Araştırma Makalesi DOI: **10.46810/tdfd.718895** Research Article

Türk Doğa ve Fen Dergisi
Turkish Journal of Nature and Science
www.dergipark.gov.tr/tdfd

The Impact of Artificial Lightweight Aggregate on the Engineering Features of Geopolymer Mortar

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(Alınış: 12.04.2020, Kabul: 31.05.2020, Online Yayınlanma: 18.06.2020)

Keywords
Cold bonding pelletization, Compressive strength, Geopolymer mortar, Artificial lightweight aggregate, Workability

Abstract: In this study, a research on the effectiveness of artificial lightweight aggregate (A-LWA) on the fresh and hardened properties of geopolymer mortars is presented. The main aim of this study is to propose a relatively newer means of recycling of fly ash (FA) through geopolymer mortar production. Therefore, firstly, artificial lightweight aggregate (A-LWA) was produced through the cold-bonding pelletization process of FA. Then, FA based geopolymer mortars were produced with this aggregate. The geopolymer mortars manufactured in this study had constant source material and alkaline activator quantities of 600 and 300 kg m^{-3}, respectively. The proportion of Na_2SiO_3-to-NaOH was 2.5 and the molarity of NaOH was 12 M. The A-LWA sand was replaced partially with river sand up to 100%. The compressive strength, ultrasonic pulse velocity, fresh and dry densities of the geopolymer composites were measured at the age of 7 days and the flow table test was conducted to indicate the consistency of the geopolymer mixtures. The results indicated the A-LWA utilization enhanced the workability of the geopolymer mixtures and the highest increase of flow diameter of 20% was obtained using 100% A-LWA. Compressive strength values of geopolymer mortars varied between 4.28 and 32.3 MPa. A systematical decrease in the compressive strength and revealed with respect to the increasing level of A-LWA due to the softness and weakness of the A-LWA particles. Ultrasonic pulse velocity results of geopolymer mortars ranged from 1479 to 2596 m s^{-1} with related the replacement level of A-LWA.

Yapay Hafif Agreganın Geopolimer Harcın Mühendislik Özellikleri Üzerindeki Etkisi

Anahtar Kelimeler
Soğuk bağlamayla peletleme, Basınç dayanımı, Geopolimer harç, Yapay hafif agrega, İşlenebilirlik

Öz: Bu çalışmada, yapay hafif agreganın (YHA) geopolimer harçların taze ve sertleşmiş özellikleri üzerindeki etkisi üzerine bir araştırma sunulmaktadır. Bu çalışmanın ana amacı, geopolimer harç üretimi yoluyla uçucu külün (UK) geri dönüşümü için nispeten daha yeni bir alternatif önermektir. Bundan dolayı, UK kullanılarak soğuk bağlama yöntemiyle YHA üretilmiştir. Sonra bu agregalar ile UK esaslı geopolimer harçlar üretilmiştir. Bu çalışmada üretilen geopolimer harçlar, sabit miktarda 600 kg m^{-3} UK ve 300 kg m^{-3} alkali aktivatör miktarları kullanılarak üretilmiştir. Na_2SiO_3/NaOH oranı 2.5 ve NaOH molaritesi 12 M olarak alınmıştır. YHA, dere kumuyla hacimce %100'e kadar kısmi olarak yer değiştirilerek kullanılmıştır. Geopolimer harçların basınç dayanımı, ultrasonik dalga hızı, taze ve kuru birim ağırlıkları 7 günlük süre sonunda ölçülmüştür. Taze karışımların kıvamını belirlemek için geopolimer harçlarda akış tablası deneyi yapılmıştır. Sonuçlar YHA kullanımının geopolimer karışımlarının işlenebilirliğini arttırdığını ve % 20'lik en yüksek akış çapı değerinin % 100 YHA kullanılarak elde edildiğini göstermiştir. Geopolimer harçların basınç dayanımı değerleri 4.28-32.3 MPa arasında değişen değerler elde edilmiştir.. YHA parçacıklarının boşluklu ve zayıf yapısı nedeniyle YHA artış miktarına bağlı olarak basınç dayanımında sistematik bir azalma görülmüştür. Geopolimer harçların ultrasonik ses geçiş hızı sonuçları, YHA'nın ikame seviyesi ile ilişkili olarak 1479 ile 2596 m s^{-1} arasında değişen değerler elde edilmiştir.

1. INTRODUCTION

The production of ordinary portland cement causes some environmental problems such as global warming related to higher CO_2 gas emission in the atmosphere. The cement production amount in the earth is annually 4000 million tons and the research demonstrates that the production of OPC is responsible for about 7-8% of total CO_2 in the atmosphere. To eliminate this undesirable issue, it is taken into consideration to search alternative binder materials such as geopolymers [1,2]. The geopolymer concrete has been considered as a good substitute for conventional concrete since geopolymer concrete does not contain any cement. The geopolymer can be produced by polymerization of aluminosilicate with the solution of alkaline that has many desirable properties compared with conventional binders with respect to the features of durability, thermal conductivity, and mechanical performance [3,4]. Flexural and tensile strength values of geopolymers are lower compared compressive strength results similar to the other cement-based products [5,6].

Generally, the geopolymers are produced by activating the mineral admixtures like metakaolin or other waste materials obtained from the industrial byproduct such as slag and FA [7]. Conversely, the important characteristics of geopolymer materials such as low cost, fire resistance, being environmentally friendly, and good thermal properties lead to utilization of them in the different applications [8]. The use of alkali activators in the experimental studies has become the engaging attention of the researchers, especially, those related to the manufacture of geopolymers and focused on industrial wastes.

Although, there have been studies taking fly ash (FA) into account as supplementary cementing material in special concrete applications such as self-compacting concrete, still, sustainable options for utilization of FA is required. Generally, fly ash is a popular material employed as a base ingredient for geopolymer manufacturing since it is the most available by-product material to be used for this purpose throughout the world [9,10]. Many researchers across the world have exposed excellent outcomes and durability aspects of the FA-based geopolymers [11-14]. Indeed, geopolymers need longer heat curing that leads to restricting the application of geopolymer on site. However, the strength of geopolymer can be even more than the cement-based concrete thanks to an elevated temperature curing 40 – 80 °C for about a minimum of 6 hours [15,16].

There are also many studies focusing on the properties of fly ash-based geopolymer mortars considering various parameters [17-21]. Rossi et al. [22] studied the impact of construction and demolition waste replacement by sand on the fresh and hardened properties of geopolymer mortar. The fly ash and metakaolin was utilized as a binder in the study. The results demonstrated that while the usage of construction and demolition waste decreased the flowability, the compressive and flexural strength results increased related to the strong interface between aggregate and geopolymer matrix. Wongsa et al. [23] investigated the utilization of crumb rubber replacing with river sand in the production of geopolymer mortar. According to their results it was obtained that using crumb rubber resulted in a significant decrease of compressive strength values. However, it was noticed that the density and thermal conductivity values, reduced by 42% and 79%, respectively, when compared with the mortar without crumb rubber. Kaur et al. [24] searched the effects of the sodium hydroxide molarity on the features of geopolymer mortar considering sodium silicate/sodium hydroxide ratio of 2. Three different SH molarities of 12 M, 14 M, and 16 M were used and the compressive strength results were attained at the age of 3, 7, 14, and 28 days. The highest compressive strength value was achieved with SH molarity of 16 M. The increase of SH molarity and age led to the development of strength results for all mixtures. Vaibhav et al. [25] focused on the influence of using silica fume by replacing the fly ash on the geopolymer mortar produced by various substitution levels of recycle aggregate with M-sand. It was concluded that The effect of silica fume on the compressive strength result is negative due to higher water absorption. The optimum replacement level of recycle aggregate with M-sand was determined as a 50% substitution.

