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Research Article

One-part alkali-activated mortars based on clay brick waste, natural pozzolan waste, and marble powder waste

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ABSTRACT

In Türkiye, waste clay bricks (WCB) comprise significant construction and demolition waste. Most research is based on producing WCB-based two-part alkali-activated materials (AAM). Compared to their conventional, two-part alkali-activated counterparts, one-part AAM offers several advantages, such as being more practical, safe, and easy to use. Thus, they may be an excellent choice for commercial construction applications and on-site casting. However, research data on producing WCB-based one-part alkali-activated mortars is limited. The relatively low reactivity of WCB can be increased by replacing WCB with ground granulated blast-furnace slag (GGBS) and fly ash (FA). Unlike these by-products, Nevşehir pozzolan (NP) and marble powder (MP), which are produced as wastes during the stone-cutting process, may be evaluated to produce AAM. This study aims to assess the production possibilities of WCB-based one-part alkali-activated mortar, determine the optimum substitution ratios with NP and MP to improve the mechanical properties, and determine the effects of the curing period up to 365 days. Results showed that the optimum NP substitution ratio was 50%, which increased reaction development, microstructure compactness, and mechanical properties. The highest CS (UV) (3.70 km/s) and compressive strength (CS) (21.58 MPa) were obtained in 25WCB:75MP-containing samples. The increase in properties with the curing period was especially high in the first 28 days.

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1. INTRODUCTION

AAM are energy- and resource-efficient alternatives to traditional Portland cement. The reaction of amorphous alumina and silica-rich solid aluminosilicate sources with high alkali activators produces these binders. The alkali activator ensures the solid raw material's dissolution by increasing the reaction medium's pH. The dissolved components were rearranged and then condensed by polycondensation, forming a three-dimensional amorphous aluminosilicate network structure [1]. Industrial by-products such as FA, GGBS, and silica fume (SF) are often used as aluminosilicate precursors to produce AAM. However, while the continuous supply of these by-products is relatively easy in some countries, it remains limited in others [2]. Therefore, research identifying alternative sources of raw materials to produce the AAM is essential.

During the production of fired clay-based bricks and tiles, which are frequently used in the construction industry, the calcination process occurs at 850–950 °C. At these high calcination temperatures, the bound water in the clay minerals evaporates, the crystalline structure of clay col-

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lapses, and irregular amorphous SiO_2 and Al_2O_3 phases are formed [3], which ensures its reactivity [4]. Furthermore, the existence of these amorphous phases in the structure of WCB makes it a low-cost and environmentally friendly alternative aluminosilicate precursor [2]. The material is of most interest because of the abundant availability of WCB and 25–93 MPa strength [5]. A large number of WCB is produced every year on a global scale, both during brick production and construction and demolition activities. With the Transformation of Areas Under Disaster Risk in Türkiye coming into force, the increase in urban transformation practices has further increased the amount of WCB. The majority of WCB is stored in landfills. However, according to the Regulation on the Control of Excavation Soil, Construction, and Demolition Waste, these wastes should be recycled and reused as structure and building materials [6]. Using WCB in AAM is an environmentally and economically viable option as it provides a solution to solid waste management and reduces the carbon footprint in the construction sector [2].

In the research on activating WCB with a mixture of sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3=SS), Komnitsas et al. [7] investigated the effect of particle size, NaOH molarity (8–14 M), and different curing temperatures (60–90 °C). The highest CS (49.5 MPa) was determined in samples activated with 8 M NaOH and cured at 90 °C. Rakhimova and Rakhimov [8] mixed GGBS and WCB in different proportions (0:100, 20:80, 40:60, 60:40, 80:20, 100:0, by wt.) and activated them with SS or sodium carbonate (SC). The CS of the binder containing only GGBS was 97 MPa for the SS-activated binder and 61 MPa for the SC-activated binder. The CS of the sample with a GGBS: WCB ratio of 60:40 was determined to be the highest (120 MPa). In another study, Zawrah et al. [9] replaced GGBS with WCB at 20%, 40%, 60%, and 80% percentages. They found that a 60% replacement ratio gave the highest CS (64 and 83 MPa at the 7th and 90th days, respectively). The positive effects of using GGBS and WCB together were parallel with the results of Rakhimova and Rakhimov [8].

The potential to produce AAM from a combination of FA and WCB was assessed by Rovnanik et al. [10]. FA: WCB was used in the ratios of 4:0, 3:1, 1:1, and 0:4 by wt. The samples were cured for 7, 28, and 90 days under environmental conditions of 21 °C and 50% RH. According to the study results, samples containing FA and WCB had lower CS than those based only on FA. This result contradicted the findings of Rakhimova et al. [8] and Zawrah et al. [9]. Tuyan et al. [11] studied the influence of alkali activator concentration and curing conditions on the properties of WCB-based AAM. The optimum activator concentration was determined as a SiO_2/Na_2O ratio of 1.6 and a Na_2O ratio of 10%. The maximum CS of 36.2 MPa was reached after 5 days of curing at 90 °C and 40% RH. Increasing the Na_2O ratio from 4% to 10% enhanced the CS by increasing the alkalinity of the mixture and allowing more Si^{4+} and Al^{3+} ions to dissolve. Silva et al. [12] conducted an experimental study in which WCB and natural pozzolan were activated with a combination of NaOH and SS. The optimum alkali activator ratio was 0.60, the Na_2O ratio was 8%, and the water/binder ratio was 0.27. It was determined that a 7-day curing period between 65 and 80 °C resulted in the highest mechanical properties. The 7-day CS of WCB and natural pozzolan-based materials was determined to be 37 and 26 MPa, respectively. Ulugöl et al. [13] reported the effects of different curing temperatures (50–125 °C), curing periods (24–72 h), and NaOH concentrations (10–15%) on the properties of AAM produced from brick, tile, and glass-based construction and demolition waste. Using WCB and 12% NaOH, a CS of more than 45 MPa was achieved after a 24-hour curing period at 115 °C. The larger particle sizes in the glass explained the lower CS of glass-based materials. Another study [14] produced AAM by replacing NaOH-activated GGBS with 10–50% WCB. As the WCB ratio in the mixture increased, the mechanical properties decreased. However, the CS of the samples with a 10–50% WCB ratio (approximately 25–45 MPa) was sufficient and acceptable for many applications.

