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Predicting the Mechanical Properties of Waste Glass Powder Concrete under Aggressive Environments Using Artificial Neural Network

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Abstract
This study explores the viability of waste glass powder (WGP) as a sustainable, partial cement replacement in concrete, addressing both the carbon emissions from cement production and environmental impacts of landfill waste. Cement production is a major source of CO_2 *, contributing to climate change, while waste glass accumulates in landfills, causing environmental damage. Concrete samples were prepared with varying WGP replacement levels (0% to 30% in 10% increments) and subjected to immersion in 5% sulfuric acid (*H_2SO_4 *) and magnesium sulfate (*$MgSO_4$ *) solutions. By incorporating WGP at replacement levels of 0% to 30% and exposing samples to 5% sulfuric acid (*H_2SO_4 *) and magnesium sulfate (*$MgSO_4$ *) solutions, the study examines its effects on fresh and hardened concrete properties, including compressive strength, ultrasonic pulse velocity (UPV), tensile strength, and flexural strength. Notably, a 10% WGP replacement increased compressive strength by 3.51% and improved resistance to acid and sulfate attack, although higher replacement levels reduced strength due to increased porosity. The study also employed an Artificial Neural Network (ANN) model to predict compressive strength under chemical exposure, achieving high predictive accuracy with* R^2 *values of 0.98 to 0.99 and low MAE and MSE values. These results confirm WGP's potential as a sustainable alternative in concrete and validate ANN's effectiveness in forecasting concrete performance under chemical exposure.*

Keywords: *Waste glass powder, Artificial Neural Network, Mechanical properties, Cement replacement, Aggressive environmental conditions.*

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I. Introduction

Concrete is the most widely used building material globally due to its ability to take on various shapes when wet and its strength once hardened. It is primarily made from ordinary Portland cement (OPC), aggregates, and water, making the construction industry heavily reliant on OPC (Nwaobakata & Eme, 2018; Ibedu, Akinola, & Omole, 2023). As of 2023, global cement consumption reached around 4.4 billion metric tons, driven by infrastructure and urbanization, particularly in Asia and Africa (Global Cement Report, 2023). In Nigeria, cement demand has risen steadily, driven by extensive infrastructure projects and urban expansion. In 2015, the country's cement consumption was estimated at around 20 million metric tons. This figure has since increased to approximately 30 million metric tons by 2023, reflecting the continuous growth in the construction sector (Cardinal Stone, 2024). However, OPC production is costly and a major contributor to CO_2 emissions, ranking as the third-largest source globally after fossil fuels and deforestation (Salawu, 2018). To address these environmental and economic issues, the construction industry is increasingly adopting supplementary cementitious materials (SCMs), like waste glass powder, as partial substitutes for traditional cement, which can enhance sustainability and performance.

Glass powder exhibits pozzolanic characteristics, allowing it to react with calcium hydroxide in the presence of water to form additional binding compounds, much like cementitious materials. Numerous studies (Ganesan, Rajagopal, & Thangavel, 2018) have explored the potential of using glass powder as a partial cement replacement in concrete. The inclusion of glass powder in concrete mixes provides several advantages, including reducing cement consumption, repurposing waste materials, and enhancing certain concrete properties such as improved workability, mechanical properties, and decreased permeability (Najigivi, Nikbin, & Najigivi, 2020) Concrete is one of the fundamental building materials widely used in construction due to its durability, strength, and versatility. However, the production of cement as one of the key ingredient in concrete emits significant amounts of carbon dioxide, contributing to climate change. To mitigate these environmental concerns and address sustainability in construction, researchers have explored alternative materials and methods for concrete production. One such alternative is the incorporation of supplementary cementations materials (SCMs) as partial replacements for cement. Among these SCMs, glass powder has emerged as a promising candidate due to its pozzolanic properties and potential to enhance the performance of concrete (Sinha, & Thakur, 2018).

According to Environment Protection Agency (EPA, 2021), waste glass can take thousands of years to decompose, contributing to landfill expansion and potential habitat disruption. United Nations Environment Programme (UNEP, 2018) reported that around 130 million metric tonnes of glass are currently produced annually and less than 35% of glass waste is recycled around the world. Recycling of glass remains insufficient as millions of tons end up in landfills. Glass powder, a by-product of recycling processes, possesses pozzolanic properties and can contribute to the enhancement of concrete properties (Sinha, & Thakur, 2018). Glass powder has been reported to enhance the workability, compressive strength, and durability characteristics of concrete when properly utilized (Patel, Desai, & Shah, 2020; Sharma, Sinha, & Thakur, 2018). Despite the promising environmental advantages, the practical feasibility and performance of concrete incorporating WGP remain uncertain. Several factors such as the particle size and content of WGP, as well as the curing conditions, may influence the mechanical, and durability properties of the resulting concrete (Han *et al.,* 2023). Using glass powder as a partial replacement for cement offers several benefits aligned with sustainable development goals (SDGs). It reduces the demand for virgin materials, promoting sustainable resource use (SDG 9), and lowers carbon emissions associated with cement production, supporting climate action (SDG 13).

Han *et al.* (2023), the incorporation of supplementary cementitious materials like pozzolans can significantly reduce the carbon footprint of concrete by replacing a portion of cement, which is a major contributor to CO_2 emissions during production. Moreover, studies have shown that the use of pozzolans in concrete can improve its resistance to chemical attack and mitigate the risk of alkali-silica reaction (ASR).

Alkadhim *et al.* (2022) investigated the performance of ANN models in predicting the compressive strength of concrete containing silica fume as a partial cement replacement, exposed to sulfate and acidic environments. The study reported high predictive accuracy, with R^2 values exceeding 0.95, indicating the reliability of ANN models for such applications.

II. Materials and Methods

2.1 Materials

Materials that were used in this work include; cement, fine aggregate, coarse aggregates and water and glass powder.

2.2 Methods

2.2.1 Experimental design

Figure 1 explained the step procedures that were used to conduct the research analysis.

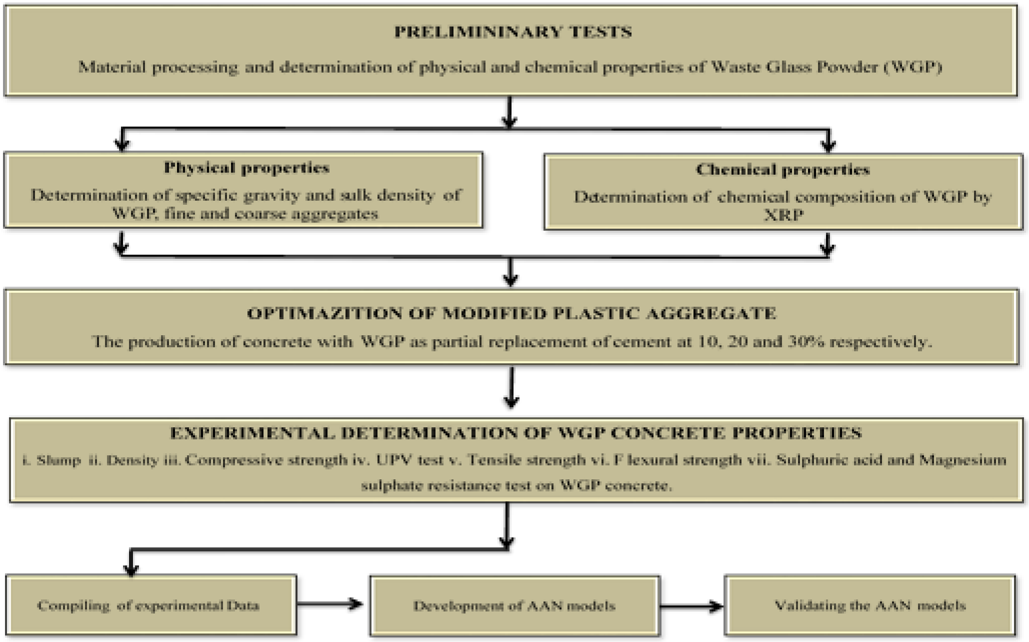

Figure 1: Flowchart describing the research design

This study investigates the mechanical properties of glass powder as a partial cement replacement in concrete. First, waste glass was sourced, mechanically crushed into powder, and sieved to a 150µm particle size. Tests determined the specific gravity and chemical composition of the glass powder. In the initial stage, glass powder replaced cement in concrete at 0, 10, 20, and 30% levels with a 0.5 water-cement ratio, with assessments of fresh, mechanical, and durability properties conducted over 7, 14, 28, and 56 days. In the next phase, experimental results were expanded using synthetic data generated in Python on Jupyter Notebook to train, validate, and test an Artificial Neural Network (ANN) model. This model, optimized via hyper parameter tuning and cross-validation, used performance metrics like MSE and R^2 to predict the impact of glass powder on concrete properties, providing valuable insights into its effectiveness as a cement alternative (Han *et al.* 2023).

