Spectrum Journal of Innovation, Reforms and Development
Volume 35, January- 2025 | **ISSN (E): 2751-1731**
WEBSITE: WWW.SJIRD.JOURNALSPARK.ORG

EXPERIMENTAL AND STATISTICAL ANALYSIS OF AGGREGATES REPLACEMENT BY DIFFERENT CERAMIC WASTE

Mohammed S. Radhi1
1 Ceramics Engineering and Building Materials
Department, University of Babylon, Babylon, Iraq
mat.mohammed.sattar@uobabylon.edu.iq

Abstract

This study investigates the utilization of ceramic waste as a partial and complete replacement for natural aggregates (fine and coarse) in concrete, aiming to enhance its mechanical features and promote sustainability in construction. Ceramic waste was incorporated at substitution ratios of 0, 25, 50, 75, and 100%, and its impact on compressive, tensile, and flexural strengths was evaluated at 7 and 28 days. Experimental findings demonstrated that fine aggregate substitution with ceramic waste achieved optimal mechanical performance at 75%, with significant improvements in strength features due to enhanced interfacial bonding and particle packing. Conversely, coarse aggregate substitution showed diminishing strength beyond 25%, indicating limited compatibility at higher levels. Statistical analysis using one-way ANOVA confirmed the significant influence of ceramic waste on concrete performance, with P-values below 0.05 for all tested features. The findings highlight ceramic waste's potential as a sustainable material for reducing dependency on natural aggregates while addressing waste management challenges. This research underscores the dual benefits of improved mechanical performance and environmental sustainability, providing a practical framework for integrating ceramic waste into eco-efficient concrete production. Future studies are recommended to explore long-term durability and lifecycle assessments to reinforce its viability in structural applications.

Keywords: Aggregates Replacement, Analysis of Variance (ANOVA), ceramic waste.

Introduction

Concrete is a commonly utilized building material for diverse projects due to its durability [1], [2], [3], [4], [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 byproduct 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].

Ceramic and brick waste fractions, constituting about 45% of total construction and demolition trash, are being generated at an accelerated pace worldwide due to the increasing renovation and reconstruction of aging buildings [11]. The ceramic industry produces substantial waste volumes that negatively impact the environment and contribute to landfill problems. In 2015, the worldwide production of ceramic tiles exceeded 12.4 billion square meters. Ceramic waste is categorized into two classes based on the origin of the raw materials. A group is formed from waste-burnt ceramics generated by structural ceramic producers that only use red pastes (blocks, bricks, and roof tiles). A separate category comprises waste-derived ceramics from stoneware ceramic items, including wall, floor, and sanitary ware. These ceramic waste products exhibit enhanced strength, wear resistance, extended durability, chemical inertness, non-toxicity, heat and fire resistance, and electrical resistance [12]. Moreover, due to the chemical composition of ceramic waste and its low thermal expansion coefficient, concrete using ceramic waste aggregate exhibits resistance to elevated temperatures [13], [14].

Furthermore, it was demonstrated that the porous characteristics of ceramic aggregate concrete resulted in significantly poor heat conductivity in the concrete mixtures with ceramic aggregates [15]. Ceramic waste is generated in substantial amounts, and its incorporation into concrete is beneficial due to its pozzolanic features, which enhance mechanical strength and durability performance. Furthermore, it benefits the ecology by mitigating the excessive exploitation of natural aggregates [12], [16]. Given that 60–75% of concrete's volume comprises aggregates, reducing the utilization of natural aggregates would significantly impact the environment. Besides the adverse environmental consequences of stone quarries, such as noise, dust, vibrations, and impacts on rural regions, non-renewable resources considerably limit their application. Shah and Huseien [17] report that the energy usage of Portland cement, at 5.13 GJ/ton, exceeds that of ceramic powder waste (CPW), estimated at 1.12 GJ/ton, by more than fourfold.

