THE EFFECT OF CURING TEMPERATURE AND WATER CONTENT ON THE PROPERTIES OF LIGHTWEIGHT GEOPOLYMERS CONTAINING EXPANDED PERLITE

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Abstract

In recent decades, lightweight concrete production has undergone significant development, and its consumption is increasing worldwide due to its importance in construction and infrastructure. A significant advancement in lightweight concrete technology was the development of industrially manufactured lightweight aggregates. Lightweight concrete offers several advantages, including reduced dead loads in structures and more effective building insulation compared to OPC. Additionally, sustainable building materials, such as geopolymers, are used to address ecological problems associated with the production of Portland cement. Lightweight geopolymer concrete combines the advantages of the two approaches. They can be produced by mixing low-specific-gravity natural or synthetic aggregates with aluminosilicate binders and an alkaline solution. In this study, geopolymer samples were produced using fly ash as an aluminosilicate precursor and expanded perlite as a partial replacement for the CEN standard sand by weight. The production of lightweight geopolymers using expanded perlite and the effects of production conditions on the mechanical and microstructural properties of the geopolymers were investigated. Geopolymer samples were produced using different water amounts and cured at different curing temperatures, and their effects on the properties were investigated. Findings revealed that using expanded perlite, particularly at 70°C curing temperature and a specific water amount (to obtain a flow diameter of 15 cm), significantly decreased density while maintaining mechanical properties by obtaining acceptable compressive strength, approximately 75% of that of the reference sample, resulting in an effective lightweight geopolymer mortar that supports sustainable practices.

KÜRLEME SICAKLIĞI VE SU İÇERİĞİNİN GENLEŞTİRİLMİŞ PERLİT İÇEREN HAFİF JEOPOLİMERLERİN ÖZELLİKLERİNE ETKİSİ

Anahtar Kelimeler
Genleştirilmiş perlit
Jeopolimer
Hafif beton

Öz

Son yıllarda hafif beton üretimi önemli ölçüde gelişmiştir. İnşaat ve altyapıdaki önemi nedeniyle dünya çapında tüketimi gün geçtikçe artmaktadır. Hafif beton teknolojisindeki önemli bir ilerleme, endüstriyel olarak üretilen hafif agregaların geliştirilmesi olmuştur. Hafif beton, yapılarda ölü yüklerin azalması ve Portland çimentosuna kıyasla daha etkili bina yalıtımı gibi çeşitli avantajlar sunmaktadır. Ek olarak, jeopolimerler gibi sürdürülebilir yapı malzemeleri, Portland çimentosu üretimiyle ilişkili ekolojik sorunları çözmek için kullanılmaktadır. Hafif jeopolimer beton iki yaklaşımın avantajlarını birleştirir. Bu karışımlar, düşük özgül ağırlıklı doğal veya sentetik agregaların alüminosilikat bağlayıcılar ve alkali bir çözelti ile karıştırılmasıyla üretilebilirler. Bu çalışmada, alumina silikat kaynağı olarak uçucu kül ve ağırlıkça CEN standart kumunun kısmi ikamesi olarak genleştirilmiş perlit kullanılarak jeopolimer numuneleri üretilmiştir. Genleştirilmiş perlit kullanılarak hafif jeopolimerlerin üretimi ve üretim koşullarının jeopolimerlerin mekanik ve mikroyapısal özellikleri üzerindeki etkileri araştırılmıştır. Farklı su miktarlarının ve farklı kürleme sıcaklıklarının jeopolimer numunelerinin özelliklerine olan etkileri incelenmiştir. Araştırma sonuçları, özellikle 70°C kürleme sıcaklığında ve belirli bir su miktarında (15 cm akış çapı elde etmek için) genleştirilmiş perlit kullanımının, mekanik özellikleri korurken yoğunluğu önemli ölçüde azalttığını ve referans numunenin yaklaşık %75'i

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kadar kabul edilebilir bir basınç dayanımı elde edilmesini sağladığını ortaya koymuştur. Bu durum, sürdürülebilir uygulamaları destekleyen etkili, hafif bir jeopolimer harç elde edilmesini sağlamıştır.

