

Regression Analysis of Shear and Tensile Strength in Sustainable Concrete with Recycled Ceramic and Glass

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Abstract: This study partially replaced cement and coarse aggregate with recycled ceramic and glass waste, and then analyzed the mechanical behaviour of the resulting concrete. Various replacement ratios were prepared for concrete mixes, then compression, splitting tensile and shear strength were performed after 28 days of curing. Empirical equations were developed using regression analysis, where the compressive strength was related to the tensile and shear strengths. After analysis, strong, positive relationships were revealed, with a coefficient of determination R^2 0.995. This value indicates a high accuracy of the produced models and can provide reliable tools for designing sustainable concrete mixes. Regression analysis also revealed the limitations of predicting the behaviour of modified concrete using conventional equations.

Keywords: Ceramic Waste, Glass Waste, Predictive Models, Regression Analysis, Shear Strength, Sustainable Concrete.

1. Introduction

Concrete production significantly contributes to global CO₂ emissions, prompting interest in sustainable alternatives. Regression analysis provides an effective tool for modeling relationships between concrete properties, particularly when incorporating alternative materials. This study aims to fill the gap in existing literature by developing predictive models for shear and tensile strength in sustainable concrete mixes using recycled ceramic and glass, materials that pose environmental disposal challenges.

The mechanical characteristics of concrete incorporating recycled glass and ceramic debris, such as compressive strength (f'_c), splitting tensile strength (f_t), and shear strength (V_u), were examined in this work using regression analysis. When assessing the efficiency of structural components like roofs, beams, and columns, these characteristics are crucial. Because concrete enhanced with recycled components has distinct chemical and physical characteristics, especially in terms of tensile and shear strength, theoretical models used for traditional concrete are frequently incorrect. Thus, the goal of this study is to create regression analysis-based models using experimental data so that the mechanical behaviour of sustainable concrete can be more accurately represented. To confirm the precision and efficacy of these models, the anticipated outcomes were also contrasted with laboratory values.

The relationship between shear strength (V_u), the dependent variable, and split tensile strength (f_t), the other dependent variable, using simple linear regression, one of the statical techniques used to examine the relationship between a dependent variable and an independent variables following regression analysis. In both instances, the independent variable was compressive strength (f'_c).

Several significant statistical indicators were used to assess the accuracy of the produced statistical models, chief among them being:

(R^2) the coefficient of determination: This metric is used to calculate the proportion of the dependent variable's variance that the independent variable can account for [1].

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The coefficient of variation (COV) is a metric used to quantify the degree of the data scatter around the mean [2].

$$\text{COV} = \frac{\text{Standard Deviation}}{\text{Mean}} * 100\% \quad (1)$$

Several recent studies have confirmed the importance of using regression analysis techniques in predicting the properties of concrete treated with alternative materials such as ceramic waste. Sharma et al. [3] demonstrated that replacing coarse aggregate with ceramic waste can improve the compressive strength of concrete. They noted a clear correlation between the replacement ratios and the resulting strength values, highlighting the need to use accurate analytical tools such as regression to extract mathematical relationships between variables.

On the other hand, A. Cekic [4] addressed the problem of predicting the compressive strength of recycled concrete using the LASSO model, a type of regularized regression analysis technique characterized by its ability to reduce redundant effects and improve modeling accuracy. The proposed model demonstrated added value in its ability to interpret underlying data and classify influencing factors, making the results more reliable and trustworthy in the context of engineering applications.

Q. Chang et al. [5] focused on estimating the properties of concrete derived from ceramic waste using an experimental data-driven approach, along with its environmental assessment. By applying regression analysis and statistical techniques, the researchers were able to observe patterns and relationships between various variables, not only in terms of structural performance but also in terms of environmental aspects, reflecting the integration of sustainability and technical precision requirements.

A. Asiri [6] this study examined a predictive analysis of the properties of concrete modified with ceramic waste using artificial neural networks (ANN) and linear regression techniques. The study aimed to build accurate mathematical models that predict the mechanical properties of concrete when a portion of the cement is replaced with ceramic waste. The results demonstrated high accuracy for the proposed models in representing the relationship between replacement ratios and concrete properties.

