



[Technical Paper]

# Mechanical and Microstructural Properties of Polypropylene Fiber-Reinforced Geopolymer Composites

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**Abstract:** Geopolymers are a kind of polymeric material that can be formed using industrial applications based on inorganic polycondensation. They can be used in applications to replace traditional cement with environmental and technical benefits. In this paper, mixtures with different silica moduli (0.8, 0.9, 1.0) and molar ratios (12, 14, 16 M) were used to prepare geopolymer mortar, and the optimum polypropylene (PP) fiber-reinforced mixture was determined. The PP fibers in the geopolymer form constituted 0, 0.5 and 1.0% of the total volume of the mixture. Geopolymer (cement-less) matrix interaction performance played an important role in identifying the characteristics of the fiber-based composites. The mechanical and microstructural properties of the mixtures were determined. The optimum mixture was obtained from the sample with a molar ratio of 16 M and 0.5% fiber. This mixture was then used to cast the fiber-reinforced geopolymer composites. These composites were produced using three different geosynthetics with the optimum mixture. The experimental behavior of the composites was investigated using PP geogrid composite (PPGC), carbon geogrid composite (CGC) and polyfelt geotextile composite (PGC) under flexural loading. We observed that the compressive strength of the composites increased as the curing temperature and NaOH concentration increased in geopolymer composites with a high molar ratio. The microstructural properties of the samples changed with temperature: the voids decreased and the calcium silicate hydrate (CSH) gels provided compact bonding during the geopolymerization process. Furthermore, the PPGC demonstrated high viscosity, good adherence and high flexural strength.

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## 1. Introduction

Geopolymers are a kind of polymeric material that can be formed using industrial applications based on inorganic polycondensation. Geopolymers are chains or networks of mineral molecules linked with co-valent bonds. In general, the inorganic materials can be synthesized by the alkali activation of materials that are rich in  $Al_2O_3$  and  $SiO_2$  [1-2]. Davidovits [3-4], the inventor and developer of geopolymerization, set a logical scientific terminology based on different chemical units, essentially for silicate and aluminosilicate materials, classified according to the Si:Al atomic ratio. The basic forms of alumino-silicate structures are of three types as Poly (sialate) ( $-Si-O-Al-O-$ ), Poly (sialate-siloxo) ( $Si-O-Al-O-Si-O$ ) and Poly (sialate-disiloxo) ( $Si-O-Al-O-Si-O-$

$Si-O$ ) [5-7]. Generally, the formula of the geopolymers is  $M_n [-(Si-O)_z-Al-O]_n \cdot wH_2O$ , where M is an alkaline cation (Na, K or Ca), z is generally assigned a value of 1, 2 or 3 and n is the degree of polymerization. [8-9].

Alkali activator types are important parameters for geopolymerization reactions. Sodium hydroxide and potassium hydroxide are the most common alkali activators in geopolymerization reactions. Many researchers have reported that sodium-based activators are more efficient than potassium-based activators for geopolymerization [10-13]. In addition, curing temperature in geopolymer composites contributes significantly to the development of mechanical properties. A high curing temperature leads to the development of strength as the heat of the raw material increases the dissolution and polycondensation. Therefore, the curing temperature

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has an important effect on the formation and densification of binding gel in geopolymerization reactions [14–15]. Davidovits has conducted many studies of fiber-reinforced composites [16]. These composites play an important role in the repair and strengthening of damaged structures thanks to their high durability, low permeability and resistance to corrosion. The most common fiber reinforcements used in composites nowadays are polypropylene (PP) geosynthetics [17]. Saranyadevi et al. [18] noted that these geosynthetics are often used in engineering applications for financial reasons; they are associated with decreases in the cost of imported materials and wastage. They are also generally more efficient in their use of resources compared with traditional structural materials [19].

Fly ash (FA) a coal combustion residue of thermal power plants has been regarded as a problematic solid waste all over the world. The annual production of fly ash reaches around more than 3.0 billion tons in the world. It is rather important to recycle the waste material. In this study, the geopolymer composites were produced by using the waste material, alkali activators and fibers. The composite materials are also a sort of polymeric material that can be formed by using industrial applications originated by inorganic polycondensation. The fiber addition in geopolymer form was performed by adding 0, 0.5 and 1% of the total volume in macrofibers and the optimum mixture was determined. After, geopolymer composites were produced by using three different geosynthetics and the optimum geopolymer with the optimum slag/FA-based geopolymer composites. The experimental behavior of composites under flexural loading was detected by the ultimate load carrying

capacity and load-deformation with the different types of geosynthetics.

## 2. Materials and methods

### 2.1 Geopolymers

A geopolymer is an inorganic aluminosilicate polymer that can be formed using industrial waste and alkaline activation. Geopolymers generally are produced via the activation of source materials. In this study, fly ash (FA) (according to ASTM C618) obtained from the EKTON group in Turkey was used as a raw material for geopolymerization. The process also involved alkaline activation by sodium silicate (water glass) and sodium hydroxide. The chemical compositions of FA, NaOH and  $\text{Na}_2\text{SiO}_3$  are provided in Tables 1 and 2.

The effects of PP fibers were evaluated based on the durability of hardened cementless geopolymer composites on geopolymer matrix interaction and the resulting properties of the corresponding materials. The PP fibers, provided by Dost Chemical Inc. (Turkey), were 12 mm long with individual fiber diameters of 13  $\mu\text{m}$ . They had a melting point of  $150 \pm 10$  °C and were non-combustible, which rendered them useful for high-temperature applications. Their small size helps to protect the brittle fibers from premature fracture and prevents them from binding to one another. The PP fibers possess the physical and mechanical properties listed below (Table 3): they have a tensile strength of 350 MPa, an effective Young's modulus of 4.2 GPa, an elongation at break ranging from 15–18% and a specific gravity of 0.91  $\text{g}/\text{cm}^3$ . The PP fibers were added to the mix in three different proportions: 0, 0.5 and 1% by volume.