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1. Introduction

The demand for durable and sustainable building materials has gained significant importance as a result of the concerns due to the climate change. Eco-friendly products that reduce negative effects on the environment and contribute to protecting resources are becoming increasingly crucial (Ozen & Stephan, 2025). In recent decades, there has been a significant increase in the search for new ecological building materials to address the ecological crises that result from the production of Portland cement. These materials can either replace cement entirely or partially with materials that have pozzolanic properties (Aziz et al., 2021).

Amorphous or semi-crystalline three-dimensional aluminosilicate materials that can be produced from aluminosilicate minerals or industrial aluminosilicate by-products are referred to as geopolymers, a term first used by Davidovits in the 1970s (Szabó et al., 2022). Geopolymers exhibit a wide range of important properties, including high compressive strength, fire resistance, and low shrinkage. Geopolymers are attractive alternative materials to conventional Portland cement due to their environmentally sustainable properties and low CO_2 emissions, primarily depending on the raw materials from which they are produced (Roviello et al., 2017).

Many natural pozzolans and artificial pozzolans produced as industrial by-products and wastes, such as fly ash, metakaolin, waste glass dust, ferrochrome slag, raw perlite, ceramic sanitaryware waste (Çelikten et al., 2022), ceramic pottery waste (Bayer Ozturk et al., 2023), and concrete demolition waste, are used as binders in geopolymer production. Fly ash is one of the artificial pozzolans commonly used in geopolymer binders (Karakaş et al., 2023). It is generated by coal-fired plants, which are responsible for 38% of global electricity production. The volume of by-products generated reached approximately 1.1 billion tonnes in 2017, making the utilization of such by-products a crucial challenge (Szabó et al., 2022). Fly ash, in accordance with the waste hierarchy established under EU Directive 2008/98/EC, can contribute to reducing waste disposal and conserving natural resources through the recovery and recycling of such industrial residues(*Decision - 2014/955 - EN - EUR-Lex*, n.d.). Fly ash-based geopolymers require 60% less energy and release 80% less CO_2 during their production process. (Bayraktar et al., 2024) Therefore, the use of fly ash in geopolymers is considered a sustainable approach to green infrastructure materials that supports Sustainable Development Goals 9 (*Goal 9: Industry, Innovation and Infrastructure - The Global Goals*, n.d.), 12 (*Goal 12: Responsible Consumption and Production - The Global Goals*, n.d.) and 13 (*Goal 13: Climate Action - The Global Goals*, n.d.; Siddiq et al., 2025; Wardhono et al., 2024) . It is estimated that geopolymers provide 10% to 30% lower costs compared to OPC (Bayraktar et al., 2024).

Lightweight concrete production has undergone significant development, and its consumption is increasing worldwide due to its importance in construction and infrastructure. A significant advancement in lightweight concrete technology was the development of lightweight aggregates that could be manufactured industrially. Lightweight concrete offers several advantages, including reduced dead loads in structures and more effective building insulation compared to OPC. Lightweight concrete is widely used in the construction of high-rise building walls, pavements, metal constructions covering the layers, prefabricated panels, and superstructures (Ibrahim et al., 2025; Tayeh et al., 2021).

Lightweight geopolymer concretes are widely used in the construction industry as structural and non-structural materials. Lightweight building materials can reduce the weight or cost of the structures, and they are economical to transport because of their lightweight. The most important characteristics of lightweight concrete are its low density, good fire resistance, and good thermal insulation properties (Gharieb & Khater, 2025).

Lightweight geopolymer concretes can be produced by mixing low-specific-gravity natural or synthetic aggregates with aluminosilicate binders and an alkaline solution. Lightweight aggregates can be divided into two categories: natural (found in the environment with little or no modification) and artificial (a by product of the heat treatment of expanding materials or a fully manufactured product). Expanded clay, expanded perlite, expanded vermiculite, schist, quartz, and slate are in the group of artificial lightweight aggregates (Tale Masoule et al., 2022). Perlite is a natural volcanic glass found in countries as diverse as Greece, Turkey, Japan, the United States, China, and Hungary. It is

estimated that there are approximately 7 billion tons of perlite reserves worldwide. Perlite is an important source of non-metallic ore that can be used to produce expanded perlite mineral materials. Raw perlite may expand up to 20 times its original volume when heated, which makes it appropriate for applications involving plastering, masonry production, and lightweight concrete construction applications requiring enhanced acoustic and thermal insulation (El-Mir et al., 2023; Gao et al., 2021).
In this study, geopolymer samples were produced using fly ash as an aluminosilicate precursor and expanded perlite as a partial replacement of the CEN standard sand, aiming to further extend the findings of our earlier work (İnal et al., 2026). The production of lightweight geopolymers using expanded perlite and the effects of production conditions on the mechanical and microstructural properties of the geopolymers were investigated. Geopolymer samples were produced using different amounts of water and cured at different curing temperatures, and their effects on the properties were investigated.

