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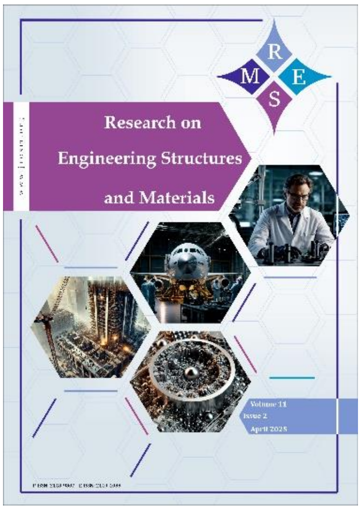

Mechanical and non-destructive evaluation of M30 grade concrete incorporating recycled ceramic waste as coarse aggregate: Experimental and statistical analysis

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Research Article

Mechanical and non-destructive evaluation of M30 grade concrete incorporating recycled ceramic waste as coarse aggregate: Experimental and statistical analysis

S. Azhagarsamy [1,a], N. Pannirselvam [*,1,b], R. Premkumar [2,c], A. Manivannan [3,d], S. Sundararaman [4,e], A. K. Kaliluthin [3,f]

[1]Department of Civil Engineering, College of Engineering and Technology, SRM Institute of Science and Technology, Kattankulathur-603203, Tamil Nadu, India
[2]Prime College of Architecture and Planning, Kilvelur, Nagapattinam District, Tamil Nadu, India
[3]Department of Civil Engineering, B. S. Abdur Rahman Crescent Institute of Science and Technology, Vandalur, Chennai-48, Tamil Nadu, India
[4]Department of Civil Engineering, Sri Manakular Vinayagar Engineering College, Puducherry, India

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Abstract

This study examines the mechanical and non-destructive properties of M30-grade concrete incorporating recycled ceramic waste as a partial replacement for natural coarse aggregates at 0, 10, 20, 30, and 40% replacement levels. Mixes were designed with a water–cement ratio of 0.45, slump values ranging from 70–85 mm, and a minimum of three specimens tested per mix. At 28 days, compressive strength decreased from 35.5 MPa (control) to 31.2 MPa (10%) and 30.4 MPa (20%), both meeting IS:456 acceptance criteria (fck ≥ 30 MPa), while flexural strength reduced from 7.8 MPa (control) to 7.0 MPa (10%) and 6.5 MPa (20%). Corrected rebound hammer (RH) values (36.5–48.2) and ultrasonic pulse velocity (UPV) results (3.7–4.2 km/s) confirmed good to excellent concrete quality. Regression analysis established strong correlations between compressive strength and NDT results ($fc = 0.30RH + 21.0$, $R^2 = 0.960$; $fc = 0.0058\,(UPV, m/s) + 7.6$, $R^2 = 0.940$), validating their predictive reliability. Statistical analysis (ANOVA) confirmed significant strength reductions beyond 20% replacement. The artificial neural network (ANN) model further supported these findings, showing high predictive accuracy (R = 0.97–0.99). The optimum replacement range of 10–20% is therefore recommended for structural applications, while higher levels are better suited for non-load-bearing elements, supporting both sustainable construction and circular economy objectives.

1. Introduction

Concrete is the most widely used construction material worldwide due to its high compressive strength, durability, and adaptability across a variety of structural applications [1]. Comprising cement, fine aggregates, coarse aggregates, and water, coarse aggregates typically account for 60–75% of the total concrete volume. Despite its excellent compressive strength, concrete exhibits low tensile strength, which is usually addressed through the use of steel reinforcement in reinforced cement concrete (RCC) [2,3]. However, large-scale extraction of natural aggregates (NA) to meet growing urbanization and infrastructure demands has led to resource depletion, environmental degradation, and increased carbon emissions [4,5]. These challenges, coupled with rising raw

*Corresponding author: pannirsn@srmist.edu.in
[a]orcid.org/0009-0001-2838-4849; [b]orcid.org/0000-0003-0776-0662; [c]orcid.org/0009-0003-6743-4743; [d]orcid.org/0009-0003-5847-687X; [e]orcid.org/0000-6002-5810-7623; [f]orcid.org/0000-0002-8739-6938
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material costs, underscore the need for sustainable alternatives in the construction industry [6]. One promising approach involves the partial replacement of natural aggregates with industrial by-products and waste materials [7]. This strategy not only conserves natural resources but also addresses waste management challenges, reducing the environmental footprint of construction while potentially enhancing the mechanical and durability properties of concrete [8]. Among various industrial wastes, ceramic waste generated from the production of tiles, sanitaryware, electrical insulators, and pottery has attracted significant attention. Approximately 20–30% of the ceramic output becomes waste, much of which is disposed of in landfills, contributing to environmental contamination and land scarcity [9,10]. Ceramic waste possesses several characteristics favorable for concrete applications. Its high-temperature manufacturing process imparts hardness, chemical inertness, and long-term durability [11]. While its angular particle morphology promotes interfacial bonding with cement paste, enhancing load transfer within the matrix [12]. Additionally, lower water absorption compared to some natural aggregates may improve long-term performance [13]. Previous studies have reported that replacing 10–40% of natural coarse aggregates with ceramic waste can maintain or improve compressive strength, flexural strength, and select durability parameters [14,15]. However, performance varies with particle size distribution, replacement level, and surface texture.

Recent research has highlighted the potential of using ceramic waste in concrete for sustainable construction. Reviews and experimental studies indicate that moderate replacement levels (up to 20–25%) preserve mechanical strength, while innovative approaches, such as the use of lightweight ceramic aggregates, can reduce density without compromising performance [11,16–20]. Furthermore, eco-friendly concrete mixes combining ceramic waste with other industrial by-products (e.g., granite cutting waste, bone China ceramic) have demonstrated enhanced compressive strength, improved durability under aggressive environments, and reduced CO_2 emissions, confirming their applicability in sustainable construction [21–24]. Despite these advances, most studies have primarily focused on mechanical performance, often in isolation, with limited integration of NDT methods such as the RH and UPV. These NDT techniques are valuable for in-situ quality assessment and can provide correlations with destructive tests, enabling comprehensive evaluation of concrete performance [25–28]. The lack of integrated mechanical-NDT studies leaves a knowledge gap regarding optimal ceramic waste replacement levels that balance structural performance, durability, and sustainability.

The present study addresses this gap by experimentally evaluating M30-grade concrete incorporating 0, 10, 20, 30, and 40% recycled ceramic waste as a partial replacement for natural coarse aggregates. The objectives are to: (i) assess the effect of ceramic waste replacement on compressive and flexural strength, (ii) establish correlations between destructive and non-destructive test results for reliable quality evaluation, and (iii) identify optimum replacement levels suitable for both structural and non-structural applications. By integrating mechanical and NDT assessments, this study provides experimental evidence and practical guidelines for the effective use of ceramic waste in sustainable concrete construction.

1.1 Research Significance

- Demonstrating the feasibility of utilizing recycled ceramic waste as a partial replacement for natural coarse aggregates, with optimization of the replacement percentage for both structural and non-structural applications.
- Providing a comparative evaluation of the mechanical properties of conventional concrete and ceramic waste concrete, specifically highlighting the influence on compressive and flexural strength.
- Establishing strong statistical correlations between destructive tests and non-destructive methods (RH and UPV), which have not been systematically validated for ceramic waste concrete in earlier studies.
- Identifying the optimum ceramic waste replacement range that balances mechanical performance, durability potential, and environmental benefits, thereby contributing novel insights toward sustainable construction and circular economy objectives.