Ahmed et al [20] conducted an experimental study on concrete prepared using ceramic waste and nylon fibers to evaluate the compressive and splitting strength. They also used predictive models based on Support Vector Machine (SVM) to analyze the relationship between mechanical properties. The results showed that the addition of these materials improved the performance of concrete, and the regression model using GBM achieved higher accuracy. This study reinforces the importance of investing waste in improving concrete properties and incorporating statistical modeling into its analysis.

This study is significant because it addresses environmental and engineering challenges by incorporating recycled ceramic and glass waste into concrete production. This research provides essential insights by developing empirical models to predict multiple strength parameters using regression analysis, contributing to the design of more sustainable, performance-based mixes.

2. Methodology

2.1 Material and Mix Design

According to ACI 211 specifications, for each concrete mix, a total of 9 specimens were cast: 3 cubes, 3 cylinders, and 3 L-shaped shear specimens. With 15 different mixes, the total number of specimens was 135, including 45 cubes for compressive strength testing, 45 cylinders for splitting tensile strength testing, and 45 L-shaped shear specimens. The mixing proportions used in this investigation were planned to reach Grade 40 concrete at 1:1.37:2.18 with w/c 0.365. Various doses of superplasticizer PC 200 as prescribed by ASTM C-494-19 [17] were treated with these ratios to guarantee comparable workability with slump (10–12) cm. This was done to eliminate the effect of workability variation and ensure that the differences in mechanical properties were due solely to the material substitutions, not to differences in fresh concrete consistency.

According to I.Q.S. [19], local Iraqi cement (Ordinary Portland Cement) from Badush Extension Factory was utilized, and in specific amounts, recycled glass and ceramic powder was substituted for cement in compliance with Iraqi regulation No. 45/1984 [18]. Fine and coarse aggregates were prepared under

saturated surface dry (SSD) conditions and graded in accordance with Iraqi specifications I.Q.S. No. 45/1984 [18], with a maximum size of coarse aggregate of 20 mm.

In concrete mixtures, different percentages of glass and ceramic powder (10%,20%,25% and 30%) by weight of cement were used to partially replace ordinary Portland cement (OPC). Additionally, the best mixtures were altered by adding (10%,15% and 20%) glass or ceramic waste in place of the coarse aggregate. For coparision's sake, a reference mix devoid of replacement was also made.

Tables (1),(2),(3) and (4) show the change in mix weights due to the partial replacement of cement in first stage and cement and coarse aggregate in second stage by recycled ceramic and glass.

Table (1) Weights of each Mix due to Cement Replacement with Ceramic

Mixes	Cement (Kg)	Gravel (Kg)	Sand (Kg)	Recycled ceramic (Kg)	Water (Kg)	Super plasticizer (L/Mix)
C _{0%} A _{0%}	19.56	42.6	26.8	0	7.04	0.098
C _{10%} A _{0%}	17.6	42.6	26.8	1.956	7.04	0.098
C _{20%} A _{0%}	15.648	42.6	26.8	3.912	7.04	0.137
C _{25%} A _{0%}	14.67	42.6	26.8	4.89	7.04	0.156
C _{30%} A _{0%}	13.692	42.6	26.8	5.868	7.04	0.176

Table (2) Weights of each Mix due to Cement Replacement with Glass.

Mixes	Cement (Kg)	Gravel (Kg)	Sand (Kg)	Recycled glass (Kg)	Water (Kg)	Super plasticizer (L/Mix)
C _{0%} A _{0%}	19.56	42.6	26.8	0	7.04	0.098
C _{10%} A _{0%}	17.6	42.6	26.8	1.956	7.04	0.098
C _{20%} A _{0%}	15.648	42.6	26.8	3.912	7.04	0.109
C _{25%} A _{0%}	14.67	42.6	26.8	4.89	7.04	0.115
C _{30%} A _{0%}	13.692	42.6	26.8	5.868	7.04	0.119

Table (3) Weights of each Mix due to Cement and Aggregate Replacement with Ceramic

Mix	Replacement Ratio	Cement (Kg)	Gravel (Kg)	Sand (Kg)	Recycled Ceramic Powder (Kg)	Water (Kg)	Recycled Ceramic As Coarse Agg. (Kg)	Super plasticizer (L/Mix)
C _{20%} A _{0%}	0%	15.648	42.6	26.8	3.912	7.04	0	0.098
C _{20%} A _{10%}	10%	15.648	38.34	26.8	3.912	7.04	4.26	0.098
C _{20%} A _{15%}	15%	15.648	36.21	26.8	3.912	7.04	6.39	0.125
C _{20%} A _{20%}	20%	15.648	34.08	26.8	3.912	7.04	8.52	0.137

Table (4) Weights of each Mix due to Cement and Aggregate Replacement with Glass.