Additionally, the use of A-LWA in the geopolymer mortar mixtures conduce toward reducing the self-weight of the geopolymer mortar, which leads to achieving more beneficial, sustainable, and applicable geopolymer mortar. Therewithal, reducing the dead weight of the buildings can be achieved by using the natural or artificial lightweight aggregate in the mortar production that would also result in reducing the required steel amount in the reinforced mortar structural members [26]. At the temperature of more than 100 ⁰ C, the geopolymer mortar containing lightweight aggregate has more resistance against the fire than that involving normal weight aggregate [27]. Lightweight aggregate that was obtained from the recycled industrial wastes or the natural sources can be employed in the lightweight mortar production. In Turkey, like other industrial countries, a huge amount of fly ash (an average of 15 million tons) as waste material has been annually produced and this creates an environmental problem by contaminating the air and water on a great domain. Besides, only a little quantity (approximately 1%) of this waste material has been utilized in the construction industry [28,29]. Growing demand for using lightweight mortar also causes a requirement for lightweight aggregate, which can be natural or artificial. There are three common methods for the production of A-LWAs by utilizing the waste materials; sintering, autoclaving, and cold bonding techniques [30-33]. Among these methods, the cold bonding pelletization needs the minimum energy consumption for the manufacturing of the aggregates, which are in the spherical particle forms attained by using a rotating disc at an inclined angle [30-32].

The unit weight of the geopolymer mortar can also be reduced like the cement-based mortar by using the lightweight aggregates in the manufacturing. Some studies have exhibited that increasing the quantity of natural lightweight aggregate or A-LWA in the mortar decreases its unit weight [34-36]. The mortar having the unit weight of less than 1920 kg m^{-3} can be taken into account as lightweight mortar, which may also have the possibility to lessen the dead load and Young's modulus, increasing the strength-to-weight ratio, improving the fire resistance, and enhancing the sound and thermal resistance [37-39]. As well as, the earthquake-resistant structures can be constructed more easily by using the lightweight mortar rather than using the normal weight mortar since the decrease in the self-weight of the structure consequently decreases the superimposed loads acting to the structure during the earthquake [40].

The use of lightweight aggregates in mortar manufacturing has an important problem encountered as high water absorption, but, this issue may easily be eliminated by providing saturated surface dry moisture conditions to the lightweight aggregate. Furthermore, it has been reported in the experimental studies in the literature that utilization of the lightweight aggregate in the saturated surface dry condition yields in a higher compressive strength of the mortar [41,42]. Besides, it has been stated that increasing the A-LWA decreases the compressive strength [35]. However, it has also been expressed that the early curing temperature influences the compressive strength of geopolymer mortar, in other words, increasing the temperature increases the compressive strength to some extent [43].

The objective of the experimental program in the current study is to determine the flow behavior, fresh and dry densities, compressive strength, and ultrasonic pulse velocity (UPV) of geopolymer mortars produced via partially replacing the normal weight fine aggregate with the fine A-LWA at six different replacement levels, namely, 0, 20, 40, 60, 80, and 100%. Thus, a total of 6 geopolymer mortar mixes were tackled at a fixed alkaline solution-to-fly ash ratio of 0.5 and the FA content of 600 kg per cubic meter. However, the mixture of Na_2SiO_3 and NaOH solution was used as an alkaline liquid by the ratio of 1/2.5. The molarity of NaOH was 12 M. The flow diameter, fresh and dry densities, compressive strength, and ultrasonic pulse velocity of the mortar specimens were determined after the 7-days of resting period.

2. MATERIALS AND METHODS

2.1. Ingredients of the Geopolymer Mortar

2.1.1. Geopolymer binder

F type FA conforming to ASTM C311[44] standards was supplied from Çatalağzı, Turkey and used in the manufacturing of both, the artificial lightweight aggregate and geopolymer mortar as a pozzolanic material. In the manufacture of the A-LWA, the fly ash was the major compound to maintain the pelletization process with the aid of Portland cement. Whereas, in the manufacturing of the geopolymer mortar, FA was employed as the binding material in the alkaline environment. The specific gravity of FA was 2.29. Portland cement and FA have the following chemical compositions given in Table 1.

Table 1. Chemical compositions of fly ash and Portland cement

Composition, %	FA	Portland cement
CaO	2.20	62.58
SiO_2	57.20	20.25
Al_2O_3	24.20	5.31
Fe_2O_3	7.10	4.04
MgO	2.40	2.82
SO_3	0.30	2.73
Na_2O	0.40	0.22
K_2O	3.40	0.92
Others	2.8	1.13

The mix of sodium silicate (Na_2SiO_3) and 12 M of sodium hydroxide (NaOH) with a constant proportion of 2.5:1was utilized as the alkaline activator. The NaOH solution must be firstly made by dissolving the solid sodium hydroxide crystals in the water to achieve 12 M concentration. This solution must be stored in a plastic flask at ambient temperature 22-25 °C for about one day, then, it should be used [45,46]. The Na_2SiO_3 chemical activator comprises 27.56% SiO_2 and 10.94% Na_2O oxides The NaOH and Na_2SiO_3 used in the experimental study had the specific gravity values of 2.13 and 1.38, respectively. The properties of the two alkaline activators were presented in Table 2.

Table 2. Properties of the alkaline activators

Material	**Sodium hydroxide**	**Sodium silicate**
Physical state	solid	liquid
Colour	white	Light yellow
Mol. weight	40.00 g/mol	122.06 g/mol
Melting	323 ºC	-
Storage	+5ºC - +30ºC	-

Besides, the commercially available superplasticizer having a specific gravity of 1.07 was used to acquire reasonable consistency in all fresh geopolymer mortar mixtures. For all geopolymer mortar mixtures, the quantity of the superplasticizer was fixed at 2% of fly ash content by mass.

2.1.2. Aggregates

The natural sand with the specific gravity of 2.64 and the fine A-LWA having the specific gravity of 1.71 was employed in the manufacturing of the geopolymer mortars. The nominal maximum particle size of both aggregate types was 4 mm.

The experimental study in this paper was separated into two stages. In the first stage, A-LWAs were manufactured by a cold bonding agglomeration process of Portland cement and fly ash. The schematic representation of the cold-bonding process was presented in the Figure 1. For that purpose, 10% of Portland cement and 90% of FA were blended in the dry powder form, then added into the pelletizer that is exhibited in Figure 2a. The pelletization disc having a 30-cm depth and 80-cm diameter, as indicated in Figure 2b, was rotated at the inclined shape having an inclination angle of 45° and with a constant rotation rate of 42 rpm to guarantee the uniformity of the mixture. The quantity of water, which was used as the coagulant medium and sprayed on the dry powder mixture during the pelletization process to produce the sphere-shaped particles with the rotating of the palletization disc, was about 20% of the total material weight [47-50]. The total manufacturing time was about 20 minutes and the water was sprayed on the dry mixture for the first 10 minutes of the process. During the second 10 minutes of the manufacturing process, the pelletization disc was allowed rotating to acquire the stiff and compacted sphere-formed pellets. As soon as after the fresh pellets were obtained from the cold bonding agglomeration process of Portland cement and FA, they were kept in a closed plastic bag, where the relative humidity was about 70%, for 28 days at ambient temperature in the laboratory condition.