Furthermore, Portland cement exhibits a significantly greater greenhouse gas release (0.904 tons/ton) than CPW (0.045 tons/ton), attributable to its elevated energy usage, expense, and greenhouse gas output. Compared to a traditional combination, the cement combined with ceramic materials produced lower greenhouse releases, irrespective of the substitution ratio. While manufacturing 1 ton of blended cement, including 40% CPW, there is a decrease exceeding 37% in greenhouse gas releases, resulting in 1 m3 of releases. Chen et al. determined that the recycling method can reduce CO2 releases by 8050–10750 kg, energy usage by 2.87–4.13 billion MJ, and disposal costs by HK$3250–9450 per ton of utilized engine oil; thus, recycling utilized engine oil into concrete is a viable and eco-friendly option [18], [19], [20], [21], [22], [23]. Analogous to greenhouse gas releases, the expense of cement production was highest due to the substantial energy usage involved in its manufacturing and the considerable efforts required for material transportation. Shah and Huseien [17] indicated that the manufacturing cost of cement was 600 RM per ton, while CPW was 170 RM per ton. Moreover, when the proportion of ceramic fine aggregate substitution for fine aggregates escalated from 0 to 25, 50, 75, and 100%, the cost of the samples of mortar diminished from above 380 to 372, 362, 351, and 341 RM/m3, respectively. Replacing 40% of the cement with a considerable volume of leftover CPW was a substantial cost reduction. Substituting CPW for cement at increments of 10, 20, 30, 40, 50, and 60% reduced the binder cost from 380 to 358, 335, 317, 287, and 264 RM/m3, respectively. Using CPW as a binder in mortar samples considerably enhanced the creation of sustainable goods.

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 byproduct 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 using an alternative resource, inexpensive waste material.

This research aims to evaluate the feasibility of using ceramic waste as a partial and complete substitution for natural aggregates in concrete, focusing on improving compressive, tensile, and flexural strengths while promoting sustainable construction practices. The study investigates the mechanical performance of concrete with ceramic waste substitution ratios of 0%, 25%, 50%, 75%, and 100%, identifying optimal levels for structural integrity. Statistical analyses, including one-way ANOVA, assess the significance of the observed improvements. By repurposing ceramic waste from industrial and construction sources, the research supports sustainable construction by reducing environmental impacts, conserving natural aggregates, and promoting eco-efficient material utilization in the built environment.

Experimental Part

This study investigates using ordinary Portland cement (OPC), produced at the Almas Cement Factory in Iraq, in standard concrete beam samples. Chemical and physical analyses, as demonstrated in Tables 1 and 2, confirmed that the cement conforms to Iraqi Standard No. 5/1984 [24]. 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, 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 and a specific gravity of 2.65. 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 partial and complete 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 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 [24]
CaO	62.77	-
SiO2	20.54	-
Al2O3	5.60	-
Fe2O3	3.29	-
SO3	2.34	≤ 2.5% if C3 A < 5% ≤ 2.8% if C3 A > 5%
MgO	2.80	≤ 5%
L.O.I.	1.95	≤ 4%
L.S.F.	0.91	0.66 – 1.02
I.R.	1.21	≤ 1.5
Main compounds (Bouge's eq.)	% by weight of cement	
Tricalcium silicate (C3S)	50.14	-
Diacalcium siliccat (C2S)	19.05	-
Tricalcium aluminate (C3A)	3.25	≤ 3.5%
Tetracalcium aluminoferrite (C4AF)	10.11	-

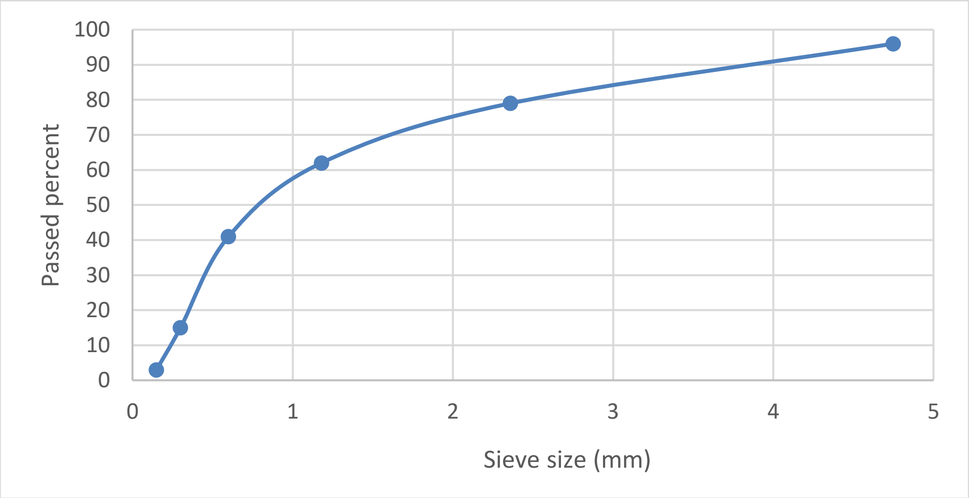

Figure 1. Fine aggregate grading.

