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Original Article

Production of perlite-based-aerated geopolymer using hydrogen peroxide as eco-friendly material for energy-efficient buildings

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ABSTRACT

Using ground raw perlite through alkali activation to produce various construction materials such as plaster, grouting, and concrete can provide economic and environmental advantages by reducing Portland cement consumption. It is aimed to produce cementless pastes and cementless mortars based on the alkali activation of raw perlite and standard sand for this study. Perlite and alkali activators (NaOH and Na_2SiO_3) were used as binding materials to produce cementless paste and mortar. In addition, aerated lightweight pastes and mortars were produced using hydrogen peroxide (H_2O_2) as a blowing agent. Thus, the aeration mechanism of the sample was examined, and the changes in apparent density, compressive strength, and flexural strength values were determined. At the same time, the thermal conductivity properties of aerated paste and mortars were investigated. Geopolymers in various Water/Perlite and H_2O_2/Perlite ratios were produced, and their thermal conductivity, apparent density, compressive and flexural strength were contrasted. The experimental finding revealed that adding 0.25% H_2O_2 (by mass of perlite) to the mixtures enabled the production of lightweight pastes and mortars with lower density and lower thermal conductivity coefficient without a significant loss of ultimate strength. The developed perlite based aerated geopolymer is a eco-friendly and energy efficient solution to the buildings. Based on the results, H_2O_2/Perlite% above 0.5% and water/Perlite% above 45% should be avoided for both paste and mortars. In order to obtain optimum results in terms of workability, strength, density, and thermal conductivity, it is recommended that the H_2O_2/Perlite ratio for all samples should be 0.25% and the Water/Perlite percentage should be 40%.

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1. Introduction

Portland-based cement was first patented by Joseph Aspdin in 1824 and has become the most common binder used in concrete. Portland cement is manufactured by firing a mixture of limestone, clay, or shale at 1350–1500 °C [1,2]. This process releases high carbon (CO_2) and consumes significant energy and raw materials [3]. For these reasons, scientists seek ways to utilized waste materials [4–13] and look for binders in the construction industry that are less air-polluting and require less energy [14–21]. Industrial wastes such as fly ash, silica fume, and natural additives such as pumice, zeolite, and perlite are used as alkali-activated binders instead of cement, resulting in significant energy and CO_2 savings. Using geopolymer concrete as an alternative to portland cement concrete provides an approximate 80% benefit in reducing carbon dioxide emissions [22]. Activation is a general term applied to a solid aluminosilicate reaction under alkaline conditions to produce a hardened binder based on a combination of aqueous alkali-alumina silicate phases. Cementitious materials may include blast furnace slag, fly ash, perlite, and zeolite. Alkaline solutions may contain hydroxides, silicates, carbonates, aluminous, and sulfates [23].

In this regard, the use of alkaline activators was suggested by Davidovits (1994) as a binder instead of portland cement. In terms of reducing global warming, these relevant active binders can reduce 80% of CO_2 emissions from cement production [24]. It is possible to produce a strong binder by using alkali activator systems from amorphous materials containing Al_2O_3, SiO_2, and CaO in their structure. While inorganic polymers are formed due to the reaction of perlite containing aluminosilicate with activators, hydrated calcium silicate gel (C–S–H) is formed. Sodium hydroxide and sodium metasilicate (sodium glass water) are widely used as activators [25]. High energy requirements and environmental problems in Portland cement production have increased the use of alkaline activators as alternative binders [26–28]. Generally, potassium hydroxide (KOH), sodium hydroxide (NaOH), sodium carbonate (Na_2CO_3), and sodium metasilicate (Na_2SiO_3) are the most used activators in cementless paste and mortar [29,30]. The choice of activator and the amount to be used affect the strength development of the geopolymer. Recent studies show that the strength of geopolymers increases with the amount of activator [26,31,32]. There are some studies on ground raw perlite mortar samples activated with NaOH solution, including standard sand and some additives [26,29,31,32]. Experimental results showed that as the curing time and temperature increased, the compressive strength of perlite mortars increased, resulting in a compressive strength of up to 37 MPa [29]. Aziz et al. (2021) investigated the contribution of ground pozzolan and raw perlite to geopolymer formation. They replaced 40% of the perlite in the mixture with pozzolan and obtained a geopolymer with a compressive strength of 50 MPa [26]. In a study, the substitution of 30% by mass of pumice dust in the production of geopolymer concretes with cement kiln dust and OPC resulted in a 23% and 8% increase in compressive strength at a test age of 90 days [33]. According to Baran et al. [27], perlite is added to the fly ash-based geopolymer mixture. It was reported that the addition of perlite controlled the elasticity of the geopolymer but did not significantly affect its strength. Çelikten [34] produced durable geopolymer mortars using andesite dust. The dust is produced as waste during cutting andesite stone and other stone processing operations. NaOH was used as an alkali activator with different molarity variations. A study on producing aerated lightweight construction elements using hydrogen peroxide showed that various mortars made porous with hydrogen peroxide could be used as an inorganic thermal insulation material by finding their thermal conductivity [35]. Some researchers working on various combinations of raw perlite powder and cement, limestone, metakaolin, and silica fume showed that the strengths of different mortar mixtures they prepared increased over time by testing them over two years [36]. In a study on perlite, an expanded paste was obtained by adding different amounts of H_2O_2 to alkali-activated perlite powder. The obtained paste produced lightweight insulating thermal insulation foam boards with low compressive and flexural strength but low density and high thermal conductivity [37]. Novais et al. [38] researched to increase the thermal insulation of geopolymer by varying the aluminum powder and fly ash ratios and the curing temperature. The study showed the effect of the polymerization rate on the curing temperature. In a research [39], waste perlite powder, furnace slag and metakaolin were used as a filling material in concrete. They showed that perlite significantly affects the concrete microstructure and positively affects the compressive strength of concrete. Lukowski [40] tested the compressive strength of mortars obtained from the thermal expansion process of ground raw perlite. It shows the possibility of using waste perlite powder in making mortar and paste rationally and efficiently. In a study on the production of perlite-based geopolymer paste varieties [41], finely ground perlite was used as a raw material. Perlite-based geopolymer pastes were prepared using low Moller (2–5) NaOH and kept in a 90-degree oven. The effects of additives in solid mortar production on compressive strength were investigated. Erdogan [42] proved that alkaline solutions could activate the amorphous ground perlite. The mixtures activated with Na_2SiO_3 showed that the compressive strengths gradually reached moderate strengths at room temperature, but the strength did not occur in those activated with NaOH.

This study used ground raw perlite, alkali activators NaOH and Na_2SiO_3, Rilem Cembureau standard sand, and water for geopolymer cementless mortar. Only the mixture of raw ground perlite (RP) and alkaline solutions was used to make the paste. Perlite is a natural volcanic rock with a glassy feature containing aluminosilicate found in many regions. Using perlite as an alternative material instead of cement provides environmental and economic benefits and better acid and fire resistance. Turkey's production, the second largest producer in the world, in 2017 was 1,166,629 tons (metric) per year. The five major countries that makeup approximately 94% of the world's perlite production are China (27%), Turkey (25%), Greece (21%), USA (13%), and Iran (8%) [43].

The availability and cost of alkaline activators influence the choice of alkaline activators and the binder material(s) to be used. Generally, the strength of perlite composites activated with NaOH and Na_2SiO_3 alkaline activators increases with increasing the activator dosage up to a certain point. Using too

much alkali causes rapid setting and flowering, but there is no common idea about how much alkaline solution is used to activate perlite. Generally, 5–16 molarity NaOH is used for cementless perlite paste and mortars [23]. The expansion of concrete and the increase in the gaps between the material reduces the thermal conductivity of concrete mixtures [44]. The thermal conductivity of lightweight aerated concrete is half that of normal-weight concrete of similar composition [45]. Reducing thermal conductivity saves energy and provides thermal comfort [44]. This study aims to obtain RP cementless pastes and mortars using alkali activators and to test their mechanical and thermal properties. Investigating the possibilities of using cementless pastes and mortars obtained by activating RP as the primary binding material with an alkaline activator in building elements is a relatively new and unique subject. In order to increase the scientific depth on this subject, the effects of varying water/perlite (W/RP) ratios in the mixtures on the flexural and compressive strengths, apparent densities, and insulation properties of the samples were investigated. In addition, it was aimed to obtain expanded light samples by foaming paste and mortars with hydrogen peroxide (H_2O_2), which is known as a blowing agent. The thermal conductivity, flexural and compressive strengths of the produced lightweight paste and mortar were tested along with the changes in their apparent densities. The original aspect of this study is to investigate the possibilities of using RP to produce lightweight and durable cementless pastes and mortars. It is much more common to use expanded perlite instead of unexpanded perlite to produce lightweight construction elements, but the compressive strengths of the products are negligible [31,46]. However, many building elements are desired to be light and durable. Although there are many technical articles on expanded perlite, research on using unexpanded raw perlite as lightweight paste and mortar is limited.

Composite elements with high strength, lightweight, and low thermal conductivity can be produced using alkali-activated RP (unexpanded). Studies in the literature on the production of cementless paste and mortar from raw perlite still need to be increased. Investigating the thermal insulation properties of aerated RP-based geopolymer is a new and original research area that maintains its attractiveness in our country and abroad. In the first stage of this study, cementless paste and cementless mortar were developed. In the second stage, aerated light paste and mortars were produced by adding H_2O_2 to the mixtures. The aeration of alkali-activated mixtures with air bubbles mainly depends on the water and H_2O_2 content. The prepared mixtures were cured in a dry environment at 80 °C for two days. It was retained at room temperature until strength tests were conducted on the 7th, 14th, and 28th days.

This study demonstrates the usability of cementless pastes and mortars of alkali-activated raw perlite as safe building materials for humans and the environment without using too many additives. Producing lightweight geopolymer pastes and mortars without significant loss in flexural strength, compressive strength, and thermal ability can provide economic and environmental advantages by reducing Portland cement consumption. Thus, alkali-activated perlite cementless pastes and mortars can be produced in an environmentally friendly manner without requiring high energy and without causing greenhouse gas emissions. Alkali-activated raw perlite can be used as an alternative binder instead of cement, especially in developing countries.

