THE REGRESSION ANALYSIS AND DETERMINATION OF MECHANICAL AND PHYSICAL PROPERTIES ON GEOPOLYMER COMPOSITES UNDER THERMAL AND WATER CURING

Özlem ÇAVDAR[1], Hülya TEMİZER[*2]

[1]Gümüşhane University, Department of Civil Engineering, Gümüşhane, Turkey,
ozlem_cavdar@hotmail.com

[2] Gümüşhane University, Department of Civil Engineering, Gümüşhane, Turkey.

[*]Corresponding Author; hlytemizer@gmail.com

Abstract

Increasing costs due to high energy consumption and the release of harmful carbon dioxide (CO_2) gases in cement production have made it necessary to explore alternative binders. This study aims to investigate the physical and mechanical properties of geopolymer mortars containing different proportions of pozzolanic wastes under different cure conditions. For this objective, fly ash (FA) obtained from the Sivas/Turkey thermal power plant and blast furnace slag (BFS) obtained from the Bolu and Iskenderun/Turkey iron-steel industries were used as the binding materials. Thermal curing and water curing were applied, and three different molar ratios (8M, 10M, 12M) of sodium hydroxide (NaOH) solution and sodium silicate (Na_2SiO_3) were used. The results showed that the reaction products, types of alkaline activators, and reaction conditions are important factors in geopolymer mortars. The highest compressive strength recorded was 84.7 MPa in the geopolymer sample which consisted of 95% blast furnace slag (BFS) and 5% fly ash (FA). Furthermore, two different binder additives (marble powder and strontium) were used and their time-dependent effects on the main binder were analysed. In addition, according to the ANOVA statistical results, the R^2 value of the independent variables (Molarity, main binder ratios) on the compressive strengths accepted as the dependent variable is 81.7%. The significance value is 0.007, and these results were considered quite significant.

Key words: Alkaline activator, Blast furnace slag, Different curing conditions, Geopolymer mortar, Fly ash.

1. Introduction

Ordinary Portland cement is a commonly used building material in the construction industry, with a production yield of approximately 4.2 billion tons in 2019 [1]. However, it has become crucial to reduce its production due to the harmful impact of cement production on the environment and improve alternative materials that can prevent global warming. Geopolymers, a novel type of binding material, have been thoroughly examined by researchers as a potential replacement for conventional cement [2]. Geopolymers are a type of inorganic binder material that consists of amorphous, semi-crystalline, and three-dimensional geopolymeric structures. They could be produced at low temperatures and harden quickly [3-6]. In the study carried out by Nergis et al., coal ash-based geopolymers with added mineral

residues activated with phosphate acid were synthesized at room temperature. Three types of aluminosilicate sources were used as single raw materials or at a ratio of 1/1 by mass to obtain five different types of H_3PO_4-activated geopolymer. In the temperature range of 20°C–300 °C, geopolymers obtained with H_3PO_4 acid have been reported to exhibit thermal behavior similar to those activated by a mixture of NaOH and Na_2SiO_3. In the temperature range of 400°C–600 °C, geopolymers with mineral residue addition exhibited exothermic reactions, while geopolymers without mineral residue addition did not show a significant phase transition [7-9]. In studies that use granulated blast furnace slag (GBFS) as the primary binder and aggregate, low energy consumption is an important topic [10-12]. Gao conducted a study of five different geopolymer structures, analyzing the mixtures of sodium hydroxide and sodium silicate. It was used as a solution. It was prepared at the mixtures with varying slag/fly ash ratios, with an increased water/binder ratio of 0.35. It was revealed that the 7 and 28-day compressive strengths of the 90/10 slag/fly ash ratio were 82.20 MPa and 100.90 MPa, respectively. Furthermore, it was observed that the compressive strengths decreased as the fly ash ratio in the mixture increased [13]. A comprehensive study was examined to analyze the effectiveness of various mixtures of slag and fly ash, each containing different percentages of fly ash ranging from 30% to 70%. The findings of the research revealed that the mixtures containing 40%, 50%, and 60% fly ash showcased superior workability performance, including but not limited to plastic viscosity, segregation resistance, and flowability, compared to the mixture comprising solely of slag [14]. In another study examining the microstructure of geopolymer samples, mixtures of fly ash and waste glass powder with high calcium content were used. In experiments with compressive strengths varying between 34-48 MPa, it was emphasized that glass powder could be used instead of fly ash, and especially high calcium fly ash and 10-20% ground glass powders resulted in improved compressive strength [15]. In another study, the low calcium F class fly ash was developed by fiber-reinforced geopolymer composite and blast furnace slag. The slag was added to the fly ash at varying rates of 0%, 10%, 20%, and 30% by mass. Slag mixed samples have higher initial cracking strength, higher tensile elasticity, and higher ultimate tensile strength compared to samples without slag (100% fly ash-0% slag), while they have lower tensile strain capacity, lower toughness, and lower stress. It is stated that it has an index. The results highlight that as more slag is used instead of fly ash, the sample becomes stronger but more brittle [17]. Recently, the cement-based composite concept has been expanded to engineering-based geopolymer composites [16-20]. In another study using different geopolymer materials, standard sand, water, sodium silicate fly ash, and press filter waste (PFA) were used. The 7, 28, and 56-daily compressive strengths of the samples prepared with a sand/binder ratio of 3.0 were determined as 18.53 Mpa, 19.58 Mpa, and 19.78 Mpa, respectively. It was observed that as the PFA ratio increased in the samples, there was a decrease in both unit mass values and compressive strength values [21]. The effect of different curing conditions on geopolymer structures is very important and needs to be investigated. It is emphasized that different curing conditions are very effective in terms of the mechanical and physical properties of geopolymer samples [22-25]. In addition, the mechanical properties of industrial waste-based geopolymers; It is emphasized in many studies that many features such as alkaline solution concentration, calcium content, cure temperature and age, Si/Al ratios, and levels of influence from additives should be revealed [26]. Metallurgical slags, such as steel slag, copper slag, ferronickel slag, and lead-zinc slag, have varying reactivities due to their different chemical components. This diversity could affect the performance of geopolymer binders. Therefore, hybrid mortars could be used for interior and exterior coatings of buildings or to repair damaged coatings [32-37].

Examined the effects of BFS and activator content on the workability and strength properties of FA-based geopolymer concrete and showed that the compressive strength of FA+BFS-based geopolymer increased with increasing BFS content at all term up to 180 days [43]. It also shows that better compressive strength and lower shrinkage were found in slag and fly ash blended geopolymer mortars and concretes [44]. Upon reviewing the results of different curing methods found in the literature, it could be concluded that heat or oven curing conditions significantly enhance compressive strength over time compared to other curing techniques. Notably, samples subjected to ambient curing conditions not only demonstrate lower strength but also encounter several detrimental effects, including early setting, the formation of micro-cracks, and drying shrinkage [45]. Furthermore, it has been noted that specimens cured in an oven demonstrate a higher modulus of rupture and elastic modulus compared to those cured at ambient temperature. This observation highlights that increased temperature accelerates chemical reactions, resulting in a stronger structure [46]. The observed increases in strength are attributed to the rate of geopolymerization [47]. Additionally, studies have shown that the compressive strength of geopolymer composites improves as the amount of blast furnace slag increases. However, substituting components like fly ash and Portland cement in specific ratios can also yield positive outcomes in terms of cost and emissions [43-46].