Mix	Replacement Ratio	Cement (Kg)	Gravel (Kg)	Sand (Kg)	Recycled Glass Powder (Kg)	Water (Kg)	Recycled Glass As Coarse Agg. (Kg)	Super plasticizer (L/Mix)
C _{10%} A _{0%}	0%	17.6	42.6	26.8	1.956	7.04	0	0.098
C _{10%} A _{10%}	10%	17.6	38.34	26.8	1.956	7.04	4.26	0.098
C _{10%} A _{15%}	15%	17.6	36.21	26.8	1.956	7.04	6.39	0.125
C _{10%} A _{20%}	20%	17.6	34.08	26.8	1.956	7.04	8.52	0.125

Where C is cement replacement and A is aggregate replacement.

2.2 Specimen Preparation and Testing Procedures

All concrete specimens were prepared and cast according to American Society for Testing and Materials (ASTM) standards. as shown in Figure (1), this system was designed to generate a pure shear zone and avoid bending effects during testing. To ensure consistent experimental conditions, the quantities of fine aggregate and the water-to-cement ratio were maintained constant across all mixes.

To evaluate compressive strength after 28 days, three concrete cubes were manufactured for each mix, measuring $150 \times 150 \times 150$ mm, according to ASTM C39 [15]. The splitting tensile strength of each mix was tested using three cylindrical specimens with a diameter of 150 mm and a height of 300 mm, according to ASTM C496 [16], as shown in Figures(2) and (3). Shear strength was measured using a modified direct shear system,

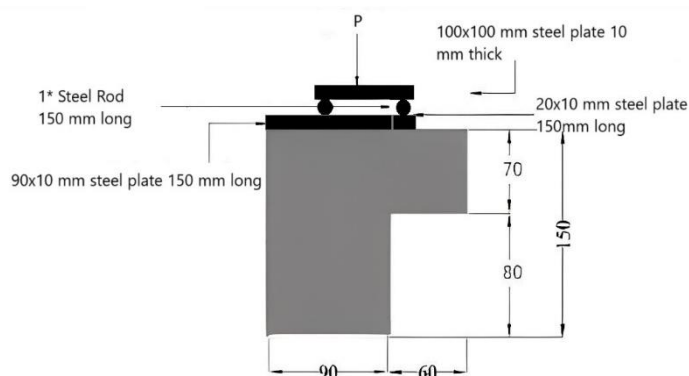


Fig. (1): Shear strength test.

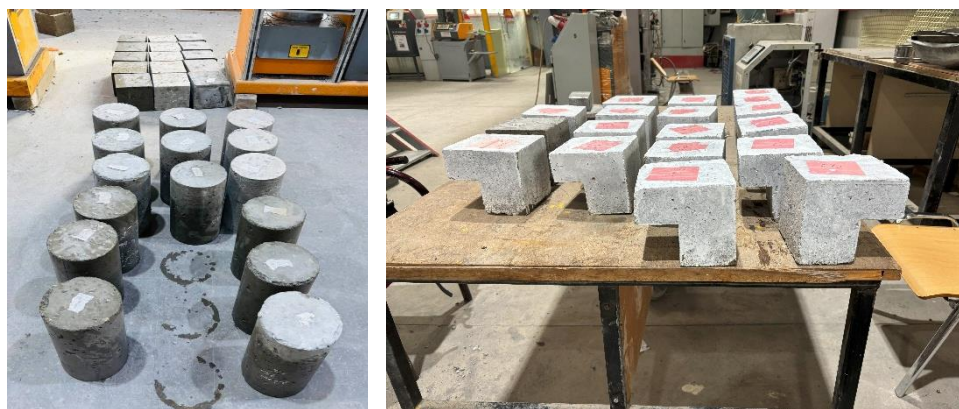


Fig. (2) Specimens before Mechanical testing



Fig. (3): Compressive strength test, splitting tensile strength test, and shear strength test.