2. Materials and Method

2.1. Material Properties and the Preparation of the Mortars

In the first step of the study, the reference mortar mixtures were prepared using fly ash, sodium silicate, water, and CEN standard sand (S) aggregates. Then, expanded perlite -incorporated samples were prepared by replacing 10% by weight of the CEN sand with expanded perlite, corresponding to a 75% volume replacement since the density of the expanded perlite used in this study was 0.05 g/cm^3. The chemical compositions of the materials are given in Table 1. Also, the granulometry of expanded perlite and CEN standard sand was provided in Figure 1.

Table 1. The chemical compositions of materials

Chemical Composition (%)	Fly Ash (FA)	CEN Standard Sand (S)	Expanded Perlite (EP)
SiO_2	59.52	97.22	74.00
Al_2O_3	20.76	nd	14.00
Fe_2O_3	6.25	nd	1.00
CaO	3.10	1.34	0.50
TiO_2	0.95	nd	nd
MgO	1.85	nd	0.50
Na_2O	1.42	nd	3.00
K_2O	2.12	nd	5.00
P_2O_5	0.53	nd	nd
SO_3	nd	nd	nd
BaO	0.12	nd	nd
L.O.I	3.38	1.44	-

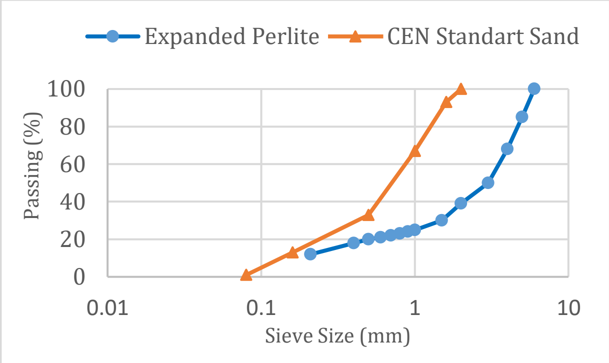

Figure 1. Granulometry curves of expanded perlite (Kılıçer, 2028) and CEN standard sand

Two different water content levels W1 and W2 were used in the mixtures based on two flow diameters, 15 cm and 21 cm, respectively. Additionally, two curing temperatures, 40 °C and 70 °C, were selected and applied for 48 hours to examine the effect of curing temperature on geopolymerization. The mixture compositions of the mortars and the appearance of the geopolymer samples after 48 hours curing were given in Table 2. and Figure 2., respectively.

Table 2. Mixture compositions of the mortars

Label	Fly ash (g)	Sodium Silicate	Sand (g)	Expanded Perlite (EP)	Water (g)
W1-40 °C-EP	900	360	540	60	100
W1-40 °C-S	900	360	600	-	41.25
W1-70 °C-EP	900	360	540	60	100
W1-70 °C-S	900	360	600	-	41.25
W2-40 °C-EP	900	360	540	60	175
W2-40 °C-S	900	360	600	-	90
W2-70 °C-EP	900	360	540	60	175
W2-70 °C-S	900	360	600	-	90

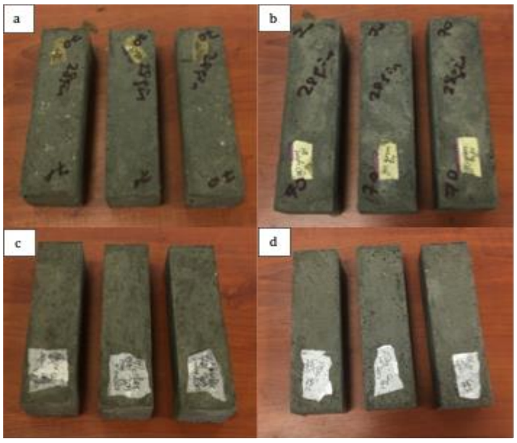

Figure 2. Appearance of the geopolymer samples after 48 hours of curing a)W1-S, b)W2-S , c)W1-EP, d)W2-EP

2.2. Determination of the Density

The bulk density of oven-dried geopolymer samples was determined on the 7th and 28th day according to the TS EN 12390–7 standard (*EN 12390-7:2019 - Density of Hardened Concrete*, n.d.).