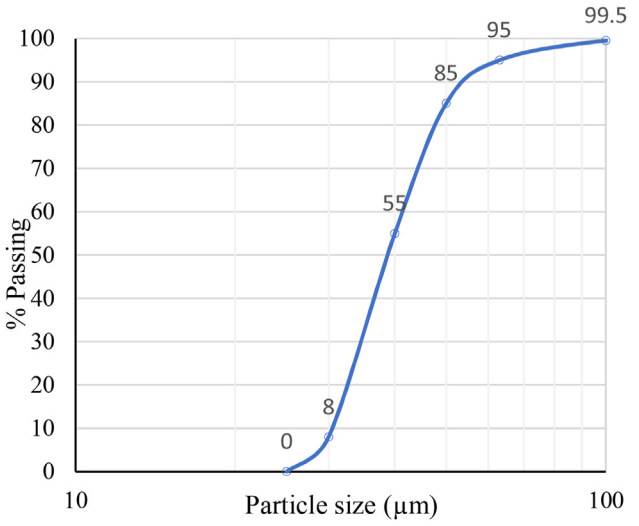


Fig. 1 – Particle size distribution of ground perlite (RP).

2. Materials and methods

2.1. Materials

Although there are raw perlite reserves around Kayseri, no firm is operating these reserves yet. Therefore, in this study, ground raw Perlite (RP) obtained from the mine site and facility of Fixmax company in Çerkeş, Turkey-Çankırı, 120 km away from Ankara, was used. The Grain distribution graph of RP is given in Fig. 1, with an approximate average grain diameter of 40 μm and a specific gravity of 2.36. Generally, the majority (90–97%) of raw perlite is volcanic glass, including crystallizing minerals such as feldspar, apatite, and biotite [47].

The chemical structure of the ground raw perlite (RP) was determined by X-Ray Fluorescence Spectrometer analysis, given in Table 1. The fact that the total of amorphous

Table 1 – The chemical analysis of the ground raw perlite (RP), percent by weight.

Major oxide	%w/w
SiO_2	71–73
Al_2O_3	13.1–14.2
Na_2O	3–3.5
K_2O	2.4–4.7
CaO	1–1.3
Fe_2O_3	1–1.1
MgO	0.15–0.22
TiO_2	0–0.13
H_2O	3–4



Fig. 2 – The materials used in the experiments.

materials containing Al_2O_3, SiO_2, and CaO is 88.4% indicates that perlite has a binding (pozzolan) feature.

The materials used in this study are shown collectively in Fig. 2 and flow chart of experiments is shown in Fig. 3. CEN standard sand was used to prepare mortar mixes. CEN Standard (100% of sand passes 2 mm and 1% passes 0.08 mm) sand is produced by Limak Cement Factory. Based on the studies in the literature [42,48–50] and preliminary laboratory

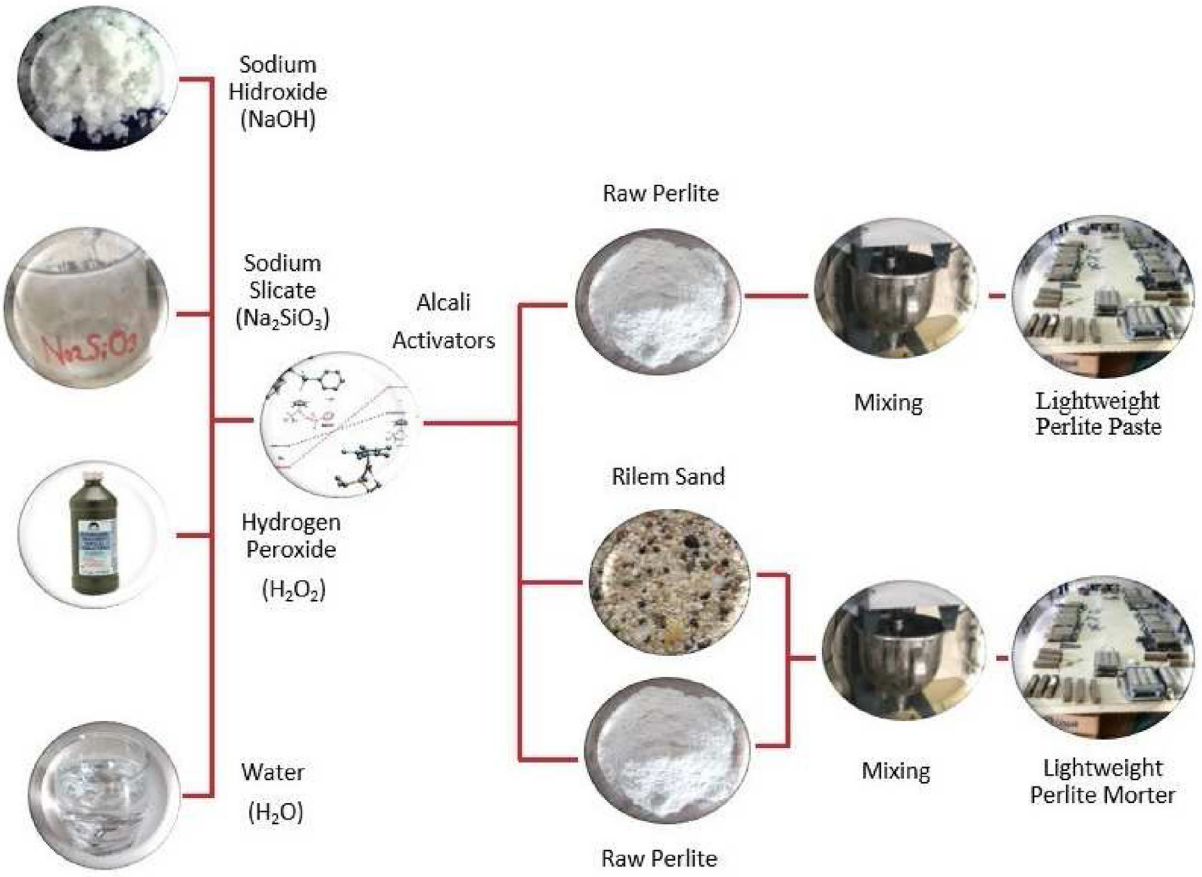


Fig. 3 – The Flow chart of the methodology.



Fig. 4 – Images of RP Paste and Mortar samples. a) Images of geopolymer RP paste sample. b) Images of molded RP Paste samples. c) Images of geopolymer RP Mortar sample. d) Images of molded RP Mortar samples.

experiments for RP, it was observed that perlite was activated quite well with a mixture of NaOH/RP ratio of 0.133 and Na_2SiO_3/RP ratio of 0.3 after two days of curing in a dry oven at 80°. Therefore, these ratios were kept constant in all tests.

2.2. *Mixing methods of perlite-based geopolymer paste and mortar*

The literature states that the best activators for perlite are sodium hydroxide or sodium silicate [22,29,51–66]. Therefore, a mix of sodium hydroxide and sodium silicate solution was preferred as an alkali activator based on previous and preliminary studies. Solid NaOH in flake form with >99% purity and distilled water was used to obtain a 16 M solution. In addition, the sodium silicate solution, the other activator, has a chemical composition of Na_2O = 9.2%, SiO2 = 29.3%, and H2O = 61.5%. The solutions were mixed at medium speed for 2 min, 24 ± 0.5 h, before mixing with the RP. A 50% w/w H_2O_2 solution is used in all samples. The density of H_2O_2 solution is 1.19 g/cm3 at 20 °C. Sodium hydroxide/perlite and sodium silicate/perlite ratios by mass were kept at 0.133 and 0.30, respectively, and this ratio did not change in all paste and mortar mixtures throughout the experiment. Air was chemically created in paste and mortar mixtures by a gas release reaction creating a cellular structure. Generally, air agents hydrogen peroxide (H2O2) are used [67]. The mixtures are aerated with H2O2 and allowed to swell. In addition, mixtures of 35%, 40%, 45%, and 50% for pastes and 40%, 45%, 47.5%, and 50% for mortars were prepared for various W(Water)/RP percentages. According to the consistency, workability, flexural tensile, and compressive strength of the paste and mortar, the most suitable W/RP percentages in the mixture were found. Some images of perlite paste and mortars are given in Fig. 4.

Table 2 – Mix Proportions of the raw perlite pastes.

Sample Mix Code	Water/ Perlite (%)	H_2O_2/Perlite (%)	Perlite (gr)	Na_2SiO_3 (gr)	16 M NaOH (gr)	Additional Water (gr)	50% w/w H2O2 (gr)
P35–0.00	35	0	1050	315	140.0	88.375	0.00
P35–0.25		0.25				85.750	5.25
P35–0.50		0.50				83.125	10.50
P35–0.75		0.75				80.500	15.75
P35-1		1.00				77.875	21.00
P40–0.00	40	0	1050	315	140.0	140.875	0.00
P40–0.25		0.25				138.250	5.25
P40–0.50		0.50				135.625	10.50
P40–0.75		0.75				133.000	15.75
P40-1		1.00				130.375	21.00
P45–0.00	45	0	1050	315	140.0	193.375	0.00
P45–0.25		0.25				190.750	5.25
P45–0.50		0.50				188.125	10.50
P45–0.75		0.75				185.500	15.75
P45-1		1.00				182.875	21.00
P50–0.00	50	0	1050	315	140.0	245.875	0.00
P50–0.25		0.25				243.250	5.25
P50–0.5		0.50				240.625	10.50
P50–0.75		0.75				238	15.75
P50-1		1.00				235.375	21.00

The sample molds are rectangular prisms with dimensions of 40mmx40 mmx160 mm and a cube of 70mmx70 mmx70mm. The mixture ratios were prepared as in Table 1 in light of the literature and our preliminary laboratory studies. The initial and final setting times of pastes and mortars were determined according to various W/RP ratios using a Vicat needle according to ASTM C191. For the mortar samples, standard sand was used with a Sand/Perlite ratio of 1. The aeration process of the samples was made with hydrogen peroxide to produce lightweight composites as insulation and semi-structural materials in the construction industry.