A review of the literature shows that different waste materials and methods are used to prepare geopolymer samples. The aim was to reveal the internal structure and mechanical properties of geopolymers with different properties such as surface area, density values, Fe, Si, and Al components. The interaction with blast furnace slag was investigated by using low proportions of class C fly ash. The physical and mechanical properties of these binders were evaluated comparatively. The effect of different slag types under three different molarities and two different curing conditions was also investigated. Besides, the relationship between the compressive strength and different parameters (unit weight, dynamic modulus of elasticity, flexural strength) was presented based on mathematical formulations. The study examined the effects of industrial and mineral waste materials on the main binder, evaluating their impact on compressive strength. The objective is to enhance sustainability and reduce costs by utilizing and recovering these naturally occurring waste additives. To achieve this, SEM/EDX analyses and microstructure assessments of the doped geopolymer composite samples were conducted. In conclusion, ANOVA analyses were used to investigate the significance of different proportions of binder material and different molarity ratios of NaOH on the compressive strength.

2. Materials And Method

In the preliminary trial process of the study, the effect of gradually changing different molarity ratios on geopolymer composites was observed. In these preliminary trials, 6M, 8M, 10M, 12M and 14M NaOH solutions were used. Especially in 6M, 8M, 10M, 12M solutions, no problems occurred in terms of workability and placement, while some problems such as placement, workability and early setting occurred in mortars prepared with 14M solution. The reason for the decrease at concentrations more than 14 M was explained as the increase in viscosity and aluminasilicate precipitation due to excessive hydroxide concentration [44]. For this reason, considering the studies in the literature, it was found appropriate to use 8M,10M,12M solutions. This study aimed to determine the mechanical and physical properties of geopolymer mortar samples produced in different mineral contents. For this purpose, fly ash obtained from the Sivas/Kangal Thermal Power Plant and ground blast furnace slag types obtained from Bolu (BSF) were tested as main binders in different proportions. In this study, alkaline activators

were prepared in NaOH and Na_2SiO_3 solutions with different molar ratios of 8M, 10M, and 12M. The main binder consisted of different proportions as 75% by mass of blast furnace slag and 25% fly ash (75BFS25FA), 85% blast furnace slag and 15% fly ash (85BFS15FA), 95% blast furnace slag and 5% fly ash (95BFS5FA), and 100% blast furnace slag (100BFS). The ratio of alkaline activators (Na_2SiO_3/NaOH) was fixed at 2.5 for all experimental series. Fig. 1 shows the geopolymer mortar production process.

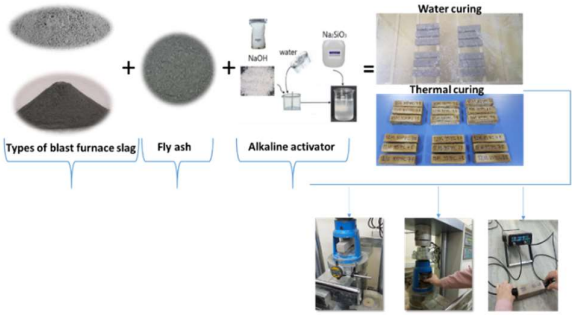


Figure 1. Geopolymer production process

The liquid/binder ratio in all geopolymer mortar samples is constant. The prepared mortars were poured into the triple moulds whose dimensions are 40x40x160 (mm). The first set of samples was subjected to thermal curing at 75°C for 24 hours. The other samples were water-cured at 23±2°C. The samples were kept in water at 23± 2℃ and in the thermal curing at 75℃ for 24 hours. After curing, the physical properties and ultrasonic pulse velocities (UPV) of the samples were determined. The flexural tensile strength and compressive strength were applied according to the test methods specified in the TSE EN 196-1 standard. The flexural tensile strength test was carried out under 50 N/sec and the compressive strength test was carried out under 2400 N/sec loading. In the flexural tests the midpoint deflections at the moment of fracture were determined using a comparator.

Table 1. Amounts in mixture for geopolymer mortar compozites

Sample ID	BFS(g) (mass,%)	FA(g) (mass,%)	Molarity (M)	Sand (g)	Liquid/ binding	Water (g)	Na_2SiO_3/ NaOH	NaOH (g)	Na_2SiO_3 (g)
75BFS25FA	375 (75%)	125 (25%)	8	1350	0.6	50	2.5	70	180
85BFS15FA	425 (85%)	75 (15%)	8	1350	0.6	50	2.5	70	180
95BFS5FA	475 (95%)	25 (5%)	8	1350	0.6	50	2.5	70	180
100BFS	500 (100%)	0 (0%)	8	1350	0.6	50	2.5	70	180
75BFS25FA	375 (75%)	125 (25%)	10	1350	0.6	50	2.5	70	180
85BFS15FA	425 (85%)	75 (15%)	10	1350	0.6	50	2.5	70	180
95BFS5FA	475 (95%)	25 (5%)	10	1350	0.6	50	2.5	70	180
100BFS	500 (100%)	0 (0%)	10	1350	0.6	50	2.5	70	180
75BFS25FA	375 (75%)	125 (25%)	12	1350	0.6	50	2.5	70	180
85BFS15FA	425 (85%)	75 (15%)	12	1350	0.6	50	2.5	70	180

95BFS5FA	475 (95%)	25 (5%)	12	1350	0.6	50	2.5	70	180
100BFS	500 (100%)	0 (0%)	12	1350	0.6	50	2.5	70	180

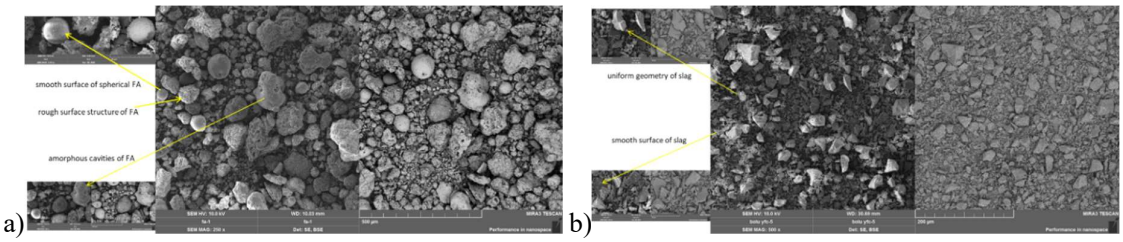
In Tab. 1, the mixing ratios of the prepared samples, indicate the mass values of geopolymer compozite. The ratio of NaOH solution and Na_2SiO_3 solution was constant at 2.5 in different molar ratios (8M, 10M, and 12M). Sodium hydroxide and sodium silicate were used as 70 g and 180 g, respectively. The sand used in the experiments was passed through a sieve with an aperture of 0-4 mm. Depending on the speed of the ultrasonic wave passing through the samples, the dynamic elasticity modulus was determined using Eq. (1) below. In Eq. (1), the symbols E, V, ρ, and μ represent the dynamic elasticity module (E) , ultrasonic wave speed, density, and Poisson ratio, respectively. Eq. (2) defines the unit mass result, where A denotes the mass of the sample in its dry state, and B denotes the volume of the sample.

$$(E)= \frac{V^2 x\, \rho(1+\mu)\, x\, (1-2\mu)}{(1-\mu)} \quad , \quad \text{Unit mass} = \frac{A}{B} \qquad (1), (2)$$

3. **Results And Dıscussıon**

3.1 Experimental findings

Examining the specific surface areas, it thought that the surface shape factor increased the homogeneity and binding ability of the mixture. The increase in the Si/Al ratio creates strong Si-O-Si bonds, causing increases in compressive strength [29]. Blast furnace slag have higher calcium oxide content compared to fly ash. In particular, the ability of calcium oxide to react with water to form calcium hydroxide accelerates the geopolymerization process, and geopolymers containing a high percentage of furnace slag generally reach higher compressive strength values [30-31]. In microstructural analysis, the internal structure of the geopolymer sample that gave the highest compressive strength was examined. Fly ash and blast furnace slag are two materials commonly used in construction. Fly ash has many spherical, void, rough, and smooth structures with smooth surfaces, while blast furnace slag has a flat geometry with no voids (Fig. 2).



a) b)

Figure 2. SEM/EDX images of the FA (a) and BFS (b) at different magnifications

Fig. 4 shows unreacted slag particles, microcracks, C-S-H, and N-(C)-A-S-H gels in the morphological images. When examining the geopolymer microstructure, it could be seen that fly ash particles are generally degraded, reacting with alkalis to form N-A-S-H gels. It could be changed in geopolymerization and formation of C-S-H gel when increasing the percentage of GGBS, which in turn increases the compressive strength [28]. This situation, which is especially visible under 2000x magnification, is thought to be effective on compressive strength. When the EDX element

distributions are examined, the atomic element distributions on the surfaces of the 95BFS5FA sample are 30.22% C, 55.70% O, 5.84% Si, 1.46% Al, 2.44% Na, 3.37% Ca and others.

