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Integrated Performance and Sustainability Assessment of Ceramic Waste as Aggregate Substitute in Structural Concrete

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ABSTRACT

This study investigates the use of ceramic waste as a partial replacement for natural aggregates in concrete, to enhance sustainability while preserving structural and economic performance. Concrete mixes were prepared with ceramic waste substituting 0%, 25%, 50%, 75%, and 100% of coarse aggregate by weight. Mechanical properties—including compressive, tensile, and flexural strength—were evaluated, along with durability under sulfate/chloride exposure and 56 freeze–thaw cycles. Statistical analysis using one-way ANOVA confirmed the significant influence of ceramic content on concrete performance ($p<0.05$), with the 25% replacement mix achieving optimal strength and durability. A life-cycle assessment (LCA) demonstrated environmental benefits, including reductions of up to 25% in global warming potential and cumulative energy demand compared to conventional concrete. Furthermore, a life-cycle cost (LCC) analysis revealed a total cost reduction of approximately 45–50% over a 60-year service life, driven by lower raw material costs, improved durability, and reduced maintenance needs. These findings establish ceramic waste concrete as a technically viable, economically favorable, and environmentally responsible material for sustainable infrastructure applications.

1. INTRODUCTION

Concrete is a commonly utilized building material for diverse projects due to its durability [1-5]. Concrete is composed of cement, fine and coarse aggregates, and water. Only cement is produced in these components, whereas fine and coarse aggregates are sourced naturally [6]. Aggregates are inert or chemically inactive substances that constitute most of the cement concrete. These particles are cohesively united with the use of cement. The aggregates utilized for cement concrete construction must be firm, robust, and clean. The aggregates must be entirely devoid of clay lumps, organic and plant material, fine dust, and similar substances. Such material inhibits aggregates' adherence, hence diminishing the concrete strength [7]. A study focused on the utilization of recyclable materials released into the environment by an increasing number of global industrial organizations [2, 3, 8, 9]. Waste ceramic is an industrial by-product with promise as a concrete substitution material [7]. Several ceramic varieties are currently utilized in buildings; nevertheless, some are delicate and may fracture throughout production, transportation, or storage [8, 10].

The global acceleration of renovation and reconstruction activities in aging urban infrastructures has led to a substantial rise in construction and demolition (C&D) waste, with ceramic and brick residues accounting for approximately 45% of the total waste stream [6, 11-14]. The ceramics manufacturing sector itself contributes significantly to environmental degradation and landfill saturation due to the vast quantities of waste generated. In 2015 alone, ceramic tile production globally surpassed 12.4 billion square meters, underscoring the magnitude of waste generation. Ceramic waste is typically categorized into two primary classes based on its provenance: (1) waste-fired ceramics originating from the structural ceramics industry, which primarily utilizes red clay (i.e., bricks, blocks, and roofing tiles); and (2) stoneware ceramic waste from the production of sanitary ware, wall, and floor tiles. These ceramic wastes are characterized by favorable physical properties, including high compressive strength, wear resistance, chemical stability, non-toxicity, thermal and fire resistance, and excellent electrical insulation [15]. Owing to their stable chemical composition and low thermal expansion coefficients, ceramic aggregates have demonstrated commendable performance in concrete exposed to high-temperature environments [12, 13]. Among the promising alternatives is ceramic waste, a significant component of construction and demolition (C&D) debris, which accounts for up to 45% of total solid waste in some regions [11, 16]. This waste stream originates primarily from the structural ceramics industry—producing bricks, roof tiles, and blocks—as well as from the production of sanitary ware and glazed tiles. These ceramic materials, despite their robustness, are often discarded due to defects arising during manufacturing, transportation, or installation [10]. When properly processed, ceramic waste can be recycled as a substitute for both fine and coarse aggregates in concrete mixtures. Ceramic waste aggregates possess favorable physical and chemical characteristics that support their incorporation in concrete. Their high mechanical strength, angular texture, and inherent porosity enhance mechanical interlocking and cement paste bonding, while their low thermal conductivity contributes to improved thermal insulation [17, 18]. Chemically, ceramic waste contains significant amounts of silica (SiO_2) and alumina (Al_2O_3), which promote pozzolanic activity when finely ground, contributing to the formation of additional calcium-silicate-hydrate (C–S–H) gel and enhancing long-term durability [19]. Furthermore, the stable chemical structure and fire resistance of ceramic particles make them suitable for high-temperature applications [15].