**Table 1** Composition of FA

Component (%)	$\text{SiO}_2$	$\text{Al}_2\text{O}_3$	$\text{Fe}_2\text{O}_3$	CaO	$\text{SO}_3$	$\text{Na}_2\text{O}$	Cr
FA	63.4	21.63	6.77	1.07	0.10	2.79	0.010
ASTM C618	$\text{SiO}_2 + \text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3 > 70$			<20	<3	<5	<0.1

**Table 2** Chemical properties of the alkaline activator solution

Activators	Chemical Properties					
	Molecular formula	Molecular weight ( $\text{g}/\text{mol}$ )	Relative Density ( $\text{g}/\text{cm}^3$ )	$\text{Na}_2\text{O}$ (%)	$\text{SiO}_2$ (%)	$\text{H}_2\text{O}$ (%)
Sodium metasilicate	$\text{Na}_2\text{SiO}_3$	122.06	1.38	8.9	28.7	64.8
Sodium hydroxide	NaOH	40.00	2.13	-	-	-

**Table 3** Properties of the PP fibers

Fiber	Mechanical Properties				
	Length (mm)	Specific Gravity ( $\text{g}/\text{cm}^3$ )	Tensile Strength (MPa)	Young's Modulus (GPa)	Elongation (%)
PP Fibers	12	0.91	350	4.2	15

The geopolymers were produced by mixing the raw material,  $\text{Na}_2\text{SiO}_3$ , NaOH solution and the fibers. First, the sodium hydroxide solution and the sodium silicate (water glass) solution (with a composition of  $\text{Na}_2\text{O} = 8.9\%$ ,  $\text{SiO}_2 = 28.7\%$  and water = 64.8% by mass) were prepared. The effect of the  $\text{SiO}_2/\text{Na}_2\text{O}$  content of the binder was determined, and the silica modulus was adjusted according to the ratio of NaOH and  $\text{Na}_2\text{SiO}_3$  in the activator solution. The liquid sodium silicate modulus was 3.22. Sufficient NaOH was added to the  $\text{Na}_2\text{SiO}_3$  solution to prepare an activator having silica moduli (Ms) of 0.80, 0.90 and 1.0. The geopolymer was produced using different mixtures with three different Ms (0.8, 0.9 and 1.0). Next, the effect of the molar ratio on the geopolymer was examined using the other different mixtures, and the molar ratio was adjusted only by molarity the NaOH solution in the activator (12, 14, 16 M). Geopolymer mortars were prepared for the determination of mechanical properties by adding FA, sand and a solution/binder in a ratio of 1.00:2.00:0.45. The specimens were cured at 105 °C for 24 hours. The detailed mixture proportions of the geopolymer are listed in Table 4.

In this experimental study, cube specimens with dimensions of 50 × 50 × 50 mm were cast to test the compressive strength of the samples. The geopolymer samples were subjected to compression test by using universal testing machine (ELE International Ltd., ELE 2000). These compressive strength experiments were conducted according to ASTM C109. Microstructural investigations were performed on samples with SEM (Scanning Electron Microscopy) (LEO Evo-40 VPX) analyses. Additionally, Ultrasonic pulse velocity (UPV) (Pundit Lab Proceq Company, PL-200) measurements were performed on samples for different silica moduli and molarities of geopolymers. The method is a nondestructive technique used to estimate the depth of cracks. The

velocity of a wave is estimated using the time that it takes the wave to travel a certain distance:

$$V = L/t \quad \text{Eq. (1)}$$

where  $V$  is the velocity of the pulse (m/s),  $L$  is the length of the sample (m) and  $t$  is time (s).

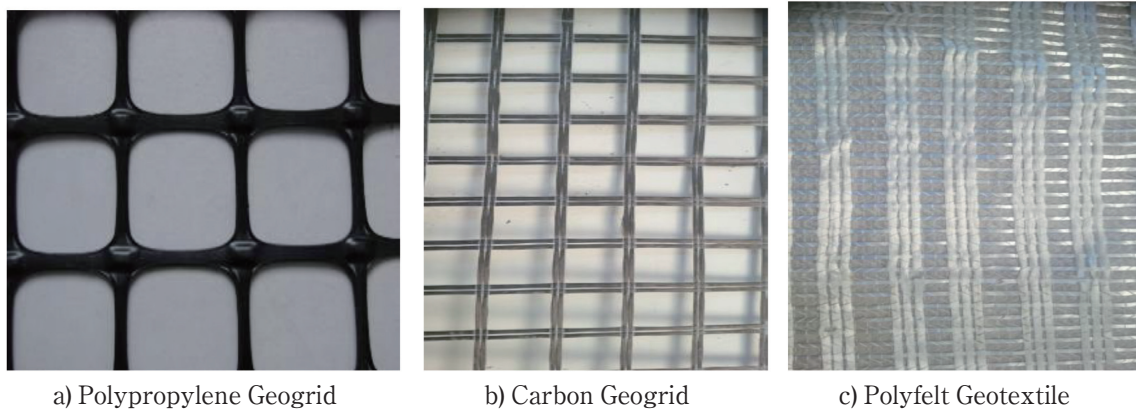
## 2.2 Geosynthetics (reinforcing materials)

Polymeric materials are a large molecule, or macromolecule, composed of millions of repeated linked units, each a relatively light and simple molecule. We investigated three types of these materials for their properties for geopolymer composites. Different types of geosynthetic materials have been used for composite reinforcement: PPG (Polypropylene Geogrid), CG (Carbon Geogrid) and PG (Polyfelt Geotextile). These geogrids are taken from GEOPLAS Company, Turkey. The properties of these geosynthetics are shown in Fig. 1. PPG is one of those most versatile polymeric materials typically polypropylene (PP), available with applications. The geogrids have high axial tensile strength in both the  $x$  and  $y$  directions and a stiff grid with square openings of size 30 × 30 mm. Carbon geogrid continuous filament to produce gridding base material with advanced knitting process, sized with silane and coated with PVC. CG is a grid of size 20 × 20 mm, and they have high tensile strength in two directions. The geogrid is obtained by weaving continuous alkaline resistant materials, and they have a highly flexible and deformable structure. Also, TenCate PG is a geocomposite consisting of two layers that are mechanically bonded from high modulus PP fibers. This geocomposite has a high load-carrying capacity and low creep strains at high maximum strength. Polyfelt exhibits excellent resistance to installation damage, outstanding long-term performance and excellent hydraulic properties [20].

