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Physical and mechanical properties of C class fly ash based light-weight geopolymer mortar produced with expanded vermiculite aggregate

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Abstract: This study presents the physical and the mechanical properties of C class fly ash (FA) based lightweight geo-polymer mortars produced with expanded vermiculite (EV) aggregate. The FA was activated with NaOH containing 12%, 14% and 16% sodium by weight. The volumetric ratios of EV/FA in the samples were chosen as 2,4 and 6 in the study. The liquid/solid ratio 0.23, 0.26 and 0.29. Lightweight geopolymer mortar (LGM) samples were produced by mixing FA, EV, NaOH and water in a mixer. The samples placed in molds were exposed to activation temperature of 100°C for 24 hours in the oven. The samples taken out of the oven were demolded and kept in air curing for 28 days at 20°C±2°C room temperature. After curing, unit weight, apparent porosity, water absorption ratio, ultrasonic pulse velocity (UPV), flexural strength and compressive strength tests were performed on the samples. In addition, the thermal conductivity coefficients of the samples were determined. As a result of the experiment, a compressive strength varying between 0.59 MPa and 3.81 MPa was obtained in lightweight geopolymers samples with a unit weight between 906 kg/m^3 and 1477 kg/m^3. Expanded vermiculite showed a good performance on thermal conductivity of LGMs and a decrease in thermal conductivity up to the 0.094 W/mK was observed.

Keywords: geopolymer, fly ash, vermiculite, flexural strength, compressive strength, thermal conductivity.

1. Introduction

Ordinary Portland Cement (OPC) has the primary binder property with an annual production increase of 9% worldwide (Amran et al. 2020). Annual greenhouse gas emissions from OPC production account for approximately 1.5 billion tons, an average of 6% of total emissions (Castel 2017; Madheswaran, Gnanasundar, and Gopalakrishnan 2013). The concentration of CO_2 in the atmosphere has increased by about 30% recently, reaching 467 Mt. Increasing greenhouse gas levels in the atmosphere cause climate change. As of 2017, total annual greenhouse gas emissions reached a record level, equivalent to 53.5 Gt of CO_2 (UEG 2018). For this reason, many studies are carried out to obtain alternative binders. The main purpose of studies known as geopolymer concrete (Davidovits 2008), alkali activated concrete (Provis 2018) or inorganic concrete (Da-vidovits 1991) is to produce an eco-friendly binder. Geopolymer helps to reduce resource and energy consumption as well as reducing emissions. Therefore, it can be used as an alternative eco-friendly material (Luo, Xu, and Li 2015). In the production of geopolymer, industrial wastes such as FA, blast furnace slag, silica fume and natural materials such as kaolin, clay, lime and red mud are used as binders (Bingöl et al. 2020; Khadka et al. 2020; Li et al. 2019; Qu et al. 2020; Sarker 2011; Sukprasert et al. 2021; Yurt 2020a, 2020b). These binders are activated with various alkalis. Alkaline activators such as sodium hydroxide (NaOH) (Atiş et al. 2015; Aygörmez 2021), potassium hydroxide (KOH) (Okoye, Durgaprasad, and Singh 2015; Puligilla, Chen, and Mondal 2019), sodium silicate (Na_2SiO_3) (Yu et al. 2017), potassium silicate (K_2SiO_3) (Chi et al. 2019) are used in the activation process. These activators can be used alone or as a mixture of NaOH + Na_2SiO_3 and KOH+K_2SiO_3 (Hosan, Haque, and Shaikh 2016; Kaya et al. 2018). A temperature of 300°C is needed for the production of sodium hydroxide (Onwudili and Williams 2009). Despite these factors, it can be said that geopolymer is more economical and more environmentally friendly compared to conventional concrete.

It is quite common to use fossil fuels to meet the energy needs around the world. Some of the electricity need is provided by burning coal in thermal power plants. As a result of the burning of coal, ash is formed both at the base of the combustion unit and in the chimney of the thermal power plant (Yılmaz, et al., 2005). Bottom ash, which is burnt coal waste, and FA from the chimney, has a polluting effect on the environment. However, it causes waste management problems such as storage. It is stated that the FA formed as a result of the burning of coal has reached 750 million tons as of 2015 in the World (Fan et al. 2018). However, currently only 25% are known to be recycled (Gowda and Latha, 2017). Therefore, there is a potential to be used as an alternative to FA OPC. The negative impact on the environment can be eliminated by using OPC and FA in concrete production or using it in geopolymer production (Kaya et al. 2018; Köksal et al. 2015). According to ASTM C618-19 (ASTM 2019), FA, which is obtained from bituminous coal and contains 70% and more SiO_2+Al_2O_3+Fe_2O_3, is defined as F class. FA, which is obtained from semi-bituminous coal and has more than 50% SiO_2+Al_2O_3+Fe_2O_3 content, is defined as Class C. It is also stated that CaO ratio is over 10% in C class FA classification.