2.3 Regression Analysis Method

After completing all mechanical tests, empirical equations were derived linking the compressive strength (f^c), split tensile strength (ft), and shear strength (Vu) using regression analysis. Both linear and nonlinear regression models were analyzed using IBM SPSS Statistics version 30. To evaluate the effectiveness of the derived models, statistical indicators such as the coefficient of determination (R^2) and the coefficient of variation (COV) were used. Scatter plots were also created to visually compare the experimental values with the predicted values and determine their congruence. These models aim to support the design of sustainable concrete mixes by providing accurate predictive tools tailored to concrete containing glass and ceramic waste.

3. Results

Tables (5) and (6), presents a detailed presentation and analysis of the laboratory results obtained from studying sustainable concrete mixes containing different proportions of ceramic and glass waste as partial replacement additives for cement and coarse aggregate. Three main mechanical properties were evaluated: compressive strength, tensile strength, and shear strength, to understand the impact of recycled materials on concrete performance.

Table (5): Test Results of Mixes that Contain Ceramic Replacement as Cement and Aggregate

Mix	Compressive Strength (MPa)	Splitting Tensile Strength (MPa)	Shear Strength Ultimate Load (MPa)
C _{0%} A _{0%}	39.77	4.15	1.158
C _{10%} A _{0%}	35.56	2.25	1.004
C _{20%} A _{0%}	38.08	3.26	1.398
C _{25%} A _{0%}	35.54	2.42	0.917
C _{30%} A _{0%}	34.51	2.28	0.744
Optimal Replacement Ratio of Cement by Ceramic is 20%			
C _{20%} A _{10%}	38.53	4.283	1.164
C _{20%} A _{15%}	34.88	3.77	0.972
C _{20%} A _{20%}	30.36	3.522	0.841

Table (6): Test Results of Mixes that Contain Glass Replacement as Cement and Aggregate.

Mix	Compressive Strength (MPa)	Splitting Tensile Strength (MPa)	Shear Strength Ultimate Load (MPa)
C _{0%} A _{0%}	39.77	4.15	1.158
C _{10%} A _{0%}	39.84	3.36	1.365
C _{20%} A _{0%}	35.53	3.11	1.086
C _{25%} A _{0%}	35.06	2.84	0.924
C _{30%} A _{0%}	34.73	2.736	0.81
Optimal Replacement Ratio of Cement by Glass is 10%			
C _{10%} A _{10%}	40.85	3.89	1.171
C _{10%} A _{15%}	37.75	4.3	1.012
C _{10%} A _{20%}	36.55	3.856	0.932

Where C is cement replacement and A is aggregate replacement.

The results demonstrate that moderate substitution ratios (10-20%) enhanced mechanical properties, which may be attributed to the filler effect and improved particle packing. However, higher ratios (25- 30%) showed a decline in strength due to weaker bonding between the recycled materials and the cement matrix. These trends align with findings by Sharma et al. [3] and Q. Chang et al. [5], who also reported performance reductions at higher waste content.

The results showed that using ceramic and glass at moderate replacement ratios (10% cement replacement

and 10% coarse aggregate replacement) resulted in a significant improvement in compressive and tensile strengths. This improvement is attributed to the filler effect and reduced porosity within the cement paste, as well as improved granular gradation due to the fine nature of the glass and ceramic particles.

However, when replacement ratios were increased to high levels, a gradual decline in mechanical properties was observed, due to the weak bond between the recycled materials and the cement paste.

The predicted empirical equations using IBM SPSS Statistics 30 software are listed in Table (7).

Table (7): Regression Models for Strength Properties Based on Replacement Materials.