In recent years, Pommer et al. [15] determined that decreasing the particle size of the WCB resulted in an increased geopolymerization rate and improved mechanical properties. On the other hand, the coarser particles led to an increase in porosity, which influenced the physical properties of the AAM. As a precursor, WCB was substituted for FA by Liang et al. [16], who found pastes containing WCB set faster than the reference paste. The energy used to produce AAM decreased with the addition of WCB. Compared to a reference sample, the total energy savings of the 40 wt% WCB-containing sample were approximately 55%. The effects of alkali activator concentration (8–12 M), alkali solution ratio (1.5–2.5), and curing temperatures (40–60 °C) on the mechanical and durability properties of WCB-based geopolymer bricks were researched by Maaze et al. [17]. The results showed that the optimum molarity, alkali solution ratio, and curing temperature were 10 M, 2.5, and 60 °C, respectively. The samples were considered suitable for high-temperature use because of their thermal stability. Their CS reduced only 3.1–5.8% after exposure to 400 °C and 7.1–8% after exposure to 1000 °C. In another study, Roy et al. [18] replaced GGBS with WCB at 5%, 10%, 15%, and 20% ratios. They found that a 10% replacement ratio with a 6 M alkali concentration gave the maximum CS of 27 MPa. Wang et al. [19] produced an eco-friendly engineered geopolymer composite by using GGBS, FA, and WCB precursors. Three WCB proportions of 20%, 50%, and 80% were used in the precursors. 18 mm polyethylene fibers were included in the samples to increase the ductility. 80% WCB incorporation resulted in the highest values of CS (approximately 50 MPa), tensile strength (higher than 4 MPa), and tensile ductility (4%). Furthermore, 80% WCB incorporation decreased the material's embodied energy, carbon, and cost by 40%, 30%, and 30%, respectively. In another research project conducted by Borçato et al. [20], 25%, 50%, and 75% of the metakaolin (MK) were replaced by WCB. 5% calcium hydroxide was incorporated in some samples because the CaO content of MK and WCB is low. Calcium hydroxide increased the CS from 12.3 MPa to 31.6 MPa on the 28th day. This increasing trend of CS originated

Table 1. Chemical composition of the raw materials (WCB, NP, and MP) by X-ray fluorescence spectroscopy

Oxide content (% wt.)	Raw materials		
	WCB	NP	MP
SiO_2	61.11	77.29	0.22
Al_2O_3	14.05	18.48	0.10
Fe_2O_3	6.11	1.71	–
CaO	8.76	0.33	55.70
MgO	1.72	1.29	0.21
K_2O	2.24	0.30	–
SO_3	0.21	0.10	–
Loss on ignition	5.80	0.50	43.77
Sum of SiO_2, Al_2O_3, and Fe_2O_3 necessary for alkali activation (>70%)	81.27	97.48	0.32

WCB: Waste clay bricks; NP: Nevşehir pozzolan; MP: Marble powder.

from the coexistence of C-A-S-H gel and N-A-S-H gel in the AAM structure. In addition, the CS was higher in the samples with higher WCB content.

Literature data show that WCB enables the production of AAM. In the studies mentioned above, the alkali activator is used in solution (in two parts). Aqueous alkali activators producing conventional two-part AAM are highly corrosive, viscous, and hazardous. Therefore, their use on an industrial scale can be problematic. In contrast, one-part AAM is produced by adding solid alkali activators to the aluminosilicate precursor. Similar to Portland cement, these binders require mixing with water before use. Therefore, using a one-part AAM is more practical and user-friendly than a conventional AAM [21]. However, research data on the production of WCB-based one-part AAM are limited. In addition, it is known that only WCB-based AAM may have poor mechanical properties because WCB has a relatively low pozzolanic activity [8, 10]. Migunthanna et al. [21] studied the production possibilities of a WCB-based one-part AAM. WCB was mixed with FA or GGBS at 20%, 40%, 60%, and 80% wt to obtain higher mechanical properties. The mechanical properties of WCB+GGBS-based samples were higher than those of WCB-based and WCB+FA-based samples. The highest CS (81.8 MPa) was obtained from 40% WCB and 60% GGBS.

In research on the production of both one-part and two-part AAM, WCB is replaced with industrial by-products such as FA and GGBS to improve the relatively low reactivity of WCB and produce materials with higher mechanical properties. Unlike these by-products, both Nevşehir natural pozzolan (NP) of Türkiye and marble powder (MP), which are made wastes during the sunstone-cutting cess, may be used in M. Therefore, this research aims to (i) evaluate the production possibilities of WCB-based one-part alkali-activated mortar; (ii) determine the optimum substitution ratios with NP and MP wastes to improve the mechanical properties of the mortar; and (iii) determine the effects of the curing time, both in the early period and up to 365 days, on the properties of the mortar.

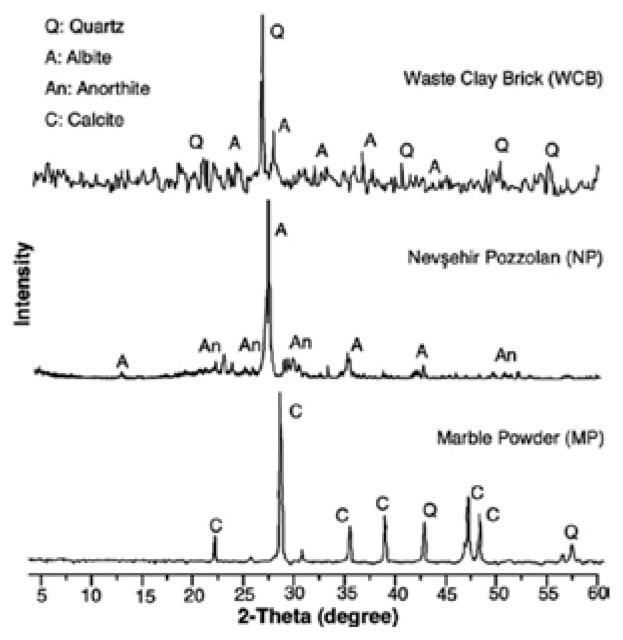

Figure 1. Mineralogical composition of the raw materials (WCB, NP, and MP) by X-ray diffraction (XRD) analysis.