In this study, two separate sample sets were prepared for Paste and Mortar to conduct the experiments. Mixture identities of the produced samples were determined by P(Paste) and M(Mortar), W/RP percentage, and H_2O_2/RP percentage by

Table 3 – Mix proportions of perlite mortar.

Sample Mix Code	Water/Perlite (%)	H_2O_2/Perlite (%)	Perlite (gr)	Na_2SiO_3 (gr)	16 M NaOH (gr)	Additional Water (gr)	50%w/w H_2O_2 (gr)	Sand (gr)
M40–0.00	40	0	600	180	80	80.500	0.0	600
M40–0.25		0.25				79.000	3.0	
M40–0.50		0.50				77.500	6.0	
M40–0.75		0.75				76.000	9.0	
M40-1		1.00				74.500	12.0	
M45–0.00	45	0	600	180	80	110.500	0.0	600
M45–0.25		0.25				109.000	3.0	
M45–0.50		0.50				107.500	6.0	
M45–0.75		0.75				106.000	9.0	
M45-1		1.00				104.500	12.0	
M47.5–0.00	47.5	0	600	180	80	125.500	0.0	600
M47.5–0.25		0.25				124.000	3.0	
M47.5–0.50		0.50				122.500	6.0	
M47.5–0.75		0.75				121.000	9.0	
M47.5–1		1.00				119.500	12.0	
M50–0.00	50	0	600	180	80	140.500	0.0	600
M50–0.25		0.25				139.000	3.0	
M50–0.50		0.50				137.500	6.0	
M50–0.75		0.75				136.000	9.0	
M50-1		1.00				134.500	12.0	

mass of RP. A trial and error procedure is carried out for the percentages of water and H_2O_2 in the mix. The mix proportions of RP paste used in this study are shown in Table 2, and the perlite mortar mixture ratios are shown in Table 3. Forty different mixtures were prepared, 20 for RP paste and 20 for RP mortar, to investigate the expansion mechanism and mechanical properties of RP-based geopolymer. These are 20 different Paste mixtures containing 35%, 40%, 45%, and 50% water, each containing 0.25%, 0.50%, 0.75%, and 1% H_2O_2, by mass of RP (Table 1.) In P40–0.25 MIX ID, P stands for perlite paste (i.e., No-sand), 40 indicates the Water/RP percentage is 40%, and 0.25 indicates the H_2O_2/RP percentage is 0.25% (Fig. 5(a)).

The mortar samples' mechanical properties and apparent densities were investigated on 20 different mixtures. The mortar mixtures containing 35%, 40%, 45%, and 50% water, each with 0.25%, 0.50%, 0.75%, and 1% H_2O_2 contents, are prepared. The mixture identity of the samples is expressed by their percentage of water and H_2O_2 content. For example, in M40–0.50 mix ID, M means the mix type is mortar, 40 means the water content is 40% by mass of perlite, and 0.50 means the H_2O_2 content is 0.50% by mass of perlite (Fig. 5(b)).

In preparation of mixtures, a 10lt capacity laboratory mixer was used for all paste and mortar samples. 40 × 40 × 160 mm molds were used to determine flexural and compressive strengths and apparent densities, and 70 × 70 × 70 mm molds were used to determine compressive strengths and expansions. In addition, 140 × 120 × 40 mm prism molds were used to determine its thermal conductivity. In the mixing process of Geopolymer pastes, RP was added immediately after the alkaline solutions were added to the bowl and mixed for 60 s. Then, the selected amount of H_2O_2 was added with slow stirring. After stirring for another 120 s, the mixture was poured into molds. The total mixing time of the paste sample was completed in 3 min. In mixing alkali-activated RP mortars, alkaline solutions, RP, and sand were mixed for 120 s, 60 s at low speed, and 60 s at medium speed.

The total mixing time of a mortar sample was completed in 4 min. The specimens prepared in 160 × 40 × 40 mm dimensions were tested for flexural and compressive strength. Varying percentages of H_2O_2 were added to the mix. The mixtures were poured into molds by mixing for an additional 120 s at medium speed.

After molding, the samples were allowed to expand freely for about 2 h. Then, just before the setting time (that is, before fully hardened), the upper surfaces of the sample's expanded and overflowed parts from the mold were cut off using a utility knife. After two days of molding at room temperature, samples were cured in a dry oven at 80° for 48 h. The samples were de-molded and kept at room temperature until the end of the 7, 14, and 28 days of testing. Compression and bending tests were performed for all samples using a portable, 100 kN capacity automatic universal testing machine with a loading speed of approximately 1.5 kN/s. Compression tests were carried out on the remaining half samples after the bending strength tests on 40 × 40 × 160mm sized samples. Tests of the samples were completed as averages of compressive and flexural strengths.

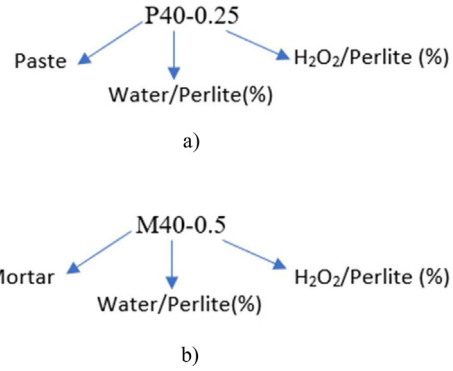


Fig. 5 – Defination of samples. a)Paste: P40-0.25, P(Paste), 40 (W/RP %), and 0.25 (H_2O_2/RP %). b)Mortar: M40-0.50, M(mortar), 40 (w/RP %), and 0.50 (H_2O_2/RP %).

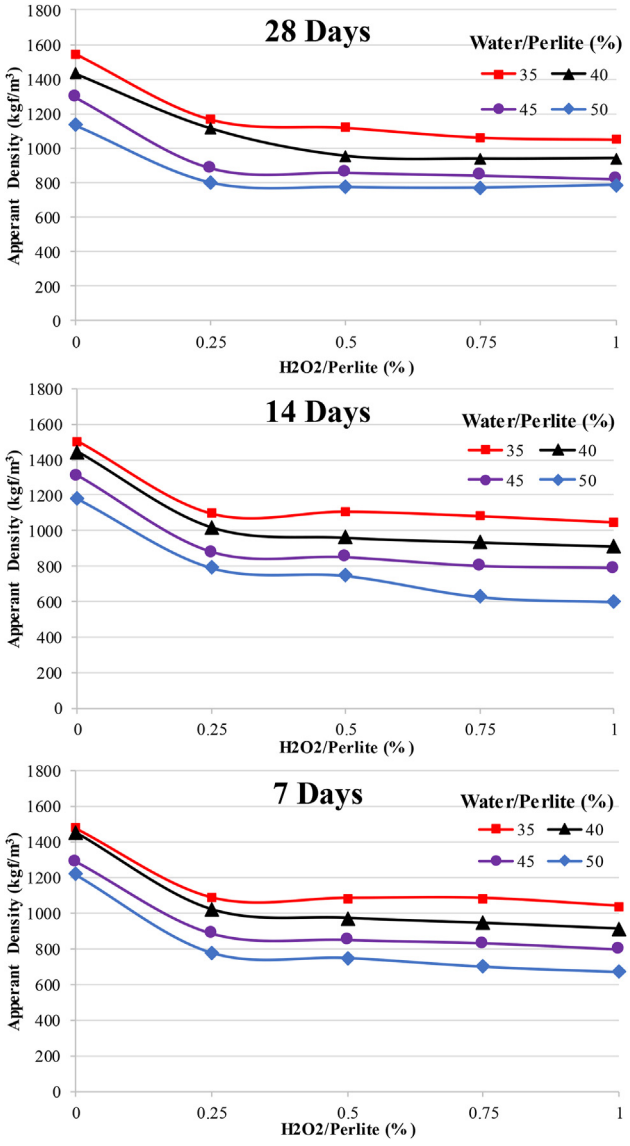


Fig. 6 – Results of apparent densities for paste samples (affected by H2O2/RP% and Water/RP%).

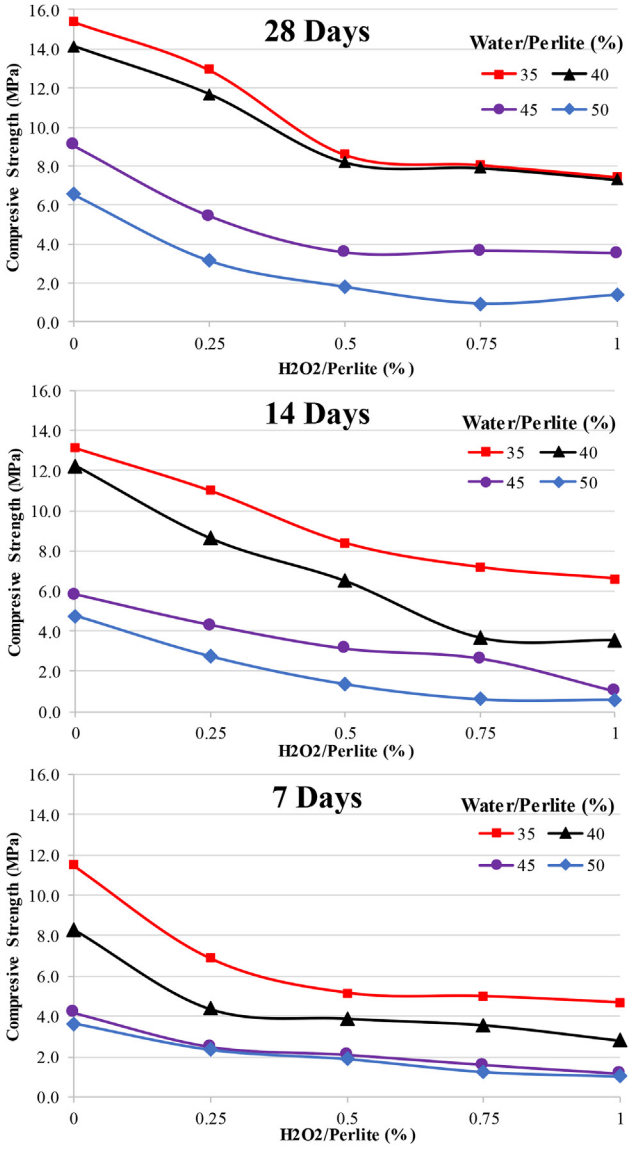


Fig. 7 – Results of compressive strength for paste samples (affected by H2O2/RP% and Water/RP%).