Model NO	Replacement Type	Dependent Variable	Regression Equation	R ²	COV
1	Cement-Ceramic	Splitting Tensile Strength	$f_t = 0.464 \cdot \sqrt{f'_c} \dots \text{eq}(2)$	0.976	20.4%
2	Cement-Ceramic	Shear Strength	$V_u = 0.177 \cdot \sqrt{f'_c} \dots \text{eq}(3)$	0.979	16.5%
3	Cement-Glass	Splitting Tensile Strength	$f_t = 0.53 \cdot \sqrt{f'_c} \dots \text{eq}(4)$	0.934	18.7%
4	Cement-Glass	Shear Strength	$V_u = 0.178 \cdot \sqrt{f'_c} \dots \text{eq}(5)$	0.981	17.10%
5	Cement and Coarse Aggregate-Ceramic	Splitting Tensile Strength	$f_t = 0.619 \cdot \sqrt{f'_c} \dots \text{eq}(6)$	0.988	11.52%
6	Cement and Coarse Aggregate-Ceramic	Shear Strength	$V_u = 0.182 \cdot \sqrt{f'_c} \dots \text{eq}(7)$	0.975	20.61%
7	Cement and Coarse Aggregate-Glass	Splitting Tensile Strength	$f_t = 0.6 \cdot \sqrt{f'_c} \dots \text{eq}(8)$	0.995	8.20%
8	Cement and Coarse Aggregate-Glass	Shear Strength	$V_u = 0.175 \cdot \sqrt{f'_c} \dots \text{eq}(9)$	0.986	15.16%

The following tables (8) (9) (10) and (11) presents a summarized comparison of experimental and predicted values of tensile and shear strength for concrete ceramic and coarse aggregate replacement. It includes compressive strength, measured results, model predictions, and Exp./Pre. allowing evaluation of both material behavior and prediction accuracy across different replacement levels.

The COV values gave slightly high values. This dispersion is also caused by the small sample size, as a limited number of data increases the sensitivity of the results to natural fluctuations, which raises the apparent dispersion value.

Table (8): Experimental and Predicted Values of Replacement Cement by Ceramic.

Rep%	$\sqrt{f'c}$ (MPa)	Experimental Tensile Splitting Strength (MPa)	Predicted Tensile Splitting Strength from Analysis (MPa)	Exp/Pre.
0	6.3	4.15	2.92	1.41
10	5.96	2.25	2.76	0.81
20	6.17	3.26	2.86	1.13
25	5.96	2.42	2.76	0.87
30	5.87	2.28	2.72	0.83

Rep%	$\sqrt{f'c}$ (MPa)	Experimental Shear Strength (MPa)	Predicted Shear Strength from SPSS Analysis (MPa)	Exp/Pre.
0	6.3	1.15	1.11	1.03
10	5.96	1.00	1.05	0.95
20	6.17	1.39	1.09	1.27
25	5.96	0.91	1.05	0.86
30	5.87	0.74	1.04	0.71

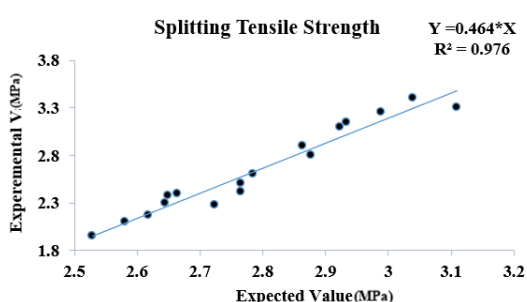


Fig (4) Experimental with Expected Splitting tensile strength

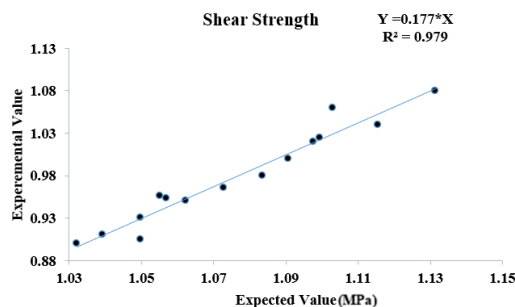


Fig (5) Experimental with Expected Shear strength

The graphs show a strong, statistically significant linear relationship. Figures (4) and (5) illustrate the relationship between the experimental and calculated values of concrete strength resulting from replacing part of the cement with ceramic. The results showed a strong linear relationship, with the ($R^2 = 0.976$ and 0.979), respectively.

Table (9): Experimental and Predicted Values of Replacement Cement by Glass.

