Journal of Architectural Sciences and Applications
JASA 2023, 8 (2), 713-734
Research article
e-ISSN: 2548-0170
https://dergipark.org.tr/en/pub/mbud

The Use of Waste Corn Cob as Aggregate in Geopolymer Mortar

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Abstract

This research aims to investigate the effects of waste corn cob aggregate on the properties of volcanic tuff-based geopolymer mortar. Nevşehir Pozzolan, which is produced as waste during the stone-cutting process, was used as an aluminosilicate source. The effect of alkali activator type, concentration, activator ratio, and sand-to-corn cob ratio on the properties was experimentally investigated. Study results revealed that waste Nevşehir Pozzolan was a suitable aluminosilicate for the production of geopolymer mortar. The optimum activator type, concentration, and activator ratios were sodium hydroxide with sodium silicate, 10 M, and 2.0, respectively, because they ensured the highest mechanical properties. Waste corn cob aggregate could be used instead of natural sand, and geopolymer mortar with various corn cob contents can meet the performance requirements of conventional wall materials.

Keywords: *Corn cob, waste aggregate, natural pozzolan, geopolymer mortar.*

Atık Mısır Koçanının Jeopolimer Harçta Agrega Olarak Kullanımı

Öz

Bu araştırmanın amacı volkanik tüf esaslı jeopolimer harcın özelikleri üzerinde atık mısır koçanı agregası kullanımının etkilerini araştırmaktır. Alüminosilikat kaynağı olarak taş kesim süreci sırasında üretilen atık halde Nevşehir Doğal Puzolanı kullanılmıştır. Alkali aktivatör türü, konsantrasyonu, aktivatör oranı ve kum/mısır koçanı oranının özelikler üzerindeki etkinliği deneysel olarak araştırılmıştır. Çalışma sonuçları Nevşehir Puzolanı'nın jeopolimer harç üretimi için alüminosilikat olarak uygun olduğunu göstermektedir. İdeal aktivatör türü, konsantrasyonu ve aktivatör oranı, en yüksek mekanik özelikleri sağlamasından dolayı, sırasıyla sodyum hidroksit ve sodyum silikat, 10 M ve 2.0'dır. Atık mısır koçanı agregası doğal kum yerine kullanılabilmektedir ve farklı mısır koçanı oranına sahip jeopolimer harçlar geleneksel duvar malzemelerinin performans gereksinimlerini karşılayabilmektedir.

Anahtar kelimeler: *Mısır koçanı, atık agrega, doğal puzolan, jeopolimer harç.*

Citation: Barış, K. E. (2023). The use of waste corn cob as aggregate in geopolymer mortar. *Journal of Architectural Sciences and Applications*, 8 (2), 713-734.
DOI: https://doi.org/10.30785/mbud.1342696

Received: *14/08/2023* – ***Accepted:*** *01/11/2023*

1. Introduction

The construction sector is among the main sectors that cause global carbon emissions due to its high energy consumption and waste generation. Efforts to "save energy and resources, reuse and recycle, appropriate management, and high consumption of waste products" in the context of seeking solutions to environmental problems have become the focal point of today's construction industry. However, more than 30 billion tons of natural aggregates are used in concrete production worldwide every year, and this amount increases by 5% annually (He et al., 2022). As a result, natural aggregate reserves decrease, and environmental damage occurs.

Globally, billions of tons of agricultural waste are produced each year. Storing these wastes in landfills creates a series of technical, social and environmental problems (Alaneme et al., 2023). The disposal of waste by incineration can cause adverse effects on the health of living things and the environment by releasing large amounts of polluting gasses and particulate matter into the atmosphere. In addition, incineration processes may adversely affect biodiversity and geomorphic processes in the soil, resulting in negative consequences for future agricultural practices (Aransiola et al., 2019; Memon et al., 2019). By using agricultural wastes instead of natural aggregates, natural raw material reserves can be protected, landfills can be reduced, and environmental pollution and carbon emissions can be reduced.

Corn Cob (CC) is an agricultural waste generated during corn harvest. Since about 18 kg of CC is obtained in 100 kg of corn production, there is a huge amount of waste CC around the world every year (Tsai et al., 2001). Unlike other crops, CC is nutrient-poor and only a certain portion is used for animal feed production or cultivated mushrooms. A large amount of corn cob is thrown into landfills or incinerated (Xu et al., 2021), resulting in the aforementioned problems for living things and the environment.

The composition of CC, which has a sponge-shaped porous microstructure, consists of cellulose, hemicellulose, and lignin (Takada et al., 2018). Therefore, CC is suitable for use as a building material because it has the same fiber components with wood (Khiari et al., 2010; Binici et al., 2016). Research shows that the ash obtained by burning CC contains more than 70% Al_2O_3 and SiO_2, that is, it has pozzolanic properties and can be used as a binder (Adesanya, 1996; Adesanya & Raheem, 2009; Memon et al., 2019). It was determined that with the use of 20% CC ash in concrete, embodied energy and CO_2 emissions were reduced by approximately 12% and 37%, respectively (Alsalman et al., 2021).

Pinto et al. (2011) evaluated the possibilities of CC as a thermal insulation material in buildings. According to the results of the research, the microstructures of the XPS thermal insulation material and CC were quite similar since both materials had a closed cellular microstructure and contained similar chemical components (oxygen, magnesium, aluminum, silicon, calcium, and iron). In another study, Faustino et al. (2012), investigated panel production possibilities by mixing CC aggregate with wood glue for impact sound insulation. It was determined that the produced material had positive acoustic properties. Pinto et al. (2012) produced Portland cement-based lightweight concrete using CC as aggregate. The unit weight (0.35-0.94 gr/cm^3), compressive strength (0.1-0.5 MPa), and thermal conductivity coefficient (1.99 W/mK) of this material were lower than those of the expanded clay-based specimen, and this material might be used for nonstructural applications. Binici et al. (2014) produced a thermal insulation material with a unit weight of 0.26-0.41 gr/cm^3, a water absorption ratio of 12-24%, and a thermal conductivity coefficient of 0.1-0.19 W/mK by mixing epoxy, gypsum, and cement with CC aggregate. Laborel-Préneron et al. (2018) investigated the thermal insulation properties of unfired soil-based building materials containing CC aggregates. As a result of the research, the thermal conductivity coefficient of the specimen containing 6% CC (0.35 W/mK) decreased by approximately 36% compared to the thermal conductivity coefficient of the soil-based specimen (0.57 W/mK). In another study, Shao et al., (2021) used CC aggregate as an alternative to river sand to produce cement-based paste. The use of CC aggregates increased the porosity and water absorption ratio and decreased the density, strength, and thermal conductivity coefficient. The optimum CC grain size was found to be 1-2 mm, and the ratio was 40%. Ramos et al. (2021) investigated the production possibilities of thermal insulation panels containing CC using polymer-based binders.

Choi et al. (2022) produced a composite panel by mixing ground CC with microencapsulated phase change material. The produced material increased the thermal performance of the building and reduced energy consumption. In another study, the use of CC aggregate enabled the production of gypsum-based partition wall elements with 34% lower thermal conductivity coefficient (Türk et al., 2022).

Literature studies provide significant data on the addition of CC in powder form or as aggregate into cement, gypsum, polymer-based binder, mortar, and concrete. However, research on the evaluation of CC as an aggregate in the production of geopolymer materials, which is more energy- and environmentally-efficient binder type compared to cement, is limited. Wang et al., (2023) incorporated CC aggregates into the geopolymer binder produced by activating the mineral powder with a mixture of NaOH and Na_2SiO_3 alkali activators. It was stated that materials with flexural and compressive strengths of 1.6 and 11.6 MPa, respectively, and thermal conductivity coefficient of 0.10-0.18 W/mK can be used as thermal insulation materials. However, the industrial waste used as a geopolymer raw material (aluminosilicate source) in this research is an artificial pozzolan. In the literature, there is no research in which waste natural pozzolan is used as an aluminosilicate source and reinforced with CC aggregate. On the other hand, since Anatolian geography is exposed to many volcanic activities, Turkey is very rich in terms of volcanic tuff reserves. According to the Mineral Research and Exploration Institute, when the visible reserve, possible reserve, and probable reserve data are taken into account, there are approximately 18 billion m^3 reserves, and Turkey has approximately 40% of the volcanic tuff reserves worldwide (Yaşar & Erdoğan, 2005).

