Experimental Study and Artificial Intelligence Modeling of Single-Component and Multi-Component Fiber-Reinforced Self-Compacting Geopolymer Concrete Based on Ground Granulated Blast Furnace Slag, with Evaluation of Fresh, Mechanical, and Shrinkage Properties

Meysam Rostami[1], Vahid Rostami[2*], AliReza Lork[1]

[1] Department of Civil Engineering, Ki.C., Islamic Azad University, Kish, Iran
[2] Department of Civil Engineering, Ha.C., Islamic Azad University, Hamedan, Iran
[3] Department of Civil Engineering, Ka.C., Islamic Azad University, Karaj, Iran

*** Corresponding author email address**: Rostami.vahid@iau.ac.ir

Received: 2025-04-01 **Reviewed:** 2025-07-11 **Revised:** 2025-07-18 **Accepted:** 2025-07-23 **Published:** 2026-06-25

Abstract

The limitations of raw materials for producing Portland cement concrete in construction processes, greenhouse gas emissions from its production, and the high costs of alternative materials have become an intriguing challenge for engineers and researchers. In this regard, fiber-reinforced self-compacting geopolymer concrete based on slag and fly ash has been developed as an eco-friendly structural mix by replacing aluminosilicate-based pozzolans with cement. This study designed and produced a stable, self-compacting mix with structural properties, incorporating polypropylene and steel fibers. The developed mixtures were prepared by varying the alkaline concentration, pozzolan content, and fiber volume and were evaluated for fresh, mechanical, water absorption, shrinkage, and microstructural properties. The study was conducted at two alkaline molarities of 8 and 12. Results indicated that increasing the molarity from 8 to 12 improves the microstructure of slag-based self-compacting geopolymer concrete, enhancing its density, uniformity, and mechanical properties. These changes lead to increased overall strength and durability of the concrete, although they may raise the cost and consumption of the alkaline solution. Additionally, steel fibers contribute to reinforcing the concrete structure by forming internal resistant networks and stress distribution, effectively enhancing the tensile and flexural strength. These fibers are particularly effective in resisting deep cracks and heavy loads. Furthermore, the study employed the Decision Tree Model for compressive strength modeling, achieving prediction accuracy of over 88% using the developed relationships.

Keywords: *Self-compacting geopolymer concrete, fibers, ground granulated blast furnace slag, fly ash, shrinkage.*

How to cite this article:

Rostami, M., Rostami, V., & Lork, A. (2026). Experimental Study and Artificial Intelligence Modeling of Single-Component and Multi-Component Fiber-Reinforced Self-Compacting Geopolymer Concrete Based on Ground Granulated Blast Furnace Slag, with Evaluation of Fresh, Mechanical, and Shrinkage Properties. Management Strategies and Engineering Sciences, 8(2), 1-20.

1. Introduction

In recent decades, concrete has gained a prominent position in the construction industry as one of the primary building materials [1]. Characteristics such as low production costs, adequate mechanical properties, and easy availability of raw materials have made concrete one of the most widely used materials worldwide [2]. According to statistics, approximately 8.3 billion cubic meters of concrete are produced annually around the globe, making it the second most consumed material by humans after water [3]. Concrete is used in various projects such as residential buildings, office complexes, transportation infrastructures, marine structures, and industrial projects including power plants and dams [4]. However, one of the major challenges in the widespread use of concrete is its heavy reliance on Portland cement as the primary material, the production of which has significant environmental impacts [5].

The production process of Portland cement is a major source of carbon dioxide emissions into the Earth's atmosphere. Studies have shown that the production of Ordinary Portland Cement (OPC) releases large amounts of CO_2 into the air, and this substantial level of pollution, combined with the high energy consumption during production, has made cement production one of the main contributors to climate change [6]. Moreover, structures made with Portland cement begin to deteriorate after about 25 to 35 years due to the inherent limitations of this material, leading to increased maintenance and repair costs [7].

In response, researchers have been exploring sustainable and environmentally friendly alternatives to replace Portland cement. One such solution is the use of geopolymer concrete [6, 8, 9]. Geopolymer concrete, made from alumino-silicate-rich materials, can be produced using pozzolanic materials such as fly ash, metakaolin, blast furnace slag, and zeolite, offering a suitable and environmentally friendly alternative to traditional concrete. These concretes not only have lower environmental impacts but also exhibit superior resistance to chemical attacks, heat, and harsh environmental conditions [10]. Therefore, using of geopolymer concrete, due to its innovative nature and superior mechanical and thermal properties, alongside its potential to reduce environmental impacts, has provided a promising avenue for widespread development and utilization [11]. The main goal of using geopolymer concrete is to eliminate a significant portion of Portland cement and replace it with mineral and industrial pozzolans, especially fly ash, blast furnace slag, and metakaolin [12]. Additionally, adding fibers to these concretes to improve their mechanical and structural properties has become a significant challenge in the geopolymer concrete production process [13]. These fibers, which can be metallic, polymeric, or glass-based, help enhance the concrete's resistance to stress and cracking, making it suitable for use in various environmental conditions and applications [14].

A study also discusses the use of fly ash and alkaline activator materials (NaOH) and Na2SiO3 to bond lateritic soil with crushed lime, reducing the use of traditional geopolymer kilns. The results showed increased compressive strength of the geopolymer mortar containing lateritic soil and molten lime for curing in water from 3 days to 28 days [8]. Similarly, Zhuang et al. (2017) demonstrated that geopolymer mortar exhibits good resistance to sodium chloride and sulfuric acid solutions [15]. Other studies have examined the effect of aggregate properties [9], lightweight aggregate waste [16], styrene-butadiene latex [17], and nano-silica based on fly ash and slag [18] on the mechanical properties and water absorption of geopolymer mortars, which indicated improvements in the properties of geopolymer mortar.

Another recent advancement in the concrete industry is the development of self-compacting concrete (SCC) [19]. These concretes, with high flowability and workability, eliminate the need for vibration during casting, enabling the construction of structures with higher quality and efficiency [20, 21]. In recent years, combining geopolymer technology with self-compacting features has resulted in the production of self-compacting geopolymer concrete, which can offer outstanding structural and environmental properties [22]. Self-compacting geopolymer concrete (SCGC) is gaining recognition as a sustainable and low-carbon alternative due to its unique properties, such as reduced reliance on mechanical vibration and high performance under compressive and tensile stress. Recent studies have shown that the addition of Ground Granulated Blast Furnace Slag (GGBFS) significantly improves the mechanical properties, flowability, and compaction of geopolymer concrete. This addition enhances adhesion and rheological properties while contributing to reduced CO2 emissions during production [1, 23]. Also, using of fillers such as microsilica and fly ash in these concretes not only enhances their workability and durability but also reduces production costs [24].

It should be noted that one of the significant challenges in constructing concrete structures using geopolymer concrete is their resistance to various stresses and environmental influences. Although geopolymer concretes generally show high resistance due to their mineral-based composition and inherent properties, undesirable phenomena such as shrinkage may occur in these concretes. Shrinkage in concrete refers to changes in its volume and dimensions over time, which can cause severe damage to the structure. This issue, especially in self-compacting geopolymer concretes, represents a major challenge. Therefore, this study focuses on the laboratory evaluation of fiber-reinforced self-compacting single and multi-component geopolymer concrete based on blast furnace slag, with an emphasis on fresh properties, mechanical properties, and shrinkage. Consequently, this research aims to not only examine the mechanical and thermal properties but also specifically address the short-term and long-term shrinkage in fiber-reinforced self-compacting geopolymer mixtures, proposing innovative solutions to mitigate this phenomenon. In addition to laboratory evaluations, this study also utilizes advanced artificial intelligence modeling techniques. AI-based modeling is data-driven and estimates computational relationships by identifying patterns between input variables and the target variable through mathematical functions and simulation algorithms. Given the focus on formulating concrete properties to evaluate them in a cost- and time-efficient manner, AI tools present a suitable solution to achieve this objective.

2. Methodology

For the preparation and development of fiber-reinforced geopolymer mixtures with polypropylene, the following materials were used: alkali solutions of sodium hydroxide, water glass (sodium silicate), sand, and polypropylene fibers of sizes 6 mm and steel fibers of 12 mm diameter from Kimiax Company, Tehran. The specifications of the fibers used are presented in Table 1. The aluminosilicate pozzolans used for producing fiber-reinforced geopolymer concrete were of mineral-based slag and fly ash types. In this research, blast furnace slag was obtained from Esfahan Steel Company, and fly ash was sourced from Arak. The chemical specifications of these pozzolanic materials are presented in Table 2.

