

USE OF WASTE GLASS IN CONCRETE AS A SUSTAINABLE AGGREGATE REPLACEMENT

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Abstract

Using recycled glass as a fine aggregate substitute in concrete offers a sustainable solution for reducing environmental impact and promoting resource efficiency. This study explores the effects of partially replacing fine aggregate with crushed waste glass at 0%, 5%, 10%, 15%, and 20% by weight. Workability, compressive strength, split tensile strength, and durability were evaluated at curing periods of 7, 28, and 90 days. Results indicate that replacements up to 15% improve compressive and tensile strength, attributed to the pozzolanic activity of the glass particles. Beyond 15%, a strength reduction occurs, likely due to increased void content and the potential causes include increased void content, weaker particle bonding, or alkali-silica reaction (ASR) a reaction between reactive silica in glass and cement alkalis that can cause cracking. The decline in strength was determined from compressive strength tests at different curing ages. Workability increased with higher glass content due to the smooth surface and low absorption of glass. Durability tests showed enhanced resistance to environmental factors within the optimal replacement range. An ANOVA analysis confirmed the statistical significance of strength variations across replacement levels. Overall, incorporating up to 15% crushed waste glass as a fine aggregate is an effective, eco-friendly approach that maintains concrete performance while supporting sustainable construction practices.

Keywords: Durability; Glass powder; Strength; Workability

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Introduction

A key component of contemporary building, concrete is renowned for its strength, resilience to fire, and durability. However, because of the ecological effect and resource depletion, the traditional use of natural aggregates, such as river sand, raises serious environmental problems. Researchers have looked into using recycled glass as a sustainable substitute for conventional aggregates in concrete in order to address these problems. With an emphasis on workability, mechanical qualities, durability, and environmental sustainability, this literature review investigates the possibility of employing waste glass in place of fine and coarse aggregates in concrete.

The incorporation of waste glass in concrete has been shown to improve workability. Studies indicate that concrete mixes containing waste glass exhibit better flow and ease of handling compared to conventional mixes. This improvement is attributed to the flat surface texture of glass particles, which reduces internal friction within the mixture (Nodehi and Taghvaei, 2021; Subba *et al.*, 2023). Concrete fresh properties are further enhanced when finely crushed glass partially replaces fine aggregate, making the concrete easier to place and handle (Khan *et al.*, 2020).

Depending on the replacement level and particle size, waste glass has varying effects on the compressive strength of concrete. Previous studies have reported that pozzolanic reactions between glass particles and cementitious phases can improve compressive strength at low to moderate replacement levels (up to approximately 20%) (Ismail and Al-Hashmi, 2009; Hasan *et al.*, 2023). However, higher replacement levels may lead to strength reduction due to the lower crushing resistance of glass compared to natural aggregates and the potential occurrence of alkali-silica reaction (ASR) (Mohammadinia *et al.*, 2019; Bostanci, 2020).

Similar trends have been observed for the flexural and tensile strengths of concrete incorporating waste glass. Moderate replacement levels may enhance these mechanical properties, whereas excessive glass content can cause deterioration. It has also been demonstrated that the incorporation of metakaolin as a supplementary cementitious material can partially mitigate strength losses associated with higher glass contents, resulting in improved flexural and tensile performance (Qaidi *et al.*, 2022).

One of the primary concerns associated with using waste glass in concrete is the risk of alkali-

silica reaction (ASR), which can cause significant expansion and cracking. However, previous studies have demonstrated that finely crushed glass can help mitigate ASR expansion. For example, replacing fine aggregate with glass particles smaller than 1 mm has been shown to reduce ASR expansion by up to 66% (Lu *et al.*, 2019; Jamellodin *et al.*, 2022). In addition, the incorporation of pozzolanic materials, such as metakaolin, can further reduce the risk of ASR (Naik, 2008; Assi *et al.*, 2018).

