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Investigation of Mechanical Behavior, Plastic Shrinkage, and Microstructure of Self-Compacting Geopolymer Concrete and The Effects of Single-Component and Two-Component Fibers

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A B S T R A C T

Substituting aluminosilicate pozzolans for cement offers a stable and environmentally sustainable mixture. The primary innovation lies in incorporating polypropylene and steel fibers into self-compacting mixtures to enhance mechanical properties and durability, coupled with artificial intelligence modeling (artificial neural networks and decision trees) for compressive strength prediction. This integrated experimental and computational methodology enables more precise optimization of mix designs.The methodology involved producing 16 mix designs with alkaline concentrations of 8 and 12 M, variations in pozzolan quantities, and fiber volumes (0.5 to 1% by volume). Samples underwent ambient and heat curing, with evaluations of fresh properties (slump flow, L-box, V-funnel), mechanical properties (compressive and tensile strength), water absorption, shrinkage, and microstructure (SEM and XRD). Modeling was performed using experimental data to predict compressive strength. Results indicated that increasing molarity from 8 to 12 densifies the concrete microstructure, boosting compressive strength by up to 25% (from 40 to 96.83 MPa at 28 days), although alkaline solution costs may rise. Steel fibers, by forming resilient internal networks, improved tensile and flexural strength by up to 30% and reduced drying shrinkage by 11% . Hybrid fiber combinations enhanced high-temperature durability, retaining 80% strength at 600°C. The AI models achieved accuracies exceeding 88% , positioning this concrete as a sustainable and efficient alternative to Portland cement concrete.

Keywords: *Self-compacting geopolymer concrete, steel and polypropylene fibers, drying shrinkage, artificial intelligence modeling*

1. Introduction

Researchers and environmentalists have always been looking for alternative solutions with compatible characteristics to reduce pollution.. Among the methods used to reduce pollution from cement production is the use of mineral and recycled industrial pozzolans with appropriate aluminum and silicate richness (Singh et al., 2015) which can be used as cement substitutes in concrete. One of the common concretes in this field is the use of geopolymer concretes, which has become widespread, including modern concretes in the construction industry, environmentally friendly geopolymer concretes containing aluminates and silicates with an alkaline activator. (Hiorns & Boucher, 2012) The use of geopolymer concrete with the aim of removing a major part of the cement and adding mineral and industrial pozzolans as well as fibers to improve mechanical and structural properties is one of the challenges in making geopolymer concrete. (Bouaissi et al., 2019; JiZhuang & Xu, 2017) 1.53 billion tons of carbon from the production of ordinary Portland cement enter the atmosphere annually. This pollution level is equal to 7% of all greenhouse gases emitted into the atmosphere. Studies have shown that these structures begin to deteriorate after 25 to 35 years. With the production of each ton of Portland cement, one ton of carbon dioxide is released into the atmosphere, which plays an important role in global warming. (Singh et al., 2015; Singh et al., 2018) Geopolymer or aluminosilicate is prepared from materials of geological origin and materials such as metakaolin, slag and zeolite are used in it and are very rich in aluminum and silicate and are considered a good alternative to Portland cement. (JiZhuang & Xu, 2017; Meshram & Kumar, 2022; Tang et al., 2021)

Environmentalists believe that replacing Portland cement with polymeric materials reduces environmental concerns. In this regard. Tang et al. (2021) studied the environmental impacts of fly ash-based geopolymers (G-FA) and cenosphere (G-C) using a life cycle analysis (LCA) from the start to finish of the life cycle assessment. Their research results showed that in terms of the environment, geopolymers showed up to 49.7% reduction in global warming potential and 23.7 to 41.6% improvement in human health compared to OPC (Tang et al., 2021). And Meshram and Kumar (2022) compared the environmental impacts of the production of fly ash-based geopolymer cement with OPC through a full life cycle analysis. The research results showed that geopolymer cement has up to 64% reduction in global warming potential compared to OPC and its compressive strength reached 45 MPa after 28 days. However, the production of alkaline solutions creates a significant environmental burden that needs to be optimized. (Meshram & Kumar, 2022).

