The influence of activator type and quantity on the transport properties of class F fly ash geopolymer

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HIGHLIGHTS

• Transport properties of class F fly ash based geopolymer were investigated.
• Influence of activator type and amount on transport properties of geopolymer were reported.
• The best results were obtained at %15 Na ratios for all transport characteristics.
• The findings could help for selection of Na ratio and activator type for geopolymers.

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ABSTRACT

It is known that transport properties of porous materials were important in terms of its durability aspect. In this paper, the effect of activator type, Na amount on the transport properties of geopolymer mortar made with class F fly ash were explored. Two different class F fly ash were employed in producing geopolymer that activated alkaline solutions. As alkali activator, sodium hydroxide solution, and combination of sodium silicate with sodium hydroxide were used. Activator contained 6%, 9%, 12% and 15% of fly ash weight as Na amount. Heat curing regimes were imposed to specimens at 100 °C temperature for 24 h duration. Tests were carried out on the geopolymer samples including water absorption, volume of permeable voids, sorptivity, depth of penetration of water under pressure, chloride ion penetration and accelerated corrosion. It is found that the transport properties of geopolymer samples are improved by increasing the Na amounts of mortar mixtures from 6% to 15%. In general, better results were obtained with 15% Na ratio. The mortars produced with only sodium hydroxide have shown better transport properties than mortars made with combination of sodium hydroxide-sodium silicate mixture.

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1. Introduction

Cement is a common binder as construction materials. The Ordinary Portland Cement (OPC) production needs limestone and clay as raw materials, and temperature reaches to 1450 °C in the production process. For each ton of production of OPC is responsible for formation of 1 kg sulphur dioxide (SO2), about 810 kg of carbon dioxide (CO2), and 10 kg waste powder [1]. In estimate, it is known that the production of fly ash-based geopolymer needs for nearly 60% less energy and has at least 80% less CO2 emissions [2] in comparison to production of OPC. There are lots of studies and developments focused on the geopolymer concrete and mortar in literature. Geopolymer is thought to be a sustainable building material for the future [3]. The production of fly ash-based geopolymer has lower CO2 emission compared to that of OPC [4–6]. Fly ash-based geopolymer concrete completely moves away from OPC and the high CO2 emission associated with OPC production [6–8].

A term geopolymer was first introduced by Davidovits in 1979 to represent the inorganic polymers. The production of geopolymer requires source materials that are rich in silica and alumina content, such as metakaolin, slag, fly ash, etc. [9]. Geopolymers can provide an alternative to OPC binders, not only for the environmental benefits, but also in terms of their strength and durability [10].

Fly ash based geopolymer mortar need heat curing for geopolymeric reaction. This can be a drawback for production of geopoly-
mer as the industrial material [10]. The properties of geopolymers are usually dependent on the characteristics of the alumina-silicate source materials i.e. content and particle size. Fineness, the content of glassy phase particle morphology, chemical property of the waste materials have important effect on the activity of the alumino-silicate sources. The alkaline solutions such as sodium hydroxide (NaOH), sodium silicate (Na₂SiO₃), and potassium hydroxide (KOH) or potassium silicate are commonly used alkali materials in preparation of geopolymers. In comparison, NaOH and KOH indicate a greater level of alkalinity. It has been found that NaOH possesses greater capacity to release silicate and aluminate monomers [11,12]. The activator can also be prepared by mixing NaOH and nSiO₂Na₂O. The most important factor in the mixing of NaOH and nSiO₂Na₂O is adjustment of the SiO₂/Na₂O ratio called the silica modulus (MS) [13]. Fly ash based geopolymers need heat curing for 24–28 h, at temperature range from 60 to 100 °C. After heat curing in oven, the geopolymer can be subjected to longer curing at ambient room temperature [1].