WCB: Waste clay bricks; NP: Nevşehir pozzolan; MP: Marble powder.

2. METHODS

2.1. Raw Materials

WCB, an urban transformation waste, was the aluminosilicate precursor for producing one-part alkali-activated mortar. WCB, with a specific gravity of 2.40, was first broken into small pieces and then dried in an oven at 90 °C for 48 hours until it reached a constant weight. Then, it was ground in a ball mill to a maximum particle size of 90 µm. The mineralogical composition of WCB consists of kaolinite, muscovite, quartz, gypsum, and carbonates. Calcination is applied at 850–950 °C for the production of bricks. While kaolinite and gypsum disappear at these calcination temperatures, quartz and muscovite continue to exist in the structure in a stable state [2]. The mineralogical composition of the raw materials was determined by X-ray diffraction (XRD) analysis using a Shimadzu XRD-6000 energy dispersive diffractometer (Fig. 1). According to the XRD analysis, the main mineralogical composition of WCB consisted of quartz and albite.

The chemical composition of the raw materials was obtained by X-ray fluorescence spectroscopy using a Philips 71 PW-2404 Spectrometer (Table 1). WCB had a high content of SiO_2 (61.11%), as well as 14.05% Al_2O_3. During the calcination stage of the clay, the bound water in the clay minerals evaporates, the crystalline structure of the clay breaks down, and irregular amorphous phases of SiO_2 and Al_2O_3 are formed [22]. These amorphous phases increase the pozzolanic activity of the material [23]. The flexural and compressive strength results (1.12 MPa and 4.56 MPa, respectively) from the pozzolanic activity test carried out according to TS 25 [24] showed that WCB has pozzolanic activity.

Figure 2. Raw materials of the study: **(a)** WCB; **(b)** NP; **(c)** MP; **(d)** NaOH; **(e)** SS; **(f)** SK.

WCB: Waste clay bricks; NP: Nevşehir pozzolan; MP: Marble powder; SS: Sodium silicate; SK: Standart Sand.

Table 2. Mix design for WCB-based one-part alkali-activated mortars

Sample code	WCB (g)	NP (g)	MP (g)	SK (g)	NaOH (g)	SS (g)	Alkali activator: aluminosilicate precursor (wt.%)	NaOH: SS (wt.%)	Binder: SK (wt.%)	Water: binder (wt.%)
100WCB	400	–	–	1200	33.6	66.6	1:4	1:2	1:3	0.65: 1
75WCB:25NP	300	100	–							
50WCB:50NP	200	200	–							
25WCB:75NP	100	300	–							
75WCB:25MP	300	–	100							
50WCB:50MP	200	–	200							
25WCB:75MP	100	–	300							

WCB: Waste clay bricks; NP: Nevşehir pozzolan; MP: Marble powder; SS: Sodium silicate; SK: Standart sand.

WCB (Fig. 2a) was substituted by two various natural stone wastes with low- and high-calcium contents to prevent strength losses due to the relatively low reactivity of WCB in environmental conditions and to produce mortar with higher mechanical properties. NP (Fig. 2b) was waste obtained from the waste storage area of a volcanic quarry in the Cappadocia Region (Nevşehir) of Türkiye. The specific gravity of NP was 2.55, the maximum particle size was 90 µm, and the specific surface area determined according to TS EN 196–6 [25] was 7648 cm^2/g. As shown in Table 1, the sum of SiO_2, Al_2O_3, and Fe_2O_3 contents was more than 70%, revealing that NP could satisfy the chemical requirements for its use in alkali activation. In addition, NP was a low-calcium source because its CaO content (0.33%) was less than 10%. Albite and anorthite, found in NP (Fig. 1), were additional indicators of its pozzolanic activity. Following the pozzolanic activity test [24], NP exhibited pozzolanic activity, as shown by its flexural and compressive strength results (1.86 and 6.81 MPa, respectively).

MP was supplied from a marble-cutting factory in Izmit (Fig. 2c). The bright white MP was dried in an oven at 90 °C for 48 h until it reached a constant weight. Then, it was ground in a ball mill to a maximum particle size of 90 µm. With 55.7% CaO content, MP was a high-calcium source. The mineralogical composition of MP mainly consisted of calcite and a small amount of quartz (Fig. 1).

In the production of AAM, an alkali activator should be used to increase the pH of the reaction medium to ensure the dissolution of the aluminosilicate precursor and the development of subsequent polycondensation reactions [26]. As alkali activators, solid sodium hydroxide (NaOH) with 98% purity (Fig. 2d) and anhydrous sodium metasilicate (Na_2SiO_3=SS) with 50–52% SiO_2 and 50–48% Na_2O ratios (Fig. 2e) were supplied by Sigma-Aldrich. Standard sand

(SK) with a specific gravity of 2.58 and a maximum particle size of 2 mm (Fig. 2f) in compliance with TS EN 196-1 [27] was used as the aggregate.

2.2. Mixing Ratios

The mixture produced only from WCB (100WCB) was accepted as the reference sample. The study attempted to determine the optimum NP and MP substitution ratios to increase the mechanical properties of WCB-based one-part alkali-activated mortar. In this context, the amount of WCB was gradually replaced by NP or MP in proportions of 25%, 50%, and 75% wt. The total alkali activator: aluminosilicate precursor, NaOH: SS, and binder: SK ratios remained constant at 1:4, 1:2, and 1:3, by wt., respectively (Table 2). No chemical additives were used in the mixtures to prevent possible interactions with the alkali solution.