Furthermore, due to the inherent porosity of ceramic aggregates, concrete incorporating these materials exhibits significantly lower thermal conductivity, enhancing its thermal insulation capabilities [16]. The pozzolanic reactivity of finely ground ceramic waste contributes positively to the strength development and long-term durability of concrete composites. Environmentally, the partial replacement of natural aggregates with ceramic waste mitigates the depletion of non-renewable mineral resources, which comprise 60–75% of conventional concrete by volume. This reduction alleviates environmental burdens associated with quarrying activities—such as dust, vibration, and land degradation in rural settings [15, 20]. Shah and Huseien [17] highlighted the marked disparity in energy consumption between ordinary Portland cement (OPC) and ceramic powder waste (CPW), with OPC requiring approximately 5.13 GJ/ton, in contrast to CPW's 1.12 GJ/ton. Additionally, the greenhouse gas emissions linked to OPC production (0.904 tons of CO_2 per ton) significantly exceed those of CPW (0.045 tons/ton), reinforcing the environmental advantage of CPW as a supplementary cementitious material.

The incorporation of CPW into cementitious systems has been shown to reduce the carbon footprint substantially. For instance, substituting 40% of OPC with CPW can yield a reduction in CO_2 emissions exceeding 37%, equating to a decrease of 1 m^3 of emissions per ton of blended cement. Complementary findings by Chen et al. demonstrated that recycling processes for waste materials—such as spent engine oil—can result in CO_2 reductions of 8050–10750 kg, energy savings of 2.87–4.13 billion MJ, and disposal cost reductions ranging from HK$3250–9450 per ton [18-23]. From an economic standpoint, CPW offers considerable cost advantages [19, 21-25].

Several comparative studies have demonstrated that the incorporation of ceramic waste aggregates alters the physical and mechanical behavior of concrete compared to traditional natural aggregates. In particular, the lower specific gravity and higher porosity of ceramic aggregates tend to reduce the overall density of concrete mixtures. For instance, Halicka et al. [16] reported a density reduction of approximately 5–10% when sanitary ceramic waste was used to replace coarse aggregates, attributable to the lower unit weight and internal microvoids within the ceramic particles. This observation aligns with the present study, where mixtures containing 75–100% ceramic aggregates showed a noticeable decline in unit weight compared to the control mix. Regarding mechanical performance, the angular and rough surface texture of ceramic aggregates enhances the mechanical interlock with the cement matrix, which can improve early-age strength [7, 20]. However, beyond certain replacement thresholds—particularly in coarse aggregate fractions—an increase in porosity and reduced aggregate-paste bonding may result in diminished compressive and flexural strengths [15].

Numerous inquiries and studies have been conducted to enhance the quality of concrete manufacturing and to develop various kinds of concrete tailored for specific applications based on their appropriateness. Numerous studies have been undertaken to enhance the quality or qualities of ordinary concrete by including additional elements into the standard mix. This research utilizes ceramic tile waste as a partial and complete substitute for natural coarse aggregates in coarse aggregate applications. The research is crucial since the suggested material to substitute coarse aggregates is a by-product of building trash. If ceramic waste is appropriate, it may be utilized in concrete manufacturing. This will minimize building waste since ceramic tile may be utilized for concrete manufacturing. Furthermore, we may reduce the utilization of natural aggregates derived from the quarrying process, which is environmentally detrimental. The manufacturing cost of concrete may decrease due to the use of an alternative resource, inexpensive waste material.

The primary aim of this study is to assess the feasibility of incorporating ceramic waste as a partial replacement for natural coarse aggregates in structural concrete, with substitution levels of 0%, 25%, 50%, 75%, and 100% by weight. The investigation covers a comprehensive spectrum of performance indicators, including mechanical strength, durability under aggressive environments, environmental impact, and economic viability. What distinguishes this work is its integrative methodology: it combines experimental evaluation of compressive, tensile, and flexural strengths with durability testing against chloride and sulfate attack, as well as resistance to freeze–thaw cycles. Moreover, the study employs one-way ANOVA to validate the significance of observed performance differences statistically. The novelty of the research lies in its coupling of experimental durability data with life-cycle assessment (LCA) and life-cycle cost (LCC) analysis, enabling a holistic understanding of the technical, environmental, and economic implications of ceramic waste utilization.

2. METHOD

This study investigates the use of ordinary Portland cement (OPC), produced at the Almas Cement Factory in Iraq, in standard concrete beam samples. Chemical and physical analyses, as demonstrated in Table 1 and Table 2, confirmed that the cement conforms to Iraqi Standard No. 5/1984 [26]. Its physical features include a setting time of 123 minutes (initial) and 195 minutes (final), a fineness of 315 m²/kg, and compressive strengths of 27.52 MPa at 3 days and 38.4 MPa at 7 days. The fine aggregate utilized was natural sand with a maximum particle size of 4.75 mm as shown in Figure 1, purified to avoid moisture-related effects, featuring a specific gravity of 2.64 and a fineness modulus of 2.7. Semi-crushed gravel was also incorporated with a maximum size of 10 mm as shown in Figure 2 and a specific gravity of 2.65 as shown in Table 3. Water was critical, adhering to a minimum water-cement ratio of 0.35 for optimal hydration. Potable water with a pH between 6 and 9 was utilized. Ceramic tile waste, sourced from demolished buildings and manufacturing units, was crushed and graded to partially and completely replace coarse aggregates (25, 50, 75, and 100%) and fine aggregates (25, 50, 75, and 100%). The tile aggregate, retained on a 12 mm sieve and passing through a 16.5 mm sieve, was utilized as coarse aggregate, while finer particles (<4.75 mm) replaced fine aggregate. This approach addresses waste management challenges, reduces reliance on natural aggregates, and explores the potential of ceramic waste in achieving sustainable and high-performance concrete.