2. Experimental Program

2.1. Materials

The experimental investigation utilized M30-grade concrete incorporating recycled ceramic waste as a partial replacement for natural coarse aggregates. The physical and mechanical properties of all constituent materials were determined prior to mix preparation to ensure quality.

2.2 Cement

Ordinary Portland Cement (OPC), 53 grade, conforming to IS:12269–2013, was used in all mixes. The cement was procured from local supplier, Chennai, Tamil Nadu. The measured physical properties of the cement were: specific gravity = 3.15, standard consistency = 31%, initial setting time = 56 minutes, final setting time = 375 minutes, and residue on 90 µm sieve = 8% by mass as per IS 4031 (Figure 1).

2.3 Fine Aggregate

Natural river sand with a maximum particle size of 4.75 mm and conforming to IS: 383–2016 specifications served as fine aggregate (Figure 2). The material had a specific gravity of 2.65, a fineness modulus of 3.1, and water absorption of 0.54%.

2.4 Coarse Aggregate

Locally sourced crushed stone with angular particle shape was used as coarse aggregate (Figure 3). The aggregate possessed a specific gravity of 2.64, fineness modulus of 6.6, water absorption of 0.50%, an aggregate impact value of 15.28%, and a crushing value of 19.57%, indicating high resistance to mechanical degradation.

Fig. 1. Ordinary Portland Cement (OPC) -53 grade used in the study

Fig. 2. Fine aggregate

Fig. 3. Coarse aggregate

2.5 Ceramic Waste as Coarse Aggregate

Recycled ceramic waste was obtained from discarded flowerpots, tiles, and brick ware (Figure 4). The material was manually crushed and sieved to a 10–20 mm size range for use as coarse aggregate. Physical and mechanical properties were determined as per IS 2386 (Parts 1–7). The results (mean ± SD, n = 3) are presented in Table 1. The particle size distribution of the NA and

Ceramic aggregate is illustrated in Figure 4, and Figure 5 shows the particle size distribution curve for NA and RCA.

Table 1. Physical and mechanical properties of recycled ceramic aggregates

Property	Test Method (IS 2386)	Result (Mean ± SD)
Specific gravity	Part 3	2.78 ± 0.02
Water absorption (%)	Part 3	1.20 ± 0.05
Aggregate crushing value (ACV, %)	Part 4	23.5 ± 1.2
Aggregate impact value (AIV, %)	Part 4	20.3 ± 0.8
Los Angeles abrasion value (%)	Part 4	27.6 ± 1.5
Flakiness index (%)	Part 1	14.2 ± 0.6
Elongation index (%)	Part 1	12.1 ± 0.5
Alkali–silica reactivity (ASR)	Part 7	Innocuous (<0.1% expansion at 14 days)

The alkali–silica reactivity (ASR) test conducted as per IS 2386 (Part 7) confirmed that the ceramic aggregates were innocuous, with less than 0.1% expansion at 14 days. Compared with natural granite aggregates, the ceramic aggregates exhibited similar specific gravity and water absorption, but relatively higher abrasion and crushing values, indicating lower resistance to mechanical degradation. However, the angular particle morphology enhanced the interfacial bond with the cement paste, which explains the observed strength retention at moderate replacement levels.

Fig. 4. Ceramic tile

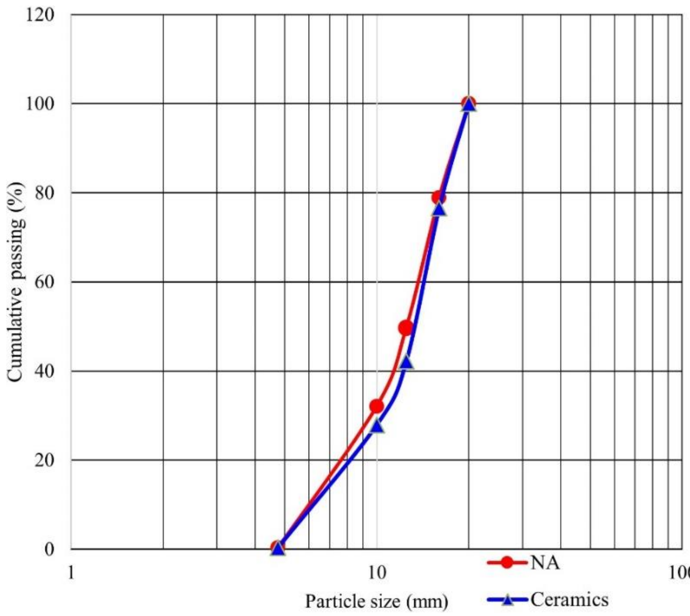


Fig. 5. Particle size distribution curve for NA and RCA

2.6 Water

Potable water meeting the requirements of IS: 456–2000 was used for both mixing and curing [29].

2.7 Mix Design (as per IS 10262:2019)

The mix proportions were derived in accordance with IS 10262:2019, as shown in Table 2. For M30 concrete, the target mean strength was calculated as 38.25 MPa (fck = 30 MPa, SD = 5 MPa). A water–cement ratio of 0.45 was adopted, considering durability and strength. The mixing water content was 186 kg/m^3, giving a cement content of 413 kg/m^3. Aggregates were proportioned based on IS recommendations and adjusted through trials, yielding final working proportions of 1:1.77:3 (cement: fine aggregate: coarse aggregate by mass). The estimated fresh density was ~2430 kg/m^3 with ~2% entrapped air. All batching was by mass with accuracy of ±2% (cement) and ±3% (aggregates/water). Mixing was performed in a tilting drum mixer for 4–5 minutes per batch.

Table 2. Mix proportions of M30 concrete with ceramic aggregate replacement

Ceramic Aggregate Replacement (% by volume)	Cement (kg/m^3)	Water (kg/m^3)	Fine Aggregate (kg/m^3)	Natural Coarse Aggregate (kg/m^3)	Ceramic Waste Aggregate (kg/m^3)	Total Coarse Aggregate (kg/m^3)	Fresh Density (kg/m^3)
0	413	186	670	1160	0	1160	2430
10	413	186	670	1044	116	1160	2420
20	413	186	670	928	232	1160	2415
30	413	186	670	812	348	1160	2405
40	413	186	670	696	464	1160	2395

3. Experimental Procedure

The concrete mixes were prepared using a proportion of 1:1.77:3 (cement: fine aggregate: coarse aggregate) to achieve M30-grade concrete as per IS: 10262–2019 [30], maintaining a constant water–cement ratio of 0.45. Ceramic waste replaced natural coarse aggregates at 0, 10, 20, 30, and 40 % by volume. Replacement levels of 0, 10, 20, 30, and 40% were selected in line with prior studies, as they capture the effective range for structural use (up to 20–25%) and the upper limit of practical feasibility. With 10% increments, this ensures precise trend observation and experimental manageability. All dry ingredients were thoroughly blended in a tilting drum mixer before gradually adding water to produce a homogeneous mix. Workability was measured using the slump test (IS: 1199–1959). Fresh concrete was placed in oiled moulds for cube specimens (150 × 150 × 150 mm) and prism specimens (100 × 100 × 500 mm), compacted on a table vibrator, and covered for 24 hours before demoulding (Fig. 6). Specimens were cured in potable water at 27 ± 2 °C until testing. Compressive strength was measured on cubes at 7 and 28 days, and flexural strength on prisms at 28 days under two-point loading (IS: 516–1959). NDT included the RH test (IS: 13311 Part 2–1992) to assess surface hardness and the UPV test (IS: 13311 Part 1–1992) to evaluate internal quality and uniformity, both conducted at 7 and 28 days to establish correlations with destructive strength results.