The alkali solutions used were sodium hydroxide and sodium silicate (Figure. 1). The sodium silicate solution was prepared in gel form, consisting of 1.54% water, 32.5% SiO_2, and 13.4% Na_2O. The sodium hydroxide solution was prepared at concentrations of 8 and 12 molar. It should be noted that NaOH, in its pellet form with 95% purity, was dissolved in water. Additionally, for preparing the NaOH solution, it is required that the solid NaOH and water be mixed 24 hours prior to the experiment to allow the exothermic process to complete and the solution to return to ambient temperature.

Figure 1. Alkali materials used

Table 1. Specifications of fibers used in this research

Length (mm)	6, 12, 18
Density (gr/cm3)	0.91
Tensile strength (MPa)	400
Water absorbency	No
Melting point	160

Table 2. Chemical specifications of pozzolanic materials

Component (%)	C	LSP	Fly ash	GGBS
SiO_2	21.9	0.45	52.1	32.57
Al_2O_3	4.86	4.86	44.7	16.98
Fe_2O_3	3.30	3.30	0.8	1.26
CaO	63.33	63.33	0.09	34.07
MgO	1.15	1.15	0.03	9.69
SO_3	2.10	2.10	-	0.84
Loss of ignition (LOI)	2.40	-	0.7	0.39

In this study, natural aggregates were used to produce fiber-reinforced geopolymer samples. The gradation of sand and gravel was performed in the laboratory according to ASTM C33 [25], and the details of this gradation are presented in Figure 2. The water absorption percentage for fine and coarse aggregates was found to be 3.2% and 1.8%, respectively. The specific gravity for each of these aggregates was 2.59 g/cm³ for fine aggregates and 2.63 g/cm³ for coarse aggregates.

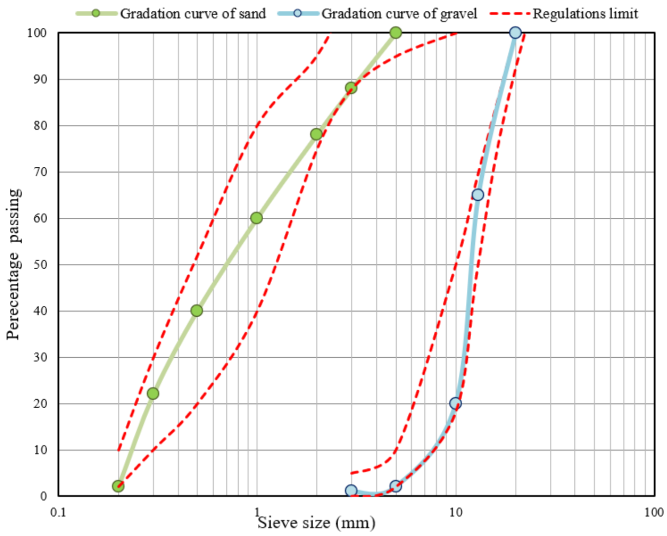


Figure 2. Particle size distribution of aggregate materials

In this study, to improve the strength properties of the geopolymer samples, 1% of closed-end steel fibers with a size of 12 mm were used, as shown in Figure 3(a). Additionally, the effect of fiber size as a variable was investigated in this study. The polypropylene fiber size was selected as 6 mm due to the gradation conditions of the self-compacting mixture and was examined in the geopolymer concrete Figure 3(b).

Figure 3. 12 mm closed-end steel fibers (a), 6 mm polypropylene fibers (b) used in this study.

2.1. Mix Design of Samples

In this study, three mix designs of geopolymer concrete with natural aggregate materials were examined. It is worth mentioning that the amount of sodium silicate for the geopolymer samples was set at 28.64 kg per cubic meter, and the amount of 12 molar water glass solution was set at 38.5. Additionally, in the developed mix designs, 0.25 kg of a carboxylate-based superplasticizer was used to achieve adequate workability and optimal vibration. The details of the proposed mix designs for fiber-reinforced geopolymer concrete are presented in Table 3. It is important to note that the preparation of the alkaline solution involves the exothermic reaction between water and NaOH, which generates significant heat. Therefore, the solution was prepared the day before use and allowed to reach ambient temperature. For the investigation of the fiber effect, 1% by volume of steel fibers and 0.5–1% polypropylene fibers were used in the mix designs. Figure 4 shows laboratory conditions for sample preparation.

Table 3. Mix Designs for Geopolymer Concrete Samples (Cubic Meter)

Sample ID	W	SCMs	C	GGBS	Fly ash	MS	LSP	CA	FA	SP (%SCMs+LSP)	Fiber (%V_f)	NaOH/Sodium	Sodium Silicate	NaOH Solution
OPC	200	450	400	-	50	0	0	800	975	0	0	-	-	-
SCC	200	450	350	-	50	50	250	550	875	1	0	-	-	-
SCC+ST	200	450	350	-	50	50	250	550	900	1	1% ST	-	-	-
SCC+PP	200	450	350	-	50	50	200	550	900	1.5	1%PP	-	-	-
SCC+ST+PP	200	450	350	-	50	50	200	550	900	1.5	0.5%ST+0.5 PP	-	-	-
G-SCGPC	142.237	450	-	450	0	0	100	500	930	2	0	2.5	64.28	38.5
F-SCGPC	142.237	450	-	0	450	0	100	500	930	2	0	2.5	64.28	38.5
M-SCGPC	142.237	450	-	0	0	450	100	500	930	2	0	2.5	64.28	38.5
SCGPC	142.237	450	-	350	50	50	100	500	930	2	0	2.5	64.28	38.5
SCGPC +ST	142.237	450	-	350	50	50	100	500	930	2	1%ST	2.5	64.28	38.5
SCGPC +PP	142.237	450	-	350	50	50	100	500	930	2	1%PP	2.5	64.28	38.5
SCGPC +ST+PP	142.237	450	-	350	50	50	100	500	930	2	0.5%ST+0.5 PP	2.5	64.28	38.5

Figure 4. Laboratory Conditions for Sample Preparation

2.2. Mixing and Sampling Procedure

The geopolymer concrete mixtures were prepared in a 50-liter pan mixer available in the laboratory of one of the research institutes. First, the coarse aggregates and fine aggregates were placed into the mixer to ensure a uniform mixture of the materials. Then, the pozzolanic materials, including fly ash and blast furnace slag, were added to the mixer to mix well with the aggregates. The polypropylene fibers used in this study were added one by one, ensuring their even distribution within the mixer. At this stage, the alkaline solution, consisting of sodium hydroxide and sodium silicate, was added to the dry mix in the mixer, and mixing continued for 2 minutes. After mixing and conducting fresh concrete tests, the concrete was cast into pre-oiled molds, and curing of the geopolymer samples commenced. The samples remained in the molds for 24 hours at 60°C in an oven, after which they were removed from the molds (Figure 5).

Figure 5. Sample Placement Conditions in the Oven at 60°C

After removing the samples from the molds, the geopolymer concrete samples were stored in the laboratory environment until the relevant testing age. Based on the evidence, it was concluded that curing the samples in water or the surrounding environment did not have a significant effect on the compressive strength of the geopolymer concrete. In fact, keeping the samples in water resulted in reduced laboratory operations in this study (Figure 6).

Since one of the most important properties of concrete is its mechanical characteristics, and the duration of the experiment is relatively short, this issue has been addressed in most of the reports presented on this matter. A 10×10 cm concrete cube sample is placed between two jaws of the machine, the safety latch is securely closed, and the dimensions of the sample are defined. Then, the loading operation is performed. The load that the concrete cube can withstand until it reaches the crack point is recorded. Finally, to lower the movable lower jaw, the safety latch is opened so that the jaw moves downward, and this operation is repeated for all the samples. The compressive strength of the sample is calculated by dividing the force that causes the breakage by the cross-sectional area of the sample. The compressive strength tests for all mix designs in this study were conducted at 28 days according to the ASTM C39-11 standard.

Figure 6. Samples produced in the laboratory in this study

3. Findings and Results

3.1. Evaluation of Water Absorption in the self-compacting geopolymer samples

In this study, the water absorption test was performed to evaluate the durability and characteristics of the self-compacting geopolymer samples under different environmental conditions according to ASTM C642 standards. Figure 7 shows the weighed samples and, subsequently, those subjected to heat treatment.