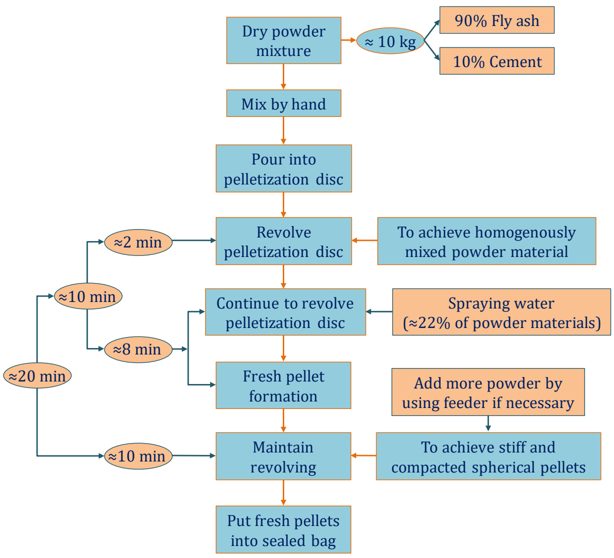


Figure 1. Cold-bonding manufacture process of A-LWA

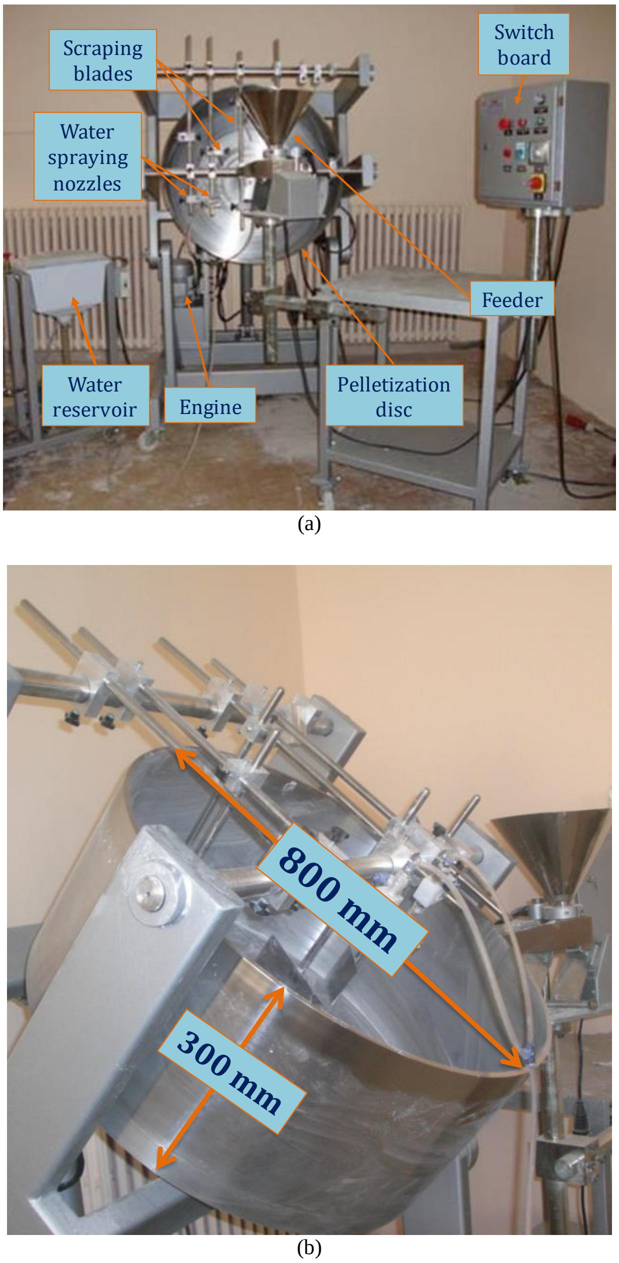


Figure 2. Photographic images of pelletization system: (a) the broad view and (b) pelletization disc

After the self-curing period, the hardened artificial lightweight aggregates were firstly crushed to achieve the fine particles and then, sieved from the sieves having 0.25 and 4-mm mesh opening to obtain the artificial lightweight aggregate having the particle size between 0.25 and 4 mm that is demonstrated in Figure 3. After the sieving process, the water absorption and specific gravity tests were performed on the artificial lightweight fine aggregates concerning ASTM C127 [51]. The water absorption of the artificial lightweight fine aggregate measured after immersing into the water for 24 hours was calculated as 22.2%. Besides, the specific gravity of the fine A-LWA in the saturated surface dry condition was measured as 1.71.

Figure 3. A photographic view of the typical artificial lightweight fine aggregate particles after crushing

2.2. Mixture Design, Production and Specimen Preparation

In the second step of the study presented herein, the geopolymer mortar mixtures were designed and produced. The fly ash with constant content of 600 kg m^{-3} was used as a solid binding component in the geopolymer mortar production. The alkaline activator-to-solid (FA) ratio was 0.5 and alkaline activator was the mix of NaOH solution having 12 M concentration and ready-made Na_2SiO_3 solution. The total content of alkaline activator was 300 kg m^{-3} and the ratio between sodium hydroxide and sodium silicate was designated as 1:2.5. The natural river sand was substituted with the artificial lightweight fine aggregate at the replacement levels of 0, 20, 40, 60, 80, and 100% by volume. In this way, in total, six geopolymer mortar mixtures were designed and their mixture proportions are given in Table 3.

At the beginning of the production process, the fine aggregates (natural and/or artificial) and fly ash were poured into the mortar mixer and it was rotated for about 30 seconds for obtaining the homogeneous mixture. Then, about half of the alkali activator solution was poured onto the solid materials in the mixer, and, blended for another one minute. After that, the superplasticizer was mixed with the rest of the alkali activator solution and they were added into the mixer. The production process continued with rotating the mixer for about three minutes and then, the fresh mix was permitted to rest for about two minutes. Finally, the geopolymer mortar mixture was achieved by mixing the rested mixture for an extra two minutes.

Table 3. Mixture quantities for geopolymer mortars

Mixture ID	Fly ash (kg m^{-3})	NaOH (kg m^{-3})	Na_2SiO_3 (kg m^{-3})	Natural sand (kg m^{-3})	A-LWA (kg m^{-3})	SP* (kg m^{-3})
GPM-L0	600	85.7	214.3	1353.9	0	12
GPM-L20	600	85.7	214.3	1083.1	175.4	12
GPM-L40	600	85.7	214.3	812.3	350.8	12
GPM-L60	600	85.7	214.3	541.6	526.2	12
GPM-L80	600	85.7	214.3	270.8	701.6	12
GPM-L100	600	85.7	214.3	0	877	12

*SP: superplasticizer

But before starting the production process of the geopolymer mortar involving the artificial lightweight fine aggregate, the artificial lightweight fine aggregate was put in the water for 24 hours. Afterward, it was taken out from the water and poured on the wire mesh and kept on there for about 30 seconds for the percolating of the excess water from the aggregate particles. Then, a dry towel was used to attain the artificial lightweight fine aggregate in the saturated surface dry condition. This is an important method used to achieve the saturated surface dry condition for such types of aggregate [47-49]. After this process had completed, the production process of the geopolymer mortar involving artificial lightweight fine aggregate started.