2.2.2 Mixing procedure and sample preparation

The mixing procedure involved manually blending cement and waste glass powder for three minutes, followed by the addition of fine aggregate and another three-minute mix. After dry mixing, water was added, and the mixture was further mixed for three minutes before casting the fresh glass concrete into 100 x 100 x 1000mm plastic moulds in three layers, with each layer vibrated for 30 seconds. The samples were covered with plastic bags and set in the laboratory for 24 hours before remoulding. Post-remoulding, specimens were cured at 27 ± 5°C, exposed to curing media of 0% concentration, 1.2% H_2SO_4, and $MgSO_4$, adhering to BS 1881: Part 108 standards and subjected to physical and mechanical properties test (Han *et al.* 2023).

2.2.3 Mechanical properties of glass concrete

Mechanical property tests are usually conducted to find out the hardened properties of the glass concretes. The tests include both destructive and nondestructive test such as compressive strength, tensile strength, and ultrasonic pulse velocity test (UPV) respectively.

2.2.3.1 Compressive Strength

The compressive strength test was carried out using the universal crushing machines conform to BS EN 12390-3 (2009). The compressive strength test was carried out at 7, 14, 28, and 56 days respectively. The average of three samples was presented as the compressive strength results.

2.2.3.2 Tensile Strength

Glass concrete cylinders of 100mm diameter by 300mm height was used to conduct the tensile strength test according to BS EN 12390-6:2009 Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens was also conducted using the universal crushing machine conform to BS EN 12390-3 (2009). The tensile strength test was conducted at 7, 14, and 28 days, respectively.

2.2.3.3 Flexural Strength

Determination of flexural strength for concrete prisms of size 100 x 100 x 500mm was conducted according to BS EN 12390-5:2000 Standard test method for flexural strength of concrete using ELE universal testing machine. The concrete specimen, the flexural strength test was conducted at 7, 14 and 28 days, respectively.

2.2.3.4 Ultrasonic Pulse Velocity (UPV)

The ultrasonic pulse velocity test is a non-destructive test conducted on concrete cubes 100 x100 x100mm before the compressive strength tests at 7, 14, 28, and 56 days respectively. The test was conducted according to BS 1881-203:2011 using PUNDIT (ultrasonic pulse velocity machine). The Average of three results was taking as the UPV result for each mixture.

2.2.4 Artificial neural networks (ANN) model development and validation

This study developed an Artificial Neural Network (ANN) model to predict the durability properties of concrete using waste glass powder (WGP) as a partial cement replacement in aggressive environments, with replacement levels of 0%, 10%, 20%, and 30%. Twelve variables, including material properties and mechanical strengths, were used as inputs in a feed forward ANN with ReLU-activated hidden layers and a linear output layer to predict compressive strength under H_2SO_4 and $MgSO_4$ conditions. Pre-processing steps included min-max normalization, data augmentation via CTGAN to expand the dataset, and a 70-30 train-test split with 5-fold cross-validation for parameter tuning. The training utilized Mean Squared Error (MSE) as the loss function and the Adam optimizer, with early stopping after 1,000 epochs to prevent over fitting. Model performance was evaluated using metrics like R^2, Mean Absolute Error (MAE), and MSE, highlighting the model's accuracy and its suitability for predicting the impact of WGP on concrete durability. To evaluate the performance of the ANN model, the following metrics were utilized (Alkadhim *et al.* 2022).

2.2.4.1 Coefficient of Determination (R^2)

R^2 measures the proportion of the variance in the dependent variable predictable from the independent variables, with values ranging from 0 to 1, where 1 indicates perfect prediction as shown in Equation (1).

$$R^2 = 1 - \frac{SS_{res}}{SS_{tot}} \qquad (1)$$

Where SS_{res} is the sum of squares of the residuals, $\sum(yi - \hat{y}i)^2$
$SStot$ is the total sum of squares, $\sum(yi - \bar{y})^2$
y_i are the actual values
$\hat{y}_i$ are the predicted values
$\bar{y}$ is the mean of the actual values.

2.2.4.2 Mean Absolute Error (MAE)

MAE measures the average magnitude of errors in predictions without considering their direction, indicating how far off predictions is from actual outcomes on average. MAE provides an idea of how far off predictions is from the actual outcomes, on average as shown in Equation (2).

The equation gives it:

$$\mathrm{MAE} = \frac{1}{n}\sum_{i=1}^{n}|y_i - \hat{y}_i| \quad (2)$$

Where n is the number of observations.
y_i are the actual values.
$\hat{y}_i$ are the predicted values.

2.2.4.3 Mean Squared Error (MSE)

MSE measures the average of the squares of errors, giving more weight to larger errors, thus providing a measure sensitive to outliers as shown in Equation (3)

$$\mathrm{MSE} = \frac{1}{n}\sum_{i=1}^{n}(y_i - \hat{y}_i)^2 \quad (3)$$

Where n is the number of observations
y_i are the actual values
$\hat{y}_i$ are the predicted values (Alkadhim *et al.* 2022).

III. Results and Discussion

3.1 Mechanical Properties

3.1.1 Compressive strength of concrete specimens cured in H_2SO_4

The compressive strength of Portland cement concrete with varying levels of waste glass powder (WGP) replacement, cured in sulfuric acid (H_2SO_4) are shown in Table 1 and Figure 2 respectively.

Table 1: Compressive Strength of Cubes Cured in H_2SO_4 in N/mm^2 (At 7, 14 and 28 days)

Replacement level	3 cubes 7 days			3 cubes 14 days			3 cubes 28 days		
	1st	2nd	3rd	1st	2nd	3rd	1st	2nd	3rd
Control mix	28.56	28.37	28.59	27.86	28.47	27.49	28.75	28.63	27.98
Average		28.51			27.94			28.45	
10% WGP	30.054	29.27	31	30.04	29.23	30.36	29.37	29.17	30.48
Average		30.11			29.88			29.67	
20% WGP	26.255	25.86	27.255	26.25	25.44	26.53	25.47	25.43	26.57
Average		26.46			26.07			25.82	
30% WGP	23.58	22.71	24.28	22.85	22.78	24.25	22.87	22.90	22.35
Average		23.52			22.96			22.71	

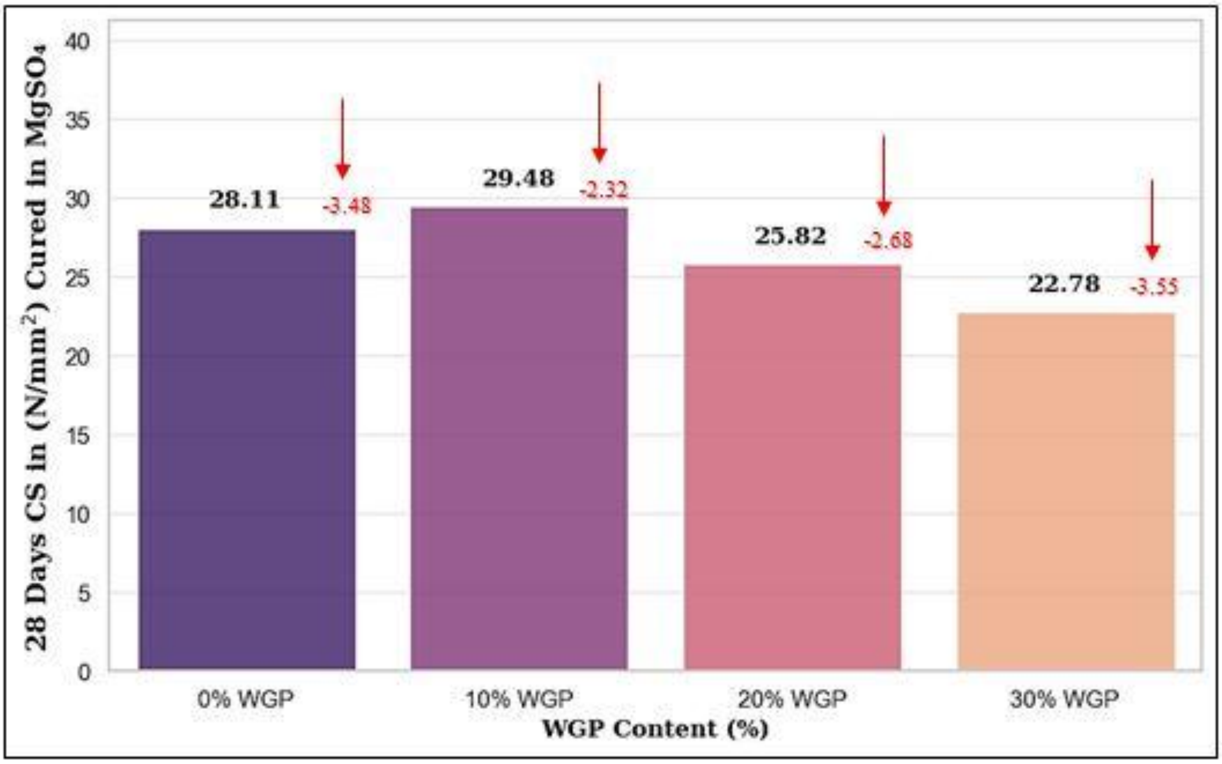

Figure 2: *Average 28 days Compressive Strength of WGP concrete in Cured in* H_2SO_4