Approximately 10-15% of the volcanic rocks extracted in our country are cut solidly and used in the construction sector, while the rest is used as filling material or stored as waste. These rocks, which have been physically crumbled and turned into dust, adversely affect the health of living things and the agricultural areas in the surrounding area and create visual pollution. Therefore, the aim of the current research is to investigate the effects of waste corn cob aggregate on the physical, mechanical, and thermal properties of geopolymer mortar produced from volcanic tuff, which is produced as waste during the stone-cutting process.

2. Material and Method

2.1. Raw Materials

Geopolymer binders are produced as a result of the reaction of an aluminosilicate source (natural or artificial pozzolans) containing a high percentage of alumina and silica with different alkali activators (Garcia-Lodeiro et al., 2015). These binders have two main components: (i) aluminosilicate source and (ii) alkali activator. The type of these components, their physical, chemical, and mineralogical properties, the type of aggregate and its properties, mixing ratios, mortar mixing, pre-curing, and curing conditions are very effective parameters for the properties of geopolymer mortars.

Because of eruptions of volcanoes, which are known to be active in geological periods such as Erciyes, Hasandağı, Melendiz, and Güllüdağ in the Cappadocia Region of Turkey, the lava coming out of the volcanoes have formed a 100-150 m thick tuff layer on the plateau, lakes, and streams. More than 1.5 billion m^3 of volcanic tuff reserves have been identified in this region (Yaşar & Erdoğan, 2005).

The natural Nevşehir Pozzolan (NP) used as an aluminosilicate source in this study was obtained from the waste storage area of the volcanic tuff quarry in the region (Figure 1a).

The specific surface area of the NP determined according to the TS EN 196-6 (2010) is 6542.16 cm^2/gr and its specific gravity is 2.45 gr/cm^3. XRF analysis results of NP are shown in Table 1.

The total SiO_2+Al_2O_3+Fe_2O_3 and the maximum SO_3 and MgO content in the composition of NP meet the criteria required to be used as a binder material according to TS 25 (2008) (Table 2). In addition, the flexural and compressive strengths performed in accordance with the pozzolanic activity test (TS 25, 2008) also reveal that NP is a binding material.

Table 1. Chemical composition of NP

Composition	NP
SiO_2	77.29
Al_2O_3	18.98
Fe_2O_3	1.71
CaO	0.33
MgO	1.29
K_2O	0.30
SO_3	0.10
Total	100

Table 2. Main requirements that a natural pozzolan should have

Requirements (TS 25, 2008)		NP
SiO_2+ Al_2O_3+ Fe_2O_3 (%)	≥ 70.0	97.98
SO_3 (%)	≤ 3.0	0.10
MgO (%)	≤ 5.0	1.29
Flexural Strength (MPa)	≥ 1.0	1.86
Compressive Strength (MPa)	≥ 4.0	6.81

The alkali activator, which is one of the two main components of the geopolymer binder, increases the pH of the reaction medium and ensures the dissolution of the aluminosilicate source (Firdous et al., 2018). In the current research, sodium hydroxide (NaOH) solution with 8, 10, and 12 molar concentrations (M) (Figure 1b) and liquid sodium silicate (Na_2SiO_3=SS) with silica modulus (SiO_2/Na_2O) 3.2 (Figure 1c) were used as alkali activators.

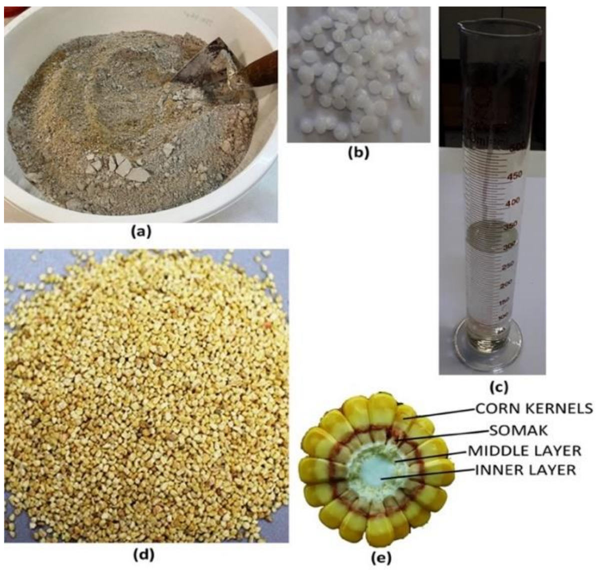

Figure 1. Raw materials used in the current study: (a) NP; (b) NaOH; (c) SS; (d) CC; (e) the cross-section of the CC

CEN Standard Sand (S) with a specific gravity of 2.56 gr/cm^3 according to TS EN 196-1 (2009) was used for the production of geopolymer mortar. The particle size distributions of NP and S is shown in Figure 2.

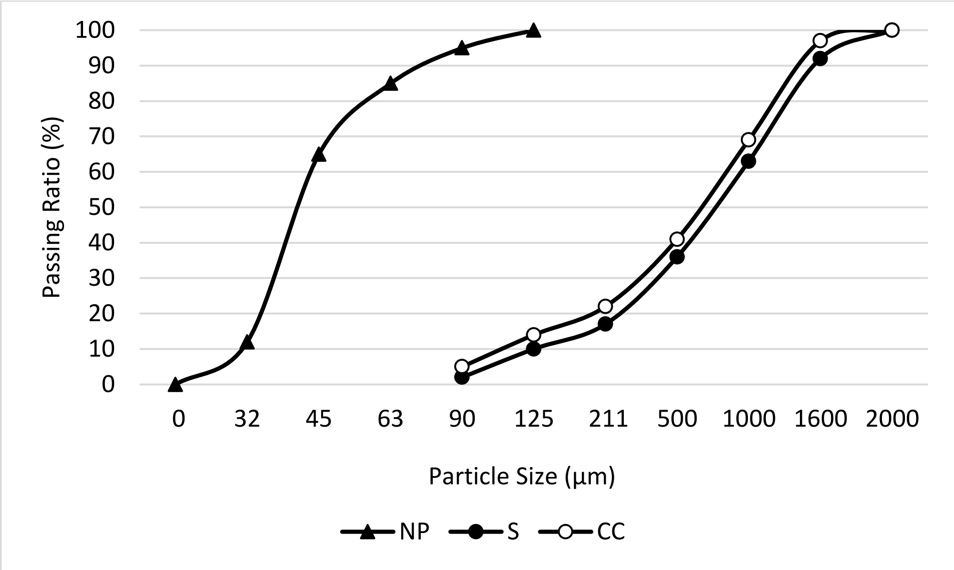

Figure 2. The particle size distributions of NP, S, and CC

CC was obtained from agricultural lands in the Black Sea Region (Ordu, Turkey) and dried at 100 °C for 48 h. Then, the weight, length, and maximum diameter of 50 randomly selected CCs were measured, and the coefficient of variation (CV) was calculated (Table 3). CC consists of cellulose, hemicellulose, pectin, lignin, and waxes (Shao et al., 2021). When the CC was cross-sectioned, a macro-structure of three concentric circles with different colors and densities appeared (Figure 1e). The innermost layer is the core layer, which is soft and easily compressible. The middle layer is darker, harder and has a wood-like texture. The outermost layer carries corn kernels and shows a soft structure (Bovo et al., 2022).

Table 3. The weight and dimensions of dried corn cobs

CC	**Dried Weight (gr)**		**Length (mm)**		**Diameter (mm)**	
	Average (gr)	**CV (%)**	**Average (mm)**	**CV (%)**	**Average (mm)**	**CV (%)**
	35.2	11.3	211	7.1	32	4.5

CV: Coefficient of variation

Since CC was used as a substitute for S, it was ground and sieved to provide the particle size distribution of S (Figure 2). Since CC does not have a regular shape, water absorption test was used to determine its density. First, the dry weight (m_{cc}) of the dried CC was recorded. Then an object of known volume (V_{object}) was attached to the CC to allow it to fully submerges in water. The CC and the object were placed in a water-filled glass container ($V_{control}$) of known volume. The volume of CC is calculated according to Equation 1:

$\Delta V = V_{final} - V_{control} - V_{object}$ (Eq. 1)

The calculated value of ΔV is the volume of CC (V_{cc}). Then the density of CC is calculated according to Equation 2:

$d_{cc} = m_{cc} / V_{cc}$ (Eq. 2)

The density (d_{cc}) of CC was calculated by taking the average of 10 specimens and was determined to be 2.51 gr/cm^3. This value is important in that it is close to the value found in another study (2.47 gr/cm^3) (Bovo et al., 2022).