Transport properties of fly ash based geopolymer were studied by water and ion transportation form. The most significant factors which influence water and ion transport are materials pore structure, pore volume, pore size distribution, connectivity and shape of the pores [14,15]. The knowledge of water transport and its relationship with microstructural properties is an important [16]. In the evaluation of the durability related properties of a geopolymer as an alternative binder, it is important to know its transport properties and microstructural properties and their relationships. Water penetration and ion diffusion properties of materials are related with pore structure of porous materials. These durability related properties are closely related to durability problems, in particular for reinforced concrete systems. Water is a carrier for Cl, SO₄ or CO₂. These ions are malicious to concrete and its reinforcement since they can take place in the reaction products and/or reach the steel/paste interface. These ions cause corrosion of steel and lead to deterioration of the reinforcement. Therefore, as durability related properties, water transport and permeability are essentially considered as important parameter [11,13].

For this purpose, there are several studies focused on the transport properties of fly ash based geopolymer mortar. The high sorptivity coefficient indicates the presence of a highly porous structure or pore network [9].

It is reported that properties of the fly ash-based geopolymer dependant on activator amount and characteristics of fly ash used. Heat curing temperature and its duration are other important factors [6,17].

Geopolymeric mortars presented higher durability related properties than OPC mortars. Particularly, this is important when they were attacked by chlorides, sulphates, acids or alkali-silica reactions [18–20]. Attaching steel reinforced bars is an important risk facilitated by the proximity steel bars to the concrete surface and are very susceptible to corrosion [19]. Chloride ions penetrate concrete and form HCl acids, reduce pH value of environment. They prepared geopolymer by activating fly ash with blend of Na₂SiO₃/NaOH mixture solution. Molar concentrations of sodium hydroxide were changed from 8 to 16 with an increment step of 2. Silica to alumina rate was kept constant. They reported that increase in molar ratio of alkali activator result with lower chloride penetration as well as corrosion of embedded steel.

Chindaprasiit and Chalee [25] were studied the influence of sodium hydroxide concentrations on chloride penetration, steel corrosion and strength of fly ash geopolymer under marine environment. They prepared geopolymer by activating fly ash with blend of Na₂SiO₃/NaOH mixture solution. Molar concentrations of sodium hydroxide were changed from 8 to 16 with an increment step of 2. Silica to alumina rate was kept constant. They reported that increase in molar ratio of alkali activator result with lower chloride penetration as well as corrosion of embedded steel.

Zhu et al. [21] investigated the durability related properties of chloride penetration of fly ash geopolymer pastes and mortars and compared them with OPC counterpart. They highlighted the significance of utilizing fly ash role with appropriate liquid/solid ratio in the development of durable fly ash geopolymer.

Noushini and Castel [9] carried out a study to investigate the transport properties of geopolymer produced using class F fly ash and at different medium. They concluded that heat cured fly ash geopolymer at 75 and 90 °C up to 24 h, developed lower sorptivity coefficient than that of samples cured at ambient conditions thereby indicating lower porosity values.

Reddy et al. [24] focused on the durability properties of geopolymer made with class F fly ash. Samples were subjected to a corrosive marine environment. They were tested geopolymer concrete beams with 13-mm rebar centrally reinforcement. Fly ash geopolymer was produced with 8 M and 14 M alkali solutions of NaOH and Na₂SiO₃. Accelerated corrosion test was carried out by exposing samples to wet and dry cycling periods in artificial seawater and an induced current. They concluded that class F fly ash geopolymer concrete showed higher resistance than that of control cement concrete to corrosion cracking due to chloride attack.

Zhuang et al. [6] carried out an experimental studied on fly ash based geopolymer. They stated that fly ash based geopolymer was a good binder and can be utilized in production of geopolymer concrete. Fly ash-based geopolymer binder represented better behavior than that of traditional cement. For instance, fly ash-based geopolymer concrete developed denser microstructure causing lower porosity. Therefore, it results with lower chloride diffusion in comparison to cement concrete.
In the literature, several studies are dealing with the permeability properties of geopolymers. On the other hand, there is scanty study on the comparative transport properties of geopolymer compositions. The effects of a number of major factors such as the use of chemical activator, particle size distribution and chemical properties of powder materials and aggressive environment exposure on the transport properties of the geopolymer mortar are exhaustively deliberated. A series of durability property tests were carried out in this study on geopolymer mortar specimens, to evaluate the effect of permeable and capillary voids after exposure to 100 °C temperature. Four different Na ratio of NaOH and Na₂SiO₃-NaOH concentration were used in order to determine the effect of activator concentration and type on geopolymer mortars. Two different F fly ashes were used in order to determine the effect of fly ash on physical and chemical properties on geopolymer mortars.

