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ARTICLE

Influence of Fly Ash, Alcofine, Alkaline Molarity, Curing Duration and Machine Learning Predictions on Geopolymer Concrete

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ABSTRACT

The study is motivated from the perspective of developing an eco-friendly and effective alternative to cement-based materials. One of the contributions of this research lies in the assessment of three different concentrations of sodium hydroxide (8M, 12M, and 16M) along with the use of Activated Low-Calcium Fly Ash (ALF) as a supplementary cementitious material. Another contribution is the use of predictive modelling on experimental data using Decision Tree regression for estimating the compressive strength. The experimental results showed that the workability, compressive strength, split tensile strength, and flexural strength of GPMC improved with the increase of fly ash content from 325 to 400 kg/m³. Also, the best mechanical performance was recorded at the highest molarity of 16M and 28 days of curing. Analysing the stress and strain showed typical elastic behaviour with gradual softening after peak stress which is a characteristic of geopolymer-based materials. Testing for water absorption showed that increase in fly ash content resulted in lower porosity which indicates increased density and long-term durability. In addition, the predictive modelling approach also reached a very high coefficient of determination, validating the model's robustness and the relationship between the input parameters and the compressive strength value. As a conclusion, the research emphasises the capabilities of optimising the mix design parameters to enhance the mechanical properties of the geopolymer concrete, making it more eco-friendly when compared to traditional Portland cement based systems.

Keywords: Alkaline Solution Molarity; Compressive Strength; Flexural Strength; Fly Ash; Geopolymer Concrete; Split Tensile Strength

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1. Introduction

Geopolymer concrete (GPMC) is emerging as a sustainable alternative to traditional Portland cement concrete, leveraging industrial by-products like fly ash to reduce carbon emissions. The incorporation of ALF, a high-performance pozzolanic material, has further enhanced the performance of GPMC. ALF not only improves workability and strength but also contributes to microstructural densification, making GPMC a viable option for various construction applications. This study explores the impact of ALF on the mechanical and microstructural properties of GPMC under different curing conditions, highlighting its potential for sustainable construction.

Over the past decade, studies linking Artificial Lightweight Fillers (ALF) and additional materials to geopolymer concrete have grown in importance. According to Parveen et al. (2017) [1], results from the initial studies demonstrated that RCHA and ALF improved the mechanical behavior of GPMC when heat-cured. Singhal and Jindal (2017) reported that the strength and workability changed with varying RHA quantities and the amount of NaOH [2]. It was proven by Saxena et al. (2018) that while curing with a microwave, the addition of ALF to pond ash-based GPMC increased both strength and durability and Singhal et al. (2018) focused on how microwave-cured GPMC benefits from the effects of ALF on its microstructure [3,4]. Jindal (2018) pointed out that mineral additives make it possible to cure GPMC ambiently [5]. It was revealed by Srinivasreddy and Balamurugan (2019) that ALF 1203 improved the consistency, setting time and strength of ternary mixtures [6].

Next, Singh and Sandhu (2020) looked at the benefits of ALF in making polymerization faster, enhancing the degree of packing and adding strength when curing conditions changed [7]. The authors found that ALF 1203 resulted in improved reaction and structure during polymerization. Their work in 2021 demonstrated that ALF-based GPMC functions well in areas with high temperatures. It has been shown that using just the right portions of fly ash and GGBFS allows GPMC to achieve up to 60 MPa strength with standard curing. Nishanth and Patil (2022) demonstrated that using high molarity NaOH led to excellent mechanical properties in SCGC and Kumar and Patil (2022) found that a mixture of fly ash:GGBFS:ALF in doses of 65:20:15 offered better durability [8,9].

Latest research has given us a clearer picture of these discoveries. ALF, according to Jayswal and Mungule (2022) [10], enhanced the durability of concrete early in its life and Sambangi et al. (2023) raised the compressive strength of M40 concrete mix to 62.74 MPa with optimized ALF inclusion [11]. Nano-Silica and Silica Fume additive, according to Paruthi et al. (2023) [12], provided better resilience to harmful chemicals. According to Gupta and Rathore (2024) along with another study by Durai et al. (2024) [13,14], both strength and workability increased with ALF under several curing methods. Kandasamy et al. (2024) and Chaudhary et al. (2024) pointed out that ALF can affect ternary blends as well as how GPMC units function in general [15,16]. Diksha et al. (2024) experimented with using machine learning for strength prediction and later Naveen Kumar et al. (2024) and Paruthi et al. (2025) tested alkaline resistance and found that mixing part of the original GGBFS with silica fume and ALF improves the overall performance [17–19].