2.2. Mixing Ratios and the Production Process

The effects of using CC aggregate instead of natural aggregate on the physical, mechanical, and thermal properties of waste volcanic tuff-based geopolymer binder were evaluated in this study. The experimental method consisted of three stages: (i) the effect of alkali activator type (NaOH and SS + NaOH); (ii) the effect of NaOH concentration (8, 10, 12 M) and activator ratio (SS:NaOH = 0.5, 1.0, 2.0); and (iii) the effect of the S:CC aggregate ratio (100:0, 70:30, 50:50, 30:70, 0:100). The optimum findings obtained in each stage were kept constant in the next stages.

Only S was used as aggregate in the first and second stages. S and CC aggregates were used in varying proportions in the third stage. As a result of the data in the first and second stages, the ideal alkali activator type (SS + NaOH), NaOH concentration (10 M), and activator ratio (2.0) were determined, and the specimen containing only S aggregate was selected as the “control specimen” in the third stage. Throughout the study the alkali activator: pozzolan and the pozzolan: aggregate ratios were kept constant at 3:10 and 1:2 by weight, respectively. The stages, specimen codes, and mixing ratios are given in Table 4.

Table 4. The stages, specimen codes, and mixing ratios

Stage	Specimen Code	Activator Type	NaOH Concentration (M)	Activator Ratio (wt %)	Activator: Pozzolan (wt %)	Pozzolan: Aggregate (wt %)
i	100S:0CC	NaOH	8	-	3:10	1:2
		SS+NaOH		0.5		
ii		SS+NaOH	8	0.5	3:10	1:2
				1.0		
				2.0		
			10	0.5		
				1.0		
				2.0		
			12	0.5		
				1.0		
				2.0		
iii	100S:0CC (Control)	SS+NaOH	10	2.0	3:10	1:2
	70S:30CC					
	50S:50CC					
	30S:70CC					
	0S:100CC					

Solid raw materials (NP, S, and CC) were mixed at 50 rpm for 5 min using a mortar mixer. Alkali activators and water were then added to this dry mixture and mixed for another 5 min at 70 rpm. The mixture was placed in steel molds of 40x40x160 mm, covered with polyethylene, and cured in a ventilated oven at 70 °C for 24 h. After the curing, the specimens were removed from the molds and kept in 22±2 °C and 55±5% RH for 28 days.

The produced specimens were coded in “aS:bCC” format. In this coding, “S” stands for standard sand, “a” stands for standard sand ratio by weight, “CC” stands for corn cob, and “b” stands for corn cob ratio by weight. While physical and mechanical tests were applied on the specimens with 40x40x160 mm, thermal conductivity coefficient, and water vapor permeability tests were carried out on circular specimens with a diameter of 100 mm and a thickness of 30 mm. Each test result was recorded by calculating the arithmetic mean of the results obtained from six specimens.

2.3. Applied Tests

The workability of the fresh binder was determined by the flow table test performed in accordance with TS EN 12350-5 (2019). In the first and second stages, the specimens were subjected to dynamic ultrasound velocity tests according to TS EN 14579 (2006) and flexural and compressive strength tests in accordance with TS EN 196-1 (2009). In the third stage, in addition to these tests, unit weight (TS EN 1015-10, 2001), water absorption ratio (TS EN 13755, 2009), and thermal conductivity coefficient (ASTM C518–17, 2021) tests were applied. The water vapor permeability of the specimens was determined according to TS EN 12086 (2013) by the dry cup method, which involved it being filled with silica gel. 90-day drying shrinkage was determined in accordance with TS ISO 1920-8 (2011). The length change of each specimen was measured on each of the following days: 1, 2, 3, 4, 5, 6, 7, 15, 22, 30, 40, 50, 60, 70, 80, and 90. The mechanical fracture behavior and toughness of the specimens were determined by drawing a flexural load-displacement diagram under flexural loads.

3. Results and Discussion

3.1. The Effect of Alkali Activator Type

The reaction mechanism of geopolymer materials is an exothermic process consisting of dissolution-agglomeration-polycondensation reactions. In the dissolution stage, the alkali solution with high pH dissolves the covalently bonded Si-O-Si and Al-O-Si groups in the aluminosilicate source. These dissolved groups transform into the colloidal phase in the second stage. Then, the dissolved phases react with each other to form an agglomerated structure, and a solidified structure is formed at the end of the polycondensation stage (Pacheco-Torgal et al., 2008).

The effect of alkali activator type on the mechanical properties of geopolymer mortar produced using NP aluminosilicate, S aggregate, and NaOH or SS + NaOH alkali activators is given in Figure 3.

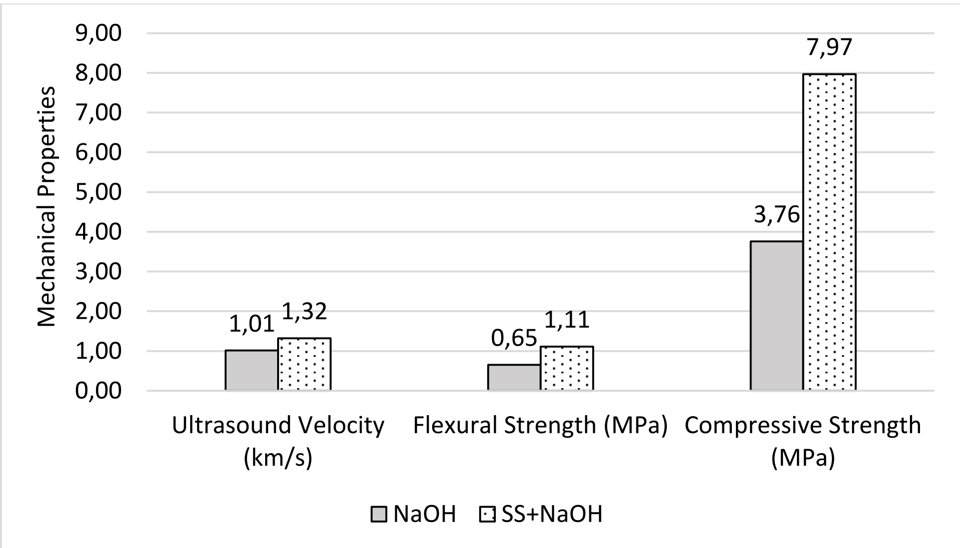

Figure 3. Effect of alkali activator type on the mechanical properties of NP-based geopolymer mortar

The ultrasound velocity of the mortar activated with SS + NaOH was 1.30 times higher than that of the mortar activated with only NaOH. Since ultrasound velocity, which is a nondestructive test method, is an indicator of the porosity of the material, it can be deduced that the geopolymer mortar body reached a more compact microstructure in the SS-containing specimens. In other words, the material structure developed to reach a more homogeneous structure, and cracks, voids, and irregularities that would reduce the rate of absorption or dispersion of the sound passing through the material were reduced. In parallel with this change, the flexural and compressive strengths of specimens activated with SS + NaOH were 1.70 and 2.12 times higher, respectively, than those activated with only NaOH. This increasing trend in mechanical properties may be because SS increases the dissolution rate of Si and Al components in the aluminosilicate source (during the dissolution stage of geopolymerization). In addition, since the Al-O bonds in the aluminosilicate source are weaker than the Si-O bonds, Al ions dissolve easily and quickly in alkali solutions. If additional Si ions are present in the reaction medium before the raw material starts to dissolve, it becomes important to add SS to the mixture as the degree of geopolymerization will increase (Nadoushan & Ramezanianpour, 2016). In addition, the presence of SS in the mixture provides stronger ion pair formation during the polycondensation stage of geopolymerization and thus longer chain silicate oligomers are formed. The presence of longer chain silicate oligomers in the mortar facilitates the formation of geopolymer reaction products (NASH gel) (Xu & Van Deventer, 2000). Therefore, it is important to add SS to the geopolymer mix. This finding is also consistent with the results of another study (Barış, 2022) in which the positive effects of SS on the properties of Datça Pozzolan-based geopolymer binder were determined.

3.2. The Effect of Alkali Hydroxide Concentration

The effect of alkali hydroxide concentration on the mechanical properties of geopolymer mortar produced using NP aluminosilicate, S aggregate, and NaOH or SS + NaOH alkali activators is given in Figure 4.