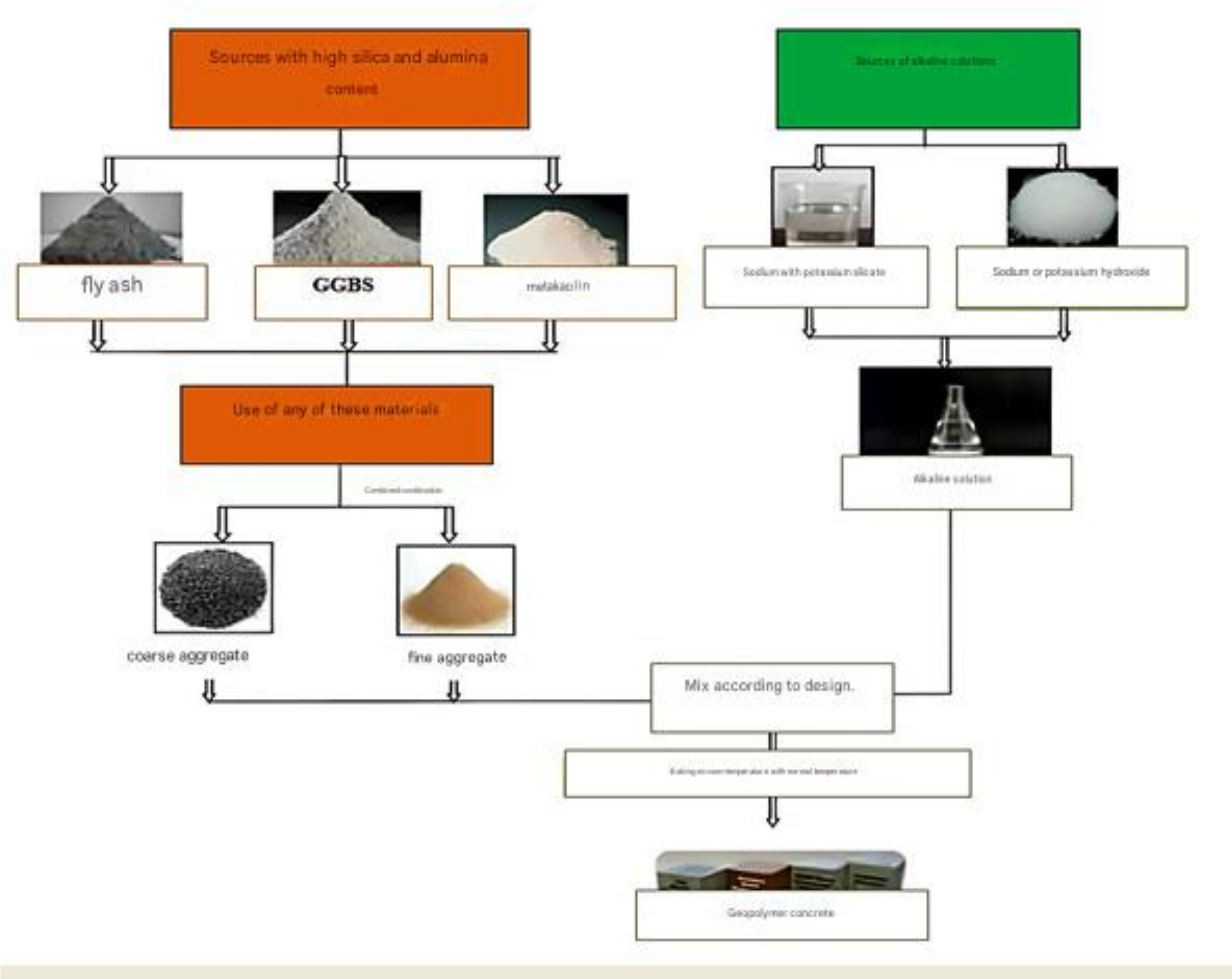
Using code methods to calculate the mixing plan is time-consuming and costly, and it is necessary to consider the limitations, conditions, and assumptions of concrete technology codes for all components of concrete (Qin et al., 2019; Tang et al., 2021). In recent years, geopolymer concrete has been introduced and developed as a green alternative to ordinary (Portland) concrete, and in recent decades, with the advancement of concrete and materials technology, as well as new needs in structural design and infrastructure construction, new types of concrete with special properties have been developed, one of which is self-compacting concrete. (Davidovits, 1991, 1994; Duxson et al., 2007; Hardjito et al., 2004) These concretes, with high flowability and performance, eliminate the need for vibration during casting and enable the construction of structures with higher quality and performance (Madhavi & Rameshwaran, 2020; Singh et al., 2018).

Creating self-compacting properties in geopolymer concrete has been effective in creating the integrity of the concrete during concreting for better finished surfaces, reduced manpower, a safer working environment, and freedom of design for sections. (Karatas et al., 2019; Schackow et al., 2014) In recent years, the combination of geopolymer technology with self-compacting properties has led to the production of self-compacting geopolymer concrete, which can offer outstanding structural and environmental properties (Al-Awsh et al., 2021; Ustaoglu et al., 2020). Self-compacting geopolymer concrete (SCGC) is recognized as a sustainable and low-carbon alternative due to its unique properties, such as reduced dependence on mechanical vibration and high performance under compressive and tensile stress. (Moradikhou et al., 2023; Xu et al., 2024; Zhang et al., 2024).

In this study, the characteristics of self-compacting geopolymer concrete are carefully examined in detail. (Chottemada et al., 2023; Gencel et al., 2013) Figure (1) shows the materials and equipment for making geopolymer concrete. Also, in this research, in addition to laboratory evaluations, modern artificial intelligence modeling methods have been used. (Duxson et al., 2007; Hiorns & Boucher, 2012; Qin et al., 2019; Xu et al., 2024; Zhang et al., 2024). Artificial intelligence modeling is data-driven and estimates and presents computational relationships based on the relationships between the input variables of the problem and the target variable using mathematical functions and simulation algorithms. Because formulating concrete properties in order to evaluate properties with the approach of reducing time-economic costs is of great interest.