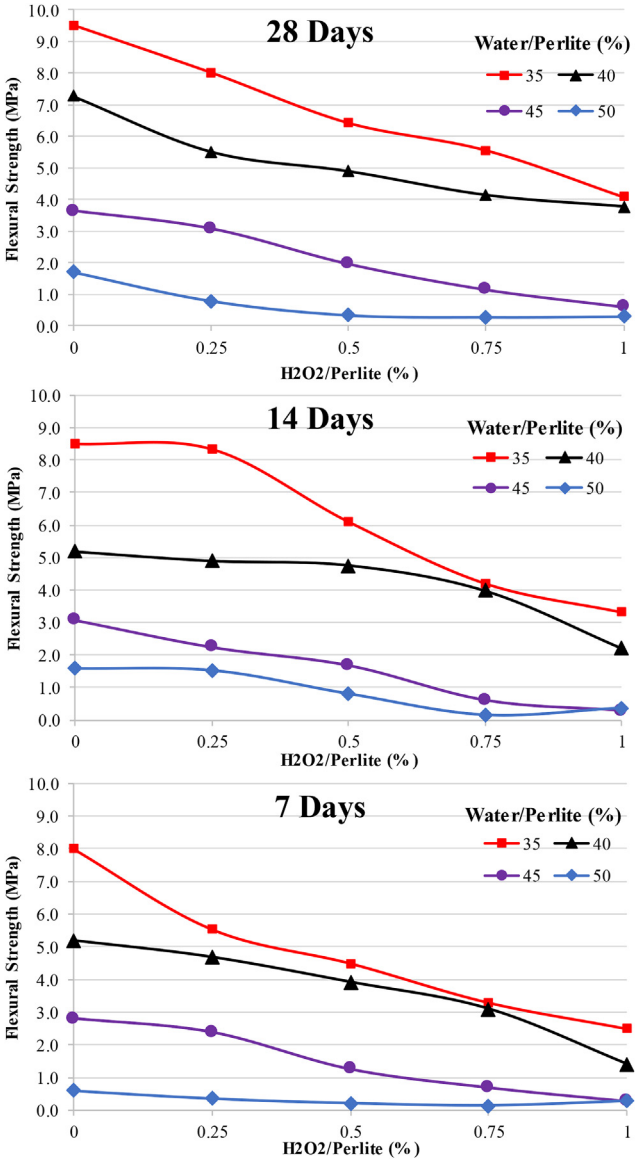


Fig. 8 – Results of flexural strength for paste samples (affected by H2O2/RP% and Water/RP%).

3. Results and discussion

3.1. *The effect of water and H_2O_2 in the RP paste*

In the experimental study, the effects of increasing water (water/RP%) and increasing hydrogen peroxide (H_2O_2/RP%) ratios on the apparent density, compressive strength, flexural strength, and thermal conductivity properties of the paste samples were investigated. The following subsections investigate these properties in detail.

3.1.1. *Density*

Water-Paste percentages (W/RP %) and hydrogen peroxide-perlite percentages (H2O2/RP%) were used to analyze the mixtures' enlarging mechanism and examine the apparent density of the produced samples. Apparent densities and compressive strength are essential qualification criteria frequently used to evaluate pastes. Fig. 6 shows the effect on the apparent density of aerated pastes at 7, 14 and 28 days with different hydrogen peroxide/RP contents. The apparent densities of non-aerated pastes were 1478.5–1221, 1503–1179, and 1543.4–1135 kg/m3 for 7, 14, and 28 days, respectively. As the water content progressed from 35% to 50%, the apparent densities decreased due to the increase in water content. Aerated pastes with 28-days apparent density range between 787 and 1543 kg/m3 while compressive strengths ranging from 1.4 to 14.4 MPa were produced. In Fig. 6, when the 28-day peroxide-free P35-0 sample was compared with the P40-0, P45-0, and P50-0 samples, the apparent densities decreased by 7%, 16% and 26%, respectively, relative to the increase in water content.

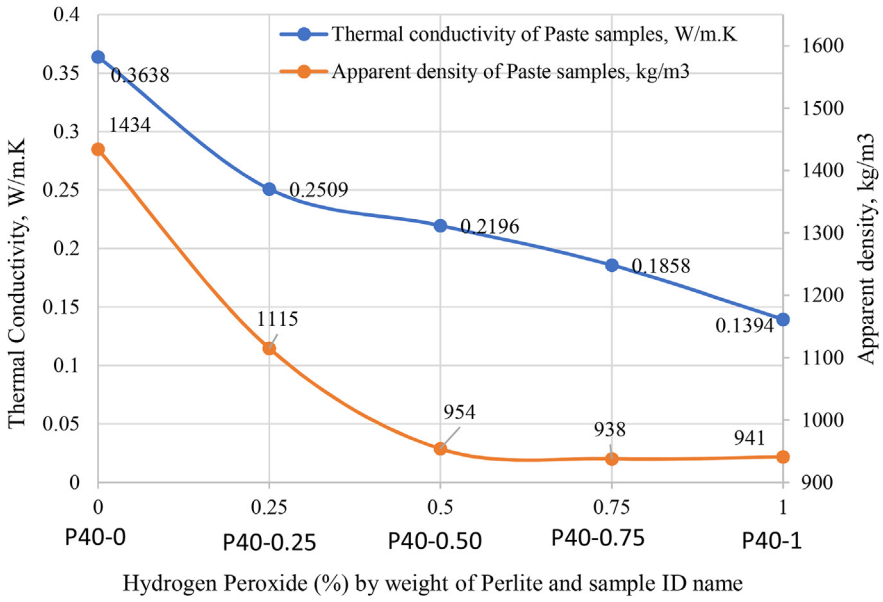


Fig. 9 – Thermal conductivity of geopolymer perlite paste (with varying H2O2/RP%).

The size and amount of the pores of the pastes increased with increasing water and hydrogen peroxide content. While the percentage of Water/RP was kept constant, the apparent density did not decrease at the same rate as the increase of hydrogen peroxide. When the percentage of H_2O_2/RP was 0.25%, the apparent density decreased significantly, but the increase continued up to 1%, and there was not much change in the apparent densities. The pastes swelled more than the mortars by air bubble formation due to the effect of hydrogen peroxide. Swelling of the paste was thought to allow the oxygen to remain trapped and cause air bubbles to form. When the hydrogen peroxide amount increased from 0% to 0.25%, the apparent density decreased by 22%.

3.1.2. *Compressive strength*

Fig. 7 shows the effect on the compressive strength of aerated pastes at 7, 14, and 28 days with different hydrogen peroxide/RP contents. In order to investigate the effect of water and hydrogen peroxide content, the compressive strength tests of the mixtures were measured after ambient dry-oven curing at 80 °C. The effect of hydrogen peroxide and water content on the size and amount of the pores of the paste samples' microstructure was investigated by SEM analysis. The compressive strength of the 28-day peroxide-free P35-0 (water-perlite ratio 35%) sample is approximately 2%, 58%, and 118% higher than pastes with 40%, 45%, and 50% water content, respectively. The 28-day compressive strengths of the P35-0 and P40-0 samples are almost close, although the development of the 7-day and 14-day compressive strengths slightly differ (Fig. 7). From this, it can be stated that the compressive strength will increase in the future, and the results are getting closer.

Significant decrease in compressive strength was detected when H_2O_2/Perlite% is above 0.5% and/or Water/Perlite% is above 40%. In order to obtain optimum results in terms of compressive stress and workability, it is recommended that the H2O2/Perlite ratio for paste be 0.25% and Water/Perlite percentage 40%. It is known that with the increase in water ratio, the compressive strength decreases, and accordingly, there is an increase in water absorption and porosity [68]. The concrete becomes lighter due to the contribution of the air bubbles formed by inflating the raw perlite with H2O2. It is possible to obtain light and durable pastes with mixtures with an H2O2-perlite ratio of 0.25%–0.5% and a water-perlite ratio of 35–40%. When the hydrogen peroxide content increased by 0.25%, there was no significant decrease in the compressive strength, but the continued increase in the hydrogen peroxide from 0.25% to 1% significantly reduced the compressive strength of the samples. This may be due to a decrease in apparent density and an increase in the size and amount of pores in the microstructure of the samples, as given in the SEM analysis (Fig. 16).

3.1.3. *Flexural strength*

Fig. 8 shows the effect of the 7-day, 14-day, and 28-day flexural strengths of pastes with different hydrogen contents. Flexural strengths were adversely affected much more by water increments. When the 28-day peroxide-free P35-0 sample was compared with the P40-0, P45-0, and P50-0 samples, flexural strengths decreased by 23%, 62%, and 82%, respectively, relative to the increase in water content. Shi et al. (2020) stated that the compressive strength and flexural strength decrease with the increase in H_2O_2, while the decrease in the flexural strength is approximately three times the decrease in the compressive strength [69]. The results also show that the decrease in flexural strength is more than the compressive strength, similar to the literature results for the paste samples.