The 10 M NaOH concentration was the limit at which mechanical properties were reversed. While the alkali activator ratio was constant, increasing the NaOH concentration from 8 M to 10 M resulted in an increase in ultrasound velocity and flexural and compressive strengths of the specimens. This finding indicated that the voids in the internal structure of the mortar decreased. The highest ultrasound velocity (3.07 km/s), flexural strength (2.09 MPa), and compressive strength (18.21 MPa) were obtained in the specimens activated with 10 M NaOH and with the highest activator ratio (2.0). This increasing trend may be explained by the fact that the higher OH^- ions in the reaction medium increase the dissolution rate of the aluminosilicate source (NP) (Kani & Allahverdi, 2009). Increasing dissolution positively affects microstructure development by increasing the dissolved Si and Al components required for the development of the next geopolymerization reaction stage, polycondensation (Panagiotopoulou et al., 2007). In other words, by activating the NP with 10 M NaOH, a higher degree of dissolution was achieved and the development of polycondensation reactions and thus the mechanical properties of the material were supported. However, it was determined that as a result of further increasing the NaOH concentration (12 M), a structural deformation occurred in the mortar structure and accordingly the mechanical properties decreased. Ultrasound velocity, flexural and compressive strengths of all specimens activated with 12 M SS + NaOH decreased by 0.72-0.78, 0.77-0.85, and 0.73-0.79 times, respectively, compared to the specimens activated with 10 M SS + NaOH. It can be deduced from this that increasing the alkali hydroxide concentration beyond its optimum value created an immature molecular structure in the mortar. Because the existence of an excessive number of OH^- ions in the reaction medium allowed the polycondensation reaction to start earlier than expected and to develop much faster. Thus, the development of the dissolution reaction, which was the first stage, was prevented, and the NP could not find enough time to be dissolved completely (Kani & Allahverdi, 2009). However, despite the detected reduction, the mechanical properties of the 12 M SS + NaOH activated mortars were still higher than those the of control specimen activated with 8 M SS + NaOH.

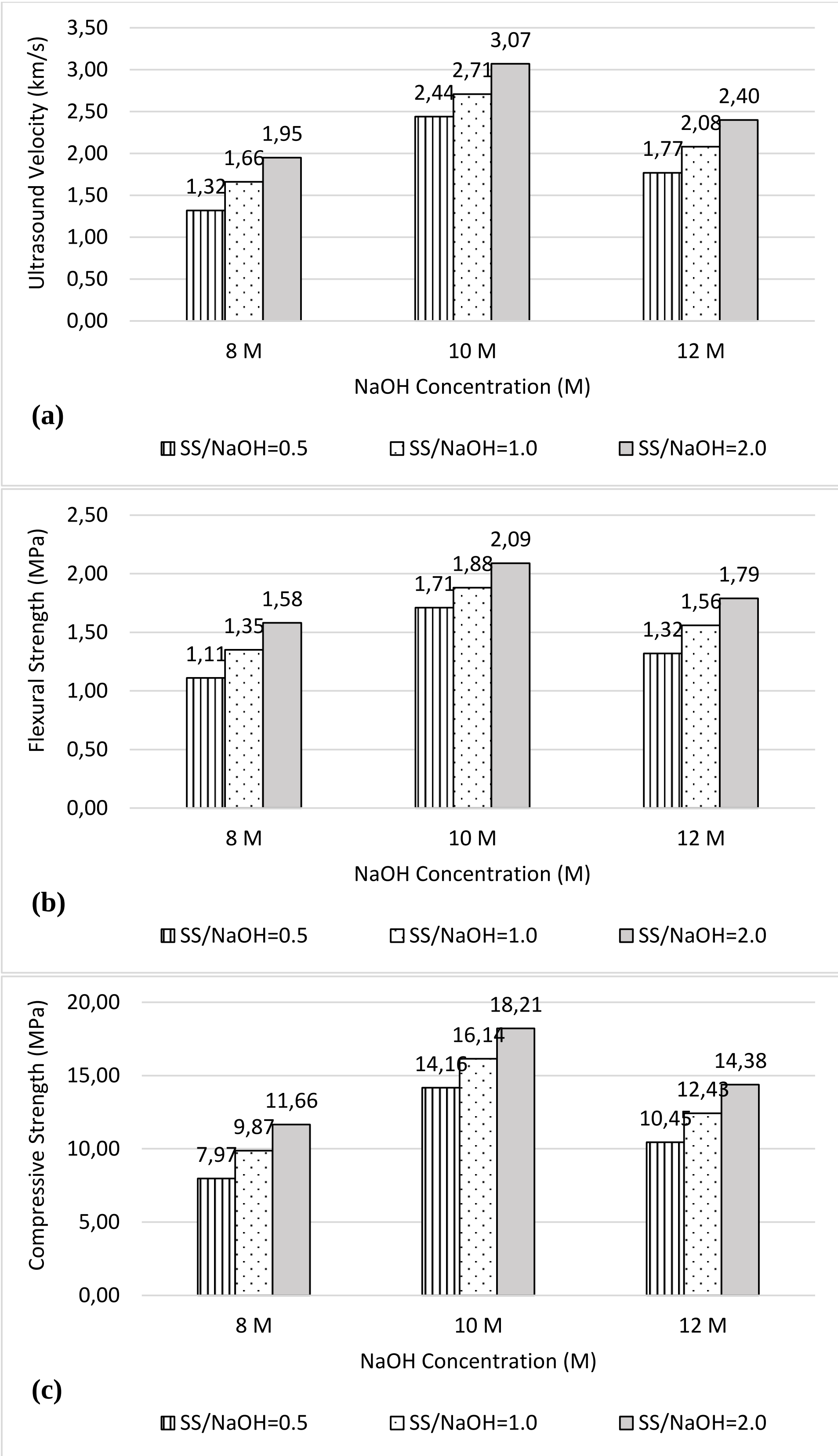

Figure 4. The effect of alkali hydroxide concentration on the mechanical properties of NP-based geopolymer mortar

3.3. The Effect of the Activator Ratio

The effect of the activator ratio (SS/NaOH) on the mechanical properties of geopolymer mortar produced using NP aluminosilicate source, S aggregate, and NaOH or SS + NaOH alkali activators is given in Figure 5.

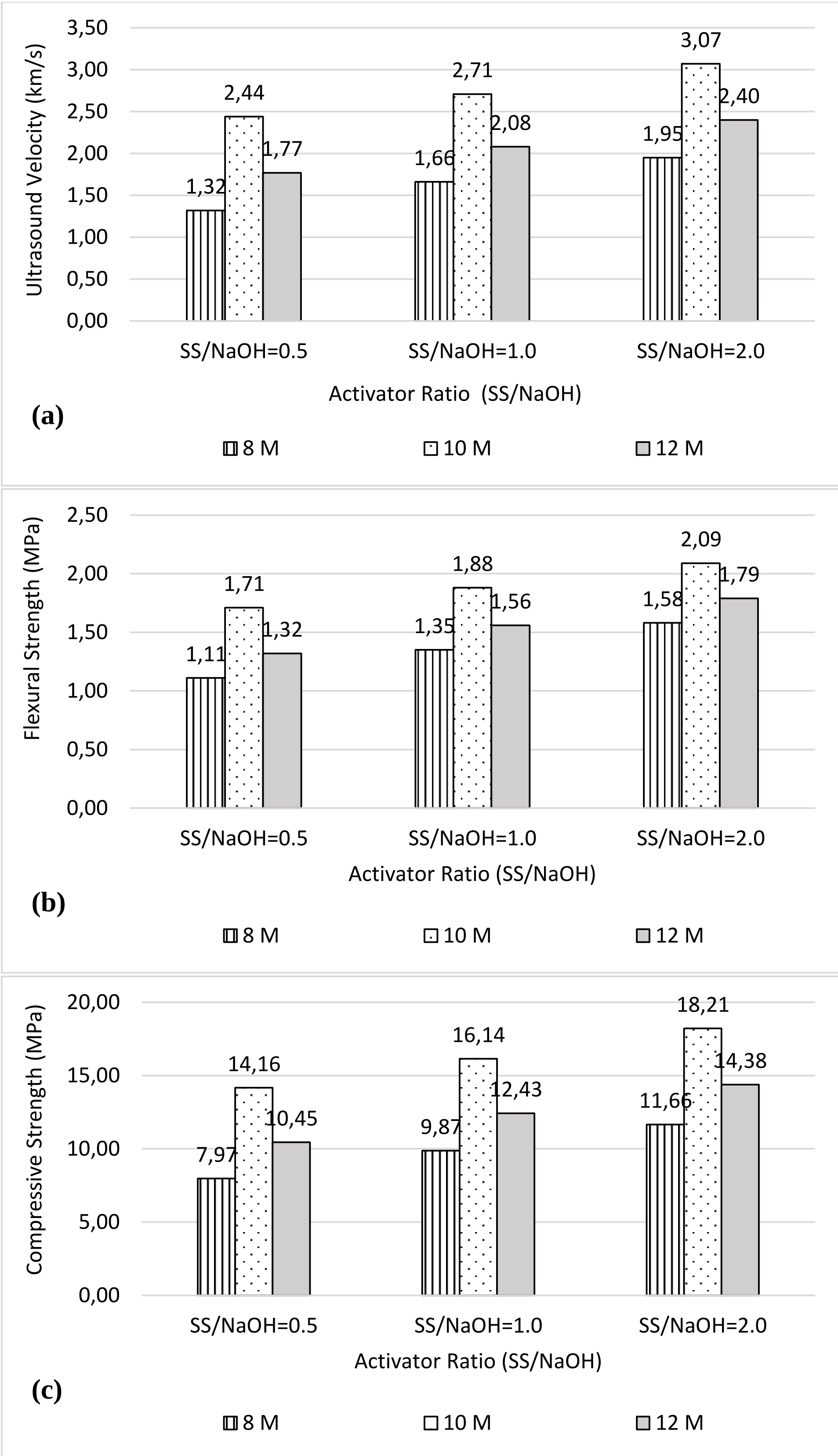

Figure 5. The effect of the activator ratio on the mechanical properties of NP-based geopolymer mortar