The deformation of different geosynthetic

**Table 4** Mixture proportions of the FA-based geopolymer mortar

Alkaline activator	Activator parameters		Alkaline activator contents		Total solution (g)	Fly-ash (g)	Sand (g)
	Silica moduli ( $\text{SiO}_2/\text{Na}_2\text{O}$ )	NaOH concent. (Molar)	$\text{Na}_2\text{SiO}_3$ (g)	NaOH Solution (g)			
NaOH + $\text{Na}_2\text{SiO}_3$	0.8	-	1000	575.1	1575.1	3500.02	7000.04
	0.9	-	1000	489	1489	3300.89	6610.78
	1.0	-	1000	420	1420	3155.50	6310.10
NaOH	-	12	-	1480	1480	3288.89	6577.78
	-	14	-	1560	1560	3466.67	6933.33
	-	16	-	1640	1640	3644.44	7288.88



**Fig. 1** Different reinforcing materials

**Table 5** Mechanical properties of geosynthetics

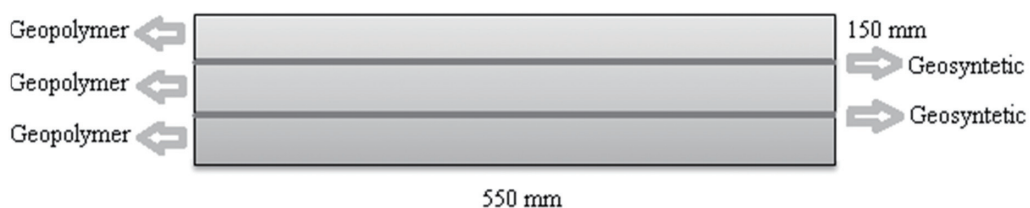
Properties	PPG	CG	PG
Grid size (mm)	30*30	20*20	-
Type	Biaxial	Biaxial	Biaxial
Tensile Strength at 2% strain (kN/m)	21	20	17
Tensile Strength at 5% strain (kN/m)	31	30	45
Ultimate Tensile Strength (kN/m)	80	70	100
Yield Point Elongation (%)	11	11	10

products was tested using a tensile loading system according to ASTM test methods D 4595, D 5262 and D 6637. Biaxial geosynthetics are manufactured with ribs oriented in two perpendicular directions to carry loads in these two directions. Two types of these geogrids, PPG and CG, and one type of geotextile, PG, were used as reinforcement in the tests. Among the biaxial geogrids used, PPG had a higher tensile strength than CG. The ultimate tensile strengths of the three types of geosynthetics were determined to be 80 kN/m for PPG, 70 kN/m for CG and 100 kN/m for PG. The properties of the geosynthetics are presented in detail in Table 5. Polyfelt geotextile has the following properties: a tensile strength of 100 N/m and a yield elongation of 11% at failure. The tensile stiffness of PG is much greater than that of PPG and CG.

### 2.3 Geopolymer mesh composite

Geopolymer mesh composites (GMC) have been considered to be attractive materials for buildings in recent years due to their good mechanical properties, low shrinkage, fire resistance and high flexural

strength. In this study, different mixtures were produced with different silica moduli (0.8, 0.9, 1.0) and molar ratios (12, 14, 16 M) in geopolymer mortar production (GMP). Then, PP fibers were added to the pure GMP mix in three different proportions: 0, 0.5 and 1% by volume. We determined the optimum geopolymer mixture. The resulting mixture was placed in molds 550 mm long, 150 mm wide and 150 mm deep. Fiber-reinforced geopolymer composites were prepared with different geosynthetic such as PPG, CG and PG. Each composite was made up of the double layers shown in Fig. 2. The composites were removed from the molds after 24 hours and left to cure in the laboratory. After curing, the composites were subjected to room-temperature, four-point flexural testing using Universal Testing Systems, following ASTM standard C78/C78M-10, for 28 days. The effectiveness of the PPG, CG and PG geosynthetics were compared. In this study, we developed geosynthetic geopolymer composites with lower weight than those of conventional mortar composites.



**Fig. 2** Double-layered geopolymer composite

### 3. Results and discussion

#### 3.1 Effects of silica modulus ( $\text{SiO}_2/\text{Na}_2\text{O}$ ) on the compressive strength of geopolymers

The important factors affecting the mechanical properties of geopolymers include the content of  $\text{SiO}_2/\text{Na}_2\text{O}$  in the alkaline activator and temperature. According to the results of Karakoc et al. [21], curing conditions, silica modulus and molar ratio are also important for determining the compressive strength of geopolymers. In this paper, geopolymers differing in  $\text{SiO}_2/\text{Na}_2\text{O}$  modulus (0.8, 0.9 and 1.0) with a water-binder ratio of 0.45 were manufactured by alkaline activating raw materials. Significant differences were observed in the compressive strength development of geopolymers with various silica moduli (Ms). At a constant 0.5% PP fiber, the compressive strength of the samples increased up to 29.5, 47.2 and 57.8 MPa, respectively, for increasing silica modulus content (i.e., 0.8, 0.9 and 1.0). These findings are shown in Fig. 3. The highest compressive strength was obtained in geopolymer composites with a  $\text{SiO}_2/\text{Na}_2\text{O}$  ratio of 1.0 and 0.5% PP fiber added. As the silica modulus ratio increased from 0.8 to 1.0, the compressive strengths of FA-based geopolymer composites generally increased. These results demonstrated that the mechanical properties of the geopolymers generally developed at the age of 28 days.