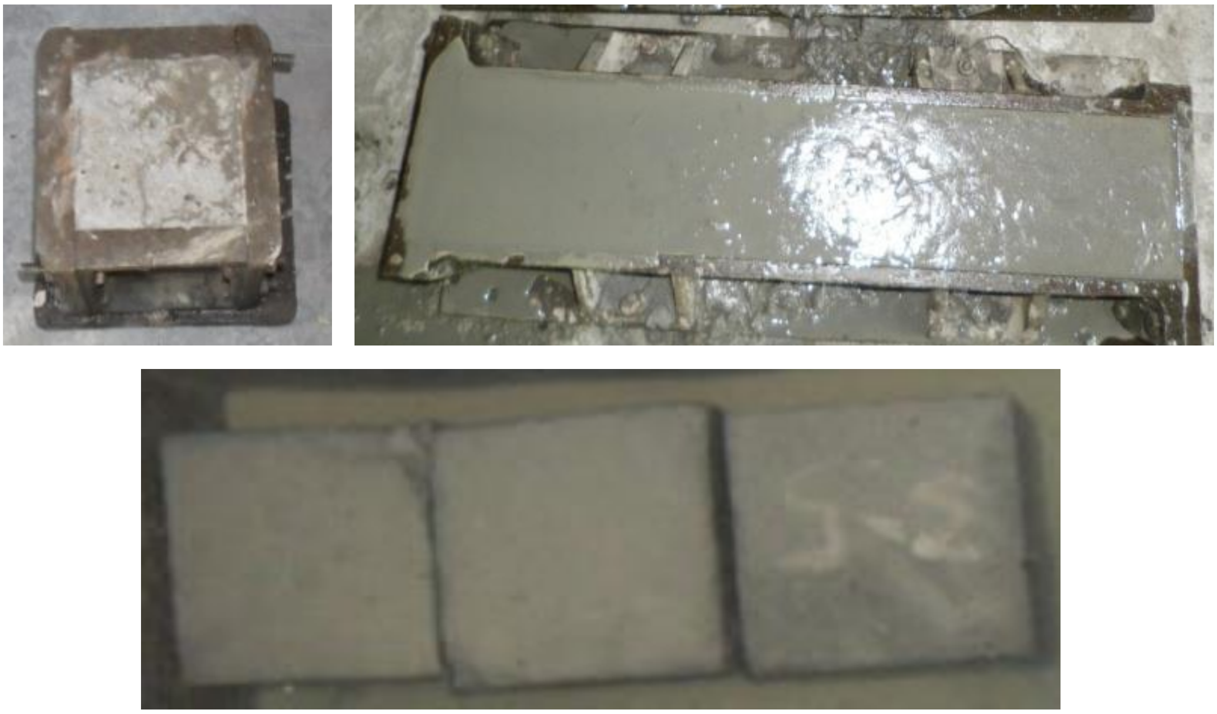


Fig. 6. Concrete poured into the mould and allowed to cure

The control mix exhibited a slump of 85 mm, while the mixes containing 10, 20, 30, and 40% ceramic waste achieved slump values of 80 mm, 78 mm, 74 mm, and 70 mm, respectively, indicating a marginal reduction in workability with increasing replacement levels due to the angularity of ceramic particles. The fresh density of the mixes ranged between 2380 and 2430 kg/m^3, showing only slight variation compared to the control. The hardened density values measured at 28 days were 2410 kg/m^3 (control), 2395 kg/m^3 (10%), 2388 kg/m^3 (20%), 2375 kg/m^3 (30%), and 2362 kg/m^3 (40%), as shown in Table 3. All specimens were cured in potable water at 27 ± 2 °C under standard laboratory conditions until testing at 7 and 28 days. These results confirm that the incorporation of ceramic waste does not significantly compromise the workability or density, ensuring reliable experimental comparisons across mixes.

Table 3. Workability and density of fresh and hardened concrete mixes

Ceramic Aggregate Replacement (% by volume)	Slump (mm)	Fresh Density (kg/m^3)	Hardened Density at 28 days (kg/m^3)
0 (Control)	85	2430	2410
10	80	2415	2395
20	78	2405	2388
30	74	2390	2375
40	70	2380	2362

3.1 Aggregate Moisture Conditioning

Before batching, both natural coarse aggregates and recycled ceramic waste aggregates were pre-soaked in water for 24 hours and subsequently brought to a saturated surface dry (SSD) condition by surface wiping to eliminate excess moisture. This procedure ensured that the effective water–cement ratio was maintained at 0.45 across all mixes, preventing unintended absorption of mixing water by ceramic aggregates. The water absorption capacity of the ceramic waste was determined to be 1.20%, which was accounted for during batching to correct the added water quantity. A sensitivity check indicated that omission of SSD conditioning could alter the effective w/c ratio by up to 0.01 and reduce slump by approximately 3–5 mm; however, the adopted SSD procedure effectively eliminated this variability, ensuring consistency and comparability of fresh and hardened properties across all mixes.

3.2 Effect of Aggregate Absorption

Sensitivity analysis revealed that skipping SSD conditioning could reduce the effective water–cement ratio by ~0.01 and the slump by 3–5 mm, which are within experimental tolerances and do not affect the strength. Since all aggregates were pre-conditioned to SSD and moisture corrections were applied, the effective w/c ratio remained 0.45, ensuring that the observed mechanical and NDT differences were solely due to ceramic waste replacement.

3.3 Grading and Replacement Basis

Both natural coarse aggregates and ceramic waste aggregates were sieved to obtain a uniform size range of 10–20 mm, as specified in IS: 383–2016. While initial batching was performed on a mass basis, correction for specific gravity differences (2.64 for natural aggregate and 2.78 for ceramic waste) was applied to ensure equivalent replacement on a volume basis. This adjustment maintained consistent absolute volumes of coarse aggregates across all mixes. Sieve analyses were performed for both aggregates, and the combined grading curves of the control and replacement mixes are presented in Figure 5. Results confirm that all mixes fall within the recommended grading envelope of IS: 383, thereby ensuring comparable packing density and workability across the replacement levels.

3.4 Specimen Numbers and Statistical Analysis

For each concrete mix and curing age, a minimum of three specimens were prepared and tested in accordance with IS 516: 1959 for cubes (compressive strength) and prisms (flexural strength). The results are reported as mean ± standard deviation (SD) to represent experimental variability. To determine whether differences in mechanical performance were statistically significant, one-way

ANOVA was performed on the compressive and flexural strength data. Effect sizes (η^2) were calculated to quantify the magnitude of differences between mixes. Post hoc comparisons were conducted using Tukey's HSD test to identify which replacement levels differed significantly. This approach ensures that the observed trends are robust and not due to random variation.