The optimum water: binder ratio that allows producing a workable mortar was determined through trials during the preliminary testing process. The optimum water: binder ratio of WCB-based two-part alkali-activated mortars should be 0.4–0.5 [28, 29], and lower water: binder ratio causes low workability [30]. However, in this study, the optimum water: binder ratio that ensures the workability of WCB-based one-part alkali-activated mortar was determined to be 0.65:1. It is possible that the increased water needs results from solid-state alkali activators, which raise mixing temperatures as soon as they come into contact with water and continue to do so throughout the dissolution process. The resulting heat caused a more significant amount of water to evaporate during mixing, thereby increasing the need for mixing water. On the other hand, in two-part alkali-activated mortars, mixing alkali activators with water for 24 hours before adding them to the mixture does not cause an increase in temperature, so there is no need for more water during mixing.

2.3. Production and Curing Conditions

WCB, NP/MP, solid alkali activators (NaOH and SS), and SK were mixed in dry form for 3 min using the one-part mixing method (Fig. 3a). Then, deionized water was gradually incorporated into the mixture and mixed for another 5 min (Fig. 3b). The fresh mixture was placed into two layers in prismatic molds measuring 40x40x160 mm (Fig. 3c). After half of the mixture was slowly poured into the mold, mechanical vibration was applied for 30 seconds to eliminate air bubbles and ensure complete settling into the mold. Then, the remaining mixture was poured into the mold, and vibration was applied again. The polyethylene-coated samples were kept in the mold at 23 °C for 24 h. The samples removed from the molds after 24 h were cured under ambient conditions of 23 °C and 55% RH for 7, 28, 90, 180, and 365 days (Fig. 3d).

2.4. Experimental Process

A dynamic UV test was applied to the samples by TS EN 14579 [31]. The UV (in km/s) is calculated using the following Eq. (1):

$$UV = l / t \quad (1)$$

Where (l) is the length of the sample and (t) is the time the pulse takes to transverse that length.

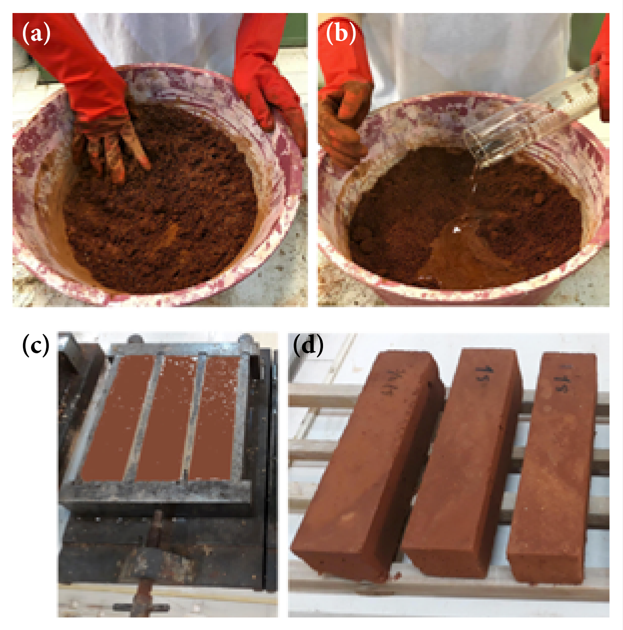

Figure 3. Production stages of WCB-based one-part alkali-activated mortars: **(a)** mixing of dry raw materials; **(b)** incorporation of deionized water to the dry mixture; **(c)** molding the fresh mixture; **(d)** curing the samples under ambient conditions of 23 °C and 55% RH up to 365 days.
WCB: Waste clay bricks.

The CS test was performed using an MFL 100 kN machine at a constant speed of 0.5 N/mm^2 according to TS EN 196-1 [27]. The CS (in MPa) was calculated using the following Eq. (2):

$$CS = F_c / A \quad (2)$$

Where (Fc) is the maximum load at fracture (in N), and (A) is the cross-section of the area of the sample resisting the load (in mm^2).

In an experiment with N measurements, one or more may deviate significantly from the others. These "bad data" may be easily discarded if an error in the experimental procedure or an unrelated effect can be found. A statistical criterion should be applied to determine which results can be rejected. Chauvenet's Criterion is an approach that establishes an acceptable statistical scattering about the mean value of a given sample of "N" measurements. According to the Criterion, every data point that falls in a range around the mean representing a probability of 1-1/(2N) ought to be kept. Data points may be rejected when the data point's deviation from the mean is smaller than 1/(2N) [32]. The current study conducted six measurements using UV and CS tests. The arithmetic means, and standard deviations of the first results were calculated. Then, "Chauvenet's Criterion table" was considered to determine whether any data point should be rejected. According to Chauvenet's Criterion for eliminating a data point, the maximum acceptable deviation was 1.73 for six measurements. All measurement results that deviate more than this value (1.73) were eliminated. Afterward, the arithmetic mean of the remaining results was calculated again [33] and declared the "test result."

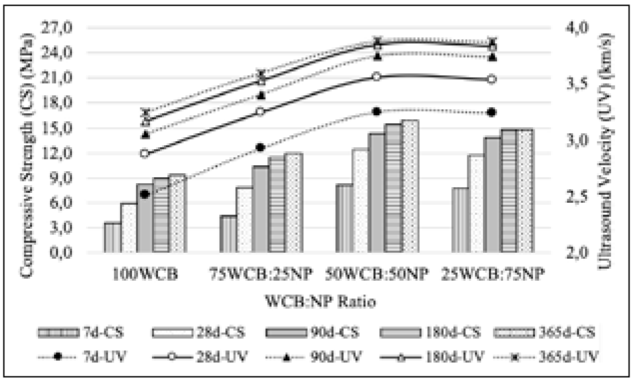

Figure 4. Effect of the WCB: NP ratio on the UV and CS of the samples.

