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Effect of natural perlite on mechanical properties of light-weight aggregate composites by alkali-silica reaction

Ham perlitin hafif agregalı kompozitlerin alkali-silika reaksiyonu ile mekanik özellikleri üzerine etkisi

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Abstract

This study was performed in order to examine the behavior of natural perlite aggregate composites against durability problems caused by alkali silica reaction (ASR). Mortars containing 5%, 10%, 25%, 50%, 75% and 100% natural perlite were subjected to the ASR test. Mechanical tests were also performed on mortar samples. In addition, scanning electron microscope (SEM) analyzes were also applied. The expansion value of the 25% natural perlite substituted mortar with the highest ASR expansion increased by 145% as compared with the control mortar. When the natural perlite ratio increased from 25% to 100%, the expansion values decreased dramatically. 5% natural perlite substituted mortar had the highest compressive and flexural strengths. The SEM analysis results were obtained to be consistent with the ASR expansion results. Experimental results proved that mortars produced from 100% natural perlite can be used effectively to reduce the durability problems caused by ASR.

Keywords: Perlite, Alkali-silica reaction (ASR), Compressive strength, Flexural strength, Scanning electron microscopy (SEM)

Öz

Bu çalışma, ham perlit agregalı kompozitlerin alkali silika reaksiyonunun (ASR) neden olduğu dayanıklılık sorunlarına karşı davranışlarını incelemek amacıyla yapılmıştır. %5, %10, %25, %50, %75 ve %100 ham perlit içeren harçlar ASR deneyine tabi tutulmuştur. Harçlar üzerinde mekanik deneyler de yapılmıştır. Ayrıca taramalı elektron mikroskobu (SEM) analizleri de uygulanmıştır. En yüksek ASR genleşmesine sahip %25 ham perlit katkılı harcın genleşme değeri kontrol harcına göre %145 oranında artış göstermiştir. Ham perlit oranı %25'ten %100'e yükseldiğinde genleşme değerleri ciddi oranda azalmıştır. %5 ham perlit katkılı harç, en yüksek basınç ve eğilme dayanımına sahip olmuştur. SEM analiz sonuçlarının ASR genleşme sonuçlarıyla tutarlı olduğu görülmüştür. Deneysel sonuçlar, %100 ham perlitten üretilen harçların, ASR'nin neden olduğu dayanıklılık sorunlarını azaltmak için etkin bir şekilde kullanılabileceğini kanıtlamıştır.

Anahtar kelimeler: Perlit, Alkali-silika reaksiyonu (ASR), Basınç dayanımı, Eğilme dayanımı, Taramalı elektron mikroskobu (SEM)

1 Introduction

Concrete is the most prevalent building material in the world and consists of materials such as aggregate, water and cement; within gravel and sand are typically used as coarse and fine aggregate, respectively [1]. Cement is the most prevalent construction material; however, it exploit significant natural resources for the generation, such as water, limestone, and gypsum is noted an expensive material [2,3]. Along with causing exhaustion of natural resources, deforestation, and overburning of fossil fuel, the cement producing sector is one of the prime sources of CO_2 emission. The global cement sector promotes about 7% of greenhouse gas emissions to the earth's atmosphere, as specified in literature [4,5]. Additionally, aggregate resources are the prevailingly overstrained natural resources in the world. In 2018 alone, the global construction industry used $360 billion of natural aggregates [6]. In addition, gravel and sand mining is considered a harm practice as it endangers natural ecosystems and water bodies [7,8]. Therefore, reducing the amount of cement and natural aggregate in concrete is critical not only economically but also to save our ecosystem by reducing the environmental dangers associated with the production of concrete constituents [9].

Waste and recycled waste materials are increasingly used in concrete to come through save energy and environmental problems [10]. Enhancements in the properties of concrete and the benefits it provides to the environment owing to the use of waste materials encourage further research on green concrete production. Many alternatives and waste materials such as demolition and construction waste [11], fly ash [12], marble waste [13], natural pozzolan, ground granulated blast furnace slag, silica fume [14], açaí fibers [15], glass powder waste [16], cement kiln powder, nano-silica, electric arc furnace powder [17], wind turbine blade waste [18] are included in production to improve the properties of mortar or concrete, to conserve energy and to reduce greenhouse gas emissions.