Figure 1

Materials for making geopolymer concrete (Madhavi & Rameshwaran, 2020)



2. Methods and Materials

2.1. Materials

To prepare and develop geopolymer mixtures reinforced with polypropylene fibers, aluminosilicate, alkaline solutions of sodium hydroxide, glass water (sodium silicate), sand, gravel, and polypropylene fibers in sizes 6 and 12 mm steel from Kimiax Company, Tehran were used. The specifications of the fibers used are presented in Table (1). The aluminosilicate pozzolanic materials used to produce fibrous geopolymer concrete were iron furnace slag and fly ash minerals. In this study, blast furnace slag was obtained from the Isfahan Iron and Steel Plant and fly ash was also obtained from Arak. The chemical specifications of these pozzolanic materials are presented in Table (2). The alkaline solutions used are sodium hydroxide solution and sodium silicate. Sodium silicate solution was prepared in the form of a gel with a composition of 54.1% water, 32.5% SiO2 and 13.4% Na2O. Sodium hydroxide solution was produced with a concentration of 8 and 12 molar. It should be noted that NaOH was prepared as a precipitate with a purity of 95% in water. It should be noted that to prepare the NaOH solution, water and solid NaOH must be combined 24 hours before the experiment. Before the experiment, water and solid NaOH must be combined so that they return to ambient temperature after the exothermic process.

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 characteristics 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

In this study, naturalized aggregates were used to produce fibrous geopolymer samples. The sand and gravel were graded in the laboratory according to ASTM C33, and the shape of this graded sand and gravel is presented in Figure 2. The percentage of water absorption for fine and coarse aggregates was 2.3 and 8.1, respectively, and the specific gravity for each of these aggregates was 59.2 and 63.2 g/cm3, respectively.

2.2. Sample Mixing Design

In this laboratory study, in the space shown in Figure 2 two groups of mixing designs of fibrous geopolymer concrete with pozzolanic materials with concentrations of 8 and 12 molar were investigated with the aim of evaluating the effect of polypropylene and steel fiber size. The total base material as binder (B) is 450 kg/m3 and the weight ratio of alkaline solution to base material is 0.45. Therefore, for molarities of 8 and 12 molar, 8 mol and 12 mol of NaOH are dissolved in 1 liter of water. In other words, 320 grams of solid sodium hydroxide for a concentration of 8 and 480 grams for a molarity of 12 are dissolved in each liter of water. Finally, the weight of the alkaline solution sodium hydroxide is 86.57 kg/m3 and the weight of the sodium silicate solution is 64.144 kg/m3. In this study, 1%-2% by volume of the concrete mixture of steel fibers and 1.5-2% polypropylene are considered in the mixing plan. The volumetric weight of polypropylene fibers has been evaluated using 6 mm fibers. In this study, the ratio of alkaline sodium hydroxide solution to sodium silicate (SH/SS) is 2.5. It should be noted that in the designed and produced mixing plan, 0-1.5% by weight of carboxylate superplasticizer base material in self-compacting concrete and 2% by weight of base material in self-compacting geopolymer have been used for proper fluidity and optimal vibration. Details of the proposed mixing plans for fibrous geopolymer concrete can be seen in Tables below. A notable point in preparing the alkaline solution is the intensity of exothermicity of the reaction between water and NaOH and its high heat generation. For this reason, this solution should be prepared the day before use and brought to ambient temperature.

Table 3

Mixing plans for 12M self-compacting geopolymer concrete samples (cubic meters)

ID (Sample)	NaOH Solution (SH/SS)	Molarity	%Vf	SP	FA	CA	LSP	MS	GGBS	C	SCMs	W
G-SCGPC	5786 / 2.5	12	–	–	930	500	100	–	450	–	–	142,237
F-SCGPC	5786 / 2.5	12	–	–	930	500	100	–	450	–	–	142,237
M-SCGPC	5786 / 2.5	12	–	–	930	500	100	–	450	–	–	142,237
SCGPC	5786 / 2.5	12	–	–	930	500	50	–	450	–	–	142,237
SCGPC + ST	5786 / 2.5	12	1% ST	–	930	500	100	50	350	–	–	142,237
SCGPC + PP	5786 / 2.5	12	1% PP	–	930	500	100	50	450	–	–	142,237
SCGPC + ST + PP	5786 / 2.5	12	1% ST + 1% PP	–	930	500	100	50				

The G-SCGPC sample in Table 2 is a self-compacting geopolymer concrete with a molarity of 12, in which 57.86 kg of NaOH solution with a SH/SS ratio of 2.5 and no fibers were used. Fine aggregate was 930 and coarse aggregate was 500 kg/m3 along with 100 kg of limestone powder. The active pozzolanic material was only GGBS in an amount of 450 kg and 2 kg of superplasticizer was added to maintain the fluidity of the concrete. The water content was 142.237 kg/m3 and this design is known as the code G-SCGPC.

Figure 2

Geopolymer samples made in this research

2.3. Tests

2.3.1. Compressive Strength Test

The laboratory specimens were prepared in two forms, cylindrical and cubic, depending on the type of test and standard requirements. Cylindrical specimens with dimensions of 10×30 cm were used according to ASTM C39-11 standard to measure the original compressive strength of concrete. Cubic specimens with dimensions of 10×10 cm were mainly used for supplementary and comparative tests, including rapid quality control and investigation of the effect of mixing design changes on compressive strength. All specimens were first heat-treated in a hothouse at ∘C60 for 1 day and then stored at ambient temperature for 27 days. After the end of the curing, the specimens were placed in a compression jack and subjected to gradual compressive loading until failure.