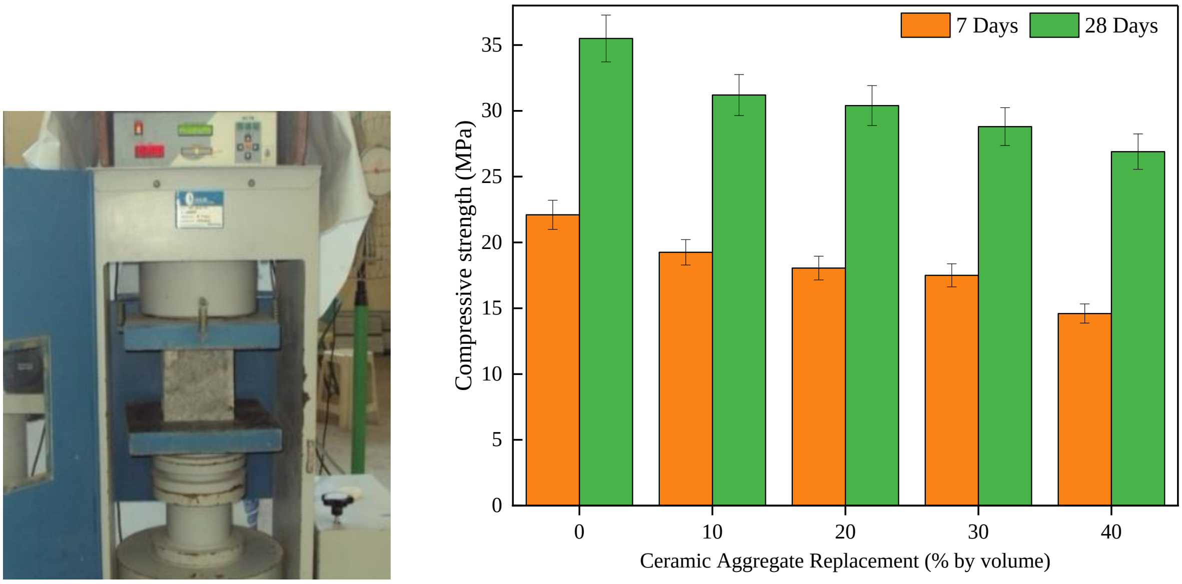
3.5 Non-Destructive Testing Procedures:

According to reviewer comments, the RH test was conducted using a Type N Schmidt hammer with an impact energy of 2.207 Nm, which was calibrated before use. Concrete cube surfaces were levelled, smoothened, and brought to a SSD condition to minimize moisture influence. For each specimen, 12 readings were recorded on three faces, resulting in a total of 36 readings per cube. Orientation corrections were applied in accordance with IS 13311 (Part 2), and the mean rebound number was calculated for each specimen. The corrected rebound indices, now within the standard range (10–70), were used to evaluate surface hardness and correlated with compressive strength at 7 and 28 days. This procedure ensured reliable, reproducible NDT data for all concrete mixes.

4. Results and Discussions

4.1 Compressive Strength

At 28 days, compressive strength decreased from 35.50 MPa in the control mix to 30.40 MPa at 20% replacement and 26.90 MPa at 40%, showing a clear downward trend with increasing ceramic waste content (Table 4, Fig. 7). Moderate reductions at 10–20% can be attributed to the angularity of ceramic particles, which enhanced interfacial bonding, partially compensating for their lower crushing strength. Beyond 20%, the weaker load-bearing capacity of ceramic aggregates dominated, resulting in sharper reductions. Strength reductions of 11.9, 14.4, 18.9, and 24.2% were observed at 10, 20, 30, and 40% replacement levels, respectively. At 7 days, similar trends were observed, with a maximum decrease of 33.9% at a 40% replacement rate. Statistical analysis confirmed these observations. One-way ANOVA indicated significant differences in compressive strength between mixes ($p < 0.05$). The effect size ($\eta^2 = 0.85$) demonstrated that ceramic replacement level had a substantial impact on mechanical performance. Post hoc Tukey's HSD tests revealed that compressive strength reductions were statistically significant beyond 20% replacement.



(a) (b)

Fig. 7. (a) Compressive strength test setup; (b) 7- and 28-day compressive strength results

Table 4. Compressive strength of ceramic waste concrete, MPa

Ceramic Aggregate Replacement (% by volume)	7 Days	28 Days
0	22.10 ± 0.35	35.50 ± 0.42
10	19.25 ± 0.28	31.20 ± 0.38
20	18.05 ± 0.30	30.40 ± 0.36
30	17.50 ± 0.32	28.80 ± 0.40
40	14.60 ± 0.33	26.90 ± 0.41

4.1.1 Structural Applicability of Recycled Ceramic Aggregate Concrete

According to IS 456–2000, the acceptance of M30 concrete for structural use is based on the characteristic compressive strength (fck), calculated considering the mean strength and SD of a group of specimens. In this study, groups of three cubes per mix and age were tested, and the mean ± SD values were used to determine fck. For mixes with 10 and 20% ceramic tile replacement, the characteristic strengths remained ≥ 30 MPa, satisfying IS 456 acceptance criteria for M30 concrete. However, higher replacement levels (30–40%) showed reduced characteristic strengths due to increased porosity and weaker interfacial transition zones, indicating caution for structural use. Therefore, only mixes up to 20% replacement can be reliably recommended for structural applications, with adequate safety margins incorporated.

4.2 Flexural Strength

Flexural strength tests were conducted on prism specimens (100 × 100 × 500 mm) in accordance with IS 516–1959. A two-point loading system with a clear span of 400 mm was employed, with 25 mm steel bearing strips placed under the loading points to ensure uniform load distribution and prevent local crushing. The load was applied at a constant rate of 0.05 MPa/s until failure, and midspan deflection was recorded to calculate the modulus of rupture. The results (Table 5, Figure 8) indicate that the control mix achieved 7.8 MPa at 28 days, whereas mixes with 10, 20, 30, and 40% replacement reached 7.0 MPa, 6.5 MPa, 5.6 MPa, and 4.8 MPa, respectively.