The idea of "Lightweight Concrete", which emerged as a result of the combination of all these factors, has become

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crucial in the building industry, where aggregate and cement can be changed with other suitable materials without sacrificing the outstanding properties of concrete. Some advantages assert from using lightweight concrete are: (i) the use of low cost raw materials; (ii) the preservation of natural resources; (iii) economic benefits beside traditional concrete [19,20]. Despite its use dating back 2000 years, Lightweight Concrete is a versatile material that has attracted great interest and industrial demand in a wide variety of construction projects in recent years [21]. There was an increase in research in the development of lightweight concrete due to its remarkable benefits, such as its outstanding heat and sound insulation properties, to conserve energy and reduce greenhouse gas emissions, which are believed to be the main cause of global warming [22]. Due to its many advantages such as its good thermal insulation and low density, lightweight concrete was widely examined as both a structural and non-structural material [23]. Lightweight aggregate concrete is a special sub-type of structural concrete [24]. It is important to select and use the appropriate lightweight aggregate to produce lightweight concrete with the requested fresh density and sufficient mechanical properties [25]. Adding lightweight aggregates to conventional concrete due to their low specific gravity can also reduce some concrete problems such as aggregate separation [26].

Lightweight aggregates, which occur naturally or obtained as a by-product from industrial processing, can be used to substitute normal aggregates in concrete [27]. Lightweight aggregates are generally categorized as natural and artificial types. Commonly used natural lightweight aggregates are diatomite, tuff, pumice and volcanic slags [28]. Artificial lightweight aggregates are colliery waste, sintered ground fuel ash, blast furnace slag, and sintered slate [29]. There are also processed natural materials such as vermiculite, expanded clay, shale and perlite that can be used as lightweight aggregates in concrete production [30]. Lightweight aggregates are used as both coarse and fine aggregates in concrete [31]. In most cases, they are used to reduce the overall density of a concrete or mortar mix, hence dead loads, as well as the load associated with transporting large prestressed concrete members [32].

Perlite [33,34], an amorphous volcanic glass with about 70% SiO_2 content, is produced by crushing the raw material (perlite ore) and subjecting it to heat treatment [35]. In its natural state, perlite has a comparatively high water content in crystalline form, which evaporates when quickly heated at 900-1200 °C [36]. When subjected to these temperature values, its volume can be increased up to 20 times by converting chemically bound water into steam [37,38]. Numerous micropores in perlite provide lightness properties as well as heat and sound insulation [39]. Perlite is an inorganic material and can maintain its properties at high temperatures. In addition, perlite is insoluble in water and does not rot [40]. Turkey, China, USA and Greece are the most important perlite producers and constitute 95% of the worldwide production (the production amount for 2016 is 4.6 million tons) [41]. Perlites are used as aggregates in concrete, cement mortars, and especially in fire-resistant plaster production [42-46].

In previous studies, where perlite was used as an aggregate in concrete production, it was stated that the workability of the mixtures decreased with the increase in the perlite ratio [26]. Yim Wan et al. [47] reported that the use of perlite in concrete as a 100% substitute for natural fine aggregates reduces slump by 21.3%. This was dedicated to the high water absorption capacity of perlite. It was stated that perlite strengthens the adherence in cementitious composites by leading to a better ITZ [48]. Barnat-Hunek et al. [49] suggested that perlite added to concrete can show satisfactory frost resistance at lower concentrations. It was stated that lightweight cementitious composites produced by incorporating perlite microspheres are generally developed with good mechanical properties and acceptable shrinkage [25]. Tajra et al. [50] stated that the drying shrinkage of concrete increased when fine perlite aggregate was used in increasing proportions. In consequence of the use of perlite aggregate in the production of foam concrete by 3D printing method, it was emphasized that the properties of lightweight concrete were significantly improved [51]. Hamidi et al. [52] produced lightweight geopolymer concrete using perlite aggregate, and according to the results obtained, it was stated that severe segregation was observed for mixtures containing 25% or more perlite.

It is widely known that cement-based materials experience very serious durability problems owing to Alkali-silica reaction (ASR) throughout their service life [53]. The chemical reaction that takes place between alkali (K^+ and Na^+) and hydroxyl (OH^-) ions in the concrete pores and reactive aggregates in the presence of high relative humidity is known as ASR [54-57]. The gel product formed as a result of this reaction negatively affects the durability properties of the structures by causing expansion and cracking in cementitious composites [58].