Concrete mixes incorporating waste glass generally exhibit lower water permeability and absorption rates. This behavior is attributed to the dense packing and smooth surface of glass particles, which reduce the overall porosity of the concrete (De Brito and Kurda, 2021; Sandanayake *et al.*, 2020). Improved water resistance enhances concrete durability, making it more suitable for applications in harsh environmental conditions (Al-Mansour *et al.*, 2019; Srinivasan *et al.*, 2024).

The use of waste glass in concrete also contributes to environmental sustainability by reducing the demand for natural aggregates and diverting glass waste from landfills (Berodier *et al.*, 2019). Several studies have reported that incorporating waste glass can significantly reduce greenhouse gas emissions and energy consumption. For instance, partial replacement of cement and aggregates with glass has been shown to reduce CO₂ emissions by up to 19% and energy consumption by approximately 17% (Albarbary *et al.*, 2023; Parthasaarathi *et al.*, 2023). Furthermore, the production cost of concrete can be lowered through the use of waste glass, making it a cost-effective alternative (Annamalai *et al.*, 2025).

Despite the well-recognized benefits of using waste glass in concrete, further research is required to investigate specific applications and long-term performance. For example, recycled-glass-based pervious concrete pedestrian pavers have demonstrated promising strength and permeability characteristics (Arasu, 2023; Kumar *et al.*, 2024). Long-term studies are still necessary to evaluate the durability and functional performance of such applications under real service conditions (Jani and Hogland, 2014; Parthasaarathi *et al.*, 2024).

Overall, the use of recycled glass as a sustainable aggregate substitute in concrete offers several advantages, including improved workability, enhanced mechanical properties at moderate replacement levels, and increased durability (Qaidi *et al.*, 2022; Sajeev *et al.*, 2025). In addition, natural rubber latex (NRL) modified concrete incorporating 10-20% bottom ash has been

shown to improve strength and microstructure at an optimal NRL dosage of 1.0%, providing a sustainable high-performance alternative for rigid pavements (Kantatham *et al.*, 2024). Similarly, the incorporation of 0.5% hemp fiber has been reported as optimal for enhancing ductility, fatigue life, and sustainability of concrete using natural or recycled aggregates in pavement applications (Hoy *et al.*, 2024a). Recent studies have also highlighted innovative sustainable pavement solutions using recycled materials, demonstrating improved performance, environmental benefits, and practical potential to replace virgin aggregates in road construction (Hoy *et al.*, 2024b).

By reducing greenhouse gas emissions and resource consumption, the use of waste glass promotes environmental sustainability. Nevertheless, replacement levels and particle sizes must be carefully controlled to minimize potential issues such as ASR. Overall, incorporating waste glass into concrete production can support the transition of the construction sector toward more sustainable practices, resource conservation, and the principles of the circular economy.

Materials and Methods

The cement used has a specific gravity of 3.15, which is typical for Ordinary Portland Cement (OPC). Its fineness is 260 m²/kg, exceeding the minimum requirement of 225 m²/kg, ensuring better hydration and strength development. The standard consistency is 30%, falling within the acceptable range of 25-35%, indicating good workability. The initial setting time is 40 minutes, which is above the minimum limit of 30 minutes, allowing adequate time for handling and placement. The final setting time is 270 minutes, well within the maximum limit of 600 minutes, ensuring timely hardening without compromising construction schedules.

The physical properties of fine aggregate (FA), coarse aggregate (CA), and waste glass powder (WGP) highlight their suitability for specific applications in construction materials. The specific gravity of FA and CA is 2.7, indicating their dense composition, while WGP is comparatively lighter at 2.44. This variation in specific gravity influences the overall weight and density of the concrete mix. The fineness modulus, which indicates particle size distribution, is 2.8 for FA, 7.21 for CA, and 1.3 for WGP, showcasing the fine nature of WGP compared to the coarser CA. This fine texture of WGP contributes to improved packing density and reactivity when used as a partial replacement material.