Geopolymer mortars were produced from two different Class F fly ashes obtained from two different Thermal Power Plants in Turkey. NaOH and blend of Na₂SiO₃-NaOH were used as separate alkaline activators. Geopolymer mortars were produced at 6%, 9%, 12% and 15% Na amount of fly ash. They were subjected to 100 °C curing for 24 h. Water absorption, volume of permeable voids (VPV), sorptivity, depth of penetration of water under pressure, chloride ion penetration, and accelerated corrosion tests were taken place on the geopolymer samples produced. Thus, the effect of activator type, composition of fly ash and activator ratio on transport properties were evaluated.

2. Materials and methods

2.1. Fly ash

Two different class F fly ashes [28] were used in the study. The pozzolanic activity index of the Sugözü (SG) fly ash obtained from the Sugözü thermal power plant is 87%, its specific gravity is 2.29, and its residue on 45 μm sieve is 19%. On the other hand, the pozzolanic activity index of the Çatalağzı (CA) fly ash obtained from the Çatalağzı thermal power plant is 83%, its specific gravity is 2.13 and its residue on 45 μm sieve is 29%. Chemical properties of fly ashes used are given in Table 1.

2.2. Standard sand

Rilem Cembureau Standard Sand in accordance with TS EN 196-1 [29] was used for geopolymer sample production. The dry specific gravity of the sand is 2.63 and the water absorption rate is 0.57%. Sieve analysis result and standard limits are given in Table 2.

2.3. Activator and water

In the experimental study, two different alkaline solutions were prepared, consisting of a mixture of sodium hydroxide (NaOH) and a blend of sodium silicate-sodium hydroxide (Na₂SiO₃-NaOH) to activate the fly ash. In appearance, NaOH (NH) is in a white flake form and Na₂SiO₃ (NS) is a transparent liquid. In addition, sodium hydroxide in Na₂SiO₃-NaOH solution contributed to lowering the MS module (SiO₂/Na₂O) of the solution. The purity of NaOH is 98.3%. The specific gravity of liquid sodium silicate is 1.4 g/cm³. MS module is 2.02. Drinkable tap water obtained from the city network was used in the production of mortars. Its chemical and physical properties were complied with TS EN 1008 [30].

3. Experimental program

3.1. Casting and curing of test specimens

CEN standard sand, class F fly ashes and two different activators (NH and NH-NS) were used in geopolymer mortar production. Sand / fly ash ratio was taken as 3 and water/fly ash ratio was taken as 0.3. Na dosage for the activator was chosen 6%, 9%, 12% and 15% of weight of fly ash. The most suitable mixture not showing rapid setting was the mortar made with MS of 0.2 in for sodium silicate-sodium hydroxide solution.

As the activator solutions were hot, they were cooled in glass jars in a laboratory environment until they reached room temperature. Following that, a Hobart type mixer was used in the preparation of the mixes. Then, fresh mortars were placed in molds. Geopolymer mixtures were given in Table 3 [29,31].

The mortar samples placed into the molds were cured in an oven at 100 °C temperature for 24 h. Three specimens for each Na ratio were subjected to transport properties tests. Results was obtained based on the average of values obtained from three samples. After heat curing period, 16 groups of samples were removed from the mold after cooling to room temperature and they were subjected to experiments.

3.2. Test procedures

The prism specimens with size of 40 × 40 × 160 mm³ were used to determine water absorption, volume of permeable voids and sorptivity coefficient in the mortars. While water absorption and apparent volume of permeable voids tests were done as per ASTM C642 [32], to determine sorptivity coefficient of the samples, the weight measurements were performed at 1, 5, 10, 20 and 30 min, at 1, 2, 3, 4, 5 and 6 h, and at 1, 2, 3, 4, 5, 6, 7 and 8 days according to ASTM C1585 [33]. 150 × 150 × 150 mm³ cube samples were produced in accordance with the TS EN 12390-8 [34] for the penetration depth of water within 24 h under pressure.