We obtained optimum results for mixtures with a silica modulus between 0.8 and 1.0. Similarly, Skvara et al. [22] reported that geopolymers were affected by the mechanical properties of the silica modulus; optimum results were obtained for a Ms between 0.6 and 1.0. However, Heah et al. [23] noted that the

geopolymer strength decreased as the Ms continued to increase from 1.5 to 2.0. Therefore, a large amount of activator solution may inhibit the geopolymerization process. In our experimental studies, we observed positive effects on the compressive strength with temperature; the geopolymer dissolved in the raw material at elevated temperatures, which increased polycondensation. Recent research has shown that variations in the ratio of alumina and silica affect curing conditions [24]. The mechanical properties of geopolymers are also related to the rate of the alumina and silica in the raw material in the geopolymerization [25]. Gao et al. [26] reported that geopolymer composites produced with aluminosilicates optimally increased the compressive strength of the geopolymer composites, which in turn caused stronger C-S-H gels between the components entering the reaction and increased the mechanical properties. A value of 1.0  $\text{SiO}_2/\text{Na}_2\text{O}$  was optimum for the geopolymerization reaction (Fig. 3). In addition, a slight decrease in the strength of some samples was observed over the course of 28 days. Similarly, Bakharev et al. [27] noted that the influence of high heat on the properties of geopolymers: temperature curing at early times accelerated the development of the compressive strength. But after some time the mechanical properties of some samples decreased in laboratory conditions. The reason for this effect, Patil et al. [28] noted, was that the geopolymer reaction had faster phase transitions at higher temperatures

#### 3.2 Effects of molar ratio on the compressive strength of geopolymers

Geopolymers are most commonly prepared by activating waste material with sodium-based alkaline

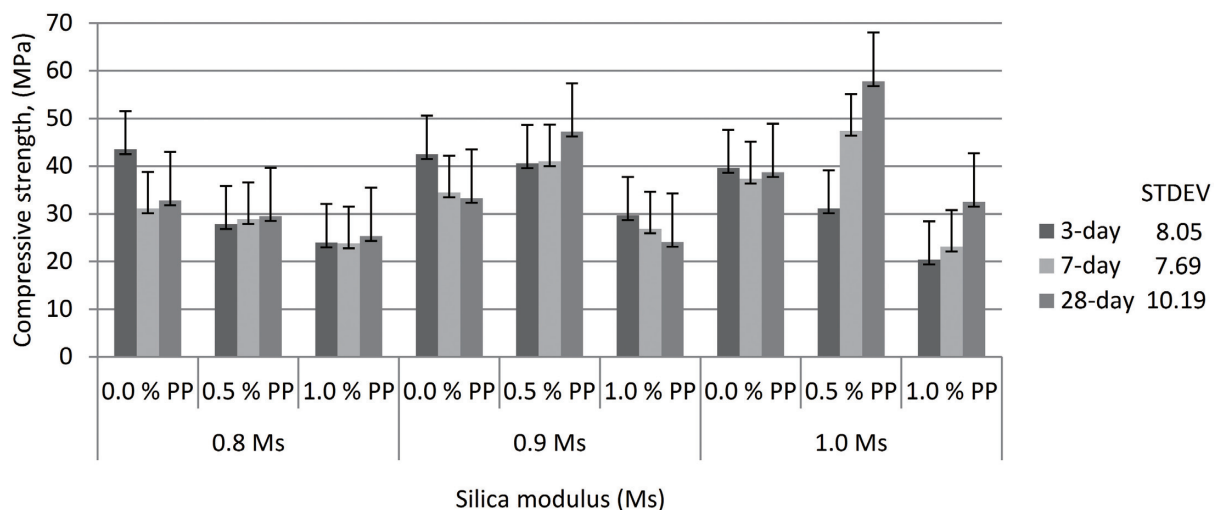


Fig. 3 Compressive strength of PP fiber-reinforced geopolymers produced with different Ms