Figure 7. Weighing and drying of geopolymer samples

As reported in past studies, increasing molarity (typically from 8 to 12 molar) results in a stronger alkaline solution that extracts more silica and alumina from raw materials (such as slag or fly ash), leading to the formation of more geopolymer gels. These gels reduce void spaces and create a denser structure, which results in reduced water absorption. At higher molarities, the microstructure of the concrete becomes less porous, and capillary pathways for water penetration are limited. This helps to lower water absorption rates. Therefore, in the present study, water absorption tests were conducted on geopolymer concrete with a 12 molar concentration.

As shown in the figure 8, the water absorption of geopolymer concrete is generally lower compared to ordinary concrete. Geopolymer concrete is produced through a reaction between silica- and alumina-rich materials and an alkaline solution, creating a microstructure primarily composed of three-dimensional silicate chains, which result in fewer voids. The denser microstructure of geopolymer concrete reduces permeability and, consequently, water absorption. This type of concrete has better resistance to water penetration, harmful ions, and environmental degradation due to reduced internal porosity. In contrast, ordinary concrete, which is based on Portland cement, has a structure that includes cement hydrates such as C-S-H and microscopic pores. These pores can absorb water, especially if the quality of mixing and curing is not optimal.

In addition, the study also investigated the effect of adding 1% fibers on the mixture. The inclusion of steel fibers helps to improve the density of the concrete structure by reducing voids in the cement matrix, leading to reduced permeability and water absorption. Steel fibers prevent the growth of microcracks, which further reduces water absorption, particularly in concrete exposed to environmental stresses.

Compared to steel fibers, polypropylene fibers (PP), particularly due to their small diameter and flexibility, help fill microvoids and improve the uniformity of the concrete structure, which also contributes to reducing water absorption. Polypropylene fibers aid in better distribution of internal stresses and prevent the propagation of microcracks, which leads to reduced water penetration into the concrete. Moreover, self-compacting concrete may experience plastic shrinkage during early stages. Polypropylene fibers help reduce this phenomenon, thereby minimizing cracks and permeability.

The results of the study, comparing the addition of 0.5% steel and polypropylene fibers, show that the addition of steel fibers reduces water absorption compared to ordinary concrete, but its effect is less than that of polypropylene fibers, as the former has more influence on mechanical properties. As shown in the SCGPC+PP sample, the water absorption decreases from day 7 to day 28 with the addition of polypropylene fibers. Geopolymer concrete is not more susceptible to fine cracking or plastic shrinkage than ordinary concrete, but polypropylene fibers can minimize these microcracks, thus reducing permeability and water absorption. Polypropylene fibers can help make the geopolymer microstructure more uniform, which also contributes to reducing water absorption.

Additionally, in the geopolymer concrete mix containing 0.5% steel fibers and 0.5% polypropylene fibers in the SCGPC+ST+PP mix design, the combination of steel and polypropylene fibers may have complementary effects. Steel fibers control large cracks and mechanical stresses, while polypropylene fibers can reduce microcracks and permeability. This combination in geopolymer concrete can significantly contribute to reducing water absorption.

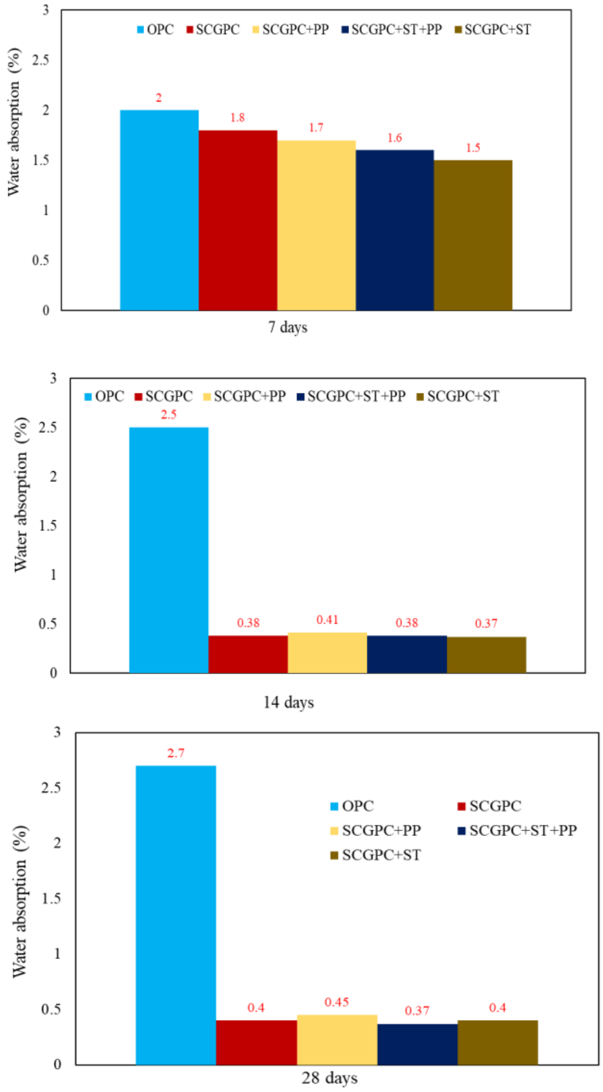


Figure 8. Water absorption results of self-compacting geopolymer samples

3.2. *Evaluation of Compressive Strength Evaluation*

High molarity can reduce the setting time and decrease the workability of concrete, which may pose challenges in maintaining the self-compacting properties of the concrete. Therefore, finding the optimal balance between molarity, workability, and compressive strength is crucial. Thus, the present study produced self-compacting geopolymer mixes at molarity ratios of 8 and 12 molar. It should be noted that the compressive strength test, following the ASTM C109 standard, was performed on cubic samples with dimensions of 10 cm at 7 and 28 days. After breaking three samples from each of the fiber-reinforced geopolymer mix designs, the average compressive strength values at the ages of 7 and 28 days at 8 molar concentrations are shown in Table 4.

In general, the laboratory results related to compressive strength indicate that the self-compacting geopolymer samples containing 1% steel fibers exhibited better performance. The results show that the SCGPC + ST sample (with 1% steel fibers and without polypropylene fibers) reported a compressive strength of 36.03 MPa at 7 days and 40.04 MPa at 28 days.

According to Table 5. the composite fiber-reinforced geopolymer mix containing polypropylene and steel also showed a satisfactory compressive strength of 34.26 MPa at 8 molar concentrations, compared to both self-compacting concrete and ordinary concrete. In self-compacting geopolymer concrete, steel fibers assist in creating a denser geopolymer matrix and improve the strength at the interface between the fibers and the matrix. This helps prevent the propagation of micro-cracks and results in a softer failure behavior, which is highly effective in geopolymer concretes. Figure 9 shows the results of fiber reinforcement in self-compacting concrete and self-compacting geopolymer at 8 molar concentrations.

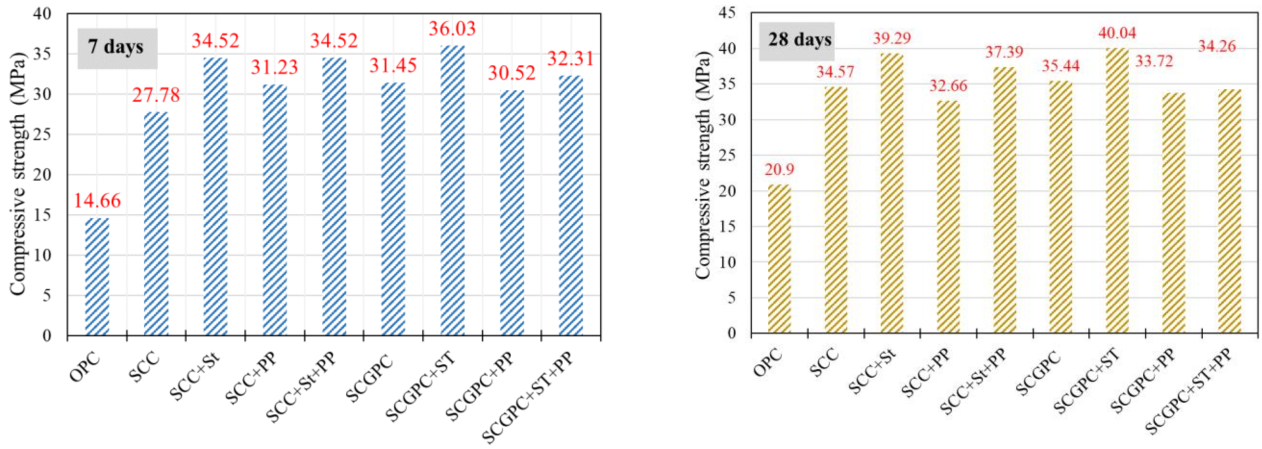


Figure 9. Compressive strength results of 7-day and 28-day self-compacting concrete samples in comparison with 8 molar self-compacting geopolymer concrete.