WCB: Waste clay bricks; NP: Nevşehir pozzolan; UV: Ultrasound velocity; CS: Compressive strength.

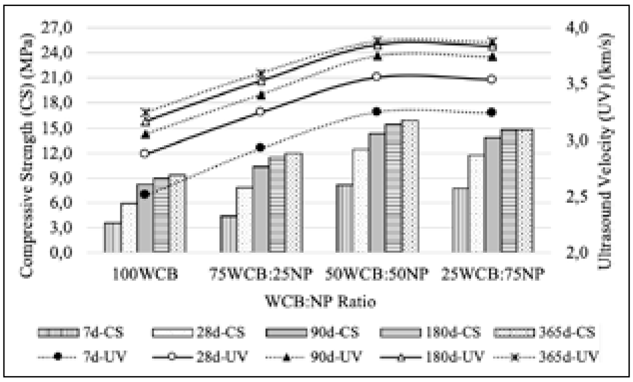

Figure 5. Effect of the WCB: MP ratio on the UV and CS of the samples.

3. RESULTS AND DISCUSSION

3.1. Effect of Mixing Ratios on Mechanical Properties

The effects of the change in the WCB: NP ratio on the UV and CS of the samples are shown in Figure 4.

The reference sample's 7- and 28-day UVs (100WCB) were 2.51 and 2.88 km/s, and the CSs were 3.61 and 5.92 MPa, respectively. The mechanical properties increased as the curing period increased. However, the effect of the long-term curing period on the properties was discussed in the next section. The lower CS of the reference sample at 7 and 28 days revealed that the reference sample was not sufficient to provide high strength when cured at room temperature. Similar to this finding, Migunthanna et al. [21] found the 7- and 28-day CSs of WCB-based mortar activated with only solid SS to be 3.3 and 5.4 MPa, respectively. Although the same aluminosilicate precursor (WCB) type was used, the CS was lower than the values obtained in this study. This may be due to the use of NaOH in addition to SS as an alkali activator. Similarly, Zawrah et al. [9], Tuyan et al. [11], and Robayo-Salazar et al. [34] found that WCB-based two-part alkali-activated mortars activated with SS and NaOH had low CS in the early period under ambient conditions. Because of the low degree of reaction of WCB under ambient conditions [11], the limitations in mechanical properties may be addressed by increasing the curing temperature [12]. However, in this study, only ambient curing was applied, considering that curing at high temperatures increases energy consumption in the production process.

By adding NP to the reference sample, enhanced mechanical properties were obtained in the early period. According to Figure 4, due to substituting WCB with 25% NP, the 7- and 28-day UVs increased to 1.17 and 1.13 times their original value, and the CSs increased to 1.21 and 1.33 times their original value, respectively. The highest mechanical properties were achieved at 50% NP substitution. The 7- and 28-day UVs of the 50WCB:50NP sample increased by 1.29 and 1.23 times compared to the reference sample, reaching 3.25 and 3.56 km/s, respectively. The same samples' 7- and 28-day CS increased by 2.27 and 2.10 times, reaching 8.21 and 12.43 MPa, respectively. For alkali activation to occur to a high degree, the SiO_2, Al_2O_3, Fe_2O_3, and CaO content in the reaction medium must be sufficient. In particular, SiO_2 and Al_2O_3 are primary components that affect the formation of the three-dimensional amorphous network. Mixtures containing high amounts of amorphous SiO_2 and Al_2O_3 allow relatively higher mechanical properties because of the more complete alkali activation reactions consisting of three stages (dissolution, rearrangement, and polycondensation) [35]. The NP's total SiO_2 and Al_2O_3 content (95.77%) was higher than that of the WCB (75.16%). This means that when NP was added to the mixture, it increased the amounts of reactive components and made it easier for the reactions to progress. Thus, higher mechanical properties were achieved. On the other hand, the effect of increasing the NP ratio by more than 50% on strength development was negligible. Similarly, in the literature, when the FA content was more than 40% in WCB+FA-based one-part alkali-activated mortars [21] and more than 50% in two-part alkali-activated mortars [10], the strengths did not increase. Considering that NP has chemical composition properties similar to FA, these results are consistent with the findings of this study.

The effects of the change in the WCB: MP ratio on the UV and CS of the samples are shown in Figure 5.

Adding MP to the reference sample obtained the highest mechanical properties early. As a result of substituting WCB with 25% MP, the 7- and 28-day UVs increased by 1.24 and 1.16 times, and the CSs increased by 2.49 and 2.33 times, respectively. Gradually increasing the MP ratio to 50% and 75% increased mechanical properties. The highest mechanical properties were detected in the 25WCB:75MP sample. This sample's 7- and 28-day UVs increased by 1.37 and 1.28 times, compared with the reference sample's, reaching 3.44 and 3.70 km/s, respectively. The same sample's 7- and 28-day CSs increased by 4.12 and 3.64 times, reaching 14.88 and 21.58 MPa, respectively. In addition, the mechanical properties of WCB+MP-based samples were higher than those of WCB+NP-based samples at the same curing period. This result might be due to the high calcium-containing components in the MP. As shown in Table 1, WCB and NP contain only 8.76% and 0.33% CaO, respectively. MP, which includes 55.7% CaO, is a calcium-rich raw material. A three-dimensional amorphous sodium aluminosilicate hydrate (N-A-S-H) gel forms during alkali activation [1], and this gel gives the mortar its main properties. In this study, the SiO_2 and Al_2O_3 components required for forming