Water absorption is another crucial property affecting workability and durability. FA has a water absorption rate of 2.5%, CA is lower at 0.6%, and WGP is relatively high at 8.8%, reflecting its porous nature. The shape of CA is angular, which enhances interlocking and strength in concrete, while FA and WGP do not exhibit defined shapes. Additionally, the surface area of WGP is significantly high at 2120 cm²/g, promoting its pozzolanic reactivity and contributing to the concrete's strength and durability.

Methodology and Mix Proposition

This study employed an experimental approach to evaluate the impact of using crushed waste glass as a partial replacement for fine aggregate in concrete. Fine aggregate was replaced with waste glass at varying levels (0%, 5%, 10%, 15%, and 20% by weight) to determine the optimal replacement ratio. Concrete mixes were prepared in accordance with relevant standards, maintaining consistent water-cement ratios to ensure comparability. Standard procedures were followed to assess key properties, including workability (slump test), compressive strength, split tensile strength, and durability. Specimens were cast in molds, cured under controlled conditions, and tested at specific intervals (7, 28, and 90 days). The pozzolanic activity of glass particles was examined through strength development trends across different curing periods. Durability was assessed by exposing the concrete to simulated environmental conditions, such as sulfate attack and chloride penetration tests, to evaluate resistance to degradation.

To ensure the statistical reliability of the results, an Analysis of Variance (ANOVA) was conducted. This method analyzed the significance of variations in strength parameters across different replacement levels, enabling a robust interpretation of the findings. The potential for alkali-silica reaction (ASR) was also monitored to identify any adverse effects at higher replacement levels. Observations revealed that replacement levels up to 15% enhanced strength and durability due to the pozzolanic reaction of glass particles. Beyond this threshold, increased void ratios and ASR potential negatively impacted performance. This methodology highlights a sustainable approach to concrete production, offering insights into waste management practices while preserving structural integrity. Table 1 shows the mix proposition of various mix.

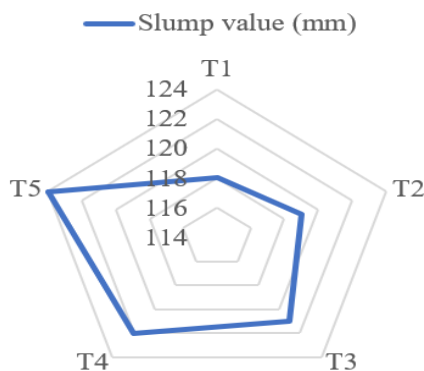
Table 1. Mix Proposition

S. No.	Mix	Designation
1	T1	Conventional Concrete
2	T2	95% Fine Aggregate + 5% Crushed Waste Glass
3	T3	90% Fine Aggregate + 10% Crushed Waste Glass
4	T4	85% Fine Aggregate + 15% Crushed Waste Glass
5	T5	80% Fine Aggregate + 20% Crushed Waste Glass

Results and Discussion

Slump Cone Test

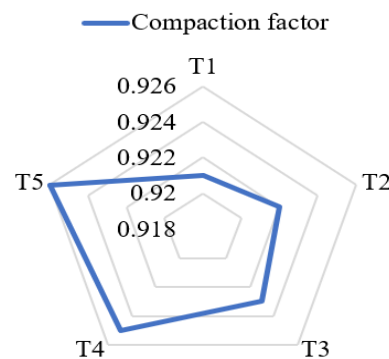
Higher percentages of crushed waste glass as a partial substitute for fine aggregate improve workability, according to the findings of the slump test. While mixes T2, T3, T4, and T5 showed progressive improvements to 119 mm, 121 mm, 122 mm, and 124 mm, respectively, conventional concrete (T1) showed a slump value of 118 mm. Because the crushed waste glass particles had a smooth, non-porous surface, there was less internal friction in the mixture, which improved workability. This trend suggests that incorporating waste glass up to 20% by weight positively impacts the flowability of fresh concrete. However, while higher glass content improves workability, other properties like strength and durability must be considered to ensure structural integrity. A thorough grasp of the performance limitations of waste glass in concrete will be possible through further investigations of compressive and tensile strength as well as durability assessments. The findings of the slump cone test are displayed in Figure 1.

