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Research Article

Predicting the mechanical properties of concrete from waste glass through the use of boost and random forest

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Abstract

This study explores the partial replacement of cement with waste glass powder (WGP) in M25 and M30 grade concrete, ranging from 0% to 20% in 2.5% increments. The mechanical properties assessed include compressive, flexural, and split tensile strengths, as well as predictive modeling using Boost and Random Forest. The optimum performance was observed at 10% WGP replacement, where compressive strength reached 30 MPa for M25 and 35 MPa for M30 after 28 days. Strength declined beyond this point due to cement dilution and possible alkali-silica reaction effects. Flexural and split tensile strengths followed a similar trend, with maximum values recorded at 20% replacement. Slump values dropped from 75 mm to 55 mm for M25 and 53 mm for M30, mainly due to the angular shape and non-absorbent nature of WGP, which reduces workability. A small density reduction of about 2.5% was also noted. Linear regression showed strong correlations between curing time and strength, with R^2 values of 0.9631 (3 days), 0.8352 (7 days), and 0.8808 (28 days). Negative R^2 values indicate the XGBoost performed worse than predicting the mean. This behavior was mostly observed for early-age data and is likely due to limited variability and sample size. It also highlighted that Random Forest consistently outperformed XGBoost, especially for 28-day strengths, with positive and moderate-to-high R^2 scores.

1. Introduction

The addition of waste glass (WG) as a partial replacement in concrete has become a growing area of research due to increasing environmental concerns and the need for sustainable construction practices. Numerous studies have investigated the feasibility of using waste glass as a replacement for cement or fine aggregate in concrete, mentioning benefits such as improved mechanical properties, lower carbon emissions, and effective waste management [1-2].

Incorporating WG in concrete can positively influence compressive strength at lower replacement levels. Researchers have reported increased compressive strength when WG replaces fine aggregates up to 10% due to the pozzolanic reaction of finely ground glass particles that produce additional calcium-silicate-hydrate (C-S-H) gel [3-5]. However, higher percentages often result in strength reduction due to the smooth, non-porous surface of glass, which weakens the bond between the paste and aggregate [6-13]. Demonstrated that waste glass could effectively replace fine aggregate up to a certain threshold without compromising concrete performance [4].

Flexural strength tends to improve marginally at lower WG content but shows a decline beyond the optimum threshold. The angularity and size of glass particles significantly affect this behavior [9-11, 14-15]. Noted improve; though compressive strength might improve; flexural and tensile strengths are more sensitive to the brittle nature of glass. Similarly, split tensile strength has been observed to decrease with increased WG content due to the brittle nature of glass [13, 16]. From a

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durability perspective, WG enhances resistance to chemical attacks and reduces water absorption, contributing to a denser concrete matrix [17-20]. Nonetheless, there is a risk of alkali-silica reaction (ASR), particularly at high glass content, which can cause expansion and cracking unless mitigated with supplementary cementitious materials like fly ash or silica fume [21-22]. The addition of mineral admixtures such as fly ash is reported to counteract ASR effectively and enhance the long-term durability of concrete incorporating WG [23].

Workability is influenced by the texture and shape of glass particles, requiring adjustments in water content or the use of superplasticizers to maintain slump values within acceptable limits [24-25]. Studies by [26-27] highlight that at higher replacement levels there may be a decline in workability due to the angular shape of glass particles, which can increase internal friction within the mix. The mechanical properties of M25 and M30 concrete containing WG have been extensively evaluated, and the optimal replacement level is generally between 10% to 20%, depending on the particle size and desired performance characteristics [28-29]. These findings indicate that WG can be effectively utilized in structural-grade concrete without compromising essential mechanical and durability parameters. The use of WG in concrete aligns with principles of sustainable construction by minimizing landfill disposal and reducing the consumption of virgin raw materials. It also contributes to the circular economy by converting waste into a valuable construction resource [30-31]. Overall, the literature supports the potential of WG as a viable material in producing environmentally friendly concrete, particularly in M25 and M30 grades [32-42].

Table 1. Mix design of M25 and M30 grade concrete [61-62]

<table>
<tr><th>Grade</th><th>WG %</th><th>Cement (kg/m^3)</th><th>WG (kg/m^3)</th><th>Water (kg/m^3)</th><th>Fine Agg. (kg/m^3)</th><th>Coarse Agg. (kg/m^3)</th></tr>
<tr><td rowspan="9">M25</td><td>0</td><td>395</td><td>0</td><td rowspan="18">186</td><td rowspan="9">713</td><td rowspan="9">1200</td></tr>
<tr><td>2.5</td><td>385.1</td><td>9.9</td></tr>
<tr><td>5</td><td>375.3</td><td>19.8</td></tr>
<tr><td>7.5</td><td>365.6</td><td>29.6</td></tr>
<tr><td>10</td><td>355.5</td><td>39.5</td></tr>
<tr><td>12.5</td><td>345.6</td><td>49.4</td></tr>
<tr><td>15</td><td>335.8</td><td>59.3</td></tr>
<tr><td>17.5</td><td>326.1</td><td>69.1</td></tr>
<tr><td>20</td><td>316.0</td><td>79.0</td></tr>
<tr><td rowspan="9">M30</td><td>0</td><td>410</td><td>0</td><td rowspan="9">680</td><td rowspan="9">1250</td></tr>
<tr><td>2.5</td><td>399.8</td><td>10.2</td></tr>
<tr><td>5</td><td>389.5</td><td>20.5</td></tr>
<tr><td>7.5</td><td>379.3</td><td>30.8</td></tr>
<tr><td>10</td><td>369.0</td><td>41.0</td></tr>
<tr><td>12.5</td><td>358.8</td><td>51.2</td></tr>
<tr><td>15</td><td>348.5</td><td>61.5</td></tr>
<tr><td>17.5</td><td>338.3</td><td>71.8</td></tr>
<tr><td>20</td><td>328.0</td><td>82.0</td></tr>
</table>

Machine learning (ML) techniques have gained wide application in civil engineering, particularly for predicting the mechanical behavior of concrete containing supplementary materials such as waste glass (WG), fly ash, or slag. These methods offer a significant advantage over traditional analytical approaches, which often struggle with the complex, nonlinear, and multidimensional interactions inherent in concrete mix compositions [43-44]. Artificial Neural Networks (ANN) have shown high accuracy in predicting compressive strength using input parameters such as cement content, WG percentage, and curing age [45]. Support Vector Machines (SVM) and Random Forest (RF) algorithms have demonstrated robustness and precision for flexural and tensile strength estimations [46-49]. Ensemble models like Gradient Boosting and Boost outperform single learners by effectively handling noise and heterogeneity in datasets, especially when incorporating recycled glass materials [50]. Hybrid approaches, such as Genetic Algorithm–ANN and fuzzy-based models, enhance optimization and adaptability [51-52]. ML reduces reliance on physical testing, improving efficiency, cost-effectiveness, and enabling rapid design iterations [53-57]. These innovations support sustainable practices and accelerate the adoption of glass waste in concrete production.

This study proposes the use of waste glass (WG) as partial replacement to cement and to find the optimum utilization of WG as sustainable and green concrete. The cement is replaced with WG from 0% to 20% by 2.5% increment in each mix. There are a total of eighteen mixes for M25 and M30 grade concrete with 486 concrete specimens were casted and tested. The compressive, flexural, and tensile strengths of concrete with waste glass were predicted using XGBoost and Random Forest. These two algorithms have been widely reported as among the most effective and accurate machine learning techniques for regression tasks in concrete-related applications [48-60], particularly due to their ability to handle nonlinear relationships and complex feature interactions.

2. Materials and Methodology

Ordinary Portland cement 53 (OPC-53) grade confirming to IS: 8112-1989 was used. The physical properties of cement were tested according to IS 4031-1988, where the consistency, initial setting time, final setting time & specific gravity were 32%, 26min, 191min, 3% & 3.10 respectively. Fine aggregate (FA) as river sand passing through 4.75mm sieve was used. All the physical properties of FA were evaluated using IS 2386 (part-1)-1963. Specific gravity, sieve Analysis/fineness modulus (IS: 383–1970), and water absorption was 2.63, 2.45 & 1.95 respectively.