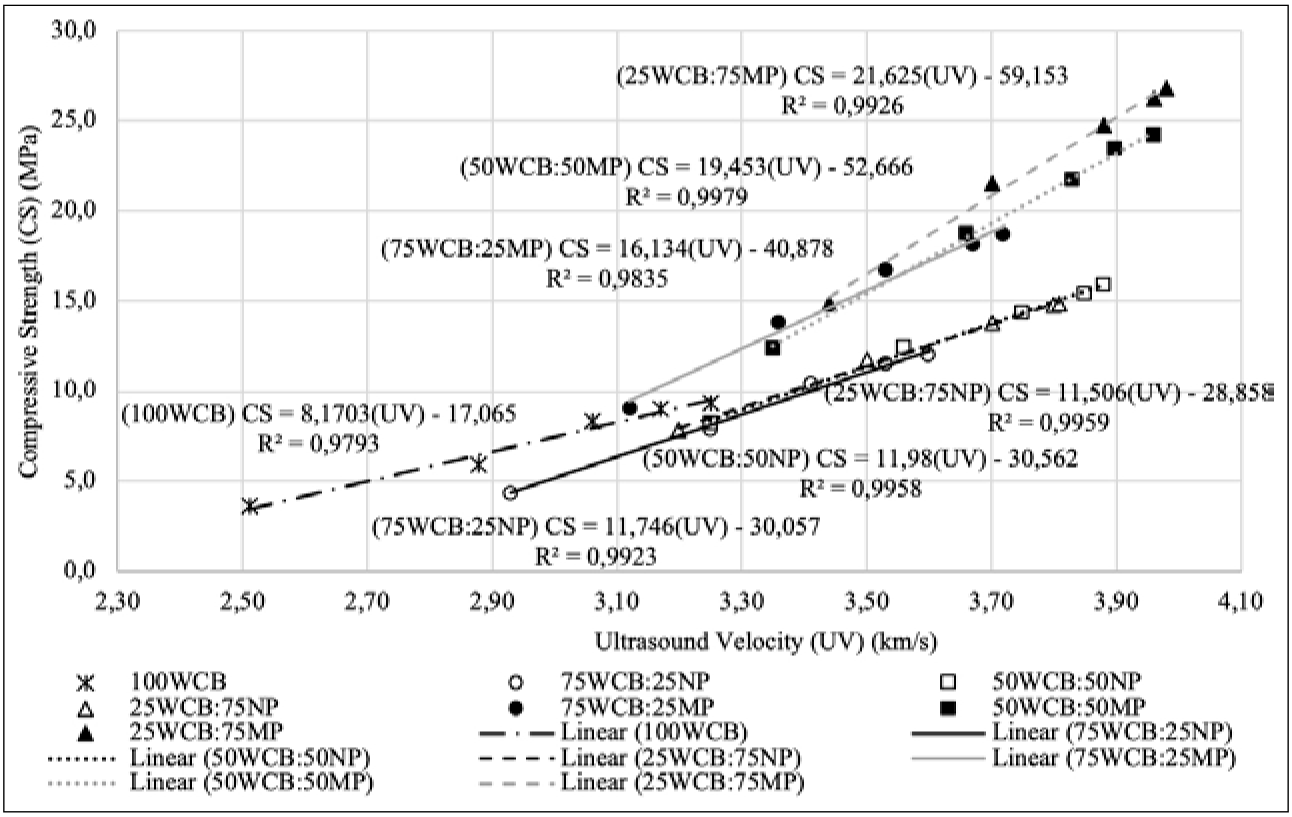

Figure 6. CS of WCB-based one-part alkali-activated mortars as a function of UV.

WCB: Waste clay bricks; NP: Nevşehir pozzolan; UV: Ultrasound velocity; CS: Compressive strength.

the N-A-S-H gel in WCB+MP-based samples were primarily supplied by WCB. During the polycondensation process, when calcium-rich components from MP were added to the reaction medium, $Na+$ ions in the N-A-S-H gel and dissolved Ca^{+2} ions were replaced, and a solid (N, C)-A-S-H gel was formed. In addition, a calcium silicate hydrate (C-S-H) gel was formed, similar to that in Portland cement. The coexistence of these gels within the aluminosilicate network resulted in higher strength development [9, 36, 37].

By measuring the UV of a material, the early reaction stages, the microstructure development, improvement of rheological properties, setting, hardening, strength development, and even durability properties can be successfully determined [38–40]. It is possible to state that materials with higher UV have a more compact microstructure, as no gaps, cracks, or damage would prevent sound from propagating through the material [41]. A more compact microstructure allows the production of materials with higher mechanical properties. Therefore, regardless of the curing period, the CS-UV relationship of the samples is shown in Figure 6. The lowest CS was determined in the reference sample, whereas the highest was in the 25WCB:75MP sample. All samples showed a similar trend in terms of the CS-UV relationship. The CS changed in direct proportion to the UV. Because the regression lines' correlation coefficients (R^2) were in the range of 0.97–0.99, the relationship between CS and UV was strong, indicating that CS of the one-part alkali-activated mortars could be estimated through UV. The Eq. (3) below represented the linear relationship between CS and UV:

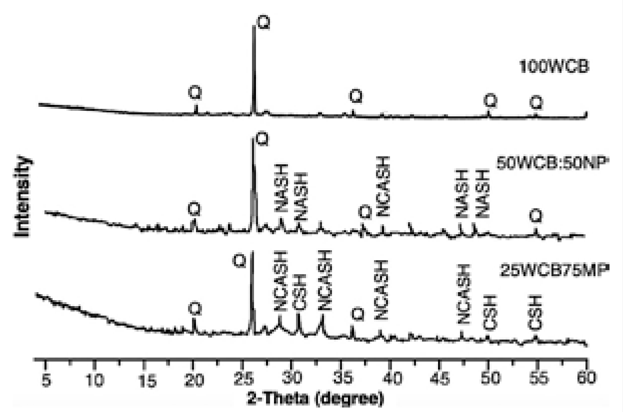

Figure 7. XRD results of one-part alkali-activated mortars.

XRD: X-Ray diffraction.

$$CS=a\ x\ UV+b \tag{3}$$

The slope of the regression lines is referred to as the value "a."