Even with all these advancements, no study has been found combining changes in fly ash, NaOH concentration and curing times, along with using Decision Tree regression to predict the properties. To narrow this gap, this study offers a united method to estimate how these parameters affect the workability, mechanical and durability performance and strength forecasting of GPMC, supporting engineers in finding eco-friendly and superior options over traditional concrete.

Many studies have addressed the effect that fly ash content, the amount of alkaline activator or the curing method has on geopolymer concrete, but there has not been a systematic study of all of these together [20-22]. In earlier days, much of the research was focused on compressive strength while missing out on tensile, flexural and durability considerations or did not relate multiple ingredient quantities to the material's mechanical features using models [23-25]. This study is unique in that all the different factors, fly ash content, NaOH molarity and curing duration, are tested jointly on how they change the GPMC's overall performance. The aim of this study is to evaluate how variations in fly ash content, alkaline solution molarity, and curing duration influence the mechanical behavior, workability, and durability of Geopolymer Matrix Concrete (GPMC). These findings provide engineers with actionable insights for optimizing geopolymer mix designs in real-world applications, enabling the development of durable, high-performance, and eco-friendly alternatives to traditional cement-based concrete (**Figure 1**).

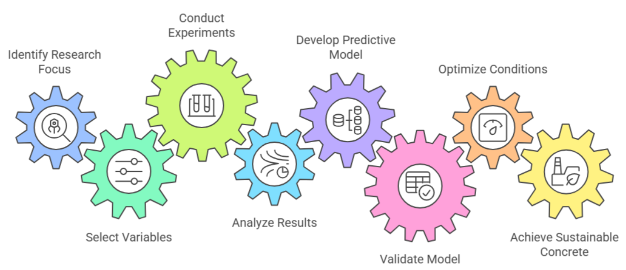

Figure 1. Geopolymer Concrete Optimization Process.

2. Experimental Program

2.1. Materials for GPMC Mixture

2.1.1. Fly Ash

In this study, indigenous accessible low calcium class-F fly ash with specific gravity 1.95 was procured from Ready Mix Concrete plant. The fly ash sample analyzed contained 63.18% SiO_2, 29.31% Al_2O_3, 4.26% Fe_2O_3, 0.22% SO_3, 1.11% CaO, 0.20% Na_2O, and 0.53% loss on ignition (LOI), with a specific surface area of 321.7 m²/kg. While the SiO_2 content was slightly below the minimum 70% mass requirement specified by IS:3812-2003, the SO_3, Na_2O, and LOI values met the standard's maximum limits of 3%, 1.5%, and 5%, respectively.

2.1.2. ALF

ALF 1203, a microfine material created on low calcium silicate slag, enhances GPMC by reducing water demand and improving workability due to its controlled granulation and ultrafine particle size. It significantly boosts GPMC strength, whether used as a cement replacement or additive, improving both fresh and hardened concrete properties.

The material's chemical composition includes 36.89% SiO_2, 6.48% MgO, 22.36% Al_2O_3, 1.25% Fe_2O_3, 0.14% SO_3, and 33.65% CaO. Its physical properties are characterized by particle size distribution with d_{10}, d_{50}, and d_{90} values of 1.8 µm, 4.4 µm, and 8.9 µm, respectively. The bulk density is 680 kg/m³, the specific gravity is 2.7, and the specific surface area is 1200 m²/kg.

2.1.3. Aggregates

All test specimens were prepared using high-quality, well-graded aggregates in a surface-dry condition. Natural fine aggregates (natural sand) and coarse aggregates with maximum sizes of 14 mm, 10 mm, and 7 mm were utilized. **Figures 2** and **3** illustrate the particle size distribution for both coarse and fine aggregate, respectively.