Table 2. Physical Properties of the materials

Properties	Cement	Fine Aggregate (FA)	Coarse Aggregate (CA)	Waste Glass (WG)
Specific gravity	3.10	2.63	2.74	2.25
Water absorption (%)	8%	1.95	0.75	0.70
Fineness modulus	-	2.45	8.35	3.46
Maximum particle size (mm)	50 µm	4.75	20	90µ
Density	1.45 g/cm^3	2400-2900 kg/m^3	1200-1450 kg/m^3	1600-1700 kg/m^3

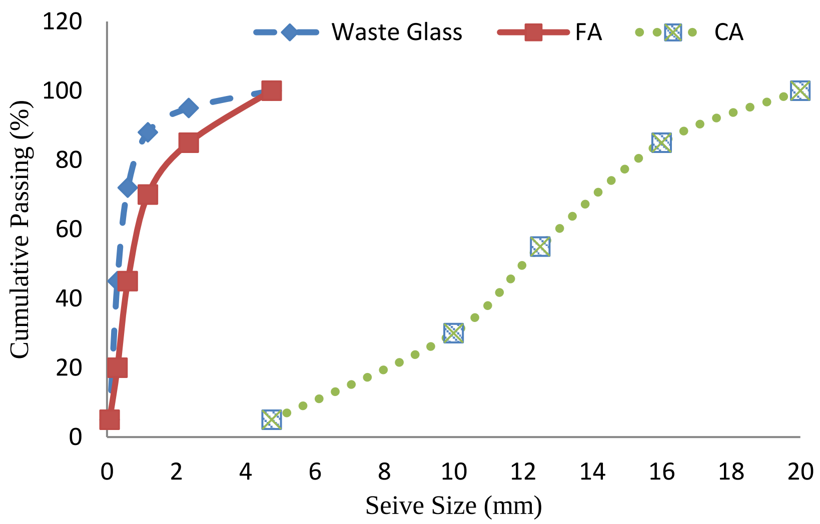


Fig. 1. Sieve Analysis of WG, FA and CA

The waste glass is collected from the local glass manufacturing vendor and the waste pieces of glass were collected, crushed in the loss Angeles apparatus in transportation lab then sieved with 90µ sieve and used as partial replacement with cement. The physical properties of WG and CA are given in Table 2. The sieve analysis of all the three materials i.e., WG, FA and CA is given in fig 1. The mix design of concrete for M25 and M30 was according to IS: 456-200 and IS: 10262-2019. The different experiments conducted are density of concrete cube, workability, compressive strength, flexural strength, and split tensile strength for M25 and M30 grade concrete. The experimental results of strength are predicted using XG Boosting and Random Forest, which are the best machine learning techniques. No chemical admixtures were added during testing; however, to meet modern casting requirements, especially at higher WGP contents, suitable dosage of superplasticizers should be optimized.

2.1. Machine Learning Models

In our study, we followed standard supervised learning practice by splitting the dataset into: 80% for training, and 20% for testing. The split was done randomly using a fixed random seed to ensure reproducibility and to avoid any form of data leakage. To ensure the robustness and generalization ability of the model, we performed k-fold cross-validation (specifically, 3-fold) during model training and evaluation. This means the dataset was divided into 3 subsets, and the model was trained and tested 3 times, each time using a different fold as the test set and the remaining as the training set. The R^2 values reported are the average results across all 3 folds, not just on the training data.

3. Results and Discussion

3.1 Different Test on M25 Grade Concrete

3.1.1 Density of Concrete

The fig 2 illustrates the average weight of 150 mm concrete cubes cured at 3, 7, and 28 days, with cement partially replaced by WG in increments ranging from 0% to 20%. A consistent decline in the average weight is observed with increasing WG content across all curing periods. This trend can be attributed to the lower specific gravity of waste glass compared to cement, which results in a reduction in the overall density of the concrete mix [7]. The 28 day cured samples consistently show slightly higher weights than those cured for 3 and 7 days, suggesting continued hydration and matrix densification over time [5]. The maximum reduction of 2.47% in density of M25 grade concrete is observed at 20% WG with cement. A linear reduction in average weight of concrete cubes is observed in all percentages of WG in concrete. The weight reduction even till 20% of WG in concrete is in acceptable limits.

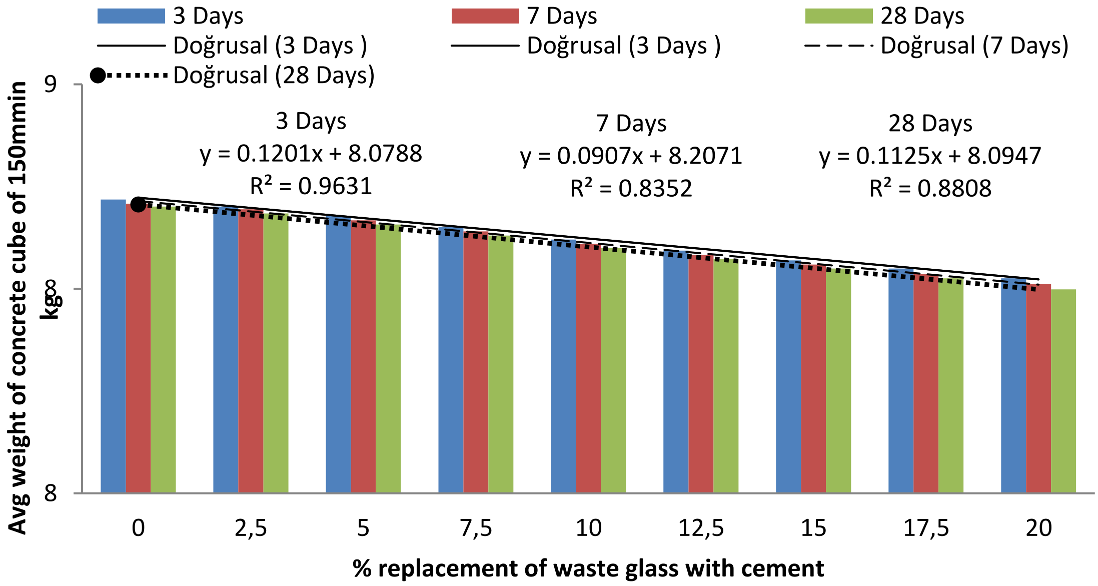


Fig. 2. Average weight of concrete with partial replacement of WG with cement

The linear regression analysis confirms the decreasing trend, with high R^2 values for 3 days as 0.9631, 7 days as 0.8352), and 28 days as 0.8808, indicating strong linear correlations. These values reflect the predictability of weight loss as waste glass content increases. The results align with previous studies which report that while waste glass incorporation reduces density, it does not significantly hinder hydration or curing, making it a feasible and environmentally beneficial partial replacement material in concrete [6,14,25]. This reinforces the potential of glass waste in producing lightweight, sustainable concrete.

3.1.2 Workability

The Fig 3 displays the variation in slump values of fresh concrete with incremental replacement of cement by waste glass from 0% to 20%. A clear declining trend in slump value is observed, decreasing from 75 mm at 0% replacement to 55 mm at 20% replacement. This suggests that increasing the proportion of waste glass reduces the workability of the concrete mix. The reduction in slump may be attributed to the angular shape and non-absorbent nature of waste glass particles, which hinder the lubrication effect and flowability of the concrete mix [6, 14].

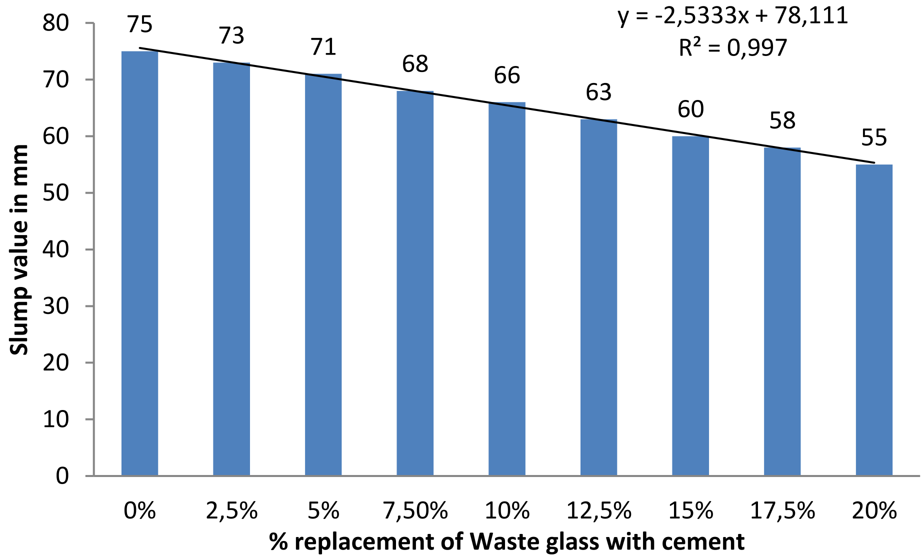


Fig. 3. Workability of M25 grade concrete using slump cone test

The linear regression line, with an equation of y = -2.5333x + 78.111 and a very high R^2 value of 0.997, indicates a strong linear correlation between increased glass content and reduced slump. The sharp decline in workability can affect compaction and placement, thus requiring either mix design optimization or the use of superplasticizers [7, 63]. Despite the decreased slump, earlier studies have affirmed that the mechanical properties of hardened concrete with waste glass can remain within acceptable limits if proper mix adjustments are made, supporting its sustainable use in construction applications [25, 64].

