compressive strength with higher amounts of ceramic powder from recycled tiles [33]. When ceramic waste used as precursor in alkali-activated mortars reached 60-70%, notable strength decline occurred, indicating disrupted matrix continuity [4]. This trend is supported by data showing decreasing compressive strength values with increasing ceramic waste powder replacement percentages [53].

The type and source of ceramic waste significantly influence compressive strength outcomes. Jwaida et al. report that waste ceramic wall and floor tiles can improve compressive, flexural, and tensile strengths, particularly when free from mortar contamination [33]. Physical and chemical characteristics such as porosity, mineral composition, and surface texture are crucial factors. In ultra-high-performance concrete (UHPC), ceramic powder waste effects remain underexplored, requiring further research [54].

Hydration processes and secondary reactions contribute to strength development in ceramic waste-based mortars. Strength gain in blended mortars links closely to secondary hydration reactions, particularly calcium silicate hydrate (CSH) formation, influenced by ceramic tile waste availability and reactivity [35]. From sustainability perspectives, ceramic waste as partial replacement offers environmental benefits while yielding comparable or improved compressive strength when replacement levels are optimized [3]. Figure 3 shows the compressive strength of UHPC with varying ceramic waste tile aggregate (CTWA) percentages at different curing days 3, 7 and 28 days. As illustrated in Figure 3, the compressive strength of UHPC generally increases as the CTWA content rises [47].

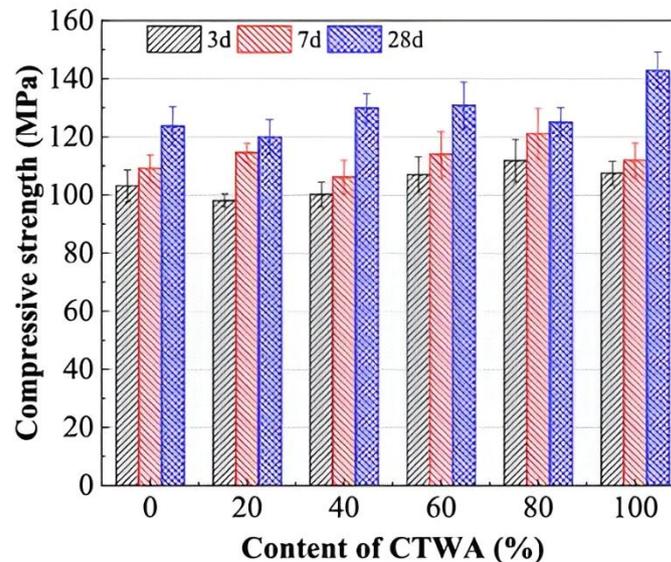


Figure 3. Compressive strength of UHPC with varying CTWA percentages [47]

### 5.1.2. Tensile and Flexural Strength

Ceramic waste incorporation influences tensile and flexural strength through both enhancements and limitations depending on replacement levels, waste types, and curing conditions. Substituting conventional aggregates with ceramic waste increases flexural and splitting tensile strengths, with ceramic waste as aggregate leading to 8.7% flexural strength increase and 15.6% split tensile strength increase compared to conventional concrete [5]. This enhancement results from ceramic particles' angularity and rough surface texture promoting better mechanical interlocking and aggregate-paste interface bonding [5, 33]. Figure 4 demonstrates the 28-day splitting tensile strength of UHPC for two groups [12]. Specimens containing 10% and 20% cement replacement with sanitary ceramic waste powder (SCWP) and wall ceramic waste powder (WCWP) exhibited higher splitting tensile strength, as shown in Figure 4. When compared to the control mix, the splitting tensile strength improved when SCWP and WCWP were used to replace cement at rates of 10% and 20%, respectively. Figure 5 shows the 28-day flexural strength of UHPC for two groups [12]. It can be observed from Figure 5 that the optimal flexural strength was observed when Ordinary Portland Cement (OPC) was replaced by 20% of SCWP by weight for the two groups. Similarly, optimal flexural performance was also observed with a 20% replacement of OPC by WCWP by weight in the two groups.

Replacing coarse aggregates with waste ceramic in M35-grade concrete resulted in higher flexural, split tensile, and compressive strengths, plus increased modulus of elasticity relative to control mixes [33]. Improved performance in both flexural and tensile domains suggests ceramic waste effectively contributes to load-bearing capacity and crack resistance at optimal replacement levels. However, effects are not universally positive across all replacement ratios and concrete types. Early-age addition of shrinkage-compensating agents and pre-soaked recycled porous ceramic aggregate to high-performance concrete slightly decreased mechanical properties, including flexural and splitting tensile strengths. Nevertheless, after 91 days of sealed curing, significant improvement occurred, highlighting curing duration importance and long-term strength gain potential [45].

Ceramic waste powder (CWP) as partial cement replacement in self-consolidating concrete presents nuanced results. Increasing CWP proportion reduced splitting tensile strength, with decline becoming more pronounced at higher replacement levels [14]. While ceramic waste enhances certain mechanical properties as aggregate, its application as cementitious substitute requires careful optimization to avoid compromising tensile performance.

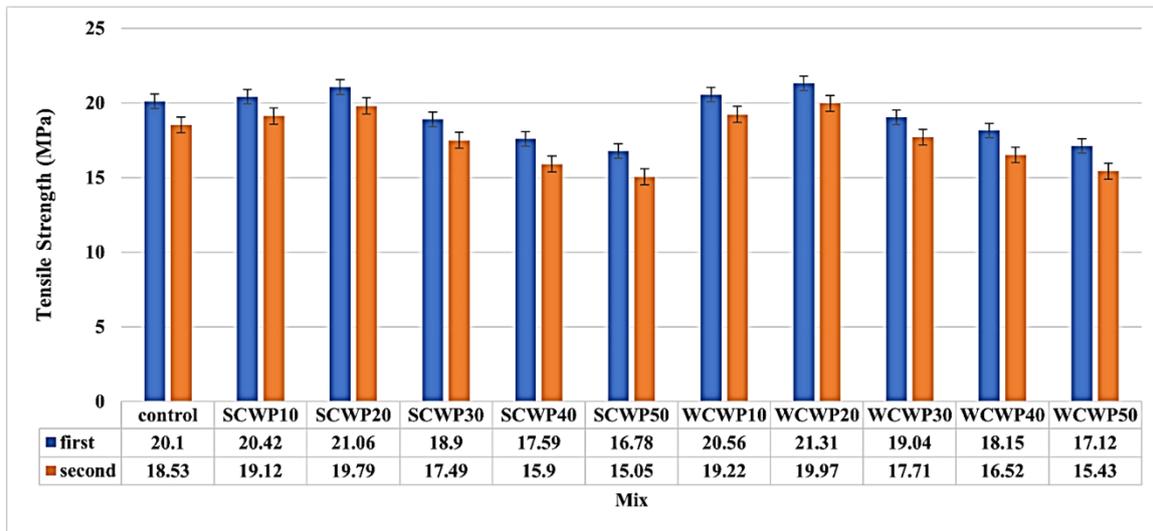


Figure 4. The 28-day splitting tensile strength of UHPC for two groups [12]