Cylinder samples with Ø100 × 200 mm size were produced for chloride ion penetration test which was carried out according to ASTM C1202 [35]. The chloride ion permeability value in Coulomb was determined depending on the resistance of the samples to chloride ion penetration. For accelerated corrosion testing, the ribbed S420 steel having 16 mm diameter was used. The pull-out samples measured Ø100 × 200 mm in cross section. Pull-out cylinders had a 600 mm length rod 16 mm diameter, placed centrally in the cylinder, with an embedment length of 175 mm. Corrosion resistance of reinforced steel was measured by applying 12 V constant current in NaCl solution. The bond strength of the reinforcements was determined according to ASTM A994 [36].

Table 1

<table>
<thead>
<tr>
<th>Oxide</th>
<th>SiO₂</th>
<th>Al₂O₃</th>
<th>Fe₂O₃</th>
<th>CaO</th>
<th>MgO</th>
<th>SO₃</th>
<th>Na₂O</th>
<th>Free CaO</th>
<th>Cl⁻</th>
<th>LOI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sugözü (SG)</td>
<td>60.51</td>
<td>21.69</td>
<td>7.85</td>
<td>1.52</td>
<td>1.65</td>
<td>0.53</td>
<td>0.92</td>
<td>0.183</td>
<td>0.010</td>
<td>2.42</td>
</tr>
<tr>
<td>Çatalağzı (CA)</td>
<td>54.68</td>
<td>25.94</td>
<td>6.81</td>
<td>3.12</td>
<td>1.55</td>
<td>0.34</td>
<td>0.39</td>
<td>0.020</td>
<td>0.004</td>
<td>3.30</td>
</tr>
</tbody>
</table>
4. Experimental results

4.1. Absorption and volume of permeable voids results

The water absorption and volume of permeable voids (VPV) values of mortars were given in Figs 1 and 2, respectively.

For SG fly ash geopolymers mortars activated with NH, water absorption values were determined between 1.4% and 5.2% while VPV values were between 3.2% and 10.7%. For SG fly ash geopolymers mortars activated with NS-NH, water absorption values were determined between 2.8% and 5.3% while VPV values were between 6.0% and 11.1%. On the other hand, for CA fly ash geopolymers mortars activated with NH, water absorption values were determined between 2.9% and 6.4% while VPV values were between 6.0% and 12.8%. For CA fly ash geopolymers mortars activated with NS-NH, water absorption values were determined between 4.4% and 6.5% while VPV values were between 9.2% and 13.2%. It can be seen from Figs 1 and 2 that the increase in the Na ratio result with a decrease in the water absorption and VPV values of the geopolymers produced regardless of ashes.

As seen in Figs 1 and 2, geopolymers produced with SG fly ash were found to be better than that of geopolymers produced with CA fly ash in terms of water absorption and VPV values. Noushini and Castel [9] reported that significant reductions occurred in void volume with increasing curing time from 8 h to 24 h as well as a temperature rising from 60 °C to 90 °C [9]. Zhu et al. [21] stated that the hardened mortars were affected by the void structure due to the grain shape and size of the fly ash supplied from different sources. In addition, it could be said that water absorption and VPV values of NH activated mortars were better than those of mortars made with NS-NH as an activator in fly ash geopolymers. Similarly, Zhang et al. [1] demonstrated that mortars containing NH exhibited more positive properties than mortars prepared with NS-NH mixture [1].

4.2. Sorptivity results

In the study, the geopolymer samples were subjected to capillary water absorption test at room temperature. In this experiment where the test setup was shown in Fig. 3, the bottom surfaces of the samples were contacted with water. After that, the primary capillary water absorption coefficient after 6 h and the secondary
capillary water absorption coefficient at the end of the 8th day were calculated [33]. The results obtained are given in Fig. 4.