When the effect of aggregates on ASR is examined, it is evaluated as a result of studies that, although it is practically difficult, the use of non-reactive aggregates in concrete/mortar production is successful in preventing ASR [59,60]. In addition, it has been stated that some non-alkaline reactive aggregates contribute to the alkalinity of concrete in the pore solution [57]. Although fly ash [61], slag [62], and non-reactive aggregates [63] are used to prevent ASR, it has also been emphasized that mineral additives with high calcium content may have the opposite effect [57,59]. Finally, as a result of the study conducted by Offei et al. [60], it was stated that the expansions caused by ASR could be reduced by using hydrophobic aggregates.

In the literature review, no research was found on ASR expansion and its effects in composites with natural perlite aggregates. This study was carried out to investigate the resistance of natural perlite, which is widely used as a lightweight aggregate, against ASR. In accordance with this purpose, the alkali silica reaction of the mortars containing 5%, 10%, 25%, 50%, 75% and 100% natural perlite and mechanical tests were performed. Comparisons were made with control mortars that did not contain perlite aggregates. In addition, evaluations were made by applying SEM analyzes in order to examine the reflections of the behavior of natural perlite mortars against ASR on the internal structure. It is thought that this original research, which was carried out on mortars with natural perlite aggregates, will be a reference in choosing the efficient aggregate ratio and type against the ASR. Finally, the potential for ASR in the ratios in which natural perlites with high silica content are used was taken into account in the study in terms of originality.

2 Experimental methods

2.1 Materials

Portland cement (CEM I 42.5 R type) was used in mortar production. Table 1 contains technical information about cement. River sand (the specific gravity of 2.63 g/cm^3) with high ASR potential, obtained from the Murgul/TR region, was used in control mortars. In order to evaluate the reactivity potential of river sand with high ASR potential, mineralogical content was provided for this sand. This content is included in Table 2. As can be seen in Table 2, river sand contains a high level of reactive silica that can lead to an alkali silica reaction.

Table 1. Technical information of cement

	CEM I 42.5 R
Chemical Compositions (%)	
SiO_2	19.49
Al_2O_3	4.68
Fe_2O_3	3.34
CaO	63.56
MgO	2.51
SO_3	2.96
Na_2O	0.37
K_2O	0.74
Cl^-	0.01
Loss on ignition	2.88
Insoluble residue	0.74
Physical Properties	
Specific surface (cm^2/g)	3443
Specific gravity	3.12
Volume expansion (mm)	1.0
Residue on a 32 micron sieve	7.44
Beginning and end of setting	2hrs-38min,3hrs-32min
Compressive strength (MPa)	
2nd day	27.5
28th day	54.9

Table 2. Mineralogical properties of river sand

	River Sand
Mineralogical Compositions (%)	
SiO_2	68.74
Al_2O_3	2.39
Fe_2O_3	1.13
CaO	16.15
MgO	0.63
TiO_2	0.10
Na_2O	0.88
K_2O	0.67
MnO	0.025
P_2O_5	0.065

Natural perlites were obtained from Erzincan/TR. Chemical properties of natural perlite (the specific gravity of 1.96 g/cm^3) are given in Table 3. As seen in Table 3, the high silica content of natural perlite indicates that it is a situation that should be examined for potential ASR danger.

Table 3. Chemical properties of natural perlite

	Natural Perlite
Chemical Compositions (%)	
SiO_2	73.79
Al_2O_3	12.90
Fe_2O_3	1.02
CaO	0.76
MgO	0.04
TiO_2	0.033
Na_2O	3.93
K_2O	4.21
FeO	0.38
MnO	0.070
P_2O_3	0.009

SEM image displaying the microstructure of natural perlite is given in Figure 1. As seen in Figure 1, the structure of natural perlite is very thin and consists of a small number of air and many capillary spaces with filigree lamellar widths [64].