Vermiculite is a naturally occurring aqueous phyllosilicate mineral (Köksal et al. 2015). It has been reported that vermiculite production in the world is approximately 2.35 million. Major producers of vermiculite are the United States, South Africa, Australia, China, India, Russia, and Uganda (Government of India MoM, 2019). When vermiculite is heated to 650ºC-1000°C, it expands to 8-30 times its original volume (Hwang and Hung 2005). Therefore, the expanded form of vermiculite shows very low density, high refractoriness, high sound insulation and low thermal conductivity (Melo et al. 2012; Schackow et al. 2014). In addition, there is no data on the formation of carbon dioxide emissions during the expansion process of vermiculite (Epa U. 1995). Expanded vermiculite is used as aggregate in the production of lightweight concrete due to its lightness, heat and sound insulation properties (Shubbar et al. 2020).

Under ASTM C-332 (ASTM 2017b), LW concrete is 0.7 MPa-2 MPa for insulating concrete applications, and LW concrete is 7 MPa - 14 MPa for masonry applications under ASTM C-331(ASTM 2017a). In structural applications, LW concrete is within the scope of ASTM C-330 (ASTM 2017c) as 17 MPa - 63 MPa. There are many studies on cement based materials produced with lightweight aggregates such as expanded polystyrene, pumice, perlite and expanded clay (Demirboğa and Gül 2003; Schackow et al. 2014; Sengul et al. 2011). However, studies done by using cementitious materials and expanded vermiculite are limited (Köksal et al. 2015; Mo et al. 2018; Shoukry et al. 2016).

There are many studies in production of geopolymer using different aggregates. Hajimohammadi et al. (2019) examined the interface chemistry in geopolymers containing fly ash. They stated that the compressive strength increased by 30% as a result of the displacement of sand and glass aggregate in the composite. Gowda and Latha (Gowda and Latha 2017) obtained a compressive strength of 6 MPa - 70 MPa at the end of 28 days in the granulated blast furnace slag based geopolymers where they used fine and coarse aggregates. In a study that produced geopolymer using expanded clay aggregate, it was found that the use of 75% expanded clay aggregate reduced the compressive strength from 69 MPa to 10.9 MPa (Hassan et al. 2019). Safari et al. (2020) reported that compressive strength decreased from 76.73 MPa to 64.28 MPa by increasing the curing temperature from 60°C to 80°C during the production of pumice powder-based geopolymer pastes. In a study where fly ash based geopolymer was produced using pumice and expanded perlite as aggregates, a strength between 10 MPa and 50 MPa was obtained (Top et al. 2020). Wongsa et al. (2018), obtained a compressive strength of 8.2 MPa–18.3 MPa and a density of 1685 kg/m^3–1749 kg/m^3 in geopolymer concretes produced using crushed clay brick and pumice aggregate. In a study where geopolymer was produced with vermiculite aggregate, density between 700 kg/m^3 and 900 kg/m^3, an average strength of 2 MPa and a thermal conductivity of 0.2 W/mK were determined (Medri et al. 2015). Gencel et al. (2021) produced fly ash based geopolymer by replacing natural sand and vermiculite aggregate. They stated that with the increase of expanded vermiculite from 15% to 30%, the viscosity decreased approximately 4%, dry unit weight 6%, compressive strength 7%, UPV 6%, thermal conductivity 18%, water absorption 9% and porosity increased 6%.

Studies using expanded vermiculite in geopolymer production are extremely limited in the literature. In this study, fly ash, which is industrial waste as binder, and expanded vermiculite as lightweight aggregate, were used and LGM was produced. The physical and mechanical properties of these composites were investigated.

2. Materials and methods

2.1. *Materials*

Class C (high-calcium) fly ash, provided from Soma thermal power plant in Turkey was used in this study. The chemical content and physical properties of fly ash are given in Table 1. The scanning electron microscope (SEM) image is also given in Figure 1. Commercially available expanded vermiculite (EV) with a grain size of 0-4 mm was used as lightweight aggregate. The picture and SEM image of EV were presented in Figure 2 and Figure 3, respectively. Some characteristics and chemical properties of expanded vermiculite used were also given in Table 2 and Table 3, respectively. NaOH was used as activator in production of LGM.

Table 1. Properties of C Class fly ash.