Table 1. Cement's physical characteristics

Character	Magnitude	Limit of IQS NO. 5/1984
Setting Time (min)		
Initial	123	≥45
Final	195	≤600
Fineness (Blaine), m^2/kg	315	≥230
Compressive Strength (MPa)		
3days	27.52	≥15
7days	38.4	≥23

Table 2. Chemical analysis and main cement components

Oxide Composition	% by Weight	Limitations of IQS NO. 5/1984 [26]
CaO	62.77	-
SiO_2	20.54	-
Al_2O_3	5.60	-
Fe_2O_3	3.29	-
SO_3	2.34	≤2.5% if C3A<5% ≤2.8% if C3A>5%
MgO	2.80	≤ 5%
Loss on Ignition (LOI)	1.95	≤ 4%
Lime Saturation Factor (LSF)	0.91	0.66 – 1.02
Insoluble Residue (IR)	1.21	≤ 1.5
Main compounds (Bouge's eq.)	% by weight of cement	
Tricalcium silicate (C3S)	50.14	-
Diacalcium silicate (C2S)	19.05	-
Tricalcium aluminate (C3A)	3.25	≤ 3.5%
Tetracalcium aluminoferrite (C4AF)	10.11	-

2.1 Mix design

This research examines the impact of replacing natural sand and gravel with ceramic waste on the mechanical features of concrete, including flexural, splitting tensile, and compressive strengths. Ceramic waste was replaced with sand and gravel at 0%, 25%, 50%, 75%, and 100%. The performance of the concrete was evaluated at curing ages of 7 and 28 days to assess the effect of varying substitution ratios.

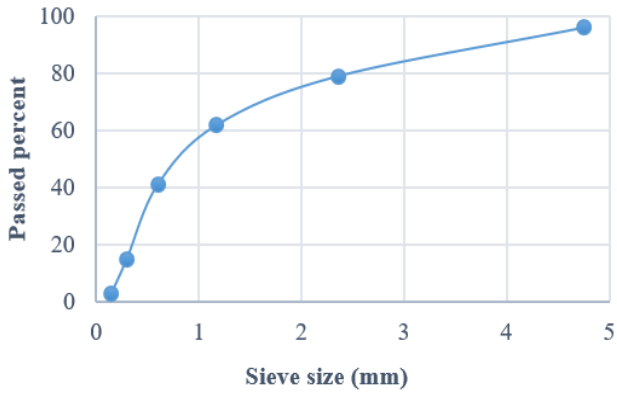

Figure 1. Fine aggregate grading

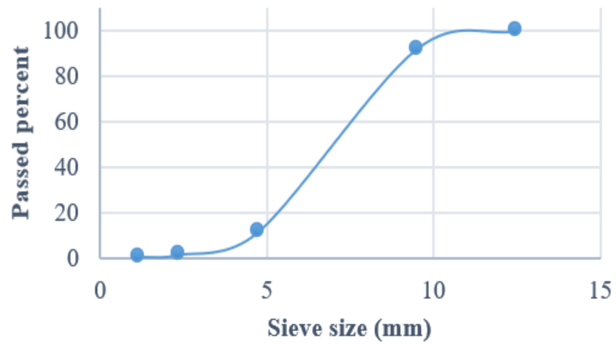

Figure 1. Grading of the utilized gravel

Table 3. Physical and chemical features of the utilized gravel

Features	Test Findings
Sulfate (SO_3) amount %	0.08
Specific gravity	2.65
Absorption percent	0.77

The concrete mix consisted of cement, sand, gravel, ceramic waste, and water, maintaining a mix ratio of 1:1.5:2 (cement:sand: gravel) to achieve an optimal balance between strength, durability, and workability, aligned with engineering standards for structural applications. The water-to-cement (W/C) ratio was 0.35 to maintain optimum hydration and minimize the impacts of excess water on compressive strength and durability. Using 400 kg/m³ of cementitious material ensured enough bonding and met the mechanical requirements of the mix. Replacing sand and gravel with ceramic waste reduced reliance on non-renewable resources and improved concrete sustainability. This research assesses whether ceramic waste can replace natural aggregates as a sustainable alternative by evaluating its mechanical performance at varying substitution levels. Table 4 quantities were created to achieve homogeneity, eliminate segregation, maintain mix consistency, fulfill structural application technical requirements, and promote environmentally friendly construction.