When the NaOH concentration was constant, increasing the activator ratio from 0.5 to 2.0 M increased the ultrasound velocity and flexural and compressive strengths of the specimens. The highest ultrasound velocity (3.07 km/s), flexural strength (2.09 MPa), and compressive strength (18.21 MPa) were obtained in the specimens with the highest activator ratio (2.0). The reason for this increasing trend was explained in the Section 3.1. However, the ideal activator ratio varies according to the type of aluminosilicate raw material used. While the ideal activator ratio is 2.5 for Datça Pozzolan (Barış, 2022) and Pasuruan Pozzolan (Risdanareni et al., 2015), it is 2.0 for blast furnace slag-based geopolymer (Hadi et al., 2019) and 1.5 for fly ash-based geopolymer (Nath & Sarker, 2014) in the literature.

3.4. The Effect of Aggregate Mixing Ratio

3.4.1. The effect of aggregate mixing ratio on physical properties

The effect of the S:CC aggregate ratio on the workability and unit weight of NP-based geopolymer mortar is given in Figure 6.

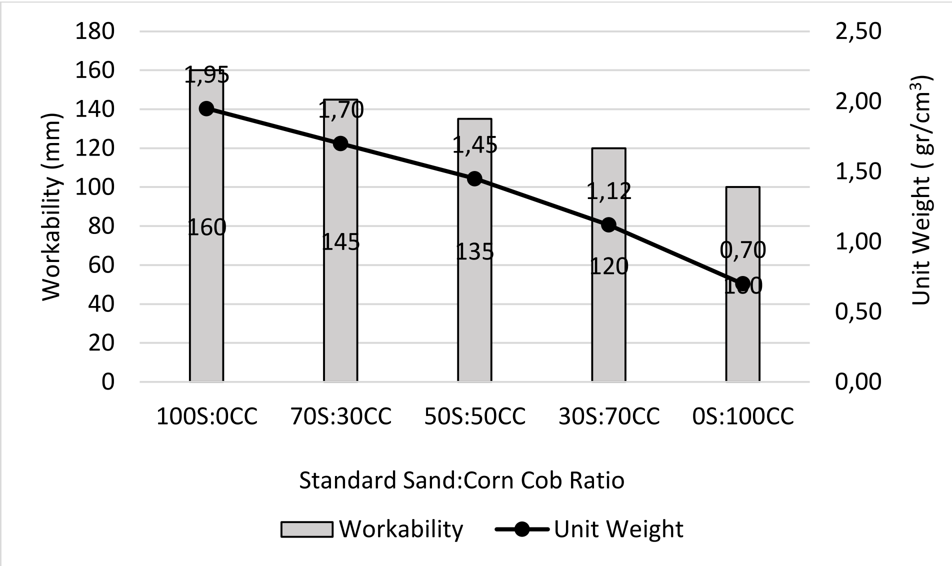

Figure 6. The effect of the S:CC ratio on the workability and unit weight relationship of NP-based geopolymer mortar

The control sample without CC (100S:0CC) had the highest workability (160 mm). With the addition of CC to the mortar mixture, the workability gradually decreased. The lowest workability (100 mm) was determined in the specimen with the code 0S:100CC. This decreasing trend was due to the decrease in the amount of mixing water because CC, which has porous structure and hydrophilic properties, absorbed the mixing water at a higher ratio than natural S. However, adding more water to the mixture to facilitate casting and molding processes would reduce the mechanical properties of the material, so, no more extra water was added to the mortar.

One of the most significant parameters affecting the physical and mechanical properties of materials is the unit weight (Shao et al., 2021). The unit weight of the mortar is significantly affected by the density and amount of the aggregate used. The unit weight of the geopolymer mortar varied between 0.70 and 1.95 gr/cm^3. The highest value (1.95 gr/cm^3) was obtained from the control specimen containing only S. The unit weight of all specimens containing CC was lower than that of the control specimen. Because CC is a material with a low unit weight due to its cellular and porous structure, the unit weight of the specimens containing 30%, 50%, 70%, and 100% CC decreased by 0.87, 0.74, 0.57, and 0.36 times, respectively, compared to that of the control mortar. Since the unit weight of all specimens included in the study is lower than 1.8 gr/cm^3, it meets the density requirement of lightweight mortar and wall materials (Corinaldesi et al., 2016). The unit weight of CC incorporated gypsum and cement-based mortar is 0.54-0.80 gr/cm^3 (Binici et al., 2016); the unit weight of only gypsum-based mortar is 0.85-1.20 gr/cm^3 (Türk et al., 2022); and the unit weight of cement-based mortar is 1.6-2.0 gr/cm^3 (Shao et al., 2021) in the literature. The values obtained in the current research are in agreement with unit weights in the literature.

The effect of the S:CC aggregate ratio on the porosity and water absorption ratio of NP-based geopolymer mortar is given in Figure 7. Accordingly, the porosity of mortars varied between 19.38-26.24%. The lowest value (19.38%) was obtained from the control specimen. Due to the porous structure of CC, the porosity of the mortar containing 30%, 50%, 70%, and 100% CC increased approximately 1.09, 1.18, 1.27, and 1.35 times, respectively, compared to the control specimen. In addition, the water absorption ratio also showed results in parallel with the change in porosity. The lowest water absorption ratio (7.14%) was obtained from the control specimen, while the highest value (13.01%) was found in the 0S:100CC specimen containing 100% CC.

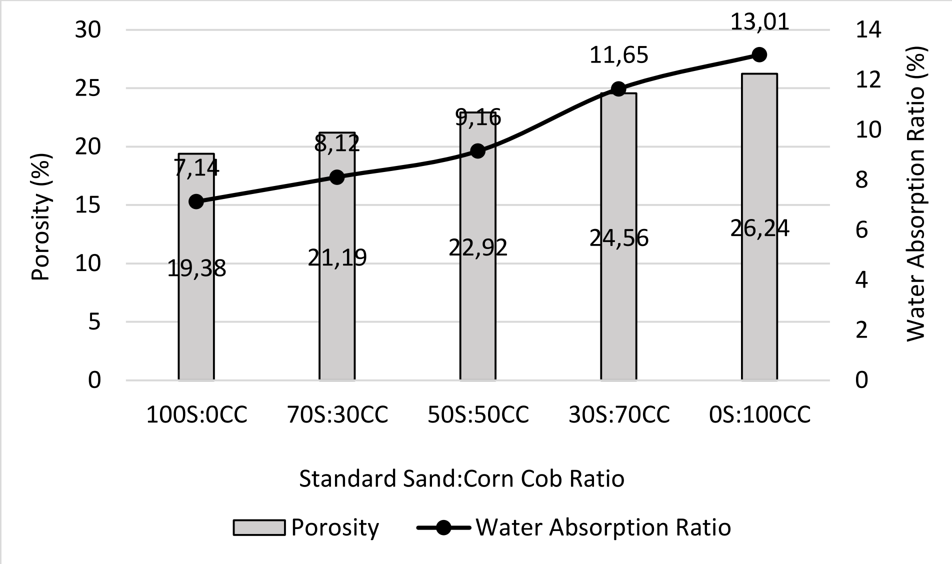

Figure 7. The effect of the S:CC ratio on the porosity and water absorption ratio relationship of NP-based geopolymer mortar

Unlike Portland cement, very little of the water used in the production of geopolymer-based binders is consumed in gel formation, and this water is called "structural water". Water, known as "free water", is added to ensure the workability of the binder. When this free water evaporates from the binder structure in an uncontrolled way, drying shrinkage may occur (Azevedo et al., 2021). The effect of the S:CC ratio on the 90-day drying shrinkage of the NP-based geopolymer mortar is given in Figure 8.