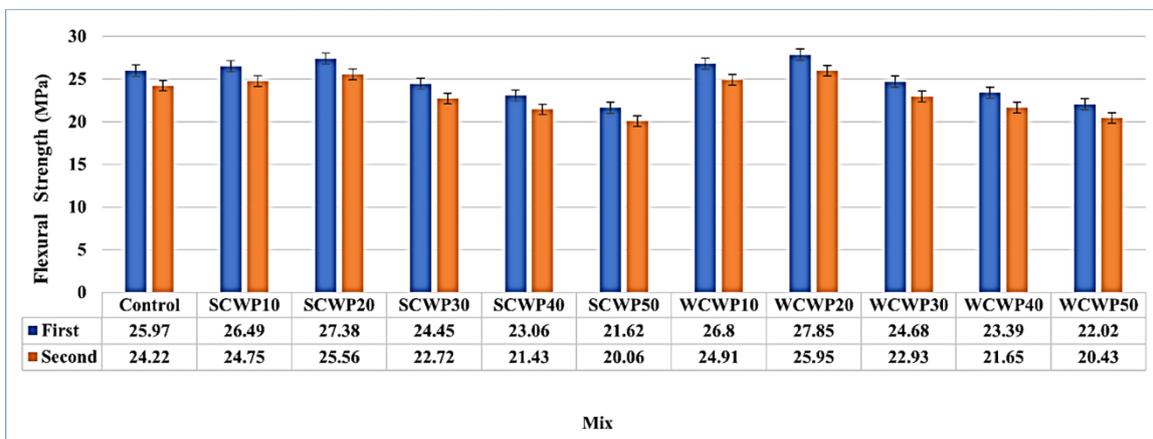


Figure 5. The 28-day flexural strength of UHPC for two groups [12]

### 5.1.3. Modulus of Elasticity

The modulus of elasticity governs concrete deformation behavior under load, directly influencing structural performance and serviceability. Ceramic waste incorporation significantly alters this property with implications for concrete structure design and durability. The modulus closely links to microstructural characteristics including porosity, aggregate-matrix bonding, and constituent material intrinsic stiffness [43].

Recycled ceramic aggregates from brick or sanitary ware waste affect modulus of elasticity in several ways. Ceramic aggregate incorporation generally reduces mechanical properties, including modulus of elasticity, particularly at higher replacement levels [14]. This reduction attributes to ceramic aggregates' higher porosity and lower density compared to natural aggregates, resulting in more compliant, less stiff concrete matrix. Decreased density with increased ceramic aggregate content associates with higher porosity and looser internal structure, both contributing to lower modulus of elasticity [44]. However, the relationship between ceramic waste content and modulus of elasticity is not strictly linear. Natural fine and coarse aggregate or cement replacement with waste ceramics can enhance mechanical properties, including modulus of elasticity, under certain conditions. Improvement is more pronounced at moderate replacement levels where finely ground ceramic waste micro-filler effect densifies the matrix and improves interfacial transition zone between aggregate and paste.

As ceramic waste proportion increases, higher water absorption and aperture formation tendencies become significant, reducing modulus of elasticity [14]. Balance between beneficial micro-filler effects and detrimental porosity increases is crucial for optimizing modulus of elasticity in ceramic waste-based concrete. Moderate incorporation of finely ground ceramic waste enhances modulus of elasticity through matrix densification and improved ITZ, while excessive replacement with coarse, porous ceramic aggregates reduces it due to increased porosity and lower aggregate stiffness [14, 43, 44]. Figure 6 demonstrates the relative elastic moduli of concretes with coarse recycled ceramics. In the floor tile series, the modulus of elasticity exhibited the greatest change in the mechanical characteristics of concrete, demonstrating a linear rise with higher levels of aggregate substitution [55].

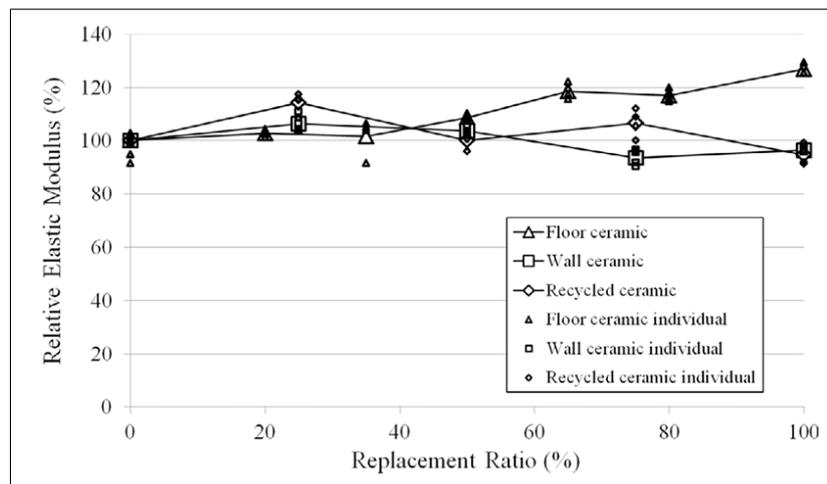


Figure 6. Relative elastic moduli of concretes with coarse recycled ceramics [55]

## 5.2. Durability Properties

### 5.2.1. Resistance to Chloride Penetration

Resistance to chloride penetration is critical for concrete durability, especially in aggressive environments where chloride-induced corrosion compromises structural integrity. Ceramic waste incorporation influences this property depending on type, proportion, and specific mix design. Experimental investigations demonstrate that sanitary waste ceramics as partial natural aggregate or cement replacement enhance concrete resistance to chloride ion penetration. Substituting natural aggregate with 20% sanitary waste ceramic leads to notable durability improvement, including increased electrical resistance and enhanced chloride ion ingress resistance. Enhancement attributes to denser microstructure and reduced capillary pore connectivity, limiting chloride ion penetration pathways [33]. Increased electrical resistance supports refined pore structure notion, less conducive to ionic transport.

Waste ceramics, particularly as fine powders or aggregate replacements, result in concrete with superior chloride penetration resistance compared to conventional mixes. Improvement links to finely ground ceramic waste filler effect, filling cementitious matrix voids, reducing permeability and hindering aggressive ion movement [56]. Additionally, ceramic waste powder pozzolanic reactivity contributes to additional calcium silicate hydrate formation, further densifying microstructure and enhancing durability [53].

The mechanism underlying enhanced chloride resistance is multifaceted. Filler effect reduces capillary pore volume and connectivity. Pozzolanic activity of certain ceramic wastes consumes calcium hydroxide and generates additional C-S-H, less permeable to chloride ions. This dual action improves physical barrier properties and chemically binds chlorides, reducing mobility within concrete [53, 56].

### 5.2.2. Water Absorption and Permeability

Water absorption and permeability critically assess ceramic waste-based concrete durability, directly influencing aggressive agent ingress and long-term performance. Ceramic waste incorporation as aggregate or partial cement replacement significantly affects these properties with both beneficial and challenging outcomes depending on type and proportion used. Capillary water absorption indicates pore structure and connectivity, governing water and dissolved substance penetration ease. Concrete incorporating ceramic aggregates exhibits notably lower capillarity water absorption coefficient compared to conventional concrete with natural aggregates. Control concrete capillary water absorption nearly doubles that of ceramic aggregate-based concrete, suggesting ceramic waste use enhances concrete resistance to water ingress and improves durability. This improvement is corroborated by observed oxygen permeability reduction [34].

High-performance concretes with ceramic waste systematically evaluated for capillary water absorption, electrical resistivity, and chloride ion penetrability demonstrate that ceramic waste-based concretes meet or exceed minimum durability requirements for demanding applications like railway sleepers [48]. However, not all studies report uniform water absorption reduction with ceramic waste use. Concrete containing ceramic insulator aggregates exhibited higher average sorptivity values compared to control concrete across all water-cement ratios [49].

Microstructural investigations elucidate mechanisms by which ceramic waste influences cement hydration and concrete strength and durability development [56]. Partial cement replacement with ceramic tile waste powder leads to additional calcium silicate hydrate gel formation, densifying matrix and reducing capillary pore connectivity. This microstructural refinement contributes to observed water absorption and permeability reductions, particularly at later ages [40].