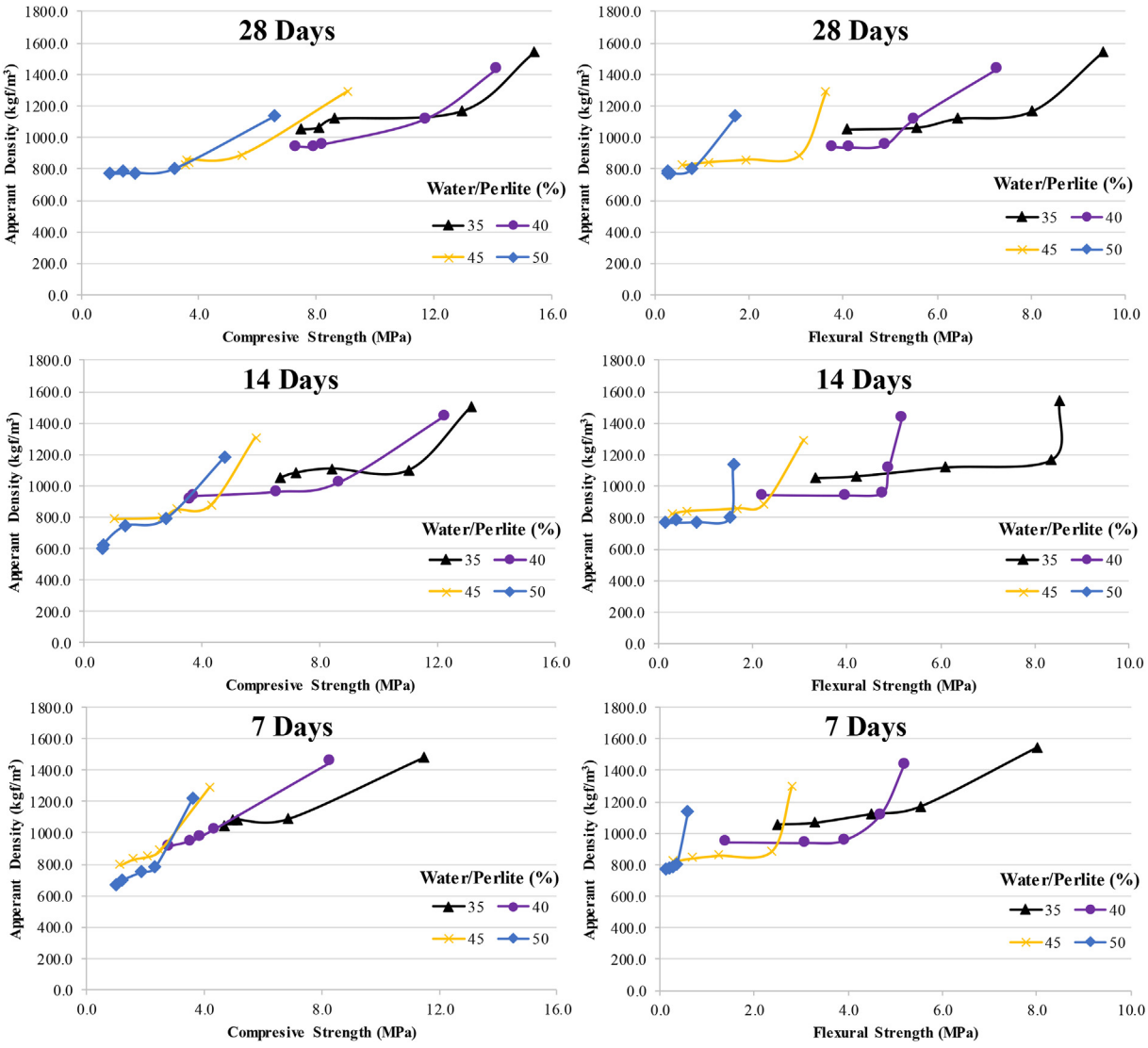


Fig. 10 – The effect of 7-day, 14-day, and 28-day compressive and flexural strength of aerated paste on apparent density.

The flexural-compression strength ratios of the non-aerated pastes ranged from about 0.10 to 0.7. The compressive and flexural strengths of the samples decreased with increasing water content, but the decrease in flexural strength was much more significant. For example, the 7, 14, and 28 days flexural strengths of samples with 40% water content are approximately 800%, 327%, and 575% higher than samples with 50% water content. The increased water content in the mixture caused porosity and cracks, significantly decreasing the flexural strength value.

3.1.4. *Thermal conductivity of paste samples*

In finding the thermal conductivity coefficients, it was determined that the best paste mix was P40-0 in workability, compression, and flexural strength (Fig. 9). Then, the thermal conductivity of the samples, which were made lightweight (i.e., to make them porous and reduce the density) with H2O2, were measured using a heat flow meter (Thermtest HFM-100) according to ASTM C518 and EN 12,667 standards. Adding H2O2 to the mixture increases the air spaces of the paste and decreases its thermal conductivity. However, adding too much H2O2 to the mixture causes the gas to escape [48]. Similar results were obtained in this study. Furthermore, the relationship between decreased material density due to the increased H2O2 ratio was revealed in the literature [69]. Considering the thermal conductivity coefficient of lightweight pastes, the amount of H2O2 added to the mixture, and the paste density, the results are reasonably compatible with the literature [70,71]. Thermal conductivity measurements were made on rectangular samples of 140 × 160 × 40 mm. The device's electrical cooling and heating system controlled the surface temperature of the samples throughout the experiment. The sample thickness was automatically measured during the test.

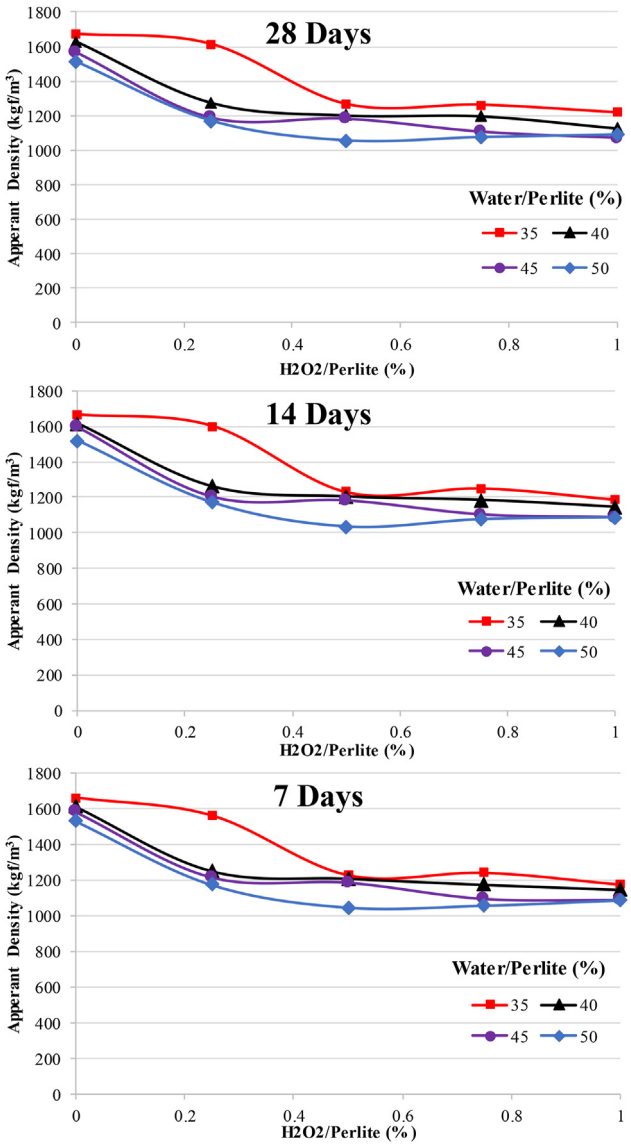


Fig. 11 – Results of apparent densities for mortar samples (affected by H2O2/RP% and Water/RP%).

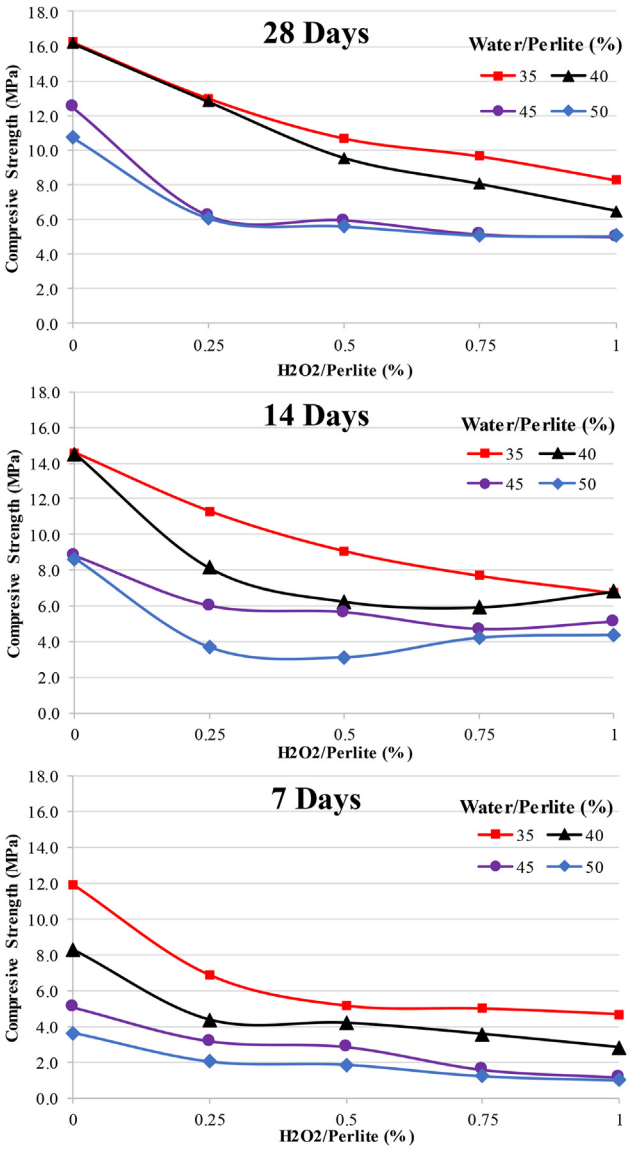


Fig. 12 – Results of compressive strength for mortar samples (affected by H2O2/RP% and Water/RP%).

In Fig. 9, the thermal conductivity of the produced lightweight pastes changed between 0.1394 and 0.3638 W/m.K, with dry densities range of 787–1543 kg/m3. When 0.25% h2O2/perlite was added to the paste mixture, the thermal conductivity coefficient decreased significantly from 0.3638 W/m.K to 0.2509 W/m.K (approximately 31% decrease). As the hydrogen peroxide ratio increased from 0.25% to 1% in paste samples, the density values did not decrease at the same rate. In addition, the thermal conductivity coefficients of pastes decreased in parallel with the apparent densities. With 25% H_2O_2 in the P40-0 mixture, the thermal conductivity coefficient suddenly decreased from 0.3638 to 0.2509. As a result, adding 0.25% (P40–0.25), 0.50% (P40–0.50), 0.75% (P40–0.75), and 1% (P40-1) hydrogen peroxide to the hydrogen peroxide-free (P40-0) geopolymer perlite paste mixture, caused a 31%, 40%, 49% and 62% reduction in thermal conductivity, respectively, as shown in Fig. 10.