Table 3. Chemical and physical features of the utilized fine aggregate.

Features	Test findings
Specific gravity	2.64
Fineness modulus	2.70
Absorption proportion	0.74
Sulfate amount (SO3) %	0.12

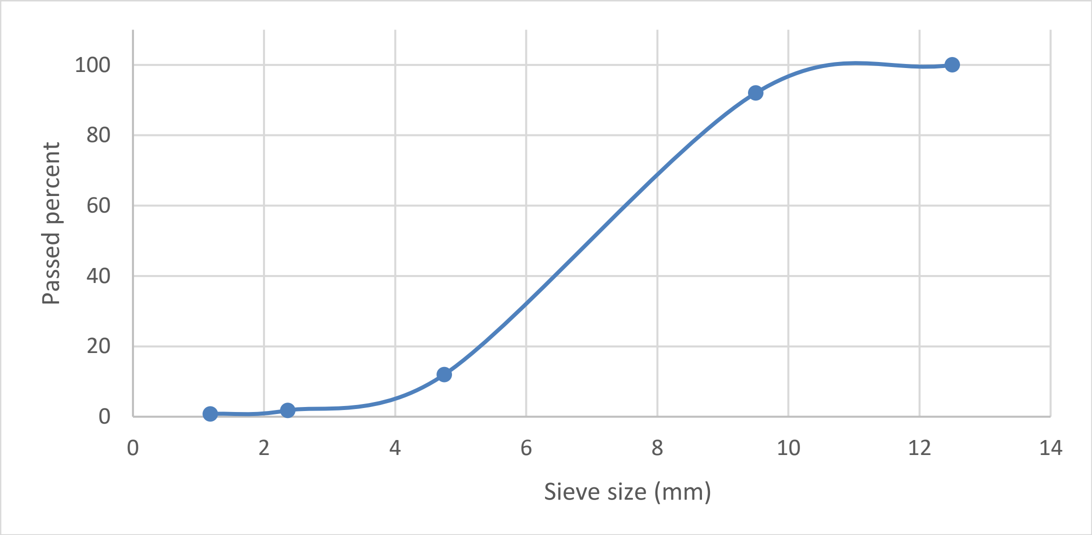

Figure 2. Grading of the utilized gravel

Table 4. Physical and Chemical features of the utilized gravel.

Features	Test findings
Sulfate (SO3) amount %	0.08
Specific gravity	2.65
Absorption percent	0.77

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 for 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.

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 mechanical requirements of the mix. Replacing sand and gravel with ceramic waste reduced reliance on non-renewable resources and improved concrete sustainability. This research shows if ceramic waste can replace natural aggregates as a sustainable alternative by assessing mechanical performance at different substitution levels. Table 5 quantities were created to achieve homogeneity, eliminate segregation, maintain mix consistency, fulfill structural application technical requirements, and promote environmentally friendly construction.

Table 5. 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

Tests

Compressive, tensile, and flexural strength tests are essential for structural engineering concrete evaluation. Compressive strength, measured in cured cylindrical or cubical specimens under axial stresses, indicates load-bearing capability. Tensile strength, measured using the split-cylinder technique, indicates concrete fracture resistance. Flexural strength measures bending resistance using beam specimens under third-point or center-point stress. Test findings are consistent and comparable since their measurements match international standards like ASTM and BS EN codes.

$$Compressive\ Strength\ (MPa) = \frac{Cross{-}sectional\ Area\ (mm2)}{Failure\ Load\ (N)} \tag{1}$$

$$\text{Tensile Strength (MPa)}= \frac{2P}{\pi \cdot L \cdot D} \tag{2}$$

Where:

- P: Maximum applied load (N)
- L: Length of the cylinder (mm)
- D: Diameter of the cylinder (mm)

$$\text{Flexural Strength (MPa)}= \frac{\mathrm{PL}}{bd^2} \tag{3}$$

Where:

- P: Applied load at failure (N)
- L: Span length (mm)
- b: Width of the beam (mm)
- d: Depth of the beam (mm)

Statistical analysis

This research uses a one-way analysis of variance (ANOVA) to determine how substituting natural sand and gravel with ceramic waste affects concrete's compressive, splitting tensile, and flexural strengths. ANOVA is used to investigate whether concrete mean strengths after 7 and 28 days curing from 0%, 25%, 50%, 75%, and 100% ceramic waste substitution ratios differ significantly.