2.3. Determination of Flexural and Compressive Strength

The flexural strength and the compressive strength tests were applied on 7th, and 28th day according to TS EN 196-1 standard(*EN 196-1:2016 - Cement Strength Testing Methods Compressive Flexural*, n.d.).

2.4. Microstructural Analysis

After the 28th day compressive strength tests, the microstructural analysis of the geopolymer samples was carried out by using a scanning electron microscope. (SEM; Supra 50VP, Zeiss)

3. Results

3.1. Density

The mean values, standard deviation, and coefficient of variation of geopolymer samples are shown in Table 3. According to the results, the density values decreased with the use of expanded perlite for various curing temperatures and water amounts. The highest density value was observed with the reference samples containing W1 water amount and cured at 40 °C. The lowest density value was obtained with the expanded perlite-containing samples with the W2 water amount and cured at 70 °C.

For the reference samples that contained only standard sand (S) and were cured at 40 °C, the density values decreased from the 7th day to the 28th day for both W1 and W2 water amounts by 5.7% and 7.7%, respectively. However, for the samples cured at 70 °C, densities increased by 1.6% and 5.3% from the 7th day to the 28th day.

For the expanded perlite-containing samples (EP) that were cured at 40 °C, the density values decreased by only 0.7% from the 7th day to the 28th day for the W1 water amount. In contrast, 2.2% increase was observed for the samples with the W2 water amount. For the samples cured at 70 °C, a slight decrease was observed, as 0.9% and 1.1% for both W1 and W2 water amounts, respectively.

Table 3. Mean density values, standard deviation and Coefficient of Variation of geopolymer samples

	7th Day			28th Day		
Label	Density (g/cm^3)	STD	CoV (%)	Density (g/cm^3)	STD	CoV (%)
W1-40 °C-EP	1635.42	31.33	1.92	1623.70	33.22	2.05
W1-40 °C-S	1812.50	38.47	2.12	1708.33	20.05	1.17
W1-70 °C-EP	1563.80	19.27	1.23	1549.48	5.97	0.39
W1-70 °C-S	1687.50	10.33	0.61	1714.84	10.33	0.60
W2-40 °C-EP	1460.94	40.78	2.79	1493.49	16.26	1.09
W2-40 °C-S	1716.15	20.05	1.17	1583.33	22.55	1.42
W2-70 °C-EP	1375.00	10.33	0.75	1359.38	6.77	0.50
W2-70 °C-S	1555.99	15.79	1.01	1638.02	25.42	1.55

3.2. Flexural Strength

The flexural strength values are given in Figure 3. According to the results, it was observed that for all sample groups, curing temperature significantly affected the early-stage flexural strength. The highest 28-day flexural strength was obtained in the reference samples cured at 70 °C and containing W1 amount of water, while the lowest 28-day flexural strength was obtained in the samples containing expanded perlite, prepared with W2 amount of water and cured at 40 °C.

In the reference samples consisting solely of standard sand (S) and cured at 40 °C, the flexural strength increased significantly from the 7th to the 28th day, with increases of 182.5% for W1 water amount and 180.6% for W2 water amount. Conversely, for the samples cured at 70 °C, there was an 8% decline in flexural strength from the 7th to the 28th day for those with W1 water amount. Meanwhile, the flexural strength for samples with W2 water amount remained relatively stable from the 7th day to the 28th day.

For the expanded perlite-containing samples (EP) cured at 40 °C, the flexural strength values increased from the 7th day to the 28th day for both water amounts, W1 and W2, by 125.3% and 15.5%, respectively. However, for the samples cured at 70 °C, the flexural strength values decreased by 5.9% for the W1 water amount from the 7th day to the 28th day. In contrast, for the samples with the W2 water amount, the flexural strength values remained nearly unchanged over the same period.

