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Effects of different grain size of expanded perlite aggregate and content of silica aerogel on the characteristics of lightweight cementitious composite

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Abstract: In this research, an attempt was made to investigate effects of expanded perlite aggregate grain size on consistency, density, compressive strength, thermal conductivity and microstructure of 15 different composite mixes with silica aerogel. As for the samples preparation, expanded perlite aggregate of 5 different groups based on grain size, were used for sample preparation, then partially replaced by volume for 20% and 40% of hydrophobic silica aerogel particles. The results showed, that density of the samples varied between 0.35 g/cm^3 and 1.5 g/cm^3, flexural strength varied between 3.4 MPa and 7.4 MPa, compressive strength was in the range between 12.3 MPa and 55 MPa, thermal conductivity coefficient was in the range between 0.130 W/mK and 0.190 W/mK. Scanning electron microscopy showed that expanded perlite aggregates and silica aerogel particles are capable of being mixed and formed homogenous mixture. Nevertheless, microscope images indicated weaker adhesion of silica aerogel particles at interfacial zone as compared with expanded perlite aggregate particles.

Results revealed, that both of the factors: grain size of expanded perlite aggregate particles silica aerogel content influenced the density, compressive strength and thermal conductivity. The study also indicated feasibility of expanded perlite aggregate and silica aerogel for achieving homogeneous mixture of the lightweight cementitious composites. Study demonstrated that using different size fractions of expanded perlite aggregate affects differently physical, mechanical and thermal characteristics of the lightweight cementitious composite with silica aerogel.

Keywords: lightweight composite, expanded perlite aggregate, silica aerogel, mechanical characteristics, thermal conductivity coefficient, scanning electron microscopy

1. Introduction

Nowadays lightweight cementitious composites characterized by low unit weight, suitable mechanical strength and good thermal insulation are more desirable as compared with traditional cement-based materials in construction sector. For example, density of conventional concretes can be in the range between 2.1 g/cm^3 and 2.7 g/cm^3, while density of the lightweight concretes, according to standard EN 206-1, can be in the range between 0.8 g/cm^3 and 2.0 g/cm^3, or even lower (Demirboğa, Gül, 2003; Mousa et al., 2018; Casini, 2020; Shah et al., 2021). The approach to design lightweight cementitious composite with silica aerogel and expanded perlite aggregate has economical, ecological benefits, owing to very low bulk density of expanded perlite aggregate and silica aerogel (0.1-0.03 g/cm^3), high surface area (160.8-1100 m^2/g), low thermal conductivity (0.02-0.04 W/mK), excellent freeze-thaw and fire resistance (Cuce et al., 2014; Khamidi et al. 2014; Adhikary et al., 2021; Jia & Li, 2021). The application of such lightweight cementitious composite can be useful, for example, for constructing envelope of low unit weight and suitable compressive strength at same time, or for thermal insulation coatings oriented towards improvement of the building energy efficiency (Fickler et al., 2015; Shah et al., 2021).

Over the years numerous researchers have also studied the effects of embedding silica aerogel on performance of concretes, composites and mortars (Adhikary et al., 2020; Ślosarczyk et al., 2022). For

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example, investigations of influence of silica aerogel content on cement matrix conducted on high performance concrete and very high-performance concrete feasibility of replacement of quartz sand for 10%, 20% and 40% of silica aerogel. As for the results, dry bulk density was between 0.73 and 1.17 g/cm3, compressive strength at 28 days was in the range between 3.0 and 23.6 MPa, thermal conductivity was in the range between 0.170 and 1.9 W/mK. Studies of others authors indicated high correlation between density, compressive strength and thermal conductivity. It was proved, that for samples with compressive strength between 8 and 45 MPa, thermal conductivity oscillated between 0.30 and 1.9 W/mK, whereas for 6 MPa and 23 MPa, thermal conductivity was between 0.170 W/mK and 0.370 W/mK (Fickler et al., 2015; Jia & Li, 2021). When another paper investigated lightweight concrete with silica aerogel, it was found that replacement 20% of silica aerogel for fine aggregate reduced compressive strength from 42 MPa to 34.33 MPa, whereas thermal conductivity was also reduced from 0.40 to 0.17 W/mK (Khamidi et al., 2014). Literature revealed, that results of different studies can also vary. For example, Gao et. al (2014) investigated effects of replacement of fine aggregate in concrete for 20%, 40% and 60% of silica aerogel. Authors reported, that samples with 60% of silica aerogel had thermal conductivity 0.26 W/mK and compressive strength 8.30 MPa, samples with 40% and 20% of silica aerogel had thermal conductivity 0.30 W/mK and 0.40 W/mK and compressive strength 13 MPa and 30 MPa correspondingly. Authors proposed promising methods for embedding silica aerogel in lightweight cementitious products as replacement for quartz sand aggregate. Nevertheless, recent studies indicate that silica aerogel is increasingly being combined with lightweight aggregates.