Figure 2 evaluated at 7, 14, 28, and 56 days. At 28 days, compressive strengths for 10%, 20%, and 30% WGP replacements were 29.67 N/mm², 25.82 N/mm², and 22.71 N/mm², respectively, with a slight decrease compared to 28.45 N/mm² for the 0% replacement control. This reduction in strength—1.67%, 1.94%, and 3.87% for WGP replacements and 2.29% for the control—indicates better acid resistance in WGP-blended concrete, especially with 10% and 20% WGP, potentially due to the pozzolanic properties of WGP that mitigate sulfate damage by reducing gypsum and ettringite formation, consistent with prior research findings on pozzolana resilience in acidic environments (Wang and Li 2023).

3.1.2 Compressive strength of concrete specimens cured in $MgSO_4$

The compressive strength of Portland cement with waste glass powder (WGP) concrete specimens cured in magnesium sulfate ($MgSO_4$) are shown in Table 2 and Figure 3 respectively.

Table 2: Compressive Strength of cubes cured in $MgSO_4$ in N/mm^2 (At 7, 14 and 28 days)

Replacement level	**3 cubes 7 days**			**3 cubes 14 days**			**3 cubes 28 days**		
	1st	2nd	3rd	1st	2nd	3rd	1st	2nd	3rd
Control mix	28.59	29.51	28.42	28.39	28.5	27.86	27.67	27.95	28.70
Average		28.84			28.25			28.11	
10% WGP	30.11	29.33	31.03	29.15	29.35	30.74	28.95	29.85	29.64
Average		30.15			29.75			29.48	
20% WGP	26.293	25.893	27.283	26.13	25.76	26.27	26.27	25.55	25.65
Average		26.49			26.05			25.82	
30% WGP	23.63	22.83	24.32	23.26	22.81	23.3	23.61	22.81	21.93
Average		23.59			23.13			22.78	

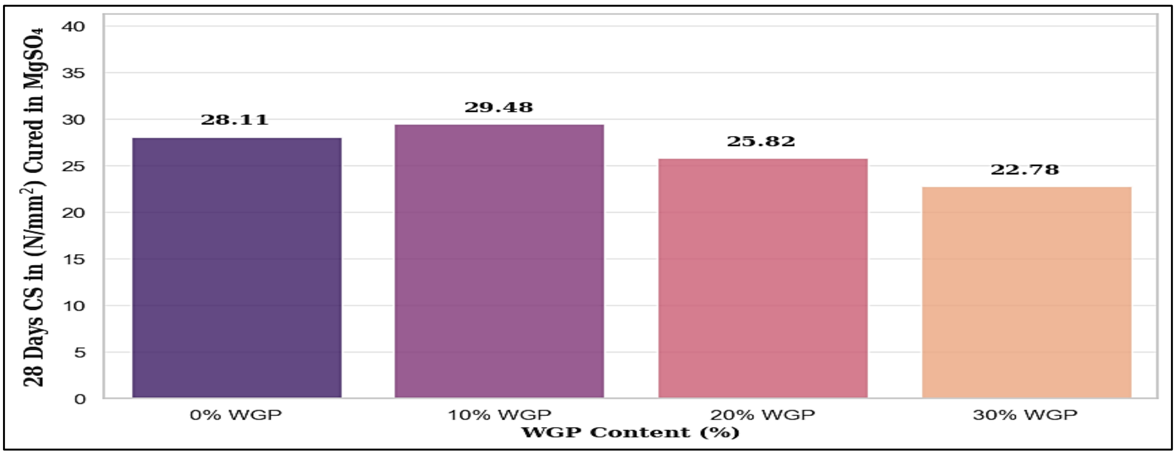

Figure 3: Average 28 days Compressive Strength of WGP concrete in Cured in $MgSO_4$

The compressive strength of Portland cement with waste glass powder (WGP) concrete specimens cured in magnesium sulfate ($MgSO_4$) was tested at 7, 14, 28, and 56 days of hydration. Specimens with 10, 20 and 30% WGP replacements achieved compressive strengths of 29.48, 25.82 and 22.78 N/mm² at 28 days, compared to 27.65 N/mm² for 0% replacement. This represents a 2.32%, 2.68%, and 3.55% decrease in compressive strengths for 10%, 20%, and 30% WGP replacements, respectively, and a 3.48 % decrease for 0% WGP replacement. The control and 30% WGP replacement samples suffered significant strength loss due to $MgSO_4$ exposure, while the 10% and 20% replacements showed better resistance. This improved performance is likely due to the pozzolanic activity in WGP, which reduces sulfate attack by minimizing gypsum and ettringite formation (Wang and Li 2023).

3.1.3 Compressive strength of concrete cured in H_2O

The compressive strengths of Portland cement with Waste Glass Powder (WGP) concrete specimens cured in normal water (H_2O) are shown in Table 3 and Figure 4 respectively.

Table 3: Compressive Strength of cubes cured in H_2O in N/mm^2 (At 28 and 56 days)

Replacement level		**3 cubes 28 days**			**3 cubes 56days**		
		1st	2nd	3rd	1st	2nd	3rd
Control mix		28.83	29.72	28.81	29.58	30.25	31.36
Average			29.12			30.4	
10% WGP		30.13	29.35	31.05	30.3	32.5	31.58
Average			30.18			31.46	
20% WGP		26.33	25.93	27.32	28.25	28.15	27.75
Average			26.53			28.05	
30% WGP		23.66	22.86	24.35	24.82	23.95	25.43
Average	23.62		24.73				

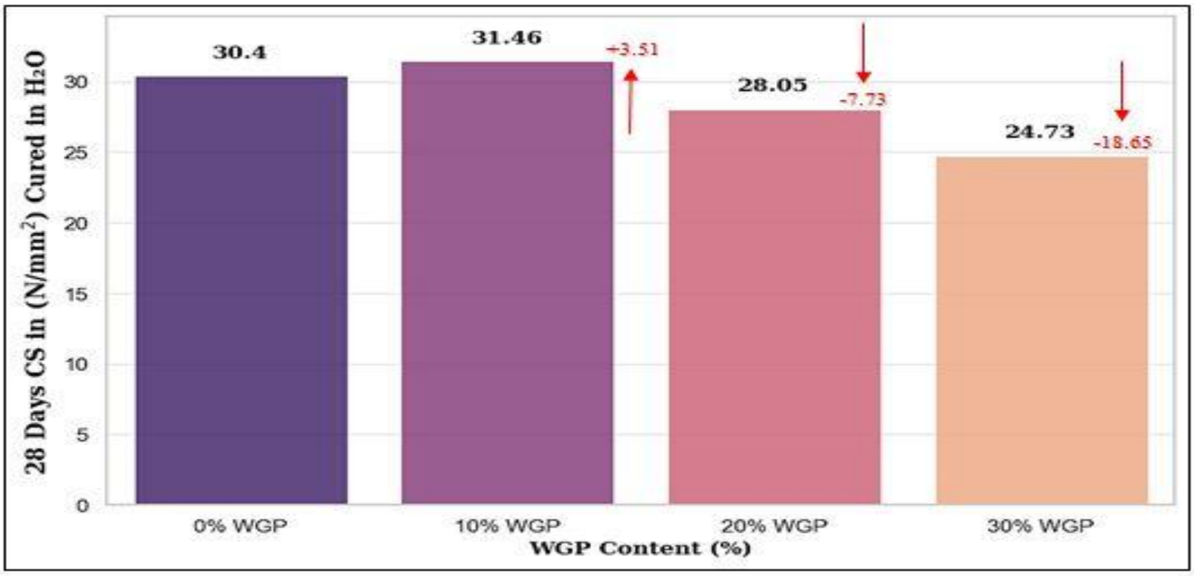

Figure 4: Average 28 days Compressive Strength of WGP concrete in Cured in H_2O

Figure 4, the compressive strengths of Portland cement with Waste Glass Powder (WGP) concrete specimens cured in normal water (H_2O) were tested at 7, 14, 28, and 56 days of hydration. Concrete samples with 10%, 20%, and 30% replacements of Portland cement with WGP achieved compressive strengths of 30.18 N/mm², 26.53 N/mm², and 23.62 N/mm², respectively, while the 0% replacement (control) achieved 29.12 N/mm² at 28 days. This represents a 3.51% increase in compressive strength for the 10% replacement over the 0% control, consistent with findings by Mohammad (2024). The compressive strengths achieved for both control and percentage replacements were below the requirement of BS EN 197-01 (2000), which specifies that concrete samples should achieve 32.5 N/mm² at 28 days. This discrepancy could be attributed to the manual compaction method used in concrete production, as the standard recommends mechanical compaction to achieve the specified results (Zhang *et al.*, 2021).