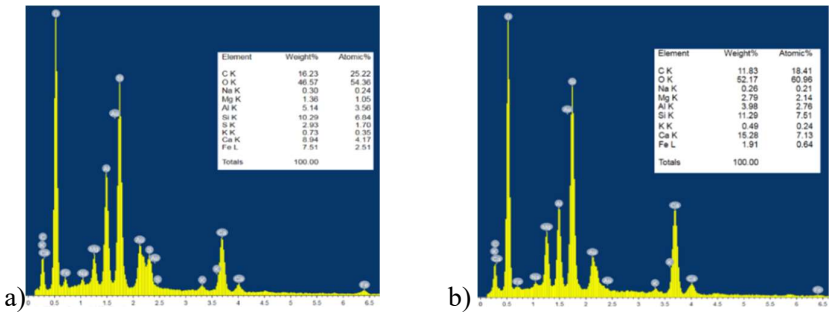


Figure 3. The element distribution of FA (a) and BFS (b)

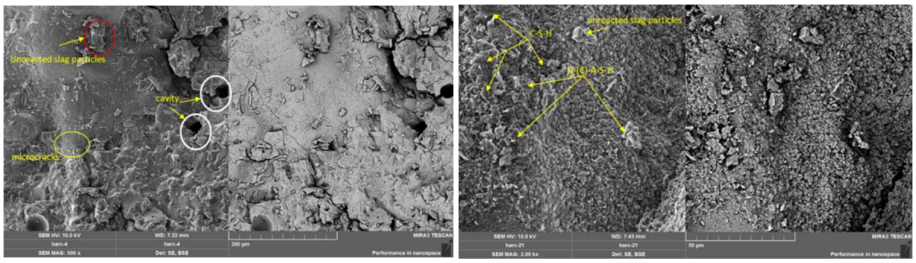


Figure 4. SEM/EDX images of geopolymer mortar at different magnification

To determine the unit mass values of the test samples, 8M, 10M, and 12M NaOH and Na_2SiO_3 solutions were added as activators to mixtures of blast furnace slag and fly ash at four different ratios. The results are presented comparatively to evaluate the effects of different cure and binder components on geopolymer materials. When the results are examined, it is seen that the unit mass of blast furnace slag and fly ash-based samples activated with alkali activators of different molarity vary between 1.98 g/cm^3 and 2.17 g/cm^3 for samples exposed to 75 °C thermal curing. The study revealed that the unit mass values of samples kept in water cure at 23±2°C varied from 2.1 to 2.2 g/cm^3. The findings suggest that the increase in blast furnace slag in the samples, which were prepared with varying proportions of blast furnace slag and fly ash, led to a general increase in unit mass. This could be attributed to the high specific gravity of blast furnace slag (2.90 g/cm^3) compared to fly ash (2.72 g/cm^3), which appears to be the primary factor responsible for these changes [27]. Additionally, the study discovered that unit mass values tended to rise as the molarity decreased while comparing three different alkaline activator molarity values used. Fig. 5 shows the unit mass of geopolymer samples that were exposed to different curing conditions.

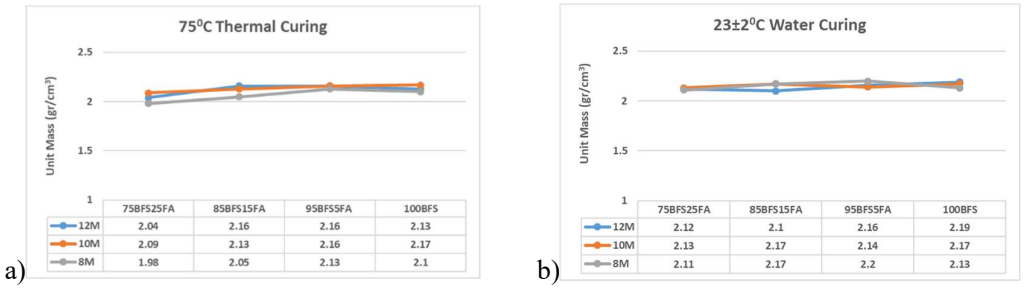
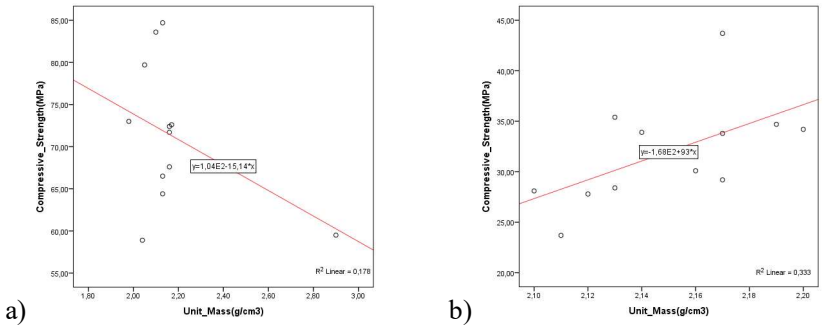


Figure 5. Unit mass of different geopolymer compozites at thermal cure (a) and water cure (b)

The elasticity modulus is a crucial mechanical property for concrete mortar compozites that operate under load. In this study, the dynamic modulus of elasticity was obtained from UPV results. Fig. 7 shows the dynamic elasticity modulus results of different samples that were activated with an alkali activator. Examined the elasticity values of samples prepared using four different binders and three different molar ratios under 75°C thermal curing and 24-hour curing conditions, it was seen that the highest increase observed by 108% (at 95BFS5FA-8M compared to 95BFS5FA-12M) due to the decrease in molarity in the mixture. Fig. 6 show the relationship between unit weight and compressive strength of samples subjected to water cure and thermal cure. It was seen in Fig. 6 that there was a negative correlation and a linear regression value. In Fig.6 (b), the R^2 value was 0.333 and there was a positive correlation between compressive strength and unit weight. When the relationship between thermal cure and unit weight was analysed, unit mass values ranging from 2 to 2.20 were observed for high compressive strengths. It was observed that there was a negative and linear relationship here. However, when the relationship between water cure and unit mass was analysed, it was seen that low compressive strengths were obtained against similar unit mass values. It was observed that there was a positive and linear relationship. Fig. 8 shows a linear relationship between dynamic elasticity and compressive strength. Here, a positive correlation was observed for both water curing and thermal curing. Fig 8 shows an average correlation with an R^2 value of 0.509.