Properties chemical composition	(%)
MgO	0.62
Al_2O_3	6.36
SiO_2	15.04
SO_3	6.92
Na_2O	0.06
K_2O	0.7
CaO	51.22
Fe_2O_3	2.29
P_2O_5	0.10
LOI	16.62
Physical properties	
Specific weight (t/m^3)	2.68
45 micron sieve remaining (%)	9.1
Blain specific surface (cm^2/g)	2460

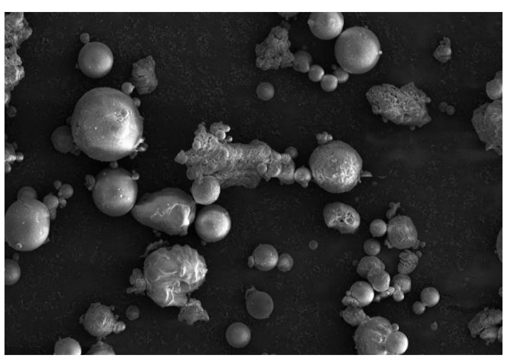


Figure 1. SEM image of class C fly ash.

Figure 2. Expanded vermiculite used.

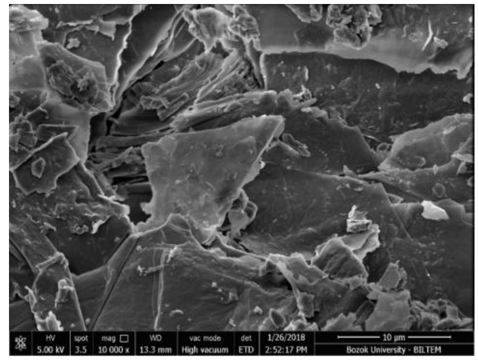


Figure 3. SEM image of expanded vermiculite.

Table 2. Some characteristics of expanded vermiculite used.

Color	Golden
Shape	Accordion shaped granule
Water holding capacity	220% (by weight) 24% (by volume)
Cation exchange capacity	50-150 meg/100 g
Thermal conductivity	0.065-0.062 W/m.K
Permeability	95%
pH	8.1
Sintering temperature	1150 ºC-1250 °C
Combustibility	Non-combustible
Specific heat	0.20–0.26 Kcal/kg °C
Specific gravity	2.6
Bulk density	147 kg/m^3

Table 3. Chemical composition of expanded vermiculite used.

Composition	(%)
$BaSO_4$	-
SiO_2	38.76
Al_2O_3	15.89
Fe_2O_3	12.06
CaO	2.32
SO_3	0.38
MgO	17.69
Na_2O	0.30
K_2O	5.50
$SrSO_4$	-
MnO	-
Loss on ignition	4.86

2.2 *Method*

In this study, fly ash was activated with NaOH containing 12%, 14% and 16% Na by weight. Vermiculite used as aggregate was adjusted to be EV/FA 2, 4 and 6 by volume. The liquid/solid ratio in the mixture was determined as 0.23, 0.26 and 0.29. mixing ratios of mortar samples are given in Table 4.

Table 4. Mixing ratio of samples.

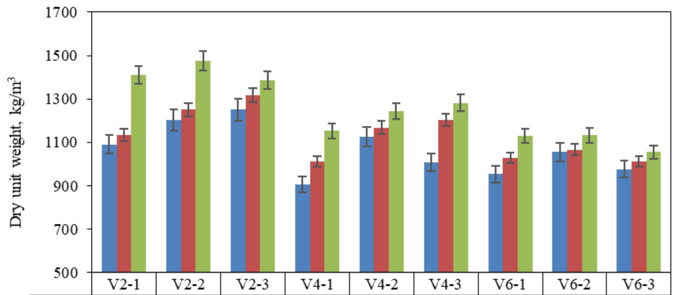
Mix No.	Mix code	Na/FA, % (weight)	EV/FA (volume)	Liquid/solid ratio
1	Na12V2-1	12	2	0.23
2	Na12V2-2	12	2	0.26
3	Na12V2-3	12	2	0.29
4	Na14V2-1	14	2	0.23
5	Na14V2-2	14	2	0.26
6	Na14V2-3	14	2	0.29
7	Na16V2-1	16	2	0.23
8	Na16V2-2	16	2	0.26
9	Na16V2-3	16	2	0.29
10	Na12V4-1	12	4	0.23
11	Na12V4-2	12	4	0.26
12	Na12V4-3	12	4	0.29
13	Na14V4-1	14	4	0.23
14	Na14V4-2	14	4	0.26
15	Na14V4-3	14	4	0.29
16	Na16V4-1	16	4	0.23
17	Na16V4-2	16	4	0.26
18	Na16V4-3	16	4	0.29
19	Na12V6-1	12	6	0.23
20	Na12V6-2	12	6	0.26
21	Na12V6-3	12	6	0.29
22	Na14V6-1	14	6	0.23
23	Na14V6-2	14	6	0.26
24	Na14V6-3	14	6	0.29
25	Na16V6-1	16	6	0.23
26	Na16V6-2	16	6	0.26
27	Na16V6-3	16	6	0.29