Results and discussion

Experimental results

The compressive strength findings reveal the impact of ceramic waste as a substitution for fine and coarse aggregates in concrete, as demonstrated in Figure 3. The control mix (NA) with natural aggregates exhibited strengths of 20.57 MPa at 7 days and 33.18 MPa at 28 days, serving as a baseline. Fine aggregate substitution (FA) with ceramic waste demonstrated significant performance improvements, with strengths increasing up to 27.05 MPa at 7 days and 39.14 MPa at 28 days at 75% substitution (FA3), indicating enhanced bonding and compatibility. However, 100% substitution (FA4) demonstrated a slight decline, achieving 19.96 MPa and 37.16 MPa at 7 and 28 days, respectively, suggesting limitations at complete substitution. Conversely, coarse aggregate substitution (CA) displayed a consistent decline in strength as the substitution ratio increased. At 25% substitution (CA1), strengths were moderately acceptable at 22.22 MPa and 30.18 MPa at 7 and 28 days, respectively, while higher substitution levels (CA3 and CA4) resulted in significant reductions due to weaker bonding and increased porosity.

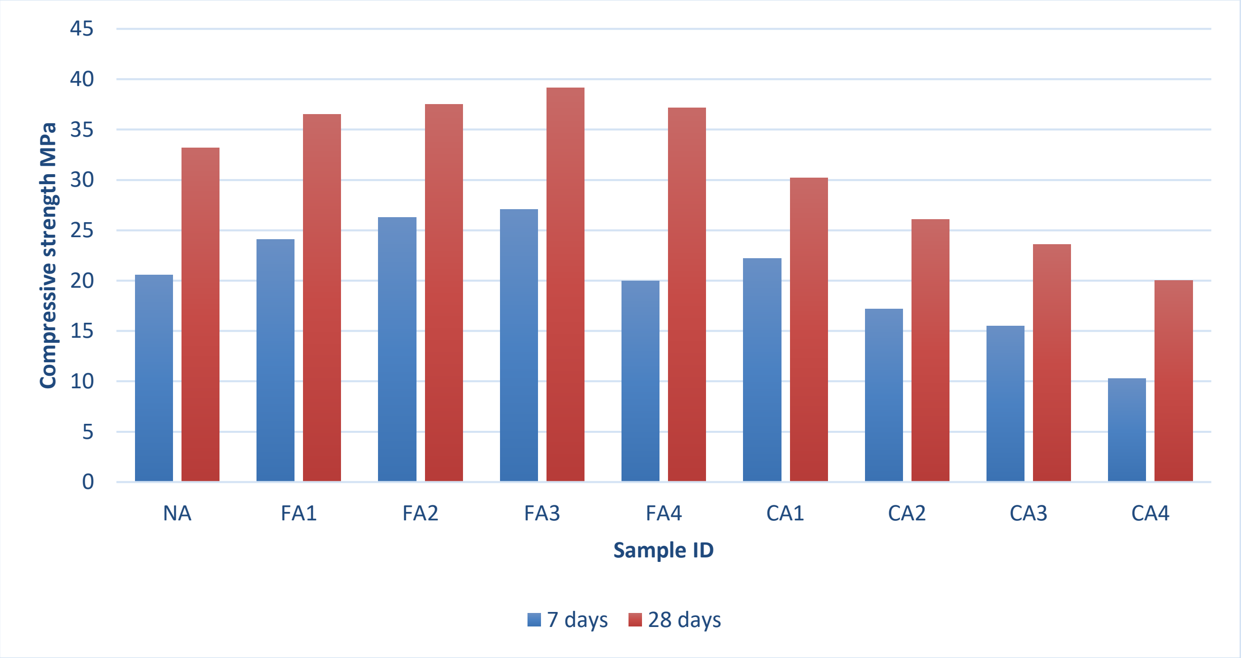

Figure 3. Compressive Strength findings before and after aggregate substitution by ceramic waste.