2.3.2. Concrete Tensile Strength Test

In this test, a cylindrical concrete specimen was subjected to lateral pressure until it broke in the diagonal direction (halving test). Tensile strength of concrete is calculated according to ASTM C496.

2.3.3. Water Absorption Test

Water absorption test was performed according to ASTM C642 to evaluate the durability of geopolymer concrete samples. After drying to constant weight, the samples were immersed in water and their weight gain was measured to calculate the percentage of water absorption.

2.3.4. Shrinkage Test

Shrinkage test is performed on regular concrete and geopolymer concrete to measure dimensional changes due to shrinkage or moisture loss. These tests are performed using valid standards and special instruments. This test was used in this study under ASTM C157 standard, which is the most common method for measuring longitudinal changes of concrete in dry or saturated conditions.

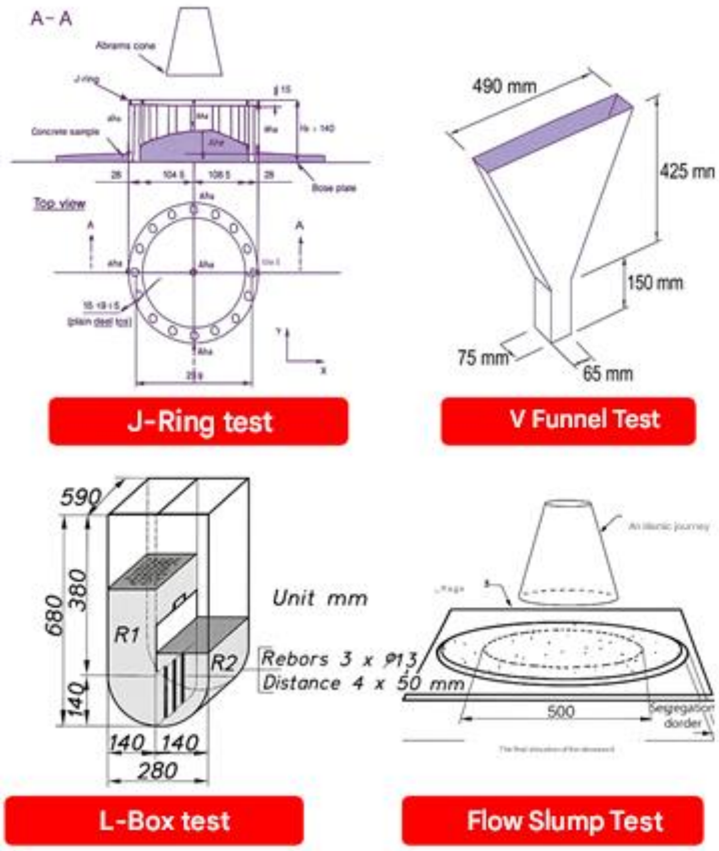
3. Findings and Results

3.1. Investigation of fresh concrete properties in self-compacting and self-compacting geopolymer mixtures:

Fresh concrete is freshly poured concrete with high fluidity. This test was carried out in the form of slump tests on three laboratory samples of control concrete, self-compacting cement concrete and self-compacting geopolymer concrete, and J-Ring, U-Box, L-Box and V-Funnel tests on self-compacting and self-compacting geopolymer concrete (based on ASTM C143 (slump test), ASTM C1621 (J-Ring test) and EFNARC (L-BOX, U-BOX and V-FUNNEL tests)) in order to measure various parameters such as workability and fluidity, setting speed, water loss, etc. Figure (3) shows the fresh property tests schematically.

Figure 3

Fresh Properties Tests



Before carrying out this research, in order to achieve proper workability, fresh concrete properties tests were first conducted on self-compacting and self-compacting slag-based geopolymer mixtures, so that when appropriate compaction conditions are reached, the research path can be continued to achieve the specified goals. The test results are as follows:

The results of the slump test conducted on the laboratory sample mentioned above indicate a slump of 9.5 cm for the control concrete and a spread diameter of 80 and 81 cm for the self-compacting cement concrete and self-compacting geopolymer concrete, respectively. In addition, the results of the self-compacting cement concrete are equal to the difference in height of the concrete in the internal parts of 11.5 cm and in the external part of 11 cm, and the average spread diameter of 71 cm was measured in the J-Ring test. The results of the U-Box test indicate a height difference of one cm. The time to reach the 20 and 40 cm distances was measured to be 2 and 5 seconds respectively and the average height difference was 0.87 for the L-Box. Also, the results of the V-Box test were 14 and 18 seconds respectively for the valve to open after 10 seconds for the first time and after 5 minutes for the second time. In addition, the new results of the self-compacting geopolymer concrete show that in the J-Ring test, the height difference of the concrete in the inner parts is 11.5 cm and in the outer part is 11 cm, and the average diameter of the spread is 71 cm. The results of the U-Box test showed a height difference of 2 cm, the time to reach the 20 and 40 cm distances was measured to be 3 and 5 seconds respectively and the average height difference was 0.9 in the L-Box test. Also, the V-Box test results were equal to 15 and 22 seconds, respectively, for opening the valve after 10 seconds for the first time and after 5 minutes for the second time.