Samples were coded depending on the Na content, the EV/FA and the liquid/solid ratios. The liquid/solid ratios of 0.23, 0.26 and 0.29 were coded as 1, 2 and 3, respectively. For instance, Na12V4-2 mix code refers the mixture with 12% Na content where EV/FA and the liquid/solid ratios are 4 and 0.26. LGM samples were prepared by mixing FA, NaOH, EV and water in a standard cement mixer. The prepared fresh mortars were placed in 40×40×160 mm^3 sized 3-cavity molds and disc molds with a diameter of 250 mm and a thickness 20 mm. After placing molds, they were placed in an oven and were kept in there for 24 hours at 100ºC activation temperature. After that, they were taken out of the oven and were kept in air curing at 22±2 ºC room temperature for up to 28 days. Physical properties of LGMs such as unit weight, apparent porosity, water absorption ratio, UPV and thermal conductivity were determined at the end of 28 days. UPV test was made in accordance with TS EN 12504-4 standard (Turkish Standard Institution 2004). Flexural and compressive strength tests were also made according to TS EN 1015-11 standard (Turkish Standard Institution 2019). Tests for physical properties and strengths were carried out on prismatic mortar samples. Thermal conductivity test was performed on plate disc samples.

3. Experimental results and analysis

3.1. Dry unit weight

Dry unit weights of the samples are given in Figure 4. Unit weights of LWG samples vary between 906 kg/m^3 and 1477 kg/m^3. The average unit weights of the samples with the EV/FA volumetric ratio of 2, 4, 6 were determined as 1280 kg/m^3, 1122 kg/m^3 and 1045 kg/m^3, respectively.



	V2-1	V2-2	V2-3	V4-1	V4-2	V4-3	V6-1	V6-2	V6-3
Na 12	1090	1203	1250	906	1125	1008	953	1055	977
Na 14	1133	1250	1316	1012	1168	1203	1027	1066	1010
Na 16	1410	1477	1387	1152	1242	1281	1129	1132	1055

Figure 4. Dry unit weights of the samples.

With the increase in the amount of EV in the mixtures, a decrease in the unit weights was observed. Since the density of EV is less than the density of FA, a decrease in unit weights has been observed with the increase in the amount of EV in the mixture. Unit weights increased with the increase of Na content in the mixtures. It is stated that unit weights increase with the increase of activator ratio in geopolymer mortars containing fly ash (Atabey et al. 2020; Çelikten 2021; Kaya and Köksal 2021). The increase in the activator ratio increases the condensation and consolidation between the particles (Görhan and Kürklü, 2014). In a study where foam concrete was produced using vermiculite, cement and silica fume, it was stated that the unit weights varied between 587 kg/m^3-1040 kg/m^3 (Koksal, Sahin, and Gencel 2020). In another study where fly ash-based geopolymer was produced using pumice and expanded perlite as aggregates, the lowest unit weight was found to be 1250 kg/m^3 (Top et al. 2020).

3.2. Apparent porosity and water absorption ratio

The apparent porosity and water absorption ratios of the LWG samples are given in Figure 5 and Figure 6, respectively. The porosities of the samples vary between 11.55% and 27.27%, and the water absorption ratios vary between 4.88% and 24.66%. The lowest porosity and water absorption ratio were obtained at 2% EV/FA where Na was 16% and liquid/solid ratio was 0.23. The highest porosity and water absorption ratio were determined in samples with a EV/FA ratio of 6, liquid/solid ratio of 0.23 produced with 12% Na. For samples with EV/FA ratios of 2, 4 and 6, the average apparent porosity was 17%, 21.47%, 23.07%, and water absorption ratios were 12%, 18.14%, 19.81%, respectively. With the increase in EV/FA ratio, an increase was observed in water absorption and apparent porosity as a result of high porous structure of expanded vermiculite. As the ratio of FA in the mixture decreased with the increase of the EV/FA ratio, the binding property of the particles decreased. For this reason, the porosity has increased in the samples. On the other hand, due to the water retention feature of EV, an increase in the water absorption ratio was observed with the increase in the amount of EV in the samples.

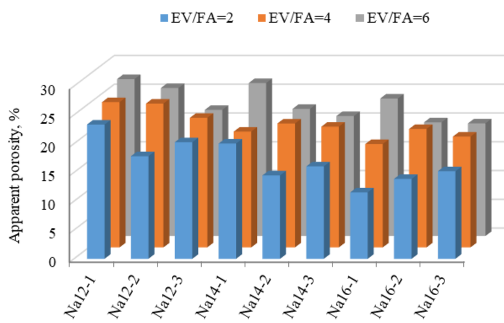


Figure 5. Apparent porosity test results.