### 5.2.3. Freeze-Thaw Resistance

Freeze-thaw resistance is critical for concrete durability in regions subjected to cyclic freezing and thawing. Ceramic waste incorporation influences this property in several ways. Waste sanitary ceramic as coarse aggregate at replacement levels up to 25% results in concrete with superior freeze-thaw resistance compared to conventional concrete. Improvement attributes to more compact interfacial transition zone between recycled ceramic aggregate and cement paste, likely reducing water ingress and mitigating internal stresses during freeze-thaw cycles [45].

Ceramic waste powder addition at 5% and 10% replacement rates enhances freeze-thaw resistance, linked to increased hydration product formation densifying matrix and reducing permeability. However, 15% replacement rate tends toward increased shrinkage cracks, decreasing freeze-thaw resistance. Hooked-end steel fiber incorporation protects residual flexural and compressive strength after freeze-thaw cycles, suggesting synergistic effect between ceramic waste and fiber reinforcement [32].

Materials capable of forming cross-linked Si–O–Al–O networks in alkaline conditions, present in ceramic waste, contribute to long-term durability including freeze-thaw cycle resistance. Amorphous network nature imparts thermal stability and low shrinkage, both beneficial for freeze-thaw performance [38]. Concrete mixtures containing ceramic waste demonstrate better freeze-thaw resistance than control mixtures, with all ceramic waste mixtures performing better than control in chloride ion diffusion, often correlated with improved freeze-thaw durability [34].

### 5.2.4. Chemical Resistance

Chemical resistance is critical for concrete durability in environments exposed to aggressive agents such as chlorides, sulfates, and acids. Ceramic waste incorporation demonstrates notable influences on resulting composite chemical resistance. Studies investigating deleterious ion penetration, such as chloride, into concrete containing ceramic waste powder or aggregates reveal enhanced resistance trends compared to conventional mixes.

At microstructural level, finely ground ceramic waste pozzolanic activity contributes to cementitious matrix densification. This densification primarily attributes to secondary hydration reactions between amorphous silica and alumina phases in ceramic waste and calcium hydroxide generated during cement hydration. Resulting additional calcium silicate hydrate gel formation reduces capillary pore connectivity, impeding aggressive ion ingress and improving chemical resistance [8, 28]. Experimental evidence supports microstructural observations. Concrete mixes incorporating ceramic powder exhibit significantly lower chloride ion penetration depths at both early and later ages compared to reference mixes without ceramic additions. This effect becomes more pronounced with increasing curing time, suggesting ongoing pozzolanic reactions continue enhancing matrix impermeability over time [43].

Ceramic waste materials' chemical inertness and high resistance further contribute to overall composite chemical durability. Ceramic aggregates, due to low reactivity with common aggressive agents, do not participate in deleterious chemical reactions compromising concrete integrity. This property is especially advantageous in environments with anticipated acid or sulfate exposure [8, 43].

## 6. Sustainability Aspects

### 6.1. Environmental Benefits

#### 6.1.1. Lower Carbon Footprint

Integrating ceramic waste into concrete significantly reduces carbon footprint by decreasing demand for energy-intensive cement production. Conventional UHPC requires high cement content exceeding 850-1000 kg/m<sup>3</sup>, creating substantial CO<sub>2</sub> emissions [54]. Partial substitution with ceramic waste directly lowers embodied carbon dioxide emissions (ECOE) [1, 4]. Previous studies show 40% ceramic waste as fine aggregate decreases both embodied energy and ECOE [1]. This reduction results from lower energy requirements for ceramic waste processing compared to Portland cement production, plus waste diversion from landfills. Life cycle assessments confirm that replacing natural sand with fine ceramic waste significantly reduces carbon footprint while maintaining mechanical performance [4].

Beyond CO<sub>2</sub> reduction, this approach addresses ceramic waste disposal issues and landfill accumulation [49], contributing to a circular economy model where waste becomes valuable resources [38]. This offers a viable pathway to lower construction material carbon footprint while aligning with global sustainability goals [1, 38, 54].

### 6.2. Resource Conservation

#### 6.2.1. Reduction in Natural Aggregate Consumption

Ceramic waste effectively substitutes natural aggregates due to comparable physical and chemical properties including particle size distribution, shape, and mineral content [29]. This substitution significantly reduces virgin aggregate demand, alleviating pressure on natural resources and reducing extraction-related environmental impact.

Ceramic waste reuse diverts substantial quantities from landfills while conserving finite natural resources [33]. Studies demonstrate that ceramic sand inclusion reduces water absorption and improves strength compared to control mixtures, while enhancing chloride diffusion resistance. Research indicates up to 40% replacement of ceramic coarse aggregate can be achieved without shrinkage, though some reductions in mechanical properties may occur [14].

### 6.2.2. Decreased Cement Use

Ceramic waste powder (CWP) as partial cement replacement substantially reduces Portland cement demand [28, 53]. Studies show 20% CWP resulted in 47.8% decreased cement content, while 30% CWP led to 54.3% reduction. However, exceeding 10% replacement may compromise load-carrying capacity [53]. Successful application depends on physical and chemical compatibility with cement matrix. Ceramic powders with appropriate particle sizes enhance durability aspects while maintaining acceptable mechanical performance at moderate replacement levels [14, 34]. However, porous ceramic waste can increase water absorption and reduce flowability, potentially requiring filler materials or admixtures [29].

### 6.3. Economic Considerations

Economic considerations are central to ceramic waste utilization assessment in concrete, as sustainable alternative viability depends on both technical performance and cost-effectiveness. Using ceramic waste as partial replacement for conventional aggregates or cementitious materials can lead to significant raw material cost reductions, especially in regions where ceramic waste is abundantly available as industrial or construction byproduct [2, 8]. By substituting natural aggregates or cement with ceramic waste, virgin resource demand diminishes, translating into lower extraction, transportation, and processing expenses [2, 44]. Figure 7 illustrates the cost advantages of using ceramic-based concrete. A reduction in the cost per cubic meter of concrete was observed with the increasing use of ceramic waste (CW), with a full 100% replacement resulting in a 13.06% decrease in cost, as shown in Figure 7 [29].

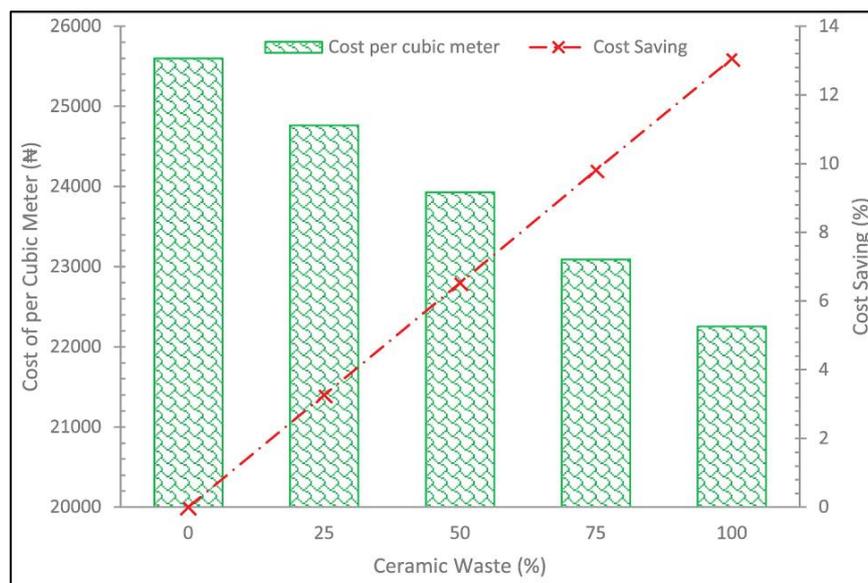


Figure 7. Cost advantages of using ceramic-based concrete [29]

This approach aligns with circular economy principles, where waste streams redirect into productive use, reducing landfill costs and associated environmental levies [44, 53]. Economic benefits amplify when considering ceramic waste's potential to improve concrete properties like workability and durability, potentially reducing maintenance and lifecycle costs [2, 39]. However, economic feasibility varies across scenarios. Ceramic waste processing, including crushing, grading, and quality control, incurs additional costs that must be weighed against raw material consumption savings [8].