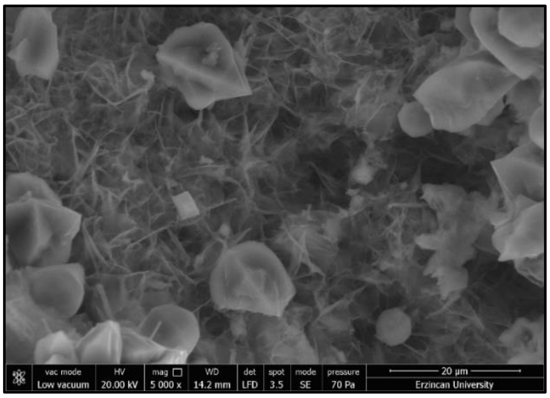

Figure 1. Structure of the natural perlite; SEM magnification x5.000

2.2 Parameters, coding and mortar mix design

The parameters selected within the scope of the study are the use of natural perlite in different proportions. Mortars with seven different mixtures were produced by substituting natural perlite aggregate with river sand at 5%, 10%, 25%, 50%, 75% and 100% by volume. Control mortars did not contain natural perlite. In order to properly ensure the workability of the samples produced using natural perlite, which is known to have high water absorption capacity, a polycarboxylate ether-based high-performance new generation superplasticizer (SP) chemical additive material was used in the study. Since the workability was negatively affected as the perlite ratio increased in the prepared mixtures, the usage ratio of chemical additives also differed slightly. In the coding, the shortening of natural perlite is shown with the first letters, natural perlite ratios are shown with numbers after the letters (without using the % sign). For example, NP25 represents the mixture containing 25% natural perlite. Control mortars are indicated by C. The mortar mix design prepared according to the TS EN 196-1 [65] standard for the study is presented in Table 4.

Table 4. Mortar mix design (cm^3)

Code	Natural Perlite (mm,%)					River Sand (0.125mm-4mm)	Cement	Water	SP (%)
	(4-2) (10%)	(2-1) (25%)	(1-0.5) (25%)	(0.5-0.25) (25%)	(0.25-0.125) (15%)				
C						990	440.00	206.80	0.6
NP5	3.65	9.12	9.12	9.12	5.47	940.50	440.00	206.80	0.65
NP10	7.29	18.24	18.24	18.24	10.94	891	440.00	206.80	0.72
NP25	18.24	45.59	45.59	45.59	27.36	742.50	440.00	206.80	0.8
NP50	36.47	91.18	91.18	91.18	54.71	495.00	440.00	206.80	0.85
NP75	54.71	136.78	136.78	136.78	82.07	247.50	440.00	206.80	0.89
NP100	72.95	182.37	182.37	182.37	109.42		440.00	206.80	0.93

2.3 *Casting, curing and testing of specimens*

ASR tests were applied on mortars designed according to ASTM C 1260 [66] standard. Mortars were designed as a result of weighing the sand and natural perlites separated into different grain classes, sieved from the sieves specified in the standard, in the stated amounts. Samples of 25x25x285 mm were produced for the ASR test. For mechanical tests, 40x40x100 mm samples were produced according to the TS EN 196-1 [65] standard. The mortar samples kept in the moulds were removed from their moulds after 1 day. The samples prepared for the ASR experiment were kept in 80ºC water for 1 day and their first lengths were measured (L_o). Then, the same samples were kept in 1 mol NaOH solution at 80 ºC and their lengths were measured at the end of the 3rd, 7th, 14th, 21st and 28th days, and the length changes were computed as %. Mechanical tests were carried out on the mortar samples, which were removed from the mould 1 day after production and kept in the curing pool for 28 days, according to TS EN 196-1 [65] standard. In the ASR tests, a total of 21 samples were produced, 3 for each series. In addition, 21 samples were produced, 3 for each series, to determine the compressive and flexural strength of the mortars. Results were created by averaging the values obtained from the samples. Scanning electron microscope (SEM) analysis was performed on the mortar samples with a QUANTA FEG 450 brand device in order to examine the changes in the internal structure as a result of the ASR experiment.

3 Results and discussion

3.1 *Alkali-silica reaction (ASR)*

As a result of the ASR test, the time-dependent expansions of the mortars with different natural perlite ratios and the control mortar are given in Figure 2. Accordingly, with the use of natural perlite, different and interesting results were obtained in the expansion values of the mortars depending on the ratio and day time.