3.1.4 Splitting tensile strength

The splitting tensile strength results of Portland cement concrete with waste glass powder (WGP) at various replacement levels are shown in Table 4 and Figure 5 respectively.

Table 4: Splitting Tensile Strength of Cylinder Cured in H_2O N/mm² (at 7, 14 and 28 days)

Replacement	**3 cubes 7 days**			**3 cubes 14 days**			**3 cubes 28 days**		
level	1st	2nd	3rd	1st	2nd	3rd	1st	2nd	3rd
Control mix	2.28	2.40	2.39	3.16	3.29	3.36	3.68	3.79	3.67
Average		2.36			3.27			3.71	
10% WGP	2.42	2.52	2.37	3.49	3.55	3.69	3.84	3.74	3.96
Average		2.43			3.58			3.85	
20% WGP	2.22	2.25	2.13	3.03	3.36	3.09	3.36	3.31	3.48
Average		2.20			3.16			3.38	
30% WGP	1.94	1.85	2.06	2.39	2.46	2.28	3.02	2.91	3.10
Average		1.95			2.38			3.01	

Source: Laboratory Research Work (2024)

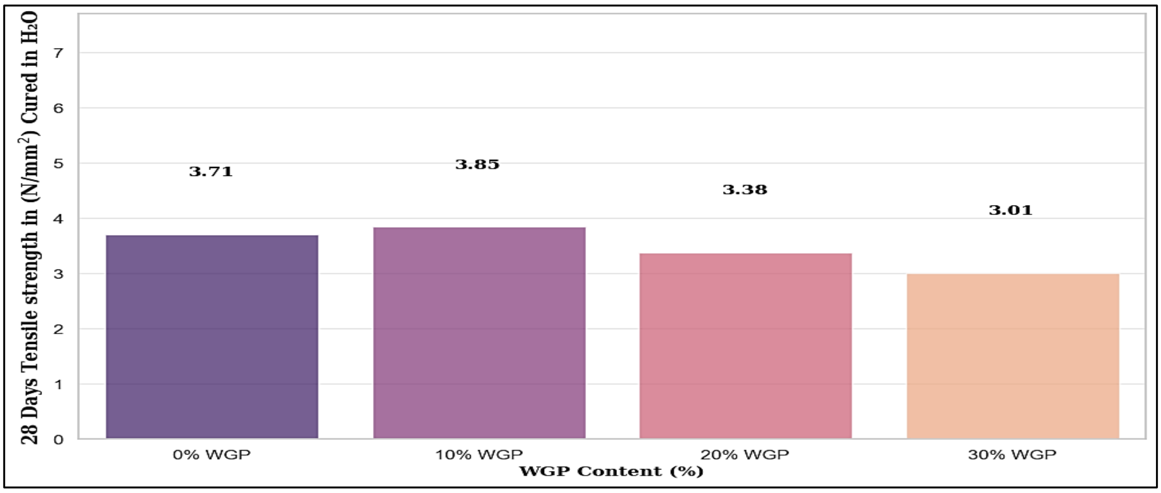

Figure 5: Average 28days Tensile strength of WGP concrete Cured in H_2O

The splitting tensile strength results of Portland cement concrete with waste glass powder (WGP) at various replacement levels was tested at 7, 14, and 28 days. The average result of three specimens for each curing period was reported. The results indicate that adding WGP reduced the tensile strength of the concrete. At 28 days, the tensile strengths for 10%, 20%, and 30% WGP replacements were 3.85 N/mm², 3.38 N/mm², and 3.01 N/mm². This represents a 3.64% increase in tensile strength for the 10% replacement over the 0% control. The reduction in tensile strength for 20 and 30% WGP replacement is likely due to the porous nature of WGP concrete sample, leading to increased water absorption as noted by (Zhang *et al.*, 2021). Unlike compressive strength, where the matrix and aggregate work together, tensile forces cause the aggregates and matrix to pull apart, weakening the concrete (Wang *et al.*, 2021). Despite this reduction, all WGP concrete specimens met the 28-day minimum tensile strength requirement set by BS EN 12390-6 (2009). This suggests that WGP can be effectively used as a supplementary cementitious material in concrete.

3.1.5 Flexural strength

The flexural strengths of Portland cement concrete specimens with waste glass powder (WGP) replacements are shown in Table 4 and Figure 5 respectively.

Table 4: Flexural Strength of Beam Cured in H_2O N/mm^2 (at 7, 14 and 28 days)

control mix	**3 cubes 7 days**			**3 cubes 14 days**			**3 cubes 28 days**		
level	1st	2nd	3rd	1st	2nd	3rd	1st	2nd	3rd
Control mix	2.73	2.88	2.87	3.79	3.94	4.03	4.41	4.55	4.41
Average		2.83			3.92			4.46	
10% WGP	2.90	3.02	2.84	4.18	4.26	4.43	4.61	4.49	4.75
Average		2.92			4.29			4.62	
20% WGP	2.22	2.25	2.13	3.63	4.03	3.71	4.03	3.97	4.18
Average		2.20			3.79			4.06	
30% WGP	2.33	2.22	2.47	2.87	2.95	2.73	3.62	3.50	3.73
Average		2.34			2.85			3.61	

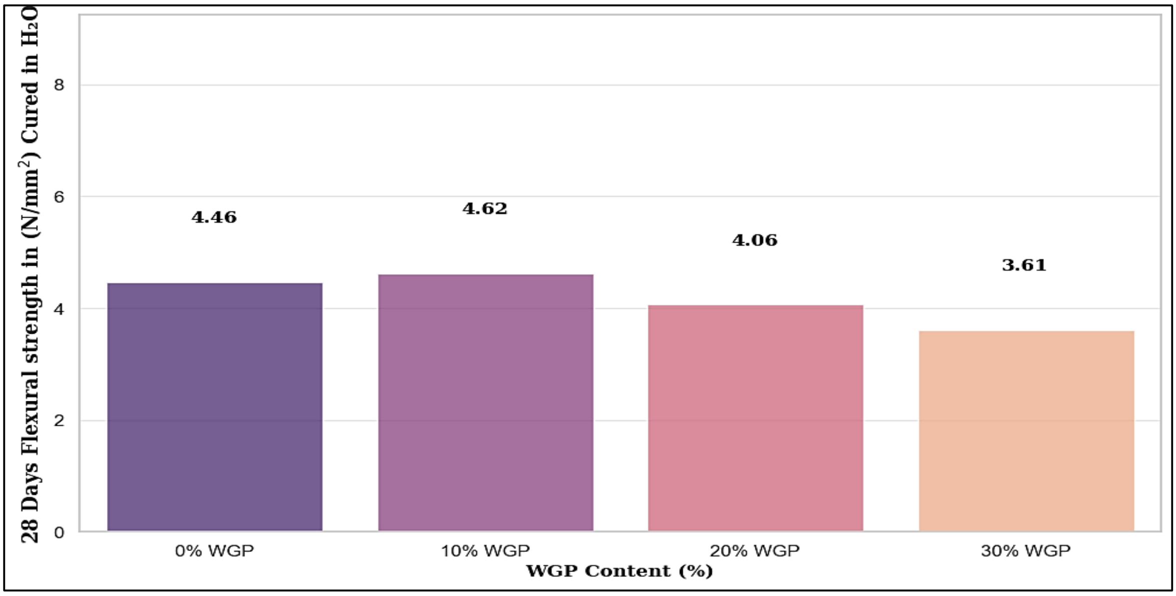

Figure 1: Average 28days flexural strength of WGP concrete Cured in H_2O

The flexural strengths of Portland cement concrete specimens with waste glass powder (WGP) replacements and tested at 7, 14, and 28 days. At 28 days, the most notable results were the flexural strengths for 10%, 20%, and 30% WGP replacements, which were 4.62 N/mm², 4.06 N/mm², and 3.61 N/mm², respectively, compared to 4.46 N/mm² for the control (0% WGP). This represents a 3.46% increase at the 10% WGP replacement level. The slight improvement in flexural strength with the 10% WGP replacement might be attributed to the pozzolanic activity of WGP, which enhances bonding and serves as filler in the concrete matrix. This observation is supported by recent studies indicating that flexural strength tends to improve with increased curing periods when pozzolanic materials are used, as they contribute to a denser and more cohesive matrix ((Zhang *et al.*, 2021).