As soon as the mixing process finished, the attained fresh geopolymer mortar was cast into the molds by two layers and each layer was compacted by hand and vibration table. Three 40x40x160-mm prismatic specimens were taken from each mortar mixtures. Following, the specimens were covered with a nylon sheet and kept in the furnace having a temperature of 65 °C for 24 hours. After then, the specimens were demoulded and kept in the laboratory, in which the temperature was about 22–25 °C, for 7 days.

2.3. Test Procedures

The flowability of the geopolymer mortar mixtures was evaluated through the flow table test. For this reason, ASTM C1437-07 [52] was followed to carry out the flow table test for the geopolymer mortar mixtures produced in this study. A conical mould having the bottom and top opening diameters of 70 and 100 mm, respectively, and the height of 50 mm was utilized in performing the flow table test. The fresh geopolymer mortar mixtures were poured into this conical mold at two equal layers and each layer was compacted by 20 tamps and immediately after, the top surface was finished with a trowel (see Figure 4a). The conical mold was removed after 1 minute after its filling and immediately tamped 25 times in 15 seconds to spread the geopolymer mortar on the table as indicated in Figure 4b. As a result, the average of two opposite diameters of the spread geopolymer mortar was presented as the flow table test result [52].

The flexural tensile strength was applied to 40x40x160-mm prismatic specimens. Same specimens were also used for UPV readings. After flexural test the remaining pieces were used for compressive strength testing via special test apparatus which has 40x40 mm to and bottom plates. Hence, the compressive strength test was performed on 40-mm cubic specimens in accordance with ASTM C109 [53]. The ultrasonic pulse velocity test was conducted following ASTM C597-02 [54].

(a) (b)

Figure 4. (a) flow table test apparatus filled with geopolymer mortar and (b) measuring the flow diameter of geopolymer mortar

3. RESULTS AND DISCUSSION

3.1. Flowability

The variation in the average flow diameter values of the geopolymer mortar mixtures in accordance with the replacement level of the fine A-LWA has been indicated in Figure 5.

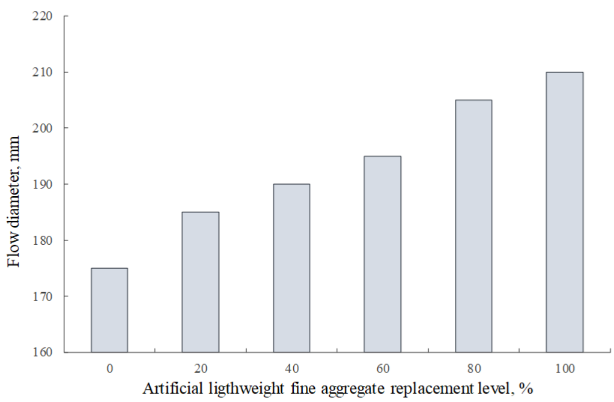


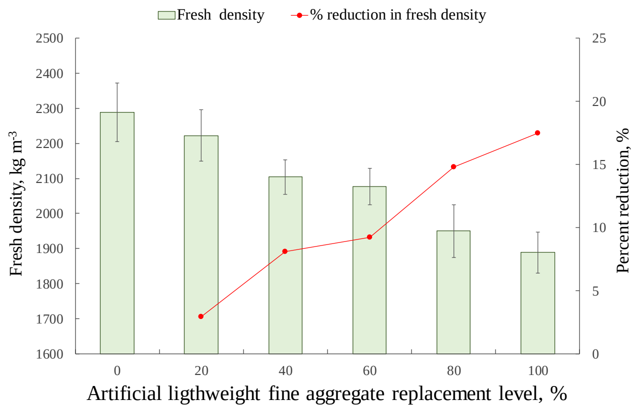
Figure 5. Variation in the flow diameter of geopolymer mortar mixtures regarding artificial lightweight fine aggregate replacement level

The flow diameter values ranging between 175 and 210 mm was measured in the geopolymer mortar mixtures produced in this study. The lowest flow diameter was measured in the mortar mixture involving no artificial lightweight fine aggregate whereas the highest flow diameter value was observed in the mortar mixture produced with fully artificial lightweight fine aggregate. The results illustrated that increasing the fine A-LWA content systematically resulted in the improvement of the flowability of the geopolymer mortar mixtures. The main reason for this situation is that the fine A-LWA was used in the saturated surface dry condition, so, no alkaline activator solution was absorbed by the A-LWA particles. For this reason, the workability of the fresh geopolymer mixtures enhanced by increasing the A-LWA content. Using 100% A-LWA in the production of the geopolymer mortar resulted in a 20% increment of the flow diameter.

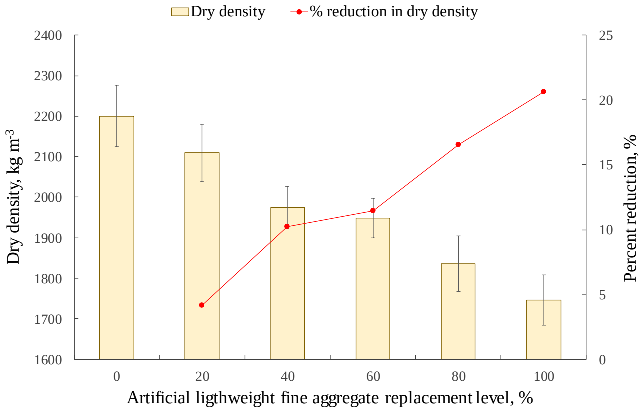
Besides, during the observational investigation, almost no segregation was sought in the geopolymer mortar mixtures.

3.2. Fresh and Dry Densities

The changes in the fresh and dry densities of the geopolymer mortars regarding the artificial lightweight fine aggregate content have been illustrated in Figures 6a and 6b, respectively. Besides, in these figures, the percent reduction values in both densities by increasing the fine A-LWA content also demonstrated. The fresh density values changing between 2289 and 1889 kg m^{-3} were observed for the geopolymer mortar mixtures while the dry density values for the same mixtures were between 2201 and 1746 kg m^{-3}. The results exhibited that when the mortar mixture produced with only natural fine aggregate has dried, about a 3.9% reduction in its density was observed, whereas the reduction in the density of the mortar mixture involving 100% artificial lightweight fine aggregate was about 7.5%. This might also be related to the moisture condition of the A-LWA. In the mortar production, the A-LWA was utilized in the saturated surface dry condition that means no water would be absorbed by the aggregates. Because of this, during stiffening and drying stages of the geopolymer mortars involving the artificial lightweight fine aggregate, more weight loss took place, so, a higher percentage reduction in the density was observed.