When the early age (3rd and 7th days) graphs were examined, the expansions increased as the natural perlite ratio increased in comparison of the control mortar. This situation occurred in the opposite way in mortars with natural perlite ratio of 75% and 100%, and the values decreased compared to the control mortar. For example, at the end of the 3rd day, the expansion (NP100) of the mortar produced from 100% natural perlite was 60% less than the control mortar (C).

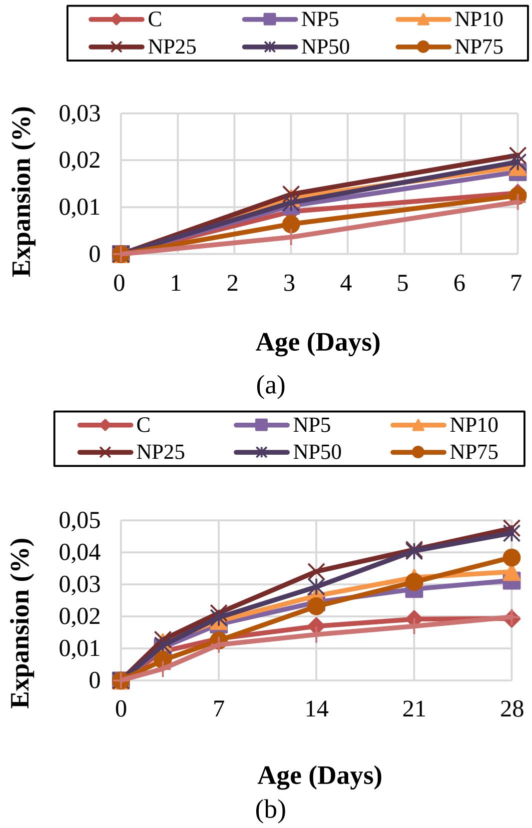

Figure 2. ASR expansion results of mortars, (a): Early ages results (1,3 and 7), (b): All ages results

When the 14-day expansion results were evaluated, especially the 25% and 50% natural perlite substituted mortar had the highest expansion values. This situation continued until the 28th day. For example, the expansion value (0.048%) of the 25% natural perlite substituted mortar on the 28th day increased by 145% compared to the control mortar (0.019%). The highest expansion values among all groups were monitored in the 25% natural perlite substituted mortar. When the natural perlite ratio increased from 25% to 100%, the expansion values for all days decreased dramatically. In fact, the expansion value (0.019%) of the 100% natural perlite substituted mortar at the end of the 28th day was 58% less than the 25% natural perlite substituted mortar (0.048%). In a few studies on alkali-silica reaction of mortars produced using natural perlite, it was reported that lightweight aggregates such as perlite with glassy phase and higher silica content can actively participate in pozzolanic reactions leading to ASR [34,67]. No visual crack was observed in the natural perlite substituted mortar bar due to the accommodation of the reaction products in the voids in the perlite aggregate. Consistency was obtained by observing this phenomenon in the SEM analysis results, where the inner part of the perlite aggregate was partially dissolved and cracked, and also deposited with reaction products (calcium-alkali-silica gel and various crystalline products) with increased Ca and alkali content. Similar behavior was reported in other studies [68,69]. However, considering the need to conduct studies on behavior at higher sample ages, it is thought that more advanced evaluations can be made on this subject. The expansions of the control mortar and the natural perlite substituted mortars remained within the limits set by ASTM C1260 [66]. This result confirmed that the use of perlite in mortars reduces the risk of ASR [53]. This study proved that the expansions that will occur as a result of alkali silica reaction can be significantly reduced with the use of natural perlite in mortars at high ratios (75% for early age, 100% for all ages). Considering the many studies using complementary cementitious materials (e.g. fly ash) to reduce the expansion problems caused by ASR [70,71], the importance and specificity of achieving this result, especially with the use of perlite aggregate at high ratios, will be better understood.

3.2 Compressive strength

The compressive strengths-expansion results of the mortars are shown in Figure 3. Natural perlites caused a decrease in the compressive strength of the mortars. The only exception to this situation was the 5% natural perlite substituted mortar (NP5) and the highest compressive strength was reached among all groups (this value is 12.94 MPa). The lowest compressive strength was obtained with 6.84 MPa in the mortar (NP100) produced from 100% natural perlite. Significant strength losses occurred compared to the control mortar, especially with the use of 25% of natural perlite. For example, the decrease in compressive strength of 75% natural perlite substituted mortar compared to the control mortar is 32%. In studies on the compressive strength of composites produced with lightweight aggregates such as natural perlite, it was observed that the strengths decreased compared to the control mortar [67,72,73]. As observed in this study, the losses in compressive strength were experienced more with the increase of the perlite substitution ratio [47,74,75]. It is thought that perlite, with its porous internal structure, significantly reduces the compressive strength together with its low density value [26,64].