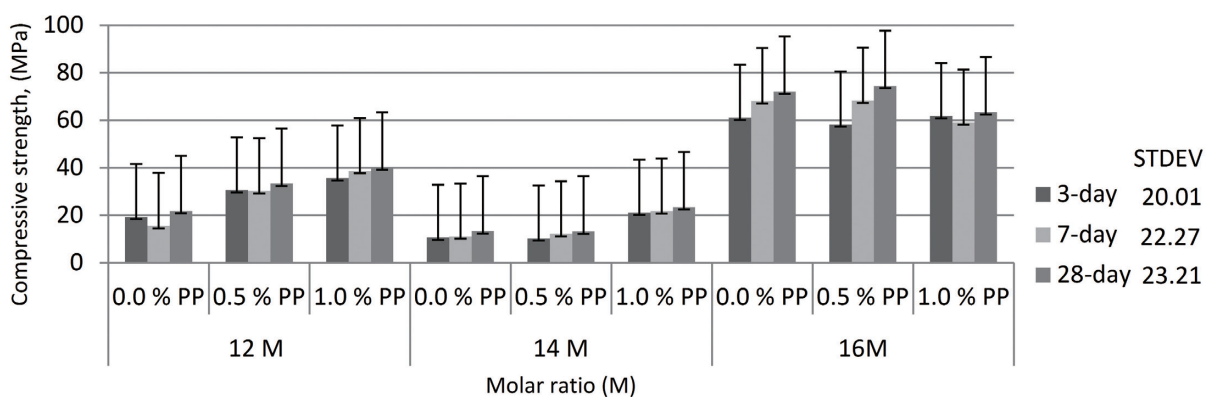


solutions. Here, we studied the effects of molar ratio and curing conditions on the compressive strength of the geopolymer mortar. The mass of sodium hydroxide in a solution changes in different molarities depending on the concentration of the solution. This study presents the experimental results of the mechanical properties of geopolymer mortar using only NaOH in molar ratios of 12, 14 and 16 M. Variations in the mechanical properties of geopolymer samples were studied at different curing ages of 3, 7 and 28 days; the results are given in Fig. 4. The influence of the molar concentration was more pronounced on the samples workability, and the molar ratio strongly affected the compressive strength. The appearance of maximum compressive strength in 16 M sodium hydroxide activated geopolymer samples has shown that sufficient alkaline conditions for geopolymerization are provided by 16 M sodium hydroxide solution. The highest compressive strength was exhibited by the sample with high molarity (16 M) can be interpreted as the possibility of achieving high mechanical strength provided that sufficient amount of alkali solution is used to minimize the raw material which is not to enter the reaction and homogeneity of matrix. The usages of NaOH at concentrations lower than 16 M sodium hydroxide decreased the alkalinity and so reduced the compressive strength. Also, the compressive strength of the samples used 14 M was obtained lower than molar ratio of 12 M. This situation sometimes shows that the high alkalinity reduces the compressive strength by preventing the formation of the geopolymerization reaction. High alkalinity has the concentration of high OH<sup>-</sup> ions in the matrix. It was speculated that these OH<sup>-</sup> ions in high amounts combine with cations such as Al and Si to form structures with no positive effect on

compressive strength.

Many researchers have reported that raw materials are a good resource material in geopolymer production and that sodium-based activators have proven to be more efficient than potassium-based activators for geopolymerization [29–38]. In our experimental studies, we observed that increasing the molar concentration from 14 to 16 M positively increased the samples compressive strength. Similarly, Kaur et al. [39] noted that the highest compressive strength was found in samples with 16 M concentrations of sodium hydroxide. Phoongernkham et al. [40] noted that geopolymer strength increased with increasing concentration of sodium hydroxide after polymerization. Furthermore, Chindaprasirt et al. [41] found that alkaline activator type in the geopolymer samples resulted in pronounced strength development with modification of the water/binder (w/b) ratio and curing temperature. In our experimental study, we observed that compressive strength increased as the curing temperature and NaOH concentration increased in the geopolymer composites with a high molar ratio. Furthermore, Al-Majidi et al. [42] reported that increasing the NaOH concentration increased the alkalinity of the medium. Therefore, the dissolution of alumina and silica bonds in the raw material was facilitated and the geopolymerization reactions increased.

We have investigated the effects of adding PP fibers in volume fractions of 0%, 0.5% and 1.0% on the mechanical properties of FA-based geopolymers. Our experimental results showed that 0.5% PP fiber-reinforced geopolymer composites exhibited the best mechanical properties. Similarly, Korniejenko et al. [43] reported that PP fibers enhanced the mechanical properties of geopolymer composites when they were



**Fig. 4** Compressive strength of PP fiber-reinforced geopolymers produced with different molarities

added at an optimum rate of 0.5%. Huseiena et al. [44] noted that the durability of fiber-reinforced geopolymers increased with increases in molarity. In addition, Ranjbar et al. [45] stated that PP fibers used in the fiber-reinforced applications resulted in flexural strength improvements due to the higher stiffness of the geopolymers.

### 3.3 Ultrasonic pulse velocity for evaluating geopolymers

Ultrasonic pulse velocity (UPV) measurements were performed on 28-day samples for different silica moduli and molarities of geopolymers samples. Here, we used UPV to measure the homogeneity of pore distribution for different mixture of geopolymers according to ASTM-C 597. Fig. 5 shows the result of the UPV test on different sample of geopolymers. The UPV value of the geopolymer samples varied from 1800–2000 m/s. Given at the age of 28 days and an increase in molar ratios, the UPV results for the geopolymer mixtures PP fiber content (i.e., 0%, 0.5% and 1.0%) increased by 1943 m/s, 2000 m/s and 1957 m/s, respectively. The test results revealed that the 16 M types exhibited higher UPV values. Our results also revealed lower velocity values than traditional concretes. Chu et al. [46] reported that an increase in of porosity stems from the inadequate distribution of PP fibers, which gives rise to a decline in the sonic pulse velocity propagation in geopolymers with fibers. Similarly, Wongsa et al. [47] noted that the UPV of geopolymers yielded lower values than conventional binders. Furthermore, fibers in geopolymers led to an increase in UPV values at high temperature [48–49].

### 3.4 Microstructural characterisations of geopolymers

Scanning Electron Microscopy (SEM) micrographs of the geopolymer samples are shown in Fig. 6. The

SEM images reveal the microstructure of the fiber-reinforced polymer, which is composed of a dense reacted product of materials. The structure of the polymer exhibits a high density of pores stemming from the inadequate distribution of PP fibers in some regions; the microfibers are surrounded by a geopolymerization product. The formation of a matrix owing to the geopolymerization reaction occurred after the mixing of the raw material with the alkaline activator and additional preparation processes.

We observed a faster geopolymerization process of the samples. We also determined that, based on the effect of temperature curing of the samples, the prevalence of voids decreased and that the gels exhibited a high level of strength during the geopolymerization process. In the SEM images of mortars, we observed that the fiber-reinforced composites were properly bonded with structures with a needle-like texture at their interface. When we compared samples with the same liquid ratio and the lowest silica modulus of the alkali activator, we noted a poor connection among grains due to the small amount of matrix; samples with higher molar activator concentration exhibited a compact matrix. This effect is believed to be due to the increase in the amount of NaOH, which is the result of an increase in the resultant geopolymerization reactions.