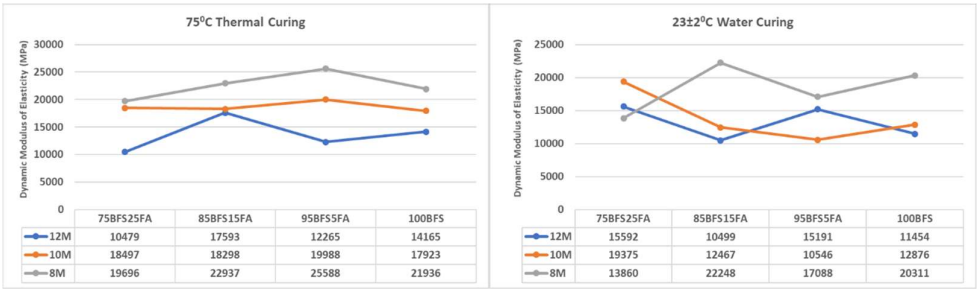
a) b)

Figure 6. Relationship between compressive strength and unit mass at thermal cure (a) and water cure (b)

Fig. 9 shows the deflection values for different cures and material components. Among the samples of 95BFS5FA subjected to 75°C heat cure, those with the highest flexural strength results were selected for further testing under different cure conditions. The samples with 8M ratios for heat and water curing showed the highest results. By examining the curing conditions, it could be concluded that heat curing provides more effective results for geopolymer compozites compared to water curing. The highest deflection values were observed under heat curing conditions at 75°C, which were found to be inversely proportional to the decrease in molarity. In addition, the changes in deflection values were found to be consistent with the flexural strength results. When these results are analyzed, a strong positive correlation is observed with a value of R^2=0.735, while a negative and low correlation is observed in Fig. 10.

Fig. 11 shows that there are similar results for the flexural strength of the samples subjected to different curing conditions. In general, looking at the flexural strength results, it could be said that the thermal cure applied to the samples kept in the thermal curing environment is more effective compared to the samples kept in water curing conditions. By increasing the reorganization of the gel with activator solubility, it is possible to reduce defects in the microstructure. The selection of activators with

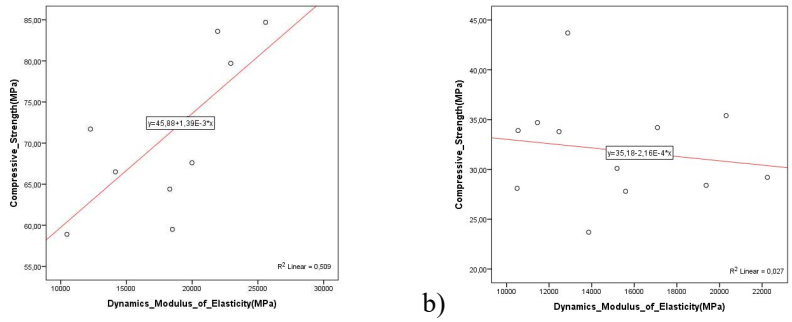
appropriate concentrations in molarity is very effective on the strength in flexural. The results showed that the geopolymer samples at 75 °C thermal curing (particularly the 8M and 95BFS5FA samples) had the highest values of flexural strength (9.3 MPa), while those at underwater cured had the lowest values (6.1 MPa). These findings suggest that temperature has a crucial factor, particularly for geopolymer samples, and that it could result in energy losses during the production phase.



	75BFS25FA	85BFS15FA	95BFS5FA	100BFS
12M	10479	17593	12265	14165
10M	18497	18298	19988	17923
8M	19696	22937	25588	21936

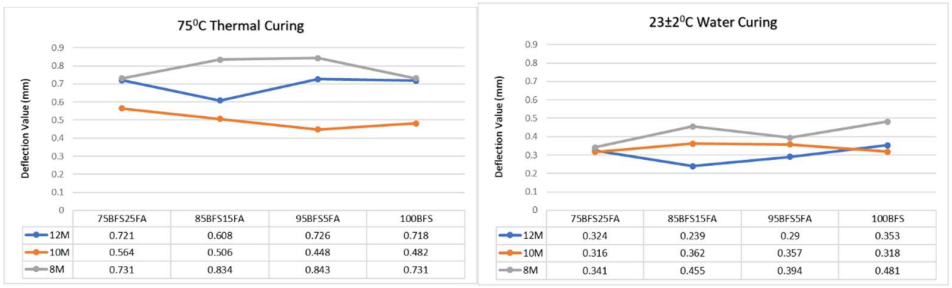
	75BFS25FA	85BFS15FA	95BFS5FA	100BFS
12M	15592	10499	15191	11454
10M	19375	12467	10546	12876
8M	13860	22248	17088	20311

Figure 7. Dynamic modulus of elasticity at different geopolymer compozites



a) b)

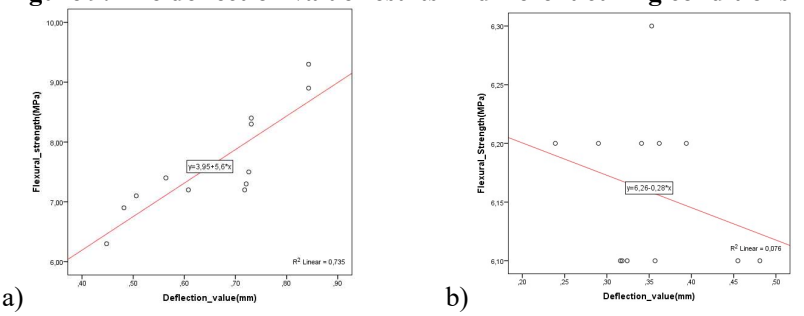
Figure 8. Relationship between compressive strength and dynamic modulus of elasticity at thermal cure (a) and water cure (b)



	75BFS25FA	85BFS15FA	95BFS5FA	100BFS
12M	0.721	0.608	0.726	0.718
10M	0.564	0.506	0.448	0.482
8M	0.731	0.834	0.843	0.731

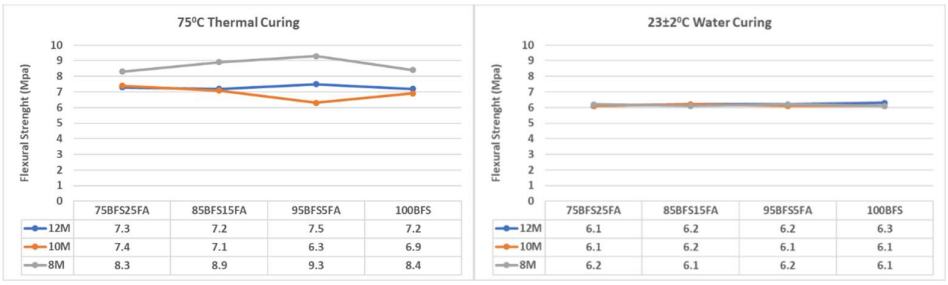
	75BFS25FA	85BFS15FA	95BFS5FA	100BFS
12M	0.324	0.239	0.29	0.353
10M	0.316	0.362	0.357	0.318
8M	0.341	0.455	0.394	0.481

Figure 9. The deflection value results in different curing conditions



a) b)

Figure 10. Relationship between flexural strength and deflection at thermal cure (a) and water cure (b)