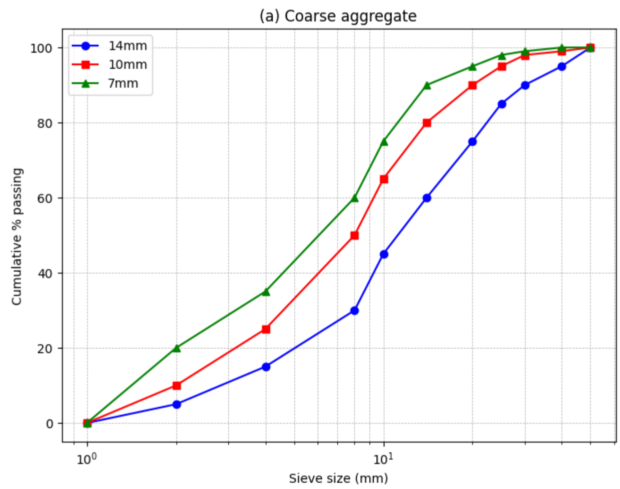

Figure 2. Particle Size Distribution of Coarse Aggregate.

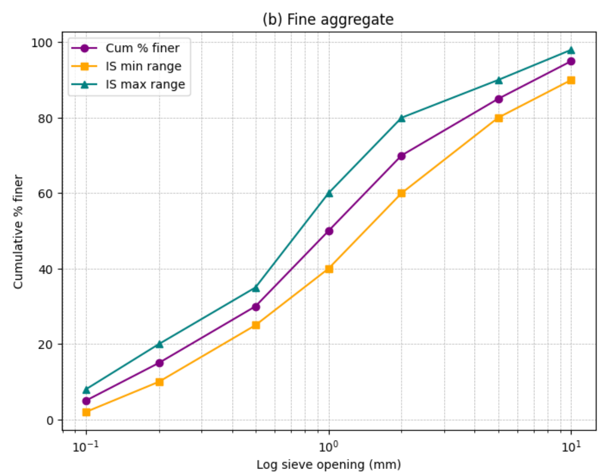

Figure 3. Particle Size Distribution of Fine Aggregate.

The fine aggregates used in the study had a specific gravity of 2.73, a fineness modulus of 3.066, and a water absorption rate of 1.50%. In comparison, the coarse aggregates had a specific gravity of 2.793, a fineness modulus of

7.455, and a lower water absorption rate of 0.80%.

2.1.4. Alkaline Activators

In this study, SDH and SDS were employed as alkaline activators, which are crucial for the geopolymerization process. SDH solutions of the desired molarity were prepared using pellets with 98% purity. Additionally, commercially obtained SDS solution (Na_2SiO_3) with a SiO_2/Na_2O ratio ranging from 1.90 to 2.01 was utilized. The SDS used in this study was a colorless solution with a density of 1.425 g/cm^3. It had a total solids content of 46.5% by mass, meeting the specified requirements for use as an activator in GPMC.

2.1.5. Superplasticizer

SDS and SDH solutions possess higher viscosity compared to water. Consequently, their inclusion results in a GPMC mix that is more cohesive and stickier than traditional concrete. To enhance the workability of the fresh geopolymer mixture, a superplasticizer based on Naphthalene Sulphonate, compliant with the IS 9103:1999 standard, is incorporated (**Table 1**). Concrete Samples Ready for Curing is mentioned in the **Figure 4**.

Figure 4. Concrete Samples Ready for Curing.

Table 1. Properties of Naphthalene Sulphonate-Based Superplasticizer (As Per IS 9103:1999).

Property	Typical Value/Range	Test Method/Standard
Appearance	Brown to dark brown liquid	Visual
Base	Naphthalene formaldehyde sulphonate	IS 9103:1999/ASTM C494
Specific Gravity @ 25 °C	1.20 ± 0.02	IS 9103:1999/ASTM C494
pH (at 25 °C)	7–9	IS 9103/ASTM D1287
Chloride Content	<0.2% (typically < 0.1%)	IS 9103:1999/IS 456
Solid Content	40 ± 2%	IS 9103:1999
Air Entrainment	<2% (depending on dosage and mix)	ASTM C231
Compatibility	Compatible with most types of cement and fly ash	IS 9103
Dosage Range	0.5% – 2.0% by weight of binder	Based on trial mix
Water Reduction Capability	10–25%	ASTM C494 (Type F)
Effect on Setting Time	Minimal to moderate retardation (depending on dosage and temperature)	IS 8142 / ASTM C403

2.1.6. Geopolymer Concrete

The composition of nine GPMC mixtures, both with and without ALF, was investigated. These mixtures were developed using insights from earlier research on GPMC. Initial trials incorporating ALF above 10% demonstrated enhanced compressive strength but were found to be economically unviable. Based on the results of these trials with varying ALF percentages, it was determined to produce all nine mixtures listed in **Table 2** using 10% ALF. The dosage of the superplasticizer was maintained at 2% of the fly ash content. The GPMC mixtures were designed by adjusting their constituent proportions, as detailed in **Table 2**.