The results of the SEM analysis using a polarization microscope carried out at IBTAM (İnönü University Central Laboratory, Turkey) were consistent with the reported composition of the raw material. We chemically analyzed the materials using electron dispersive analysis of X-rays (EDAX). The SEM/EDAX analysis of the sample revealed copious amounts of silica, calcium and iron (Fig. 7). The high

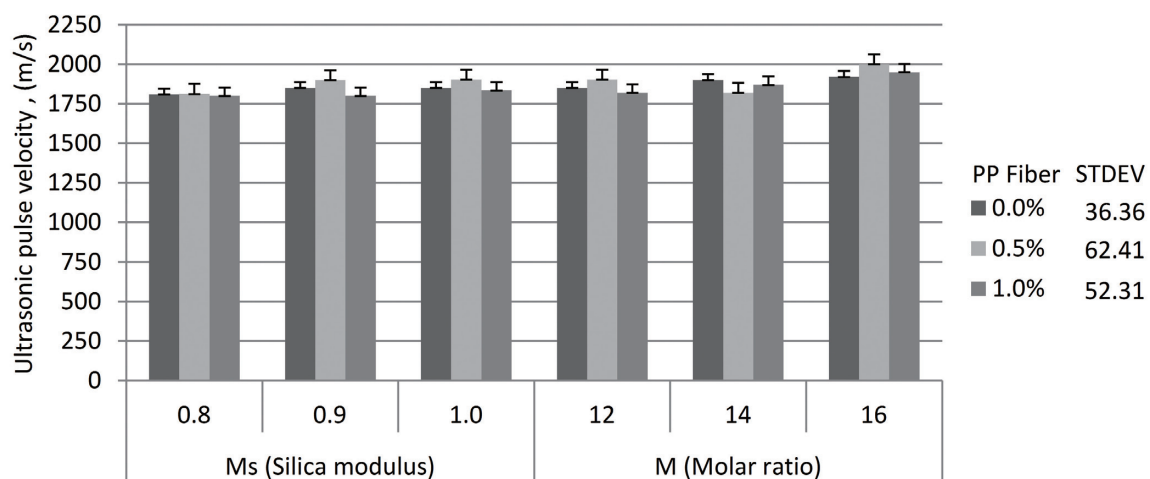
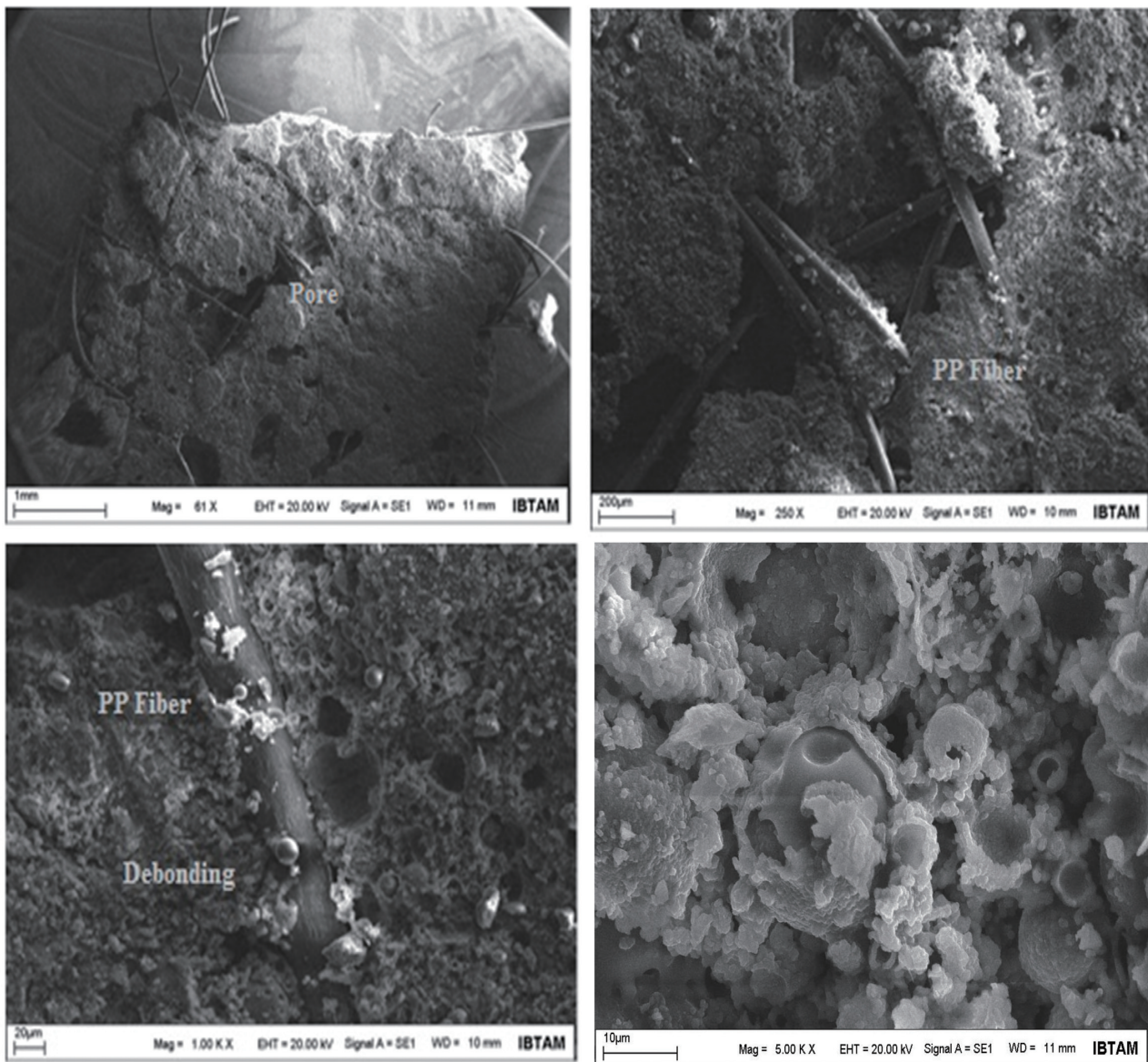