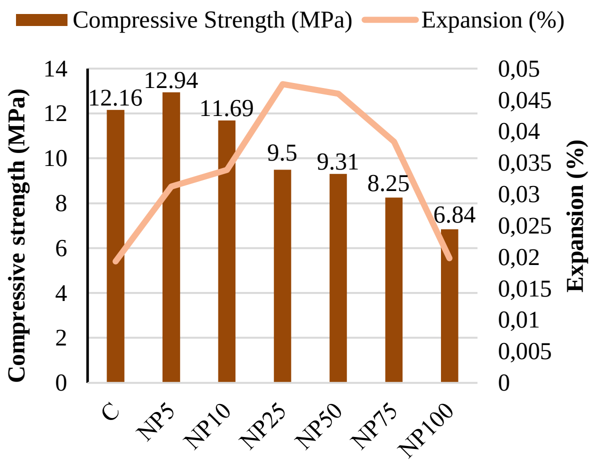

Figure 3. Compressive strengths-expansion results

3.3 Flexural strength

The flexural strength-expansion results are given in Figure 4.

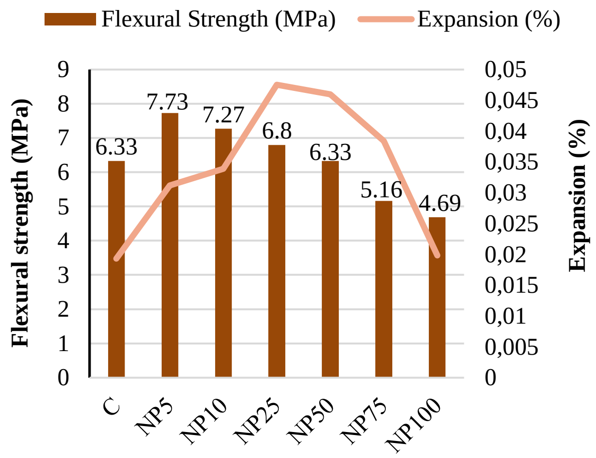

Figure 4. Relationship between flexural strength and expansion results

Just as in the compressive strength results, flexural strength results decreased as a result of increasing use of natural perlite, except for the 5% natural perlite substituted mortar. The highest flexural strength was obtained with 7.73 MPa in the 5% natural perlite substituted mortar (NP5), and the lowest flexural strength was obtained with 4.69 MPa in the mortar produced from 100% natural perlite (NP100). Although the strength results decreased with the use of natural perlite, there was no dramatic difference between the groups. It was also reported in studies that lightweight aggregate composites such as perlite had detrimental effects on flexural strength [76,77]. With the increasing use of perlite in mortars, flexural strength values decreased as observed in this study [72,78,79].

3.4 Relationship between compressive and flexural strength

When the compressive strength-flexural strength graph of the mortars with different natural perlite ratios and the control mortar given in Figure 5 is examined, it is seen that the flexural strength values increase as the compressive strength values increase.

The fact that the R^2 value (0.9088) of the equation of this graph being very close to 1 is an indication that the compressive strength-flexural strength relationship of natural perlite substituted mortars is linear. With this study, it was revealed that the flexural strengths of natural perlite substituted mortars with high compressive strength would also be higher. When the natural perlite substituted mortars are evaluated within themselves, it can be easily seen on the graph that both the compressive strength and flexural strength values decrease with the increase in the natural perlite ratio. The mortar with the highest compressive and flexural strength values is the samples containing 5% natural perlite. The ratio of 5% in terms of natural perlite can be expressed as the ideal ratio in terms of the compressive strength-flexural strength relationship of mortars.