3.1.3 Compressive Strength

Fig 4 illustrates the variation in compressive strength of concrete at 3, 7, and 28 days of curing with different percentages of cement replaced by waste glass powder (WGP), ranging from 0% to 20%. At all curing ages, the strength follows a parabolic trend, initially increasing with WGP content and then declining after reaching an optimum point. The highest 28-day compressive strength of 30 MPa is observed at 10% WGP replacement, indicating an enhancement in pozzolanic reactivity and particle packing at this level. Beyond 10%, a gradual decrease in strength is recorded, reaching 25 MPa at 20% replacement.

The polynomial regression equations show strong correlations for each age, with R^2 values of 0.9301, 0.9464, and 0.9784 for 3, 7, and 28 days respectively. This signifies a well-fitting model to predict the strength behavior. The improvement in early strength is relatively modest, whereas the 28-day strength gain demonstrates the long-term benefits of secondary hydration reactions due to the amorphous silica in WGP [14, 64].

The decline in strength at higher replacements can be attributed to dilution of cementitious material and potential alkali-silica reaction concerns at elevated WGP content [5]. These results align with previous findings suggesting that an optimal replacement level of 10–15% can yield performance benefits while promoting sustainability in concrete production [7, 25].

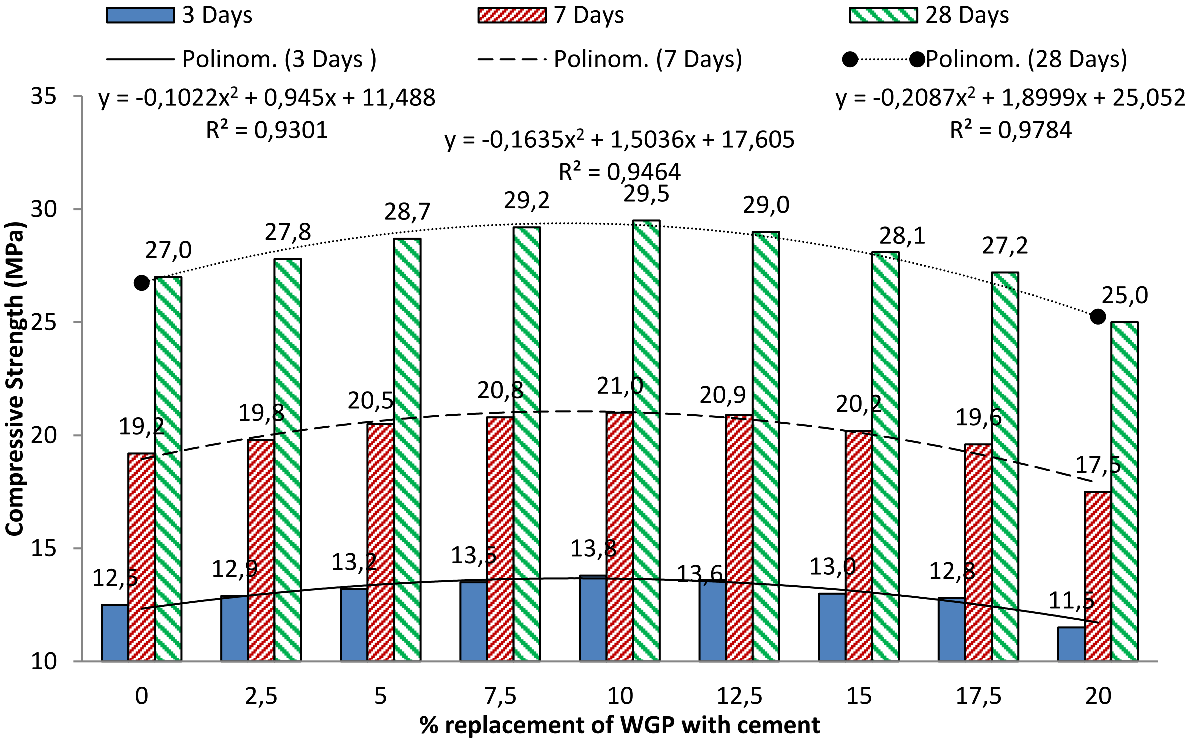


Fig. 4. Compressive Strength of M25 grade concrete with partial replacement of WG

3.1.4 Flexural Strength

Fig 5 illustrates the impact of incorporating waste glass powder (WGP) as a partial replacement for cement on the flexural strength of concrete at curing ages of 3, 7, and 28 days. As shown, the flexural strength generally increases with WGP content up to approximately 10–12.5%, after which it begins to decline. This trend is consistent across all curing durations. At 3 days, the highest strength is observed at 10% replacement, reaching approximately 2.35 MPa. The flexural strength was maximum at 10% and 12.5% replacement of WG in concrete with 4MPa at 7days and it was reduced to 3.5MPa at 28 days for 20% replacement. The polynomial regression equation (1) fits the data well, with an R^2 value of 0.9295, indicating a strong correlation. Similarly, at 7 days, the peak flexural strength of around 3.05 MPa occurs at 10% WGP, as represented by the equation (2) and R^2 = 0.8693. For the 28-day curing period, the flexural strength reaches a maximum of approximately 4.05 MPa between 10% and 12.5% WGP replacement.

$$y=-0.0152x2+0.1432x+1.9417 \tag{1}$$

$$y=-0.0177x^2+0.1642x+2.7024 \tag{2}$$

$$y=-0.0255x^2+0.2321x+3.444 \tag{3}$$

This relationship is captured by the regression equation model (3) with an R^2 value of 0.9179. These findings suggest that moderate levels of WGP (around 10–12.5%) can enhance the flexural performance of concrete, likely due to the pozzolanic activity of finely ground glass, which contributes to improved bonding and a denser microstructure. However, at higher replacement levels (above 15%), a reduction in strength is observed, possibly due to the dilution of cementations materials and insufficient reactive components. This aligns with findings from earlier research indicating that optimal use of WGP can improve mechanical properties while contributing to sustainability in construction [65-66].