The tensile strength findings highlight the effect of replacing natural aggregates with ceramic waste on concrete performance, as demonstrated in Figure 4. The control mix (NA) achieved baseline strengths of 2.54 MPa at 7 days and 3.23 MPa at 28 days. Fine aggregate substitution (FA) with ceramic waste exhibited a progressive increase in tensile strength, peaking at 2.91 MPa and 3.50 MPa at 75% substitution (FA3) for 7 and 28 days, respectively, due to improved particle packing and enhanced interfacial bonding. At 100% substitution (FA4), tensile strength slightly declined but remained above the control mix, demonstrating the feasibility of complete fine aggregate substitution. Conversely, coarse aggregate substitution (CA) demonstrated a consistent reduction in tensile strength with increasing ceramic waste content. At 25% substitution (CA1), tensile strengths were comparable to the control mix (2.64 MPa at 7 days and 3.08 MPa at 28 days). However, higher ratios resulted in significant reductions, with 100% substitution (CA4) yielding 1.80 MPa at 7 days and 2.50 MPa at 28 days due to weaker interfacial bonding and increased porosity.

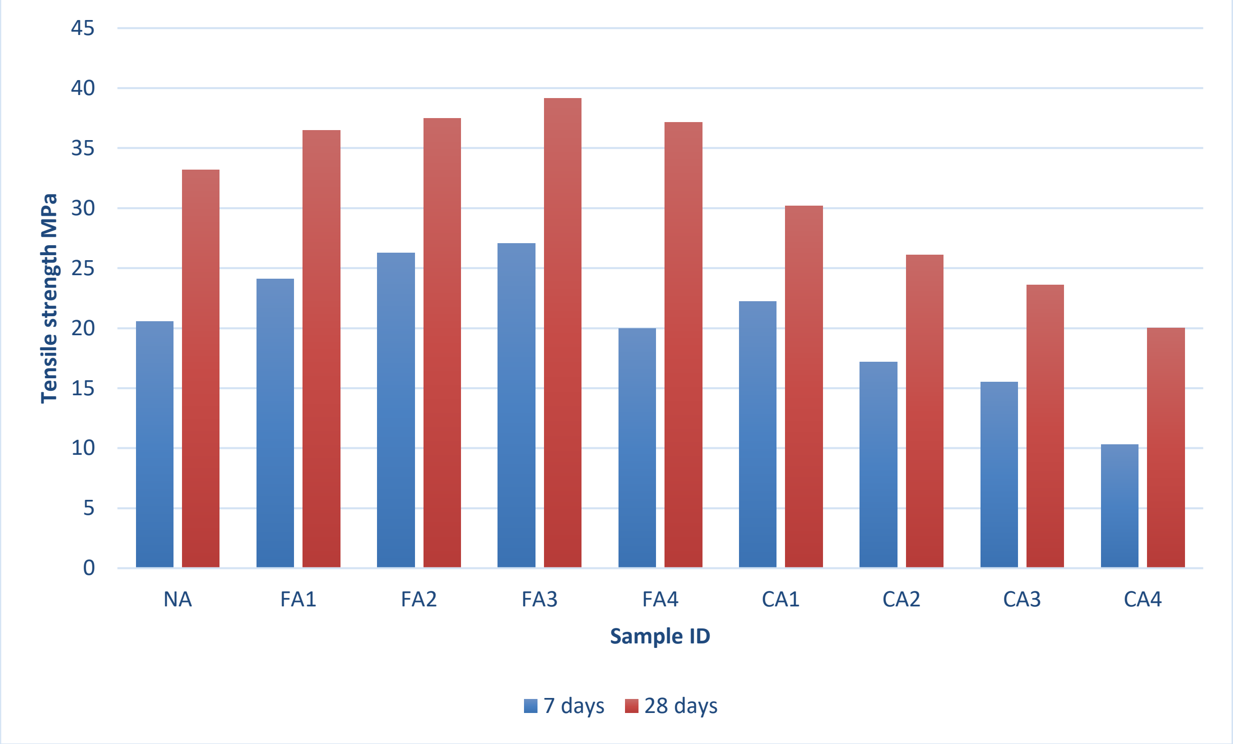

Figure 4. Tensile Strength findings before and after aggregate substitution by ceramic waste.