Increasing the concentration of the alkaline solution leads to the formation of more geopolymer gels and higher density in the concrete structure. This can enhance the compressive strength of the concrete due to improved bonding between particles. Although higher molarity can reduce the setting time and decrease the workability of the concrete, which may pose challenges in maintaining the self-compacting property, it is crucial to find an appropriate balance between molarity, workability, and compressive strength. In this study, self-compacting geopolymer mixtures were developed at a 12 molar concentration and evaluated. Table 4 presents the compressive strength results at 12 molarity.

Increasing the alkaline solution concentration from 8 to 12 molar generally led to an increase in the compressive strength of the geopolymer concrete. This is attributed to the greater formation of geopolymer gels (such as aluminosilicate gels) and the increased density of the concrete structure. As a result, the bonding between particles and structural density improve. At higher molarity, the alkaline solution is able to extract more silica and alumina from raw materials, leading to a better reaction and the formation of a denser geopolymer matrix, which enhances compressive strength.

Table 4. Compressive Strength Results of 7 and 28-Day Geopolymer Concrete Samples at 12 Molar Concentration

Sample ID	C	GGBS	Fly ash	MS	CA	FA	Fiber (%Vf)	CS 7 days	CS 28 days
OPC	400	-	50	0	800	975	0	14.66	20.9
SCC	350	-	50	50	550	875	0	27.78	34.57
SCC+ST	350	-	50	50	550	900	1% ST	34.52	39.29
SCC+PP	350	-	50	50	550	900	1%PP	31.23	32.66
SCC+ST+PP	350	-	50	50	550	900	0.5%ST+0.5PP	34.52	37.39
SCGPC	-	350	50	50	500	930	0	33.17	37.69
SCGPC +ST	-	350	50	50	500	930	1%ST	38.35	48.15
SCGPC +PP	-	350	50	50	500	930	1%PP	32.54	35.29
SCGPC +ST+PP	-	350	50	50	500	930	0.5%ST+0.5PP	35.12	39.45

As shown in Figure 10, steel fibers, particularly at low percentages (0.5–1.5% by weight), can control cracking and crack propagation, thereby increasing the compressive strength of concrete. In this study, the self-compacting geopolymer sample containing 1% steel fibers showed a 25.5% increase in compressive strength as the molar concentration increased from 8 to 12. This increase was less pronounced in samples containing polypropylene (PP) fibers, with an increase of less than 2%. This is because polypropylene fibers typically have less direct impact on the compressive strength of concrete; instead, their effect is more focused on controlling shrinkage-induced cracks and improving durability, which in turn indirectly enhances the compressive strength of the concrete.

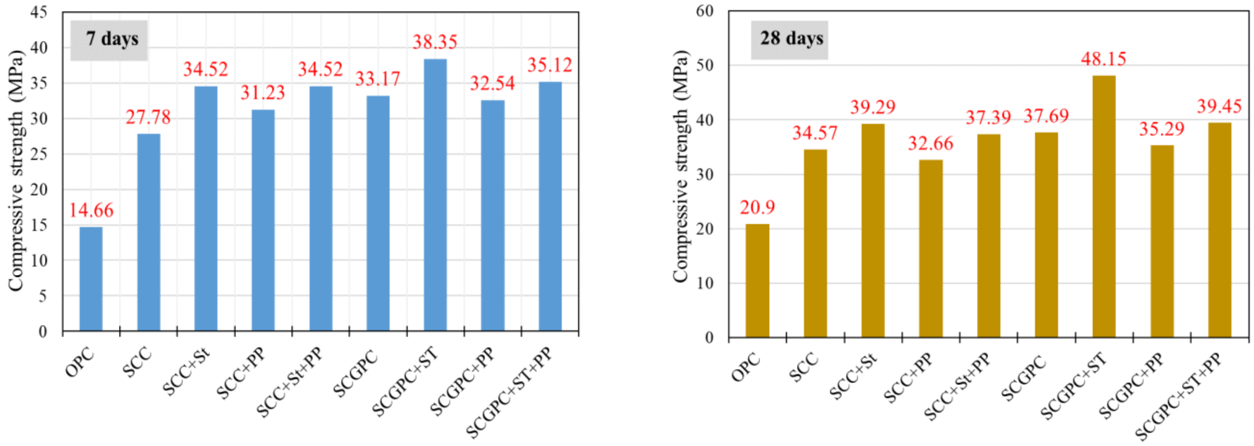


Figure 10. Compressive strength results of 7 and 28-day self-compacting concrete samples compared with self-compacting geopolymer at 12 molar concentration.

3.3. Evaluation of Tensile Strength

The tensile strength of slag-based self-compacting geopolymer concrete is influenced by the molarity of the alkaline solution. At different molarities (such as 8 and 12), differences in microstructure and bonding between geopolymeric particles occur, which directly impact the tensile strength. The tensile strength test on the samples in this study was conducted following ASTM C496 standards.

Tables 5 and 6 present the tensile strength results of self-compacting concrete and geopolymer self-compacting concrete at molarities of 8 and 12, respectively. The tensile strength of slag-based geopolymer concrete at molarity 12 is approximately 20–30% higher than at molarity 8. This increase is due to the improved density and bonding of the geopolymeric microstructure, resulting from more effective alkaline reactions at higher molarity. A higher molarity (12) leads to a reduction in voids and an increase in structural density, which enhances tensile strength. Additionally, at molarity 12, the geopolymeric bonds are stronger, and the concrete matrix has better integrity. Another reason for this could be that not all the silica and alumina present in the slag are fully activated at molarity 8, resulting in a more porous geopolymer structure and weaker chemical bonds between the geopolymeric gels.

Table 5. Tensile Strength Results of 28-Day Geopolymer Concrete Samples at Molarity 8

Sample ID	C	GGBS	Fly ash	MS	CA	FA	Fiber (%Vf)	TS 28 days
OPC	400	-	50	0	800	975	0	2.18
SCC	350	-	50	50	550	875	0	2.93
SCC+ST	350	-	50	50	550	900	1% ST	3.32
SCC+PP	350	-	50	50	550	900	1%PP	3.19
SCC+ST+PP	350	-	50	50	550	900	0.5%ST+0.5PP	3.09
SCGPC	-	350	50	50	500	930	0	3.01
SCGPC +ST	-	350	50	50	500	930	1%ST	3.44
SCGPC +PP	-	350	50	50	500	930	1%PP	3.84
SCGPC +ST+PP	-	350	50	50	500	930	0.5%ST+0.5PP	3.61

Table 6. Tensile Strength Results of 28-Day Geopolymer Concrete Samples at Molarity 12

Sample ID	C	GGBS	Fly ash	MS	CA	FA	Fiber (%Vf)	TS 28 days
OPC	400	-	50	0	800	975	0	2.18
SCC	350	-	50	50	550	875	0	2.93
SCC+ST	350	-	50	50	550	900	1% ST	3.32
SCC+PP	350	-	50	50	550	900	1%PP	3.19
SCC+ST+PP	350	-	50	50	550	900	0.5%ST+0.5PP	3.09
SCGPC	-	350	50	50	500	930	0	3.67
SCGPC +ST	-	350	50	50	500	930	1%ST	4.36
SCGPC +PP	-	350	50	50	500	930	1%PP	4.89
SCGPC +ST+PP	-	350	50	50	500	930	0.5%ST+0.5PP	4.49

Based on the results analyzed, due to the relative weakness of the matrix at molarity 8, the presence of steel fibers has a more significant effect, as it helps compensate for the lack of strength in the matrix. Polypropylene fibers, due to their lower strength and bonding compared to steel fibers, are more effective in reducing microcracks and improving durability. In a denser matrix, the performance of polypropylene fibers improves, and they can be more effective in controlling microcracks and enhancing tensile strength. The increase in tensile strength in this case is around 20%, which shows better performance compared to molarity 8. The SCGPC +PP sample at molarity 12 had a tensile strength of 4.89 MPa, which, compared to molarity 8, represents a 27% increase in self-compacting geopolymer samples. Figures 11 and 12 show the results of the effect of fiber reinforcement (steel and PP) at molarities 8 and 12.