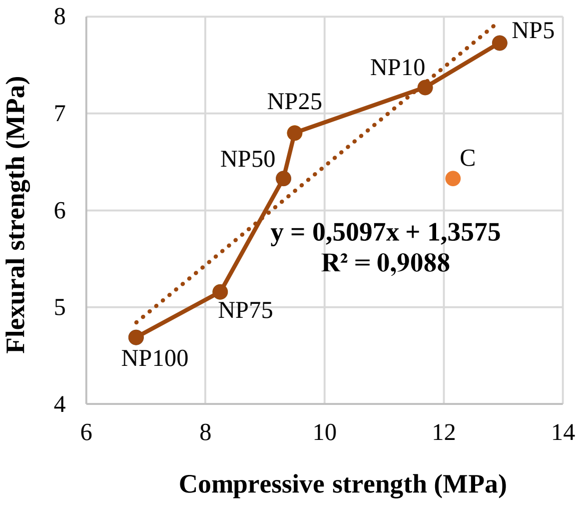

Figure 5. Relationship between compressive-flexural strength values

3.5 Scanning electron microscopy (SEM) analysis

At the end of the 28th day, the microstructure of the mortar bars subjected to the ASR test was investigated by SEM analysis. Along with the control mortar, SEM images of the mortars with the highest ASR expansion (25% and 50% natural perlite substituted) and the mortar with the lowest ASR expansion (100% natural perlite substituted mortar) were also given in Figures 6-9. Figure 6 includes control mortar, Figure 7; 25% natural perlite substituted mortar, Figure 8; 50% natural perlite substituted mortar and Figure 9; SEM images of 100% natural perlite substituted mortar. In Figure 6, the formation of ASR gel with the hydration products in the control mortar can be clearly seen.

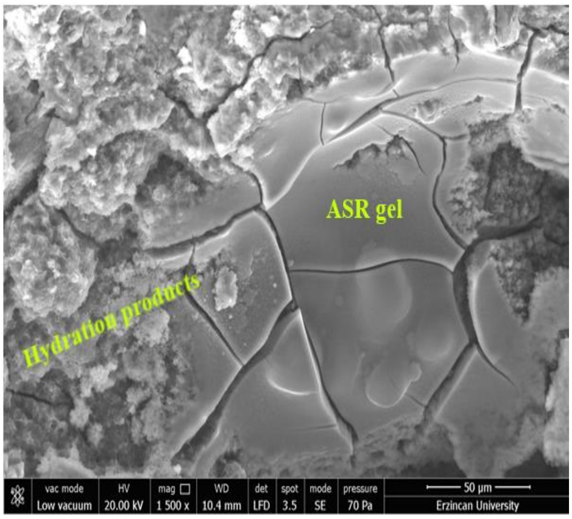

Figure 6. Structure of the control mortar; SEM magnification x1.500

In Figure 7 of the SEM image representing the 25% natural perlite substituted mortar, map-shaped cracks were evident with the density of the ASR gel compared to the control mortar.

In Figure 8, it is seen that ASR gel formations are obtained in more than one place in the internal structure of 50% natural perlite substituted mortar.

As can be clearly seen in Figure 9, no evidence of gel formation in the internal structure was obtained as a result of the ASR experiment with the use of 100% natural perlite in mortars. Only crack formations were observed around the perlite and in itself.

In parallel with the results obtained from this study, gel formations and map-shaped cracks resulting from ASR have been observed both experimentally through SEM analyzes and in practice in studies in the literature [80-86].

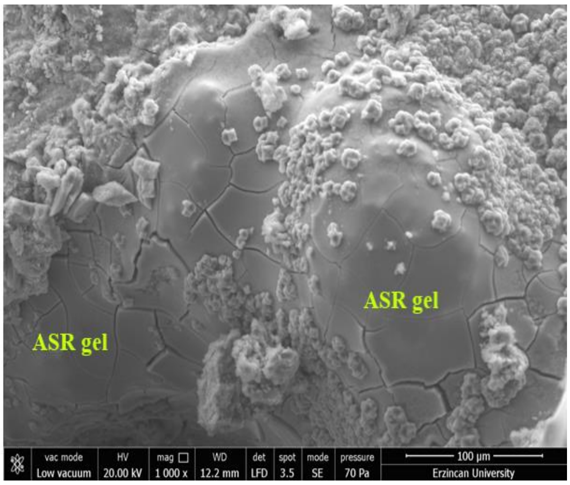

Figure 7. Structure of the 25% natural perlite substituted mortar; SEM magnification x1.000