3.1.5. *General comments*

Fig. 10 shows the relation between 7-day, 14-day, and 28-day compressive and flexural strength of aerated mortar and apparent density. When the curves of the paste mixtures are examined, it is seen that the ideal water ratio is 40% water/RP percentage. Although the P35-0 mixture shows similar or slightly higher strength properties than the P40-0 mixture, the ideal mixture in workability is P40-0. RP Pastes are thought to prevent significant amounts of oxygen from escaping and retain the oxygen in their bodies. For this reason, the low amount of hydrogen peroxide put into the mixture caused the pastes to swell more. However, adding more than 0.5% H_2O_2 to the mixture did not swell the pastes at the same rate.

On the contrary, it caused an increase in the mixture's water content, which is thought to facilitate the escape of oxygen. Fig. 10 shows the effect on the apparent density of aerated

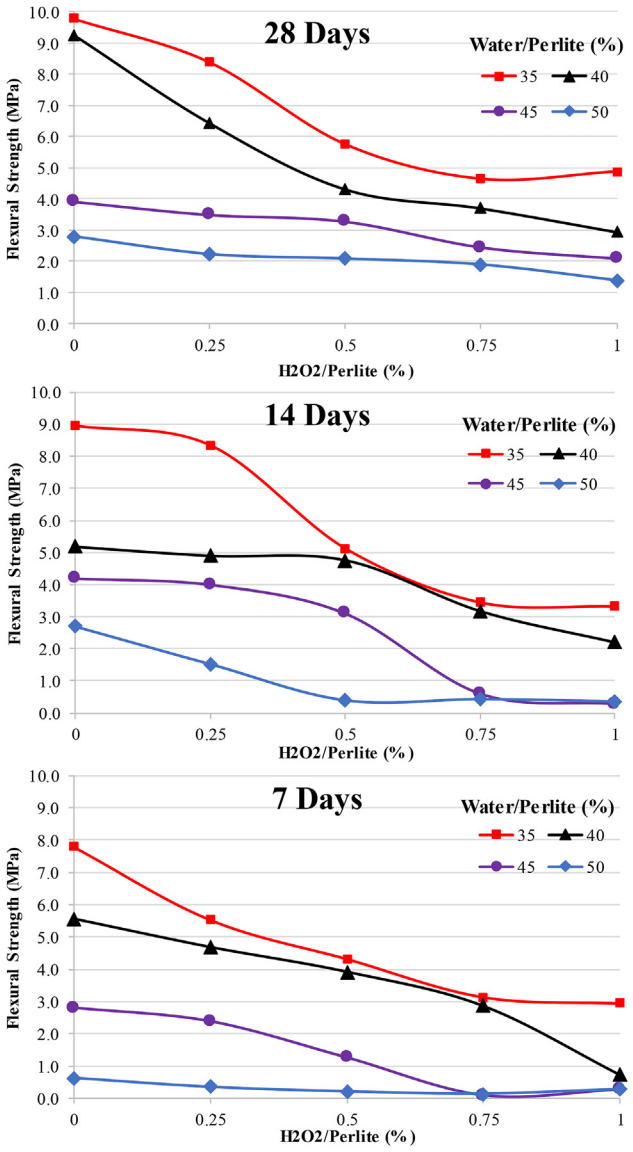


Fig. 13 – Results of flexural strength for mortar samples (affected by H2O2/RP% and Water/RP%).

pastes prepared with different hydrogen peroxide/RP contents. When the amount of hydrogen peroxide was 0.25%, a significant decrease was observed in the apparent density by 22% and the thermal conductivity coefficient by 31%, while the compressive stress was reduced by 17%. According to the results, H_2O_2/Perlite over 0.5% and water/Perlite over 40% should be avoided for paste. In order to obtain optimum results in terms of workability, compressive strength, apparent density, and thermal conductivity, it is recommended that the H_2O_2/Perlite ratio be 0.25% and the Water/Perlite ratio 40% in pastes. Thus, it will be possible to produce building materials that are strong and light enough to be used in many construction works.

3.2. *Effect of water and H_2O_2 in geopolymer RP mortar*

In the experimental study, the effects of increasing water (water/RP%) and increasing hydrogen peroxide (H_2O_2/RP%) ratios on the apparent density, compressive strength, flexural strength, and thermal conductivity properties of the mortar samples were investigated. The following subsections investigate these properties in detail.

3.2.1. *Density*

After 7-day, 14-day, and 28-day curing, changes in the apparent densities of perlite mortars were determined. Fig. 11 shows the effect of Water-to-RP% and H2O2-to-RP% content on the apparent density of mortars. The apparent densities in non-aerated mortars were 1582–1529, 1602–1518 and 1675-1515 kg/m3 for 7, 14 and 28 days, respectively. As the water content progressed from 40% to 50%, the apparent densities decreased due to the increase in water content, but the differences were less compared to pastes. While the 28-day apparent densities of non-aerated perlite mortars with different water contents (i.e., M40–0, M45–0, M47.5–0, and M50-0) are in the range of 1675–1515 kg/m3, the samples with 0.25% H2O2 added to the mixture (i.e., M40–0.25, M45–0.25, M47.5–0.25, and M50–0.25), their apparent densities decreased as H2O2 increased and became between 1277 and 1170 kg/m3. As a result, adding 0.25% H2O2 to mortar mixes caused its density to increase by about 22%. As the hydrogen peroxide content increased from 0.25% to 0.50%, the apparent density slightly decreased. Continuing to increase more than 0.50% H2O2 did not affect the apparent density at all. Adding 0.25% hydrogen peroxide to the mortar mix effectively reduces the apparent density. Although the apparent density values in this study were higher than the literature [37], similar results were obtained regarding the effect of 0.25% peroxide on the apparent densities of the mortars. Since the densities of the obtained perlite-based geopolymer mortars are between 1277 and 1170 kg/m3, they can be used in the production of semi-structural concrete elements [72]

Very close values were obtained when M40–0 and M45-0 mortars were compared in apparent densities and strength properties. This result showed that the W/RP percentage of the ideal mixture is between 40% and 45%. The M45-0 mix was more workable and easier to process compared to M40-0. When 0.25% H_2O_2 was added to the M45-0 mortar mix, the apparent density decreased significantly, but the further increase of hydrogen peroxide did not affect the apparent density much. As a result, it is thought that the oxygen may quickly escape without expansion due to sand, or the air bubbles collapse easily with the increase in the mortar density by adding sand.

3.2.2. *Compressive strength*

Fig. 12 shows the effect on compressive strength of aerated mortars on days 7, 14, and 28 with different hydrogen peroxide/RP contents. When the 28-day peroxide-free M40-0 sample was compared with M45–0, M47.5–0, and M50-0 samples, the compressive strength decreased by 1%, 23%, and 34%, respectively, due to water content variations. In Fig. 12, the 28-day compressive strengths of M40–0 and M45-0 samples are almost close, but the evolution of the 7-day and 14-day compressive strengths increased over time. Consequently, H2O2/Perlite% should be less than 0.5% for mortar mixes, and Water/Perlite% should be less than 45%. In order to obtain optimum results in terms of compressive

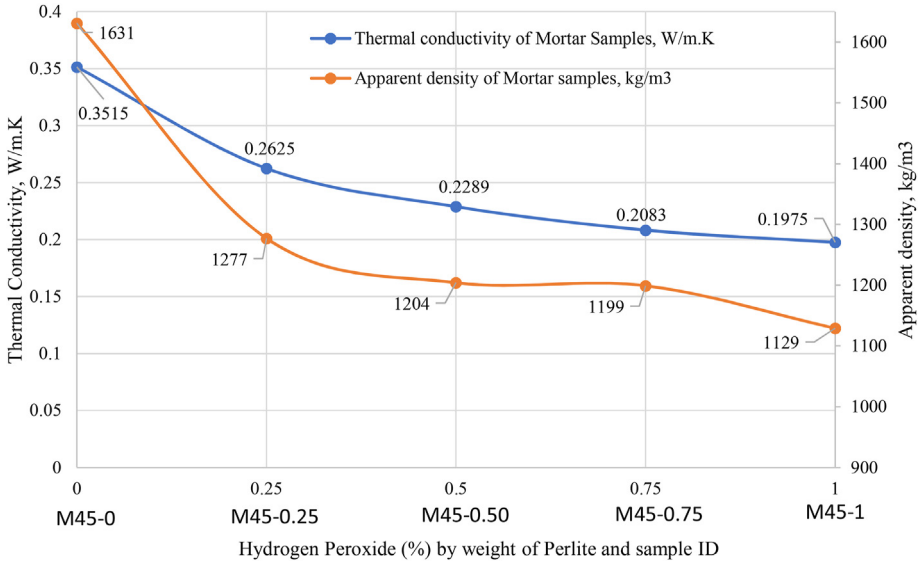


Fig. 14 – Thermal conductivity of geopolymer perlite mortar with varying H2O2/RP%.

stress and workability, it is recommended that the H2O2/Perlite ratio be 0.25% and the Water/Perlite ratio 45% in the mortar.

Similar to pastes, the increased percentage of hydrogen peroxide causes a decrease in the compressive strength of the mortars. This may be because the pores and pore size of the samples increased due to the increased hydrogen peroxide content. The increase in the densities of the mortars provided an increase in their compressive strength. When non-aerated samples are referenced for a given percentage of water-perlite, it can be concluded that it is easier to achieve lower densities and high compressive strengths by using 45% water content in mortars.