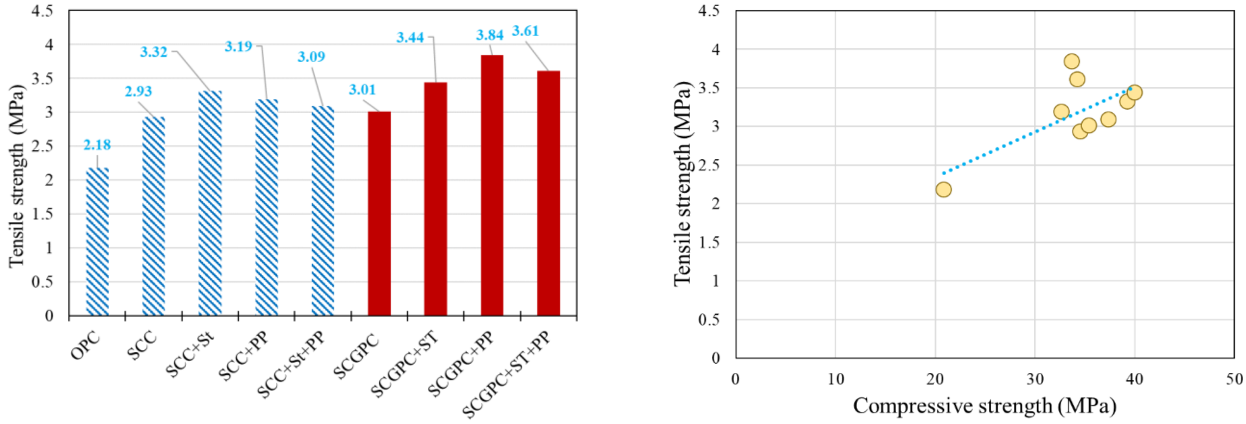


Figure 11. Tensile strength of geopolymer mixtures at molarity 8.

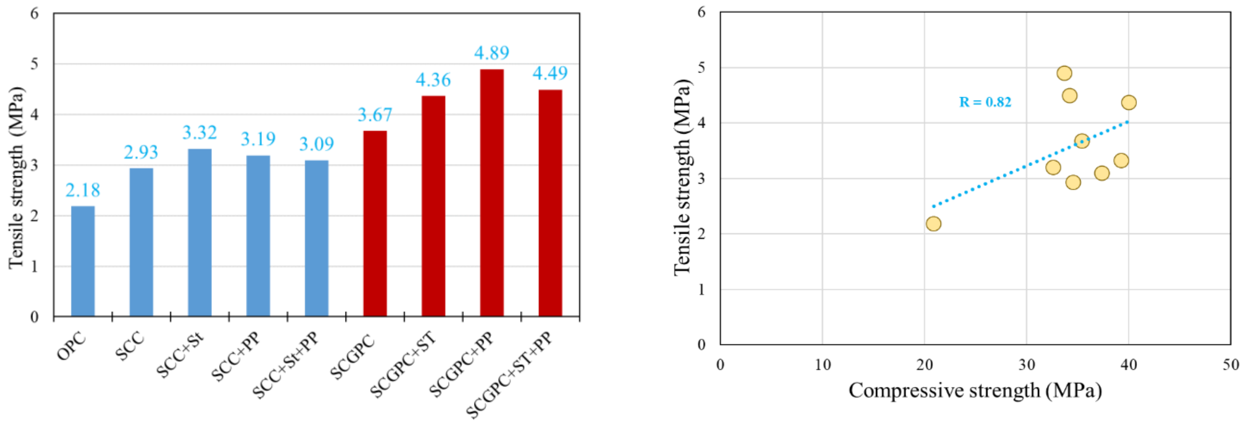


Figure 12. Tensile strength of geopolymer mixtures at molarity 12.

3.4. Shrinkage due to Contraction in Self-Compacting Geopolymer Concrete

The results of this study, in a broader comparison, indicated that at lower molarities, the geopolymer reaction is less complete, the concrete matrix has greater porosity, and the bonding between particles is weaker. These conditions create an environment with more weaknesses for the fibers to function, allowing steel and polypropylene fibers to provide better performance in terms of both resistance and structural integrity.

The shrinkage test for self-compacting and self-compacting geopolymer concrete mixtures at molarities of 8 and 12 in this study was conducted according to the ASTM C157 standard, which is the most commonly used method for measuring length changes in concrete under dry or saturated conditions. Additionally, a device called an extensometer, which includes a dial gauge with an accuracy of 0.001 mm and a specimen holder, was used to measure the length change of the concrete samples.

In a molarity of 8, due to the higher porosity and weak compaction of the microstructure, more water remains within the concrete matrix. As a result, higher shrinkage occurs because the evaporation of free water and moisture loss from the larger pores is easier. In contrast, the geopolymer reaction in molarity 12 is more complete, and the concrete matrix becomes denser and less porous. Shrinkage decreases in this molarity because there is less free water, and the denser structure prevents rapid moisture evaporation. Furthermore, the presence of a denser matrix limits shrinkage caused by moisture loss.

Figure 13 illustrates the results of the drying shrinkage test at molarity 12. As shown in the figure, steel fibers in reinforced self-compacting mixtures demonstrate better resistance to shrinkage, clearly observed in the SCGPC+ST sample. Steel fibers, by creating an internal network within the concrete matrix, prevent shrinkage caused by drying and contraction. This internal network inhibits particle movement and increases dimensional stability. The use of steel fibers reduces shrinkage by 15-20% compared to fiberless concrete. In comparison to steel fibers, polypropylene fibers are especially effective in preventing cracks caused by initial shrinkage and indirectly reduce drying shrinkage by retaining moisture inside the concrete and slowing down rapid water evaporation. This effect is visible in samples containing polypropylene fibers (SCGPC+ST+PP and SCC+ST+PP) in Figure 13.

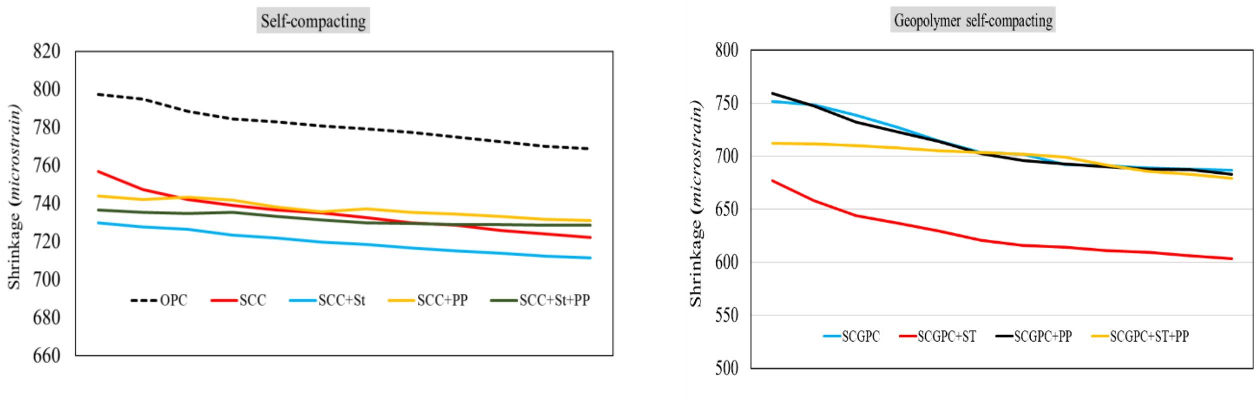


Figure 13. Results of the shrinkage test for self-compacting and geopolymer self-compacting mixtures

3.5. Investigation of Microstructure in Geopolymer Self-Compacting Concrete

In this study, self-compacting geopolymer concrete was developed at molarities of 8 and 12. Figure 14 shows a comparison of the microstructure in these two molarity mixtures of self-compacting geopolymer. The microstructure was evaluated using scanning electron microscopy (SEM) at a magnification of 100x.

At molarity 8, the concentration of the alkaline solution is lower, and the geopolymerization reaction is not fully completed. The formation of silicate and aluminate gels is reduced, resulting in a less dense and weaker microstructure compared to the higher molarity. The matrix of this concrete has higher porosity, which can reduce the bonding and overall strength of the concrete. The cross-sectional view of the concrete in this case may appear less homogeneous, with a less regular nanometric scale. The formed geopolymer gels are dispersed and discontinuous between the slag particles. In contrast, at molarity 12, the concentration of the alkaline solution is higher, and the geopolymerization reaction is more complete. The formation of silicate and aluminate gels is more pronounced, and the matrix of the concrete becomes denser and exhibits better mechanical properties. The microscopic structure of this concrete is more uniform, with the geopolymer gels continuously and uniformly distributed between the slag particles. Other phases, such as non-reactive materials and smaller particles, are also observed in this structure, which can improve the concrete's strength. Consequently, the denser and more continuous microstructure at molarity 12 results in increased compressive strength. Additionally, the more regular microstructure at molarity 12 is expected to provide better resistance against shrinkage and cracking.