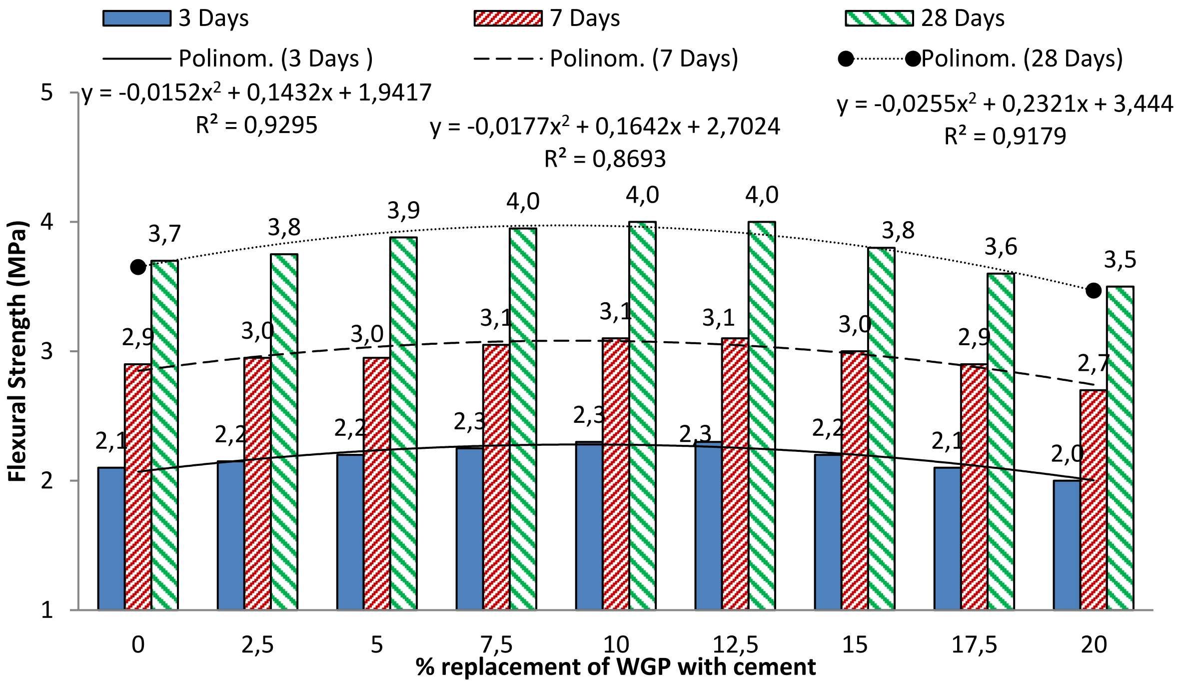


Fig. 5. Flexural strength of M25 grade concrete with WG replacement

3.1.5 Split Tensile Strength

Fig 6 demonstrates the effect of replacing cement with waste glass powder (WGP) on the flexural strength of concrete over three curing periods: 3 days, 7 days, and 28 days. The fig 6 shows a consistent trend across all curing times; flexural strength improves with increasing WGP content up to a certain point (10–12.5%), then declines beyond this range. At 3 days, the flexural strength increases slightly from 1.8 MPa at 0% WGP to about 2.0 MPa at 10% WGP replacement. This trend is captured by the regression model equation (4) with an R^2 value of 0.8853, indicating a reasonably good fit. For 7-day curing, strength peaks at 10% WGP, reaching approximately 2.4 MPa, as modeled by the equation (5) (R^2 = 0.826). At 28 days, the concrete shows its highest flexural strength at around 10–12.5% WGP replacement (approximately 3.1 MPa), following the equation (6) with an R^2 of 0.8655.

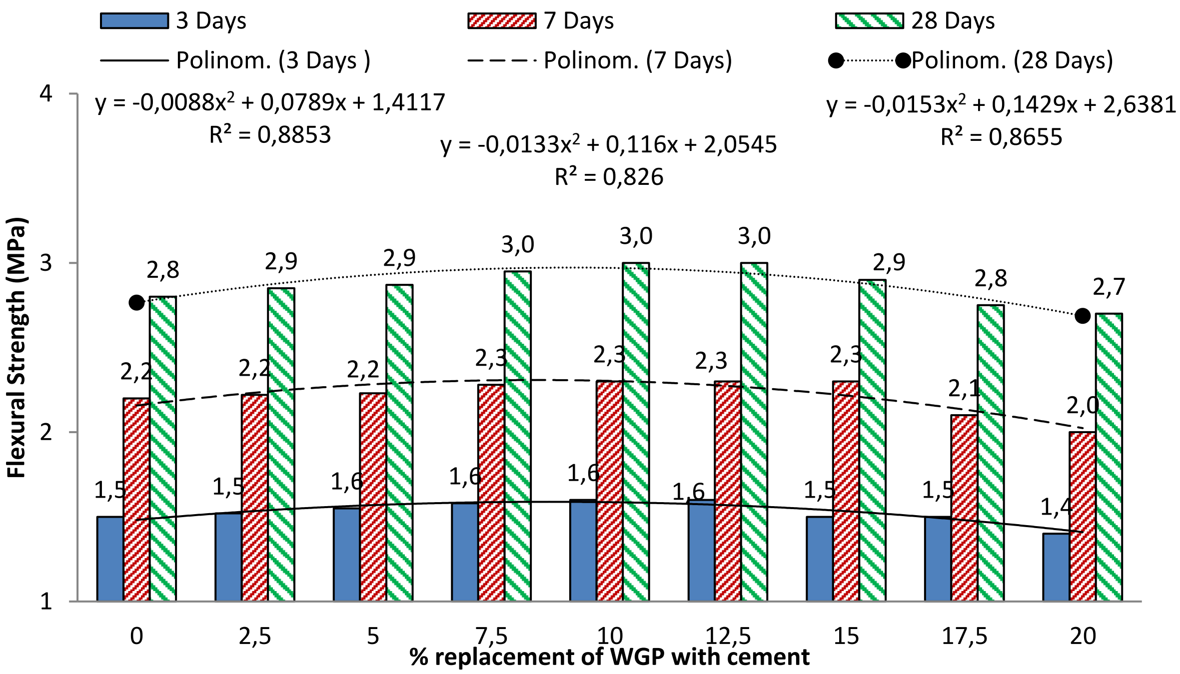


Fig. 6. Split Tensile strength of M25 grade concrete with partial replacement of WG

These results suggest that moderate incorporation of WGP (up to around 10–12.5%) can improve concrete's flexural strength due to the pozzolanic activity of the glass powder, which refines the pore structure and enhances the bonding between cementitious components. However, exceeding this optimal range appears to diminish strength, likely due to reduced availability of reactive cement, weakening the overall matrix. These observations align with earlier studies highlighting the potential of finely ground waste glass as a supplementary cementitious material when used in appropriate proportions [65-66].

$$y = -0.0088x2 + 0.0789x + 1.4117 \tag{4}$$

$$y = -0.0133\,x2 + 0.116x + 2.0545 \tag{5}$$

$$y = -0.0153\,x2 + 0.1429x + 2.6381 \tag{6}$$

3.2 Different Test on M30 Grade Concrete

3.2.1 Density of concrete

Fig 7 presents the relationship between the percentage replacement of cement with waste glass powder (WGP) and the average weight of a 150 mm concrete cube over different curing durations: 3, 7, and 28 days. From fig 7, it is evident that the weight of concrete cubes decreases consistently as the percentage of WGP increases, regardless of the curing age. At 0% WGP, the average weight is highest (around 8.3–8.35 kg), and it gradually decreases to approximately 8.1 kg at 20% replacement. The trend is linear for all three curing periods, as indicated by the respective linear regression equation (7): for 3 days, with an R^2 value of 0.9967, for 7 days equation (8) (R^2 = 0.9961); and for 28 days the equation (9) (R^2 = 0.9988). These high R^2 values indicate a strong linear correlation between WGP content and cube weight.

$$y = -0.0263x + 8.3507 \tag{7}$$

$$y = -0.0259x + 8.3396 \tag{8}$$

$$y = -0.0259x + 8.3314 \tag{9}$$

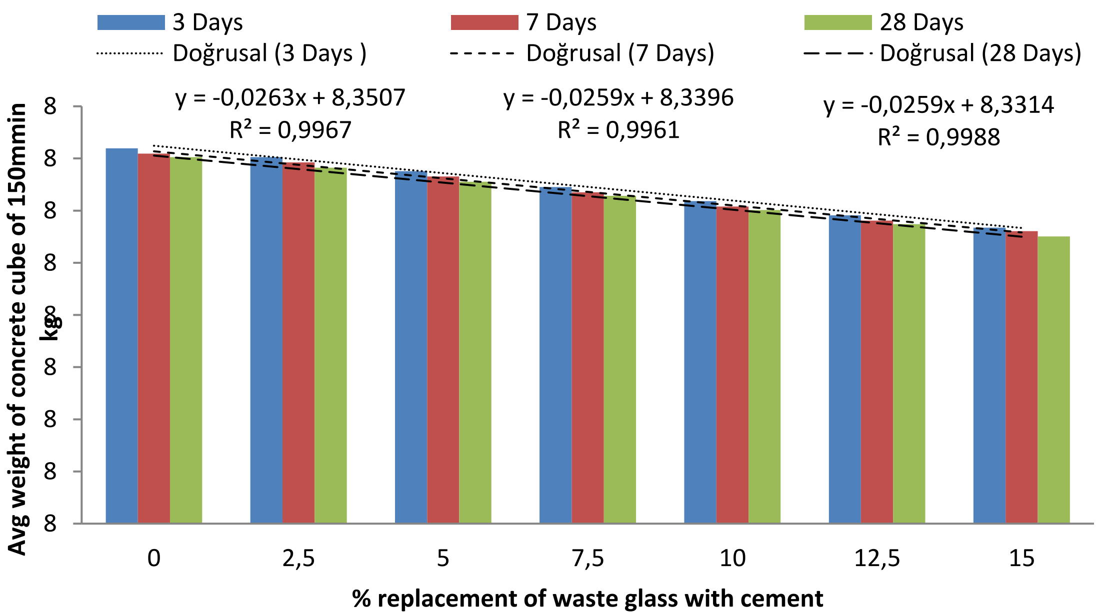


Fig. 7. Average weight of concrete cube with partial replacement of WG in M30 grade concrete

The decrease in weight is attributed to the lower specific gravity of glass powder compared to cement. As more cement is replaced by WGP, the overall density of the concrete mix reduces, resulting in lighter concrete cubes. Although this reduction in weight could have implications for structural density and performance, it may offer advantages in applications requiring lighter concrete, such as precast elements or non-load-bearing structures. These findings are consistent with previous research suggesting that the incorporation of lightweight supplementary materials like glass powder can influence concrete's density without significantly compromising its mechanical behavior at optimized levels [65, 66].