The CS-UV relationship of the samples at each mixture ratio was expressed according to the following Eqs. (4–10):

$$(100WCB)\ CS=8.17\ x\ UV-17.06 \tag{4}$$

$$(75WCB{:}25NP)\ CS=11.74\ x\ UV-30.05 \tag{5}$$

$$(50WCB{:}50NP)\ CS=11.98\ x\ UV-30.56 \tag{6}$$

$$(25WCB{:}75NP)\ CS=11.50\ x\ UV-28.85 \tag{7}$$

$$(75WCB{:}25MP)\ CS=16.13\ x\ UV-40.87 \tag{8}$$

$$(50WCB{:}50MP)\ CS=19.45\ x\ UV-52.66 \tag{9}$$

$$(25WCB{:}75MP)\ CS=21.62\ x\ UV-59.15 \tag{10}$$

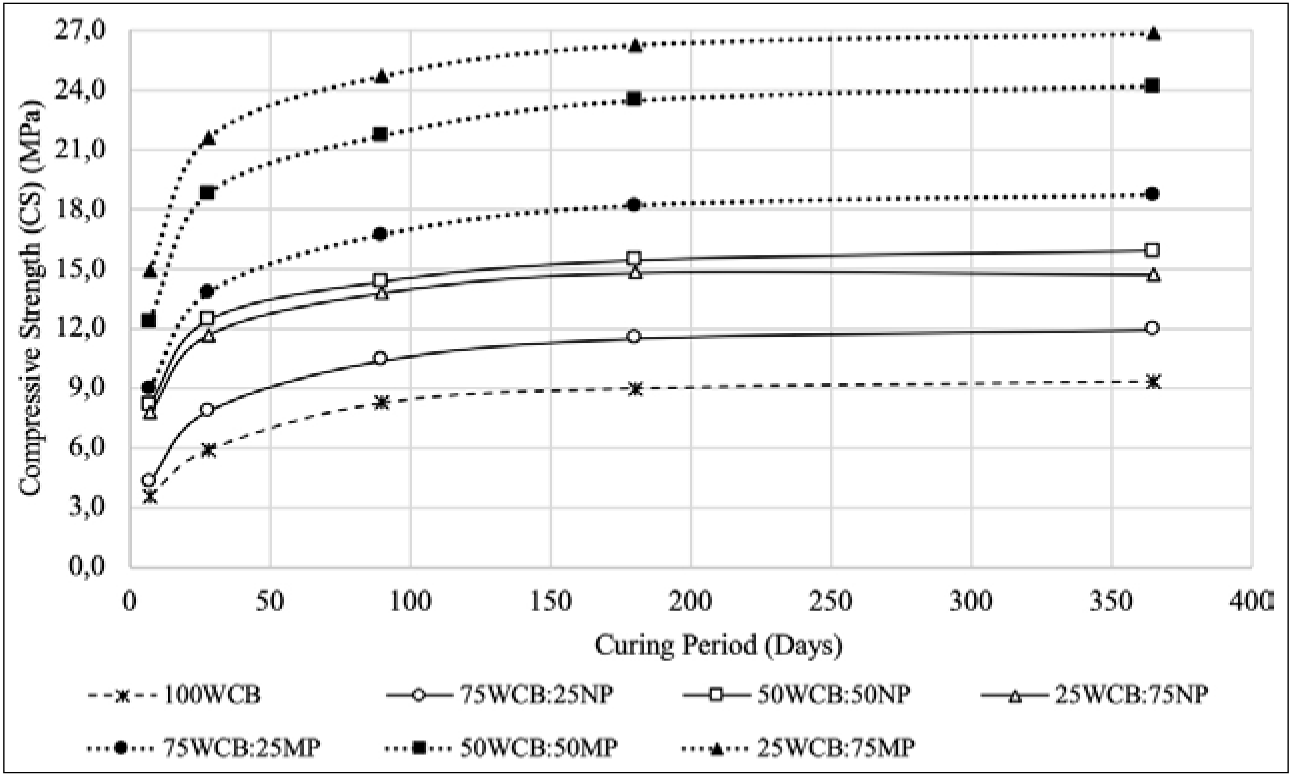

Figure 8. Effects of the curing period on the CS of the samples.

WCB: Waste clay bricks; NP: Nevşehir pozzolan; UV: Ultrasound velocity; CS: Compressive strength.

3.2. Effect of Mixing Ratios on Mineralogical Properties

Figure 7 shows the XRD results of the reference sample and the samples containing NP/MP with the highest mechanical properties (50WCB:50NP and 25WCB:75MP) after ambient curing for 28 days. Quartz mineral (Q) was the main crystalline phase in the reference sample. After alkali activation reactions, no new phase formation was observed. This might be because WCB had a relatively low reactivity, i.e., a low amorphous character, and the reactions could not develop sufficiently under ambient conditions. The low amorphous character of WCB was due to the bricks being allowed to cool slowly after calcination [11]. This finding obtained from the XRD analysis was parallel to the low mechanical properties exhibited by the reference sample after a 28-day curing period under ambient conditions.

The XRD pattern of geopolymer mortars containing various amounts of NP and MP had a similar XRD pattern to the reference sample; however, new amorphous and semi-crystalline phases were present. After the alkali activation of 50WCB:50NP, a mixture high in SiO_2 and Al_2O_3 formed an alkali three-dimensional amorphous aluminosilicate (N-A-S-H) gel called geopolymer gel. In addition, a sodium calcium aluminosilicate hydrate ((N, C)-A-S-H) phase at $2\theta=39.8°$ was present in the mortar. These newly formed gel types provide a better-developed internal structure and, therefore, higher mechanical properties than the reference sample. On the other hand, hydration products in the 25WCB:75MP sample are composed of semi-crystalline phases of calcium silicate hydrate (C-S-H), which have intense peaks centered around $2\theta=32.2°$, 50.1°, and 55.1°, and (N, C)-A-S-H in amorphous geopolymer structure. This semi-crystalline phase improved the mechanical properties of the mortar by serving as nucleation sites for the development and accumulation of the amorphous geopolymer products [37]. In other words, the coexistence of both gel phases within the same network structure promoted alkali activation and ensured the internal structure development with higher CS of the mortar.