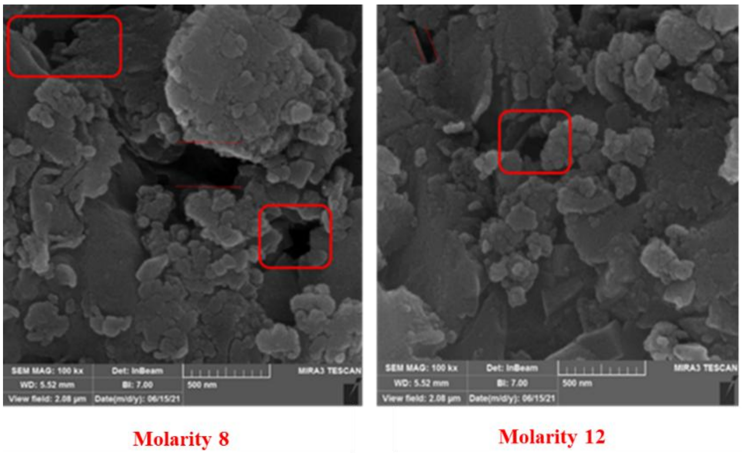


Figure 14. Examination of SEM Microstructure in Self-Compacting Geopolymer Mixtures at Molarities 8 and 12

3.6. Effect of Steel and Polypropylene Fibers on the Microstructure of Self-Compacting Geopolymer Concrete Based on Slag

The impact of steel and polypropylene fibers on the microstructure of self-compacting geopolymer concrete based on slag can lead to improvements in the overall performance of the concrete by altering the stress distribution and microscopic properties of the material. These fibers can affect the physical and chemical properties of the concrete matrix and help strengthen the structure and reduce cracking. As shown in Figure 15, steel fibers, due to their high strength and load-bearing capacity, create an internal reinforcement network within the concrete matrix, which can help distribute stresses more evenly. These fibers, by filling voids in the matrix and enhancing the bond between slag particles, improve the strength and cohesion of the structure. In scanning electron microscopy (SEM), it can be observed that steel fibers are either dispersed or form regular networks within the concrete matrix, gathering at critical points of the structure, such as high-stress areas. In the microstructure of the concrete, polypropylene fibers are distributed within the matrix and are easily visible along the cross-section of the concrete. These fibers generally do not bond with the slag particles but, by attaching to the concrete matrix, can prevent surface cracks and reduce shrinkage effects.

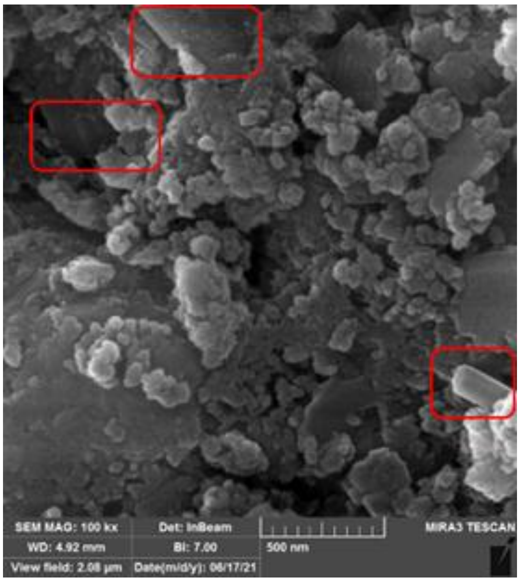


Figure 15. Examination of the Microstructure of SCGPC+ST+PP Samples in SEM Analysis

3.7. Analysis of Variance for Significance of Conducted Experiments

Due to the large number of experiments in this study, an analysis of variance (ANOVA) was conducted, and the results are reported in Table 7.

Table 7. Results of Analysis of Variance for the significance of conducted experiments

Experimental factors	DF	SS	Var	P-value	Contribution (%)
Compressive strength (MPa)					
%V_f fibers	3	9.93	3.317	0.187	14.37
GGBS	3	56.61	18.871	0.133	81.74
Error	6	5.34	0.899	0.079	3.89
Total	12	71.88	23.088	-	100
Tensile strength (MPa)					
%V_f fibers	3	0.133	0.044	0.181	29.22
GGBS	3	0.276	0.092	0.151	60.57
Error	6	0.09	0.015	0.079	10.21
Total	12	1.368	0.152	-	100
Water absorption					
%V_f fibers	3	0.164	0.054	0.198	16.76
GGBS	3	0.809	0.269	0.155	82.65
Error	6	0.011	0.002	0.079	0.60
Total	12	2.939	0.326	-	100
Shrinkage (micro strain)					
%V_f fibers	3	1.315	0.438	0.21	12.97
GGBS	3	8.518	2.839	0.152	83.98
Error	6	0.61	0.103	0.079	3.05
Total	12	30.431	3.381	-	100

The purpose of this analysis is to investigate the effect of independent variables, namely the fiber volume percentage and slag weight, on the compressive strength, tensile strength, water absorption, and plastic shrinkage of self-compacting geopolymer concrete using the statistical method of analysis of variance (ANOVA). As shown in

Table 7, the ANOVA results for compressive strength (CS), tensile strength (TS), water absorption, and shrinkage for all mixes of SCC, GPC, and SCGPC show high variance values, indicating a significant impact on the performance of the mixtures. These findings suggest that the impact of fiber volume percentage (%Vf) is more significant than particle size in all mechanical properties and durability parameters.

3.8. Results of Artificial Intelligence Performance in Simulating Compressive Strength of Self-Compacting Geopolymer Concrete

After preparing the geopolymer concrete samples and conducting mechanical tests, the results were collected in an Excel file. In this study, the first goal was to select variables (model inputs) that could be easily determined through laboratory tests, and second, that the results would be accessible with minimal cost. After recording the results from the laboratory tests, the database, consisting of 181 data points, was compiled, with 173 data points extracted from 21 studies by Alishah et al. (2022) and the remaining 8 mix designs from this geopolymer study. The modeling components included the percentage of fly ash (%FA), percentage of slag (%GGBS), the alkaline solution-to-base material ratio (S/B), curing temperature (T) as model inputs, and compressive strength (CS) as the output or target parameter of the model. To avoid overfitting of the developed models, the dataset was divided into training and testing groups. In this technique, 75% of the data was used for training and 25% for evaluating the network created during the training phase. The equation (1) represents the function under consideration using artificial intelligence methods.

$$CS = f\,(\%GGBS,\ \%FA,\ S/B,\ T) \quad (1)$$

Table 8 reports the statistical specifications of the modeling database used in this study.

Table 8. Statistical Analysis of Model Input Variables and Output Variable

Variable	Blast Furnace Slag (%)	Fly Ash (%)	S/B	Curing Temperature (°C)	Compressive Strength (MPa)
Min	0	0	0.2	20	12
Max	100	100	0.5	60	82

3.9. Implementation of the M5P Tree Model

The M5P tree model is a machine learning method used for regression problems. This model was introduced by Quinlan and is a combination of decision trees and linear regression models [25].

In this study, the decision tree model for predicting the compressive strength of self-compacting geopolymer was a binary tree model. Initially, the data was split into two categories based on the GGBS ratio. Then, for each category, additional binary splits were performed. The branching process was repeated at each node until the terminal node (leaf) was reached, where the sum of the squared deviations from the mean of the data approximately equaled zero. After pruning unnecessary branches, the optimal tree was formed. Finally, after constructing the tree model for the output variable, the predicted values by the model were calculated using the training and testing data, based on the corresponding equations.

The proposed M5P technique includes 4 input parameters and 1 output parameter, which were developed using 4 rules in the form of linear equations.

Therefore, the schematic diagram for the formation of the tree from the M5P method, in the form of rules for predicting the compressive strength of self-compacting geopolymer, is shown in Figure 16.