The flexural strength findings demonstrate the influence of ceramic waste as a fine and coarse aggregate substitution in concrete, as demonstrated in Figure 5. The control mix (NA), with 0% ceramic waste, achieved strengths of 3.17 MPa at 7 days and 4.03 MPa at 28 days, serving as the baseline. Fine aggregate substitution (FA) exhibited consistent improvements, with flexural strength peaking at 75% substitution (FA3), achieving 3.64 MPa at 7 days and 4.38 MPa at 28 days due to enhanced particle packing and interfacial bonding. At 100% substitution (FA4), a slight reduction in strength was observed, though it remained superior to the control mix, indicating the viability of complete substitution. Conversely, coarse aggregate substitution (CA) demonstrated a gradual decline in flexural strength as the substitution ratio increased. At 25% substitution (CA1), strengths of 3.30 MPa at 7 days and 3.85 MPa at 28 days were recorded, comparable to the control mix. However, higher substitution levels (CA3 and CA4) resulted in significant strength reductions, with 100% substitution (CA4) yielding the lowest magnitudes of 2.25 MPa and 3.13 MPa, respectively, due to weaker bonding and increased porosity.

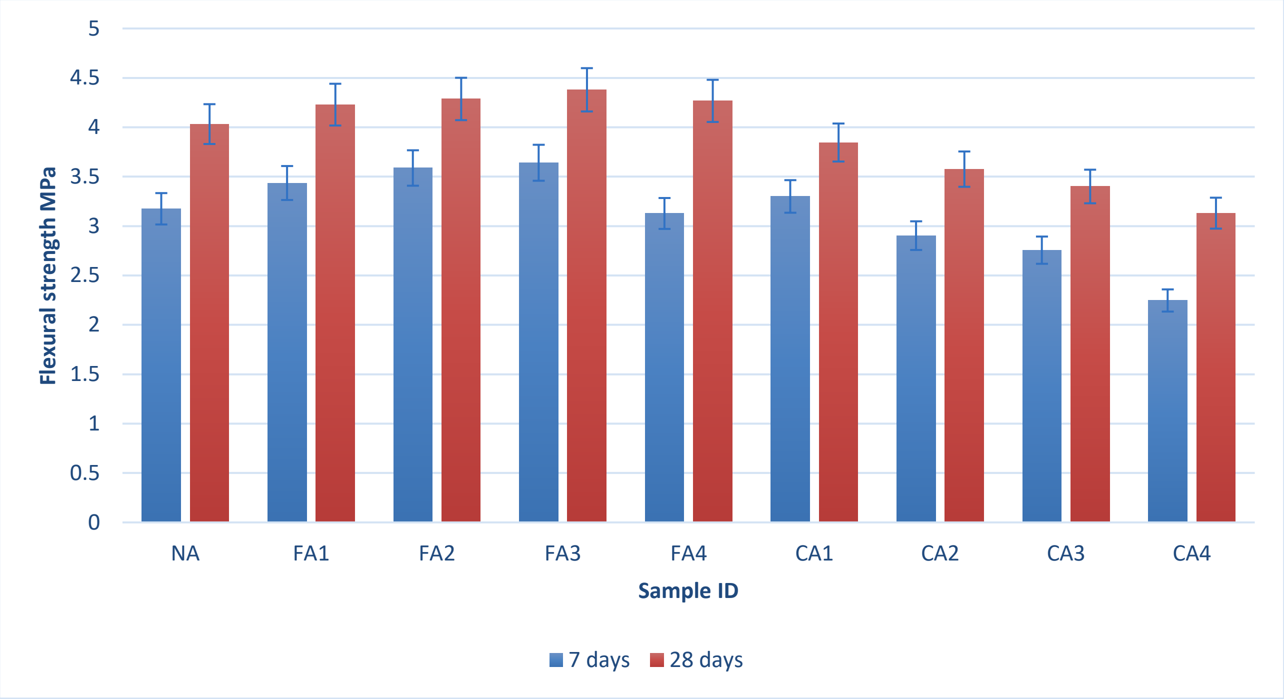

Figure 5. Flexural Strength findings before and after aggregate substitution by ceramic waste.