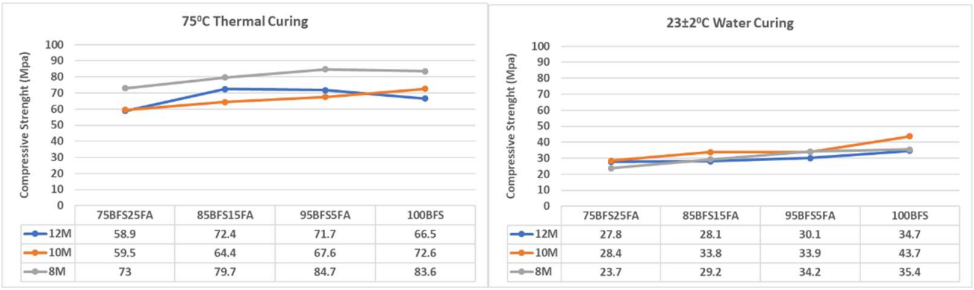


	75BFS25FA	85BFS15FA	95BFS5FA	100BFS
12M	7.3	7.2	7.5	7.2
10M	7.4	7.1	6.3	6.9
8M	8.3	8.9	9.3	8.4

	75BFS25FA	85BFS15FA	95BFS5FA	100BFS
12M	6.1	6.2	6.2	6.3
10M	6.1	6.2	6.1	6.1
8M	6.2	6.1	6.2	6.1

Figure 11. Flexural strength results at 8M, 10M, and 12M of geopolymer samples

Fig. 12 shows the compressive strengths of geopolymer samples. Upon examination of the results, it is made that the lowest compressive strength was obtained by water-cured samples, while the highest strength value was achieved under thermal cure conditions. Upon comparing the overall results, it could be concluded that the highest strength (84.7 MPa) occurs in the 8M solution as an alkaline activator and the 95BFS5FA geopolymer sample. Upon examining the comparative percentages of samples subjected to distinct curing conditions, it was observed that there were more significant increases in samples utilizing 8M solutions. Conversely, an overall decline was noted as the fly ash percentage in the blend increased.



	75BFS25FA	85BFS15FA	95BFS5FA	100BFS
12M	58.9	72.4	71.7	66.5
10M	59.5	64.4	67.6	72.6
8M	73	79.7	84.7	83.6

	75BFS25FA	85BFS15FA	95BFS5FA	100BFS
12M	27.8	28.1	30.1	34.7
10M	28.4	33.8	33.9	43.7
8M	23.7	29.2	34.2	35.4

Figure 12. Compressive strength results at 8M, 10M, and 12M of geopolymer samples

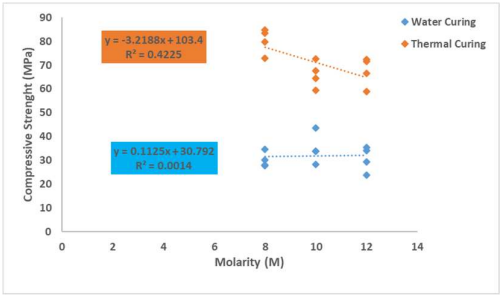
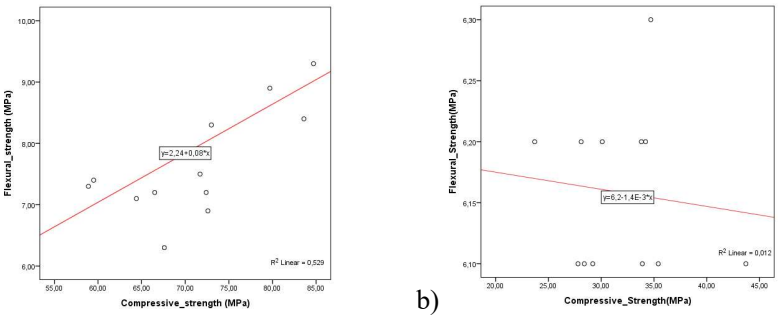


Figure 13. Relationship graph of thermal cure and water cure depending on molarity and compressive strength

The prevalent theory suggests that cracks and pores that may arise in microstructures due to elevated fly ash ratios in the geopolymer sample lead to the formation of C-(A)-S-H gels and a subsequent reduction in density [14,16,41]. On the other hand, as the molarity ratio decreases, there are generally increases in strength values. NaOH in low molarity causes geopolymer mortars to have higher strength [27]. When the physical properties of the blast furnace slag and fly ash used in the study were examined, it was stated that furnace slag contained higher amounts of silica and aluminum oxide than fly ash. It could be said that this situation may create more Si-O-Si and Al-O-Al bonds for the components containing slag at high amounts, which has positive effects on compressive strength [28]. Fig. 14 (a) shows an

average geopolymer mortar correlation with an R^2 value of 0.529. Scientific studies show that R^2 values ranging from 0.7 to 1 are considered significant, and these results are considered to be strong predictive models [38].



a) b)

Figure 14. Relationship between compressive strength and flexural strength at thermal cure (a) and water cure (b)

3.2. Influence of additives

In this part of the study, we investigated the effects of various additives on geopolymer composite structures. We selected marble powder, an industrial waste, and strontium, a mineral waste, as the additives. In the main binder mixtures, we added 5% marble powder and 5% strontium as substitutes. To assess the performance of the samples over time, we applied ambient curing for 7, 28, 56, and 90 days. The analysis revealed that the highest compressive strengths were achieved in the geopolymer mortar samples containing marble powder. However, the samples experienced a compressive increase during the 28-day curing period (as shown in Fig. 15), while losses in compressive strength were observed at 90 days curing periods. Fig. 16-18 presents the SEM/EDX images of the geopolymer samples.

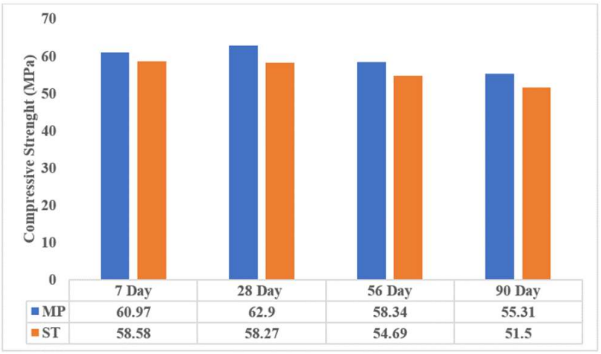


Figure 15. Compressive strengths of additives in geopolymer mortars

The relatively high compressive strengths of binders with a high slag content can be attributed to the density of the C-S-H (calcium silicate hydrate) and C-A-S-H (calcium aluminosilicate hydrate) gel phases, as well as their microstructure. EDX analyses of strontium and marble powder in geopolymer mortars indicate that higher Si/Al ratios lead to a greater degree of integration in C-A-S-H gels (Fig. 18). This effect was particularly pronounced in the samples that were cured for a longer period, specifically 90 days.

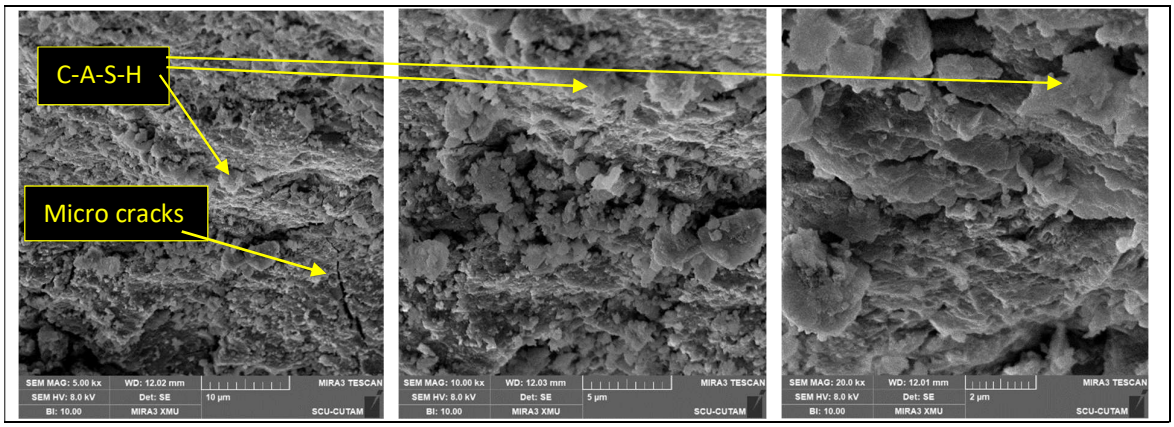


Figure 16. SEM analysis of strontium added geopolymer mortars (90-day)