**Figure 1. Slump cone test results**

Compaction Factor Test

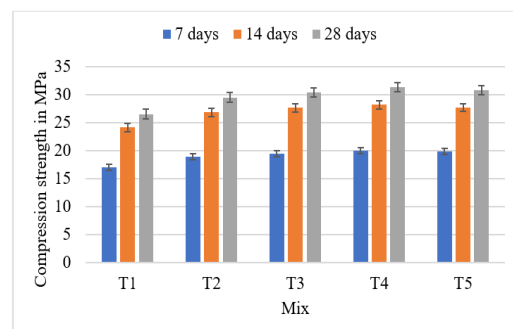
The compaction factor results reveal a slight yet consistent improvement in workability with increasing crushed waste glass (CWG) content. Conventional concrete (T1) exhibited a compaction

factor of 0.921, while T5, incorporating 20% CWG, achieved the highest value of 0.926. The incremental increase across mixes, from T2 (0.922) to T4 (0.925), suggests that CWG enhances the mix's cohesiveness and ease of compaction due to its particle characteristics. These results confirm that CWG is an effective partial fine aggregate replacement, contributing to better workability while maintaining the structural integrity of concrete. Figure 2 shows the compaction test results.

**Figure 2. Compaction test results**

Compressive Strength Test

The compressive strength results show an improvement with the addition of crushed waste glass (CWG) up to 15%. At 28 days, conventional concrete (T1) achieved 26.47 MPa, while T4, with 15% CWG, exhibited the highest strength at 31.30 MPa a 18.3% increase. Mixes T2 (29.46 MPa) and T3 (30.35 MPa) also showed notable improvements, demonstrating CWG's positive impact on strength development. However, a slight reduction is observed for T5 (30.75 MPa), suggesting that excessive CWG may lead to reduced bonding or microstructural inefficiencies. These findings highlight 15% CWG as an optimal replacement for enhancing compressive strength in concrete. Figure 3 shows the compressive strength test results.

**Figure 3. Compressive strength test results**

Split Tensile Strength Test

The split tensile strength results reveal an improvement with increasing crushed waste glass (CWG) content up to 15%. At 28 days, conventional concrete (T1) exhibited a tensile strength of 1.74 MPa, while T4, with 15% CWG, achieved the highest value of 2.06 MPa, marking an 18.4% increase. Mixes T2 (1.93 MPa) and T3 (1.99 MPa) also displayed enhanced performance, indicating CWG's contribution to better tensile strength due to improved particle packing and microstructural integrity. T5 (2.04 MPa) showed a marginal decrease, suggesting diminishing returns beyond 15% CWG. These results recommend 15% CWG for optimal tensile strength in concrete. Figure 4 shows the split tensile strength test results.

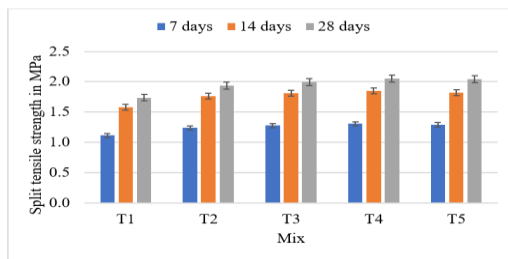


Figure 4. Split tensile strength test results

Flexural Strength

The flexural strength results indicate an enhancement with increased crushed waste glass (CWG) content up to 15%. At 28 days, T4, with 15% CWG, recorded the highest flexural strength of 2.83 MPa, representing an 18.4% improvement compared to conventional concrete (T1) at 2.39 MPa. Mixes T2 (2.66 MPa) and T3 (2.74 MPa) also exhibited significant gains, suggesting better distribution of stresses due to CWG's angularity and improved bonding. T5 (2.81 MPa) showed a slight decrease, indicating that higher CWG proportions may reduce structural efficiency. These findings highlight 15% CWG as optimal for enhancing flexural strength in concrete. Figure 5 shows the flexural strength test results.