As given in Fig. 4, initial (In) capillary water absorption coefficients were calculated between 0.0116 and 0.0303 and secondary (Sec) capillary water absorption coefficients were calculated between 0.0012 and 0.0014 for SG fly ash geopolymers activated by NH. The primary capillary water absorption coefficients of SG fly ash geopolymers activated by NS-NH mixture were calculated between 0.0067 and 0.0281 while the secondary capillary water absorption coefficients were calculated between 0.0013 and 0.0022. The high Na dosage reduced primary capillary water absorption values as a result of the decrease in porosity. However, there was no significant change in secondary capillary water absorption values depending on Na dosage. The use of NS-NH instead of NH as an activator for the SG fly ash group resulted in an increment in capillary water absorption.

On the other hand, primary capillary water absorption coefficients ranged from 0.0208 to 0.0336 and secondary capillary water absorption coefficients ranged from 0.0015 to 0.0019 for CA fly ash geopolymers activated by NH. The primary capillary water absorption coefficients of CA fly ash geopolymers activated by NS-NH mixture ranged from 0.0235 to 0.0314 while the secondary capillary water absorption coefficients ranged from 0.0012 to 0.0015. As with SG fly ash, primary capillary water absorption decreased with the increase in Na ratio, but there was no decrease in secondary capillary water absorption. The reason for this is that geopolymers are produced as a result of heat curing and gain their sensitivity to water in primary sorptivity time.

In general, primary capillary water absorption values decreased from 6% to 15% with the increase in Na ratio in activation of SG and CA fly ash with NH. In mortar specimens activated by both NH and NS-NH, the primary capillary water absorption coefficient is the lowest for 15% Na dosage. In geopolymers produced with SG and CA fly ash, the secondary capillary water absorption coefficient has not changed much with the increase of Na and close values have been obtained. As the geopolymer samples were cured in the oven, they lost the water in their structures. So, mortars tended to absorb water in a short time for primary capillary water absorption; this situation did not produce very large differences compared to secondary capillary water absorption.

4.3. Depth of penetration of water under pressure results

The highest level of water penetration was measured after splitting test of cube specimens. The penetration depths of water under pressure were given in Fig. 5 for geopolymer mortars, and the test setup was shown in Fig. 6.

The penetration depths of water under pressure for the NH-activated SG fly ash geopolymers were measured between 9 and 150 mm, while these values were between 18 and 150 mm in the mixture with NS-NH. Also, the penetration depths of water under pressure for the NH-activated CA fly ash geopolymers were measured between 11 and 150 mm, while these values were between 21 and 150 mm in the mixture with NS-NH. The most effective activator concentration for low water penetration depth was 15% Na dosage. So, these values for SG and CA fly ash were between 9 and 11 mm in activation with NaOH and between 18 and 21 mm in activation with NS-NH mixture. The most effective activator for low water penetration depth was NH at 15% Na dosage, which resulted in 9 mm depth for SG fly ash. The fact that the physical and chemical properties of SG fly ash are slightly better than CA fly ash also contributed to this situation. The low activator dosage negatively affected the permeability. Water under pressure reached the top of the samples with SG and CA fly ash activated by 6% Na for both activators. Water reached almost the top surface (146 and 138 mm) in SG and CA fly ash samples activated by NH at 9% Na. However, the sample activated with NS-NH at 9% Na let to pass water entirely. Water penetration depth under pressure was measured at 18 and 27 mm in SG and CA fly ash samples activated with NH at 12% Na, and 69 and 48 mm in samples activated with NS-NH mixture. Accordingly, those that were activated with NaOH were observed to give better results. The Na dosage increasing from 6% to 15% reduced the penetration depth of water under pressure in SG and CA fly ash samples activated by both NH and NS-NH. Samples produced with SG fly ash had better permeability values than CA fly ash for high Na ratio. The reason for this is that SG fly ash has a less value (18.47%) than CA fly ash (29%) in terms of the residue on 45 μm sieve [37]. It is also stated that fly ash improves the microstructure and positively affects the capillarity properties in concrete depending on the replacing with cement [38]. In addition, low pore structure geopolymer mortar can be obtained with fly ash. Amran et al. stated that 80% of total porosity has been presented in pore diameters of 10–50 nm in alkali-activated binder containing of 100% fly ash. In addition, 20% is between 10 and 100 nm [39]. As seen in Fig. 7, at the same Na ratio and activator type and the physical properties of different fly ashes, depth of penetration of water under pressure is similar to the porosity. The decline in the depth of penetration of water pressure values with an increase in NH and NS-NH concentrations were noticeable at this stage. The increase in concentration of activator by reducing w/b (0.30) caused an
Fig. 5. Depth of penetration of water under pressure results of geopolymers.