The average porosity of the samples containing 12%, 14% and 16% Na were 23.2%, 20.3%, 18.0%, and the water absorption ratios were 19.9%, 16.6% and 13.5%, respectively. The increase in activator ratio increases the concentration and consolidation between particles (Görhan and Kürklü 2014). For this reason, with the increase of Na ratio in the samples, apparent porosity and water absorption ratios decreased. (Tekin et al. 2020) produced geopolymer using zeolitic tuff and marble powder. They found 32% porosity, 22.4% water absorption ratio in samples containing 5 M NaOH (M: concentration of sodium hydroxide in alkaline solution), and 32.8% porosity and 22.3% water absorption ratio in samples containing 10 M NaOH. It has been observed in previous studies that samples produced with high activator concentration have low porosity and water absorption ratios than samples produced with low activator concentration (Aliabdo, et al., 2016; Kaya and Köksal, 2021).

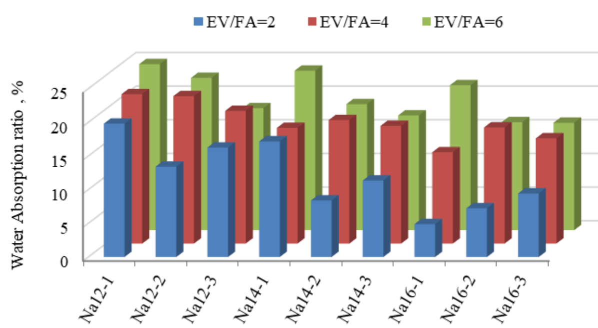
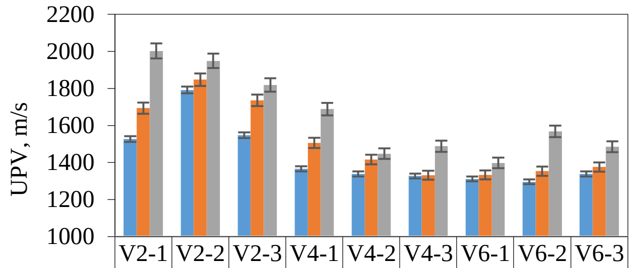


Figure 6. Water absorption ratio test results.

3.3. Ultrasonic pulse velocity (UPV)

UPV values of the LWG samples are given in Figure 7. The UPV of the samples vary between 1296 m/s - 2003 m/s. With the increase in the amount of activator in the samples, the porosity decreased, and consequently, an increase in the UPV was observed. The average UPV values for samples with EV/FA ratio 2, 4 and 6 were determined as 1768 m/s, 1435 m/s and 1384 m/s. With the increase in the amount of vermiculite in the samples, a decrease in the UPV was observed. In a study that produced high calcium fly ash geopolymer using crushed clay bricks and pumice as aggregates, it was detected between 1586 m/s-1858 m/s in pumice aggregated samples (Wongsa et al., 2018). In a study where geopolymer was produced using EV and FA, samples produced with 10 M NaOH showed 3%-11% less UPV ratio compared to samples produced with 15 M NaOH (Tekin et al., 2020). Therefore, the results obtained are consistent with the previous geopolymer studies (Kim et al., 2014). Increasing the activator concentration causes an increase in UPV (Kaya and Köksal 2021; Tekin et al. 2020). UPV is also directly related to the porosity of concrete (Muñoz-Sánchez, Arévalo-Caballero, and Pacheco-Menor 2016).



	V2-1	V2-2	V2-3	V4-1	V4-2	V4-3	V6-1	V6-2	V6-3
Na 12	1527	1792	1547	1366	1339	1328	1311	1296	1339
Na 14	1694	1848	1736	1506	1417	1332	1333	1353	1376
Na 16	2003	1949	1818	1689	1448	1488	1398	1568	1485

Figure 7. UPV values of the samples.

In a previous study, it was stated that UPV in concrete is significantly affected by aggregate type, unit weight and concrete density (Mohammed and Rahman 2016). In a study where foam concrete was produced using EV and silica fume, UPV values between 1.02 km/s and 1.83 km/s were determined (Koksal et al., 2020). The relationship between the porosity of the samples and the UPV is given in Figure 8. There is a strong correlation with R^2 = 0.816 between the porosity and UPV values of the samples. In a study where geopolymer was produced with natural sand and expanded clay aggregate, it was stated that ultrasonic pulse velocities decreased with the increase of clay aggregate (Bhogayata et al., 2020). UPV values increased with the decrease in the void ratio in the samples. The unit weight increases with the decrease in the void ratio in the samples. In a light geopolymer study, there is a R^2=0.89 relationship between UPV and unit weight (Wongsa et al., 2018).