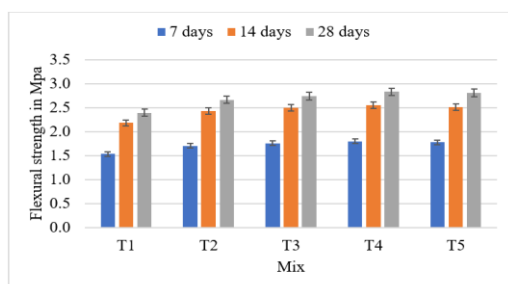


Figure 5. Flexural strength test results

The permeability results indicate a general decrease with the inclusion of crushed waste glass (CWG), improving the concrete's resistance to water ingress. Conventional concrete (T1) exhibited the highest permeability at all ages (0.057, 0.053, and 0.049×10^{-6} mm/sec at 28, 56, and 90 days, respectively). Mixes with CWG, such as T3, demonstrated the lowest permeability at 90 days (0.047×10^{-6} mm/sec), suggesting enhanced pore refinement due to CWG's contribution to densification. However, mixes T4 and T5 showed similar permeability values (0.054 to 0.048×10^{-6} mm/sec), indicating that beyond 15% CWG, improvements plateau. These findings confirm CWG's effectiveness in reducing permeability. Figure 6 shows the permeability test results.

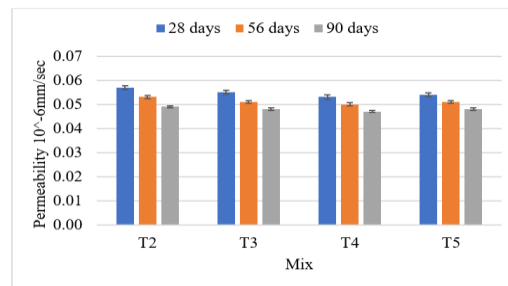


Figure 6. Permeability test results

Sorptivity Test

The permeability results reveal a consistent reduction with increasing crushed waste glass (CWG) content up to 15%. Conventional concrete (T1) exhibited higher permeability values, while T4, with 15% CWG, achieved the lowest permeability at 28, 56, and 90 days (0.053, 0.050, and 0.047×10^{-6} mm/sec, respectively). This indicates enhanced densification and reduced void content due to CWG's packing efficiency. T2 and T3 also showed reductions in permeability compared to T1, while T5 demonstrated marginally higher values than T4, suggesting excessive CWG may slightly compromise uniformity. Overall, 15% CWG optimally improves permeability, supporting its use in durable concrete. Figure 7 shows the sorptivity test results.