Table 2. Mix Proportions Used in This Study.

Mix	Fly Ash (kg/m³)	Fine Aggregate (kg/m³)	Coarse Aggregate (kg/m³)	Total Alkaline Solution (kg/m³)	NaOH (kg/m³)	Na_2SiO_3 (kg/m³)	Extra Water (kg/m³)	Super-plasticizer (kg/m³)	ALF (% of Fly Ash)	Molarity NaOH [M]
M8M1	325	553.4	1291.4	153.8	44	109.8	24.8	6.9	0	8
M8M2	340	546	1274	161	46	115	26	7.2	2	8
M8M3	355	543.6	1268.2	163.4	46.6	116.8	26.4	7.3	4	8
M8M4	370	536.4	1250.8	170.6	48.4	122.2	27.6	7.6	6	8
M8M5	385	528.8	1233.4	177.8	50.6	127.2	28.8	7.9	8	8
M8M6	400	521.2	1216	185	52.8	132.2	30	8.2	10	8
M12M1	325	553.4	1291.4	153.8	44	109.8	24.8	6.9	0	12
M12M2	340	546	1274	161	46	115	26	7.2	2	12
M12M3	355	543.6	1268.2	163.4	46.6	116.8	26.4	7.3	4	12
M12M4	370	536.4	1250.8	170.6	48.4	122.2	27.6	7.6	6	12
M12M5	385	528.8	1233.4	177.8	50.6	127.2	28.8	7.9	8	12
M12M6	400	521.2	1216	185	52.8	132.2	30	8.2	10	12
M16M1	325	553.4	1291.4	153.8	44	109.8	24.8	6.9	0	16
M16M2	340	546	1274	161	46	115	26	7.2	2	16
M16M3	355	543.6	1268.2	163.4	46.6	116.8	26.4	7.3	4	16
M16M4	370	536.4	1250.8	170.6	48.4	122.2	27.6	7.6	6	16
M16M5	385	528.8	1233.4	177.8	50.6	127.2	28.8	7.9	8	16
M16M6	400	521.2	1216	185	52.8	132.2	30	8.2	10	16

Aggregates were brought to a saturated surface dry state before mixing. SDH solution was prepared 24 h in advance and combined with SDS solution an hour before mixing. Fly ash, aggregates, and ALF were dry-mixed, followed by adding the activator solutions and mixing for about 5 min to produce fresh ALF-activated GPMC. A superplasticizer and extra water, if needed, were added during mixing. The mixture was compacted on a vibrating table for 2–3 minutes, and 150 mm cubes were cast for strength tests. The specimens were cured at 27 °C in ambient conditions, following Indian Standard procedures for sampling and testing.

Table 2 provides a detailed composition of GPMC mixtures with varying proportions of fly ash, fine aggregate, coarse aggregate, total alkaline solution, NaOH, Na_2SiO_3, extra water, and superplasticizer. Additionally, the mixtures incorporate ALF as a percentage of fly ash and vary the molarity of NaOH at levels of 8M, 12M, and 16M. The compositions highlight the relationship between these variables, emphasizing the role of fly ash content and molarity in determining the mixture's overall performance and characteristics. The data supports a systematic analysis of the influence of these parameters on the concrete's properties.

3. Results and Discussion

3.1. Workability

The workability of freshly prepared GPMC was evaluated right after mixing using the slump cone test. The slump cone apparatus had dimensions of 100 × 200 × 300 mm, and the procedure followed the guidelines outlined in IS 1199: 1959. The slump values of GPMC, incorporating ALF, were measured at varying fly ash contents and molarity levels, and the results are illustrated in the corresponding **Table 3**.

Table 3. Slump of GPMC with Different Fly Ash Contents.