Porous nature of ceramic waste aggregates can lead to increased water demand and reduced flowability, necessitating supplementary filler materials or admixtures that may offset initial cost savings. Ahmad et al. [29] indicate that ceramic waste absorption characteristics can negatively impact concrete strength and durability, suggesting economic assessments must account for potential performance-enhancing additive needs. Economic justification strengthens when environmental externalities are internalized. Reduction in greenhouse gas emissions and energy consumption associated with conventional aggregate and cement production and transportation can be quantified as economic savings, particularly in jurisdictions with carbon pricing or strict environmental regulations [44, 53]. Özkılıç et al. [53] emphasize that ceramic waste-based material selection should be guided by production costs, energy consumption, and greenhouse gas emission metrics.

Scalability is influenced by waste supply chain consistency and reliability. In regions with established ceramic industries, steady waste generation supports continuous production and cost predictability [2, 8]. Conversely, in areas with limited ceramic waste availability, transportation costs may erode economic benefits, making local context critical for feasibility assessments [44]. Integration may require existing infrastructure modifications or quality assurance protocol updates, entailing upfront investments offset by long-term operational savings.

Statistical and experimental design methods, such as Box-Behnken Design (BBD), enable ceramic waste content optimization in concrete mixes with minimal experimental runs, reducing research and development costs while maximizing predictive accuracy for mechanical properties [2]. Despite advantages, economic challenges remain. Ceramic waste composition and property variability necessitates rigorous quality control, increasing operational costs [49]. Lack of standardized guidelines for ceramic waste utilization may hinder widespread adoption without clear regulatory support, requiring coordinated research, policy, and industry practice efforts to realize economic benefits without compromising performance or sustainability [2, 8, 53].

## 7. Applications of Ceramic Waste Concrete

### 7.1. Conventional Concrete

Ceramic waste integration into conventional concrete shows promising results for mechanical performance, durability, and sustainability. Ceramic waste powder (CWP) as partial cement replacement maintains structural integrity, with 10% substitution, showing minimal deviation increases (below 5%) in deflection behavior [3]. Replacement levels from 0-40% by weight yield satisfactory results for M25 and M50 strength grades, with mechanical properties remaining within acceptable limits [14].

The ceramic waste type critically influences outcomes. Sanitary ceramics enhance compressive strength, while red ceramic and brick waste may have adverse effects due to differences in porosity and composition [33]. Water absorption varies: fine ceramic aggregate reduces absorption, while coarse mixed aggregate may increase it by up to 5% [14]. Density and thermal properties are affected by replacement ratios [44], and chemical composition is generally compatible with concrete matrices [57].

Sustainability benefits include reduced natural material demand and waste diversion from landfills. Machine learning approaches can predict compressive strength accurately [36]. Challenges remain in higher water absorption and research gaps in long-term durability [3, 33, 36].

### 7.2. High-Performance Concrete

High-performance concrete (HPC) and ultra-high-performance concrete (UHPC) are advanced materials characterized by superior mechanical strength, durability, and tailored functional properties. The integration of ceramic waste into these matrices has attracted significant attention due to both environmental and technical motivations. Ceramic waste, when processed appropriately, can serve as a supplementary cementitious material or as a replacement for natural aggregates, influencing the microstructure and performance of HPC. The use of ceramic waste in high-performance concrete is supported by its pozzolanic activity, which arises from the presence of reactive silica and alumina phases. These constituents can react with calcium hydroxide during cement hydration, forming additional calcium silicate hydrates that densify the matrix and enhance strength. Jawad Ahmad et al. indicate that the incorporation of ceramic waste up to a certain threshold, such as 20% replacement of sand, can yield concrete with satisfactory mechanical performance, attributed to the formation of additional binding phases [1].

However, the pozzolanic reactivity is sensitive to the fineness and mineralogical composition of the ceramic waste, necessitating careful selection and processing. In the context of ultra-high-performance concrete, the partial substitution of cement or aggregates with ceramic waste has been shown to influence both compressive and tensile strengths. For example, mixtures incorporating ceramic powder as a mineral addition can benefit from the pozzolanic effect, which contributes to the development of a denser microstructure and improved mechanical properties. The authors of state that the optimization of fiber content and the use of industrial by-products, including ceramics, can further enhance the mechanical and durability properties of UHPC. However, the effect of ceramic waste on strength is not universally positive; certain replacement levels or combinations with other industrial wastes may lead to marginal reductions in compressive strength, as observed in some experimental studies [8]. Thermal performance is another critical aspect of high-performance concrete, especially in applications where fire resistance or thermal insulation is required. The addition of ceramic aggregates has been found to reduce the thermal conductivity of concrete, thereby improving its thermal insulation properties. Wang et al. outline that increasing the proportion of ceramic aggregate in concrete leads

to lower density and thermal conductivity, which is advantageous for applications demanding enhanced thermal resistance [44]. Furthermore, geopolymers, which can incorporate ceramic waste, exhibit excellent resistance to high temperatures, making them suitable for specialized high-performance applications where conventional concrete may not suffice [58]. Durability is a defining feature of HPC, and the inclusion of ceramic waste can have both beneficial and adverse effects depending on the replacement level and the interaction with other mix constituents. For instance, the use of ceramic waste as aggregate or powder can improve the resistance of concrete to environmental degradation, such as freeze-thaw cycles, by refining the pore structure and enhancing the interfacial transition zone [57].

However, the long-term durability, particularly under aggressive exposure conditions, remains an area requiring further investigation to establish optimal replacement ratios and processing methods. From a sustainability perspective, the integration of ceramic waste into high-performance concrete contributes to the reduction of natural resource consumption and the mitigation of CO<sub>2</sub> emissions. Zhang et al. demonstrate that the use of ceramic waste in UHPC formulations can lead to significant reductions in carbon emissions, especially when combined with other recycled materials, thus supporting the development of greener construction materials [59]. The environmental benefits are further amplified by the diversion of ceramic waste from landfills and the conservation of natural aggregates [36]. Despite these advantages, several challenges persist. The variability in the properties of ceramic waste, stemming from differences in source material and processing, can lead to inconsistent performance in HPC. Additionally, the optimal replacement levels for achieving a balance between mechanical performance, durability, and sustainability are not yet fully established. The literature highlights the need for systematic studies addressing the long-term behavior of ceramic waste concrete under service conditions, as well as the development of standardized processing and quality control protocols [39]. In summary, the application of ceramic waste in high-performance concrete offers promising avenues for enhancing mechanical properties, durability, and sustainability. The scientific evidence underscores the importance of tailored mix design, rigorous material characterization, and comprehensive durability assessment to fully realize the potential of ceramic waste in advanced concrete technologies [8, 41].