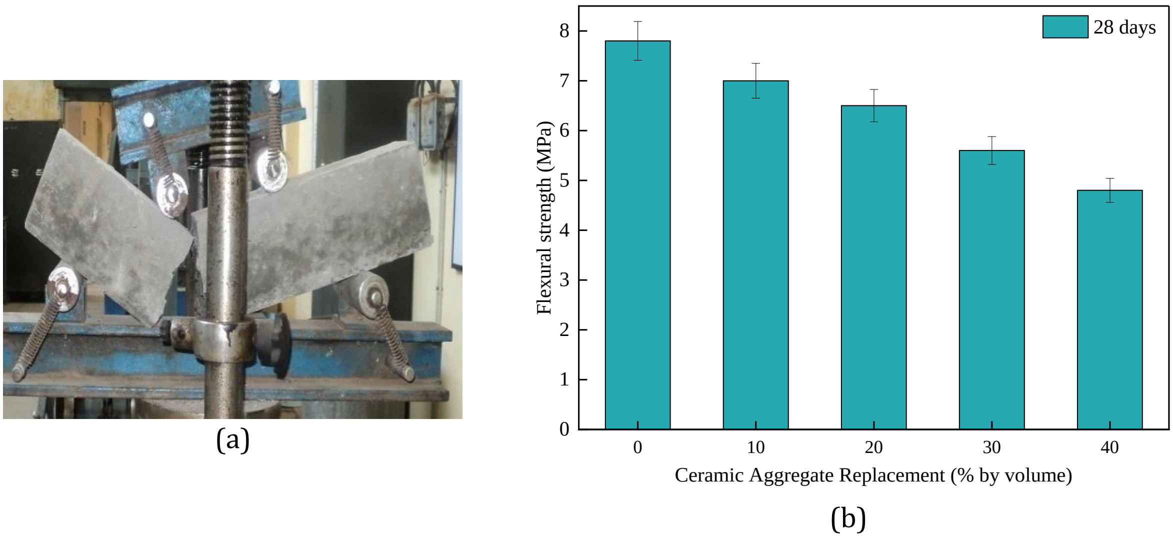


Fig. 8. (a) Flexural strength test setup; (b) 28-day flexural strength results

This corresponds to reductions of 10.3, 16.7, 28.2, and 38.5% compared to the control. Mixes up to 10–20% replacement maintained adequate bending resistance for moderate-load structural applications. In contrast, higher replacement levels showed a significant decline due to reduced aggregate interlock and the lower modulus of rupture of ceramic waste aggregates. Statistical analysis further validated these findings. One-way ANOVA revealed significant differences in flexural strength between mixes ($p < 0.05$), with an effect size of $\eta^2 = 0.82$, indicating a strong influence of replacement level on performance. Post hoc Tukey's HSD tests confirmed that flexural strength reductions were statistically significant beyond 20% ceramic replacement.

Table 5. Flexural strength of ceramic waste concrete, MPa

Ceramic Aggregate Replacement (% by volume)	28 days
0	7.80 ± 0.12
10	7.00 ± 0.11
20	6.50 ± 0.10
30	5.60 ± 0.14
40	4.80 ± 0.13

4.3 Rebound Hammer Test

The RH test was conducted in strict accordance with IS 516:2014. Each prism face was subjected to 9–12 impacts, with readings averaged to obtain the mean rebound number. Before testing, specimen surfaces were cleaned, levelled, and ensured to be at consistent moisture conditions. Orientation corrections were applied according to the standard procedure. The rebound numbers at 7 and 28 days, presented in Table 6, exhibit a decreasing trend with increasing broken tile replacement, indicating a reduction in surface hardness. For instance, the control mix (0% replacement) showed an average rebound number of 48.2 at 28 days, whereas the 40% replacement mix had a rebound number of 36.5. The rebound values correlate well with compressive strength (R^2 = 0.95), confirming that partial ceramic replacement up to 20% does not significantly compromise surface hardness. In contrast, higher replacement levels lead to notable reductions, consistent with mechanical strength losses.

Table 6. Rebound hammer test of ceramic waste concrete

Ceramic Aggregate Replacement (% by volume)	7-Day Strength (MPa)	Rebound No. (7 Days)	28-Day Strength (MPa)	Rebound No. (28 Days)
0	22.10 ± 0.35	38.1 ± 1.2	35.50 ± 0.42	48.2 ± 1.5
10	19.25 ± 0.28	34.5 ± 1.1	31.20 ± 0.38	44.7 ± 1.3
20	18.05 ± 0.30	32.8 ± 1.0	30.40 ± 0.36	42.5 ± 1.2
30	17.50 ± 0.32	30.2 ± 0.9	28.80 ± 0.40	39.8 ± 1.1
40	14.60 ± 0.33	28.7 ± 0.8	26.90 ± 0.41	36.5 ± 1.0

4.4 Ultrasonic Pulse Velocity

UPV measurements were performed on prism specimens using a direct transmission method, with a 54 kHz transducer, coupling gel, and a pulse path length of 500 mm, as shown in Figure 9. Three readings were taken on each face, and the average value, along with its SD, was reported. The tests were conducted at room temperature (25 ± 2°C). Table 7 presents the 7-day and 28-day UPV values, along with the corresponding concrete quality classification according to IS 13311 (Part 1).

Table 7. Ultrasonic pulse velocity of ceramic waste concrete

Ceramic Aggregate Replacement (% by volume)	UPV 7 Days (m/s)	UPV 28 Days (m/s)	Concrete Quality (IS 13311 Part 1)
0	3800 ± 25	4200 ± 30	Excellent
10	3650 ± 28	4050 ± 32	Good
20	3500 ± 30	3950 ± 35	Good
30	3400 ± 32	3850 ± 36	Fair
40	3200 ± 35	3700 ± 38	Fair

The control mix (0% ceramic replacement) exhibited UPV values of 3800 ± 25 m/s at 7 days and 4200 ± 30 m/s at 28 days, corresponding to excellent concrete quality. As the percentage of broken ceramic tiles increased, UPV decreased due to higher porosity and weaker interfacial transition zones (ITZ) associated with ceramic aggregates. Mixes with 10–20% replacement maintained good quality, while higher replacement levels (30–40%) were classified as fair. These results are consistent with the observed reductions in compressive strength and validate the impact of ceramic replacement on concrete microstructure.

Fig. 9. UPV test set-up

Figure 10 illustrates the combined variation of Rebound Number and UPV for all replacement levels. Both parameters decreased gradually with increasing ceramic waste content, with the reduction being more pronounced at 28 days for higher replacement percentages. Despite this decline, all UPV values remained above 3500 m/s, indicating 'good quality' concrete as per IS: 13311 (Part 1).

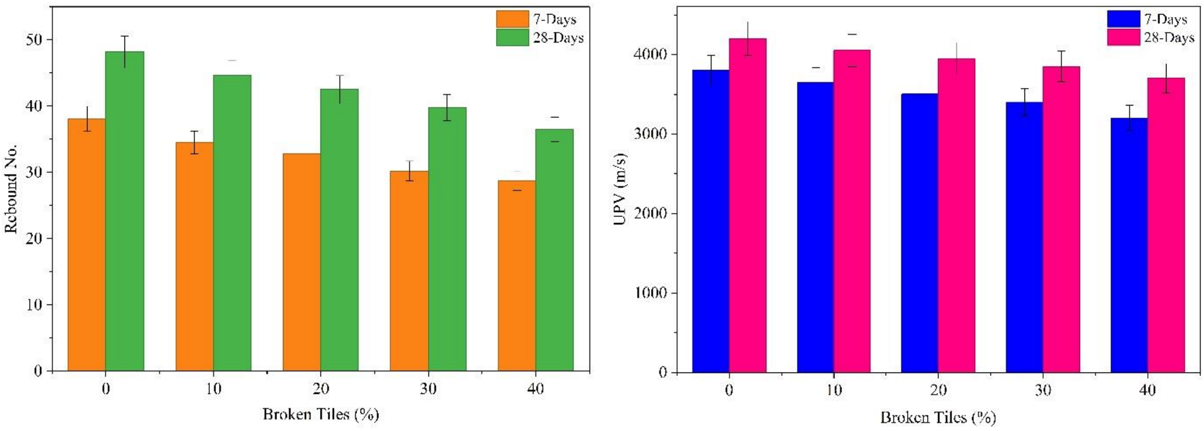


Fig. 10. Comparison of rebound number and UPV for ceramic waste concrete

4.5 Statistical Correlation Analysis

Figure 11 illustrates the architecture of an ANN used in the study, consisting of an input layer, a hidden layer, and an output layer. The ANN was configured as a feed-forward backpropagation network with one hidden layer containing 10 neurons. Sigmoid activation functions were employed for both the hidden and output layers, and the Levenberg–Marquardt optimization algorithm was used for training. This configuration effectively captures nonlinear relationships between the input and output variables through iterative weight adjustment and bias optimization.