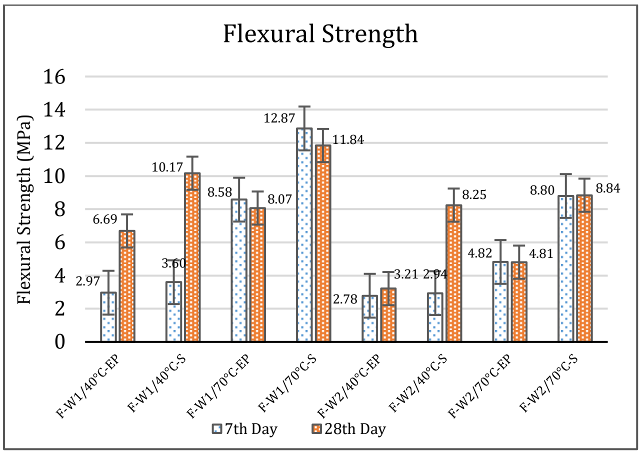

Figure 3. Flexural strength values of the geopolymer samples

3.3. Compressive Strength

The compressive strength values are given in Figure 4. When the results were examined, it was observed that for all sample groups, curing temperature significantly affected the early-stage compressive strength. The highest 28-day compressive strength was obtained in the reference samples cured at 70 °C and containing W1 amount of water, while the lowest 28-day compressive strength was obtained in the samples containing expanded perlite, prepared with W2 amount of water and cured at 40 °C. While the use of expanded perlite was expected to lead to a decrease in compressive strength, using the W1 amount of water and a curing temperature of 70 °C resulted in an acceptable compressive strength, approximately 75% of that of the reference sample.

In the reference samples that featured only standard sand (S) and were cured at 40 °C, there was a notable increase in compressive strength values from the 7th day to the 28th day, with increases of 288.69% for W1 water amount and 257.97% for W2 water amount. In contrast, for the samples cured at 70 °C, the compressive strength values showed little change from the 7th day to the 28th day for the W1 water amount, while samples with W2 water amount experienced a minor increase of 3.29%.

For the expanded perlite-containing samples (EP) cured at 40 °C, compressive strength values increased from the 7th day to the 28th day for both W1 and W2 water amounts by 209.33% and 26.46%, respectively. However, for the samples cured at 70 °C, compressive strength values decreased by 4.81% and 1.27% from the 7th day to the 28th day for W1 and W2 water amounts, respectively.

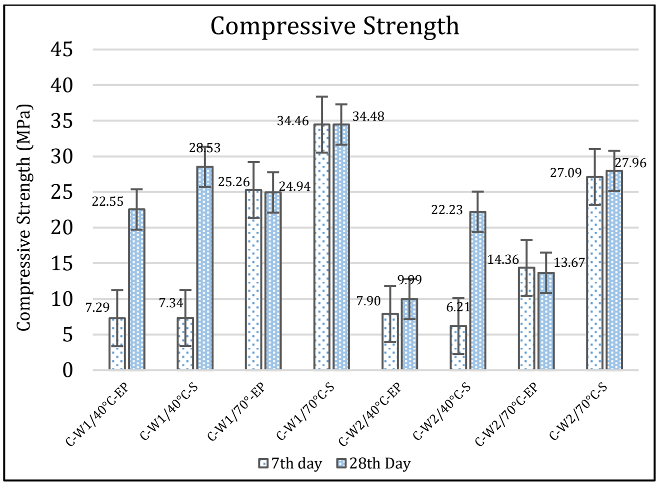

Figure 4. Compressive strength values of the geopolymer samples

3.4. Microstructural Analysis Results

SEM images of samples prepared using sand with the W1 water amount (15 cm flow diameter) are given in Figure 5. SEM images of samples prepared using sand with the W1 water amount revealed that a significant amount of spherical particles were present in the structure of samples cured at 40°C. As the temperature was increased from 40°C to 70°C, the geopolymer gel structure covered the particles, resulting in a more homogeneous structure.