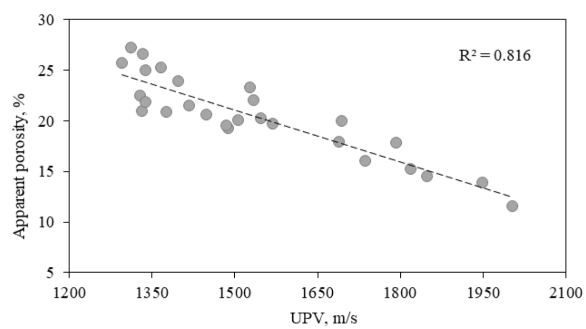


Figure 8. Relationship between apparent porosity and UPV.

3.4 Thermal conductivity

Thermal conductivity values of LGMs were determined by the tests, in which the hot wire method was used, on plate disc samples. The hot wire method is a method based on measuring the temperature rise at a certain distance using a linear heat source (hot wire) embedded in the material to be tested (Davis, 1984). Hot wire method is used to measure and calculate the effective thermal conductivity of granular materials (Gonzo, 2002; Liang and Li, 2006; Tavman, 1996) and building materials (Bouguerra 1999; Bouguerra et al. 1998; Stefanidou et al. 2010). The thermal conductivity test setup and measured values are shown in Figure 9 and Figure 10, respectively.

A significant decrease in thermal conductivity was observed with increasing EV/FA ratio or the amount of EV in the LGM mixture. In a study where foam geopolymer was produced with fly ash, it was stated that the thermal conductivity coefficient decreased with the decrease in density (Shao et al. 2018). In another study where geopolymer was produced with fly ash, a low thermal conductivity up to 0.107 W/mK was detected in the sample with a density of 560 kg/m3 (Novais et al. 2016). In a study where conventional mortar samples were produced using cement and EV, thermal conductivity was found between 0.076-0.105 W/mK (Novais et al. 2016). Al-Si Geopolymer systems have lower thermal conductivity coefficients due to higher void ratios compared to traditional portland cement systems (Pan et al. 2018). In a study where LGW was produced using EPS (expanded polystyren foam), the presence of EPS led to a significant decrease in thermal conductivity. It was stated that the thermal conductivity reached the highest value in samples with the highest unit weight, while the thermal conductivity was at the lowest value in samples with the smallest unit weight (Colangelo et al. 2018). In foam concretes containing fly ash, the thermal conductivity was reported to be 0.15-0.48 W/mK in samples with densities varying between 585 and 1370 kg/m3 (Zhang et al. 2015). EV is a good thermal insulation material due to its high porosity structure. The reductions in thermal conductivity with adition of EV to LGM mix can be explained as a result of the low thermal conductivity and mineralogical structure of the EV itself. Thermal conductivity values obtained in this experimental study vary between 0.094 W/mK-0.323 W/mK. The lowest thermal conductivity measured as 0.094 W/mK was observed on LGM mixture at which Na content of 12% and EV/FA ratio of 6.

Figure 9. Thermal conductivity test setup.

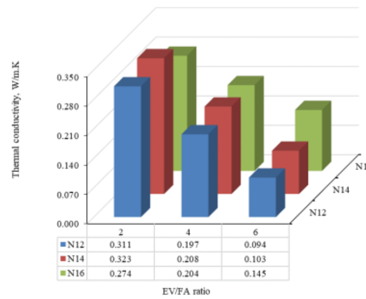
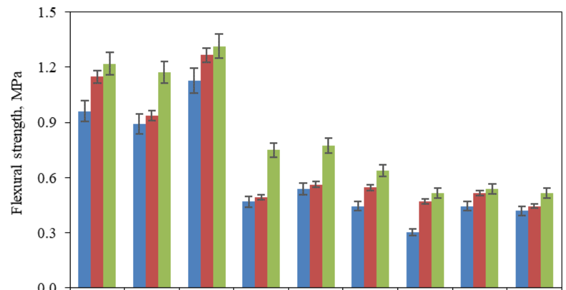


Figure 10. Thermal conductivity test results.