The objective to investigate the influence of expanded perlite aggregate grain size on density, compressive strength and thermal conductivity of cementitious composites aroused from analysis of the related papers and own preliminary experiments. They indicated that effects of expanded perlite aggregate on dry bulk density and compressive strength and varied, when waste powder and coarse grains were scrutinized. Coarser grains of expanded perlite aggregate (^{3} 2 mm) can be used as replacement for sand or as lightweight aggregate instead conventional aggregates in concretes, owing to low density and high surface area (Kramar, Bindiganavile, 2011; Koukouzas et al., 2013). Various studies showed that expanded perlite powder (0-1 mm) have beneficial effect on mechanical characteristics of the concrete, owing to significant pozzolanic effect. Therefore, perlite powder can be used as active mineral admixture in concretes (Topçu, Işikdağ, 2008). This problem was also investigated in by others authors. For example, Różycka et al. (2016) studied effect of the expanded perlite powder on lightweight concrete. Study indicated, feasibility of replacing of quartz sand for expanded perlite aggregate in different ratios. Results showed, that the density of the autoclaved aerated concrete samples with 0%, 20% and 40% of expanded perlite aggregate was 0.65 g/cm^3, 0.45 g/cm^3, 0.35 g/cm^3; compressive strength was 1.75 MPa, 1.50 MPa, 1.00 MPa, thermal conductivity was 0.125 W/mK, 0.110 W/mK, 0.070 W/mK correspondingly.

However, only two studies had been recently published related to cementitious composites with silica aerogel and expanded perlite aggregate. First study investigated method for preparing fly ash-based silica aerogel/expanded perlite aggregate composite with low thermal coefficient (Chen et al., 2020). Second study measured effects of modification of cement binder with silica fume on compressive strength and thermal conductivity of the composite. According to results, samples had density between 0.5 g/cm3 and 0.9 g/cm3, compressive strength between 3.79 MPa and 14.47 MPa and thermal conductivity between 0.10 W/mK and 0.19 W/mK (Jiu & Li, 2021).

Literature review indicated increasing attention of scientists in the field of concrete products around problem of embedding silica aerogel in cementitious composites. As for indicated problems, can be named: adhesion between silica aerogel and cement matrix, improvement of mechanical characteristics of composites with silica aerogel, improvement thermal characteristics of the composite with silica aerogel, need for creative approaches to design of cementitious composites with silica aerogel.

This study contributes to the advancement of knowledge and understanding in field of lightweight cementitious composites with silica aerogel. Authors incorporated a systematic and approach to the problem of designing cementitious composites with expanded perlite aggregate and silica aerogel. Five different grain-size of expanded perlite aggregate 0-1 mm, 1-1.5 mm, 1.5-1.8 mm, 1.8-2 mm, 2-2.25 mm incorporated for preparing 5 corresponding groups of the samples. In addition to that, for each of 5 groups three types of samples were prepared with 0%, 20% and 40% of hydrophobic silica aerogel particles. Not only study provides insightful information about effects of each grain-size of expanded perlite aggregate on physical, mechanical and thermal characteristics of the composite, but simultaneously study contrasts how these effects differ after incorporation of 20% and 40% of silica aerogel. What differs this study from others papers in the field, is that it demonstrates interesting aspect about different effects of one lightweight aggregate but of different grain-size incorporated in cementitious composite with different content of silica aerogel; study might create place for the discussion and further investigations of studied problem of effects of different grain-size of expanded perlite aggregate on characteristics of the composite with silica aerogel.