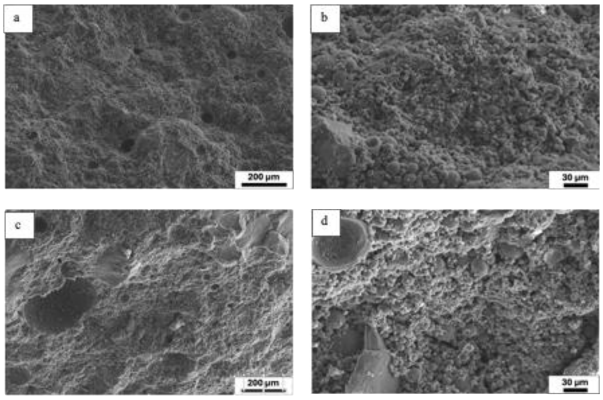

Figure 5. SEM images of W1/40°C-S samples a) with magnification 200x b) with magnification 1000x and W1/70°C-S samples c) with magnification 200x d) with magnification 1000x

The SEM images of geopolymer samples prepared with expanded perlite with the W1 water amount (15 cm flow diameter) are given in Figure 6. SEM images of samples prepared using expanded perlite revealed porosity due to the natural structure of perlite. Microcracks were observed in the structures of samples cured at both temperatures. Increasing the temperature to 70°C revealed a more compact gel structure. The presence of more pores in the structures of samples prepared using expanded perlite clearly indicates that the densities and compressive strengths of samples prepared using expanded perlite are lower than those of samples prepared using sand.

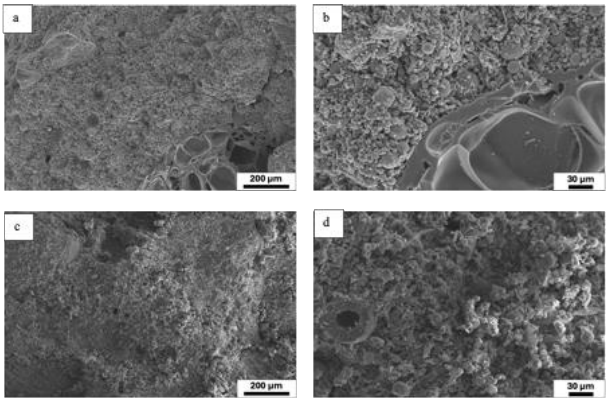

Figure 6. SEM images of W1/40°C-EP a) with magnification 200x b) with magnification 1000x and W1/70°C-EP c) with magnification 200x d) with magnification 1000x

Figure 7. represents the SEM images of geopolymer samples prepared with sand with the W2 water amount (21 cm flow diameter). When the SEM images of the samples prepared with sand aggregate were examined, it was seen that the porosity increases with the increase in the amount of water. The porous structure observed in samples cured at 40°C was particularly pronounced, whereas the structure of the sample cured at 70°C was less porous and more homogeneous. However, the spherical particles still remained in the structure. The lower strength results obtained at lower temperatures may be attributed to the higher porosity observed in samples cured at 40°C. At the same time, increasing the amount of water led to the formation of a more heterogeneous and porous structure.

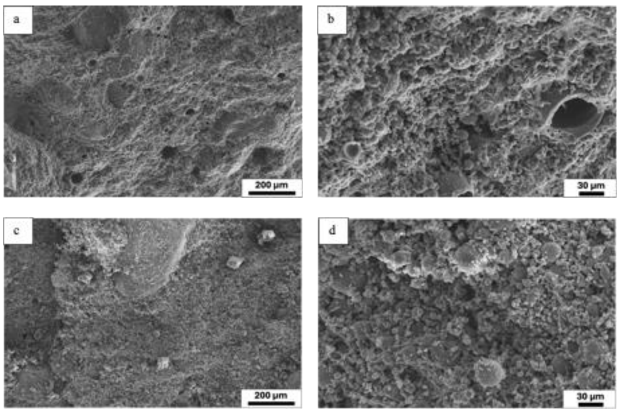

Figure 7. SEM images of W2/40°C-S samples a) with magnification 200x b) with magnification 1000x and W2/70°C-S samples c) with magnification 200x d) with magnification 1000x

SEM images of samples prepared with expanded perlite aggregate with the W2 water amount (21 cm flow diameter) are given in Figure 8. It was observed in the SEM images of the samples prepared with expanded perlite aggregate and with the W2 water amount that a highly porous structure was obtained. A large number of spherical particles remained in the structure of the sample cured at 40°C. The number of particles decreased with increasing temperature, which may be attributed to the fly ash reacting more rapidly with increasing temperature. Increasing the amount of water resulted in increased flow, which in turn increased segregation and porosity. It was observed that the most irregular and heterogeneous structures were formed in these samples. Their lowest compressive strength is also due to their structure.