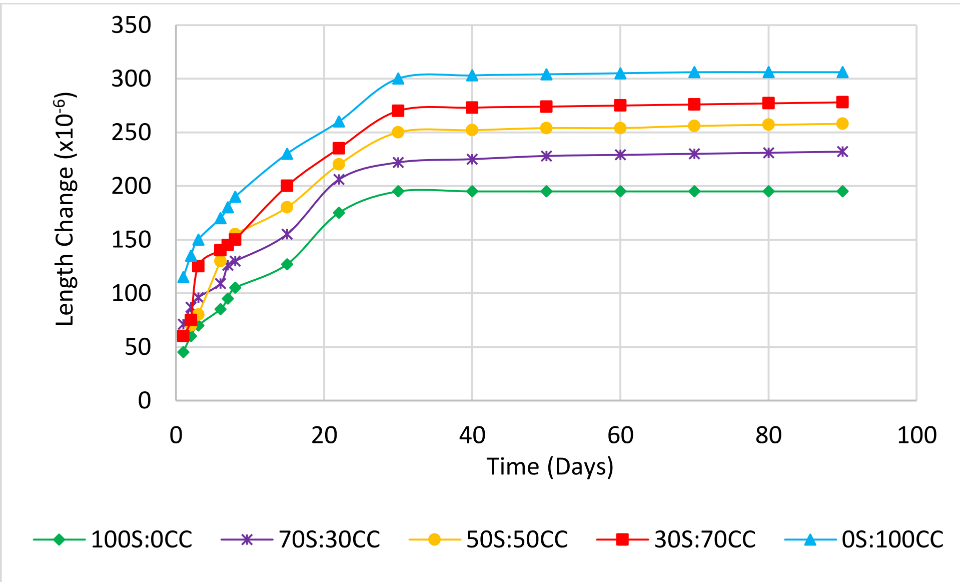

Figure 8. The effect of the S:CC ratio on the drying shrinkage of the NP-based geopolymer mortar

According to Figure 8, because of the higher free water content in all specimens in the early period, the shrinkage in the first 21 days was more effective. In the following period, the shrinkage value became constant. The lowest drying shrinkage (195x10-6) was obtained from the control specimen containing only S. The drying shrinkage of the specimens containing 30%, 50%, 70%, and 100% CC increased by 1.19, 1.32, 1.43, and 1.57 times, respectively, compared to the drying shrinkage of the control mortar. The main factor in this increase was that the modulus of elasticity (rigidity) of CC was lower than that of S. Thus, the specimen with higher CC contents had a higher shrinkage ratio. On the other hand, S with higher rigidity was more successful in preventing drying shrinkage.

It is important to design building materials that allow the passage of water vapor to prevent condensation and related problems that may occur during the use of the material. The effect of the S:CC ratio on the water vapor permeability and porosity relationship of NP-based geopolymer mortar is given in Figure 9.

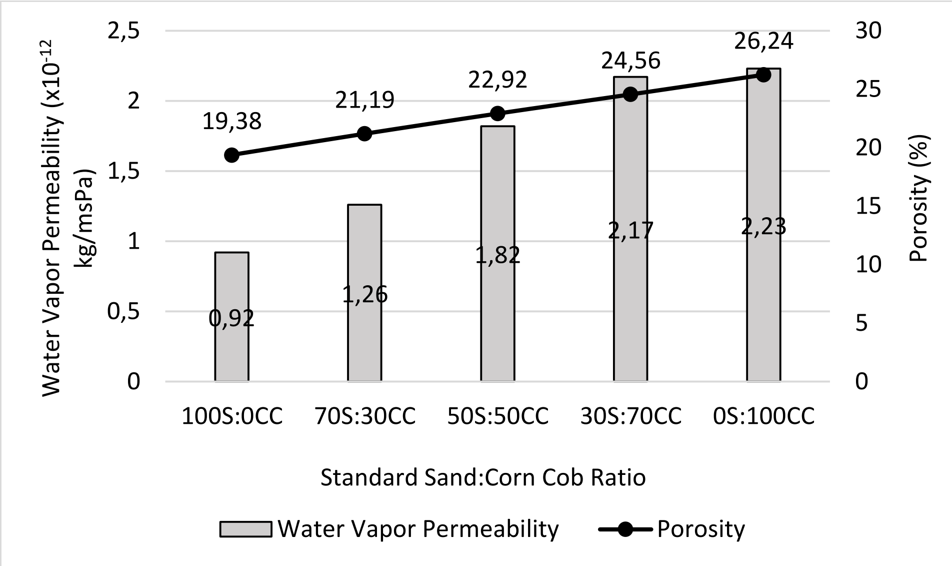

Figure 9. The effect of the S:CC ratio on the water vapor permeability and porosity relationship of NP-based geopolymer mortar

The lowest water vapor permeability (0.92×10^{-12} kg/msPa) was obtained from the control specimen. The water vapor permeability increased as the ratio of the substitution of S by CC increased. The vapor permeability (1.82×10^{-12} kg/msPa) of the specimen containing 50% CC (50S:50CC) was approximately 2 times that of the control specimen. Increasing the CC ratio to 70% and 100% increased the vapor permeability by 2.36 and 2.42 times, respectively, compared to the control specimen. In addition, the vapor permeability values were closely related to the porosity values. CC with porous structure allowed the vapor to pass through the material more easily, and consequently, the formation of condensation might be prevented.

3.4.2. The effect of aggregate mixing ratio on thermal properties

Since the thermal conductivity coefficient is an important indicator of the energy efficiency of a material, this property should be determined in an experimental study (Wang et al., 2023). As a waste material with a porous structure, CC has a good thermal insulation advantage with its low thermal conductivity coefficient (0.093 W/mK, Viel et al., 2018). The effect of the S:CC ratio on the thermal conductivity coefficient and unit weight relationship of the NP-based geopolymer mortar is given in Figure 10. The thermal conductivity coefficient of the produced geopolymer mortars varied between 0.28-0.96 W/mK. The highest value (0.96 W/mK) was obtained from the control specimen. The thermal conductivity coefficient of the specimens containing CC decreased gradually by 0.78, 0.52, 0.41, and 0.29 times, respectively, compared to the control mortar. This decrease in the thermal conductivity coefficient was related to the fact that CC increased the porosity and decreased the density of the geopolymer mortar. Furthermore, the thermal conductivity coefficients of the CC aggregate (0.093 W/mK) and the air in the voids of CC (0.026 W/mK) are lower than that of the matrix (0.96 W/mK).

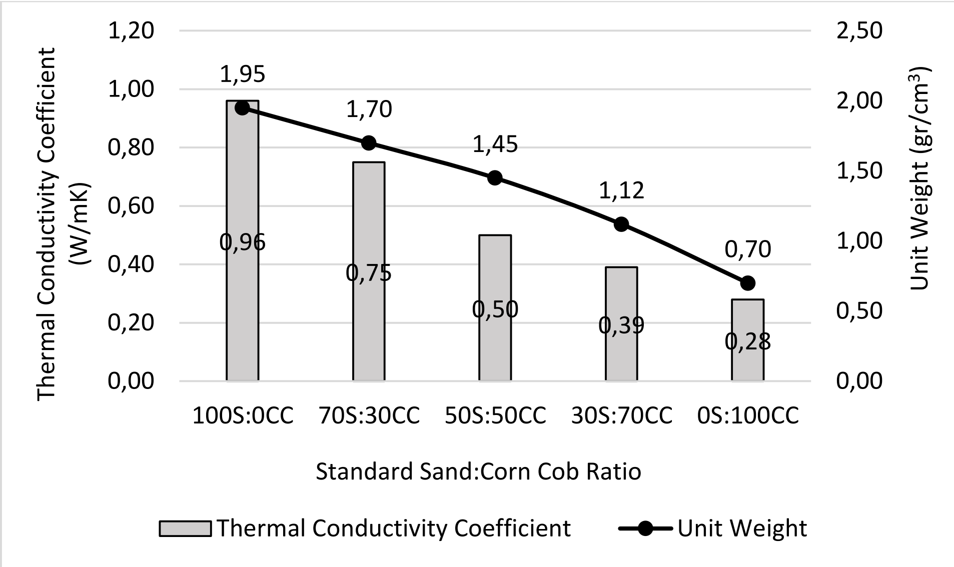

Figure 10. The effect of the S:CC ratio on thermal conductivity coefficient and unit weight relationship of NP-based geopolymer mortar