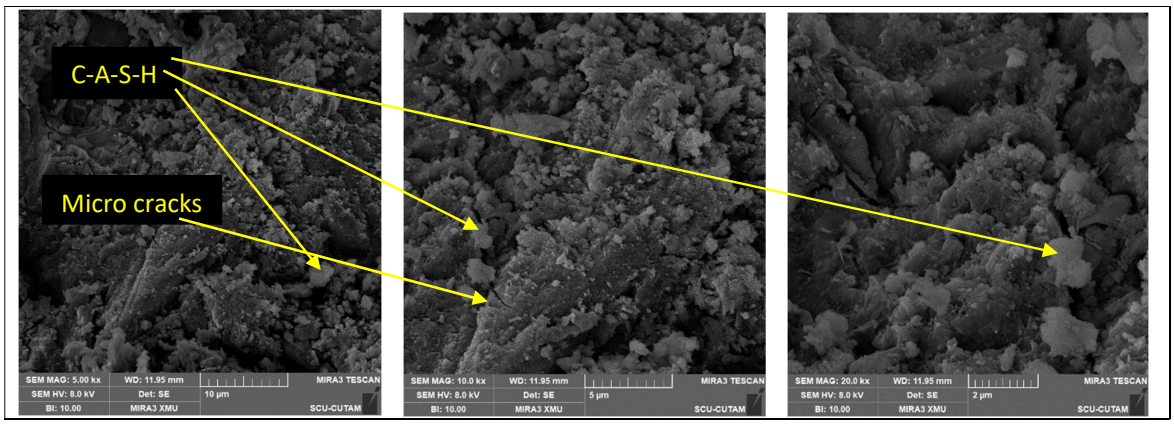
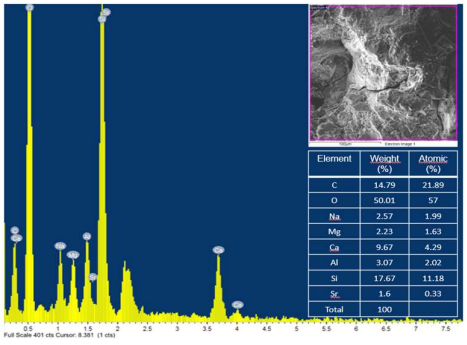


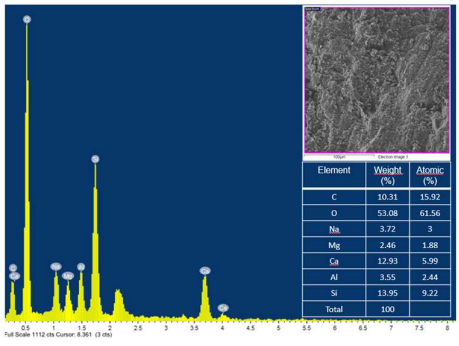
Figure 17. SEM analysis of marble powder added geopolymer mortars (90-day)

a)



Element	Weight (%)	Atomic (%)
C	14.79	21.89
O	50.01	57
Na	2.57	1.99
Mg	2.23	1.63
Ca	9.67	4.29
Al	3.07	2.02
Si	17.67	11.18
Sr	1.6	0.33
Total	100	

b)



Element	Weight (%)	Atomic (%)
C	10.31	15.92
O	53.08	61.56
Na	3.72	3
Mg	2.46	1.88
Ca	12.93	5.99
Al	3.55	2.44
Si	13.95	9.22
Total	100	

Figure 18. EDX analysis of strontium (a) and marble powder (b) (90-Day)

3.2. Data analysis

Analysis of variance (ANOVA) is used to test hypotheses regarding whether the differences between the means of two or more groups are significant. When comparing the means of more than two groups, the F test, which is a part of ANOVA, is employed. The primary goal of the F test is to determine whether the independent variable (X) has a simultaneous effect on the dependent variable (Y). If the significance value (p-value) is less than 0.05, it indicates that the independent variable (X) does indeed affect the dependent variable (Y). The hypotheses for this study are as follows:

H_0 = Independent variable affects the dependent variable simultaneously;

H_1 = Independent variable simultaneously does not affect the dependent variable; [39,40]

As seen in SPSS Tab. 2, the coefficient of determination R^2 value is also given to estimate how much all the independent variables simultaneously contribute to the dependent variable. Here the R Square value was found to be. 668 or 66.8%, which indicates the effect of the main binder ratio and molarity on the compressive strength variable and is considered to have an average acceptability. When Tab. 3 was analyzed, it was seen that the sig value was 0.007 which was less than 0.05. At the same time, it could be said that molarity and main binder rate parameters are effective on compressive strength at the same time.

Table 2. Model Summary

Model Summary[b]				
Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.817[a]	.668	.594	5.37846

a, Dependent Variable: Compressive Strength - b,Predictors: (Constant),Molarity, Main Binder Rate

Table 3. ANOVA results

Anova[a]					
Model 1	Sum of Squares	df	Mean Square	F	Sig.
Regression	524.266	2	262.133	9.062	.007[b]
Residual	260.350	9	28.928		
Total	784.617	11			

a, Dependent Variable: Compressive Strength - b, Predictors: (Constant),Molarity, Main Binder Rate

The partial t-test in Tab. 4 partially determines the effect of the independent variable (X) on the dependent variable (Y). If the Sig. Value is less than 0.05, the independent variable (X) affects the dependent variable (Y) partially or separately. The hypotheses in this section are as follows:

H_0 = The independent variable partially affects the dependent variable;

H_1 = The independent variable has partially no effect on the dependent variable;

- If Sig value < 0.05, H_0 is accepted, If Sig value > 0.05, H_1 is accepted [42].

The main binder ratio variable has a significance value of 0.03 (< 0.05), which means that H_0 is accepted and H_1 is rejected, in other words, it can be concluded that the main binder ratio variable has a partial effect on the compressive strength. The molarity variable has a significance value of 0.008 (< 0.05), which means that H_0 is accepted and H_1 is rejected or in other words, it can be concluded that the main binder ratio has a partial effect on compressive strength.

Table 4. Coefficients results

Coefficients[a]					
Model	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
1	B	Std. Error	Beta		
(Constant)	66.360	17.285		3.839	.004
Main Binder Rate	.417	.162	.496	2.581	.030
Molarity	-3.219	.951	-.650	-3.385	.008

a, Dependent Variable: Compressive Strength

Here the regression Eq. (3) is taken from the B value in the Unstandardized Coefficients section and expressed by the following regression. (Y: Compressive Strength, x_1: Main_binder_rate, x_2: Molarity)

$$Y = 0.417x_1 - 3.219x_2 + 66.360. \quad (3)$$

It shows the histogram plot of the dependent variable compressive strength (Fig 19). Here the distribution of errors is given. It is seen in the graph that the errors are mostly within the limits of the standard curve and the standard error is 0.905.