3.2.3. *Flexural strength*

Fig. 13 shows the effect of the 7-day, 14-day, and 28-day flexural strengths of mortars with different hydrogen contents. Flexural strengths of mortars were adversely affected much more by water increments. When the 28-day peroxide-free M40-0 sample was compared with the M45–0, M47.5–0, and M50-0 samples, flexural strengths decreased by 5%, 60%, and 71%, respectively, relative to the increase in water content (Fig. 13). The flexural-compression strength ratios of the non-aerated mortar ranged from about 0.10 to 0.90. The compressive and flexural strengths of the samples decreased with increasing water content, but the decrease in flexural strengths was much more pronounced. For example, 7, 14, and 28 days flexural strengths of mortar samples with 45% water content are approximately 900%, 192%, and 331% higher than samples with 50% water content. The significant decrease in flexural strength of mortars is likely due to increased porosity and cracks due to increased water content.

Table 4 – Thermal conductivity coefficients of some building materials (TS825) [73].

Building materials	Thermal Conductivity Coefficient (w/m.K)
Marble	3.5
Portland Cement Mortar	1.6
Reinforced concrete	2.5
vertical hole brick	0.5–1.4
Extruded polystyrene foam (XPS) sheets	0.030–0.040
Glass wool	0.035–0.050

3.2.4. *Thermal conductivity*

The thermal conductivity of the geopolymer mortar samples, M45–0, M45–0.25, M45–0.5, M45–0.75, and M45-1, decreased with the increase of the hydrogen peroxide percentage. The thermal conductivity coefficient of the M45-0 sample was initially 0.3515 W/m.K. When 0.25% H_2O_2 was added to the mortar mix (M45-0), the thermal conductivity coefficient decreased significantly to 0.2625 W/m.K, and the apparent density decreased from 1631 kg/cm^3 to 1277 kg/cm^3. These results showed a remarkable decrease in thermal conductivity and density. This significant decrease can be attributed to the higher overall porosity of M45–0.25 compared to M45-0. As a result of the increase in pores, the thermal conductivity coefficients decreased. It seems to match the result obtained by Ref. [44]. Adding 0.25% (M45–0.25), 0.50% (M45–0.50), 0.75% (M45–0.75), and 1% (M45-1) hydrogen peroxide to M45-0 mortar mix are shown in Fig. 14. Thermal conductivity decreased 25.3%, 34.9%, 40.7%, and 43.8%, respectively. Compressive strengths decreased by 21%, 41%, 50%, and 60%, respectively, while flexural strengths decreased by 31%, 54%, 51%, and 69%, respectively.

Some construction materials' thermal properties are given in Table 4. According to Table 4, it has been proven that geopolymer paste and mortars are suitable building materials in terms of thermal insulation. Compared to vertical hole brick

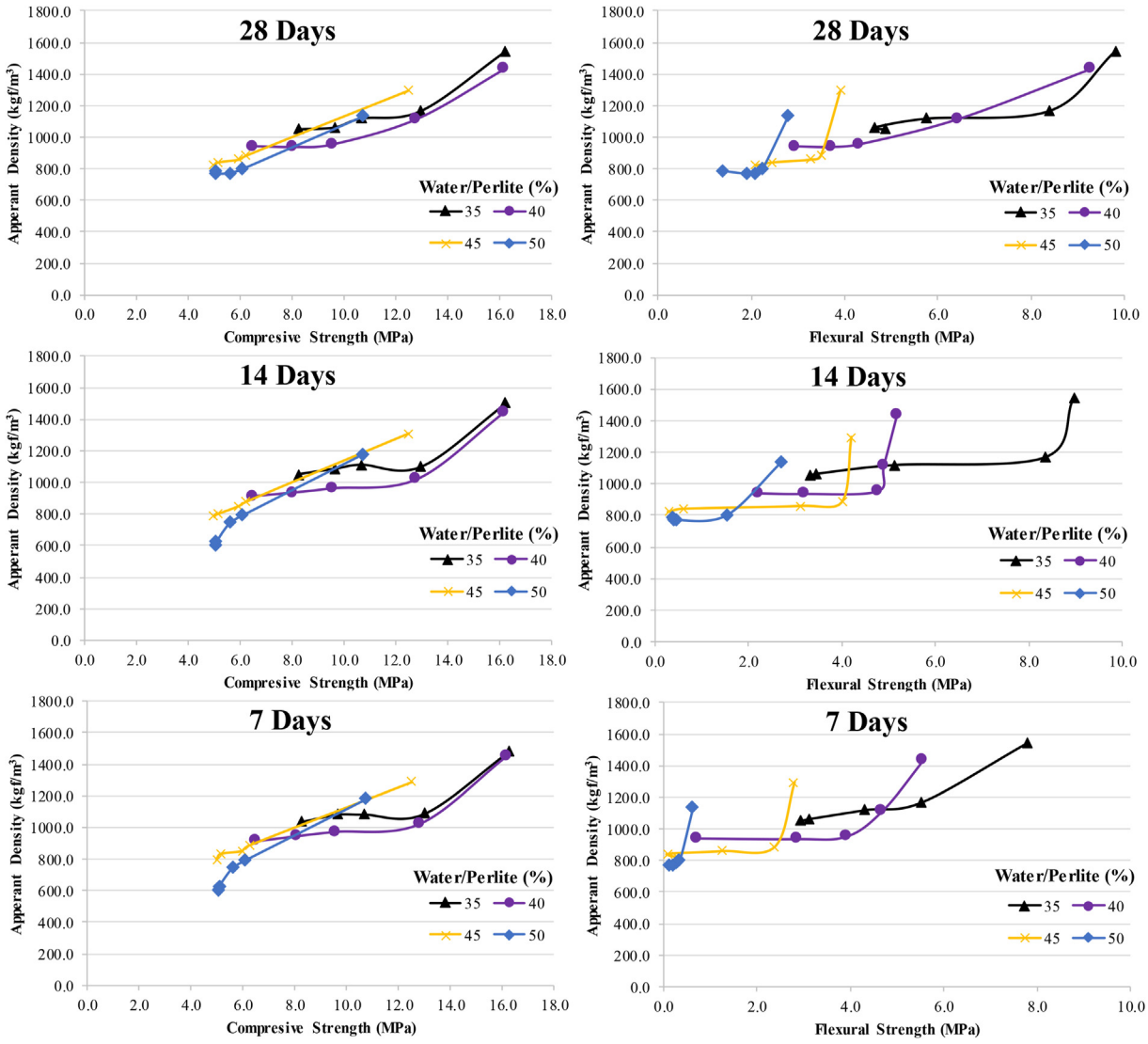


Fig. 15 – The relation between 7-day, 14-day, and 28-day compressive and flexural strength of aerated mortar and apparent density.

building materials in Table 4, geopolymers obtained from perlite have better thermal conductivity and similar compressive strength (about 14 MPa). In addition, due to its superior fire resistance properties (100% non-combustibility), classified as Fire Class A1 according to DIN4102, it can be used in the production of various construction materials such as plaster, joint filler, and concrete.

3.2.5. *General comments*

Fig. 15 shows the relation between 7-day, 14-day, and 28-day compressive and flexural strength of aerated mortar and apparent density. When the hydrogen peroxide ratio increased from 0% to 0.25%, the apparent density of the mortar decreased by 22% from 1631 kg/cm3 to 1277 kg/cm^3, while the compressive strength decreased by 20% and flexural strength by 31% (Figs. 12–13-14). Due to the increase in hydrogen peroxide content, oxygen was produced, and the separation rate increased. It is thought that air bubbles precipitate or leave the mixture quickly in perlite mortars. Adding 1% H_2O_2 to the mortars decreased the compressive strength by 65% and the flexural strength by 85%. The strength decrease is interpreted as the formation of a heterogeneous structure in geopolymer and the emergence of zeolitic phases. [71]. In recent studies, it has been suggested that adding H_2O_2 to lightweight foam concrete obtained by adding materials such as methacholine and expanded polystyrene reduces the strength but preserves its thermal conductivity [74–77]. This study with raw perlite confirms previous studies showing good thermal insulation performance since the pores swelled with H_2O_2 are filled with air bubbles. In addition, compressive and flexural strengths can be three times higher than foam concrete. It is possible to produce these results with

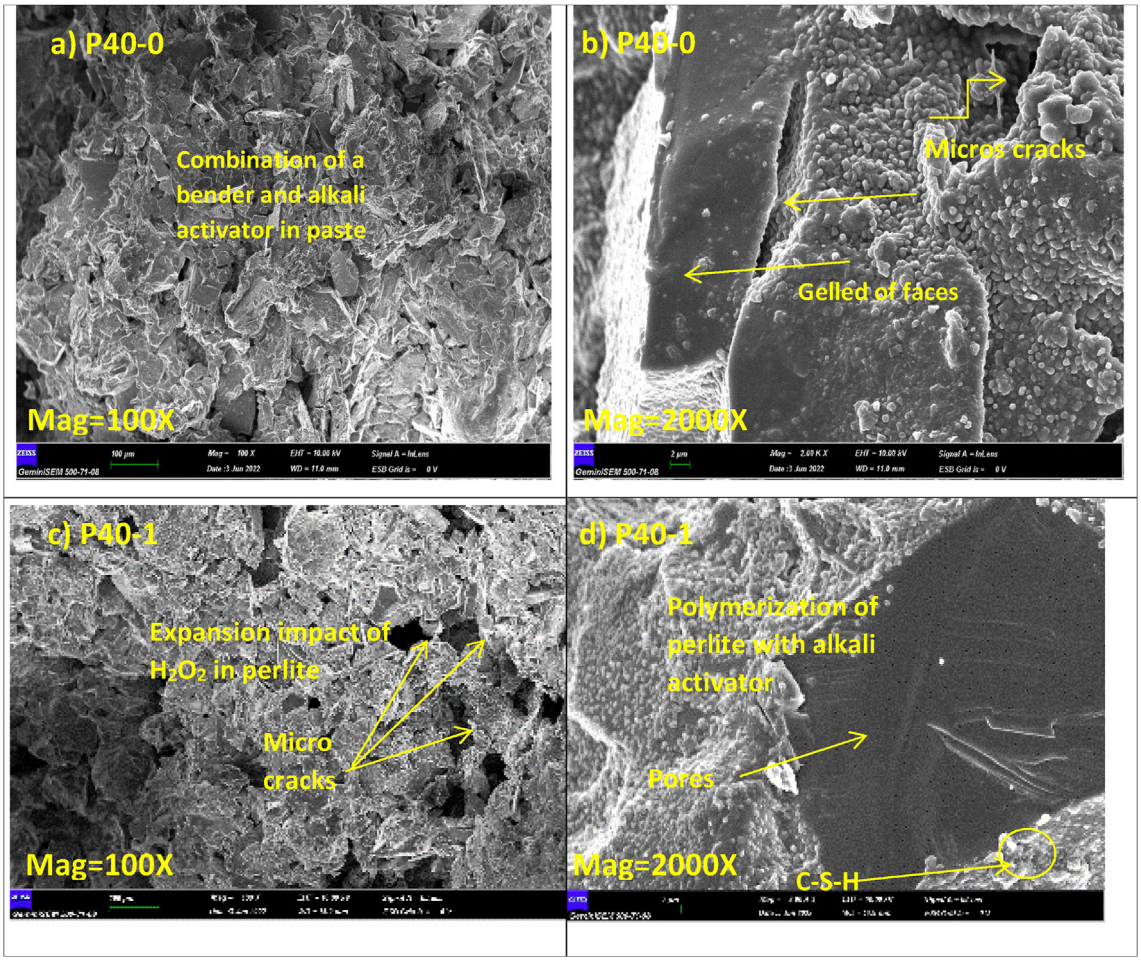


Fig. 16 – 28-day SEM images of paste samples according to varying H_2O_2 content.