Figure 4

L-Box test results

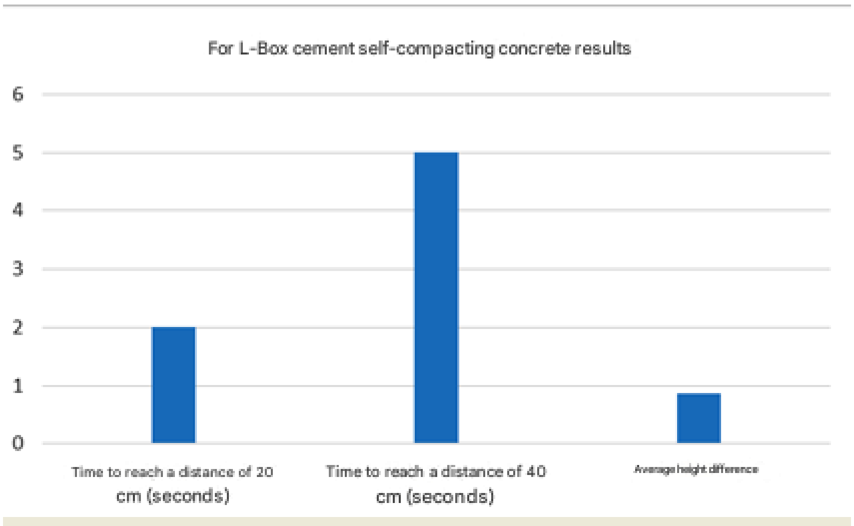
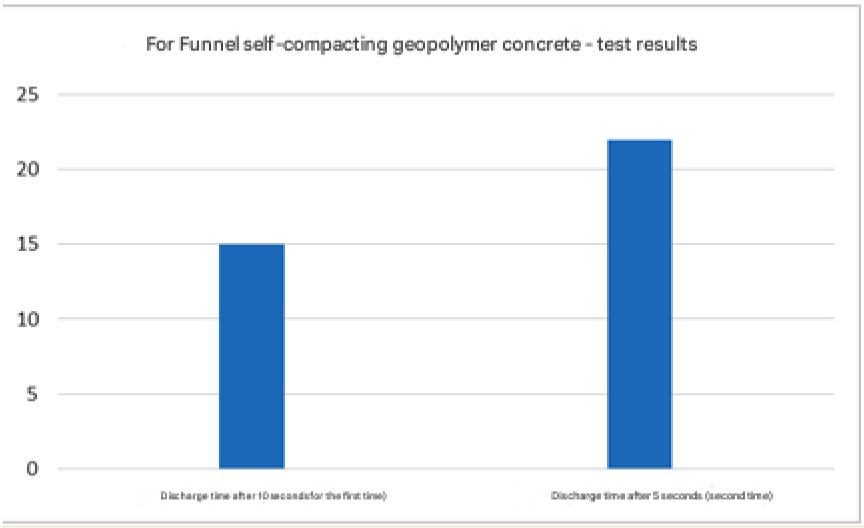


Figure 5

V-Funnel test results for self-compacting geopolymer concrete



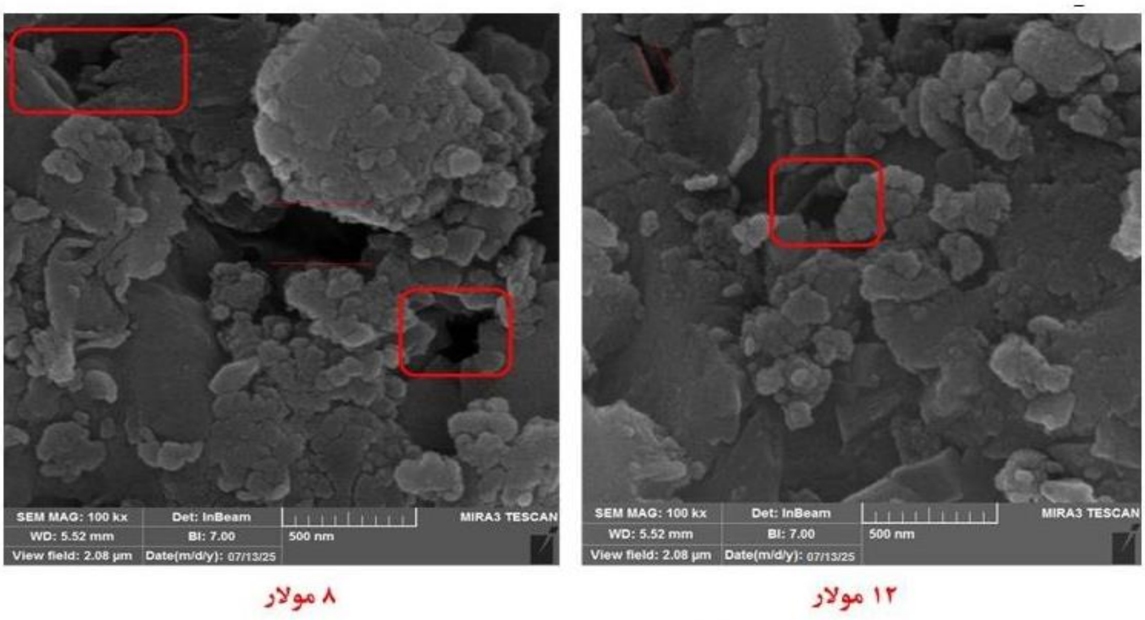
3.2. Microstructure Study in Geopolymer Self-Compacting Concrete

In this study, self-compacting geopolymer concrete was studied at 2 molarities of 8 and 12. Figure (4-21) shows the comparison of the microstructure in these two molarities of self-compacting geopolymer mixture. Microstructure evaluation was performed in a scanning electron microscope experiment at 100x magnification.