Fig. 6. Depth of penetration of water under pressure test setup (TS EN 12390-8).

Fig. 7. The relationship between depth of penetration of water under pressure –VPV.
important acceleration of dissolution rate that it also reduced porosity [40].

The total depth of penetration in mortars with 6%-15% all NH concentrations were determined 649 mm, but all NS concentrations were determined 756 mm. Depth of penetration of water under pressure values are generally correlated with VPV and water absorption values (Fig. 7). According to activator type, geopolymerization reactions increase at the optimum temperature and curing time. 100 °C curing temperature, 24 h curing time and concentration of NH were directly affected porosity and depth of water penetration. It was emphasized in the previous works: decrease in the water absorption of the samples with increase in the NH concentration was also observed [27,40,41]. Additionally in literature, lower porosity and water absorption were determined when higher Na ratio content activators were used in the production of geopolymer samples [27,42,43]. A higher concentration of NH had better ability to dissolve fly ash particles and resulted in better geopolymerization [44].

4.4. Chloride ion penetration results

The rapid chloride ion penetration results for geopolymer mortars were given in Fig. 8 and the test setup was shown in Fig. 9. As given in Fig. 8, rapid chloride ion penetration results of SG fly ash geopolymers mortars activated by NH were determined between 391°C and 721°C, while rapid chloride ion penetration results were determined between 376°C and 604°C for SG fly ash geopolymers mortars activated with NS-NH. For both NH and NS-NH, SG fly ash geopolymers activated with 6% and 9% Na were in the high chloride permeability class according to ASTM C1202 [35] since they exceeded 4000 C limit. Additionally, SG fly ash geopolymers specimens activated by 12% Na were low class while those activated by 15% Na were very low class in terms of rapid chloride ion penetration as per this standard.

On the other hand, rapid chloride ion penetration results of CA fly ash geopolymers mortars activated by NH were determined between 699°C and 7254°C, while rapid chloride ion penetration results were determined between 649°C and 6561°C for CA fly ash geopolymers mortars activated with NS-NH. For both NH and NS-NH, CA fly ash geopolymers activated with 6% and 9% Na were in the high chloride permeability class according to ASTM C1202 [35] since they exceeded 4000 C limit. Additionally, CA fly ash geopolymers activated by 12% Na were low class while those activated by 15% Na were very low class in terms of rapid chloride ion penetration as per this standard.

Though high chloride penetration was observed in geopolymer samples at 6% and 9% Na dosages, rapid chloride ion penetration in alkali-activated samples decreased with Na dosage increasing from 6% to 15%. So, for the SG and CA fly ash geopolymers mortars activated by NH and NS-NH, low and very low chloride ion penetration results were obtained at 12% and 15% Na, respectively. Zhu et al. stated in their study that chloride penetration depended on porosity and liquid/solid ratio [21]. Since the liquid/solid ratio of the samples produced in our study was a low value as 0.30, low chloride penetration results were obtained at high Na ratios. Furthermore, a relationship can be established between porosity and chloride penetration depending on the Na dosage increment. Namely, since a high NH concentration leads to more compact structure solving more Si and Al from fly ash, the decrease in porosity reduces chloride permeability values of mortar specimens for high Na dosages [6,45].