Fly Ash Content (kg/m³)	8M Slump (mm)	12M Slump (mm)	16M Slump (mm)
325	50	60	70
340	67.5	72.5	77.5
355	85	95	105
370	100	110	115
385	125	132.5	137.5
400	150	155	160

The study investigates the influence of fly ash content on the workability of concrete at varying slump values. The experimental results indicate a direct correlation between increased fly ash content and higher slump measurements across all tested intervals (8M, 12M, and 16M). Specifically, as the fly ash content rises from 325 kg/m³ to 400 kg/m³, the slump values increase progressively, with the 8M slump ranging from 50 mm to 150 mm, the 12M slump ranging from 60 mm to 155 mm, and the 16M slump ranging from 70 mm to 160 mm. These findings suggest that higher fly ash content enhances the fluidity of the mix, which may influence the ease of placement and compaction in concrete applications. Specimen Making of the Concrete is mentioned in the **Figure 5**.

Figure 5. Specimen Making of the Concrete.

3.2. Compressive Strength

The results are represented by the compressive strength values observed at various fly ash content levels.

Figure 6 demonstrates the influence of fly ash content, curing duration, and alkaline solution molarity on compressive strength. Higher fly ash content enhances compressive strength due to increased binding material. Similarly, longer curing periods (from 3 to 28 days) allow more time for the geopolymerization or hydration process, leading to higher strength. The role of molarity is significant: higher molarity (16M) accelerates the reaction, producing greater compressive strength across all curing periods. For instance, at 28 days, the 16M solution consistently outperforms 8M and 12M, indicating that a stronger alkaline solution improves material strength. This behavior highlights that compressive strength depends on the combined effects of fly ash content, molarity, and curing duration, with higher values of each factor contributing to better material performance.

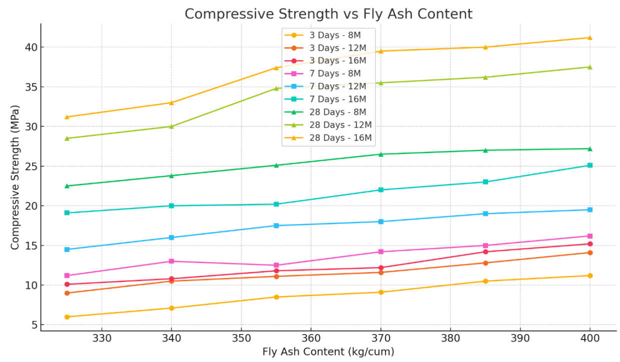

Figure 6. Compressive Strength v/s Fly Ash Contents.

3.3. Splitting Tensile Strength

The load is applied at a controlled rate ranging between 1.2 N/(mm²/min) and 2.4 N/(mm²/min), ensuring smooth application without any abrupt shocks. This test is conducted in accordance with the guidelines outlined in IS 5816-1999. Specimens are tested at different curing ages, specifically at 3, 7, and 28 days, with varying fly ash content and NaOH molarity.

The influence of fly ash content and molarity on the splitting tensile strength of ambient-cured GPMC specimens is analyzed at the aforementioned curing ages. The results illustrating these variations are presented in **Figure 7**, highlighting the relationship between material composition and mechanical performance over time.

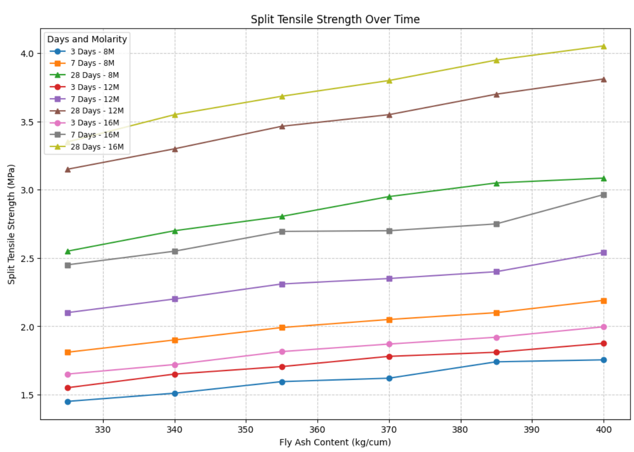

Figure 7. Splitting Tensile Strength v/s Fly Ash Contents.