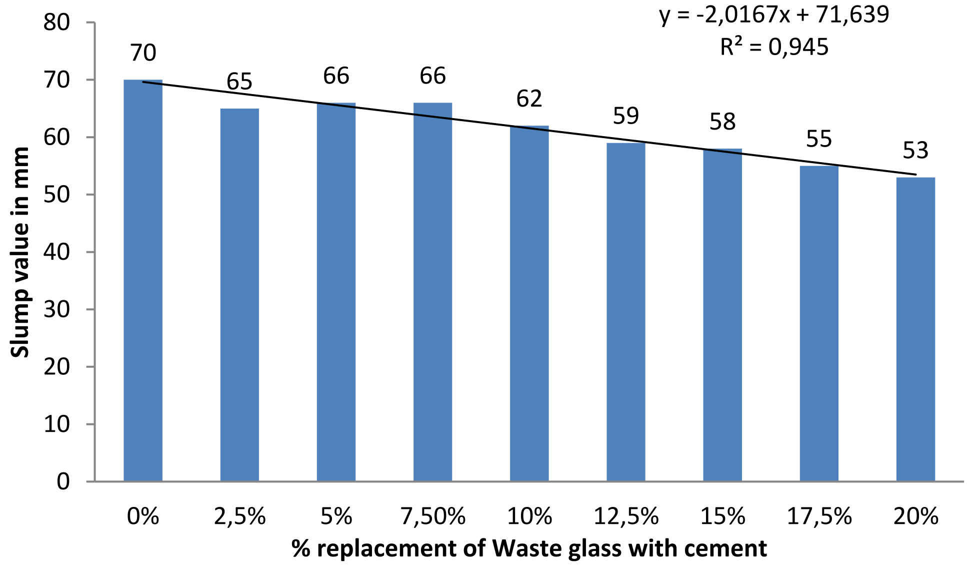


Fig. 8. Workability of M30 grade concrete with various % replacement of WG

3.2.2 Workability of Concrete

Fig 9 illustrates the effect of replacing cement with waste glass powder (WGP) on the slump value of fresh concrete, which is a measure of workability. The trend clearly indicates a gradual reduction in slump as the WGP content increases. At 0% replacement (control mix), the slump value is 70 mm, indicating relatively high workability. As WGP is incorporated, the slump steadily decreases, reaching 53 mm at 20% replacement. The relationship is well-described by the linear equation (10) with a strong coefficient of determination R2=0.945, suggesting a high degree of linear correlation.

$$y=-2.0167x+71.639 \tag{10}$$

The slump with increasing WGP content is attributed to the angular shape and finer particles of glass powder, which increase internal friction and reduce the lubricating effect of free water in the mix. This results in lower mobility and hence lower workability of the concrete. Despite this decline, the slump values observed remain within acceptable limits for general concrete applications, particularly up to 10% replacement, making WGP a viable supplementary cementitious material when controlled for mix design and application requirements. These findings are in line with previous studies which have noted similar trends when incorporating pozzolanic materials such as ground glass into concrete mixtures [65-66].

3.2.3 Compressive Strength of Concrete

Fig 10 illustrates the effect of varying percentages of waste glass powder (WGP) used as a partial replacement for cement on the compressive strength of concrete at 3, 7, and 28 days of curing. Fig 10 shows that compressive strength improves initially with WGP incorporation, peaking around 5% to 10% replacement, and then gradually declines. At 28 days, the compressive strength increases from 35 MPa (control) to a maximum of 37 MPa at 5–10% WGP, then declines to 34 MPa at 20% replacement. A similar trend is seen for 7-day and 3-day strengths, where the strength slightly increases up to a certain WGP percentage before dropping. The polynomial regression equations (11, 12 & 13) for each curing age demonstrate a parabolic relationship, with strong R^2 values (0.9624 for 3 days, 0.9687 for 7 days, and 0.984 for 28 days), indicating a good fit to the experimental data.

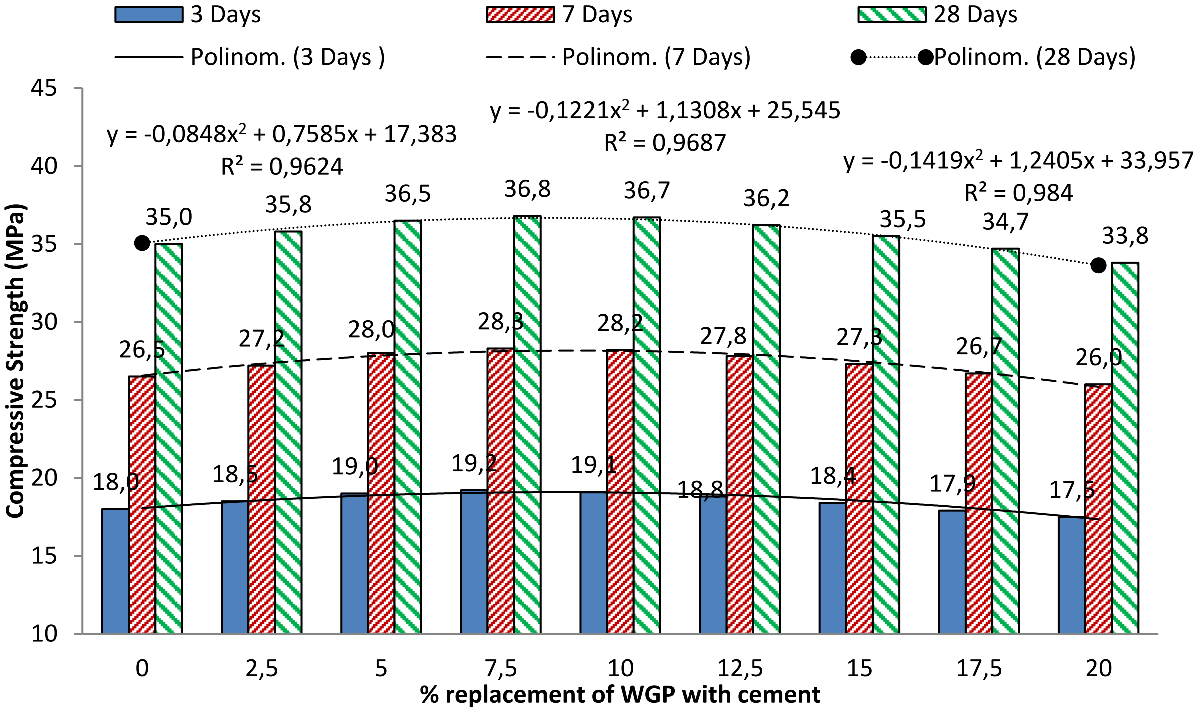


Fig. 9. Compressive strength of M30 grade concrete with partial replacement of WG

The increase in compressive strength at lower WGP replacements is likely due to the pozzolanic reactivity of finely ground glass powder, which reacts with calcium hydroxide to form additional calcium silicate hydrate (C-S-H), thereby enhancing strength. However, at higher replacements, the dilution effect becomes dominant, reducing the cementitious content and leading to a decrease in strength. These results align with previous findings indicating the beneficial but limited use of glass powder in concrete mixtures [65-66].

$$y = -0.0848x2 + 0.7585x + 17.383 \tag{11}$$

$$y = -0.1221x2 + 1.1308x + 25.545 \tag{12}$$

$$y = -0.1419x2 + 1.2405x + 33.957 \tag{13}$$

3.2.4 Flexural Strength of concrete

Fig 11 illustrates the effect of replacing cement with varying percentages of waste glass powder (WGP) on the flexural strength of concrete at curing periods of 3, 7, and 28 days. The Fig 11reveal that flexural strength increases with the addition of WGP up to a certain level, particularly around 7.5–10%, and then begins to decline. For instance, the 28-day flexural strength increases from 4.8 MPa (at 0%) to a peak of 5 MPa at 7.5–10% replacement, before falling slightly to 4.5 MPa at 20% replacement. The 7-day strength follows a similar trend, peaking at 4 MPa and maintaining that level up to 10%, before slightly reducing. For 3 days, the strength starts at 2.8 MPa, peaks near 3 MPa, and decreases modestly afterward.