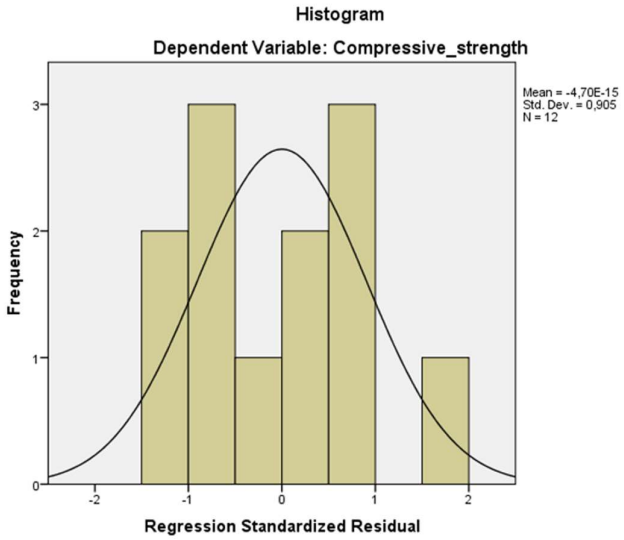


Figure 19. Histogram graph of the compressive strength

3. Conclusıons

This study was conducted to investigate the physical and mechanical effects of various waste materials and curing conditions on geopolymer mortars. The results showed that the reaction products, types of alkaline activators, and reaction conditions are crucial factors in determining the outcome of the experiment. When the effect of curing conditions on mechanical properties was analyzed, thermal curing gave approximately 88% higher values for compressive strength and approximately 20% higher values for flexural tensile strength compared to water curing. Unit mass values were approximately the same. The thermal curing samples, which have higher flexural and compressive strengths, also have approximately 2 times higher deformation capabilities, as expected. For dynamic elasticity modulus, contrary to expectations, no significant increase or decrease was detected. When the effect of the change in molarity on mechanical properties was examined, no significant difference was observed, especially with water cure. However, with the effect of thermal curing, the flexural tensile strength of 8M samples is about 24% higher than 10M and 12M samples. For compressive strength, again this difference is about 6-10% more in favor of 8M. Among the samples kept in a 75°C thermal curing, the lowest flexural strength was obtained as 6.3 MPa for the 95BFS5FA -10M sample, and the highest value was 9.3 MPa for the 95BFS5FA -8M sample. Compressive strength results were measured in the lowest 75BFS25FA-12M (58.9MPa) among the samples exposed to a 75°C thermal curing. The highest value was obtained from the sample 95BFS5FA-8M (84.7 MPa). In samples exposed to 23±°C water curing, the lowest compressive strength value was measured as 23.7 MPa in the sample 75BFS25FA-8M, and the highest compressive strength value was measured as 43.7 MPa in the 100 BFS-10M. It was determined

as a result of the study that the samples with higher slag content showed higher compressive strength. Type C fly ash has particularly low compressive strength, but in this study, it has shown positive results on compressive strengths with the use of certain ratios and its usability at low ratios has been demonstrated in a research study. Especially compared to the samples exposed to water curing process, it could be said that the temperature factor with thermal curing application increases the effectiveness of the activators and increases the binding ability between the components. This is thought to have a positive effect on the compressive strengths.

The optimisation studies could be carried out for different curing conditions, different temperatures, different molarity, different waste materials and ratios for geopolymer mortar samples. In addition, durability tests and microstructural analyses could be performed.

Nomenclature

BFS: Blast furnace slag
FA: Fly ash
MP: Marble Powder
S: Strontium
M: Molarity
ºC: Degree centigrade
MPa: Megapascals
mm: Milimeter

Acknowledgments

This study was carried out within the scope of project number 2907-23.E3101.07.01 supported by the Gümüşhane University Scientific Research Projects Coordination Unit (GÜBAP).

References

[1] Ganesh, A. C., Muthukannan, M., Development of high performance sustainable optimized fiber reinforced geopolymer concrete and prediction of compressive strength, *Journal of Cleaner Production*, 282, (2021),124543.
[2] Akbulut, F., Polat, R., , Karagöl, Fatma., Investigation of Using Perlite of Erzurum Pasinler Region in Geopolymer Production, *Tr. J. Nature Sci.* 10, Issue 1, Page 37-45, (2021).
[3] Çavdar, A., Yetgin, Ş., Investigation of abrasion resistance of cement mortar with different pozzolanic compositions and subjected to sulfated medium, Construction and Building Materials 24 (4), 461-470,(2010).
[4] Phoongernkham, T., Maegawa, A., Mishima, N., Hatanaka, S., Chindaprasirt, P., Effects of Sodium Hydroxide and Sodium Silicate Solutions on Compressive and Shear Bond Strengths of FA–GBFS Geopolymer, *Construction and Building Materials*, 91: 1–8,(2015).
[5] Abdulrahman, H., Muhamad, R., Visintin, P., Shukri, A.A., Mechanical properties and bond stress-slip behaviour of fly ash geopolymer concrete, *Construction and Building Materials*,327,126909, (2022).
[6] Casero, M.A.G., Arana, C.D.D., Rodriguez, J.S.B.,Villarejo, L.P., Physical, mechanical and thermal properties of metakaolin-fly ash geopolymers, *Sustainable Chemistry and Pharmacy*, 26,100620, (2022).
[7] Nergis, D.D.B., Vizureanu, P., Sandu, A.V., Nergis, D.P.B., Bejinariu, C., XRD and TG-DTA Study of New Phosphate-Based Geopolymers with Coal Ash or Metakaolin as Aluminosilicate Source and Mine Tailings Addition, *Materials*, 15, 202, (2022).
[8] Topçu, İ.B., Toprak, M.U., Productıon Of Alkalı Actıvated Lıghtmass Bottom Ash Mortar, *Journal of Engineering and Architecture Faculty of Eskişehir Osmangazi University*, 22, 2, (2009).
[9] Koçak, Y., The Effect of Thermic Power Plant Waste Fly Ash on Properties of Portland Cement, *Journal of Polytechnic*,14,2, 135-140, (2011).