Figure 7 illustrates the relationship between fly ash content (330–400 kg/cum) and split tensile strength (MPa) at different curing durations (3, 7, and 28 days) for varying molarities of the alkaline solution (8M, 12M, and 16M). It demonstrates that split tensile strength improves with increasing fly ash content, curing time, and molarity. At 3 days, tensile strength is relatively low for all molarities, with gradual improvement as fly ash content increases. By 7 days, the tensile strength shows moderate growth, with higher molarity (16M) achieving more noticeable gains. At 28 days, tensile strength peaks across all conditions, with 16M producing the highest values, followed by 12M and 8M. Higher molarity consistently leads to better tensile strength, as stronger alkaline solutions enhance the material's bonding and reaction processes. The trends highlight the importance of combining higher fly ash content, longer curing durations, and stronger alkaline solutions to achieve optimal tensile strength development.

3.4. Flexural Strength

An investigation was conducted to evaluate the flexural strength of geopolymer samples, considering the effects of NaOH molarity, curing age, and binder content, including the addition of ALF. The assessment was performed at intervals of 3, 7, and 28 days. The specimens were maintained under curing conditions at a constant temperature of 27 °C, and the average strength values were determined from 3 samples for each test. The results are illustrated in **Figure 8**.

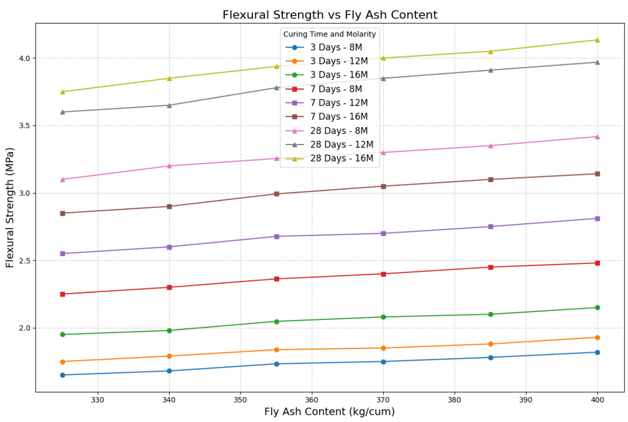

Figure 8. Flexural Strength v/s Fly Ash Contents.

Figure 8 illustrates the relationship between fly ash content (330–400 kg/cum) and flexural strength (MPa) at different curing durations (3, 7, and 28 days) for varying molarities of the alkaline solution (8M, 12M, and 16M). It highlights that flexural strength increases with higher fly ash content, longer curing periods, and greater molarity. At 3 days, flexural strength is relatively low across all molarities, showing gradual improvement as fly ash content increases. By 7 days, there is a moderate increase in flexural strength, with higher molarity (16M) showing more pronounced gains. At 28 days, flexural strength reaches its peak, with 16M consistently achieving the highest values, followed by 12M and 8M. The trends suggest that higher molarity significantly enhances the reaction and bonding, leading to improved flexural performance. Overall, the graph demonstrates the critical roles of fly ash content, curing duration, and molarity in optimizing the material's flexural strength.

3.5. Stress-Strain Behavior

Understanding the stress-strain behavior of construction materials is essential for developing accurate constitutive models. This study evaluated the stress-strain response of GPMC samples prepared with varying NaOH molarity and fly ash content at ambient temperature.

Tests were conducted under controlled conditions, recording load and strain until failure. The stress-strain response of GPMC resembled that of conventional concrete, with an initially slower strain rate up to 80% of peak stress. Beyond this point, deformation increased rapidly, likely due to micro-cracks forming near peak stress, as reported in previous studies. All specimens exhibited brittle failure, with maximum strain values ranging from 1.85–2.25 × 10^{-3} mm/mm.

The stress-strain curves were influenced by compressive strength but not by variations in loading or strain rates. The experimental results aligned well with the analytical model, validating its use for predicting the stress-strain behavior of GPMC under compression.

Figure 9 illustrates the relationship between stress (measured in MPa) and strain for various materials or conditions denoted as M8M1, M8M2, M8M3, M12M1, M12M2, M12M3, M16M1, M16M2, and M16M3. Each curve represents a distinct combination of parameters or material conditions. The general trend for all curves begins with a linear increase in stress as strain increases, indicating an elastic behavior. As the strain continues to increase, the stress reaches a peak, representing the material's maximum strength or stress capacity. Beyond this peak, the stress decreases, suggesting the onset of material softening or failure.