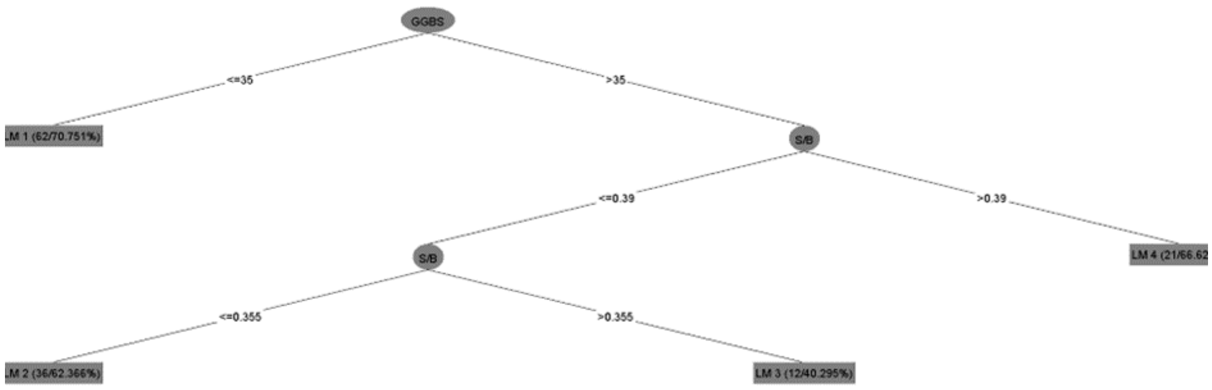
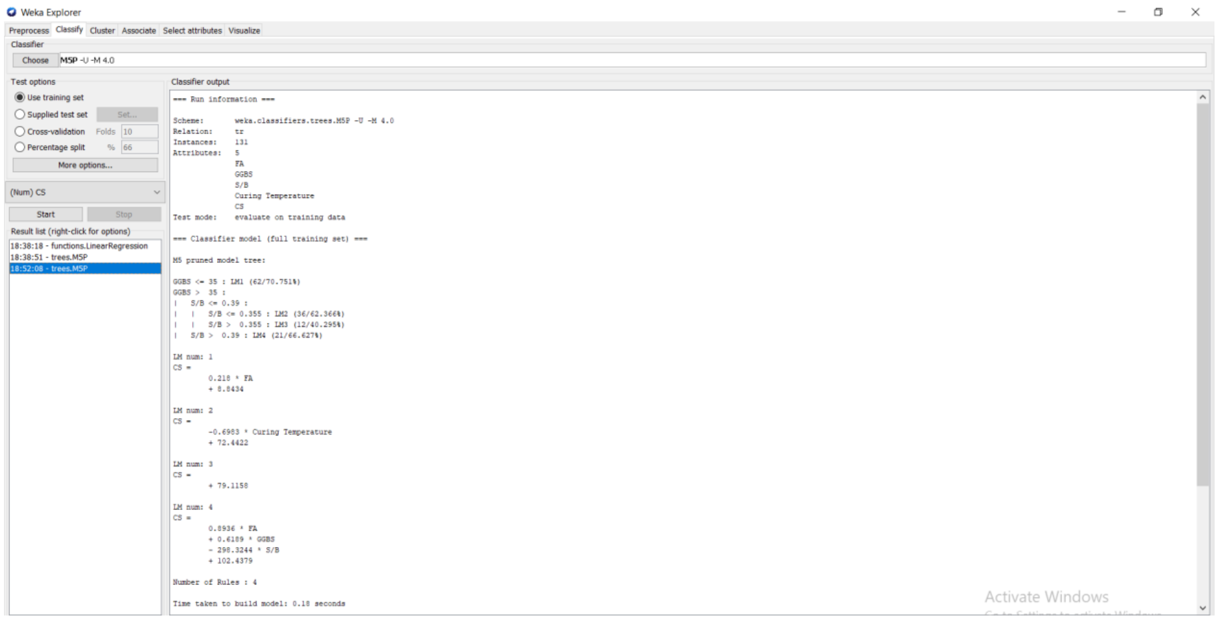


Figure 16. Tree structure derived from the M5P model for predicting the compressive strength of self-compacting geopolymer.

Based on the tree structure, the splitting variable for providing equations (3) and (4) is the slag percentage parameter, which was determined to be 35%. Additionally, the S/B ratio variable is used in models 2 to 5, initially with a ratio of 0.39 and later with a ratio of 0.355 in the conditions for using models 2 and 3. The S/B ratio with values of 0.355 and 0.39 served as the splitting parameter in the tree structure. In this modeling process, all four modeling components were considered in the decision tree model, with the data being categorized according to specific conditions and specified ratios for use. Figure 17 shows the development of the tree model and the settings of the influential parameters in Weka 3.7 software. Moreover, the developed model showed good performance with a correlation coefficient of 0.92 during the training phase and 0.88 during the testing phase. The mean absolute error during testing was 12.215 MPa, and the root mean square error was 16.27 MPa.



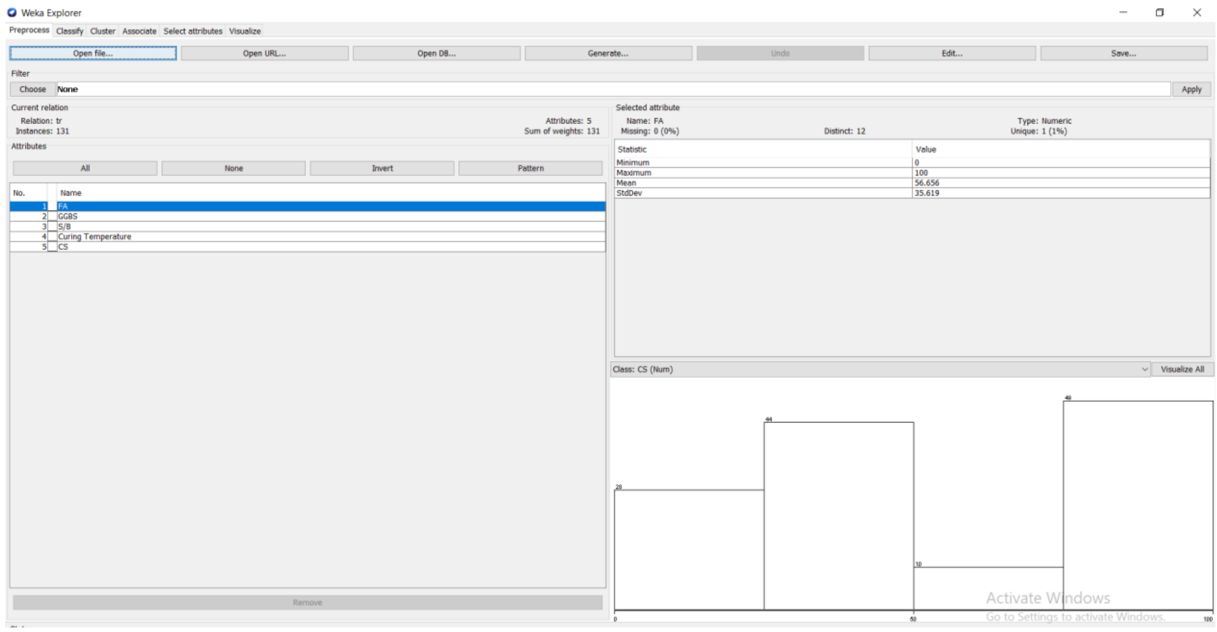


Figure 17. Weka software display for developing the tree model.

4. Discussion and Conclusion

Overall, this study showed that a high molarity can reduce the setting time and decrease the workability of the concrete, which may cause challenges in maintaining the self-compacting properties of the concrete. Therefore, finding the appropriate balance between molarity, workability, and compressive strength is crucial. The use of steel and polypropylene fibers in slag-based self-compacting geopolymer concrete with an alkaline solution can have a significant impact on the mechanical properties, durability, and microstructure of the concrete. The results of this study are as follows:

- Polypropylene fibers, due to their anti-crack properties and moisture retention ability, are effective in reducing early shrinkage and can be used in geopolymer concrete to reduce surface cracks. These fibers are also effective in controlling shrinkage-induced cracks and improving concrete behavior during the early stages. They prevent contraction and limit fine cracks by reducing water evaporation and distributing moisture within the concrete matrix.
- Steel fibers, in addition to reducing shrinkage, enhance the overall strength of the concrete and can help prevent deep cracks, thus improving concrete durability. These fibers strengthen the concrete structure by creating resilient internal networks and distributing stress. They are particularly effective in improving tensile and bending resistance, especially against deep cracks and heavy loads.
- Increasing molarity to about 12 molar decreases water absorption in geopolymer concrete, as the microstructure becomes denser and more impermeable. However, very high molarity should be used cautiously, as it may cause microcracking and increased water absorption. Additionally, increasing the molarity from 8 to 12 improves the microstructure of the slag-based self-compacting geopolymer concrete, enhancing its density, uniformity, and mechanical properties. These changes lead to an increase in overall strength and durability of the concrete, although they may also raise the cost and consumption of the alkaline solution.
- The choice of fiber type should be based on the specific needs of the project and desired mechanical properties. Combining both steel and polypropylene fibers can provide the shared benefits of both types of reinforcements and minimize shrinkage effects. The use of a combination of these fibers can help increase durability, reduce cracking, and improve the mechanical properties of the concrete.
- In this study, the decision tree model method was used to model the compressive strength of self-compacting geopolymer concrete. By aggregating data from previous studies and this research, a database was developed, and the decision tree model provided relationships for estimating values with over 88% accuracy.