3.3. Effect of Curing Period

The effects of the curing period on the CS of the samples are given in Figure 8.

A tendency to increase in the CS of all samples was observed as the curing period increased. The highest slope of the curve, between 7 and 28 days, indicated that the mortar structure developed rapidly during the early period. During the early curing period, reactions occurred rapidly because the raw materials, water, and sufficient ambient temperature required for alkali activation were present in the mortar. The three-dimensional amorphous network structure produced as a result of the reactions enabled the filling of the voids in the mortar, the development of a more compact internal structure, and thus a rapid increase in mechanical properties [42]. The slope of the CS-curing period curve of the reference sample was relatively low, leading to slower strength development. The fastest strength development in the early period was detected in samples containing WCB and MP. The 25WCB:75MP samples showed the highest UV (3.44 km/s) and

CS (14.88 MPa) after 7 days. These properties improved quickly over time; therefore, the samples retained their highest mechanical properties during the subsequent curing periods. In other words, the development of alkali activation in the first 7 days later contributed to the material's performance.

On the other hand, regardless of the mixing ratio, the increase in CS of all samples decreased gradually starting from the 90th day and tended to remain constant, especially after the 180th day. In particular, the rate of increase between 90 and 365 days was negligible compared with the growth rate between 7 and 90 days. This finding could be attributed to the fact that the reaction products (both the (N, C)-A-S-H and C-S-H gels) that occurred during the early curing period have already filled the voids of the one-part alkali-activated mortar structure, causing the mortar structure to become more compact. The tendency for mechanical properties to remain constant in the later curing period is also compatible with the results of other experimental research in the literature. The strength increment of FA-based one-part AAM between 180 and 365 days was also stated as "negligible" by Haruna et al. [42].

The production of geopolymers from WCB, NP, and MP wastes would lower the cost of storing these wastes, the land demand required for storage, and the requirement for raw materials. Lowering the demand for raw materials would help to decrease greenhouse gas emissions and energy requirements. In addition, using these wastes to synthesize one-part alkali-activated mortars makes them a more environmentally friendly alternative to the traditional ones. The results of this experimental study demonstrate that WCB, NP, and MP wastes can be efficiently used to produce one-part alkali-activated mortars at the laboratory scale. However, the potential challenges for large-scale implementation should be identified to make the one-part alkali-activated mortars available in real-world industrial applications. For instance, the continuity of the waste raw material sources must be ensured. With the use of raw materials on an industrial scale, there might be a shortage of these sources in the foreseeable future. Since the chemical composition of raw materials (SiO_2, Al_2O_3, Fe_2O_3, and CaO contents) significantly influences the development of geopolymerization reactions and the properties of the resulting product in both fresh and hardened states, raw materials with constant chemical composition should be used. It should be considered that the greater transportation distances of the source materials would reduce the environmental benefits of the one-part alkali-activated mortars. In addition, in laboratory-scale applications, mixture preparation, molding, and curing can be easily implemented. However, for this production process to be carried out on an industrial scale, equipment and labor requirements should be defined correctly, and practical application methods should be developed. The production cost of the material on an industrial scale could be another challenge due to the higher cost of alkali activators. Therefore, a detailed cost analysis of WCB-based one-part alkali-activated mortars is required.

4. CONCLUSION

It is possible to draw the following conclusions from the results:

- WCB, obtained as construction and demolition waste, is an aluminosilicate precursor that can produce one-part alkali-activated mortar.
- Solid sodium hydroxide and sodium metasilicate are activator types that can activate WCB-based one-part alkali-activated mortars.
- The early low strength of the WCB-based mortar can be increased by substituting SiO_2- and Al_2O_3-rich NP waste or CaO-rich MP waste with the mortar composition.
- The optimum NP substitution content is 50%, which enhances the development of the reaction, allows the production of mortar with a more compact microstructure, and thus provides higher mechanical properties. Adding NP above this content is insufficient to enhance the properties.
- The highest mechanical properties are obtained in the mortar containing 25% WCB and 75% MP, possibly because this mortar is rich in SiO_2, Al_2O_3, and CaO components.
- WCB+NP-based samples have a three-dimensional amorphous sodium aluminosilicate hydrate gel structure. In addition to this gel structure, calcium silicate hydrate gel in the WCB+MP-based samples enables higher mechanical properties.
- The CS and the UV of WCB-based one-part alkali-activated mortars exhibit a directly proportional relationship.
- The mechanical properties of the samples increase with the curing period. The rate of increase is exceptionally high in the first 28-day curing period. However, the growth rate between 90 and 365 days is negligible compared to that in the early period.
- One-part alkali-activated mortar composed of WCB, NP, and MP may assist in overcoming the waste problem that occurs during urban transformation by making cost-effective use of existing raw materials and minimizing environmental damage.
- Although experimental study findings provide promising data on the production of WCB-based one-part alkali-activated mortars at the laboratory scale, the potential challenges for industrial-scale production, such as the continuity of these wastes, the consistency of chemical composition of the raw materials, greater transportation distances, higher costs of alkali materials, and the stages of mixture preparation, molding, and curing, should be taken into consideration.
- Apart from the WCB, NP, and MP used in this research, the possibility of using other waste types with similar chemical compositions to produce one-part alkali-activated mortar should be explored. Additionally, the durability properties of the material, such as under freezing-thawing, wetting-drying, and high-temperature effects, should be determined in future studies. In addition, detailed economic analyses should be carried out to develop practical solutions for mixing and curing conditions for industrial-scale applications and to use the material economically under Turkish conditions.

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ETHICS

There are no ethical issues with the publication of this manuscript.

DATA AVAILABILITY STATEMENT

The author confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declare that they have no conflict of interest.

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