### 7.3. Ultra-High-Performance Concrete

Ultra-high-performance concrete (UHPC) represents a class of advanced cementitious materials characterized by exceptional mechanical strength, durability, and dense microstructure. The integration of ceramic waste into UHPC formulations has attracted increasing attention due to both environmental imperatives and the potential for performance enhancement. The literature indicates that the use of ceramic waste, particularly in powder or aggregate form, can influence the microstructural and mechanical properties of UHPC, although the effects are nuanced and depend on the specific characteristics and proportions of the ceramic waste employed [8]. A key consideration in UHPC is the optimization of the binder matrix, which is typically rich in cement and supplementary cementitious materials. The partial replacement of Portland cement with ceramic waste powder (CWP) has been shown to be feasible at significant substitution levels, ranging from 20% to 40%. While early-age compressive strength may be reduced, the late-age strength of UHPC containing CWP can approach or even match that of reference mixes without CWP. This behavior is attributed to the pozzolanic reactivity of finely ground ceramic waste, which contributes to the formation of additional calcium silicate hydrate (C-S-H) gel, thereby densifying the matrix and enhancing long-term strength [36, 56].

The durability of UHPC incorporating ceramic waste is a critical aspect, especially for applications in aggressive environments. Studies have demonstrated that ceramic waste aggregates can affect water absorption, chloride penetration, and carbonation resistance. For instance, the use of ceramic waste aggregate (CWA) may lead to increased carbonation depth and shrinkage, yet it can also reduce chloride ingress, particularly when combined with other supplementary materials such as slag. This duality suggests that the microstructure of UHPC is sensitive to the type and proportion of ceramic waste, and that synergistic effects with other additives can be exploited to tailor durability performance [2, 45]. From a mechanical perspective, the inclusion of ceramic waste in UHPC does not always result in a significant reduction in strength parameters. Some investigations report that the physical and strength properties of UHPC with red ceramic aggregates are comparable to those of conventional UHPC, provided that the aggregate grading and mix design are carefully controlled. However, the high-water absorption capacity of certain ceramic aggregates can lead to increased porosity and potential leaching of cement paste, which may compromise the compactness and impermeability of the UHPC matrix [41].

Zegardło et al. [6] indicated that excessive absorption by ceramic aggregates can render the concrete mix leaky, underscoring the importance of aggregate selection and pre-treatment. The sustainability benefits of incorporating ceramic waste into UHPC are substantial. The valorization of ceramic waste not only diverts significant quantities of industrial by-products from landfills but also reduces the demand for virgin raw materials and the associated carbon footprint of cement production. The environmental advantages are further amplified when ceramic waste is used in

synergy with other recycled or industrial by-products, such as fly ash or slag, to produce high-performance, durable concretes suitable for demanding structural applications [5, 8]. Despite these promising findings, several research gaps remain. There is a need for comprehensive long-term durability studies to assess the performance of UHPC with ceramic waste under real-world exposure conditions, including freeze-thaw cycles, sulfate attack, and sustained loading. Additionally, the optimal replacement levels of ceramic waste, balancing mechanical performance, durability, and sustainability, require further elucidation through systematic experimental and numerical investigations. The use of advanced modelling techniques, such as finite element analysis, can provide valuable insights into the structural behavior and service life of UHPC incorporating ceramic waste, complementing experimental data and guiding future mix design strategies [3, 8]. In summary, the integration of ceramic waste into ultra-high-performance concrete offers a promising pathway toward sustainable, high-performance construction materials. The effects on mechanical and durability properties are closely linked to the characteristics of the ceramic waste and the overall mix design, necessitating careful optimization and further research to fully realize the potential of this approach [6, 45, 56]. Figures 8 and 9 demonstrate how the compressive strength and the flexural strengths of UHPC with different amounts of ceramic tile waste powder (CTWP) are generally increasing [40].

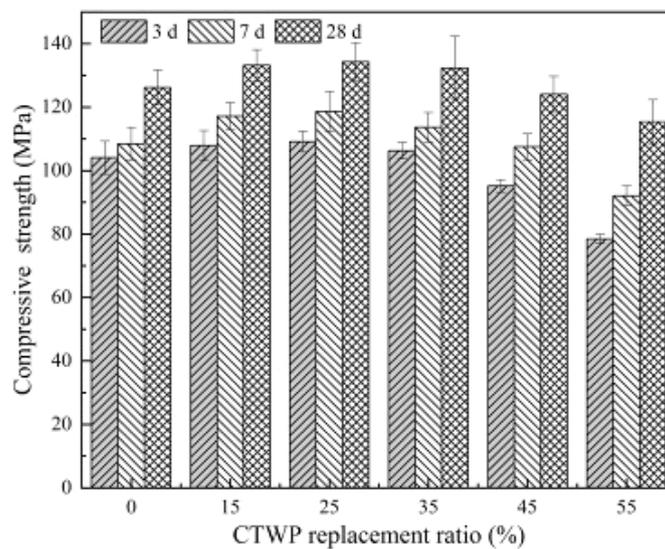


Figure 8. Compressive strength of UHPC incorporating different CTWP contents [40]

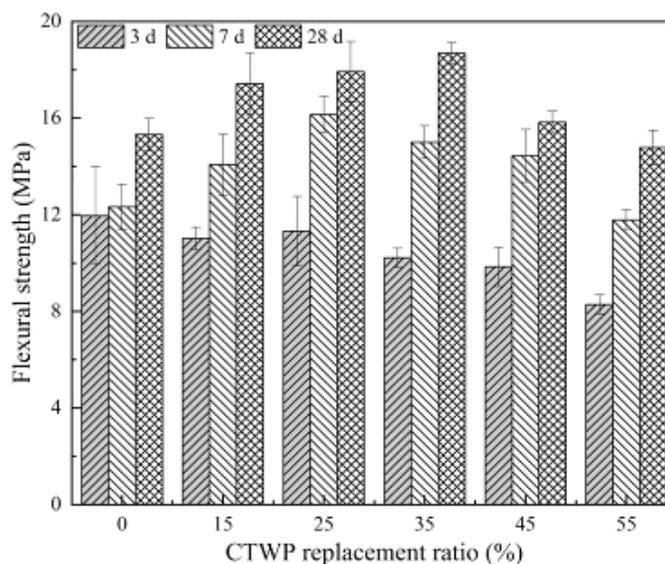


Figure 9. Flexural strength of UHPC incorporating different CTWP contents [40]

Figures 10 and 11 show the average compressive strength results at 1, 7, 28, and 56 days for two groups [12]. In the UHPC mixes, Sanitary ceramic waste powder (SCWP) and Wall ceramic waste powder (WCWP) were used to partially replace up to 50% of the cement by weight. Overall, the concrete samples containing SCWP and WCWP had higher compressive strengths when the cement substitution rate was raised to 20% by mass.

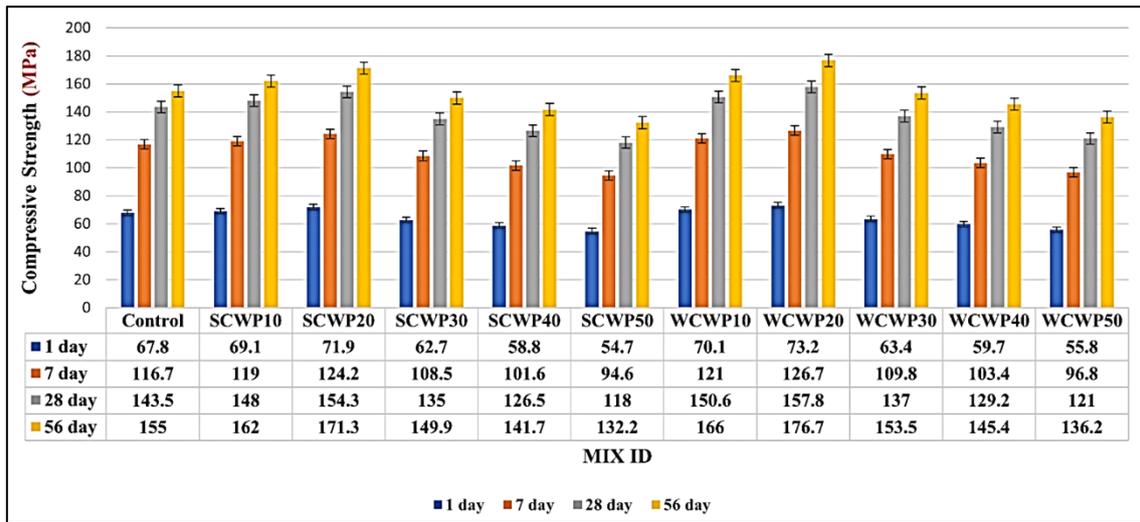


Figure 10. The compressive strength of UHPC after 1, 7, 28, and 56 days for the first group [12]