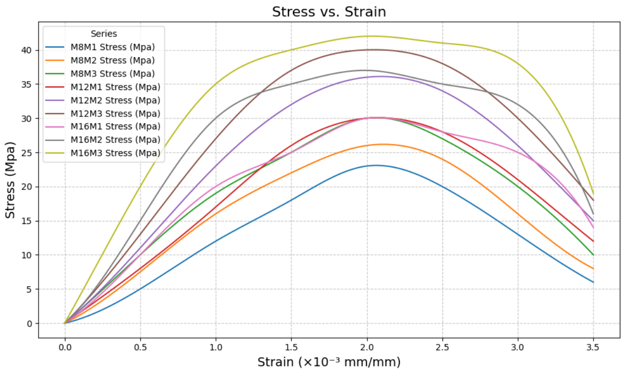

Figure 9. Stress v/s Strain Curve for the Geopolymer Concrete.

3.6. Water Absorption

An investigation was carried out to evaluate the influence of NaOH concentration and fly ash content on the water absorption characteristics of GPMC. This study included an extensive examination of all the mix proportions presented in **Table 3**. The percentage of water absorption for the various GPMC mixes was determined, and the findings are graphically illustrated in **Table 4**.

Table 4. Water Absorption Properties of GPMC at Different NaOH Molarities.

Fly Ash Content (kg/cum)	Water Absorption (%) (8M)	Water Absorption (%) (12M)	Water Absorption (%) (16M)
325	6.05	5.72	5.39
340	5.5	5.2	4.9
355	5.23	4.94	4.65
370	4.95	4.68	4.41
385	4.7	4.45	4.22
400	4.455	4.212	3.969

Table 4 presents the water absorption percentages for GPMC mixes with varying fly ash contents (325–400 kg/m³) and different molarities of NaOH (8M, 12M, and 16M). The missing values were estimated using linear interpolation, based on the observed trend where water absorption decreases as fly ash content increases. This behavior indicates that higher fly ash content likely improves the density and reduces the porosity of GPMC, thereby lowering water absorption. The results highlight the combined influence of fly ash content and NaOH molarity on the water absorption properties of GPMC.

3.7. Model Performance Visualization: Actual vs Predicted Compressive Strength

This analysis focuses on predicting the compressive strength of concrete mixtures based on varying factors such as fly ash content, NaOH molarity, and curing period. Using a Decision Tree regression model, we aim to assess the relationship between these input variables and the resulting compressive strength at different curing stages (3, 7, and 28 days). The model's performance is evaluated by comparing the predicted compressive strength values against the actual measured values, providing insights into the model's accuracy and its ability to generalize to unseen data. This approach helps understand the influence of key factors on concrete strength, which is crucial for optimizing mix designs.

Figure 10 visualizes the performance of the Decision Tree regression model in predicting compressive strength values. The X-axis represents the actual compressive strength (Mpa) measured experimentally, while the Y-axis represents the predicted compressive strength values output by the model. The blue scatter points show the predicted vs. actual values, with points closer to the red dashed line indicating accurate predictions. The red dashed line represents the ideal fit, where the predicted values perfectly match the actual values. Most scatter points align closely with this line, suggesting that the model performs well in predicting compressive strength. The Mean Squared Error (MSE) of 2.03 and R^2 Score of 0.98 indicate strong model performance, with a low error and high explanatory power. This suggests that the Decision Tree regression model effectively captures the relationship between fly ash content, NaOH molarity, curing period, and compressive strength, providing reliable predictions with minimal error.

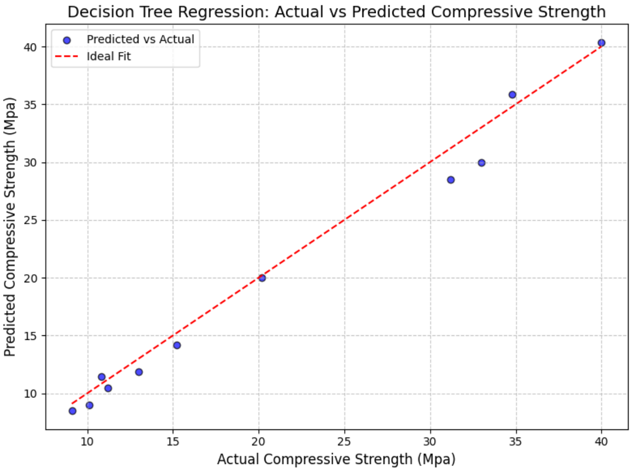

Figure 10. Decision Tree Regression: Actual vs Predicted Compressive Strength.