(a)



(b)

Figure 6. Change in: (a) fresh density and (b) dry density values in accordance with the volume fraction of the fine A-LWA

The results also revealed that utilizing the fine A-LWA in the production of the geopolymer mortar significantly reduced both, fresh and dry, densities. Based on the conclusions in the literature about the traditional mortar produced by the lightweight aggregate, the gradual decreases in fresh and dry densities could be observed by using lightweight aggregates in the mortar production [32,35,49]. When the percent reduction values submitted in Figures 6a and 6b were investigated, about 17.5% reduction in the fresh density and 20.7% reduction in the dry density values were achieved by producing the geopolymer mortar with fully artificial lightweight fine aggregate. Also, from these figures, it could be easily seen the gradual decrease in the density of the geopolymer mortar mixtures in conjunction with increasing the volume fraction of the artificial lightweight fine aggregate. According to TS EN 206-1 [55], the mortar having an oven-dried density between 800 and 2000 kg m^{-3} is considered as lightweight mortar. Since there is no classification for the geopolymer mortars, the given criteria can also be considered for the geopolymer mortar and mortar. Therefore, it could be expressed that all geopolymer mortar mixtures containing more than 40% artificial lightweight fine aggregate replacement level are in the lightweight mortar class since their dry densities are less than 2000 kg m^{-3}. On the other hand, by ACI Committee 213R-03 [56], the upper limit of density for considering the mortar as lightweight mortar is specified as 1950 kg m^{-3} for the air-dried mortar.

3.3. Compressive Strength

The compressive strength is a significant mechanical feature of the concrete that mostly mirrors the whole hardened characteristics of concrete during the service life. The variation of compressive strength values of the geopolymer mortar mixtures with respect to the A-LWA replacement level is demonstrated in Figure 7a. The geopolymer mortar mixtures produced in this study had the compressive strength values changing between 32.3 and 4.28 MPa. The extreme compressive strength value was observed in the geopolymer mortar mixture containing 100% natural sand while the minimum value was seen in the mixture involving 100% artificial sand. The compressive strength was gradually diminished by increasing the substitution level of the fine A-LWA and this is directly associated with the weakness of the A-LWA particles when compared with the river sand. Another reason beneath the compressive strength reduction by the A-LWA can be its softness. The A-LWA particles produce mediums softer than the hardened geopolymer matrix and during the loading, the softer medium would perform higher displacement than the geopolymer matrix that can result in the cracking occurrence in the geopolymer matrix. Therefore, an important decrease in the strength of the geopolymer mortar could be observed as the artificial lightweight aggregate content increased.

Additionally, the artificial lightweight aggregate particles manufactured with cold bonding pelletization process have smooth surfaces whereas, the natural aggregate used in the current study consists of rough particles that would increase the adherence between the geopolymer matrix and the aggregate particles [35,43,57-60]. Besides, the strength loss by employing the A-LWA is related to the porous nature of the structure of the artificial aggregate [57,61]. To illustrate the effect of the fine A-LWA amount on the compressive strength, Figure 7b, in which the relative compressive strength values are pointed out, are presented. The results indicated that about 87% reduction in the compressive strength was seen when the fine A-LWA content increased from 0% to 100% while the reduction was about 52% when the 20% of the river sand was substituted with the fine A-LWA.

Figure 8 was presented to show the relationship between the compressive strength and the dry density of the geopolymer mixtures according to the replacement level of the A-LWA content. The exponential correlation was used to evaluate the relationship between strength and density. When the coefficient of determination (R-squared) value of 0.937 given in Figure 8 was considered, it would be revealed that there is a robust relationship between the compressive strength and dry density of the geopolymer mixtures produced in this study. The similar evaluations for the relationship between the strength and density of the geopolymer mortar can be found in the literature [62].

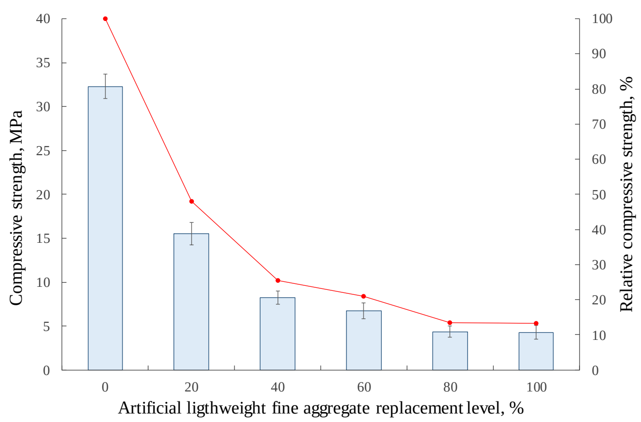


Figure 7. Compressive strength and relative compressive strength of the geopolymer mortar mixtures versus the A-LWA substation level

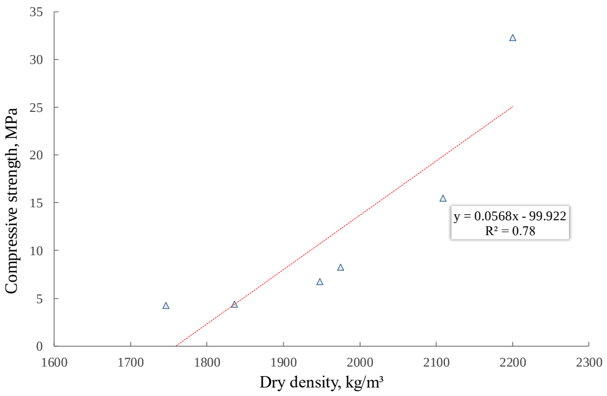


Figure 8. Relationship between the compressive strength and dry density of the geopolymer mortar mixtures

Additionally, to assess the performance and productivity of the geopolymer mortars produced in the study, the structural efficiency, described as the ratio of compressive strength-to-dry density, was determined and presented in Figure 9. This parameter can aid to compare the normal weight and lightweight mortar strengths based on the density. Figure 9 indicated that there was a reduction in the self-weight of the geopolymer mortar as the artificial lightweight fine aggregate content increased. But when this decrease was compared with the change in the compressive strength, it would be comprehended that it was not enough sufficient for equilibrating or ignoring the compressive strength loss. In other words, the reason for the minimum structural efficiency value in the geopolymer mixture containing 100% artificial lightweight fine aggregate appears to be obtaining a larger decreasing rate in the compressive strength than in the dry density [63].

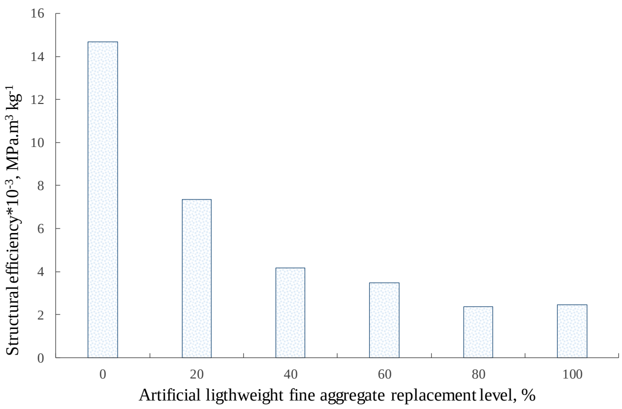


Figure 9. Structural efficiency values versus artificial lightweight fine aggregate replacement level

3.4. UPV

The UPV test can be considered as one of the most important non-destructive testing methods, by which the mortar quality can be determined. By this test, the time passed through the traveling of the sound from the transmitter to the receiver is measured and then, the velocity of the sound is calculated to determine the material quality. For this reason, delaying the time passing during the traveling of the sound would cause the lower ultrasonic pulse velocity and it is well-known the ultrasound can travel very well through the solid mediums whereas it cannot travel quickly through the porous medium. Moreover, The elastic characteristics and the density of the materials are effective parameters, which can affect the ultrasonic pulse velocity. In light of this information, it can be stated that the higher ultrasound pulse velocity means good quality-material. Besides, in the literature, there is a table as given in Table 4 [64-66], by which the quality of the mortar can be classified in terms of the ultrasonic pulse velocity value.