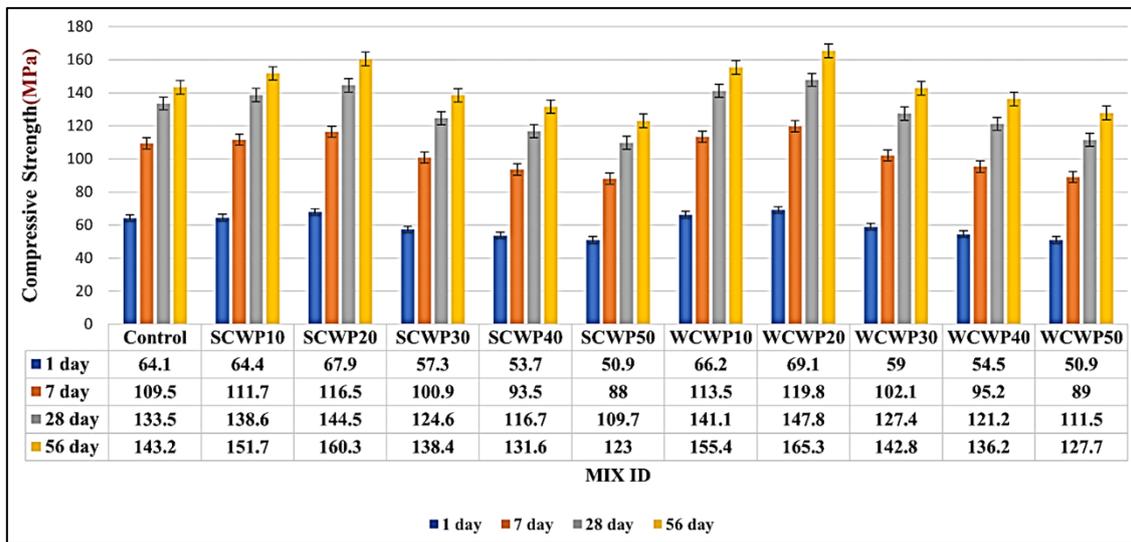


Figure 11. The UHPC's compressive strength after 1, 7, 28, and 56 days for second group [12]

### 7.4. Precast Elements and Non-Structural Applications

Ceramic waste integration into concrete for precast elements and non-structural applications has attracted attention for enhancing construction sector sustainability and resource efficiency. White cement used in exterior cladding and precast applications demonstrates improved mechanical performance with partial fibrous and ceramic waste replacement. Residual compressive strength under freeze-thaw conditions can increase up to 27% compared to conventional white cement, while residual flexural strength may rise by 54% average. Microstructural analyses reveal denser, more cohesive matrices with ceramic waste presence [32].

Ceramic waste aggregates, including recycled tiles and bricks, are characterized by high fire resistance and abrasion, making them suitable for non-structural applications like partition walls, façade panels, and decorative elements. These aggregates typically exhibit higher water absorption, lower elastic modulus, and reduced density compared to natural aggregates. These properties can be advantageous in non-structural contexts where reduced weight and enhanced thermal insulation are desirable, contributing to lower transportation costs and sustainable concrete development [33].

Mortar workability containing ceramic waste aggregate may decrease due to porous structure, but this same porosity enhances matrix-aggregate adherence, leading to improved strength through pozzolanic activity and better interfacial bonding [51]. In non-structural applications, geopolymer-based materials incorporating ceramic waste exhibit fast setting time, easy workability, and strong adhesion, primarily exploited in construction sectors with high chemical resistance benefits for aggressive environment exposure or long-term durability requirements.

Ricciotti et al. demonstrate that ceramic waste-derived geopolymer-based pastes have been successfully used for porcelain stoneware and ceramic artifact restoration and repair, highlighting versatility beyond traditional structural

roles [38]. Despite advantages, challenges remain in optimizing ceramic waste use in precast and non-structural elements. Porous and sometimes flaky ceramic waste aggregates can increase overall concrete porosity, potentially reducing compressive strength without proper management. Large ceramic particles may also lead to microcracking and matrix detachment, particularly at higher replacement levels [5, 7].

Environmental benefits of ceramic waste utilization in precast and non-structural applications are significant. Natural aggregate and cement substitution with ceramic waste conserves natural resources while reducing energy consumption and landfill burden associated with ceramic industry by-products [14]. Recycled ceramic material use aligns with broader sustainability goals by promoting circular economy principles within construction industry.

Wang et al. indicate ceramic aggregate concrete mix design can be tailored to meet specific consistency and performance requirements, expanding possible application ranges [44]. Ceramic waste concrete adaptability to various non-structural and precast uses underscores its potential as a sustainable alternative in modern construction practices.

## 8. Challenges and Limitations

### 8.1. Variability in Ceramic Waste Properties

Ceramic waste incorporation into concrete faces significant challenges due to inherent property variability from diverse origins (sanitary ware, kitchenware, insulators, bricks, tiles), each contributing distinct physical and chemical characteristics. Manufacturing process variations result in differences in mineralogical composition, firing temperature, and porosity, causing substantial fluctuations in concrete mechanical performance.

Compositional differences are notable: floor tiles contain 50 wt.% clay, 40 wt.% feldspar, and 10 wt.% quartz fired at 1180°C, while wall tiles substitute feldspar with calcite at lower firing temperatures [43]. Angular particle morphology and high-water absorption significantly influence concrete workability and mechanical properties. When replacing cement or aggregate, increased surface area and water demand reduce flowability [33], while high porosity causes inconsistent water distribution and variable strength development [43].

Universal standards absence for ceramic tile waste (CTW) amplifies variability impacts, requiring tailored technical adjustments for each waste batch [5]. Under controlled conditions, ceramic waste can enhance concrete properties through internal curing effects, but optimal proportions depend heavily on specific waste characteristics [50]. Property variation complicates durability predictions and limits widespread adoption due to additional variability in water demand and mix design [8, 43].

### 8.2. Lack of Universal Standards and Specifications

Ceramic waste integration into concrete is significantly hindered by universal standards and specifications absence, creating substantial variability in research outcomes and practical applications. This lack of standardized guidelines for CTW production results in material quality, performance assessment, and reporting practice inconsistencies across studies and industrial implementations. Diverse ceramic waste origins and properties, differing in chemical composition, particle size distribution, and physical characteristics, exacerbate variability. Technical adjustments including mixing ratio optimization, mortar formulation, and sintering temperature must be tailored for each CTW source, challenging finding generalization and best practice establishment [5, 49].