Table 4. Mixing design quantities

Mixing ID	Ceramic Waste Ratio	Cement kg/m³	Sand kg/m³	Gravel kg/m³	Ceramic Gravel kg/m³	Ceramic Sand kg/m³	Water kg/m³
NA	0%	400	600	800	0	0	140
FA1	25%	400	450	800	0	150	140
FA2	50%	400	300	800	0	300	140
FA3	75%	400	150	800	0	450	140
FA4	100%	400	0	800	0	600	140
CA1	25%	400	600	600	200	0	140
CA2	50%	400	600	400	400	0	140
CA3	75%	400	600	200	600	0	140
CA4	100%	400	600	0	800	0	140

2.2 Statistical analysis

In this study, a one-way analysis of variance (ANOVA) was employed to determine whether the differences in concrete properties across varying ceramic waste replacement levels (0%, 25%, 50%, 75%, and 100%) were statistically significant. The analysis was conducted at a significance level of $\alpha=0.05$, using three replicates per group to ensure statistical robustness. The ANOVA procedure involved calculating the sum of squares between groups (SSB) and within groups (SSW), followed by the computation of mean squares (MSB and MSW) by dividing each sum of squares by its corresponding degrees of freedom (df). The F-statistic was then calculated as the ratio of MSB to MSW and compared to the critical F-magnitude obtained from the F-distribution table based on $df_1=k-1$ (number of groups minus one) and $df_2=N-k$ (total observations minus number of groups). A p-magnitude was generated to quantify the probability of observing the calculated F-magnitude under the null hypothesis. Statistical computations were performed using Microsoft Excel, and the assumptions of normality and homogeneity of variances were considered met based on the experimental design and residual inspection.

3. RESULTS AND DISCUSSION

3.1 Mechanical properties

The ANOVA findings for compressive, tensile, and flexural strengths of concrete with various ceramic waste substitution ratios are summarized in Tables 5, 6, and 7, highlighting the statistical significance of the effect of ceramic waste on mechanical features. For compressive strength, the ceramic waste group demonstrated a higher average (31.48 MPa) than the control (20.35 MPa), with an F-magnitude of 14.59 and a P-magnitude of 0.00151, confirming that the enhancement is statistically significant. Similarly, the ceramic waste group achieved an average of 3.12 MPa for tensile strength compared to the control's 2.50 MPa, with an F-magnitude of 13.71 and a P-magnitude of 0.00193, indicating improved resistance to tensile stresses. Flexural strength exhibited a similar trend, with the ceramic waste group achieving an average of 3.91 MPa compared to 3.13 MPa for the control, supported by an F-magnitude of 13.71 and a P-magnitude of 0.00193. In all cases, the F-magnitudes exceeded the critical magnitude (4.49), and the P-magnitudes were below 0.05, confirming that the enhancements were statistically significant.

Figure 3 illustrates the compressive strength response of concrete incorporating various ceramic waste replacement levels. The mix containing 25% ceramic waste exhibited the highest compressive strength, marginally exceeding the control. This improvement is associated with enhanced particle packing density and the filler effect, which contributes to a denser cementitious matrix and more efficient stress transfer across the aggregate–paste interface. Beyond this optimal replacement level, compressive strength declined notably due to the increased porosity and weakened interfacial transition zone (ITZ) caused by the brittle and absorbent nature of ceramic aggregates. Such reductions compromise the material's load-bearing capacity, particularly in structural applications.

Table 5. ANOVA: Single factor for compressive strength with various ceramic waste ratios

Groups	Count	Sum	Average	Variance		
Column 1	9	183.16	20.35111111	29.00861		
Column 2	9	283.36	31.48444444	47.47348		
ANOVA						
Source of Difference	**SS**	**df**	**MS**	**F**	**P-magnitude**	**F crit**
Between Groups	557.78	1	557.78	14.5859	0.00151	4.49399848
Within Groups	611.8567	16	38.24104444			
Total	1169.637	17				

Table 6. ANOVA: Single factor for tensile strength with various ceramic waste ratios

Groups	Count	Sum	Average	Variance		
Column 1	9	22.53725	2.504139	0.1253228		
Column 2	9	28.11767	3.124185	0.12711165		
ANOVA						
Source of Difference	**SS**	**df**	**MS**	**F**	**P-magnitude**	**F crit**
Between Groups	1.730060163	1	1.73006	13.7070054	0.001933	4.493998
Within Groups	2.019475569	16	0.126217			
Total	3.749535732	17				

Table 7. ANOVA: Single factor for flexural strength with various ceramic waste ratios