3.1.6 Ultrasonic pulse velocity (UPV) of Concrete Cured in H_2 O

The Ultrasonic Pulse Velocity (UPV) is shown in Tables 5a, 5b and Figure 6 respectively.

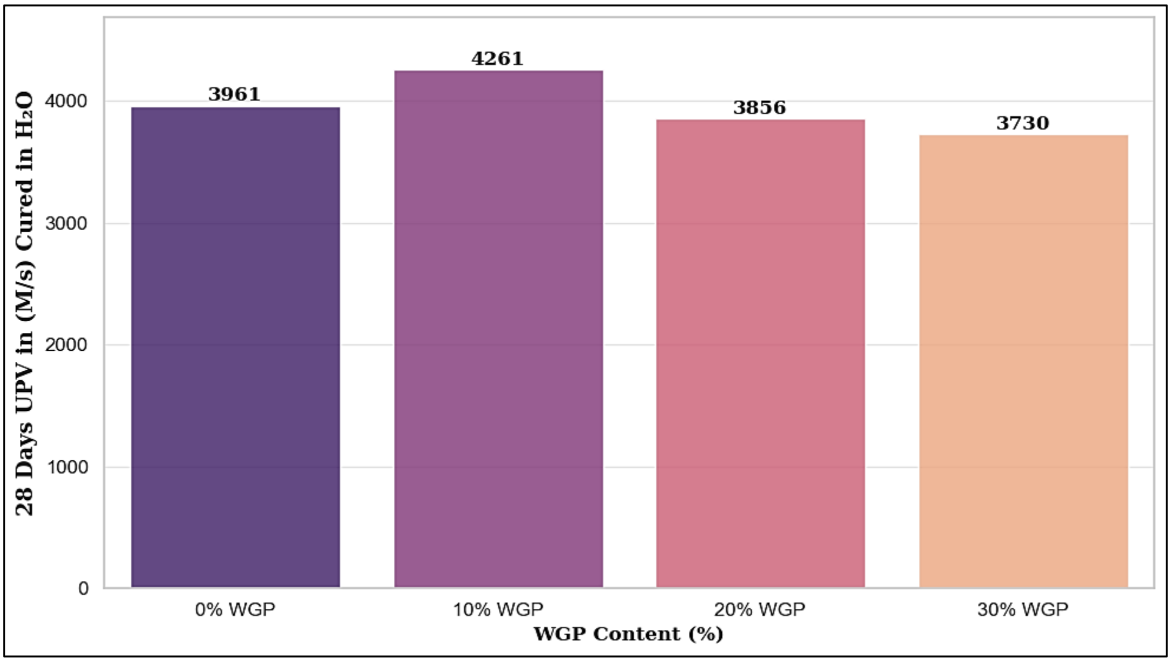

Figure 6: Average 28 days UPV of WGP concrete Cured in H_2O

Table 5a: Ultrasonic pulse velocity (UPV) of cubes cured in H_2O in m/s (At 7, and 14days)

Replacement	3 cubes 7 days			3 cubes 14 days		
level	1st	2nd	3rd	1st	2nd	3rd
Control mix	3503	3527	3484	3802	3774	3745
Average		3505			3774	
10% WGP	3774	3891	3802	4054	4082	4049
Average		3822			4061	
20% WGP	3375	3490	3465	3609	3634	3615
Average		3443			3619	
30% WGP	3213	3229	3237	3579	3657	3542
Average		3226			3593	

Table 5b: Ultrasonic pulse velocity (UPV) of cubes cured in H_2O in m/s (At 28 and 56 days)

Replacement	3 cubes 28 days			3 cubes 56days		
level	1st	2nd	3rd	1st	2nd	3rd
Control mix	3953	3922	4008	4405	4464	4444
Average		3961			4438	
10% WGP	4255	4246	4283	4651	4694	4608
Average		4261			4651	
20% WGP	3856	3843	3830	4432	4498	4482
Average		3843			4471	
30% WGP	3707	3698	3784	4222	4359	4257
Average		3730			4280	

The Ultrasonic Pulse Velocity (UPV) test was conducted at 7, 14, 28, and 56 days, and the results are displayed in Tables 5a, 5b, and Figure 6. The test revealed that the inclusion of Waste Glass Powder (WGP) in Portland cement concrete specimens decreased UPV readings initially. This reduction is attributed to increased porosity from WGP, aligning with recent findings that WGP introduces more micro pores into the concrete (Zhang *et al.*, 2021). However, as the curing period increased, UPV values gradually rose across all samples, indicating a refinement in the concrete's microstructure over time (Lee & Kim, 2022). Notably, the 10% WGP specimens showed the highest UPV readings at each testing interval, outperforming the control specimens by 8.32%, 7.08%, 7.04%, and 4.58% at 7, 14, 28, and 56 days, respectively. This improvement suggests that the pozzolanic reaction of the glass powder contributed to a denser matrix (Gupta *et al.*, 2023).

3.1.7 Ultrasonic pulse velocity (UPV) of concrete specimens cured in H_2SO_4

The Ultrasonic Pulse Velocity (UPV) is shown in Table 6 and Figure 7 respectively.

Table 6: Ultrasonic pulse velocity (UPV) of cubes cured in H_2SO_4 in m/s (At 7,14 and 28 days)

Replacement	3 cubes 7 days			3 cubes 14 days			3 cubes 28 days		
level	1st	2nd	3rd	1st	2nd	3rd	1st	2nd	3rd
Control mix	3381	3405.0	3362	3680	3652	3623	3843	3812	3908
Average		3383			3652			3854	
10% WGP	3652	3769	3680	3932	3960	3927	4235	4216	4263
Average		3700			3939			4238	
20% WGP	3253	3368	3343	3487	3512	3493	3846	3733	3820
Average		3321			3497			3799	
30% WGP	3091	3107	3115	3457	3535	3419	3627	3578	3674