Polynomial trend lines for each curing age describe a parabolic relationship between WGP content and flexural strength. The regression equations show high R^2 values (0.9538 for 3 and 7 days, and 0.9795 for 28 days), indicating a strong correlation. The initial increase in strength can be attributed to the pozzolanic action of finely ground glass powder, which contributes to the formation of additional calcium silicate hydrate (C-S-H), improving the concrete's microstructure. However, at higher replacement levels, the reduction in cementitious material and possible poor particle packing lead to a decline in flexural strength. This result confirms that an optimal WGP replacement range of 7.5–10% offers improved flexural performance without compromising structural integrity. The findings align with similar studies advocating limited partial cement replacement with WGP for enhanced durability and sustainability.

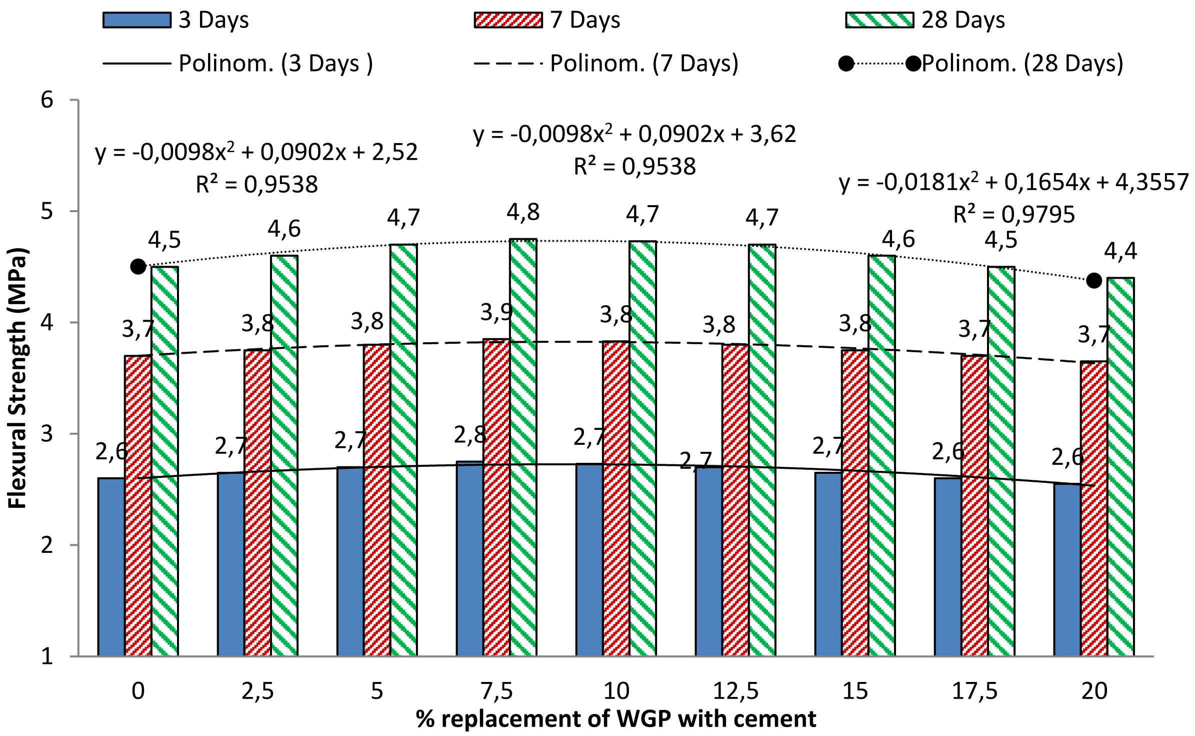


Fig. 11. Flexural Strength of M30 grade concrete with partial replacement of waste glass

$$y = -0.0098x2 + 0.0902x + 2.52 \quad (14)$$

$$y = -0.0098x2 + 0.0902x + 3.62 \quad (15)$$

$$y = -0.0181x2 + 0.1654x + 4.3557 \quad (16)$$

3.2.5 Split Tensile Strength

The provided Fig 12 illustrates the variation in split tensile strength of concrete at 3, 7, and 28 days of curing with different percentages of waste glass powder (WGP) replacing cement, ranging from 0% to 20%. At 28 days, the split tensile strength remains steady at 3 MPa up to a 12.5% replacement level, after which it slightly declines but still maintains a value of 3 MPa even at 20% replacement. The 7-day strength remains consistent at 2 MPa up to 15% WGP, dipping slightly to 1.9 MPa at 20%. At 3 days, the strength increases from 1.6 MPa at 0% WGP to a peak of about 2 MPa at 10%, then declines to 1.4 MPa at 20% replacement.

The polynomial trend lines for all three curing durations exhibit a parabolic shape, indicating that strength initially improves with increasing WGP content, peaks around 7.5–10%, and then gradually decreases beyond this range. The R^2 values, which range from 0.826 to 0.8853, indicate a moderate to strong correlation between WGP content and split tensile strength with the equations (17, 18 & 19). These results suggest that partial replacement of cement with WGP up to about 10% enhances flexural strength, likely due to pozzolanic reactions and filler effects. However, at higher replacement levels, the dilution of cementitious materials likely outweighs these benefits, resulting in a gradual decline in strength. Compared to previous graphs showing higher strength values, this data indicates a generally lower strength profile, which may be due to different mix proportions or material properties. Overall, the results support the conclusion that up to 10% WGP replacement offers optimal split tensile performance in concrete.

$$y = -0.0088x2 + 0.0789x + 1.4117 \quad (17)$$

$$y = -0.0133x2 + 0.116x + 2.0545 \quad (19)$$

$$y = -0.0153x2 + 0.1429x + 2.6381 \quad (19)$$

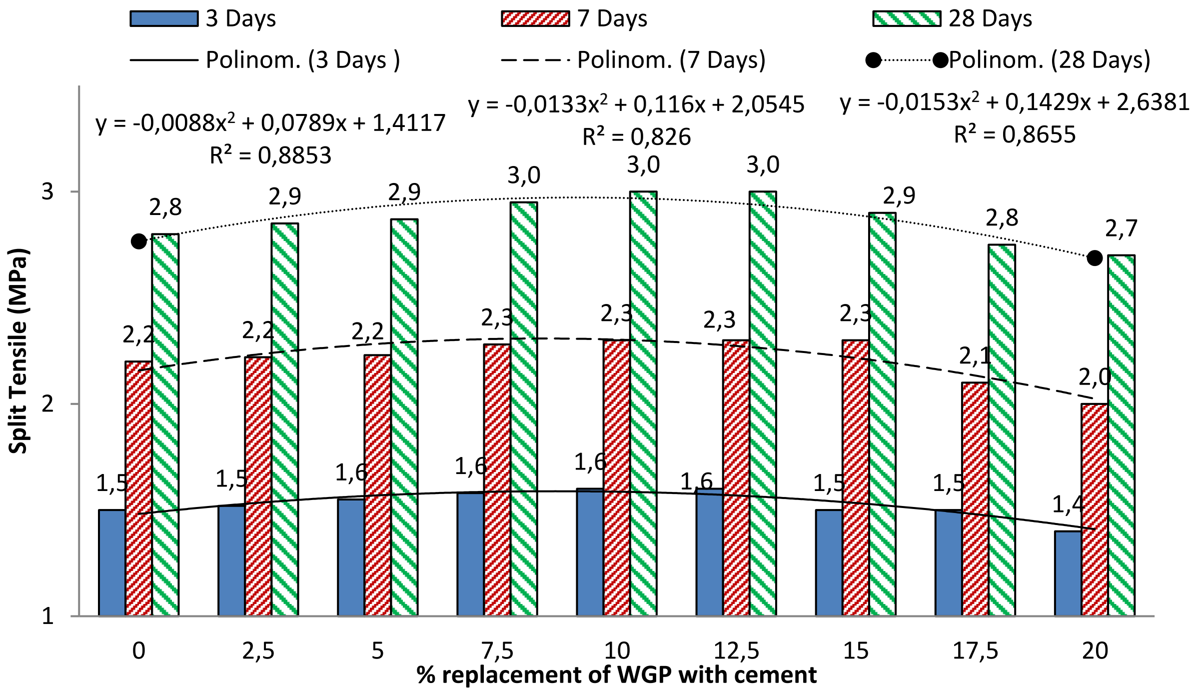


Fig. 12. Split Tensile Strength of M30 grade concrete with partial replacement of waste glass

The polynomial trend lines for all three curing durations exhibit a parabolic shape, indicating that strength initially improves with increasing WGP content, peaks around 7.5–10%, and then gradually decreases beyond this range. The R^2 values, which range from 0.826 to 0.8853, indicate a moderate to strong correlation between WGP content and split tensile strength with the equations (17, 18 & 19). These results suggest that partial replacement of cement with WGP up to about 10% enhances flexural strength, likely due to pozzolanic reactions and filler effects. However, at higher replacement levels, the dilution of cementitious materials likely outweighs these benefits, resulting in a gradual decline in strength. Compared to previous graphs showing higher strength values, this data indicates a generally lower strength profile, which may be due to different mix proportions or material properties. Overall, the results support the conclusion that up to 10% WGP replacement offers optimal split tensile performance in concrete.