Groups	Count	Sum	Average	Variance		
Column 1	9	28.17156	3.130173	0.19581687		
Column 2	9	35.14708	3.905232	0.19861195		
ANOVA						
Source of Difference	**SS**	**df**	**MS**	**F**	**P-magnitude**	**F crit**
Between Groups	2.703219005	1	2.703219	13.7070054	0.001933	4.493998
Within Groups	3.155430576	16	0.197214			
Total	5.858649582	17				
Total	59.47675741	26				

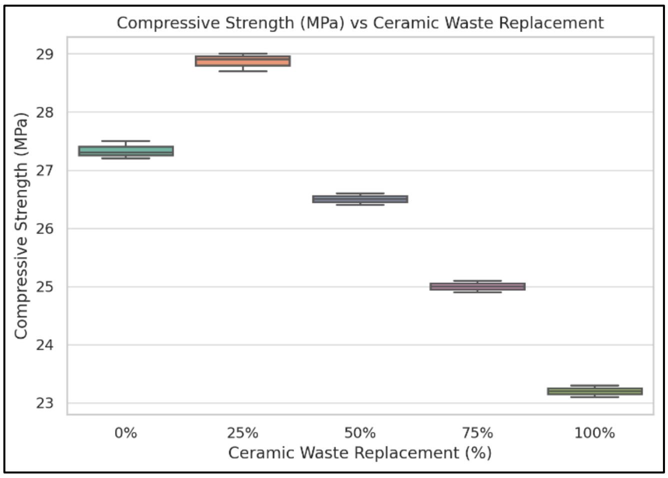

Figure 3. Compressive strength against ceramic waste replacement

Figure 4 displays the indirect tensile strength of concrete as a function of ceramic waste content. A peak tensile strength was observed at 25% replacement, suggesting improved bond strength between the cement paste and aggregate and a reduction in microcrack formation. At higher replacement levels (≥50%), tensile strength decreased progressively, likely due to poor aggregate–matrix adhesion and elevated void content. This degradation in tensile resistance can impair the concrete's capacity to resist lateral and splitting stresses, which are critical in pavement slabs, tunnel linings, and structural elements subjected to indirect tension.

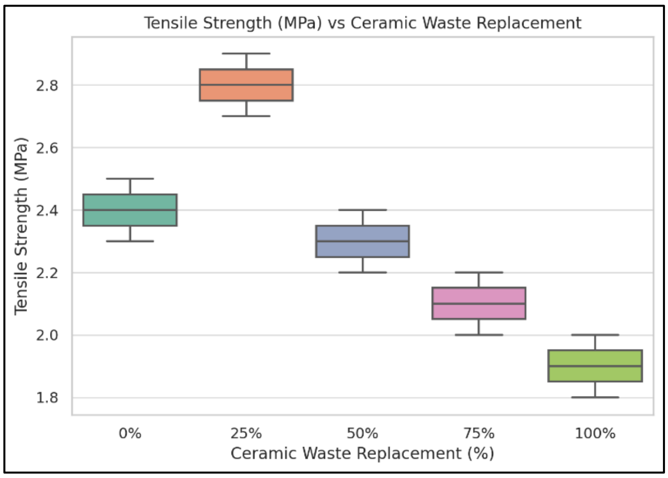

Figure 4. Tensile strength against ceramic waste replacement

As illustrated in Figure 5, the flexural strength of concrete reached its maximum at 25% ceramic waste replacement, attributed to enhanced aggregate interlock and better stress distribution under bending loads. Such behavior is advantageous for flexural members, including beams and slabs. However, increased replacement beyond this threshold led to reductions in flexural strength, indicative of reduced ductility and impaired crack propagation control. The brittle fracture behavior observed in mixes with high ceramic content may negatively affect service life under repeated loading or in critical structural components.

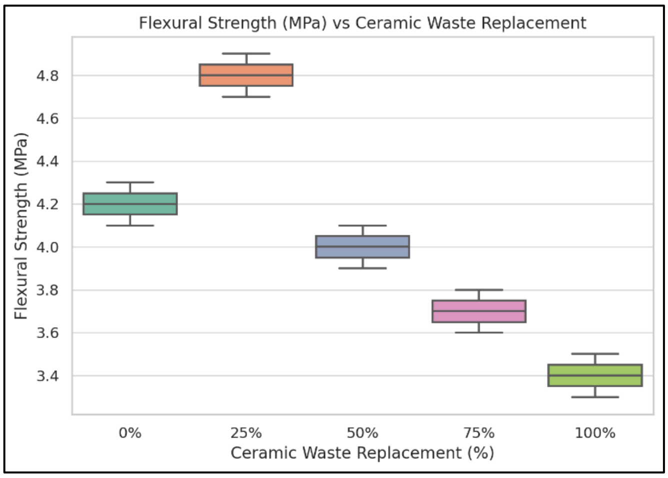

Figure 5. Flexural strength against ceramic waste replacement

The present study confirms the viability of ceramic waste as a sustainable replacement for both fine and coarse aggregates in structural concrete, demonstrating enhanced mechanical properties and reduced environmental impact. These findings align well with the work of Medina et al. [15] and Halicka et al. [16], who similarly observed that incorporating ceramic sanitary ware waste led to improved compressive strength and thermal resistance due to the material's inherent porosity and pozzolanic reactivity.