4. Conclusions

The study provides comprehensive insights into the behavior and performance of GPMC under varying conditions of fly ash content, alkaline solution molarity, curing duration, and other factors. Key conclusions drawn from the analysis are:

(1) **Mix Design and Workability**: The composition of GPMC mixtures reveals a significant impact of fly ash content and NaOH molarity on workability. Higher fly ash content (from 325 to 400 kg/m³) leads to increased slump values, enhancing fluidity and ease of placement. The increase in molarity (from 8M to 16M) also improves slump values across all tested mixtures.

(2) **Compressive Strength**: The compressive strength of GPMC improves with increased fly ash content, longer curing durations, and higher NaOH molarity. For instance, 16M molarity produces the highest compressive strength at 28 days compared to 8M and 12M. This highlights the synergistic effect of these variables in enhancing material strength through improved geopolymerization and bonding.

(3) **Tensile Strength**: Split tensile strength increases with higher fly ash content, longer curing durations, and stronger alkaline solutions. At 28 days, the 16M solution achieves the highest tensile strength, followed by 12M and 8M. This trend underscores the importance of optimizing material composition and curing conditions to maximize tensile performance.

(4) **Flexural Strength**: Similar to tensile and compressive strength, flexural strength is significantly influenced by fly ash content, curing duration, and NaOH molarity. The 16M solution consistently delivers the best flexural performance, demonstrating the critical role of molarity in enhancing the material's flexural properties.

(5) **Stress-Strain Behavior**: The stress-strain graph reveals that GPMC exhibits elastic behavior up to its peak stress, beyond which it softens and eventually fails. Different material conditions (M8M1 to M16M3) show varying maximum stress capacities, reflecting the influence of fly ash content, molarity, and other parameters on mechanical behavior.

(6) **Water Absorption**: Water absorption decreases with higher fly ash content, indicating improved density and reduced porosity in GPMC. This suggests that fly ash contributes to better compaction and durability, with NaOH molarity further influencing these properties.

(7) **Predictive Modeling**: The Decision Tree regression model effectively predicts compressive strength, with an R^2 score of 0.98 and MSE of 2.03, indicating high accuracy and low error. This demonstrates the model's capability to capture the relationships between key variables and provide reliable predictions for material performance.

Overall, the study highlights the critical roles of fly ash content, alkaline solution molarity, and curing duration in optimizing the workability, mechanical properties, durability, and predictability of geopolymer concrete.

4.1. Limitations

Although the results were encouraging, this study has some limitations. Much of the research was carried out in laboratories with controlled settings, but this often does not match the conditions of actual construction sites in terms of temperature, humidity and curing practices. Also, just one fly ash type and just one ALF variation were studied, meaning the results may not apply to other materials used in cement. Researchers analyzed short-term mechanical and durability properties only, up to the 28-day mark and did not study how the material performed in the longer term or how it reacted to various chemicals. Even so, using Decision Tree as the one machine learning method limits application in other sectors, meaning it is not easy to compare it with other available algorithms for predicting compressive strength.

4.2. Recommendations

Future work should examine how GPMC tunnels hold up and function after being exposed to different environments such as cold cycles, salt exposure and carbonation. Examining how the source and quality of fly ash and ALF affect the geopolymer behavior will help improve its adaptability. Training the model using Random Forest, Support Vector Machines or Artificial Neural Networks besides Logistic Regression may improve its power to predict and handle new data. Moreover, when findings from experiments are used in construction work and evaluated for practicality, low cost and impact on the environment, GPMC could become widely accepted as a sustainable concrete for structural engineering.

Author Contributions

S.A.B. has performed this study based on the guidance of B.H.S. All authors reviewed and approved the final version of the manuscript.

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Conflicts of Interest

The authors declare no conflict of interest

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