4.5. Accelerated corrosion testing results

The adherence test (pull-out) was performed to determine the adherence loss of the reinforcement located in the middle of Ø100 × 200 mm cylindrical samples subjected to accelerated corrosion test. The maximum force obtained was recorded and adherence strength was determined [46]. The test setup was shown in Fig. 10 and accelerated corrosion testing results for geopolymer mortars were given in Fig. 11.

The adherence strength of non-corroded geopolymer control samples with SG fly ash activated with NH is between 4.2 and 13.4 MPa. After corrosion, it was determined between 3.6 and 8.2 MPa. The adherence strength of non-corroded geopolymer control samples with SG fly ash activated with NS-NH is between 4.2 and 12.6 MPa. After corrosion, it was determined between 2.9 and 8.7 MPa. In control samples containing SG fly ash, the highest adherence resistance was obtained with NH having 15% Na dosage, while the highest adherence resistance was obtained with NS-NH at 15% Na after corrosion. However, the values were very close to each other.

The adherence strength of non-corroded geopolymer control samples with CA fly ash activated with NH is between 5.0 and

![Fig. 8. Rapid chloride permeability results of geopolymers (ASTM C1202).](image-url)
12.7 MPa. After corrosion, it was determined between 4.7 and 9.5 MPa. The adherence strength of non-corroded geopolymer control samples with CA fly ash activated with NS-NH is between 4.7 and 8.8 MPa. After corrosion, it was determined between 3.0 and 4.6 MPa. Before and after corrosion for CA fly ash, the highest adherence resistance was obtained with NH having 15% Na dosage, while the lowest adherence resistance values were obtained from the geopolymer specimens activated by NS-NH. The fact that the physical and chemical properties of CA fly ash are different from SG fly ash and that the effective activator is NH is thought to be the reason for this.

In general, mortars activated with alkali at high Na ratios have high corrosion resistance. In similar studies, the superiority of geopolymers has been revealed. Saraswathy et al. [47] accentuates that the reinforcement corrosion resistance of the mixtures activated with alkali is similar to the mortars obtained with OPC binders, while Miranda et al. [48] emphasized that the pH level of alkali-activated fly ash binders which will cause corrosion is better than OPC binder systems.

5. Conclusions

The conclusions described in the following can be summarized based on the experimental results conducted in this study:

- Water absorption and VPV values of geopolymer mortars activated by alkali decreased with the Na ratio increasing from 6% to 15%. Additionally, SG fly ash had better values than samples
produced with CA fly ash due to its physical properties, while those produced with NH gave better values than samples containing NS-NH.

- For both primary and secondary capillary water absorption values, improvements were observed depending on the increment in the Na ratio. Primary capillary water absorption amount were higher than the secondary capillary. This is due to the loss of water in the pores after thermal curing.

- The penetration depth of water under pressure decreased with the increase of Na ratio. However, all mixture groups at low Na (6%) ratio reached high permeability. This resulted from high porosity in these samples. So, it is thought that it would be appropriate to have Na value above 10% for decreasing the water permeability under pressure.

- Rapid chloride permeability is related to the pore structure and ion density in the voids. More Si and Al ions from fly ash in the higher Na ratios accumulate in the voids, reducing the penetration of chloride ion.

- Before and after corrosion, an improvement in adherence strengths was generally seen with the increase of Na dosage in geopolymer mortars. However, CA fly ash was more affected due to its differences in physical and chemical properties despite the decrease in strength of all groups after corrosion.

- The grain size distribution of fly ash directly affects the permeability properties. For this reason, geopolymers produced with SG fly ash having the low residue amount over 45 μm size exhibited better properties than those obtained with CA fly ash.

- The activator type showed difference properties on samples. For example, NH alone provided better permeability properties than NS-NH mixture.

- Although the increment in Na dosage affected positively the properties of samples, the similar results were obtained for 6% and 9% Na ratios. However, 12% and 15% were Na ratios which gave better results for all permeability characteristics.

CRediT authorship contribution statement

Ismail Isa Atabey: Investigation, Resources, Writing - original draft, Visualization. Okan Karahan: Resources, Writing - original draft, Project administration. Cahit Bilim: Writing - review & editing, Visualization. Cengiz Duran Atis: Methodology, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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