[10] Kürklü, G., The Investigation of Physical and Mechanical Properties of Geopolymer Mortars with Granulated Blast Furnace Slag Cured at Room Temperature, *Afyon Kocatepe University Journal of Science and Engineering*,16,025604,356-367, (2016).
[11] Sağlamtimur, N.D., Geopolymer Buıldıng Materıal Productıon From Wastes Of Bottom Ash And Pumıce, *Omer Halisdemir University Journal of Engineering Sciences,* 7, 2,590-599, (2018).
[12] Çavdar, A., and Çavdar Ö., Availability of sedimentary and volcanic rock deposits on Northeastern Turkey as concrete aggregates, Physics and Chemistry of the Earth, Parts A/B/C 134, 103567, (2024).
[13] Gao, X., Alkali activated slag-fly ash binders: design, modeling and application, Eindhthermal curing University of Technology., Ph.D. Thesis, Netherlands., 229p, 2017.
[14] Huseien , G.F., Sam, A.R.M.S., Alyousef,R., Texture, morphology and strength performance of self-compacting alkali-activated concrete: Role of fly ash as GBFS replacement, *Construction and Building Materials*,270 121368, (2021).
[15] Tho-In,T., Sata, V., Boonserm, K., Chindaprasirt, P., Compressive strength and microstructure analysis of geopolymer paste using waste glass powder and fly ash., Journal of Cleaner Production., 172, 2892-2898, (2018).
[16] Cheah, C.B., Tan,L.E., Ramli,M., The engineering properties and microstructure of sodium carbonate activated fly ash/ slag blended mortars with silica füme, *Composites Part B*., 160, 558–572, (2019).
[17] Ling,Y., Wang,K., Li,W., Shi,G., Lu, P., Effect of slag on the mechanical properties and bond strength of fly ashbased engineered geopolymer composites., Composites Part B, 164, 747–757, (2019).
[18] Kubba, Z., Huseien, G.F., Sam,A.R.M., Shah,K.W., Ismail,M.A.A.M., Tahir,M.M., Jahangir Mirza,J., Impact of curing temperatures and alkaline activators on compressive strength and porosity of ternary blended geopolymer mortars, *Case Studies in Construction Materials*, 9,(2018).
[19] Pehlivan, H., Nano silica added trachytic tuff based geopolymer mortars investigation of properties in different curing environment, *Gümüşhane University Journal of Science and Technology*, 13(3), 580-594, (2023).
[20] Eryılmaz, K., Polat,R., Karagöl,F., Turhan,D.,Investigation of Usability of Aggregates Obtained from Geopolymer Concrete Wastes in Geopolymer Concrete, *Journal of the Institute of Science and Technology*, 13(1), 419-431, (2023).
[21] Topçu, İ.B., Sofuoğlu, T., Evaluation of Unit Mass and Compressive Strength of Geopolymer Mortars Obtained with Press Filter Waste and Fly Ash under Different Conditions, *El-Cezerî Journal of Science and Engineering*,7,2, (2020).
[22] Durak,U., Şimşek,A.A., Investigation of The Use of Waste Iron Powder Instead of Aggregate in Fly Ash and Blast Furnace Slag Based Geopolymer Systems, *Journal of The Institute of Science and Technology*, 5(2), 812-828, (2022).
[23] Kalaycıklı,I,E. The Varıatıon Of Compressıve Strength And Durabılıty Performance Of Dıfferent Geopolymer Concrete Wıth Tıme (M.Sc. Thesis). *Istanbul Gelısım Unıversity, Instıtute Of Scıence*, January 2020.
[24] Altındal,I., The Change Of Compressıve Strength Of Dıfferent Geopolymer Concretes Under Dıfferent Curıng Condıtıons (M.Sc. Thesis), Istanbul Gelısım Unıversity, Instıtute Of Scıence, January 2020.
[25] Lıban.L.R., Desıgn Of Zeolıte Based Geopolymer Mortars Wıth Fly Ash And Lımestone Addıtıves By Taguchı Method, Ph. D Thesıs, Konya Technical University, Institute of Graduate Studies, Department of Civil Engineering,2022.
[26] Şenol,A.F., Properties of Geopolymer Mortar and Concrete Produced with Industrial Waste Powders, *2nd International Conference on Innovative Academic Studies*, 28 - 31, Türkiye, 2023.
[27] Kop, M., Yazıcıoğlu, S., Mechanical Properties of Fly Ash and Blast Furnace Slag Based Geopolymer Mortars in Thermal Curing Environment, *Gazi University Journal of Science*, 11(3): 756-765 (2023).
[28] Nagajothi, S. Elavenil,S., Effect of GGBS Addition on Reactivity and Microstructure Properties of Ambient Cured Fly Ash Based Geopolymer Concrete, *Silicon*, 13, 507–516 (2021). https://doi.org/10.1007/s12633-020-00470-w.
[29] Zhuang X.Y, Liang C, Komarneni S, Zhou CH, Tong DS, Yang HM, Yu WH, Wang H (2016). Fly ash based geopolymer: clean production, properties and applications. *J Clean Prod*., 125:253–267.

[30] Yaprak H, Alnkaa A, Memis, et al. Effects of different curing conditions on the properties of geopolymeric mortar. *MOJ Civil Eng*. 5(1), (2019), 45-50.
[31] Yilmazoglu, A, Yildirim, ST, Behçet, ÖF, Yıldız, S. Performance evaluation of fly ash and ground granulated blast furnace slag-based geopolymer concrete: A comparative study. *Structural Concrete*, (2022), 23: 3898– 3915.
[32] Kretzer M.B, Effting C, Schwaab S, Schackow A. Hybrid geopolymer-cement coating mortar optimized based on metakaolin, fly ash, and granulated blast furnace slag. *Cleaner Engineering and Technology,* (4), (2021), 100153.
[33] Liu,K. Zhang,Z. Sun,J. Advances in Understanding the Alkali-Activated Metallurgical Slag, *Advances in Civil Engineering*, vol. 2021, 8795588, 16, 2021. https://doi.org/10.1155/2021/8795588.
[34] Tsai C.J, Huang R, Lin W.T, Wang H.N. Mechanical and cementitious characteristics of ground granulated blast furnace slag and basic oxygen furnace slag blended mortar, *Materials and Design,* 60, (2014), 267-273.
[35] Mohammed D.T, Yaltay N. Strength and elevated temperature resistance properties of the geopolymer paste produced with ground granulated blast furnace slag and pumice powder. *Ain Shams Engineering Journal,* 15, (3), 2024, 102483.
[36] Chindaprasirt P, Jaturapitakkul C, Chalee W, Rattanasak U. Comparative study on the characteristics of fly ash and bottom ash geopolymers. *Waste Management,* 29, (2), (2009), 539-543.
[37] Tu W, Fang G, Dong B, Hu Y, Zhang M. Behaviour of alkali-activated fly ash-slag paste at elevated temperatures: An experimental study. *Cement and Concrete Composites,* 147, (2024), 105438.
[38] Matsimbe J, Dinka M, Olukanni D, Musonda I, Performance evaluation and mix design of ambient-cured fly ash-phosphogypsum blended geopolymer paste and mortar. *Results in Engineering,* 24, (2024), 103280.
[39] Karongkong L,L, Setiawan A,A, Hardjasaputra H, Predicting of geopolymer concrete compressive strength using multiple linear regression method. *International Journal of Applied Science and Engineering,* 19(2), 2021272, March 24, 2022.
[40] Ozturk S. Application of ANOVA and Taguchi Methods for Evaluation of the Surface Roughness of Stellite-6 Coating Material, *Materials Testing,* vol. 56, no. 11-12, (2014), pp. 1015-1020. https://doi.org/10.3139/120.110665.
[41] Radulovic R.M,et al., Sustaınabılıty Aspect Of Possıble Materıal Substıtutıon In Constructıon Industry, *Thermal Scıence*, (2023), 27, 6B, 4961-4973.
[42] Kaya M, Uysal M, Yılmaz K. Investigation of the relationship between strength, curing temperature and void ratio in geopolymer mortars using variance analysis. *Sakarya University Science Institute Journal,* 22 (2), 248~256, (2018).
[43] Öznur Öz H., Güneş M., Mechanical and microstructural properties of engineered cement based composites and fly ash and slag based engineered geopolymer composites, *NOHU J. Eng. Sci*., (2023),12(2), 452-471.
[44] Çınar, M., Erbaşı B., Investıgatıon of the usabılıty of geopolymers in geotechnical applications: a literature study, *KSU J Eng Sci*, 25(4), 2022).
[45]Nuruddin MFN, Kusbiantoro AK, Qazi SQ, Darmawan MSD, Husin NAH., Development of geopolymer concrete with different curing conditions. *IPTEK J Technol Sci.* (2011), https:// doi. org/ 10.12962/ J2088 2033. V22I1. 54.
[46] Azarsa P, Gupta R Comparative study involving effect of curing regime on elastic modulus of geopolymer concrete. *Buildings* 10(6):101. (2020), https:// doi. org/ 10. 3390/ BUILD INGS1 00601 01.
[47] Albitar M, Visintin P, Mohamed Ali MS, Drechsler M., Assessing behaviour of fresh and hardened geopolymer concrete mixed with class-F fly ash. *KSCE J Civ Eng* 19(5):1445−1455. (2015), https://doi. org/ 10. 1007/ S12205- 014- 1254-Z/ METRI CS
[48] Mohammed, D.T. ve Yaltay, N. (2024). Strength and elevated temperature resistance properties of the geopolymer paste produced with ground granulated blast furnace slag and pumice powder. Ain Shams Engineering Journal, 15,3, 102483.

Received: 16.2.2025.
Revised: 13.4.2025.
Accepted: 14.4.2025.