Average	3104	3471	3626

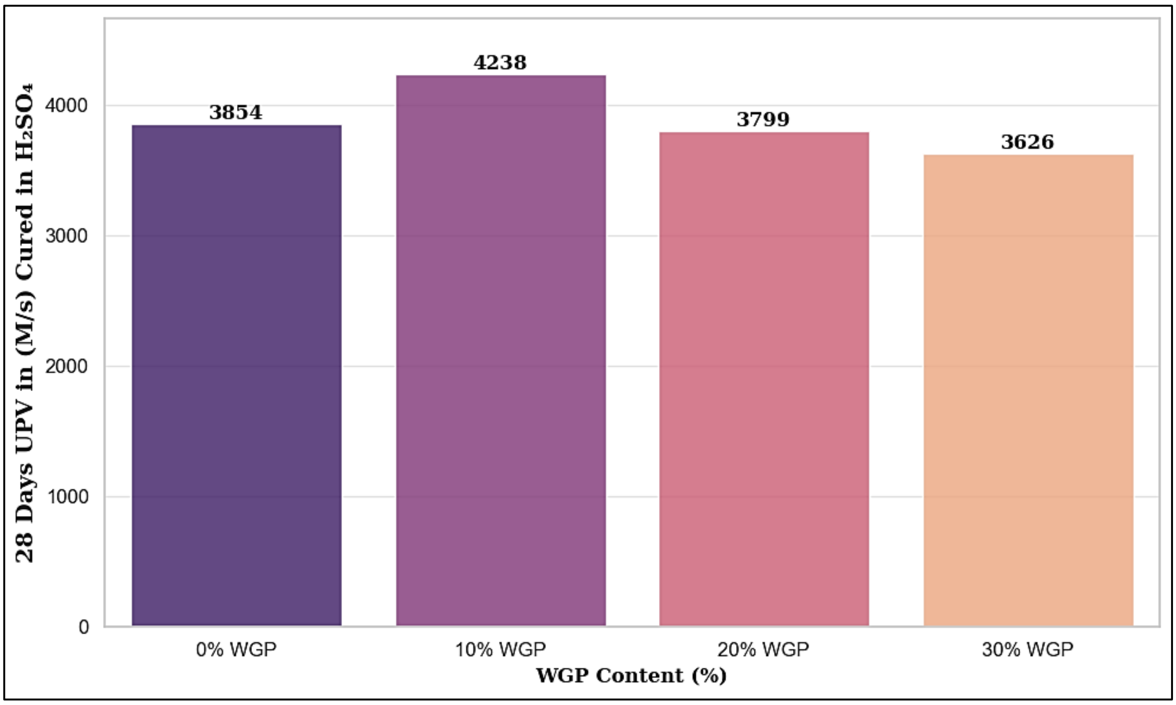

Figure 7: Average 28 days UPV of WGP concrete Cured in H_2SO_4

The Ultrasonic Pulse Velocity (UPV test results for Portland cement with waste glass powder (WGP) concrete specimens cured in sulfuric acid (H_2SO_4) are presented in Table 6 and Figure 7. These specimens were tested at 7, 14, 28, and 56 days of hydration. At 28 days, specimens with 10%, 20%, and 30% WGP replacements had UPVs of 4238, 3799, and 3626 m/s, respectively, compared to 3854 m/s for the control. This represents a 0.54%, 1.13%, and 2.87% decrease in UPVs for 10%, 20%, and 30% WGP replacements, respectively, and a 2.70 % decrease for 0% WGP replacement. The control samples (0% WGP) experienced a significant reduction in strength when exposed to the sulfuric acid medium. In contrast, the concrete specimens with 10% and 20% WGP replacements exhibited better resistance to the acid, suggesting that WGP enhances the durability of concrete in acidic environments. This improved resistance is likely due to the pozzolanic activity of WGP, which acts as a filler or binder, contributing to a denser and less permeable matrix as noted by (Zhang *et al.*, 2021).

3.1.8 Ultrasonic pulse velocity (UPV) of concrete specimens cured in $MgSO_4$

The Ultrasonic Pulse Velocity (UPV) is presented in Table 7 and Figure 8.

Table 7: Ultrasonic pulse velocity (UPV) of cubes cured in $MgSO_4$ in m/s (At 7, 14 and 28days)

Replacement	**3 cubes 7 days**			**3 cubes 14 days**			**3 cubes 28 days**		
level	1st	2nd	3rd	1st	2nd	3rd	1st	2nd	3rd
Control mix	3403	3500	3384	3702	3664	3655	3831	3800	3836
Average		3429			3674			3822	
10% WGP	3724	3831	3772	4034	4052	4026	4133	4124	4161
Average		3776			4037			4139	
20% WGP	3275	3390	3345	3509	3234	3502	3734	3721	3708
Average		3336			3415			3721	
30% WGP	3103	3109	3117	3449	3547	3431	3585	3576	3662
Average		3110			3476			3608	

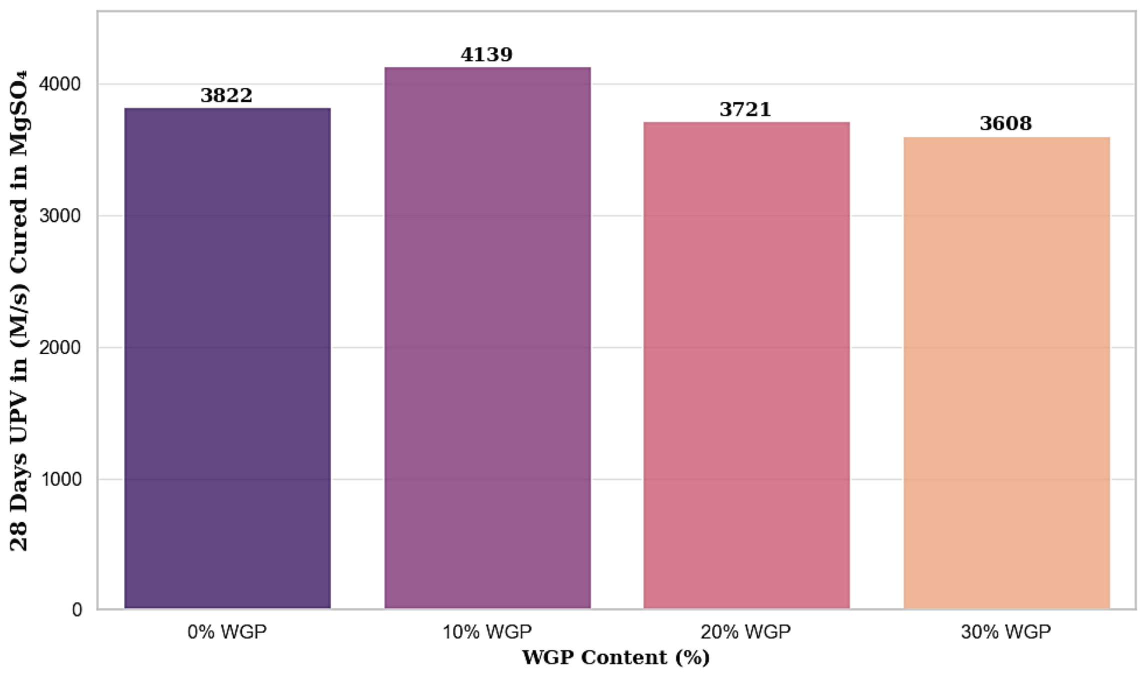

Figure 8: Average 28 days UPV of WGP concrete Cured in $MgSO_4$

The Ultrasonic Pulse Velocity (UPV) test results for Portland cement concrete specimens with waste glass powder (WGP) cured in magnesium sulfate ($MgSO_4$) was tested at the 28-day mark, the concrete specimens with 10%, 20%, and 30% WGP replacements achieved UPVs of 4139, 3721, and 3607 m/s, respectively, compared to 3822 m/s for the control specimen with 0% replacement. This represents a 2.86%, 3.28%, and 3.30% decrease in UPVs for 10%, 20%, and 30% WGP replacements, respectively, and a 3.50 % decrease for 0% WGP replacement. The control samples were more affected by $MgSO_4$, which is known to decompose key cement components, leading to the formation of non-binding hydrated magnesium silicate. In contrast, WGP-modified concrete, particularly at 10% and 20% replacements, showed better resistance due to the pozzolanic activity of WGP, which reduces the formation of sulfate attack products like gypsum and ettringite (Zhang *et al.*, 2021).

3.2 Validation of Artificial Neural Networks (ANN)

3.2.1 Validation of the ANN model for predicting the compressive strength of WGP concrete exposed to H_2SO_4

Table 8: Statistical Assessment of Error in the Developed ANN Model

Statistical Checks	R^2	MAE	MSE
Training	0.9870	0.2667	0.1346
Testing	0.9804	0.2418	0.2124

y_pred (N/mm^2) = 0.9409 * X + 1.5862 ($R^2 = 0.98$)
Where:
y_pred is the predicted value for compressive strength of WGP concrete exposed to H_2SO_4
X represents the variables values.
X is express as, $X = \beta_0 + \beta_1X_1 + \beta_2X_2 + \beta_3X_3 + \ldots + \beta n\ Xn + \epsilon$
$X_1, X_2, \ldots, Xn$ are the independent variables.
$\beta_0, \beta 1, \ldots, \beta n$ are the coefficients.
0.9409 is the gradient of the regression line.
1.5862 is the point where the line crosses the y-axis.

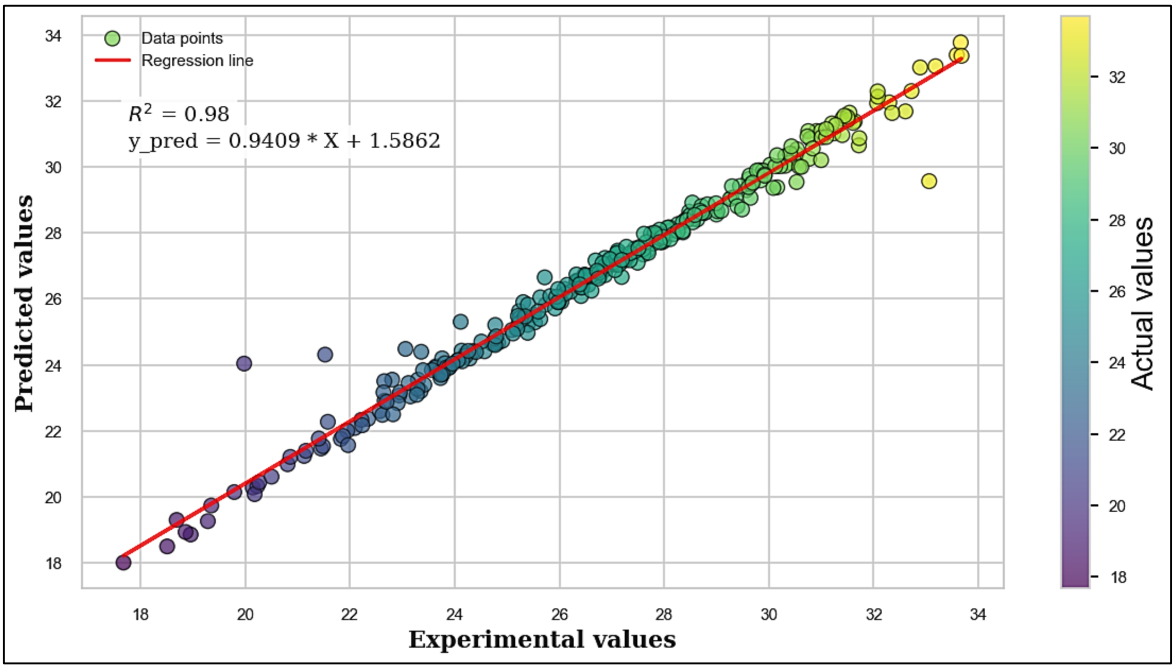

Figure 9: Correlation between Experimental and Predicted Compressive Strength after H_2SO_4 Attack