Statistical Analysis Results

The analysis of variance (ANOVA) findings for compressive, tensile, and flexural strengths of concrete with various ceramic waste substitution ratios are summarized in Tables 6, 7, and 8, 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.

Table 6. 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 Variation	*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 7. 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 Variation	*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 8. 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 Variation	*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				

Conclusion

The experimental and statistical analyses of ceramic waste as a partial substitution for natural aggregates in concrete demonstrated its potential to enhance mechanical performance while promoting sustainability. Compressive strength demonstrated significant improvement with acceptable aggregate substitutions, peaking at 75% ceramic waste with magnitudes reaching 39.14 MPa at 28 days. Tensile and flexural strengths followed a similar trend, with optimal findings at 75% fine aggregate substitution, highlighting enhanced particle interaction and bonding. However, coarse aggregate substitution exhibited diminishing returns beyond 25%, with 100% substitution significantly reducing strength features due to increased porosity and weaker bonding. Statistical analysis through one-way ANOVA confirmed these findings, showing highly significant differences ($P < 0.05$) in mechanical features for concrete incorporating ceramic waste compared to control samples.

The integration of ceramic waste offers dual benefits: reducing environmental impacts by mitigating industrial and construction waste and preserving natural aggregate resources. The findings underscore the feasibility of using ceramic waste in structural concrete applications, particularly as a fine aggregate substitution, achieving optimal performance at moderate substitution ratios (25–75%). This study advocates further research into long-term durability and lifecycle analyses to solidify the role of ceramic waste in sustainable construction practices, aligning with global efforts to promote eco-friendly and resource-efficient building materials.

References

[1] Z. S. Al-Khafaji *et al.*, “The Impact of Using Different Ratios of Latex Rubber on the Characteristics of Mortars Made with GGBS and Portland Cement,” *IOP Conf. Ser. Mater. Sci. Eng.*, vol. 1090, no. 1, p. 012043, 2021, doi: 10.1088/1757-899x/1090/1/012043.

[2] A. Z. S. A.-K. Dr. Abdullah Jabar Hussain, “The Fields of Applying the Recycled and Used Oils by the Internal Combustion Engines for Purposes of Protecting the Environment against Pollutions,” *J. Adv. Res. Dyn. Control Syst.*, vol. 12, no. 01-Special Issue, pp. 666–670, 2020, doi: DOI: 10.5373/JARDCS/V12SP1/20201119.

[3] A. J. Hussain and Z. S. Al-Khafaji, “The fields of applying the recycled and used oils by the internal combustion engines for purposes of protecting the environment against pollutions,” *J. Adv. Res. Dyn. Control Syst.*, vol. 12, no. 1 Special Issue, 2020, doi: 10.5373/JARDCS/V12SP1/20201119.

[4] H. S. Majdi *et al.*, “Experimental data on compressive strength and ultrasonic pulse velocity properties of sustainable mortar made with high content of GGBFS and CKD combinations,” *Data Br.*, vol. 31, p. 105961, 2020.

[5] Q. S. R. Marshdi, A. J. Dakhil, and Z. Al-Khafaji, “Investigation of strength and durability performance of concrete with varying crude oil waste ratios,” 2024.

[6] Q. S. R. Marshdi, S. A. Hussien, B. M. Mareai, Z. S. Al-Khafaji, and A. A. Shubbar, “Applying of No-fines concretes as a porous concrete in different construction application,” *Period. Eng. Nat. Sci.*, vol. 9, no. 4, pp. 999–1012, 2021, doi: 10.21533/pen.v9i4.2476.

[7] R. Nasare, V. Shah, T. Joshi, U. Dave, and S. H. Ghaffar, “Exploring sustainable utilization of ceramic waste in heat-resistant concrete: A comprehensive review,” *Int. J. Appl. Ceram. Technol.*, p. e15021, 2024.

[8] F. Gu, J. Guo, W. Zhang, P. A. Summers, and P. Hall, “From waste plastics to industrial raw materials: A life cycle assessment of mechanical plastic recycling practice based on a real-world case study,” *Sci. Total Environ.*, vol. 601, pp. 1192–1207, 2017.