Table 4. Classifications for concrete quality based on ultrasonic pulse velocity values [50-52]

Concrete quality	Ultrasonic pulse velocity (m s^{-1})
Excellent	> 4500
Good	3600 – 4500
Questionable	3000 – 3600
Poor	2100 – 3000
Very poor	< 2100

The elasticity of the artificial lightweight aggregate influences the ultrasonic pulse velocity more than its density [67,68]. Therefore, in this experimental study, the effect of artificial lightweight fine aggregate on the quality of the geopolymer mortar was measured in terms of the UPV. The variation in the UPV values of the geopolymer mortar mixtures per the replacement level of the fine A-LWA has been indicated in Figure 10. The ultrasonic pulse velocity values changing between 2596 and 1479 m s^{-1} were achieved in this study. While the highest ultrasonic pulse velocity value was achieved in the geopolymer mortar mixture produced with fully natural aggregate, the lowest value was obtained in the mixture involving 100% artificial aggregate. There may be many factors caused this result, but, one of them is the porous structure of the fine A-LWA. The density of the mortar can be the second reason because the ultrasound can more easily propagate in the denser mediums than the looser mediums [67,69]. When the results compared with the classifications given in Table 4, it would be easily seen that the geopolymer mortar mixtures containing more than 40% artificial lightweight fine aggregate can be classified in a very bad qualified class. However, the geopolymer mortar mixtures involving 0 and 20% artificial lightweight fine aggregate are in the poor class regarding the values given in Table 4.

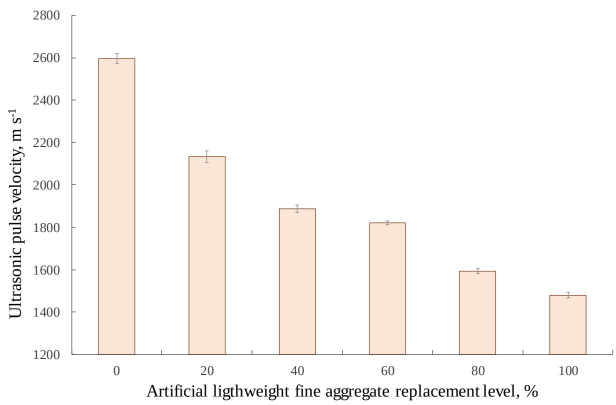
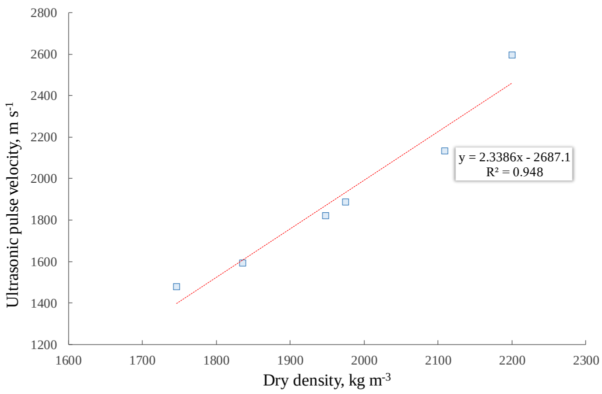


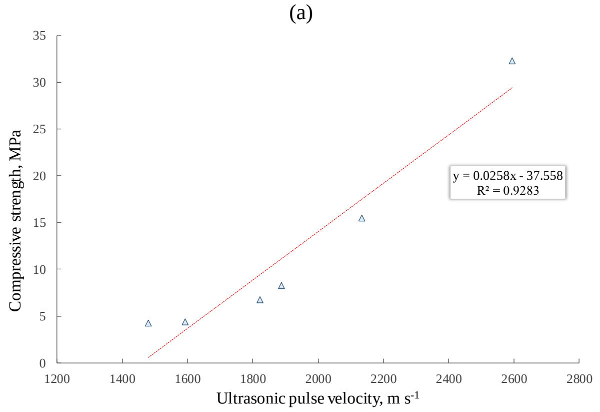
Figure 10. Variation in the UPV of geopolymer mortar mixtures regarding artificial lightweight fine aggregate replacement level

Figure 11a was presented to show the relationship between UPV and the dry density of the geopolymer mortar mixtures in accordance with the substitution level of the A-LWA content. The linear correlation was used to determine the relationship between pulse velocity and density. When the coefficient of determination (R-squared) value of 0.948 given in Figure 11a was regarded, it would be revealed that there is a strong relationship between the compressive strength and dry density of the geopolymer mixtures produced in this study. In other words, it means that when a denser geopolymer mixture is achieved, a higher ultrasonic pulse velocity will be attained, namely, a high quality-mixture will be obtained.

Besides, since the quality of the geopolymer mortar is directly related to its compressive strength, the relationship between the compressive strength and the UPV was presented in Figure 11b. The relationship between strength and UPV was determined in terms of the exponential correlation. When the coefficient of determination (R-squared) value of 0.985 given in Figure 11b was considered, it would be revealed that there is a statistically perfect relationship between the compressive strength and ultrasonic pulse velocity of the geopolymer mixtures produced in this study. Namely, by having the ultrasonic pulse velocity values, the comments about the compressive strength of such type of geopolymer mortar can be done. Demirboğa et al. [69] also concluded that the UPV values can be used in the evaluation of the compressive strength of the mortar.



(a)



(b)

Figure 11. Relationship between: (a) UPV and dry density and (b) the UPV and compressive strength of the geopolymer mortar mixtures

4. CONCLUSIONS

In this experimental study, it was aimed to manufacture geopolymer mortars using various contents of A-LWA produced by cold bonded fly ash. The effects of utilizing different replacement levels of the A-LWA on the workability, density, compressive strength, and ultrasonic pulse velocity values were investigated.
Depending on the aforementioned findings, the conclusions below can be drawn:

- The geopolymer mortar can be produced by only fine A-LWA without segregation and/or bleeding.
- Utilization of the fine A-LWA and increasing its content decreased the flow diameter of the geopolymer mortar mixtures. The flow diameter values are between 175 and 210 mm and the highest flow diameter increase of 20% was obtained using 100% A-LWA.
- The increase in replacement level of A-LWA resulted in a decrease of both fresh and dry density values. Geopolymer mortar having a dry density of less than 2000 kg m^{-3} was produced by replacing 40% or more natural sand with A-LWA. While the fresh density values of the geopolymer mixtures varied between 2289 and 1889 kg m^{-3} the dry density values for the same mixtures were between 2201 and 1746 kg m^{-3}.
- The compressive strength results of geopolymer mortars varied between 4.28 and 32.3 MPa. The increase of A-LWA content from 0% to 100% led to about 87% reduction of strength values. The compressive strength results proved that fine A-LWA significantly reduced the compressive strength of the geopolymer mortar mixes. This finding can be attributed to the weakness, softness, porous structure, and smooth surface of A-LWA particles.
- A strong exponential relationship between the compressive strength and dry density of geopolymer mortar mixtures was established with the coefficient of determination (R-squared) value of 0.937 in this study.
- The range of ultrasonic pulse velocity values of geopolymer mortars is 1479 - 2596 m s-1 according to the variable A-LWA content. The highest and lowest ultrasonic pulse velocity values were detected with 0% and 100% replacement level of A-LWA, respectively. Ultrasonic pulse velocity results showed that using more than 20% fine A-LWA in the geopolymer mortar production results in the poor quality of pore structure.
- Also, there was a strong exponential relationship between the compressive strength and UPV of the geopolymer mixtures with the coefficient of determination (R-squared) value of 0.985.
- The findings also indicated the fact that geopolymer mortars having lower densities were attained by substituting the A-LWA with the natural sand.