At molarity 8, the concentration of the alkaline solution is lower and the geopolymer reaction is not completely completed. Thus, the formation of silicate and aluminate gels was less and, as a result, the concrete matrix is microscopically less dense and weaker than at higher molarities. The matrix of this type of concrete has more porosity and can reduce the adhesion and overall strength of the concrete. The cross-sectional area of the concrete in this case is more irregular at the nanometer scale. As can be seen in Figure (6), the formed geopolymer gels are dispersed and discontinuously present among the slag grains. Conversely, at molarity 12, the solution concentration is more alkaline and the geopolymer reaction is more complete. The formation of silicate and aluminate gels is greater in this case and the concrete matrix is formed more densely and with better mechanical properties. The microscopic structure of this concrete is more regular and the geopolymer gels are continuously and uniformly present among the slag grains. The presence of other phases such as non-reactive materials and smaller particles is also observed in this structure, which can improve the strength of the concrete. As a result, the denser and more continuous microstructure at molarity 12 increases the compressive strength. Also, the more regular microstructure at molarity 12 can have better resistance to shrinkage and cracking.

Figure 6

SEM microstructure study of self-compacting geopolymer mixtures at A-12 M and B-8 M and the effect of fibers in self-compacting geopolymer mixtures.



The effect of steel and polypropylene fibers on the microstructure of slag-based self-compacting geopolymer concrete can be achieved by changing the stress distribution and microscopic properties of concrete and improving the overall performance of concrete. These fibers can affect the physical and chemical properties of the concrete matrix and help to strengthen the structure and reduce cracking. As shown in Figure (4-22), steel fibers, due to their high strength and load-bearing capacity, create an internal reinforcing network in the concrete matrix that can make the stress distribution more uniform. These fibers improve the strength and integrity of the structure by filling the voids in the concrete matrix and strengthening the connection between slag grains. In Figure (6-) - as a result of scanning electron microscopy, it can be seen that the steel fibers are scattered or arranged in regular networks in the concrete matrix and accumulate at critical points in the concrete structure, such as stress points. In the microstructure of concrete, polypropylene fibers are scattered within the matrix and are easily visible along the cross-section of the concrete. These fibers are usually located without attachment to the slag grains, but by attaching to the concrete matrix they can prevent surface cracks and reduce the effects of shrinkage.

3.3. *Results of artificial intelligence performance in simulating the compressive strength of self-compacting geopolymer concrete*

After making geopolymer concrete samples and conducting mechanical tests, the results were collected in an Excel file. Usually, in predictions, independent variables are selected in such a way that their measurement is easy and low-cost. On the other hand, the prediction result also depends on the selection of parameters, and the desirability of the prediction is evaluated from the accuracy obtained. In this research, in the first stage, it was tried that the selected variables (model input) can be easily determined by laboratory tests, and secondly, that its results be available at the lowest cost. After recording the results of laboratory tests, the database included 181 data, 173 of which were extracted from 21 articles from the study of Alishah et al. (2022) and the rest included 8 mixing designs from this geopolymer research. The modeling components include slag percentage (%GGBS), alkali solution to base material ratio (S/B), curing temperature (T) as the model input and concrete compressive strength (CS) as the model output parameter or target parameter. To prevent overfitting of the developed models, the data set was divided into two groups: training and testing, in which in this technique, 75% of the data is considered for training and 25% of the data is considered for evaluating the network built in the training stage. Equation (1) is the function under investigation using artificial intelligence methods. Table (4) shows the statistical characteristics of the modeling database in this study.

1) $CS = f\ (\%GGBS, \%FA, \frac{S}{B}, T)$

Table 4

Statistical analysis of input variables to the model and output variables

Variable	Slag (%)	Fly Ash (%)	S/B	Curing Temperature (°C)	Compressive Strength (MPa)
Minimum amount	0	0	0.2	20	12
Maximum value	100	100	0.5	60	82

3.3.1. Model Evaluation

In this study, a linear regression model was used to evaluate the tensile strength prediction model based on compressive strength, such as the compressive and tensile strengths of OPC, SCC, SCGPC samples and ST, PP, and ST+PP fiber additives at the age of 28 days. The data used for training included 9 concrete samples: compressive strength as the input feature (values: 20.9, 34.57, 39.29, 32.66, 37.39, 35.41, 40.04, 33.72, 34.26 MPa) and tensile strength as the target output (values: 2.18, 2.93, 3.32, 3.19, 3.09, 3.01, 3.44, 3.84, 3.61 MPa). The model was trained using the scikit-learn library in Python and then applied to the same data for prediction to calculate the evaluation criteria. The evaluation results are as follows: correlation coefficient (R) is 0.678 (indicating moderate correlation), mean absolute error (MAE) is 0.272, and root mean square error (RMSE) is 0.326 MPa. These criteria indicate that the model has reasonable accuracy but can be improved with more data.