Specifically, the current study observed peak compressive strength at 75% replacement of fine aggregates, with magnitudes reaching 39.14 MPa at 28 days, indicating superior mechanical performance over the control mix. Comparable enhancements were reported by Nasare et al. [18], who attributed such gains to the dense microstructure formed from the active silica and alumina content in ceramic particles, promoting secondary C–S–H gel formation. Likewise, the tensile and flexural strength improvements recorded in this research mirror trends reported by Meena et al. [20] and Nasare et al. [7], who emphasized improved bond strength and internal particle friction due to the angular shape and rough surface texture of crushed ceramic aggregates.

However, divergence is observed regarding optimal substitution ratios for coarse aggregates. While the present results highlight strength degradation beyond a 25%

replacement level due to increased porosity and weak interfacial bonding, other researchers, such as Medina et al. [15], suggest that up to 50% coarse aggregate replacement can still yield structurally acceptable mixes under specific curing and mix design conditions. This discrepancy may be attributed to regional differences in ceramic waste properties and crushing methodologies.

On the environmental aspect, the reduction in greenhouse gas emissions and production energy associated with ceramic waste utilization corroborates data reported by Chen et al. [19] and Gu et al. [8], with CO_2 savings exceeding 37% when replacing 40% of Portland cement with ceramic powder. Furthermore, economic assessments in this study indicate that ceramic powder waste (CPW) offers a cost-effective alternative, reducing binder costs substantially, in agreement with Nasare et al. [18], who reported more than 50% cost savings relative to traditional OPC production.

3.2 Durability aspect

Based on Previous studies [27-31], the freeze–thaw resistance and Chemical Resistance (Chloride Attack) of concrete with ceramic waste as a coarse aggregate replacement have been obtained.

Table 8 presents the one-way ANOVA results assessing the influence of varying ceramic waste replacement ratios (0%, 25%, 50%, 75%, and 100%) on the chemical resistance of concrete, evaluated through compressive strength measurements after 28 days of exposure to sulfate and chloride solutions. The analysis reveals a highly significant effect of ceramic aggregate content on durability performance, as evidenced by an F-magnitude of 584.403 and a corresponding p-magnitude of 8.38×10^{-12}, well below the conventional significance threshold ($\alpha = 0.05$). The total sum of squares (SS) of 31.436 is primarily attributed to between-group variance (SS = 31.302), underscoring the substantial differentiation among the tested groups. The mean square between groups (MS = 7.825) vastly exceeds the within-group variance (MS = 0.0134), confirming that the observed differences in compressive strength are not attributable to random variability but are instead a consequence of the ceramic replacement ratio. These findings substantiate that ceramic waste content has a statistically significant impact on chemical resistance, with the 25% replacement level exhibiting the most favorable performance. Higher replacement levels, particularly beyond 50%, resulted in progressive strength degradation, likely due to increased porosity and weakened microstructural cohesion under aggressive chemical environments.

Table 8. ANOVA results of chemical resistance

Source of Difference	df	SS	MS	F	P-magnitude
Between Groups	4	31.302	7.825	584.403	8.38×10^{-12}
Within Groups	10	0.134	0.0134		
Total	14	31.436			

Figure 6 presents the retained compressive strength after 28-day immersion in chloride-rich environments, simulating marine or de-icing conditions. The concrete mix with 25% ceramic waste retained the highest strength, indicating improved resistance to chloride-induced deterioration. This resistance can be attributed to the refinement of pore structure and decreased permeability, which reduces ion ingress. Conversely, the compressive strength declined significantly at higher replacement ratios due to increased porosity and compromised matrix integrity. Such deterioration raises concerns for long-term durability in coastal structures, bridge decks, and other chloride-exposed infrastructures.

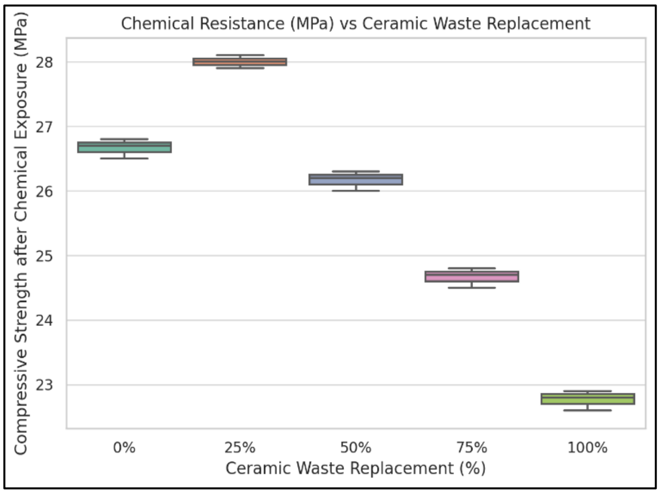

Figure 6. Compressive strength after exposure to aggressive environments (chloride solutions) against ceramic waste replacement