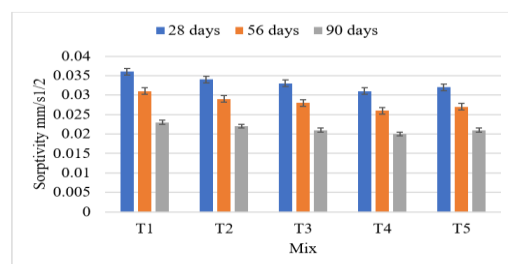


Figure 7. Sorptivity test results

Numerical Approach

Slump Cone Test

Table 2 shows the ANOVA of slump cone test results. The slump cone test results show a modest increase in slump values across the five tested mixes (rows), ranging from 118 mm to 124 mm. The average slump value is 120.8 mm, with a variance of 5.7, indicating consistent workability and a uniform distribution of mix characteristics. The two-factor ANOVA without replication reveals no statistically significant differences across rows or columns. The F-value for rows (1.00) is well below the critical F-value (6.388), and the p-value (0.5) confirms that the variation is not significant at common confidence levels. Similarly, the column effect is also not significant, with an F-value of 0.561 and a p-value of 0.495. These findings suggest that variations in slump among mixes are minor and likely due to random error rather than systematic differences. The absence of significant interaction or error effects further supports the consistency and homogeneity of the tested concrete mixes. In conclusion, the slump test and ANOVA results jointly indicate stable workability across the samples, validating the reliability of the mix design and experimental conditions.

Compaction Factor Test

Table 3 shows the ANOVA of compaction factor test results. The compaction factor test results indicate a stable range of values across the five tested mixes, reflecting consistent workability and

cohesive behavior. The slight differences observed among the rows suggest minimal variability in mix uniformity. The two-factor ANOVA without replication was conducted to assess the statistical significance of variation between the mixes (rows) and the effect of the test factor (columns). The row factor yielded an F-value of 1.0, which is well below the critical F-value of 6.388. The corresponding p-value of 0.5 confirms that the differences between mixes are not statistically significant, indicating consistent performance across all samples. In contrast, the column factor showed a highly significant effect, with an F-value of 6822.744 far exceeding the critical value of 7.708. The extremely low p-value (1.29E-07) highlights a statistically significant impact of the tested variable on compaction factor results-implying that the influencing factor (e.g., CWG content or admixture type) played a dominant role. The very low error term (SS = 8.6E-06) suggests that the test was well-controlled, and external variability was minimal. The compaction factor results demonstrate good consistency across different mixes, while the ANOVA analysis confirms that the column variable had a highly significant influence on the compaction behavior of the concrete. This supports the reliability of the test and the sensitivity of the compaction factor to the specific variable under study.

Compressive Strength Test

Table 4 shows the ANOVA of compressive strength test results. The compressive strength results show a progressive increase in average

Table 2. ANOVA of Slump cone test results

Source of Variation	SS	df	MS	F	P-value	F crit
Rows	11.4	4	2.85	1	0.5	6.388233
Columns	1.6	1	1.6	0.561404	0.495354	7.708647
Error	11.4	4	2.85			
Total	24.4	9				

Table 3. ANOVA of Compaction test results

Source of Variation	SS	df	MS	F	P-value	F crit
Rows	8.6E-06	4	2.15E-06	1	0.5	6.388233
Columns	0.014669	1	0.014669	6822.744	1.29E-07	7.708647
Error	8.6E-06	4	2.15E-06			
Total	0.014686	9				

Table 4. ANOVA of Compressive strength test results

Source of Variation	SS	df	MS	F	P-value	F crit
Rows	29.90876	4	7.47719	56.50383	6.64E-06	3.837853
Columns	307.1016	2	153.5508	1160.357	1.39E-10	4.45897
Error	1.058645	8	0.132331			
Total	338.069	14				

values across rows, ranging from 22.499 MPa to 26.454 MPa, with variances spanning from 24.59 to 34.62, reflecting differences in the mixes' strength properties. Across columns, the average compressive strengths vary from 18.98 MPa to 29.66 MPa, with variances indicating consistent increases in strength. The ANOVA analysis highlights statistically significant variations both across rows and columns. The row effect ($SS = 29.91$, $F = 56.50$, $P = 6.64 \times 10^{-66.64} \times 10^{-6}$) confirms notable differences in compressive strength due to variations in mix formulations. The column effect ($SS = 307.10$, $F = 1160.36$, $P = 1.39 \times 10^{-101.39} \times 10^{-10}$) suggests that different test conditions or mix components strongly influence the compressive strength. Minimal error ($SS = 1.06$) emphasizes reliable experimental control. In conclusion, the results demonstrate that mix compositions and experimental setups significantly impact compressive strength, with high statistical confidence supporting the observed trends.