3.5. Flexural strength

Flexural strengths of the LGMs are given in Figure 11. Flexural strength varies between 0.30 MPa and 1.31 MPa. The lowest flexural strength is 0.30 MPa in the sample with an EV/FA ratio of 6 and a liquid/solid ratio of 0.23 produced with 12% Na. The highest flexural strength was determined as 1.31 MPa in the sample with an EV/FA ratio of 2 and a liquid/solid ratio of 0.29 produced with 16% Na. In all samples, an increase in flexural strength was observed with the increase in the activator ratio and the increase in the liquid/solid ratio. The average flexural strengths of the samples with Na ratios of 12%, 14%, 16% were determined as 0.62 MPa, 0.71 MPa and 0.83 MPa, respectively. With the increase of Na ratio from 12% to 16%, the flexural strength increased by 33.8%. Average flexural strengths of samples with a liquid/solid ratio of 2,4,6 were determined as 1.11 MPa, 0.58 MPa and 0.46 MPa, respectively. With the liquid/solid ratio increasing from 2 to 6, the flexural strength decreased by 41.44%. In a study where pumice based geopolymer paste was produced, it was reported that the flexural strength increased at 8 M-12 M NaOH concentration and decreased between 14 M-18 M (Safari et al., 2020). Atiş et al. (Atiş et al. 2015) stated that the flexural strength increases with the increase of Na ratio in fly ash geopolymers that they kept at 105 °C for 24 hours. Kaya and Köksal (2021) stated that the flexural strength of the cement added geopolymer concretes decreased with the increase of the Na/binder ratio. In a study where FA based geopolymer was produced, it was reported that the flexural strength increased by 3.5% with the molarity increasing from 8 to 10 (Mustafa Al Bakri et al., 2012). In another study where geopolymer lightweight concrete was produced with FA, it was stated that the flexural strengths decreased with the decrease of the sample unit weight (Brooks et al., 2010). In this study, unit weights and flexural strengths decreased with the increase of EV/FA ratio as a result of EV's low bulk density as well as low resistance to load. Variation of the flexural strength in the study, depending on the activator ratio, liquid/binder ratio and EV/FA ratio are similar to the literature.

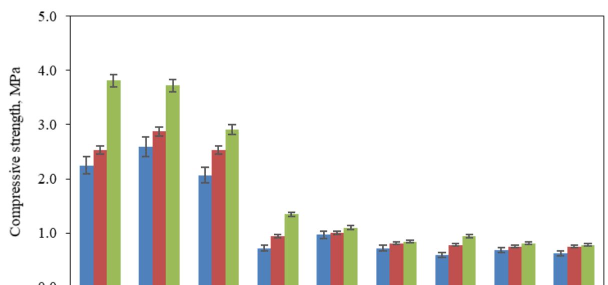


	V2-1	V2-2	V2-3	V4-1	V4-2	V4-3	V6-1	V6-2	V6-3
Na 12	0.96	0.89	1.13	0.47	0.54	0.45	0.30	0.45	0.42
Na 14	1.15	0.94	1.27	0.49	0.56	0.55	0.47	0.52	0.45
Na 16	1.22	1.17	1.31	0.75	0.77	0.64	0.52	0.54	0.52

Figure 11. Flexural strength test results.

3.6. Compressive strength

The compressive strengths of the LGM samples are given in Figure 12. Compressive strength varies between 0.59 MPa and 3.81 MPa. The lowest compressive strength is 0.59 MPa in the sample with a EV/FA ratio of 6 and a liquid/solid ratio of 0.23 produced with 12% Na.



	V2-1	V2-2	V2-3	V4-1	V4-2	V4-3	V6-1	V6-2	V6-3
Na 12	2.25	2.59	2.06	0.72	0.97	0.72	0.59	0.69	0.63
Na 14	2.53	2.88	2.53	0.94	1.00	0.81	0.78	0.75	0.75
Na 16	3.81	3.72	2.91	1.34	1.10	0.84	0.94	0.81	0.78

Figure 12. Compressive strength test results.