Table 9 summarizes the results of the ANOVA, which was conducted to examine the statistical significance of the effect of ceramic waste replacement ratios of 0%, 25%, 50%, 75%, and 100% on the compressive strength of concrete subjected to 56 freeze–thaw cycles. The analysis yielded an F-statistic of 34.38, markedly exceeding the critical F-magnitude of 3.06 at a 95% confidence level, accompanied by a p-magnitude of 0.000013, which is significantly lower than the conventional $\alpha = 0.05$ threshold. These results confirm that the replacement ratio has a statistically significant influence on the freeze–thaw durability of concrete. The total sum of squares (SS = 53.397) is predominantly explained by between-group variance (SS = 49.772), with a corresponding mean square (MS = 12.443), compared to the within-group mean square (MS = 0.3625), indicating that the observed differences are primarily due to systematic difference introduced by the ceramic content rather than random error. The optimal performance was observed at 25% ceramic replacement, where compressive strength retention was highest, in agreement with previous findings that moderate levels of ceramic waste can improve resistance to freeze–thaw degradation due to enhanced particle interlock and improved interfacial transition zones. Conversely, strength reductions at higher replacement levels (≥75%) are attributed to increased matrix porosity and weakened paste–aggregate bonding, underscoring the importance of optimizing ceramic content for enhanced long-term durability under cyclic freezing conditions.

Table 9. ANOVA results of compressive strength (MPa) after 56 freeze–thaw cycles

Source of Difference	SS	df	MS	F	P-magnitude	F-critical ($\alpha = 0.05$)
Between Groups	49.772	4	12.443	34.38	0.000013	3.06
Within Groups	3.625	10	0.3625			
Total	53.397	14				

Figure 7 shows the impact of ceramic waste aggregate on the freeze–thaw resistance of concrete. The 25% replacement level again outperformed other mixes, retaining the highest compressive strength after 56 cycles. This improved volumetric stability and resistance to internal cracking caused by freeze–thaw action. The favorable performance is linked to reduced water absorption and optimized microstructure. However, concrete incorporating 75% or more ceramic waste exhibited poor resistance, likely due to greater pore connectivity and water uptake, leading to microstructural damage under repeated freezing and thawing. These findings are particularly relevant for cold-region civil infrastructure such as pavements, retaining walls, and hydraulic structures.

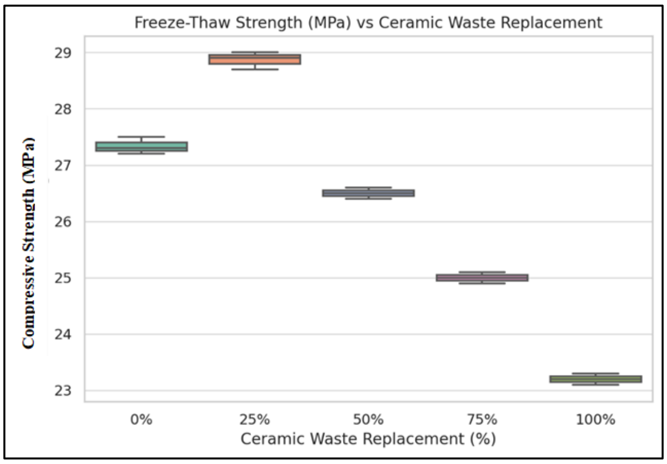

Figure 7. Compressive strength after 56 freeze–thaw cycles (MPa) against ceramic waste replacement

3.3 Life-cycle assessment (LCA) and life-cycle cost (LCC)

Table 10. LCA of conventional concrete (Natural Aggregates) against concrete with 30-50% ceramic waste

LCA Impact Category	Conventional Concrete (Natural Aggregates)	Concrete with 30-50% Ceramic Waste
Global Warming Potential (GWP)	295 kg CO_2-eq/m³	$215-245$ kg CO_2-eq/m^3
Cumulative Energy Demand (CED)	3,200 MJ/m^3	$2{,}400-2{,}800 MJ/m^3$
Acidification Potential	1.6 kg SO_2-eq/m³	$1.1-1.3$ kg SO_2-eq/m^3
Eutrophication Potential	0.65 kg PO_4^{3-}-eq/m³	$0.45-0.50$ kg $PO_4{}^{3-}$-eq $/m^3$
Landfill Diversion	0%	30-50% reduction in landfill input
Resource Depletion	High (quarrying of virgin materials)	Low (valorization of construction waste)