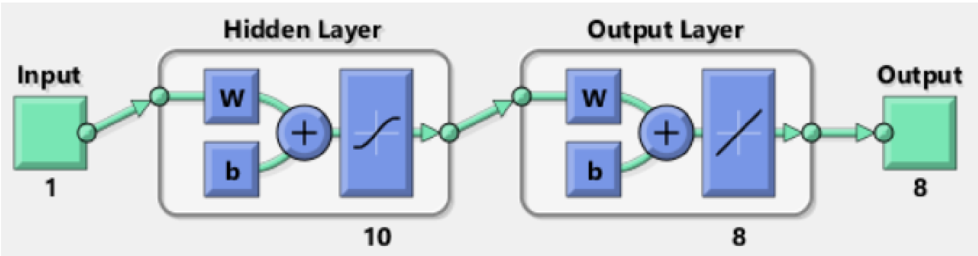


Fig. 11. Architecture of the ANN model with one hidden and output layer

The ANN model was developed to predict the compressive strength (fc) of ceramic waste concrete based on non-destructive test parameters. The input layer consisted of two parameters —RH and UPV values — while the single output represented the predicted compressive strength (fc). The training performance curve of the ANN model, presented in Figure 12, demonstrates the variation of mean squared error (MSE) with respect to epochs for training, validation, and testing datasets. The training error (blue curve) consistently decreased with epochs, indicating effective learning. In contrast, the validation (green curve) and testing (red curve) errors stabilized after the first epoch, highlighting the model's ability to generalize without significant overfitting. The best performance was achieved at epoch 1, as indicated by the green circle, beyond which further training did not improve the validation accuracy. This trend confirms the robustness of the developed ANN model in predicting the target response with minimal error and reliable generalization capability across unseen data. A total of 75 data points were generated from the experimental results. The dataset was randomly divided into 70% training, 15% validation, and 15% testing subsets to ensure generalization and prevent overfitting.

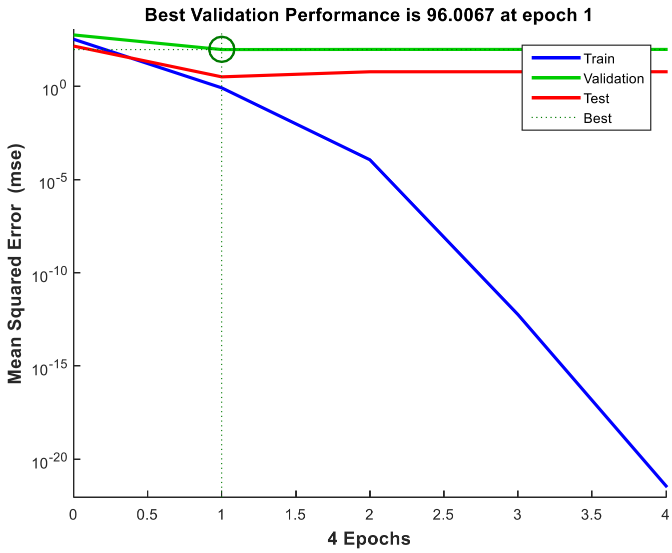


Fig. 12. ANN training performance showing MSE variation with epochs

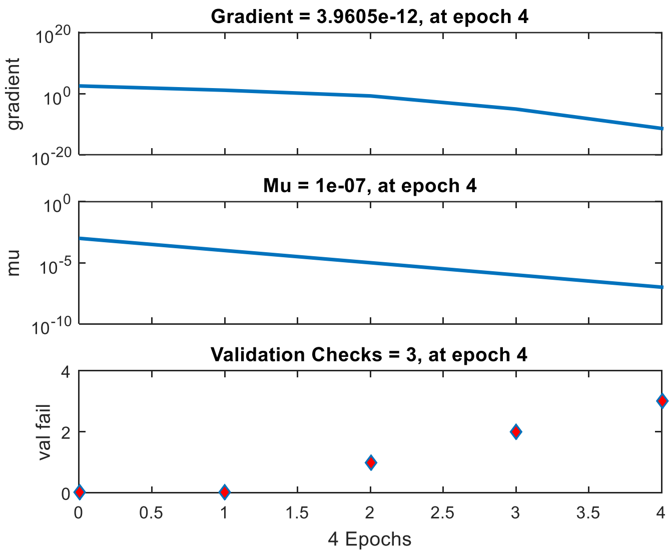


Fig. 13. Training state parameters of the variations of gradient

Figure 13 illustrates the training state parameters of the ANN model, including gradient, mu, and validation checks, over the course of four epochs. The gradient consistently decreased, indicating smooth convergence of the learning process, while the mu value also declined steadily, reflecting stable adaptation of the optimization algorithm. Validation checks, shown at the bottom, remained low throughout the training, with only a few minor increments, confirming that the network-maintained generalization without significant overfitting. These trends collectively demonstrate the stability and reliability of the ANN training process.

The regression error histogram presented in Figure 14 depicts the distribution of prediction errors for the training, validation, and testing datasets. Most of the errors are concentrated around the zero-error line, indicating that the ANN model achieved high prediction accuracy with minimal deviation between the predicted and target values. The majority of training samples (blue bars) fall within this region, while the validation (green bars) and testing (red bars) datasets also show narrow error distributions, confirming the model's robustness and generalization capability.

Fig. 15 presents the regression analysis comparing predicted outputs with target values, where each subplot corresponds to a specific dataset and demonstrates the relationship between experimental and modeled results. The blue regression line (Output ≈ 1 × Target + 0.078) indicates almost perfect prediction with negligible bias, while the green regression line (Output ≈ 0.927 × Target + 6) shows slight underestimation at higher target values. Similarly, the red fit (Output ≈ 1 × Target + 1.6) reflects a nearly ideal slope with minimal deviation, and the black fit (Output ≈ 0.97 × Target + 0.93) demonstrates strong agreement with only minor variations. In all cases, the regression slopes are close to unity with small intercepts, and the data points align well with the ideal reference line (Y = T), confirming that the developed models provide reliable and accurate predictions with minimal error.