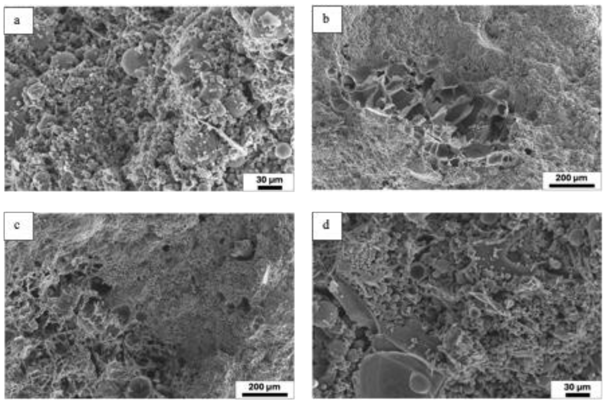

Figure 8. SEM images of W2/40°C-EP a) with magnification 200x b) with magnification 1000x and W2/70°C-EP c) with magnification 200x d) with magnification 1000x

4. Discussion

Water plays a critical role in geopolymerization reactions, and its optimal amount is essential for the material's structural development and performance (Ma & Ye, 2025). When water content exceeds the optimal value, it leads to higher porosity and reduced compressive strength (Park & Pour-Ghaz, 2018; Zuhua et al., 2009). According to the results, the W2 water amount exceeded the limits for both the reference samples and the expanded perlite-incorporated samples. Proper thermal curing also has great importance in enhancing the geopolymerization reaction (Aredes et al., 2015; Hasnaoui et al., 2020). In the geopolymerization process, higher temperatures accelerate the dissolution of aluminosilicates, which enhances the movement of ions within the system. This increased activity supports the geopolymerization process and the formation of geopolymers, ultimately leading to improved compressive strength of the samples (Yu et al., 2025). According to the results, a curing temperature of 40 °C was below the optimal curing temperature, as 7th-day strength values were significantly lower than 28th-day strength values. In contrast, there was a slight difference in the early and ultimate strength values for samples cured at 70°C for both the reference and expanded-perlite-containing samples. The highest compressive strength values were obtained at 70°C curing temperature. Furthermore, the density changes of samples using expanded perlite and sand, produced under the same curing conditions and water ratios, were found to be consistent with the changes in compressive strength. In general, the densities of samples using sand were higher than those using perlite. Similarly, an increase in compressive strength values was observed with the increase in density.

5. Conclusion

Lightweight geopolymers demonstrate encouraging outcomes, positioning it as an excellent alternative to traditional lightweight concrete for promoting more sustainable construction practices. From the test results and discussions provided, the following conclusions can be made:

• With the use of expanded perlite, especially for the 70°C curing temperature and W1 water amount, the density values significantly decreased without compromising much of the mechanical properties. That created a lightweight geopolymer mortar that delivers the best physical and mechanical properties to satisfy the requirements of sustainable environmental practices.

• The curing temperature and water content significantly affected both flexural and compressive strength. The highest flexural and compressive strength values were obtained by using W1 amount of water and curing at 70°C temperature for both the reference samples and expanded-perlite containing samples. At a curing temperature of 40°C, significant increases in strength were observed between 7 and 28 days, whereas at 70°C, very little change or slight decreases were observed over the same period. This result has been attributed to the possibility that geopolymerization may have been completed in 7 days at a curing temperature of 70°C.

• While the use of expanded perlite was expected to lead to a decrease in compressive strength, using the W1 amount of water and a curing temperature of 70 °C resulted in an acceptable compressive strength, approximately 75% of that of the reference sample.

• The results from the SEM analysis were consistent with the compressive strength results. It was noted that as the amount of water increased, a more porous structure developed, while a more gel-like structure was produced with rising temperatures.

Contributions of the Researchers

In this research, Ahmet İnal conducted the laboratory experiments and contributed to the preparation of the article; Derya Över determined the methodology, supervised, reviewed, and edited the article; Evren Arıöz conducted the SEM analysis and reviewed and edited the article.

Conflict of Interest

No conflict of interest has been declared by the authors.

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