3.4.3. The effect of aggregate mixing ratio on mechanical properties

The effect of the S:CC ratio on ultrasound velocity, compressive, and flexural strengths of NP-based geopolymer mortar is given in Figure 11. Ultrasound velocity, compressive, and flexural strengths of geopolymer mortars varied between 1.74 and 3.07 km/s, 3.12 and 18.21 MPa, and 0.60 and 2.09 MPa, respectively. The highest values (3.07 km/h, 18.21 MPa, and 2.09 MPa, respectively) were obtained from the control specimen containing only S. The compressive strength of the specimens containing 30%, 50%, 70%, and 100% CC decreased by 0.56, 0.46, 0.31, and 0.17 times, respectively, compared to the compressive strength of the control mortar. The change in the S:CC ratio on flexural strength was also parallel to the change in compressive strength. This decrease in strength due to the addition of CC was related to the fact that CC increased the void ratio in the geopolymer matrix, and these voids created weak zones in the material. These porous structure and weak zones were also observed by digital images of the specimens determined after the flexural strength test, as can be seen in Figure 12. In addition, this situation coincides with the 0.57-0.82 times decrease in ultrasound velocity with the addition of CC compared to the control mortar. Furthermore, since the modulus of elasticity (rigidity) of CC was lower than that of S, stresses occurring in the specimen under pressure load led to an earlier fracture, and thus the strength decreased. However, the strength development of the mortars would be affected not only by the aggregate properties and mixing ratio but also by the properties of the interface between the matrix and the aggregate.

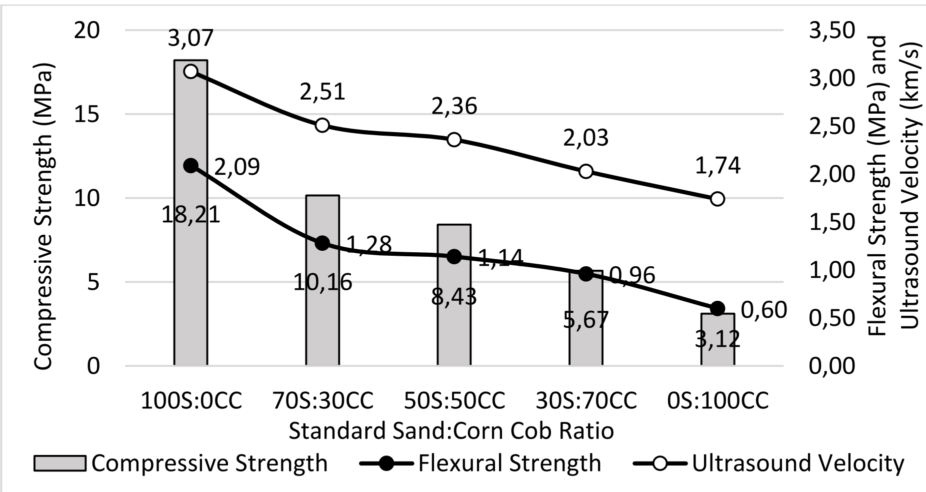

Figure 11. The effect of the S:CC ratio on ultrasound velocity, compressive and flexural strength relationship of NP-based geopolymer mortar

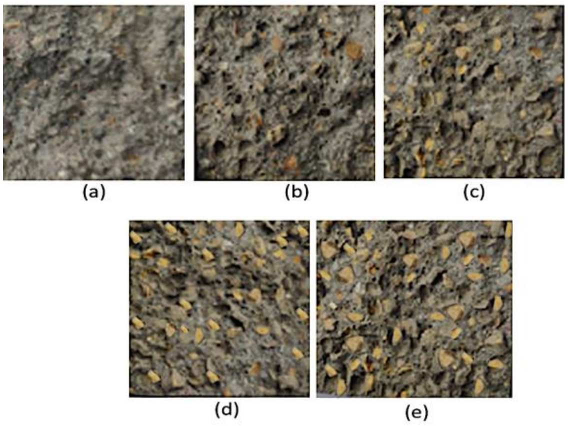

Figure 12. Digital images of the specimens after flexural strength test: 100S:0CC (a); 70S:30CC (b); 50S:50CC (c); 30S:70CC (d); 0S:100CC

The effect of the S:CC ratio on the flexural/compressive strength ratio of NP-based geopolymer mortar is given in Figure 13a. The flexural strength of conventional concrete is approximately 10-15% of its compressive strength (Wang et al., 2023). The flexural/compressive strength ratios calculated in this study were in the same range or higher than conventional concrete. In particular, the flexural/compressive strength ratios (0.17 and 0.19, respectively) of 30S:70CC and 0S:100CC specimens with higher CC contents were higher than the upper limit specified for concrete. This result might be attributed to the high elasticity of the CC aggregate and its fibrous internal structure, which increased its tensile property (Wang et al., 2023). Thus, the toughness of the material with high flexural/compressive strength was also high. As a matter of fact, this finding was also confirmed by the toughness diagram given in Figure 14. In Figure 13b, the correlation between the compressive and flexural strengths of all specimens produced in the study is expressed. Accordingly, the relationship between the compressive and flexural strengths of the NP-based geopolymer mortar was determined according to Equation 3:

$F_c=0.7152(F_f)^2 + 8.3351(F_f)-2.3984$ (Eq. 3)

F_c and F_f symbolize compressive and flexural strengths, respectively. Since the R^2 value in this relation was 98%, there was a high correlation between the compressive and flexural strengths of the specimens.

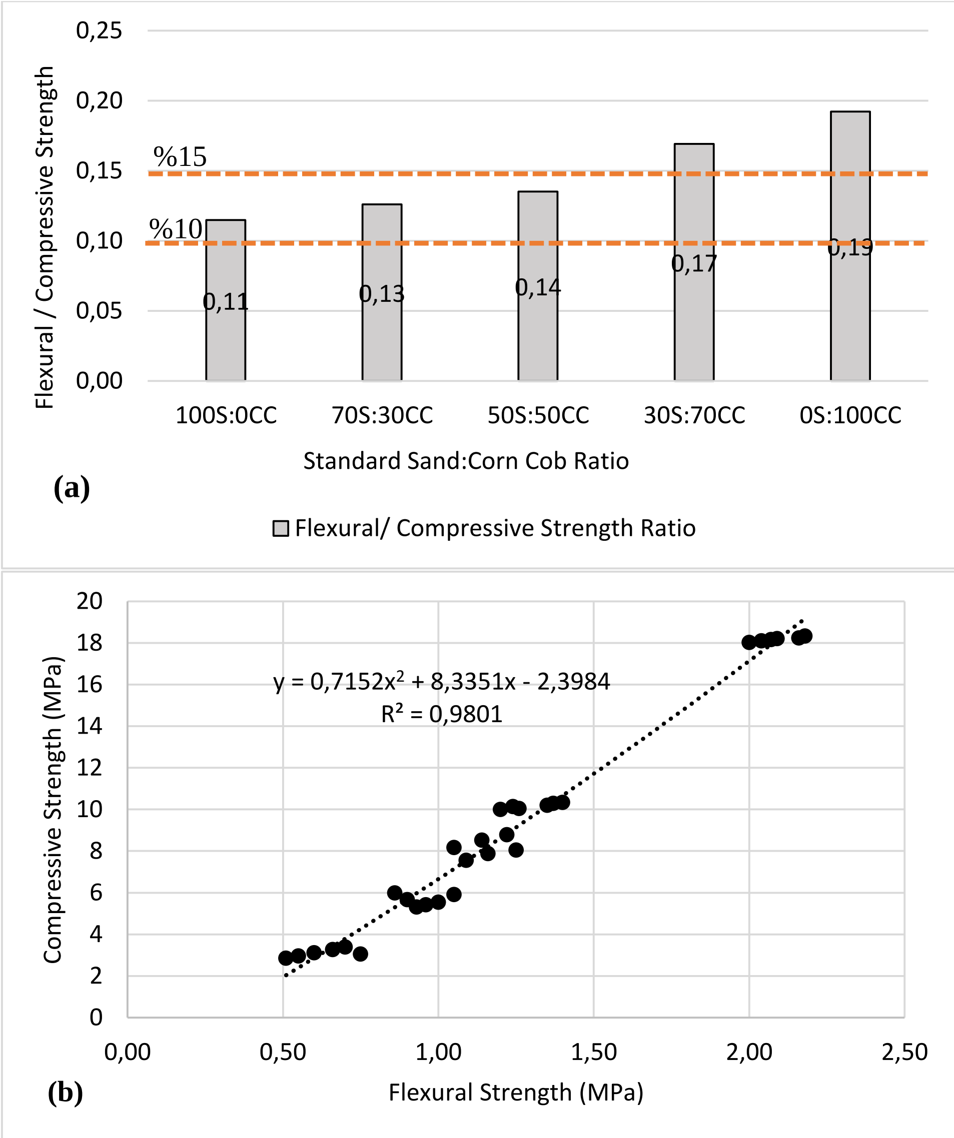

Figure 13. (a) The effect of the S:CC ratio on the flexural/compressive strength ratio of NP-based geopolymer mortar; (b) The correlation between compressive and flexural strength values