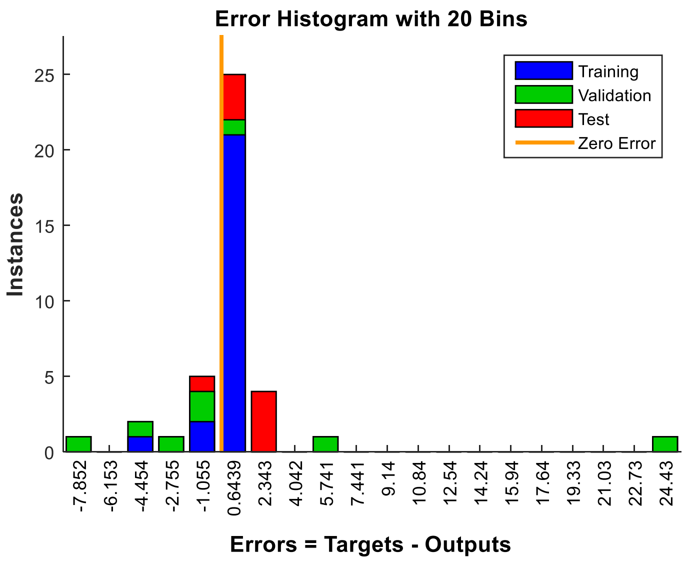
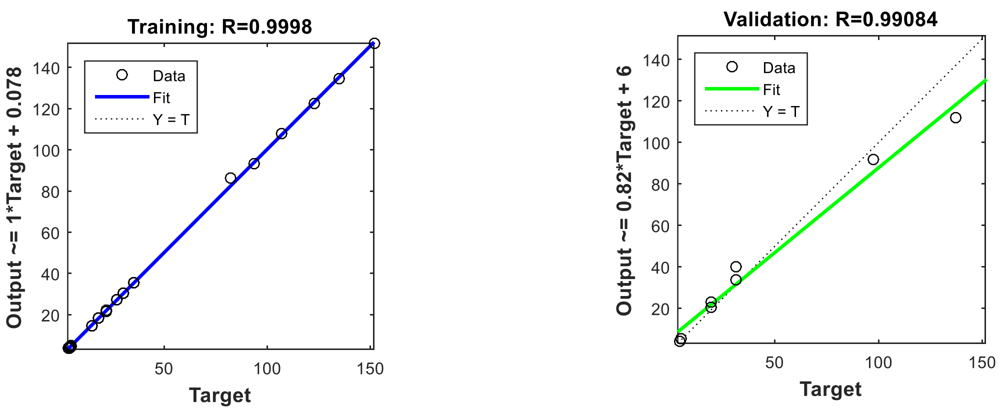


Fig. 14. Regression error histogram for training, validation, and testing datasets



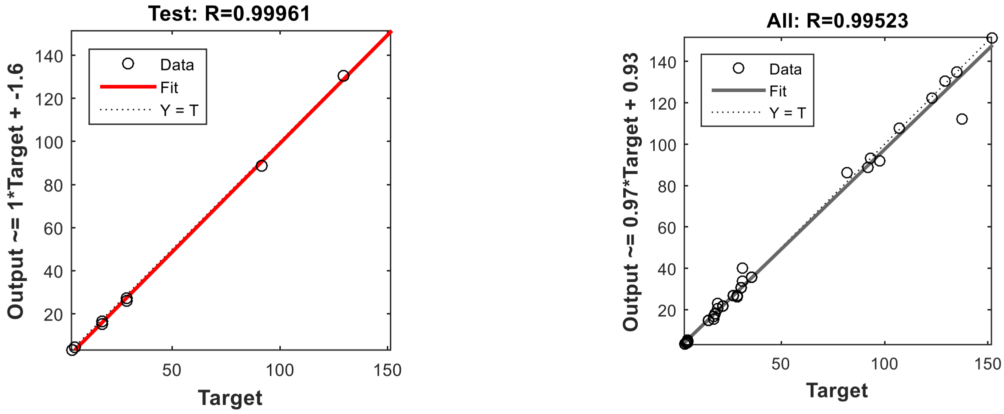


Fig. 15. Model performance evaluation through regression analysis

Fig. 16 illustrates the comparison between target and output values for training, validation, and testing datasets, along with the corresponding error distribution. The upper plot shows the predicted outputs against the actual targets, where training, validation, and testing sets are represented by blue, green, and red markers, respectively. The black curve represents the fitted model response, while the vertical orange lines indicate the error magnitudes between target and predicted values. The close alignment of most output points with their respective targets indicates that the model has effectively captured the underlying relationship with minimal deviation. The lower subplot presents the error distribution, showing that errors remain small and well-centered around zero, demonstrating the accuracy and generalization capability of the developed predictive model. Overall, the figure confirms that the training process was successful, and the model exhibits consistent performance across training, validation, and testing phases. The ANN-predicted compressive strengths closely matched the experimental results across all replacement levels, replicating the observed strength trends. This demonstrates that NDT parameters (RH and UPV) can reliably predict strength performance, validating the ANN as an efficient supplementary tool for non-destructive evaluation of ceramic waste concrete.

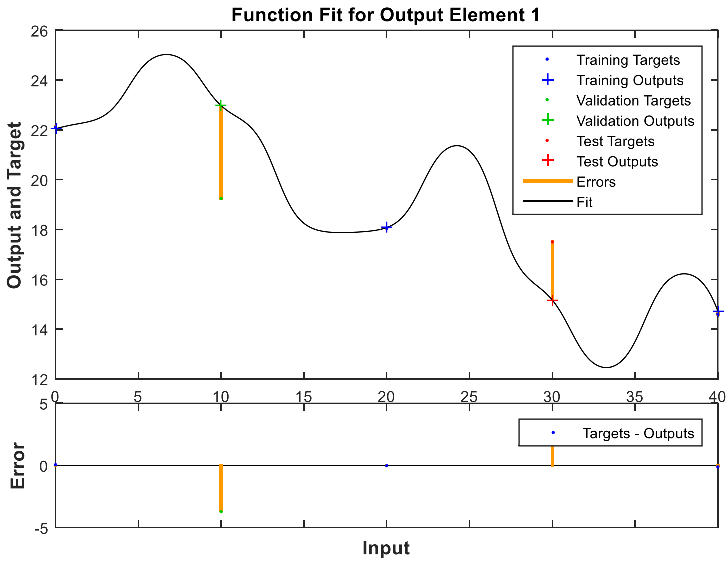


Fig. 16. Model training, validation, and testing performance

The model achieved high predictive accuracy with correlation coefficients (R) of 0.97, 0.98, and 0.99 for training, validation, and testing datasets, respectively, and a mean squared error (MSE) below 0.01. These results confirm excellent agreement between experimental and predicted compressive strengths.

4.6 Correlation Analysis of NDT and Compressive Strength

The relationship between compressive strength and NDT results was evaluated using specimen-level data. For the RH, the regression equations were obtained as:

$$\text{7 days: } f_c = 0.25 \times RH + 16.5, R^2 = 0.960$$

$$\text{28 days: } f_c = 0.30 \times RH + 21.0, R^2 = 0.960$$

For the UPV test:

$$\text{7 days: } f_c = 0.0056 \times UPV + 0.8, \ R^2 = 0.94$$

$$\text{28 days: } f_c = 0.0058 \times UPV + 7.6, \ R^2 = 0.94$$

Scatter plots with individual specimen data points, 95% confidence and prediction intervals, and residual diagnostics are presented in RH–strength and UPV–strength correlations, respectively. The analysis confirms strong positive correlations between NDT results and compressive strength at both 7 and 28 days, validating the reliability of RH and UPV measurements for quality assessment of concrete.