The highest compressive strength was determined as 3.81 MPa in the sample with an EV/FA ratio of 2 and a liquid/solid ratio of 0.23 produced with 16% Na. In all samples, an increase in compressive strength was observed with the increase in activator ratio and increase in liquid/solid ratio. The average compressive strength of the samples with 12%, 14%, 16% Na ratio was determined as 1.25 MPa, 1.44 MPa and 1.81 MPa, respectively. With the increase of Na ratio from 12% to 16%, the compressive strength increased by 44.8%. Average compressive strengths of samples with liquid/solid ratios of 2, 4, 6 were determined as 2.81 MPa, 0.94 MPa and 0.75 MPa, respectively. With the liquid/solid ratio increasing from 2 to 6, the compressive strength decreased by 73.3%. In a study where lightweight geopolymer panels were produced with vermiculite, the average compressive strength was determined as 2 MPa (Medri et al., 2015). In a study where FA based geopolymer was produced using crushed clay brick and pumice, a strength between 2.7 MPa and 18.3 MPa was obtained. It was stated that the compressive strength values of geopolymers produced with light aggregates decreased compared to samples produced with natural aggregate (Wongsa et al., 2018). As the geopolymer reaction and dissolution increase with the increase of NaOH concentration, an increase in compressive strength is observed (Görhan and Kürklü 2014; Hanjitsuwan et al., 2014; Kaur et al., 2018; Rattanasak and Chindaprasirt, 2009). Compressive strengths of LGMs decreased by increasing the amount of EV (or EV/FA ratio) in mixtures. Similar result has been reported by Gencel et al (Gencel et al. 2021). Figure13. shows the relationship between UPV and compressive strength. There is a relationship between UPV-compressive strength with R^2=0.847. Figure 14 shows the relationship between compressive and flexural strength. There is a relationship between compressive strength and flexural strength with R^2=0.849. The relationship between UPV and compressive strength is similar to the literature (Safari et al., 2020). The relationship between flexural strength and compressive strength is similar to FA based geopolymers in the literature (Kaya et al., 2020). In Figure 15, the SEM image of the sample with a EV/FA ratio of 2 and a liquid/solid ratio of 0.29 produced with 12% Na is given after the compressive strength test. The stratified distribution of expanded vermiculite and N-A-S-H gel formation are seen on the Figure 15. In addition, it has been determined that the sample has a gap structure. The layered distribution of expanded vermiculite in the structure and large gaps cause weak bond strength (Tekin et al., 2020).

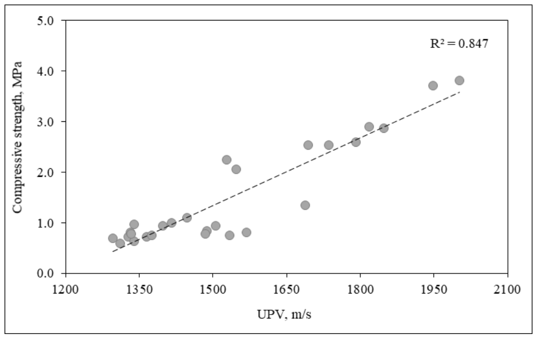


Figure 13. Relationship between UPV and compressive strength.

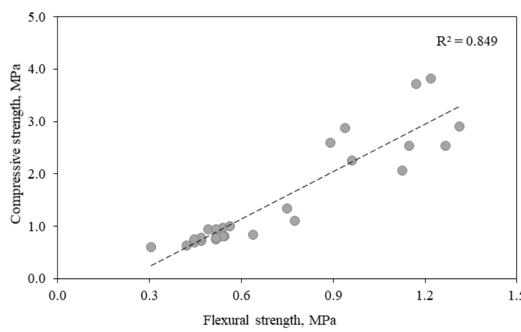


Figure 14. Relationship between flexural and compressive strengths.

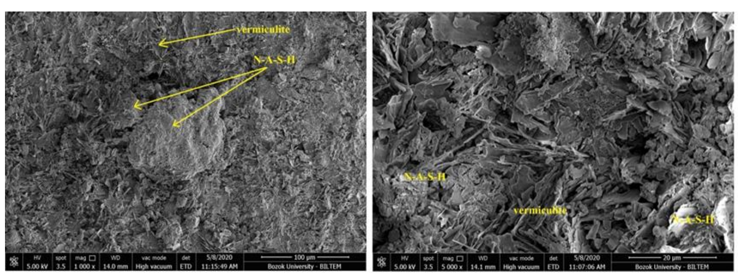


Figure 15. SEM images of LGM coded N12V2-3.

4. Conclusions

In this study, in which vermiculite was used as aggregate in fly ash based LGM, the following results were obtained.

1. Unit weights of LGM samples were determined between 906 kg/m^3 and 1477 kg/m^3, UPV values between 1296 m/s and 2003 m/s, and flexural strengths between 0.30 MPa and 1.31 MPa.
2. The increase in the amount of activator and liquid/solid ratio increased the reaction of the fly ash in the geopolymer. Thus, geopolymer has a more compact structure. For this reason, water absorption ratio decreased, flexural and compressive strength increased.

3. With the increase of EV/FA ratio, apparent porosity, water absorption ratio increased, but UPV decreased. Pore structure of expanded vermiculite has played very important role on all those properties of LGMs. On the other hand, due to the low strength of expanded vermiculite itself, the flexural and compressive strengths decreased with the increase in the EV/FA ratio. Compressive strength varying between 0.59 MPa and 3.81 MPa was obtained in LGM samples with unit weights varying between 906 kg/m^3 and 1477 kg/m^3.
4. Improvements were observed in the thermal insulation properties of fly ash based geopolymer mortars with the addition of expanded vermiculite, and LGM with a thermal conductivity of 0.094 W/mK was obtained. So expanded vermiculite could be alternative to other lightweight aggregates such as pumice, expanded clay, etc. for geopolymer insulation material production.

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