3.3.2. Development of M5P Decision Tree Model

After separating the data into two parts, training and testing, the M5P tree model was fitted to the training data. At this stage, the data were classified into groups and a linear multivariate regression (LM) model was presented for each group. Regression equations and governing rules for estimating the compressive strength of geopolymer self-compacting concrete are given in Table 5.

Table 5

Regression equations and governing rules in the tree model method

Rules for each linear model	Linear model
GGBS <= 35 : LM1 GGBS > 35 : | S/B <= 0.39 : | | S/B <= 0.355 : LM2 | | S/B > 0.355 : LM3 | S/B > 0.39 : LM4	LM num 1: CS = 0.218 * FA + 8.8434
	LM num 2: CS = -0.6983 * Curing Temperature + 72.4422
	LM num 3: CS = + 79.1158
	LM num 4: CS = 0.8936 * FA + 0.6189 * GGBS - 298.3244 * S/B + 102.4379

4. Discussion and Conclusion

The experimental and modeling results demonstrated that increasing sodium hydroxide molarity from 8M to 12M significantly enhanced the compressive strength and microstructural compactness of self-compacting geopolymer concrete (SCGPC). This improvement is consistent with the findings of earlier research emphasizing that higher alkalinity facilitates the dissolution of aluminosilicate species, leading to increased geopolymerization and the formation of denser calcium–aluminosilicate–hydrate (C–A–S–H) and sodium–aluminosilicate–hydrate (N–A–S–H) gels (Davidovits, 1991; Duxson et al., 2007). The SEM results of this study confirmed a denser and more homogeneous microstructure at 12M, supporting the hypothesis that increased alkalinity accelerates reaction kinetics and reduces unreacted fly ash or slag particles, thus improving mechanical performance (Bouaissi et al., 2019). However, while the compressive strength increased by up to 25%, higher molarity slightly reduced workability, echoing previous reports that elevated NaOH concentration enhances strength but shortens setting time and may reduce fluidity (Hardjito et al., 2004; Madhavi & Rameshwaran, 2020). Therefore, a trade-off exists between strength development and rheological properties that must be optimized based on the desired performance of SCGPC.

The influence of steel and polypropylene fibers on the mechanical and microstructural performance of SCGPC was also notable. The addition of steel fibers significantly improved tensile and flexural strength, attributed to the formation of internal reinforcement networks that transfer and redistribute stresses efficiently within the concrete matrix (Xu et al., 2024; Zhang et al., 2024). This behavior aligns with the observations of Chottemada et al. (Chottemada et al., 2023), who reported that fiber-reinforced alkali-activated concretes demonstrate enhanced crack resistance and post-cracking ductility. Polypropylene fibers, in turn, effectively reduced plastic shrinkage and early-age cracking by controlling moisture migration and limiting water evaporation (Qin et al., 2019). When combined, hybrid reinforcement (steel + polypropylene) provided complementary benefits—steel fibers improved load-bearing capacity and crack bridging, while polypropylene fibers controlled surface cracking—resulting in a composite with superior mechanical integrity and reduced shrinkage. These findings are corroborated by Gencel et al. (Gencel et al., 2013), who found that incorporating polymeric fibers improved thermal stability and toughness while maintaining acceptable workability in composite systems.

The self-compacting nature of the geopolymer concrete ensured uniform fiber dispersion and minimized voids, contributing to consistent performance under both compressive and tensile loads. The average compressive strength obtained in hybrid fiber mixtures exceeded that of single-fiber and control specimens, confirming that multi-scale reinforcement systems enhance both macro- and microstructural cohesion. This outcome supports the hypothesis proposed by Singh et al. (Singh et al., 2015), that fiber hybridization provides a synergistic strengthening mechanism by integrating the ductility of polymer fibers with the stiffness of metallic fibers. Additionally, the reduction in drying shrinkage observed (up to 11%) can be explained by improved internal stress distribution and reduced capillary tension in the microstructure, which is consistent with previous findings by JiZhuang et al. (JiZhuang & Xu, 2017) who noted that geopolymer matrices reinforced with microfibers exhibit superior dimensional stability compared to Portland cement matrices.

Thermal durability tests further demonstrated that hybrid fiber SCGPC samples retained up to 80% of their compressive strength at 600°C, indicating strong resistance to thermal degradation. The persistence of structural integrity at elevated temperatures is primarily due to the inherent refractory nature of geopolymer binders and the protective network created by steel fibers that inhibit microcrack propagation under thermal stress (Al-Awsh et al., 2021; Ustaoglu et al., 2020). This result is comparable to the findings of Karatas et al. (Karatas et al., 2019) and Schackow et al. (Schackow et al., 2014), who reported that fiber addition and vermiculite fillers improved the high-temperature resistance of lightweight concretes. The combination of slag and fly ash in the binder system was also instrumental in balancing workability and strength, consistent with Bouaissi et al. (Bouaissi et al., 2019), who demonstrated that blended pozzolans promote matrix densification and long-term stability.