3.4 Machine Learning Models

3.4.1 XG Boost and Random Forest

In the case of split tensile strength from Fig 13c, a similar parabolic trend is evident. Both M25 and M30 grades show improved tensile performance up to around 10% waste glass, aligning with the expected indirect relationship to compressive strength. XGBoost captures sharper changes, while Random Forest yields more stable transitions. The actual tensile strength values closely follow the model predictions, validating the influence of glass particles on internal cohesion and crack resistance within the concrete matrix.

Lastly, the flexural strength from Fig 13b reveals trends that not only mirror the earlier properties but also highlight enhanced sensitivity of flexural performance to waste glass content. Flexural strength increases up to about 10–12.5% replacement before tapering off. This observation is based on our experimental findings, where mixes with moderate waste glass replacement (typically between 7.5% and 15%) demonstrated improved flexural strength. It is likely that the angular and rigid nature of finely ground glass particles helps bridge micro-cracks, enhancing the load transfer across the matrix. Similar behavior has been reported by [63, 67-68], who observed that waste glass can improve post-cracking behavior in concrete by acting as a micro-filler and internal reinforcement. Overall, the mechanical response of concrete incorporating waste glass replacement indicates an optimal performance window at approximately 10% replacement. Beyond this point, performance declines uniformly across all measured properties. Both XGBoost and Random Forest models exhibit strong predictive power, especially within this optimal range.

These results support the viability of using waste glass as a sustainable and performance-enhancing additive in conventional concrete, especially when precision in modeling is applied.

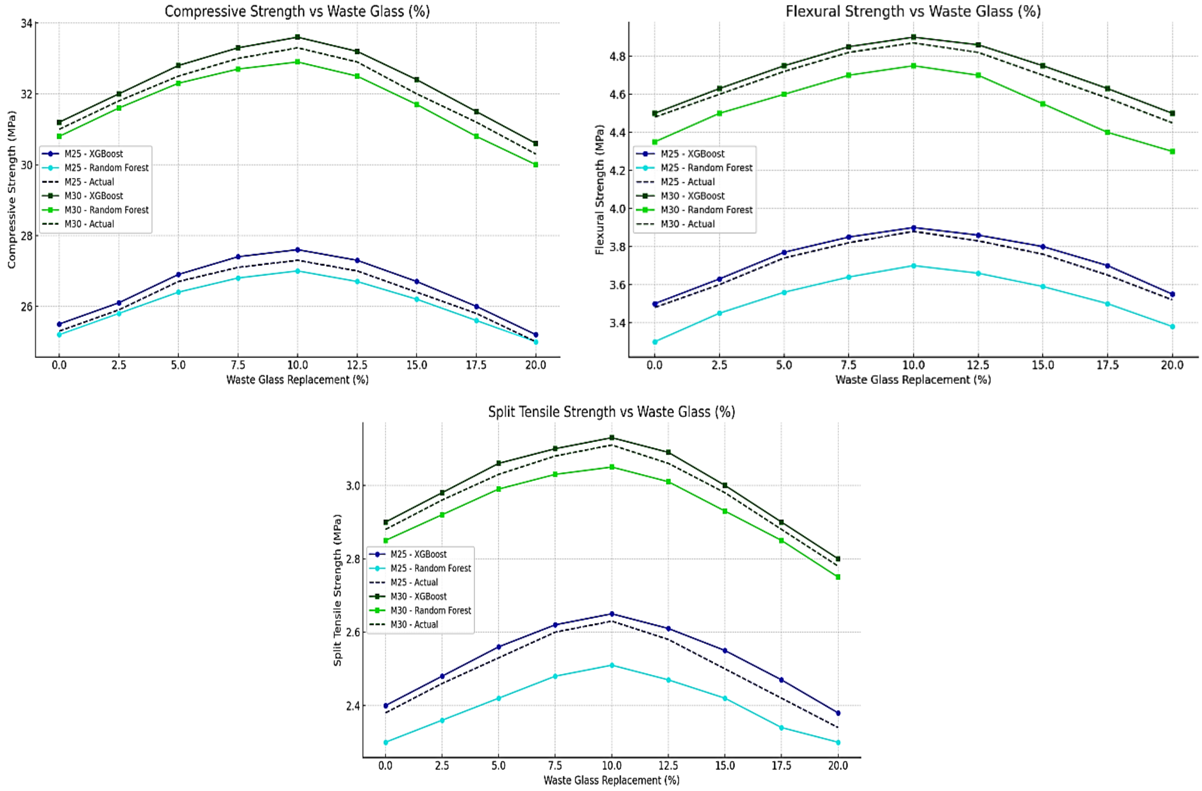
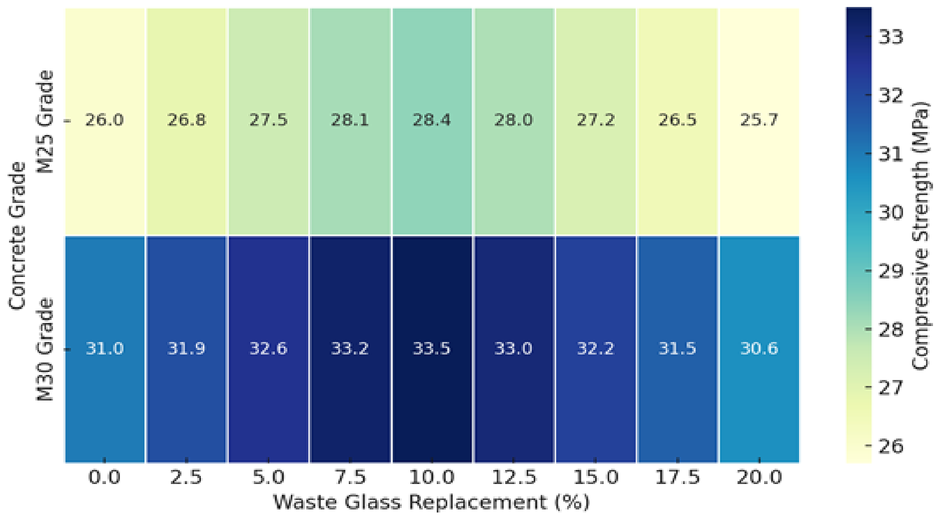


Fig. 13. XG Boost and Random Forest technique for prediction of a) Compressive Strength b) Flexural Strength c) Split Tensile Strength

3.4.2 Heat Map

This heatmap from Fig 14a illustrates how compressive strength changes as waste glass is added to concrete, from 0% to 20% in 2.5% steps. For both M25 and M30 grades, the strength increases gradually up to around 10% replacement, reaching a peak. Beyond this point, the strength starts to drop slightly. This trend suggests that a moderate addition of waste glass improves the material's compactness and pozzolanic activity, but excessive glass content might interfere with bonding or hydration.