lightweight and usable concrete raw perlite-based mortars without using too many additional materials.

As a result, the Water/RP percentage of the ideal mixture is between 40% and 45%, but M45-0 was more workable and easier to process than M40-0. When 0.25% H_2O_2 was added to the M45-0 mortar mix, the apparent density decreased significantly, but the further increase of hydrogen peroxide did not affect the apparent density much. As a result, it is thought that adding sand to the mixture increases the weight of the mortar and allows air bubbles to collapse quickly.

3.3. *SEM analysis*

As a result of the experimental study of light concrete made with ground raw perlite, SEM analysis was carried out on sandless (Paste) and sandy (Mortar) samples. SEM analysis is performed to observe internal structure formations, cavities, and cracks in concrete [20]. The effects of H_2O_2 on perlite expansion can be seen in the SEM results obtained by magnifying 500 times. Fig. 16(a–d) paste and Fig. 17(a–d) present essential sections from the mortar samples. As the H_2O_2 ratio increases, the perlite expands, but the increased porosity causes surface cracks and internal voids. These images prove the flexural compressive strength drop due to voids.

Fig. 16(a) shows that perlite forms a good bond with alkali activators (NaOH and Si_2O_3). Fig. 10(b) shows the pore bum and voids in perlite along with the gelled surfaces. In forming perlite geopolymer, calcium carbonate crystals transform into aragonite, and calcite forms [78]. These structures are seen in Fig. 16 (c) in a spherical or crystalline geometric form. There are microfissure formations in Fig. 16(b and d). Calcite symptoms in SEM images show similarities with [79]. The H_2O_2 effect is seen less in sandy models. Sand particles do not swell after a certain rate. It is seen that the sandy model Fig. 17(a) provides good bonding with perlite and contains fewer voids than the sandless model. Although less expansion was seen in the sandy models, the compressive and flexural strength performance was better. In Fig. 17(b) limestone form, calcium carbonate ($CaCO_3$) is seen with good bonding between calcium silicate hydrate (CSH) sand particles. Fig. 17(c) shows more clearance and expansion reduction. In Fig. 17(d), $CaCO_3$ and C–S–H formations are more striking. At the same time, in Fig. 17(d) interfacial transition

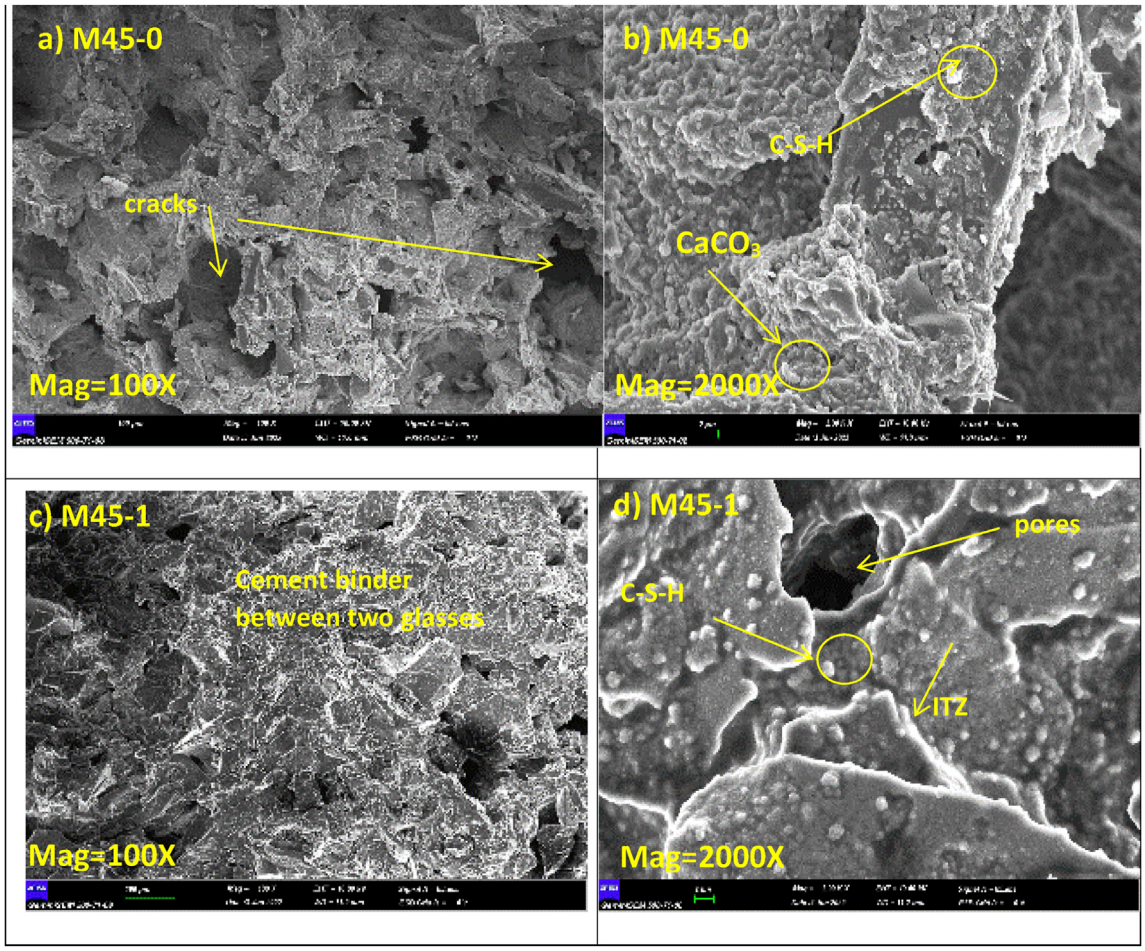


Fig. 17 – 28-day SEM images of mortar samples according to varying H_2O_2 content.

zone (ITZ) is shown, with the boundary at 20 μm approximately indicated.

4. Conclusion and recommendations

In this study, cementless paste and mortar were produced based on the alkali activation of raw perlite, and it was proven that they could be used as construction materials. They were also aerated with a foaming agent called H2O2 (a blowing agent) to produce low-density paste and mortar. Thus, the binding and pore formation mechanism, apparent densities, flexural strength, compressive strength, and thermal properties of all samples produced were tested. The durability of the mixtures decreased with increasing water content. Geopolymer pastes and mortars produced from raw perlite are lightweight and, at the same time, have adequate flexural and compressive strength and low thermal conductivity. The aeration of mixtures mainly depends on the water and hydrogen peroxide content. The apparent density decreased as the percentage of hydrogen peroxide increased in both paste and mortar samples. When the percentage of hydrogen peroxide in the paste mixture increased by 0.25%, the apparent density in the paste sample decreased by 22%. In addition, there was a significant 31% reduction in the thermal conductivity coefficient, while there was only a 20% reduction in the compressive strength. Similar results can be stated for mortar mixes. As expected, there was an inverse relationship between apparent density and hydrogen peroxide content. As a result of this study, it has been found that alkali-activated perlite cementless pastes and mortars can be produced environmentally friendly without requiring high energy and without causing greenhouse gas emissions. Alkali-activated raw perlite can be used as an alternative binder instead of cement, especially in our country. It can provide economic and environmental advantages by reducing Portland cement consumption.

Important conclusions can be summarized as follows.

- Cementless paste and cementless mortar were produced based on the alkali activation of raw perlite, and it was proven that they could be used as construction materials.
- The durability of the mixtures decreased with increasing water content in both paste and mortar.
- Lightweight geopolymer pastes and mortars with significant flexural and compressive strength and low thermal

conductivity were produced by alkali activation of ground raw perlite.
- The apparent density decreased as the percentage of hydrogen peroxide increased in both paste and mortar.
- Cementless pastes and mortars can be produced in environmentally friendly without requiring high energy and without causing greenhouse gas emissions
- Alkali-activated raw perlite can be used as an alternative binder instead of cement
- Produced geopolymer pastes can be used as an alternative binder instead of cement and provide economic and environmental advantages by reducing Portland cement consumption.
- Adding 0.25% H2O2 in a mix by mass of perlite, durable, light, and low thermal conductivity concrete can be produced.

Based on the results, H2O2/Perlite% above 0.5% and water/Perlite% above 45% should be avoided for both paste and mortars. In order to obtain optimum results in terms of workability, strength, density, and thermal conductivity, it is recommended that the H2O2/Perlite ratio for all samples be 0.25% and the Water/Perlite percentage for paste and mortar 40% and 45%, respectively.

As a recommendation for future research, steel or composite fibers can be added to the mixture of paste and mortar to increase the strength capability of the perlite-based aerated geopolymer. These materials can also be obtained from recycled materials to improve the sustainability of the proposed mix design.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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