Authors' Contributions

Authors equally contributed to this article.

Acknowledgments

Authors thank all participants who participate in this study.

Declaration of Interest

The authors report no conflict of interest.

Funding

According to the authors, this article has no financial support.

Ethical Considerations

All procedures performed in this study were under the ethical standards.

References

[1] B. Nikmehr, B. Kafle, and R. Al-Ameri, "Developing a sustainable self-compacting geopolymer concrete with 100% geopolymer-coated recycled concrete aggregate replacement," *Smart and Sustainable Built Environment,* vol. 13, no. 2, pp. 395-424, 2024, doi: 10.1108/SASBE-08-2023-0228.

[2] M. K. Jameel *et al.*, "Biogas: Production, properties, applications, economic and challenges: A review," *Results in Chemistry,* p. 101549, 2024, doi: 10.1016/j.rechem.2024.101549.

[3] V. Mehta, "Sustainable approaches in concrete production: An in-depth review of waste foundry sand utilization and environmental considerations," *Environmental Science and Pollution Research,* vol. 31, no. 16, pp. 23435-23461, 2024, doi: 10.1007/s11356-024-32785-1.

[4] H. Mostafaei, Z. Keshavarz, M. A. Rostampour, D. Mostofinejad, and C. Wu, "Sustainability evaluation of a concrete gravity dam: Life cycle assessment, carbon footprint analysis, and life cycle costing," *Structures,* vol. 53, pp. 279-295, 2023, doi: 10.1016/j.istruc.2023.04.058.

[5] N. Mohamad, K. Muthusamy, R. Embong, A. Kusbiantoro, and M. H. Hashim, "Environmental impact of cement production and Solutions: A review," *Materials Today: Proceedings,* vol. 48, pp. 741-746, 2022, doi: 10.1016/j.matpr.2021.02.212.

[6] J. Naresh, B. Lavanya, and K. S. Kumar, "A Study on bond strength of normal concrete to high volume fly ash concrete," in *IOP Conference Series: Materials Science and Engineering*, 2021, vol. 1057, 1 ed., p. 012082, doi: 10.1088/1757-899X/1057/1/012082.

[7] Y. J. Patel and N. Shah, "Study on workability and hardened properties of self compacted geopolymer concrete cured at ambient temperature," *Indian Journal of Science and Technology,* vol. 11, no. 1, pp. 1-2, 2018.

[8] S. M. Sayfullah, S. A. Pramono, and H. Ponda, "Comparison of Laterite Soil and Slaked Lime to the Strength of Mortar Geopolymer Press on Curing In Water," *PalArch's Journal of Archaeology of Egypt/Egyptology,* vol. 17, no. 7, pp. 4749-4755, 2020.

[9] K. Mermerdaş, S. Manguri, D. E. Nassani, and S. M. Oleiwi, "Effect of aggregate properties on the mechanical and absorption characteristics of geopolymer mortar," *Engineering Science and Technology, an International Journal,* vol. 20, no. 6, pp. 1642-1652, 2017, doi: 10.1016/j.jestch.2017.11.009.

[10] J. Rahman, K. S. Ahmed, N. I. Khan, K. Islam, and S. Mangalathu, "Data-driven shear strength prediction of steel fiber reinforced concrete beams using machine learning approach," *Engineering Structures*, vol. 233, p. 111743, 2021, doi: 10.1016/j.engstruct.2020.111743.

[11] N. Shehata, O. A. Mohamed, E. T. Sayed, M. A. Abdelkareem, and A. G. Olabi, "Geopolymer concrete as green building materials: Recent applications, sustainable development and circular economy potentials," *Science of the Total Environment,* vol. 836, p. 155577, 2022, doi: 10.1016/j.scitotenv.2022.155577.

[12] B. B. Jindal, T. Alomayri, A. Hasan, and C. R. Kaze, "Geopolymer concrete with metakaolin for sustainability: a comprehensive review on raw material's properties, synthesis, performance, and potential application," *Environmental Science and Pollution Research*, pp. 1-26, 2022.

[13] U. Sharma *et al.*, "Behavior of fibers in geopolymer concrete: A comprehensive review," *Buildings*, vol. 14, no. 1, p. 136, 2024, doi: 10.3390/buildings14010136.

[14] N. K. Barman, S. S. Bhattacharya, and R. Alagirusamy, "Textile structures in concrete reinforcement," *Textile Progress,* vol. 56, no. 1, pp. 1-229, 2024, doi: 10.1080/00405167.2023.2266930.

[15] H. J. Zhuang, H. Y. Zhang, and H. Xu, "Resistance of geopolymer mortar to acid and chloride attacks," *Procedia Engineering*, vol. 210, pp. 126-131, 2017, doi: 10.1016/j.proeng.2017.11.057.

[16] J. Yliniemi *et al.*, "Alkali activation-granulation of hazardous fluidized bed combustion fly ashes," *Waste and Biomass Valorization*, vol. 8, pp. 339-348, 2017, doi: 10.1007/s12649-016-9580-7.

[17] W. K. Lee and J. S. Van Deventer, "The effects of inorganic salt contamination on the strength and durability of geopolymers," *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, vol. 211, no. 2–3, pp. 115-126, 2002, doi: 10.1016/S0927-7757(02)00239-X.

[18] C. Zanotti, P. H. Borges, A. Bhutta, Y. Du, and N. Banthia, "NB Bond Strength of PVA Fiber Reinforced Geopolymer repair to Portland Cement Concrete Substrate," in *9th RILEM International Symposium on Fiber Reinforced Concrete-BEFIB 2016*, 2016, vol. 2016.

[19] H. N. Ruslan, K. Muthusamy, F. M. Yahaya, M. A. Fauzi, M. A. Ismail, and Z. Ali, "Review on performance of self compacting concrete containing solid waste and bibliometric properties: A review," *Journal of Building Engineering,* p. 108752, 2024, doi: 10.1016/j.jobe.2024.108752.

[20] M. H. R. Sobuz *et al.*, "High-strength self-compacting concrete production incorporating supplementary cementitious materials: Experimental evaluations and machine learning modelling," *International Journal of Concrete Structures and Materials*, vol. 18, no. 1, p. 67, 2024, doi: 10.1186/s40069-024-00737-1.

[21] R. Kumar, S. Kumar, B. Rai, and P. Samui, "Development of hybrid gradient boosting models for predicting the compressive strength of high-volume fly ash self-compacting concrete with silica fume," *Structures*, vol. 66, p. 106850, 2024, doi: 10.1016/j.istruc.2024.106850.

[22] P. Pradhan, S. Panda, S. K. Parhi, and S. K. Panigrahi, "Factors affecting production and properties of self-compacting geopolymer concrete-A review," *Construction and Building Materials*, vol. 344, p. 128174, 2022, doi: 10.1016/j.conbuildmat.2022.128174.

[23] Y. Luo *et al.*, "Effect of GGBFS on the mechanical properties of metakaolin-based self-compacting geopolymer concrete," *Journal of Building Engineering*, vol. 96, p. 110501, 2024, doi: 10.1016/j.jobe.2024.110501.

[24] A. A. Shahmansouri, M. Yazdani, S. Ghanbari, H. A. Bengar, A. Jafari, and H. F. Ghatte, "Artificial neural network model to predict the compressive strength of eco-friendly geopolymer concrete incorporating silica fume and natural zeolite," *Journal of Cleaner Production*, vol. 279, p. 123697, 2021, doi: 10.1016/j.jclepro.2020.123697.

[25] J. R. Quinlan, "Learning decision tree classifiers," *ACM Computing Surveys (CSUR)*, vol. 28, no. 1, pp. 71-72, 1996, doi: 10.1145/234313.234346.