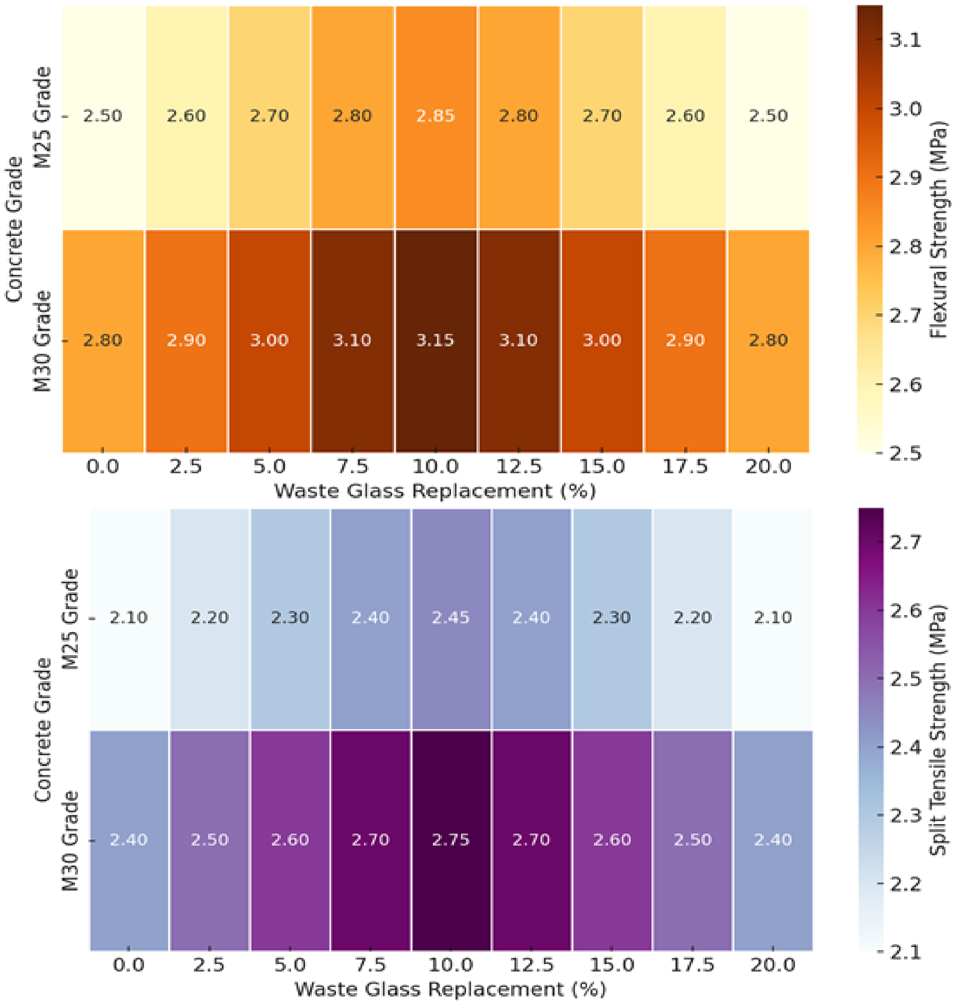


Fig. 14. Heat map of M25 and M30 grade concrete with partial replacement of WG in a) Compressive Strength b) Flexural Strength c) Split Tensile Strength

Fig 14b shows the flexural (bending) strength of concrete at varying levels of glass replacement. Similar to compressive strength, there is a positive trend up to 10%, after which the performance slightly declines. Flexural strength is especially important in pavement and slab applications, and this graph shows that incorporating a small percentage of waste glass can improve resistance to bending stresses.

The Fig 14c focuses on split tensile strength, which measures the concrete's ability to resist cracking under tension. The pattern here mirrors the previous two charts strength improves up to around 10% glass replacement and then tapers off. This confirms that while waste glass enhances tensile resistance to a certain limit, too much can reduce bonding between cement paste and aggregates.

3.4.3 Coefficient of Determination (R2) Values

The table 3 presented compares the performance of two machine learning models Random Forest and XGBoost against actual values for predicting different mechanical properties of concrete: compressive strength, flexural strength, and split tensile strength, for two concrete grades, M25 and M30. The table 3 includes 24 datasets, covering all three types of strength properties for each grade. The R^2 values indicate the proportion of variance in the target variable that can be explained by the input features.

For M25 grade concrete, RF showed marginal prediction capability at early ages, with an R^2 of 0.0167 for 3-day compressive strength, improving slightly to 0.1092 at 28 days. XGB, however, produced negative R^2 values across all curing periods, suggesting poor generalization and possibly model overfitting or insufficient data variability. Flexural strength predictions using RF improved over time, reaching 0.2735 at 28 days, whereas XGB hovered around zero or negative values. Split tensile strength prediction was particularly challenging, where RF and XGB yielded notably low and even extreme negative R^2 scores (e.g., –33.93 at 7 days for RF), indicating a failure to capture the underlying patterns.

Table 3. Actual and predicted values of R^2 for different ML models

Test	Grade of Concrete	Days	Actual value	Random Forest	XGBoost
Compressive Strength	M25	3	0.9301	0.0167	-1.3966
		7	0.9464	-0.0511	-1.5390
		28	0.9784	0.1092	-0.8877
Flexural Strength		3	0.9295	-0.1727	-0.4167
		7	0.8693	-0.7392	-1.0845
		28	0.9179	0.2735	-0.0027
Split Tensile Strength		3	0.8853	0.1968	-0.5743
		7	0.826	-33.9295	-49.6321
		28	0.8655	-0.7176	-1.0504
Compressive Strength	M30	3	0.9624	0.3992	-0.0155
		7	0.9687	0.2654	-0.3401
		28	0.984	0.4175	-0.0274
Flexural Strength		3	0.9538	0.1777	-0.0633
		7	0.9538	0.1873	-0.0633
		28	0.9795	0.3076	0.0045
Split Tensile Strength		3	0.8853	0.1968	-0.5743
		7	0.826	-33.9295	-49.6321
		28	0.8655	-0.7176	-1.0504

In contrast, for M30 grade concrete, RF provided relatively better performance. For compressive strength, R^2 values increased steadily from 0.3992 (3 days) to 0.4175 (28 days). Flexural strength showed moderate accuracy with RF (R^2 = 0.3076 at 28 days), while XGB remained close to zero. Overall, RF outperformed XGB for all strength parameters across curing ages, consistent with findings from other studies suggesting that ensemble-based models like RF are more stable with smaller datasets and noisy features [51, 60].

The limited size of the dataset, especially after dividing it by curing age and grade (e.g., M25 at 3 and 7 days), reduced the model's ability to generalize effectively during cross-validation. Early-age strength development in concrete is highly variable and influenced by complex hydration and curing behavior, which may not be fully captured by the input features used in this study. XGBoost, while a powerful algorithm, tends to overfit on small or noisy datasets without sufficient hyperparameter tuning or regularization, which likely contributed to its poor generalization here. Negative R^2 values indicate the model performed worse than predicting the mean. This behavior was mostly observed for early-age data and is likely due to limited variability and sample size. These results underscore the importance of data quality, feature relevance, and model selection when applying ML techniques to predict concrete properties.

4. Conclusion

The following conclusions are drawn from the work carried out.

- The maximum reduction in density of concrete by 2.47% at 20% replacement is observed. The linear regression analysis confirms the decreasing trend, with high R^2 values for 3 days as 0.9631, 7 days as 0.8352), and 28 days as 0.8808, indicating strong linear correlations. A clear declining trend in slump value is observed, decreasing from 75 mm at 0% replacement to 55 mm at 20% replacement for M25 grade concrete.
- The reduction in slump may be attributed to the angular shape and non-absorbent nature of waste glass particles, which hinder the lubrication effect and flowability of the concrete mix.

- The highest 28-day compressive strength of 30 MPa is observed at 10% WGP replacement, indicating an enhancement in pozzolanic reactivity and particle packing at this level. Beyond 10%, a gradual decrease in strength is recorded, reaching 25 MPa at 20% replacement.
- The decline in strength at higher replacements can be attributed to dilution of cementitious material and potential alkali-silica reaction concerns at elevated WGP content.
- The flexural strength was maximum at 10% and 12.5% replacement of WG in concrete with 4MPa at 7days and it was reduced to 3.5MPa at 28 days for 20% replacement. A similar trend is observed in split tensile strength.
- At 0% WGP, the average weight is highest (around 8.3–8.35 kg), and it gradually decreases to approximately 8.1 kg at 20% replacement for M30 grade concrete. As WGP is incorporated, the slump steadily decreases, reaching 53 mm at 20% replacement.
- At 28 days, the compressive strength increases from 35 MPa (control) to a maximum of 37 MPa at 5–10% WGP, then declines to 34 MPa at 20% replacement. The 28-day flexural strength increases from 4.8 MPa (at 0%) to a peak of 5 MPa at 7.5–10% replacement, before falling slightly to 4.5 MPa at 20% replacement. At 28 days, the split tensile strength remains steady at 3 MPa up to a 12.5% replacement level, after which it slightly declines but still maintains a value of 3 MPa even at 20% replacement.
- The limited size of the dataset, especially after dividing it by curing age and grade (e.g., M25 at 3 and 7 days), reduced the model's ability to generalize effectively during cross-validation. Early-age strength development in concrete is highly variable and influenced by complex hydration and curing behavior, which may not be fully captured by the input features used in this study. The XGBoost, while a powerful algorithm, tends to overfit on small or noisy datasets without sufficient hyperparameter tuning or regularization, which likely contributed to its poor generalization here.
- Negative R^2 values indicate the XGBoost performed worse than predicting the mean. This behavior was mostly observed for early-age data and is likely due to limited variability and sample size. It also highlighted that Random Forest consistently outperformed XGBoost, especially for 28-day strengths, with positive and moderate-to-high R^2 scores.

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