Split Tensile Strength Test

Table 5 shows the ANOVA of split tensile strength test results. The split tensile strength results demonstrate a consistent increase in average values across rows, ranging from 1.477 MPa to 1.738 MPa, with variances between 0.106 and 0.149. This trend suggests a gradual improvement in tensile performance across the mixes. In terms of columns, the average values range from 1.245 MPa to 1.952 MPa, with relatively low variances, indicating uniformity in testing conditions. The ANOVA results reveal statistically significant variations both across rows and columns. The row effect ($SS = 0.131$, $F = 47.74$, $P = 1.27 \times 10^{-51.27} \times 10^{-5}$) highlights differences in tensile strength due to varying mix formulations. The column effect ($SS = 1.344$, $F = 979.75$, $P = 2.73 \times 10^{-102.73} \times 10^{-10}$) underscores the

strong influence of testing parameters or specific material combinations on tensile strength. The minimal error ($SS = 0.0055$) indicates robust experimental consistency. In conclusion, the findings confirm that both mix composition and testing parameters significantly impact split tensile strength, with high statistical reliability supporting the observed trends. This emphasizes the importance of precise control over material proportions and test conditions.

Flexural Strength

Table 6 shows the ANOVA of flexural strength test results. The flexural strength test results show a steady increase in average strength values across rows, ranging from 2.033 MPa to 2.390 MPa, with variances between 0.201 and 0.283, indicating consistent improvement in flexural performance with varying mix compositions. Across columns, the average values range from 1.712 MPa to 2.686 MPa, with low variances, suggesting stable testing conditions. The ANOVA analysis reveals statistically significant variations for both rows and columns. The row effect ($SS = 0.248$, $F = 47.74$, $P = 1.27 \times 10^{-51.27} \times 10^{-5}$) confirms notable differences in flexural strength due to variations in mix formulations. The column effect ($SS = 2.544$, $F = 979.75$, $P = 2.73 \times 10^{-102.73} \times 10^{-10}$) highlights the substantial influence of test conditions or material properties on the results. Minimal error ($SS = 0.010$) underscores the consistency of the experimental setup. In summary, the observed trends and significant statistical findings suggest that both material composition and testing parameters play critical roles in determining flexural strength. The results emphasize the importance of optimizing mix designs and maintaining precise control during testing to achieve consistent and reliable performance.

Table 5. ANOVA of Split tensile strength test results

Source of Variation	SS	df	MS	F	P-value	F crit
Rows	0.131006	4	0.032752	47.73764	1.27E-05	3.837853
Columns	1.34437	2	0.672185	979.7546	2.73E-10	4.45897
Error	0.005489	8	0.000686			
Total	1.480865	14				

Table 6. ANOVA of Flexural strength test results

Source of Variation	SS	df	MS	F	P-value	F crit
Rows	0.247913	4	0.061978	47.73764	1.27E-05	3.837853
Columns	2.544051	2	1.272026	979.7546	2.73E-10	4.45897
Error	0.010386	8	0.001298			
Total	2.802351	14				

Permeability Test

Table 7 shows the ANOVA of permeability test results. The permeability test results indicate slight variations in average permeability values across rows, ranging from 0.050 to 0.053, with very low variances (1.23×10^{-5} to 1.6×10^{-5}). This suggests uniformity in the permeability characteristics of the tested materials. Across columns, the averages decrease from 0.0546 to 0.048, with variances consistently low, reflecting controlled testing conditions. The ANOVA analysis reveals statistically significant differences across both rows and columns. The row effect ($SS = 1.43 \times 10^{-5}$, $F = 16.46$, $P = 0.00063$) indicates variations in permeability attributable to material differences. The column effect ($SS = 1.09 \times 10^{-4}$, $F = 251.38$, $P = 6.02 \times 10^{-8}$) highlights a substantial influence of testing conditions or other factors on the permeability results. Minimal error ($SS = 1.73 \times 10^{-6}$) demonstrates high experimental precision. In summary, the permeability results show strong consistency with statistically significant influences from material composition and testing conditions. These findings underscore the importance of optimizing mix properties to achieve desired permeability while maintaining tight control over experimental parameters.