Rep%	$\sqrt{f'c}$ (MPa)	Experimental Tensile Splitting Strength (MPa)	Predicted Tensile Splitting Strength from Analysis (MPa)	Exp/Pre.
0	6.29	4.15	3.33	1.24
10	6.3	3.36	3.34	1
20	5.95	3.11	3.15	0.98
25	5.91	2.84	3.13	0.9
30	5.89	2.73	3.12	0.87
Rep%	$\sqrt{f'c}$ (MPa)	Experimental Shear Strength (MPa)	Predicted Shear Strength from Analysis (MPa)	Exp/Pre.
0	6.3	1.15	1.12	1.02
10	5.96	1.36	1.13	1.2
20	6.17	1.08	1.06	1.01
25	5.96	0.92	1.05	0.87
30	5.89	0.81	1.05	0.77

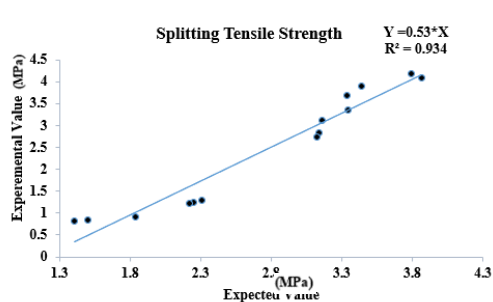


Fig (6) Experimental with Expected Splitting tensile strength

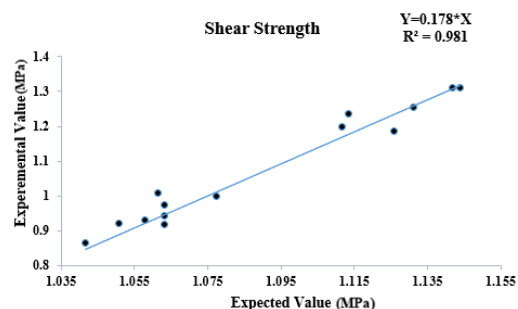


Fig (7) Experimental with Expected Shear strength

The graphs show a statistically significant linear relationship between the experimental and calculated concrete strengths when cement was replaced by glass waste, as shown in Figures (6) and (7). The regression line confirmed the suitability of the model through its good agreement with the experimental data, with the coefficient of determination ($R^2 = 0.934$ and 0.981), respectively.

Table (10): Experimental and Predicted Values of Replacement Cement and Coarse Aggregate by Ceramic

Rep%	$\sqrt{f'c}$ (MPa)	Experimental Tensile Splitting Strength (MPa)	Predicted Tensile Splitting Strength from Analysis (MPa)	Exp/Pre.
10	6.20	4.28	3.84	1.11
15	5.90	3.77	3.65	1.03
20	5.50	3.52	3.40	1.03
Rep%	$\sqrt{f'c}$ (MPa)	Experimental Shear Strength (MPa)	Predicted Shear Strength from Analysis (MPa)	Exp/Pre.
10	6.20	1.16	1.13	1.02
15	5.90	0.97	1.07	0.9
20	5.50	0.84	1.00	0.83

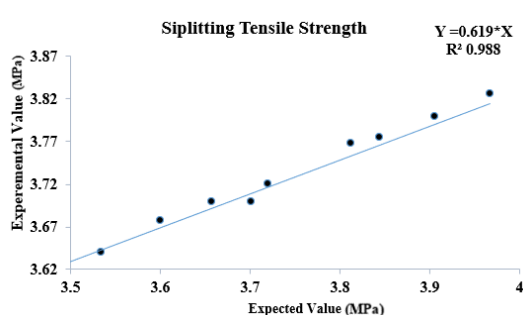


Fig (8) Experimental with Expected Splitting tensile strength

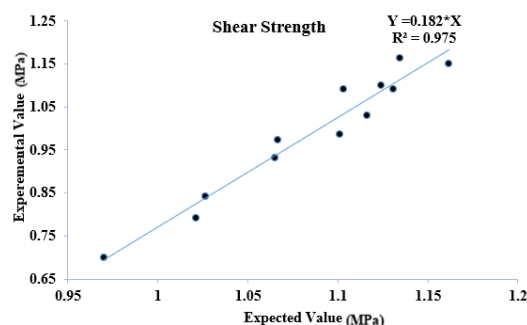


Fig (9) Experimental with Expected Shear strength

The plots show a strong linear correlation between the experimental values of concrete strength and the strength calculations when replacing coarse aggregate with ceramic, as shown in Figures (8) and (9). The high values of the coefficient of determination ($R^2 = 0.988$ and 0.975) indicate the accuracy of the model and its ability to reliably predict concrete strength.