Harmonized standards absence complicates mechanical properties and durability evaluation. While some studies employ international standards like ISO-1920 [60], others use local protocols, creating result comparison difficulties. This extends to strength testing where different loading rates, specimen sizes, and curing regimes impede knowledge base development [12, 40]. Concrete performance is highly sensitive to waste material properties without standardized requirements, making mix design trial-and-error and compromising reproducibility [49]. Universal standards absence also impacts sustainability assessments, and as the standardized LCA methodologies is lacking, that makes it difficult to quantify the benefits, limiting credibility and hindering mainstream adoption [5, 40, 60].

### 8.3. Technical Barriers in Production and Application

#### 8.3.1. Mix Design Optimization

Mix design optimization represents a central challenge in ceramic waste concrete production. Ceramic waste heterogeneity from diverse sources introduces significant variability in particle size distribution, chemical composition, and physical properties, complicating universal mix design standard establishment [5]. Standardization lack leads to inconsistent performance outcomes, making cross-study comparison difficult.

Mix proportion optimization is complicated by ceramic waste influence on fresh and hardened concrete properties. Ceramic waste incorporation affects workability, setting time, and strength development. Studies show progressive slump decrease with increasing ceramic waste content [33], while strength increases with moderate replacement levels (10-15%) but decreases with excessive replacement (20%+) [31].

Early-age and long-term strength development presents challenges, with recycled concrete exhibiting unstable early-stage strength requiring careful cement content regulation [5]. Unreacted ceramic particles can hinder hydration product formation, compromising strength and durability [1]. Advanced methodologies like response surface methodology (RSM) show promise but remain limited in ceramic waste concrete applications [2].

### 8.3.2. Scaling Up from Laboratory to Field

Scaling ceramic waste concrete from laboratory to field applications introduces technical barriers requiring resolution for reliable performance. Laboratory studies benefit from controlled conditions and precise material characterization, but field-scale production presents consistency and quality challenges [28, 36]. Primary barriers include ceramic waste property variability from different origins, with universal standards absence leading to material quality inconsistencies [5]. Water absorption capacity and porosity vary widely depending on source and processing history [37]. Laboratory-optimized mix designs may not translate directly to field conditions without adjustments.

Production process optimization at scale is difficult, as precise laboratory control over mixing parameters becomes challenging in large-scale operations [5]. Standardized procedure absence can result in batch-to-batch variability affecting mechanical and durability properties [28]. Concrete density is sensitive to scaling effects, with ceramic aggregate replacement causing density reductions up to 31.2% at 100% replacement [44]. Unfortunately, there is no verified documentation of a full-scale "field" construction project using ceramic waste in concrete for actual building or infrastructure. Most research, including the study by Kiran Kumar Poloju, focuses on laboratory experiments such as partial replacement of cement with ceramic waste for sustainable concrete production but does not report real-world field implementation [61].

### 8.3.3. Quality Control

Quality control represents a significant barrier in ceramic waste concrete production. Ceramic waste heterogeneity from source variations, manufacturing processes, and post-consumer usage leads to physical and chemical property inconsistencies directly impacting concrete performance in strength, durability, and workability. Universal standards absence for CTW concrete use creates challenges, with no consensus on optimal mixing ratios, processing methods, or quality benchmarks. Technical adjustments must be tailored to specific CTW characteristics, requiring mixing ratio, mortar formulation, and sintering temperature optimization [5].

Raw material quality standardization is crucial for high-quality recycled products. Industrial manufacturing requires production batch specification documentation including material characteristics, process parameters, and quality control outcomes for traceability and process optimization. Ceramic waste chemical composition must be monitored for system compatibility and impurity avoidance [35, 58]. Advanced production techniques like computer-assisted process control show potential for improving consistency and quality [33].

## 8.4. Performance Trade-offs and Mitigation Strategies for Ceramic Waste Concrete in Time-Sensitive Construction Projects

Concrete incorporating ceramic waste as a partial cement replacement presents significant performance challenges for time-sensitive construction projects, particularly in early strength development. Research consistently demonstrates that ceramic waste addition results in reduced early-age compressive strength\* during the initial curing period (7 days) [19]. Specifically, when ceramic waste replaces 15% of fine aggregate, compressive strength decreases by 15.31% at 7 days compared to reference concrete [19]. This reduction becomes more pronounced with higher replacement levels, with 30% replacement showing a 23.68% decrease in early strength [19].

The underlying mechanisms for this early strength reduction include:

- Limited pozzolanic activity in early stages, as ceramic waste's reactive silica requires time to react with calcium hydroxide to form additional calcium-silicate-hydrate (C-S-H) gel [19];
- Increased porosity and angular roughness of ceramic particles, creating a less compact microstructure initially [19];
- Higher water absorption of ceramic waste (52.65% greater than natural sand), reducing free water available for cement hydration [19];
- Reduced workability due to ceramic waste's angular texture and water absorption characteristics [19].

Mitigation strategies for time-sensitive projects, include:

- Chemical Accelerators.

The most effective approach for addressing early strength deficits involves incorporating hardening accelerators that accelerate cement hydration and improve early strength development [62]. These admixtures work by:

- Increasing calcium ion concentration to speed up tricalcium silicate-water reactions;
- Providing nucleation sites for hydration products;
- Reducing repulsion between cement particles to accelerate hardening [62].

## 9. Research Gaps

### 9.1. Insufficient Real-World Applications

Despite promising laboratory results for ceramic waste incorporation in concrete, there is a significant gap in real-world applications and large-scale field implementations. Most studies remain confined to controlled experimental settings, with ceramic waste powder (CWP) and ceramic aggregates showing enhanced mechanical and durability properties under laboratory conditions but lacking validation in actual construction projects [4, 53].

The absence of field trials limits understanding of ceramic waste-modified concrete performance under complex real-world conditions including temperature fluctuations, humidity, and extended loading periods. Current reliance on experimental and computational approaches like finite element analysis (FEA) provides insights into structural behavior, but as Rajamanickam et al. highlight, validation remains within laboratory-scale beams rather than full-scale structures or long-term service environments [3]. Most FEA models use short-term experimental data that may not capture environmental degradation or real-world stressors.

Key barriers include: lack of standardized protocols for ceramic waste collection, processing, and incorporation at construction sites; variability in ceramic waste properties affecting concrete performance [4, 14]; and absence of practical guidelines despite well-documented environmental and health implications [53]. Long-term durability documentation is limited, with laboratory studies on chloride penetration, carbonation, and temperature stability [4, 45] typically conducted over short durations without accounting for cumulative environmental effects. Research focuses mainly on specific applications like ultra-high-performance geopolymer concrete (UHPC) [4, 44] rather than mainstream construction, making scalability uncertain [3, 45, 53].

### 9.2. Inconsistencies in Study Outcomes

Literature on ceramic waste utilization in concrete reveals significant inconsistencies in reported outcomes, particularly regarding mechanical properties, durability, and replacement ratios. Some studies show that partial substitution enhances compressive strength (CS) at lower replacement levels (5–9%) [29], while others report CS decline with higher proportions, especially in aggregate form, with up to 20% reduction at 15% replacement. Powdered ceramic waste may mitigate strength losses compared to aggregate form, indicating that physical form and particle size significantly influence performance [7, 36].

Water absorption and permeability effects vary across studies. Some research shows decreased water absorption with increased ground waste ceramic powder (WCP) substitution, while others report increased water penetration with recycled sanitary ware replacement (11% and 20% increases for 20% and 25% replacement respectively) [14]. These conflicts may stem from differences in ceramic waste type, porosity, and mix design.

Durability properties like chloride penetration show mixed results. Some studies find lower pore volume in ceramic waste mortars, correlating with reduced chloride diffusion [63], while others report positive relationships between compressive strength and transport properties [8]. Tensile strength results also vary, with Hashim et al. [43] reporting up to 23.5% increase with ceramic powder, though optimal replacement percentages remain debated [14, 29].