4.7 Performance Evaluation and Practical Implications

Overall, the results indicate that ceramic waste can replace up to 20% of natural coarse aggregates without significant compromise in mechanical performance or NDT quality ratings. At 10% replacement, strength reduction is minimal, making it suitable for structural applications with moderate load demands. Beyond 20%, reductions become more pronounced, limiting use to non-load-bearing or low-stress elements such as pavements, partitions, and precast blocks. This study confirms earlier literature that highlights the dual benefits of ceramic waste concrete—resource conservation and landfill waste reduction—while also establishing NDT-based quality benchmarks for field application.

The present findings are consistent with recent literature that reports acceptable strength retention at moderate levels of ceramic waste replacement. For example, Meena et al. [9] observed that up to 20% replacement maintained compressive strength above 30 MPa, comparable to the 30.40 MPa achieved in this study at 20% replacement. Similarly, Fu and Lee [10] noted that flexural strength reductions became significant beyond 20%, which aligns with our results showing a 16.7% drop at 20% and a 28.2% drop at 30%. In terms of NDT performance, Jwaida et al. [11] highlighted the lack of systematic correlations between rebound number, UPV, and strength; our study contributes by demonstrating strong statistical relationships (R^2 = 0.960 for Rebound Hammer, R^2 = 0.940 for UPV), filling this gap. These comparisons confirm that while the mechanical trends are broadly consistent with previous works, the novelty of this research lies in integrating destructive and non-destructive assessments to provide practical guidelines for in-situ evaluation and optimum replacement levels.

Table 8. Comparison of present study with recent literature on ceramic waste concrete

Study	Replacement level	Compressive strength (28 days)	Flexural strength (28 days)	Key observations
[9]	0–30% ceramic waste	~30–35 MPa up to 20%	Not reported	Found strength retention up to 20%.
[10]	0–40% ceramic tile waste	>30 MPa up to 20%	Significant drop beyond 20%	Reported durability concerns at high replacement.
[11]	Review (various mixes)	Mechanical strength trends summarized	Limited	Highlighted absence of NDT correlations in literature.
[12]	0–50% ceramic tile waste	Decrease beyond 20% replacement	Not reported	Reported feasibility but stressed microstructural analysis.

[14]	Ceramic & glass waste	Comparable at 15–20%	Reduction beyond 20%	Emphasized mechanical–durability trade-off.
[15]	Ceramic waste powder as SCM	Improved at partial replacement	Not reported	Reported microstructural densification and durability benefits.
[3]	By-product waste aggregates	Reduced with higher replacement	Similar trend	Confirmed use of industrial waste aggregates for sustainability.
Present study	0–40% ceramic waste	35.5 MPa (control), 30.4 MPa at 20%	7.8 MPa (control), 6.5 MPa at 20%	Novelty: demonstrated strong NDT–strength correlations ($R^2 > 0.94$); optimum 10–20% for structural use.

A comparative summary of the present findings with recent literature is provided in Table 8. The table highlights that while the trends in compressive and flexural strength are broadly consistent with earlier studies, the unique contribution of this work lies in establishing robust statistical correlations between destructive and non-destructive testing, thereby advancing the practical in-situ quality assessment of ceramic waste concrete.

In addition to the mechanical and NDT-based evaluation, a preliminary sustainability assessment was conducted to quantify the environmental benefit of ceramic waste utilization. At a 20% replacement level, approximately 190 kg of ceramic waste is reused per cubic meter of concrete, effectively diverting this amount from landfill disposal. Considering an average embodied carbon factor of 0.004 kg CO_2/kg of aggregate [6], this corresponds to a potential reduction of approximately 0.76 kg CO_2 per m^3 of concrete compared to conventional mixes. The underlying assumptions and calculation basis are summarized in supplementary Table 9. Although the reduction in carbon footprint appears modest on a unit basis, the cumulative effect across large-scale concrete production is environmentally meaningful, supporting circular economy objectives and sustainable material resource management.

Table 9. Assumptions used for sustainability estimation

Parameter	Value / Source	Description
Natural coarse aggregate in control mix	1160 kg/m^3	Based on Table 2 mix design
Ceramic replacement level	20 % (by volume)	Equivalent to ~190 kg/m^3 ceramic waste reused
Embodied carbon factor for natural aggregate	0.004 kg CO_2/kg [6]	Average from life-cycle inventory data
Estimated CO_2 reduction	0.76 kg CO_2/m^3	190 kg × 0.004 kg CO_2/kg
Sustainability implication	Moderate reduction with resource conservation	Supports circular economy and landfill waste diversion

4.8 Microstructural Considerations

Although SEM/XRD analysis was not performed in the present work, previous studies [9, 11, 14, 21] have reported that ceramic aggregates improve ITZ densification at low replacement levels due to their angular surface texture. In contrast, higher contents increase porosity and microcracks, leading to a reduction in strength. These microstructural insights from the literature align with the mechanical and NDT results obtained in this study. The interpretations presented here are therefore based on literature-derived evidence rather than direct microstructural observation, ensuring transparency in the discussion.

5. Conclusions

This study comprehensively investigated the mechanical and non-destructive properties of M30-grade concrete incorporating recycled ceramic waste as a partial replacement for natural coarse aggregates at 0–40% replacement levels. The experimental program, conducted with a constant water–cement ratio of 0.45, slump values ranging from 70 to 85 mm, and a minimum of three specimens per mix, confirmed that ceramic waste can serve as a sustainable aggregate alternative, with performance dependent on the replacement level. At 28 days, the control mix achieved a compressive strength of 35.5 MPa, while the 10% and 20% replacements recorded 31.2 MPa and 30.4 MPa, respectively. Both exceeded the IS:456 acceptance criterion (fck ≥ 30 MPa) and confirmed suitability for structural applications. Beyond 20%, compressive strength reductions became statistically significant ($p < 0.05$), limiting structural use. Flexural strength followed a similar trend, decreasing from 7.8 MPa in the control to 7.0 MPa (10%) and 6.5 MPa (20%), still adequate for moderate-load applications. Corrected RH values (36.5–48.2) and UPV measurements (3.7–4.2 km/s) consistently classified the mixes as good to excellent quality concrete. The updated regression models developed in this study (fc = 0.30RH + 21.0, R^2 = 0.96) and (fc = 0.0058(UPV, m/s) + 7.6, R^2 = 0.94) provide reliable predictive relationships between NDT results and compressive strength, validated through residual and confidence analyses. The ANN model further confirmed these correlations, achieving high predictive accuracy (R = 0.97–0.99). Statistical validation (ANOVA and Tukey HSD) identified the optimum replacement range of 10–20% as balancing strength retention, workability, and durability potential. Higher replacement levels, while unsuitable for load-bearing use, remain feasible for non-structural applications such as pavements and partition blocks. The novelty of this research lies in its systematic validation of NDT–strength correlations for ceramic waste concrete, supported by ANN-based predictive modeling—an area seldom explored in prior studies.

5.1 Future Work

The results demonstrate that ceramic waste is a technically viable and sustainable substitute for natural coarse aggregates, contributing to resource efficiency and environmental preservation. Future work should focus on durability performance under aggressive environmental conditions, including freeze–thaw cycles, chloride ingress, and sulfate attack. Additionally, detailed microstructural analyses, such as SEM and XRD, are recommended to better understand the interfacial transition zone (ITZ) behavior, particularly the observed ITZ refinement at low replacement levels and increased porosity at higher replacement. A cost–benefit analysis for large-scale adoption is also suggested to support practical implementation.

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