Sorptivity Test

Table 8 shows the ANOVA of sorptivity test results. The sorptivity test results show a decreasing trend in average values across rows, ranging from 0.030 to 0.0257, with variances between 3.03×10^{-5} and 4.3×10^{-5} . These results suggest a gradual improvement in the material's resistance to capillary water absorption. Across columns, the

averages vary from 0.0332 to 0.0214, with consistently low variances, indicating controlled testing conditions. The ANOVA analysis reveals statistically significant differences both across rows and columns. The row effect ($SS = 3.29 \times 10^{-5}$, $F = 35.29$, $P = 3.96 \times 10^{-5}$) highlights meaningful variations in sorptivity due to differences in mix compositions. The column effect ($SS = 3.51 \times 10^{-4}$, $F = 751.71$, $P = 7.85 \times 10^{-10}$) indicates a strong influence of experimental conditions or other factors on sorptivity. The minimal error ($SS = 1.87 \times 10^{-6}$) underscores the precision of the experimental setup. In conclusion, the results indicate that both material composition and testing conditions significantly affect sorptivity. The findings confirm that optimized material properties lead to reduced sorptivity, enhancing the durability of the mixes. The statistical analysis validates the reliability of the observed trends with high confidence.

Conclusion

The results from the various concrete mixes incorporating crushed waste glass as a partial replacement for fine aggregate demonstrate promising improvements in mechanical properties and durability. Mixes T2 to T5, which gradually increase the percentage of crushed waste glass, show enhanced compressive, split tensile, and flexural strength compared to the conventional concrete (T1), especially at 28 days.

In particular, mix T4 (85% Fine Aggregate + 15% Crushed Waste Glass) exhibited the highest compressive strength at 28 days (31.30 MPa), and also showed improvements in split tensile and flexural strengths. Additionally, the inclusion of

Table 7. ANOVA of Permeability test results

Source of Variation	SS	df	MS	F	P-value	F crit
Rows	1.43E-05	4	3.57E-06	16.46154	0.000629	3.837853
Columns	0.000109	2	5.45E-05	251.3846	6.02E-08	4.45897
Error	1.73E-06	8	2.17E-07			
Total	0.000125	14				

Table 8. ANOVA of Sorptivity test results

Source of Variation	SS	df	MS	F	P-value	F crit
Rows	3.29E-05	4	8.23E-06	35.28571	3.96E-05	3.837853
Columns	0.000351	2	0.000175	751.7143	7.85E-10	4.45897
Error	1.87E-06	8	2.33E-07			
Total	0.000386	14				

crushed waste glass positively impacted permeability and sorptivity, with values progressively improving as the percentage of waste glass increased, indicating a reduction in water absorption and better durability.

The analysis of sorptivity test results highlights the significant influence of both material composition and testing conditions on the water absorption behavior of the tested materials. Variations in mix designs were found to play a crucial role, as evidenced by the statistically significant differences in sorptivity across rows, with an F-value of 35.29 ($P = 3.96 \times 10^{-53.96} \times 10^{-5}$). Additionally, testing conditions showed an even greater impact, demonstrated by a column F-value of 751.71 ($P = 7.85 \times 10^{-107.85} \times 10^{-10}$).

The minimal error variance underscores the reliability and precision of the experimental setup. These findings emphasize the importance of optimizing mix proportions and maintaining consistent testing protocols to improve the durability and water resistance of materials. The results validate that reducing sorptivity through tailored material compositions can significantly enhance the lifespan of construction materials exposed to moisture, making this a vital consideration in sustainable construction practices.

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