Fig. 5 Ultrasonic pulse velocity of geopolymers



**Fig. 6** SEM image of the geopolymer samples

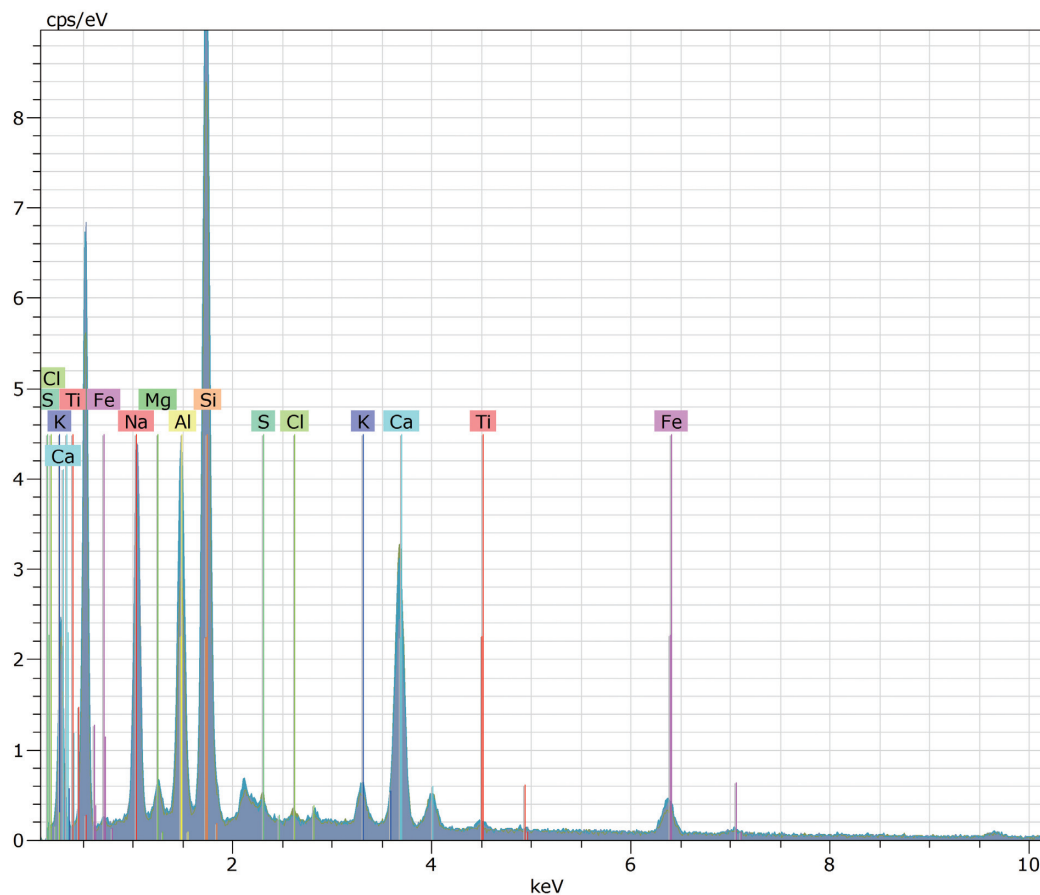
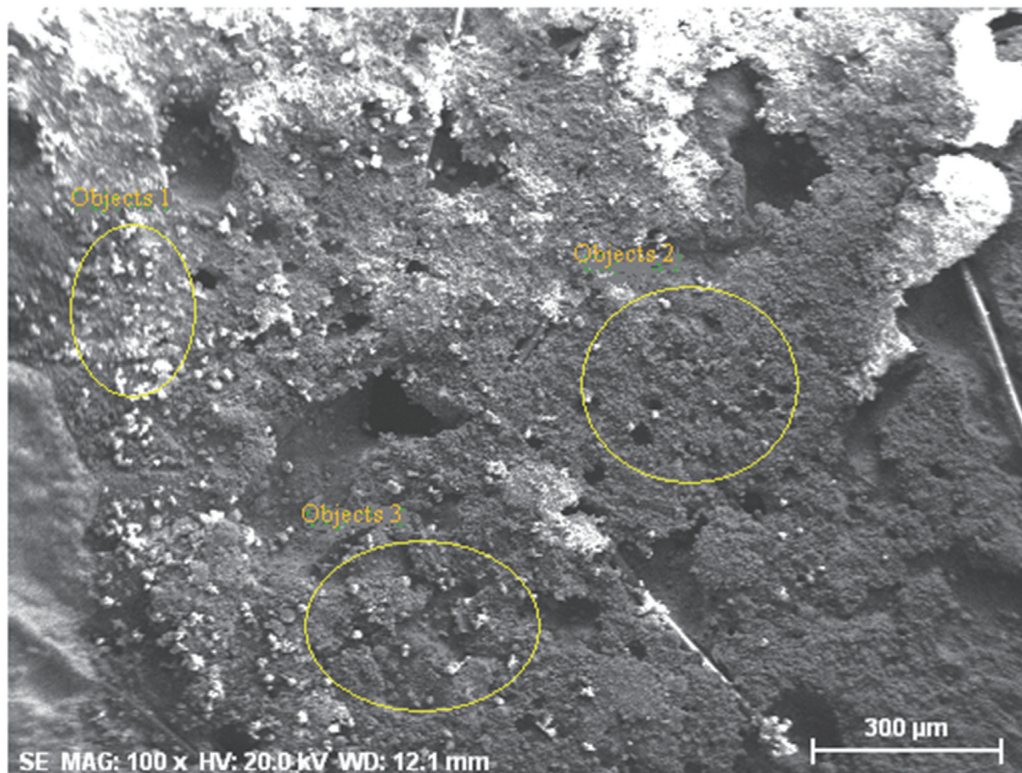
percentage of silica reveals that FA was used in the preparation of the mortar. The amount of silica in the mortar matrix and the amount of calcium in the aggregates exceeded that in the interfaces. These results reveal that raw materials and pozzolanic aggregates reacted and formed hydraulic products, namely, C-S-H at the interfaces, and that the formation of such products afforded desirable mechanical properties to the mortars. The good mechanical properties that developed over the long term in the geopolymer composites hinged on the inhibition of the spreading of larger cracks in the microstructure. This process was due to C-S-H gel formation during ongoing reactions and resulted in an increase in performance. Similarly, Wardhono et al. [50] noted that an increase in the concentration of the gel also affected the modulus of elasticity of the matrix positively and increased the likelihood of