Toughness is the area under the stress-strain curve and is a measure of the ability of materials to absorb energy and withstand crack formation during plastic deformation under applied loads. The flexural load-displacement diagram of the NP-based geopolymer mortar is given in Figure 14. The amount of CC significantly affected how the geopolymer mortar was broken. Linear elastic deformation was observed during the initial loading period. As the load was increased, microcracks developed and the curve evolved into nonlinear deformation. The specimen with the highest peak point, i.e., the one that took the highest load, was the control specimen. However, the toughness of these specimens was low, as the area under the load-displacement curve was the lowest. When reaching the maximum load, the curve of the control specimen suddenly dropped, exhibiting a brittle fracture behavior. On the other hand, the fracture behavior of the CC-incorporated specimens was more ductile than that of the control specimen. In contrast to the control mortar, the specimens containing more CC had a higher energy-absorbing capacity (toughness).

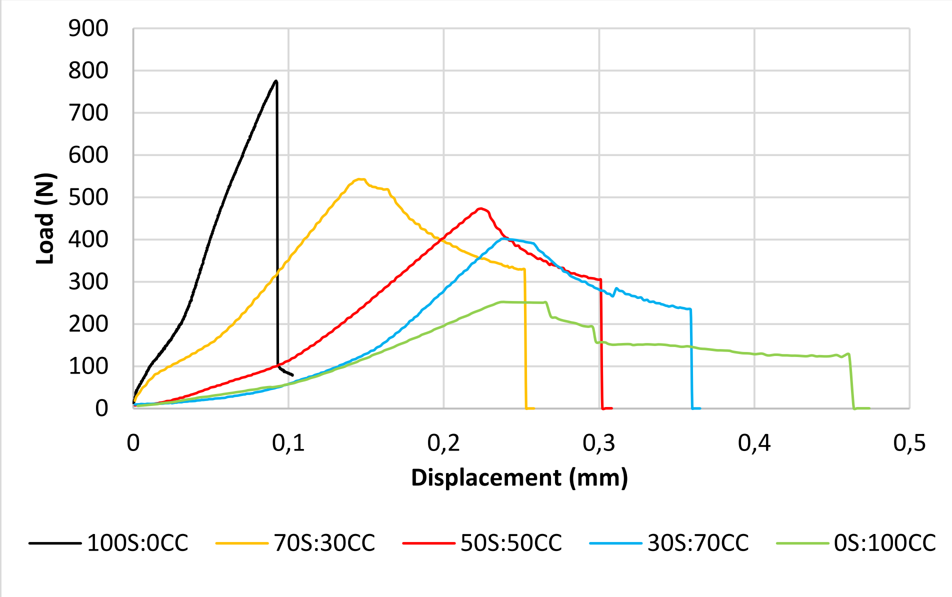

Figure 14. The effect of the S:CC ratio on the flexural load-displacement diagram of NP-based geopolymer mortar

3.5. Using Possibilities of The Produced Geopolymer as A Partition Wall Material

The unit weight, thermal conductivity coefficient, water absorption ratio, and compressive strength values of the NP-based geopolymer mortar were compared with various inorganic partition wall materials used in the construction industry (Table 5). According to this comparison, the unit weight, thermal conductivity coefficient, and water absorption ratio of the control (100S:0CC) and 30% and 50% CC-containing specimens (70S:30CC, 50S:50CC) complied with the requirements of lightweight aggregate concrete, vertically perforated fired clay, and lime-sandstone blocks. The compressive strength of these specimens was higher than that of lightweight aggregate concrete and was in a similar range to that of vertically perforated fired clay and lime-sandstone blocks. The properties of 30S:70CC specimen met the requirements of lightweight aggregate concrete, pumice blocks, and lime-sandstone blocks. The specimen containing 100% CC (0S:100CC), with the lowest unit weight and thermal conductivity coefficient, met the criteria for pumice blocks and aerated autoclaved concrete blocks. As a result of all this evaluation, it is promising that the geopolymer mortar with CC aggregate can serve as an alternative to the traditional partition wall materials widely used in the construction industry. However, the durability performance of the material under various agents should be determined by another experimental research. In addition, the developed mixture should be produced in the nominal size of the traditional inorganic partition wall materials compared here, and the influence of the size on the properties should be investigated.

Table 5. Comparison of NP-based geopolymer mortar properties with conventional partition wall materials

Material	Unit Weight (gr/cm³) (TS 825, 2013)	Thermal Conductivity Coefficient (W/mK) (TS 825, 2013)	Water Absorption Ratio (%)	Compressive Strength (MPa)
Lightweight Aggregate Concrete	0.8-2.0	0.39-1.60	-	1.5-7.5 (TS EN 771-3+A1, 2015)
Pumice Block	0.4-1.3	0.12-0.47	8-35 (Güzel, 1993)	3.0-7.5 (TS EN 771-3+A1, 2015)
Aerated Autoclaved Concrete	0.4-0.8	0.11-0.31	8-18 (Kocataşkın, 2000)	1.5-7.5 (TS EN 12602, 2016)

Fired Clay Brick (Vertically Perforated)		1.2-2.0	0.50-1.40	8-18 (Kocataşkın, 2000)	6-24 (TS EN 771-1+A1, 2015)
Fired Clay Brick (Horizontally Perforated)		0.6-1.0	0.33-0.45	8-18 (Kocataşkın, 2000)	2.5-7.5 (TS EN 771-1+A1, 2015)
Lime- Sandstone Block		0.7-2.2	0.35-1.30	-	5-30 (TS EN 771-2+A1, 2015)
The Current Research	100S:0CC	1.95	0.96	7.14	18.21
	70S:30CC	1.70	0.75	8.12	10.16
	50S:50CC	1.45	0.50	9.26	8.43
	30S:70CC	1.12	0.39	11.65	5.67
	0S:100CC	0.70	0.28	13.01	3.12

4. Conclusion and Suggestions

The conclusions from this research are as follows:

- Nevşehir Pozzolan (NP) as a waste material produced during the extraction and cutting of volcanic stones is a suitable source of aluminosilicate for the production of geopolymer mortar.
- By optimizing important parameters such as activator type and ratio, concentration, and aggregate mixing ratio, geopolymer mortar with a flexural strength of 2.09 MPa and compressive strength of 18.21 MPa can be produced.
- The optimum alkali activator type, NaOH concentration, and activator ratio for NP-based geopolymer mortar are SS + NaOH, 10 M, and 2.0, respectively, because they allow the production of geopolymers with the highest mechanical properties.
- NP-based geopolymer mortar is also suitable for production with corn cob (CC) aggregate, which is an agricultural waste. Thus, new building material is developed by using two different wastes together in this research. The effectiveness of the S:CC aggregate ratio on the physical, thermal, and mechanical properties of NP-based geopolymer mortar is so important that it cannot be ignored.
- Geopolymer materials containing 30% and 50% CC meet the performance requirements of lightweight aggregate concrete, vertically perforated fired clay brick, and lime-sandstone block, which are widely used as partition wall materials in the construction industry. Geopolymer material containing 70% CC meets the criteria for lightweight aggregate concrete, pumice block, and lime-sandstone block, and 100% CC meets the requirements for pumice block and aerated autoclaved concrete. Therefore, it is possible to produce a geopolymer material with desired purposes and properties, by changing the CC ratio, as an alternative to traditional partition wall materials. However, the size effect on the properties should be investigated in another research by producing the nominal dimensions of traditional wall materials.
- The durability of the developed NP-based geopolymer material during the usage period should be determined by further research.

Acknowledgements and Information Note

The article complies with national and international research and publication ethics. Ethics Committee approval was not required for the study.

Author Contribution and Conflict of Interest Declaration Information

The article has a single author and there is no conflict of interest.

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