Contributing factors to inconsistencies include: diversity of concrete types investigated from conventional to ultra-high-performance concrete (UHPC) [4]; varying effects on workability and slump values [49]; lack of standardized testing protocols; wide range of replacement levels (5–100%) making comparisons difficult [14, 29]; and inconsistent reporting of curing duration and environmental conditions. While machine learning approaches like artificial neural networks (ANN) may help reconcile inconsistencies [36], their accuracy depends on input data quality, which remains challenging given current literature inconsistencies [29, 43, 63].

## 10. Future Directions and Recommendations

### 10.1. Standardization and Guideline Development

Ceramic waste utilization in concrete requires comprehensive standardization to ensure performance reliability and industry adoption. Current lack of harmonized procedures creates barriers to consistent quality and research comparability. Existing standards like EN 1015-2 are not specifically designed for ceramic waste, highlighting the need for dedicated standards considering ceramic waste's unique properties [35].

Current mechanical testing standards (TS EN 196–1) don't account for ceramic waste's specific influences on hydration kinetics and durability [58]. Pozzolanic activity evaluation procedures may lead to result misinterpretation in ceramic waste systems [56]. Literature reviews reveal inconsistencies in outcomes due to varying methodologies and absence of universally accepted guidelines [31].

Environmental considerations are critical, with 5% of global CO<sub>2</sub> emissions linked to cement production and 30% of ceramic materials becoming waste. Standardized approaches for quantifying environmental benefits would support sustainability benchmarks [14, 33]. Guidelines must address optimal replacement levels, as literature reports varying effective dosages [35, 42], and consider influences on workability and admixture compatibility [6]. Creating a universal standard for ceramic waste faces significant feasibility constraints due to extreme compositional heterogeneity across ceramic types, sources, and geographical regions [64, 65]. Research indicates that ceramic waste exhibits vastly different physical and chemical properties depending on manufacturing processes, raw material origins, and intended applications [66].

**Compositional Variability:** Different ceramic types - from sanitary ware to industrial ceramics - present distinct mineralogical phases including mullite, cordierite, and zircon [65], making unified characterization challenging. International practices vary dramatically - while some UK facilities recycle 40% of ceramic waste and Japanese companies achieve nearly 100% utilization rates, many regions still rely on landfill disposal [67]. This disparity reflects different technical capabilities and regulatory frameworks that would complicate universal standardization. The lack of standardized collection, sorting, and preparation methods creates inconsistent material streams that resist uniform classification approaches. Current evidence suggests that regional or application-specific standards may be more practical than a single universal framework, given the fundamental variability in ceramic waste properties and existing infrastructure limitations.

Future research should prioritize developing international standards encompassing ceramic waste types, processing methods, and applications through collaborative multidisciplinary efforts [14, 31, 33]. As this will accelerate the official adoption of this new, innovative and sustainable method of concrete production.

## 10.2. Optimization of Mix Designs

Mix design optimization for ceramic waste concrete requires systematic approaches balancing performance, durability, and sustainability. Advanced techniques like Response Surface Methodology with Box–Behnken design (RSM-BBD) effectively model variables such as ceramic content, fly ash percentage, and concrete age using second-order polynomial equations [2].

Ceramic waste integration affects compressive strength, density, and transport properties. Optimal replacement levels depend on waste type, fineness, and performance targets, with excessive content potentially diminishing performance [8]. Microstructural homogeneity is crucial, requiring precise control over particle distribution and mixing protocols [38].

Challenges include reduced tensile properties and increased void content from ceramic aggregates' angularity and water absorption characteristics [7, 14]. Optimization must address workability, shrinkage, and long-term durability alongside strength maximization.

Advanced computational modeling like finite element analysis (FEA) helps simulate behavior under various conditions. Integration of experimental data with simulation accelerates sustainable concrete development [3]. Environmental benefits include reduced natural aggregate demand and lower CO<sub>2</sub> emissions, but sustainability gains must not compromise performance [43].

Future research should develop multi-objective optimization frameworks considering mechanical, durability, and environmental criteria, potentially incorporating machine learning for enhanced efficiency [29, 31].

## 10.3. Comprehensive Life Cycle Assessment Studies

Comprehensive life cycle assessment (LCA) studies are essential for quantifying environmental impacts of ceramic waste in concrete. While technical feasibility has been investigated, environmental implications across the entire life cycle remain insufficiently explored. LCA provides systematic frameworks to evaluate benefits and trade-offs, crucial for substantiating sustainability claims [31].

Current research lacks detailed LCA studies specifically for ceramic waste concrete. Korat et al. [12] highlight the need for complete environmental impact analysis, emphasizing that quantifying eco-benefits is necessary for holistic sustainability understanding. Ceramic waste composition (predominantly SiO and AlO) suggests environmental profile benefits, but advantages depend on transportation distances, processing energy, and recycling potential [5].

The European ceramic industry generates substantial waste (10% of production to landfills), which could be diverted to concrete production [57]. However, without robust LCA studies, quantifying net environmental benefits is

challenging. Long-term durability considerations are important, as enhanced durability could amplify environmental benefits by reducing repair frequency [57]. Variability in ceramic waste types necessitates tailored LCA studies for specific waste streams and applications. Fu & Lee [5] suggested LCA should account for operational differences in recycling rates and processing methods.

Future research requires comprehensive LCA studies encompassing direct and indirect environmental impacts, integrating durability, processing, and end-of-life management. Combining LCA with technical performance data will provide robust evidence for ceramic waste concrete adoption [12, 31, 33].

## 11. Conclusions

- Ceramic waste incorporation in concrete significantly contributes to sustainability by reducing landfill use and conserving natural resources. It aligns with circular economy principles by transforming waste into a valuable resource, thereby minimizing the environmental impact of both waste disposal and raw material extraction.
- When optimally incorporated, ceramic waste enhances concrete's compressive and tensile strengths, as well as its durability. This is achieved through pozzolanic reactions that densify the microstructure and mechanical interlocking at the aggregate-paste interface, leading to improved performance in structural applications.
- The inconsistency in ceramic waste properties, due to its diverse sources and manufacturing processes, complicates mix design and quality control. Standardized processing methods and classification systems are essential to ensure consistent performance and facilitate broader adoption in the construction industry.
- Ceramic waste concrete demonstrates versatility across various applications, including conventional concrete, high-performance concrete, ultra-high-performance concrete, and non-structural elements. Its adaptability makes it a viable option for a wide range of construction needs, from load-bearing structures to decorative features.
- Despite extensive laboratory research, there is a notable lack of field trials and long-term durability studies. This gap limits the validation of laboratory findings under real-world conditions and hinders the practical implementation of ceramic waste concrete in large-scale projects.
- Comprehensive life cycle assessments (LCAs) are crucial to quantify the environmental benefits of ceramic waste concrete. These assessments should encompass the entire life cycle, from waste processing to end-of-life management, to provide a holistic understanding of its sustainability advantages and guide policy and industry practices.

## 12. Declarations

### 12.1. Author Contributions

Conceptualization, A.R.A.O.; methodology, A.R.A.O. and A.T.; resources, A.R.A.O.; writing—original draft preparation, A.R.A.O.; writing—review and editing, A.T.; supervision, A.T. All authors have read and agreed to the published version of the manuscript.

### 12.2. Data Availability Statement

Data sharing is not applicable to this article.

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### 12.4. Institutional Review Board Statement

Not applicable.

### 12.5. Informed Consent Statement

Not applicable.

### 12.6. Declaration of Competing Interest

The authors declare that there are no conflicts of interest concerning the publication of this manuscript. Furthermore, all ethical considerations, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancies have been completely observed by the authors.

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