Table (11): Experimental and Predicted Values of Replacement Cement and Coarse Aggregate by Glass.

Rep%	$\sqrt{f'c}$ (MPa)	Experimental Tensile Splitting Strength (MPa)	Predicted Tensile Splitting Strength from Analysis (MPa)	Exp/Pre.
10	6.39	3.89	3.83	1.01
15	6.14	4.3	3.68	1.16
20	6.04	3.85	3.62	1.06
Rep%	$\sqrt{f'c}$ (MPa)	Experimental Shear Strength (MPa)	Predicted Shear Strength from Analysis (MPa)	Exp/Pre.
10	6.39	1.17	1.12	1.04
15	6.14	1.01	1.07	0.94
20	6.04	0.93	1.05	0.88

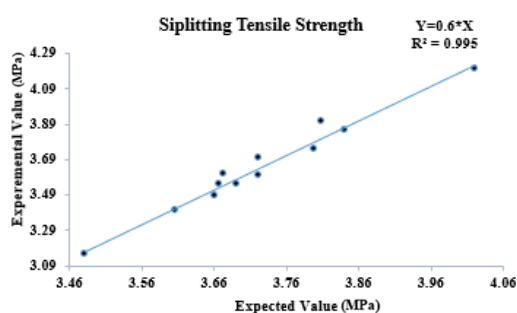


Fig (10) Experimental with Expected Splitting tensile strength

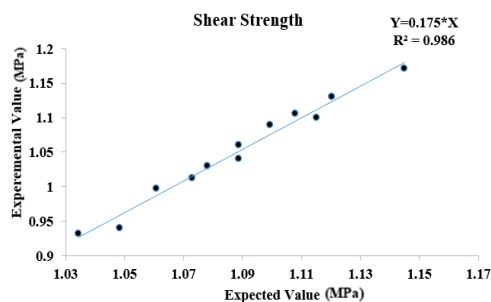


Fig (11) Experimental with Expected Shear strength

The plots indicate a strong linear correlation between the experimental values of concrete strength and the strength calculations when replacing the coarse aggregate with glass, as shown in Figures (10) and (11). The regression line that fits well with the data, with coefficient of determination ($R^2 = 0.995$ and 0.986), reflects the high ability of the model to accurately predict.

Regression analysis revealed strong and statistically significant correlations between compressive, tensile, and shear strengths, particularly in mixes containing ceramic waste. The highest coefficients of determination were observed in ceramic-modified mixes, indicating an exceptional level of prediction reliability. This improved performance can be attributed to the enhanced interface transition zone (ITZ) between the ceramic particles and the surrounding cement matrix, which contributes to improved stress transfer and mechanical integrity an explanation derived from the consistent trends observed in mechanical tests. In contrast, mixes containing glass waste particularly under double replacement conditions—showed slightly lower R^2 values. This can be linked to the inherent properties of glass particles, such as their angularity, brittleness, and dense surface texture, which can increase internal friction and limit adhesion to the cement matrix. The coefficient of variation (COV), which ranged from 8.2% to 20.65%, enhanced the stability of the models but was slightly high due to the small number of models used. This behavior emphasizes the critical role of optimizing replacement levels to maintain mechanical consistency and reduce performance variability in recycled concrete.

4. Conclusion

The results of this study demonstrate that recycled ceramic and glass waste can be effectively utilized in structural concrete, particularly when applied in optimal proportions. The regression models developed offer a highly accurate and practical tool for predicting tensile and shear strength, with clear statistical validity supported by high R^2 values and acceptable COV ranges

Ceramic-based mixes yielded superior consistency, highlighting their potential as a reliable alternative in sustainable mix designs. While glass-based mixes exhibited greater variability, they still provided valuable structural contributions, especially when used at moderate replacement levels. These findings emphasize that the mechanical behavior of sustainable concrete is highly dependent on both the type and proportion of recycled materials used

Importantly, the insights gained from this study are grounded in experimental evidence. Although microstructural testing was not performed, the mechanical behavior observed provides a sound basis for understanding the influence of recycled components on concrete performance.

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