desirable mechanical properties.

### 3.5 Flexural behavior of geopolymer mesh composites

We examined the experimental behavior of the geopolymer composites under flexural loading. Therefore, the optimum geopolymer mortar (16 M and 0.5% fiber) was used for casting the composites. We compared the flexural strength of composites reinforced with three types of geosynthetics: PPG composite (PPGC), PG composite (PGC) and GC composite (CGC). Composites measuring 150 × 150 × 550 mm were used for measuring the 28-day flexural strength according to ASTM C78. The load and deformation curves for all tested geopolymer composites were obtained from the data acquisition system of the universal testing machine (UTEST). For each mixture, three composites were cast and tested. Then, the equivalent load-deformation curve



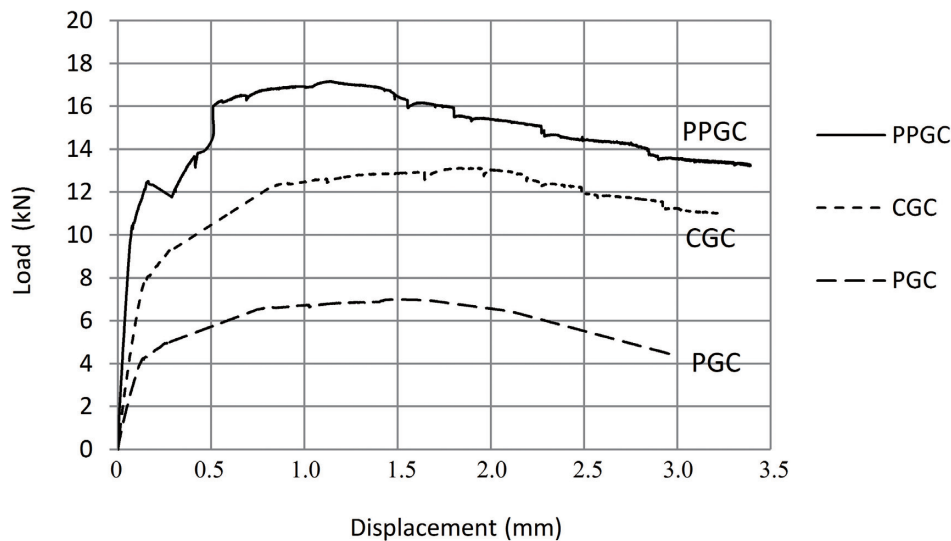


**Fig. 7** SEM / EDAX microstructure examinations and analysis of the geopolymers

was presented that represents the average of the three curves that resulted from the tests.

The geopolymer composites were tested

experimentally under flexural loading using a simply supported condition. Fig. 8 shows the behavior of the carbon mesh geogrid, PPG and PG with different



**Fig. 8** Load–displacement curve of geopolymer mesh composites

materials. Additional increases in the load on the specimens led to the mobilization of the internal geosynthetics to carry the load until failure. All of the geopolymer specimens under flexural load demonstrated linear behavior until the first crack occurred on the tension surface. The PPGC mesh exhibited significantly better flexural behavior than the CGC mesh and PGC. In addition, the flexural strength results of the geopolymer composite reinforced with carbon mesh were found to be better than those of the composition reinforced with polyfelt. The PP mesh contributed a crucial enhancement to the energy absorbed upon deformation with the geopolymers. Similarly, Nematollahi et al. [51] observed that newly developed fiber-reinforced geopolymer composites exhibited significant ductility and toughness properties under bending and bending behaviors. As a result, the geopolymer control composites displayed an equivalent load-displacement behavior to that reported in the literature [52–53].

#### 4. Conclusion

Structural composites have been a popular area of research in the field of many engineering industries for finding new construction materials with good mechanical properties, increased stiffness and lower weights. This investigation focused on improving our understanding of the effect of a geopolymer composite's behavior on its mechanical properties. We found the following:

- Comparing the compressive strength effects of silica modulus ( $\text{SiO}_2/\text{Na}_2\text{O}$ ) and molar ratio in geopolymerization, we found that the molar ratio

plays an important role in dictating the properties of geopolymer composites.

- The appearance of maximum compressive strength in 16 M sodium hydroxide activated geopolymer samples has shown that sufficient alkaline conditions for geopolymerization are provided by 16 M sodium hydroxide solution.
- C-S-H gels provided compact structures during the geopolymerization process.
- The geopolymer samples exhibited lower UPV values than traditional binders.
- The natural bonding in between the geopolymer infill and geogrid was stronger than that of binders.
- PP fiber-reinforced geopolymer composites indicated high viscosity, good adherence and good mechanical performance.
- Comparing the load-deformation curves of PPGC and CGC, PPGC exhibited more softening behavior than CGC.
- Geopolymer composites have the ability to exhibit high compressive and tensile strength at lower weight point than conventional precast mortar composites.
- The casting of composites will become more economical and efficient, which will decrease costs and also decrease carbon emissions.

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