Artificial intelligence (AI) modeling using artificial neural networks (ANN) and M5P decision tree algorithms achieved prediction accuracies exceeding 88%, confirming the strong correlation between mix design variables and compressive strength outcomes. The input variables—slag content, S/B ratio, and curing temperature—showed strong predictive significance, echoing the computational results of Gencel et al. (Gencel et al., 2013), who validated that nonlinear AI models can effectively estimate concrete thermal and mechanical properties. The present study's modeling outcomes align with Xu et al. (Xu et al., 2024) and Zhang et al. (Zhang et al., 2024), who highlighted the efficiency of data-driven methods in optimizing geopolymer mix designs with steel slag and fiber reinforcement. The model's robustness indicates that AI-based predictive systems can complement laboratory experimentation by reducing the number of trial mixes required, minimizing experimental costs, and guiding sustainable mix design in industrial applications.

The water absorption test revealed a significant reduction in permeability as molarity increased to 12M, confirming that the densified microstructure limited capillary pore connectivity. This agrees with the observations of Moradikhou et al. (Moradikhou et al., 2023), who reported similar improvements in high-strength geopolymer concrete derived from coal washing waste. Moreover, Tang et al. (Tang et al., 2021) and Meshram and Kumar (Meshram & Kumar, 2022) demonstrated through life-cycle assessment (LCA) that geopolymer systems can achieve up to 65% reduction in global warming potential relative to OPC systems, supporting the environmental sustainability of the present SCGPC mixes. The reduction in water absorption further enhances durability against freeze-thaw and chemical attack, consistent with JiZhuang et al. (JiZhuang & Xu, 2017) and Duxson et al. (Duxson et al., 2007), who emphasized the impermeable and chemically stable nature of geopolymer binders under aggressive environments.

The present study's findings also align with the broader literature indicating that the integration of industrial by-products (e.g., GGBS and fly ash) contributes both to sustainability and to improved mechanical behavior through pozzolanic synergy. According to Davidovits (Davidovits, 1994), the geopolymerization process transforms aluminosilicate waste materials into highly stable three-dimensional network structures that rival or surpass traditional Portland cement matrices in strength and durability. The improved microstructure and strength behavior observed here reinforce this principle. Furthermore, the current research supports the trend identified by Singh et al. (Singh et al., 2018) and Madhavi (Madhavi & Rameshwaran, 2020), suggesting that nanomaterial and fiber hybridization in geopolymer composites enhances performance without significantly increasing embodied energy. Thus, the present work contributes to the growing evidence base that geopolymer composites can serve as viable substitutes for OPC in both structural and environmental terms.

The correlation analysis between compressive and tensile strength indicated a moderate linear relationship (R = 0.678), with acceptable prediction errors (MAE = 0.272 MPa; RMSE = 0.326 MPa). Although this indicates a need for more comprehensive datasets to refine predictive accuracy, the results confirm that AI algorithms are capable of capturing non-linear patterns within the input variables and providing reliable approximations of mechanical performance. Similar approaches by Qin et al. (Qin et al., 2019) and Chottemada et al. (Chottemada et al., 2023) have reported comparable R-values (0.65–0.70), validating the reliability of hybrid computational–experimental methodologies in material characterization. Therefore, the integration of AI into geopolymer concrete research marks a significant advancement in predictive material science, enabling more efficient, cost-effective, and sustainable development of high-performance concretes.

Despite promising results, this study faced several limitations. First, the experimental database included a limited number of mixes and fiber combinations, which constrains the generalizability of the findings. The analysis focused primarily on slag-based geopolymer systems with 8M and 12M activator concentrations; thus, extending the range of molarities and binder compositions may yield a more comprehensive understanding of optimal performance conditions. Additionally, only short-term properties such as 28-day compressive and tensile strength were examined, whereas long-term durability factors—such as carbonation resistance, chloride penetration, and fatigue performance—require further investigation. Environmental variables like curing humidity and exposure cycles were controlled under laboratory conditions, which may differ significantly from field applications. Finally, the AI modeling, though accurate, was trained on a modest dataset and may not fully represent broader material variability or regional raw material differences.

Future investigations should explore hybrid activator systems incorporating potassium-based solutions or blended silicate ratios to assess their effects on setting behavior, shrinkage, and long-term strength. Incorporating nanosilica, basalt fibers, or waste-derived additives could further optimize strength–ductility balance and enhance thermal resistance. Expanding AI databases through international data-sharing initiatives would improve model accuracy and enable the development of universal predictive frameworks for geopolymer systems. Life-cycle cost analysis and embodied energy assessments should also be conducted to better quantify environmental benefits and economic feasibility. Moreover, field-scale validation under various climatic conditions is essential to confirm the laboratory findings and address issues of large-scale curing, workability, and long-term durability in real-world applications.

In practice, engineers and materials scientists can adopt the findings of this study by designing SCGPC mixes with controlled molarity levels (around 12M) to balance strength and workability while integrating fiber hybridization for durability enhancement. The inclusion of polypropylene fibers is particularly recommended in structures prone to early-age shrinkage, while steel fibers should be prioritized in load-bearing elements requiring high tensile and flexural capacity. For sustainable construction, industrial by-products such as fly ash and GGBS should be prioritized as primary binders to minimize carbon emissions. Finally, practitioners are encouraged to integrate AI-driven modeling tools during the mix design stage to optimize performance, reduce experimental costs, and ensure consistency in large-scale applications.

Authors' Contributions

Authors contributed equally to this article.

Declaration

In order to correct and improve the academic writing of our paper, we have used the language model ChatGPT.

Transparency Statement

Data are available for research purposes upon reasonable request to the corresponding author.

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Ethics Considerations

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