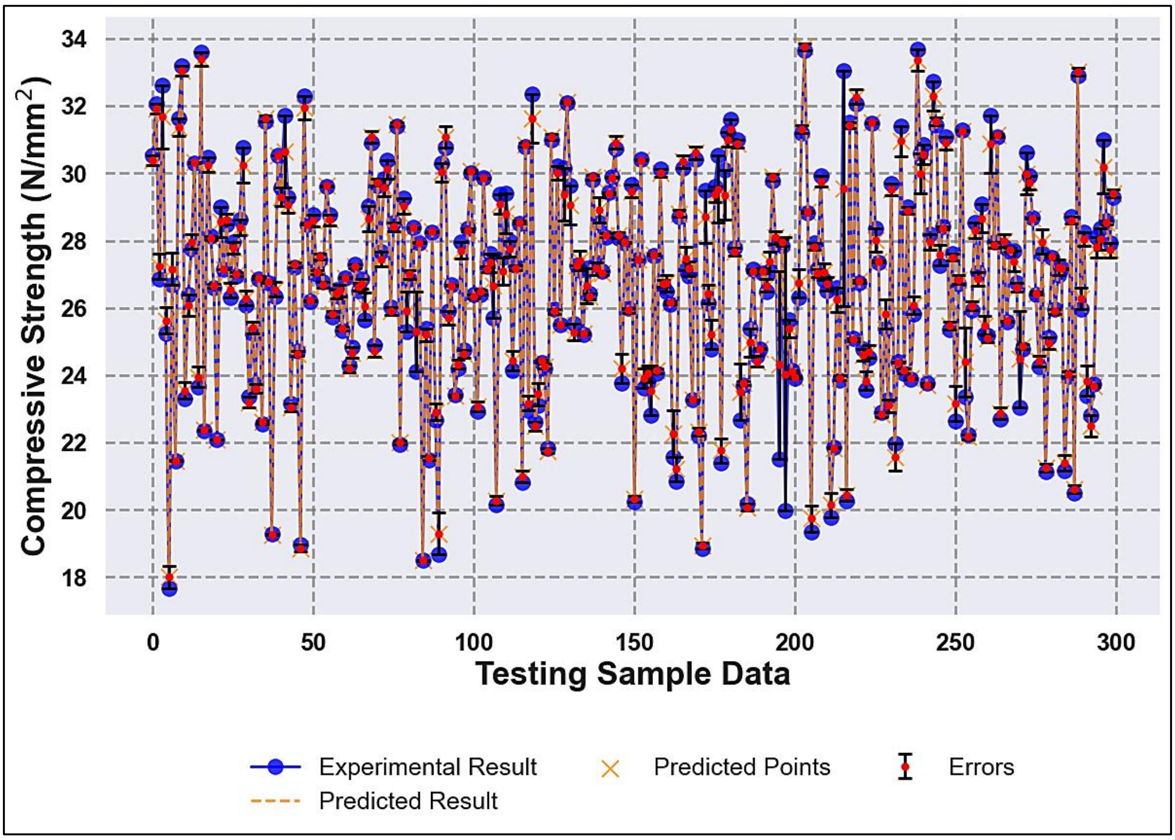

Figure 10: Representation of Experimental, Predicted, and Error Values

The ANN model used to predict the compressive strength of WGP concrete exposed to H_2SO_4 shows strong performance, as evidenced by the metrics provided, as shown in Table 8 Figure 9 and 10 present the training r² value of 0.9870 indicates that the model explains about 98.70% of the variance in the training data, demonstrating its effectiveness in capturing the relationships within the dataset. The testing r² value of 0.9804 is also high, reflecting the model's robust generalization to new data. This suggests that the model performs well in predicting the compressive strength of WGP concrete under acidic conditions, as supported by similar findings in recent study of (Zhang *et al.*, 2021). Additionally, the low MAE and MSE values further underscore the model's a ccuracy and reliability. With training MAE of 0.2667 and testing MAE of 0.2418, the model shows minimal average error in its predictions. The MSE values, 0.1346 for training and 0.2124 for testing, indicate that the model effectively minimizes larger prediction errors. These results suggest that the WGP concrete maintains considerable strength even when exposed to sulfuric acid, making it a viable material for environments prone to acid exposure. This finding is also supported by recent studies such as (Zhang *et al.,* 2021).

3.2.2 Validation of the ANN model for predicting the compressive strength of WGP concrete exposed to $MgSO_4$

The ANN model's performance in predicting the compressive strength of WGP concrete cured in $MgSO_4$ is outstanding, as shown in Table 9 and Figure 11 and 12 present the training r^2 value of 0. 9916 indicates that the model accounts for 99.16% of the variance in the training data, demonstrating its ability to accurately capture the relationships within this dataset and the testing R^2 value of 0.9919, which suggests that the model generalizes remarkably well to new data.

This high level of accuracy highlights the model’s effectiveness in predicting the compressive strength of WGP concrete under $MgSO_4$ exposure as supported by (Zhang *et al.*, 2021). The low MAE and MSE values further reinforce the model's precision. The training MAE of 0.1842 and testing MAE of 0.1583 reflect minimal average prediction errors, with the model showing particularly strong performance on the testing dataset. The MSE values of 0.0698 for training and an exceptionally low 0.0556 for testing indicate that the model effectively minimizes prediction errors, especially with new data. These results suggest that WGP concrete maintains excellent durability and strength in $MgSO_4$ environments, making it a promising material for use in such conditions which align with the findings of (Gupta *et al.*, 2023).

Table 9: Statistical Assessment of Error in the Developed ANN Model

Statistical Checks	**R^2**	**MAE**	**MSE**
Training	0.9916	0.1842	0.0698
Testing	0.9919	0.1583	0.0556

y_pred (N/mm^2) = 0.9390 * X + 1.8092 ($R^2 = 0.99$)

Where:

y_pred is the predicted value for compressive strength of WGP concrete exposed to $MgSO_4$

X represents the variables values.

X is express as, $X = \beta_0 + \beta_1X_1 + \beta_2X_2 + \beta_3X_3 + \ldots + \beta n\ Xn + \epsilon$

$X_1, X_2, \ldots, Xn$ are the independent variables.

$\beta_0, \beta 1, \ldots, \beta n$ are the coefficients.

0.9390 is the gradient of the regression line.

1.8092 is the point where the line crosses the y-axis.