REFERENCES

[1] Malhotra VM. Introduction: sustainable development and concrete technology. Concr Int. 2001; 24(7):22.

[2] Olivier JG, Peters J, Janssens-Maenhout G. Trends in global CO2 emissions 2012 report. 2012.

[3] Provis JL, Van Deventer JSJ. Geopolymers: structures, processing, properties and industrial applications. Elsevier; 2009.
[4] Ranjbar N, Mehrali M, Behnia A, Alengaram UJ, Jumaat MZ. Compressive strength and microstructural analysis of fly ash/palm oil fuel ash based geopolymer mortar. Materials & Design. 2014;59(0):532-9.
[5] Alomayri T, Shaikh FUA, Low IM. Synthesis and mechanical properties of cotton fabric reinforced geopolymer composites. Composites Part B: Engineering. 2014;60(0):36-42.
[6] Dias DP, Thaumaturgo C. Fracture toughness of geopolymeric concretes reinforced with basalt fibers. Cement and Concrete Composites. 2005;27(1):49-54.
[7] Aleem MA, Arumairaj P. Geopolymer concrete–a review. International Journal of Engineering Sciences and Emerging Technologies. 2012;1(2):118-22.
[8] He P, Jia D, Lin T, Wang M, Zhou Y. Effects of high-temperature heat treatment on the mechanical properties of unidirectional carbon fiber reinforced geopolymer composites. Ceramics International. 2010;36:1447-53.
[9] Ortega EA, Cheeseman C, Knight J, Loizidou M. Properties of alkali-activated clinoptilolite. Cement and Concrete Research. 2000;30:1641-6.
[10] Villa C, Pecina ET, Torres R, Gómez L. Geopolymer synthesis using alkaline activation of natural zeolite. Construction and Building Materials. 2010;24:2084-90.
[11] Fernández-Jiménez A, Palomo A. Composition and microstructure of alkali activated fly ash binder: effect of the activator. Cement and Concrete Research. 2005;35(10):1984-92.
[12] Albitar M, Visintin P, Mohamed AMS, Drechsler M. Assessing behaviour of fresh and hardened geopolymer concrete mixed with class-F fly ash. KSCE Journal of Civil Engineering. 2015;19(5):1445-55.
[13] De Vargas, Alexandre Silva, et al. The effects of Na2O/SiO2 molar ratio, curing temperature and age on compressive strength, morphology and microstructure of alkali-activated fly ash-based geopolymers. Cement and concrete composites. 2011;33(6):653-660.
[14] Rao, G. Mallikarjuna, and TD Gunneswara Rao. "Final setting time and compressive strength of fly ash and GGBS-based geopolymer paste and mortar." Arabian Journal for Science and Engineering. 2015;40(11):3067-3074.
[15] Duxson P, Fernández-Jiménez A, Provis JL, Lukey GC, Palomo A, van Deventer JSJ. Geopolymer technology: the current state of the art. Journal of Materials Science. 2007;42(9):2917-33.
[16] Hardjito D, Wallah SE, Sumajouw D, Rangan BV. On the development of fly ash-based geopolymer concrete. ACI Materials Journal. 2004;101(6):467-72.
[17] Hardjito D, Cheak CC, Ing CHL. Strength and setting times of low calcium fly ash-based geopolymer mortar. Modern applied science. 2008;2(4):3-11.
[18] Sathonsaowaphak A, Chindaprasirt P, Pimraksa K. Workability and strength of lignite bottom ash geopolymer mortar. Journal of Hazardous Materials. 2009;168(1):44-50.
[19] Adak D, Sarkar M, Mandal S. Effect of nano-silica on strength and durability of fly ash based geopolymer mortar. Construction and Building Materials. 2014;70:453-459.
[20] Colangelo F, Cioffi R, Roviello G, Capasso I, Caputo D, Aprea P, Ferone C. Thermal cycling stability of fly ash based geopolymer mortars. Composites Part B: Engineering. 2017;129:11-17.
[21] Mermerdaş K, Algin Z, Ekmen Ş. Experimental assessment and optimization of mix parameters of fly ash-based lightweight geopolymer mortar with respect to shrinkage and strength. Journal of Building Engineering. 2020;101351.
[22] De Rossi A, Ribeiro MJ, Labrincha JA, Novais RM, Hotza D, Moreira RFPM. Effect of the particle size range of construction and demolition waste on the fresh and hardened-state properties of fly ash-based geopolymer mortars with total replacement of sand. Process Safety and Environmental Protection. 2019;129:130-137.
[23] Wongsa A, Sata V, Nematollahi B, Sanjayan, J, Chindaprasirt P. Mechanical and thermal properties of lightweight geopolymer mortar incorporating crumb rubber. Journal of Cleaner Production. 2018;195:1069-1080.
[24] Kaur M, Singh J, Kaur M. Synthesis of fly ash based geopolymer mortar considering different concentrations and combinations of alkaline activator solution. Ceramics International. 2018; 44(2):1534-1537.
[25] Vaibhav KS, Nagaladinni M, Madhushree M. Priya BP. Effect of Silica Fume on Fly Ash Based Geopolymer Mortar with Recycled Aggregates. In Sustainable Construction and Building Materials. Springer, Singapore. 2019;595-602.
[26] Topcu IB. Semi-lightweight concretes produced by volcanic ash. Cement and Concrete Research. 1997;27(1):15-21.
[27] Abdulkareem OA, Mustafa AM, Bakri AI, Kamarudin H, Khairul Nizar I, Saif AEA. Effects of elevated temperatures on the thermal behavior and mechanical performance of fly ash geopolymer paste, mortar and lightweight concrete. Constructiona and Building Materials. 2014;50:377-87.
[28] Turkish Statistical Institute [Internet]. Thermal Power Plants Water, Wastewater and Waste Statistics; 2013 [cited 2020 March 29]. Available from http://www.turkstat.gov.tr/HbPrint.do?id=16164
[29] Tokyay M. Betonda Uçucu Kül Kullanımı (Türkiye Deneyimi). End. Atıkların İnşaat Sektöründe Kul. Semp. Ankara. 18-19 Kasım 1993;29-36,
[30] Arslan H, Baykal G. Utilization of fly ash as engineering pellet aggregates. Environmental Geology. 2006;50(5):761-70.