[9] A. J. Hussain and Z. S. Al-Khafaji, “Reduction of environmental pollution and improving the (Mechanical, physical and chemical characteristics) of contaminated clay soil by using of recycled oil,” *J. Adv. Res. Dyn. Control Syst.*, vol. 12, no. 4 Special Issue, pp. 1276–1286, 2020, doi: 10.5373/JARDCS/V12SP4/20201604.

[10] D. D. F. Del Rio *et al.*, “Decarbonizing the ceramics industry: A systematic and critical review of policy options, developments and sociotechnical systems,” *Renew. Sustain. Energy Rev.*, vol. 157, p. 112081, 2022.

[11] N. Gaibor, J. Coelho, D. Leitão, T. Miranda, P. Tavares, and N. Cristelo, “Alkali activation of recycled ceramic aggregates from construction and demolition wastes,” *Mater. Construcción*, vol. 70, no. 339, pp. e222–e222, 2020.

[12] C. Medina, M. I. S. De Rojas, and M. Frías, “Reuse of sanitary ceramic wastes as coarse aggregate in eco-efficient concretes,” *Cem. Concr. Compos.*, vol. 34, no. 1, pp. 48–54, 2012.

[13] S. R. Al-Taai, N. M. Azize, Z. A. Thoeny, H. Imran, L. F. A. Bernardo, and Z. Al-Khafaji, “XGBoost Prediction Model Optimized with Bayesian for the Compressive Strength of Eco-Friendly Concrete Containing Ground Granulated Blast Furnace Slag and Recycled Coarse Aggregate,” *Appl. Sci.*, vol. 13, no. 15, p. 8889, 2023, doi: 10.3390/app13158889.

[14] Z. Ahmed Abed, M. Abd Al-Hussein Kazem, and Z. Al-Khafaji, “Statistical Analysis of

Total Replacement of Coarse Aggregate by Sustainable Recycled Aggregates," in *BIO Web of Conferences*, EDP Sciences, 2024, p. 120.

[15] A. Halicka, P. Ogrodnik, and B. Zegardlo, "Using ceramic sanitary ware waste as concrete aggregate," *Constr. Build. Mater.*, vol. 48, pp. 295–305, 2013.

[16] R. V. Meena, J. K. Jain, H. S. Chouhan, and A. S. Beniwal, "Use of waste ceramics to produce sustainable concrete: A review," *Clean. Mater.*, vol. 4, p. 100085, 2022.

[17] K. W. Shah and G. F. Huseien, *Recycled Ceramics in Sustainable Concrete: Properties and Performance*. CRC Press, 2020.

[18] H. Chen, C. L. Chow, and D. Lau, "Recycling used engine oil in concrete: Fire performance evaluation," *J. Build. Eng.*, vol. 64, p. 105637, 2023.

[19] H. Chen, C. L. Chow, and D. Lau, "Developing green and sustainable concrete in integrating with different urban wastes," *J. Clean. Prod.*, vol. 368, p. 133057, 2022.

[20] A. Shubbar, M. Nasr, M. Falah, and Z. Al-Khafaji, "Towards net zero carbon economy: Improving the sustainability of existing industrial infrastructures in the UK," *Energies*, vol. 14, no. 18, p. 5896, 2021, doi: 10.3390/en14185896.

[21] M. M. Sulaiman, Z. Al-khafaji, Z. N. Shareef, and M. Falah, "Carbon Capture Based on Chemical Absorption : Process Design and Techno-Economic Assessments," vol. 11, no. 1, pp. 1–6, 2025.

[22] A. A. Shubbar *et al.*, "Properties of cement mortar incorporated high volume fraction of GGBFS and CKD from 1 day to 550 days," *J. Build. Eng.*, vol. 30, 2020, doi: 10.1016/j.jobe.2020.101327.

[23] Z. O. . Al-Masoodi, Z. Al-Khafaji;, H. M. Jafer;, A. Dulaimi;, and W. Atherton, "The effect of a high alumina silica waste material on the engineering properties of a cement-stabilised soft soil," in *The 3rd BUiD Doctoral Research Conference*, Dubai, AUE, 2017.

[24] IQS-5, "Iraqi Standard Specification for the Portland Cement," *Central Organization for Standardization and Quality Control, Baghdad, Iraq*, 2005.