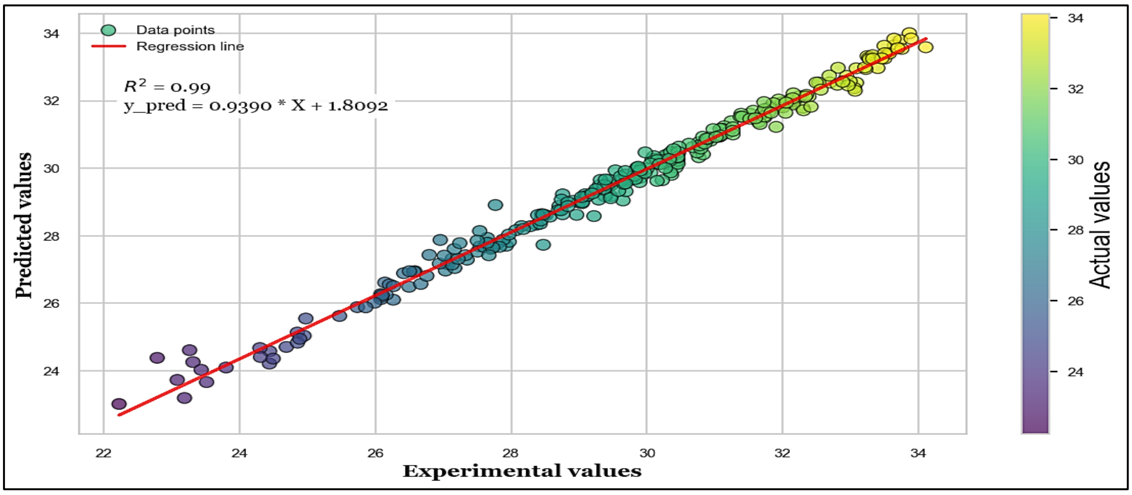

Figure 11: Correlation between Experimental and Predicted Compressive Strength after $MgSO_4$ Attack

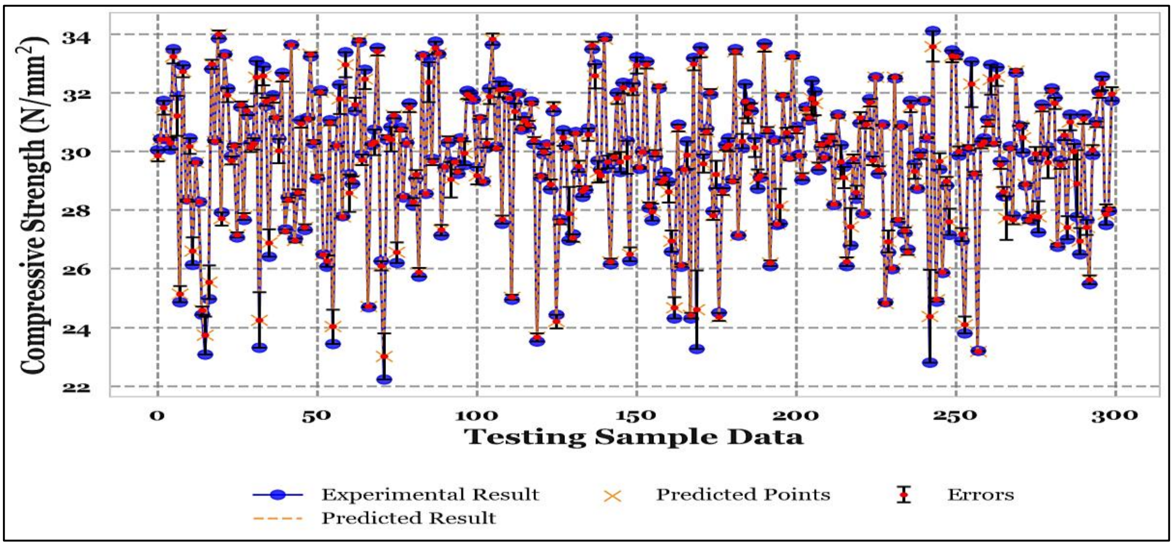

Figure 12: Representation of Experimental, Predicted, and Error Value

IV. Conclusion

The study concluded that waste glass powder (WGP) as a partial cement replacement enhances concrete's durability in aggressive chemical environments. Compressive strength tests showed that 10% WGP replacement achieved a 3.51% increase in strength over the control when cured in water, though none met BS EN 197-1 standards. WGP-enhanced mixes, particularly those with 10% and 20% replacements, showed improved resistance in sulfuric acid (H_2SO_4) and magnesium sulfate ($MgSO_4$) environments. Ultrasonic Pulse Velocity (UPV) tests initially revealed increased porosity and reduced UPV, but these values improved over time, indicating a denser matrix and enhanced chemical resistance. While tensile strength declined at higher WGP levels (20% and 30%), mixes with 10% and 20% WGP met BS EN 12390-6 standards, with slight flexural strength gains attributed to WGP's pozzolanic effects. An Artificial Neural Network (ANN) model accurately predicted compressive strength under H_2SO_4 and $MgSO_4$ exposure, achieving high R² values of 0.99 in training and 0.98-0.99 in testing, with low Mean Absolute Error (MAE) and Mean Squared Error (MSE), validating WGP concrete's resilience in acidic environments

References

[1]. Alkadhim, H. A., Amin, M. N., Ahmad, W., Khan, K., Nazar, S., & Faraz, M. I. (2022). Evaluating the strength and impact of raw ingredients of cement mortar incorporating waste glass powder using machine learning and Shapley Additive Explanations (SHAP) methods. Materials, 15(20), 7344.https://doi.org/10.3390/ma15207344

[2]. British standard instruction, "BS EN 197-1:2000. Part 1. Cement composition, Specifications and Conformity criteria for common cement. British standard institution (BSI), London, UK," in BSOL, ed. 2000.

[3]. British Standards Institution, "BS EN 1992-1-1:2000. Euro code 2: Design of Concrete Structures, Part 1-1: General Rules and Rules for Buildings. BSI, London, UK," ed, 2004.

[4]. British Standards Institution. (2000). BS EN 12390-5:2000 – Testing hardened concrete. Part 5: Flexural strength of test specimens. BSI Standards Limited.

[5]. British Standards Institution. (2000). BS EN 206-1:2000 – Concrete – Part 1: Specification, performance, production, and conformity.

[6]. British Standards Institution. (2013). BS EN 206-1:2013 Concrete – Part 1: Specification, performance, production, and conformity. London, UK: Author.

[7]. British Standards Institution. (2022). BS 812-2: Sampling and testing aggregates. London: BSI.

[8]. BS EN 12390-3. (2009). Testing hardened concrete. Compressive strength of test specimens.

[9]. BS EN 12390-6. (2009). Testing hardened concrete. Tensile splitting strength of test specimens. British Standards Institution.

[10]. Cardinal Stone. (2024). Nigerian cement market report 2023. Retrieved from https://www.cardinalstone.com

[11]. Environmental Protection Agency. (2021). Inventory of U.S. greenhouse gas emissions and sinks: 1990–2019. U.S. Environmental Protection Agency. https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks

[12]. Ganesan, K., Rajagopal, K., & Thangavel, K. (2018). Study on mechanical properties of concrete with glass powder. Construction and Building Materials, 160, 610-617.

[13]. Gupta, A., Siddique, R., & Sengupta, P. (2022). An economic feasibility analysis of glass powder as a partial replacement of cement in concrete. Journal of Cleaner Production, 334, 130609.

[14]. Han, B., Yu, R., & Ou, J. (2023). A review on the application of graphene oxide in cement- based materials. Cement and Concrete Composites, 117, 105922.

[15]. Ibedu, M. U., Akinola, S. R., &Omole, D. O. (2023). The influence of ordinary Portland cement on the mechanical properties of concrete: A review. International Journal of Structural Engineering, 29(1), 45-60.

[16]. Lee, D., & Kim, Y. (2022). Towards standardized regulations for waste glass powder in concrete: A review of current challenges and solutions. Journal of Sustainable Construction Materials, 45(3), 213-227.

[17]. Muhammad, F. U. (2024). Enhancing the visualization of a neural network architecture diagram using Matplotlib in Python.

[18]. Nguyen, H., Tran, T., & Nguyen, H. (2020). Predicting the compressive strength of concrete using machine learning algorithms. Advances in Civil Engineering, 2020, 1-11.

[19]. Nwaobakata, C., & Eme, D. B. (2018). Properties and composition of ordinary Portland cement and its comparison with other types of cement. Journal of Building Materials, 32(3), 115-128.

[20]. Patel, A., & Singh, M. (2020). Machine learning models for concrete compressive strength prediction: A review. Advances in Engineering Software, 142, 102905.

[21]. Salawu, R. A. (2018). Environmental impact of cement production and the need for sustainable solutions. Environmental Science and Pollution Research, 25(13), 12345-12358.

[22]. Sharma, S., & Chauhan, S. (2021). Predictive modeling of concrete compressive strength using machine learning techniques. Journal of Civil Engineering and Management, 27(1), 1-10.

[23]. United Nations Environment Programme. (2018). Global chemicals outlook II: From legacies to innovative solutions. United Nations Environment Programme. https://www.unep.org/resources/report/global-chemicals-outlook-ii

[24]. Wang, X., & Li, T. (2023). The effect of glass powder characteristics on concrete properties: A comprehensive review. International Journal of Concrete Research, 50(2), 105-120.

[25]. Zhang, Q., Li, Q., & Zhang, Z. (2021). Effect of glass powder on the strength and microstructure of cementitious materials. Journal of Materials in Civil Engineering, 33(3), 04020462.