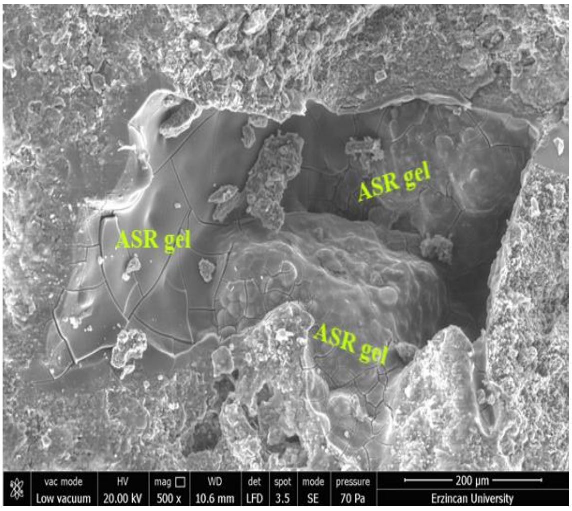

Figure 8. Structure of the 50% natural perlite substituted mortar; SEM magnification x500

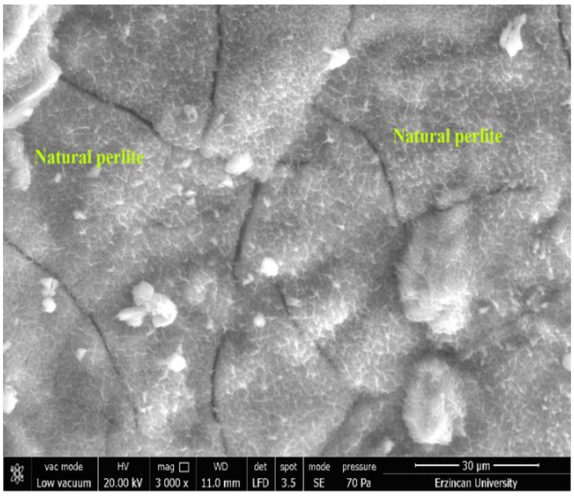

Figure 9. Structure of the 100% natural perlite substituted mortar; SEM magnification x3.000

When the results of SEM analysis were evaluated in general; parallel to the ASR expansion results, although the density was less in the control mortar, ASR gel formations and cracks in the internal structure were clearly observed as a result of the use of 25% to 50% natural perlite in the mortars. In addition, the SEM analysis images of the 100% natural perlite substituted mortar, wherein ASR expansion value was almost non-existent, were also found to confirm this result.

4 Conclusion

The main results obtained from the experiments carried out in this study are evaluated below:

1. The mortar with the highest ASR expansion was 25% natural perlite substituted mortar. It was revealed that with the increase of natural perlite usage ratio to 75% and 100%, the expansions due to ASR could be reduced dramatically.
2. Although expansions were observed as a result of ASR in all mortar groups, it was determined that these values remained between the limit values and were not harmful. This result showed that natural perlite substituted mortars could be used effectively against the problems caused by alkali silica reaction.
3. 5% natural perlite substituted mortar had the highest compressive and flexural strength among all groups. In this study, it was determined that the use of 5% natural perlite in mortars was the ideal ratio in terms of mechanical properties. Compressive and flexural strengths decreased with the increase of natural perlite replacement ratio.
4. The compressive strength-flexural strength relationship of the mortars produced using natural perlite was found to be linear and significant with the R^2 value (0.9088) being very close to 1. It was revealed that the higher the compressive strength of the natural perlite added mortars, the higher the flexural strengths can be obtained.
5. SEM analysis results were found to be consistent with the ASR expansion results. Especially in the internal structure of the 25% and 50% natural perlite substituted mortars, map-shaped cracks were clearly observed with the formation of an intense ASR gel. No structure of gel formation was observed in the SEM image of 100% natural perlite substituted mortar, which had the lowest ASR expansion among all mortar groups.
6. Experimental findings have proven that mortars produced from 100% natural perlite can be used effectively to reduce durability problems caused by alkali silica reaction. It was proved by the results of this study that natural perlite would take place as a reference in the selection of aggregate type and ratio to be used against ASR.

Conflict of interest

The author declares that there is no conflict of interest.

Similarity rate (iThenticate): 12%

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