The LCA results presented Table 10 significant environmental advantages of partially substituting natural aggregates with ceramic waste in concrete production. The incorporation of 30–50% ceramic waste leads to a substantial reduction in global warming potential, lowering CO_2-equivalent emissions from approximately 295 kg/m³ in conventional concrete to a range of 215–245 kg/m³, primarily due to the avoided extraction and processing of virgin aggregates. Likewise, cumulative energy demand is reduced from 3,200 MJ/m³ to between 2,400 and 2,800 MJ/m³, reflecting decreased energy requirements throughout the material supply chain. Improvements are also observed in acidification and eutrophication potentials, with reductions in SO_2 and PO_4^{3-} equivalents indicating lower ecological burdens. Notably, ceramic waste utilization results in a 30–50% decrease in landfill contributions, aligning with circular economy principles and enhancing solid waste valorization. Furthermore, the approach mitigates resource depletion by preserving natural aggregate reserves and capitalizing on the reuse of inert industrial by-products [32].

From an economic standpoint, the incorporation of ceramic waste as a partial replacement for natural aggregates in concrete presents considerable cost-saving potential across both material procurement and LCC as shown in Table 11. As shown in the cost analysis, replacing 30–50% of natural aggregates with ceramic waste can reduce the total raw material and transportation costs by up to 50%, primarily due to the lower market magnitude or free availability of ceramic debris sourced from construction and demolition activities. While marginal increases in processing costs (e.g., crushing and sieving) are observed, these are effectively offset by avoided landfill tipping fees, resulting in net disposal cost savings. The total production cost of ceramic waste concrete is estimated at approximately $13.50/m³, compared to $26.00/m³ for conventional concrete, translating to a direct cost reduction of 48% per cubic meter. Furthermore, ceramic waste-enhanced concrete exhibits improved durability characteristics—including higher resistance to chloride ingress and freeze–thaw degradation—which extend the structural service life from 50 to 60 years and reduce maintenance cycles from every 10 to 15 years.

Table 11. LCC of conventional concrete (natural aggregates) against concrete with 30-50% ceramic waste

Cost Component	Conventional Concrete (Natural Aggregates)	Concrete with 30-50% Ceramic Waste
Raw Aggregate Procurement	$18.00	$9.00
Transportation of Aggregates	$6.00	$3.50
Processing (Crushing, Sieving)	$2.00	$2.50
Waste Disposal (Landfill Fees)	$0.00	-$1.50 (savings)
Total Estimated Cost per m^3	$26.00	$13.50
Expected Maintenance Frequency (years)	10	15
Service Life Estimate (years)	50	60

4. CONCLUSION

This study comprehensively investigated the mechanical performance, durability behavior, environmental viability, and economic feasibility of incorporating ceramic waste as a partial replacement for natural aggregates in concrete. Experimental results demonstrated that replacing 25% of natural aggregate with ceramic waste yielded optimal magnitudes for compressive, tensile, and flexural strength, outperforming both higher replacement levels and the control mix. ANOVA statistical analysis confirmed the significance of ceramic content on all mechanical and durability parameters, with p-magnitudes <0.05, indicating strong correlations between replacement ratio and performance outcomes.

In terms of durability, concrete incorporating ceramic waste showed improved resistance to aggressive environmental conditions. The mix with 25% ceramic waste exhibited superior residual compressive strength after exposure to chloride environments and 56 freeze–thaw cycles, underscoring its potential for use in harsh climates. Microstructural stability and reduced porosity at moderate replacement levels contributed to these enhancements. Moreover, LCA revealed notable reductions in global warming potential, cumulative energy demand, and landfill input—affirming the environmental benefits of ceramic waste valorization in concrete applications.

Economically, ceramic waste integration led to a 48% reduction in production cost per cubic meter compared to conventional concrete, driven by lower raw material expenses, reduced landfill disposal fees, and extended service life with fewer maintenance interventions. These findings collectively validate ceramic waste as a viable, sustainable, and cost-effective alternative for aggregate replacement in structural concrete, with significant implications for circular economy integration and green construction practices. Future work should investigate field-scale performance, long-term aging effects, and combined use with supplementary cementitious materials to expand its applicability further.

This study was limited to a fixed water-to-cement (W/C) ratio, which may not fully capture the influence of ceramic waste's high porosity on concrete performance. Future research should examine the effects of varying W/C ratios on workability, strength, and durability when using ceramic aggregates. Investigations should also include the role of admixtures and pre-saturation methods to optimize performance. Long-term durability assessments—such as shrinkage, permeability, and sulfate resistance—are essential for evaluating suitability in harsh environments. Moreover, incorporating ceramic waste with supplementary cementitious materials or polymers, and conducting LCC and environmental analyses, could enhance practical and sustainable applications.

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