[31] Baykal G, Döven, AG. Utilization of fly ash by pelletization process; theory, application areas and research results. Resources, Conservation and Recycling. 2000;30(1):59-77.
[32] esoğlu M. Effects of lightweight aggregate properties on mechanical, fracture, and physical behavior of lightweight concretes [dissertation]. İstanbul: Boğaziçi University; 2004.
[33] Gesoğlu M, Güneyisi E, Öz HÖ. Properties of lightweight aggregates produced with cold-bonding pelletization of fly ash and ground granulated blast furnace slag. Materials and structures. 2012;45(10):1535-46.
[34] Raj DM, Raju JVN, Suneel M. An experimental study on effect of partial replacement of normal weight aggregates with lightweight aggregates in fly ash based geopolymer concrete. International Research Journal of Engineering and Technology. 2018;5(6):1090-6.
[35] Öz HÖ, Gesoğlu M, Güneyisi E, Sor NH. Self-consolidating concretes made with cold-bonded fly ash lightweight aggregates. ACI Materials Journal. 2017;114(3):385-95.
[36] Top S, Vapur H, Altiner M, Kaya D, Ekicibil A. Properties of fly ash-based lightweight geopolymer concrete prepared using pumice and expanded perlite as aggregates. Journal of Molecular Structure. 2019;127236.
[37] Mousa A, Mahgoub M, Hussein M. Lightweight concrete in America: presence and challenges. Sustainable Production and Consumption. 2018;15:131-44.
[38] Zhang H, Hou S, Ou J. Smart aggregates for monitoring stress in structural lightweight concrete. Measurement. 2018;122:257-63.
[39] Dhir K, Mays RGC, Chua HC. Lightweight structural concrete with aglite aggregate: mix design and properties. International Journal of Cement Composites and Lightweight Concrete. 1984;6(4):249-61
[40] Jafari S, Mahini SS. Lightweight concrete design using gene expression programing. Construction and Building Materials. 2017;1390:93-100.
[41] Kabay N, Aköz F. Effect of prewetting methods on some fresh and hardened properties of concrete with pumice aggregate. Cement and Concrete Composites. 2012;34(4):503-7.
[42] Shen D, Jiang J, Shen J, Yao P, Jiang G. Influence of prewetted lightweight aggregates on the behavior and cracking potential of internally cured concrete at an early age. Construction and Building Materials 2015;99:260-71.
[43] Görhan G, Kürklü G. The influence of the NaOH solution on the properties of the fly ash-based geopolymer mortar cured at different temperatures. Composites Part B: Engineering. 2014;58:371-7.
[44] ASTM C311. Standard Test Methods for Sampling and Testing Fly Ash or Natural Pozzolans for Use as a Mineral Admixture in Portland-Cement Concrete. ASTM International, West Conshohocken, PA; 2000.
[45] Hardjito D, Wallah SE, Rangan BV. Research into engineering properties of geopolymer concrete. International Conference on Geopolymer, 2002. Melbourne, Australia; 2002.
[46] Hou Y, Wang D, Zhou W, Lu Ho, Wang L. Effect of activator and curing mode on fly ash-based geopolymers. Wuhan University Journal of Natural Sciences Ed. 2009;24(5):711-5.
[47] Arslan H, Baykal G. Utilization of fly ash as engineering pellet aggregates. Environmental Geology. 2006;50(5):761-70.
[48] Güneyisi E, Gesoğlu G, İpek S. Effect of steel fiber addition and aspect ratio on bond strength of cold-bonded fly ash lightweight aggregate concretes. Construction and Building Materials. 2013;47:358-65.
[49] İpek S, Ayodele OA, Mermerdaş K. Influence of artificial aggregate on mechanical properties, fracture parameters and bond strength of concretes. Construction and Building Materials. 2020;238:117756.
[50] Döven AG. Lightweight fly ash aggregate production using cold bonding agglomeration process [dissertation]. İstanbul: Boğaziçi University; 1998
[51] ASTM C 127. Standard test method for specific gravity and absorption of coarse aggregate. ASTM International, West Conshohocken, PA; 2007.
[52] ASTM C1437-07. Standard Test Method for Flow of Hydraulic Cement Mortar. ASTM International, West Conshohocken, PA; 2007.
[53] ASTM C109. Standard test method for compressive strength of hydraulic cement mortars. ASTM International, West Conshohocken, PA; 2008.
[54] ASTM C597. Standard test method for compressive strength of hydraulic cement mortars. ASTM International, West Conshohocken, PA; 2002.
[55] TS-EN 206-1. Concrete Part 1. Turkish Standard Institute, Turkey; 2000.
[56] ACI Committee 213R. American Concrete Institute. Guide for structural lightweight aggregate concrete. Manual of Concrete Practice. Farmington Hills, Michigan, USA; 2003
[57] Mohseni E, Mahyar JK, Mahdi K, Behnam Z, Babak B. Evaluation of mechanical and durability properties of fiber-reinforced lightweight geopolymer composites based on rice husk ash and nano-alumina. Construction and Building Materials. 2019;209:532-40.
[58] Novais RM, Luciano S, João C, Maria PS, Robert CP, João AL. Sustainable and efficient cork-inorganic polymer composites: An innovative and eco-friendly approach to produce ultra-lightweight and low thermal conductivity materials. Cement and Concrete Composites. 2019;97:107-17.
[59] Güneyisi E, Gesoğlu M, Özturan T, İpek S. Fracture behavior and mechanical properties of concrete with artificial lightweight aggregate and

steel fiber. Construction and Building Materials. 2015;84:156-68.

[60] Top S, Vapur H. Effect of basaltic pumice aggregate addition on the material properties of fly ash based lightweight geopolymer concrete. Journal of Molecular Structure. 2018;1163:10-7.

[61] Kastiukas G, Zhou X, Castro-Gomes J. Development and optimisation of phase change material-impregnated lightweight aggregates for geopolymer composites made from aluminosilicate rich mud and milled glass powder. Construction and Building Materials. 2016;110:201-10.

[62] Posi P, Chaiyapong T, Chatchai T, Suttikait L, Surasit L, Vanchai S, et al. Lightweight geopolymer concrete containing aggregate from recycle lightweight block. Materials & Design. 2013;52:580-6.

[63] Choi YW, Kim YJ, Shin HC, Moon HY. An experimental research on the fluidity and mechanical properties of high-strength lightweight self-compacting concrete. Cement and Concrete Research. 2006;36(9):1595-1602.

[64] Leslie JR, Cheeseman WJ. An ultrasonic method for studying deterioration and cracking in concretestructures. ACI Materials Journal.1949;46:17-36.

[65] Feldman RF. Non-destructive testing of concrete [Internet]. CBD-187; 1977 [cited 2020 March 29]. Available from: http://web.mit.edu/parmstr/Public/NRCan/CanBldgDigests/cbd187_e.html

[66] Saint-Pierre F, Philibert A, Giroux B, Rivard P. Concrete quality designation based on ultrasonic pulse velocity. Construction and Building Materials. 2016;125:1022-7.

[67] Bogas J, Alexandre M, Glória G, Augusto G. Compressive strength evaluation of structural lightweight concrete by non-destructive ultrasonic pulse velocity method. Ultrasonics. 2013;53(5):962-72.

[68] Bogas JA. Characterization of structural lightweight expanded clay aggregate concrete [dissertation]. Lisbon:Technical University of Lisbon, Instituto Superior Técnico; 2011. (in Portuguese)

[69] Demirboğa R, Turkmen I, Karakoç MB. Relationship between ultrasonic velocity and compressive strength for high-volume mineral-admixtured concrete. Cement and Concrete Research. 2004;34:2329–36.