2. Materials and methods

2.1. Materials

The expanded perlite aggregates of five different grain size available commercially was used for sample preparation. Physical and chemical properties of aggregate are given in Table 1. As for the cement, CEM I 42,5R, that comply with standard PN-EN 197-1, produced by Górażdże was used for sample preparation (Table 2). Silica aerogel granulate available commercially was used for sample preparation, and characteristics are given in Table 3.

Table 1. Characteristics of expanded perlite aggregate

Grain size (mm)	Chemical components (wt.%)							Bulk density (g/cm³)	Thermal conductivity (W/mK)
	SiO_2	Al_2O_3	K_2O	Fe_2O_3	CaO	MgO	other		
0-1.0	76.32	13.86	5.74	0.88	1.24	0.36	1.6	0.1-0.25	0.034-0.040
1.0-1.5								0.04-0.06	
1.5-1.8								0.06-0.08	
1.8-2.0								0.08-0.1	
2.0-2.25								0.08-0.13	

Table 2. Chemical properties of PN-EN 197-1 - CEM I 42,5R

Oxide	CaO	SiO_2	Al_2O_3	Fe_2O_3	MgO	SO_3	Cl-	K_2O	Na_2O	Insoluble residue	LOI
(wt%)	66.1	19.7	4.4	2.5	2	3.01	0.083	0.75	0.11	1.03	2.65

Table 3 Characteristics of silica aerogel granulate

Aggregate type	Surface area (m²)	Grain size (mm)	Melting point (°C)	Thermal conductivity (W/mK)	Porosity (%)	Average pore size (nm)
Silica Aerogel	400-800	2-3	800	0.012	90-95	20

2.2. Mixture proportions and sample preparation

Rectangular sample prisms of size 160x40x40 mm and 300x300x50 mm were prepared with low water/binder ratio 0.3. As for the mixing process, firstly cement and expanded perlite aggregate were mixed at speed 120 r.p.m in automated mixer for 15 seconds. Then, solution of water with polycarboxylate superplasticizer was poured into bowl and mixed for 90 seconds at the same speed. Finally, silica aerogel particles were carefully added and mixture was mixed for 60 seconds at speed 120 rpm. Finally,Mixture was cast into moulds and condensed manually by rodding.

As silica aerogel particles are highly brittle, they crack or fragmentate easily especially in contacting other particles with stronger structure. Authors observed this phenomenon during preliminary tests and made attempt to solve this problem by improving technique of mixing. During preliminary tests, dry ingredients cement and expanded perlite aggregate were mixed then, silica aerogel particles were poured and then mixed with water until obtaining homogenous mixture. The sequence was changed and silica aerogel particles instead of being poured to the mixed binder and lightweight aggregate, were poured into already obtained homogeneous mixture and mixed approximately for 20 seconds until all particles submerged in the mixture.

In the experiment the effects of expanded perlite aggregate grain size and content of silica aerogel were investigated, according to 0%, 20% and 40% of replacement of expanded perlite aggregate of each grain size for silica aerogel. Five sample groups were prepared and designated accordingly to grain size of expanded perlite aggregate. In addition, for each group three series of samples were prepared with silica aerogel content 0%, 20% and 40 %. A total number of 15 different composites were designed and tested. Mix proportions are given in Table 4.

Table 4. Mix proportions of the composites with silica aerogel and expanded perlite aggregate

Cement (g)	Water, w/c 0.3 (ml)	Water, w/c 0.37 (ml)	Expanded perlite aggregate (g)	Superplasticizer (%) of cement mass	Silica Aerogel content by volume, (g)	Silica aerogel (%)
1056	297	390	85	1	0	0
1056	297	390	68	1	15	20
1056	297	390	51	1	30	40

2.3. Consistency and workability observation

To analyzed consistency and workability flow table test was conducted according to standard PN-EN 1015-3 (Fig.1). Step-by-step process included: (1) prepare a fresh composite mixture; (2) wet and clean the tabletop and the mold from gritty materials; (3) keep the mold firmly at the center of the table; (4) fill two-layer, each layer should be one half of the volume of the mold; (5) tamp each layer 10 times using a tamping rod uniformly; (6) after tamping the top layer, struck off the excess concrete using the trowel; (7) gently clean the area of the table outside the mold; (8) remove the mold immediately by steady upward pull; (9) raise-and-drop the table at 12.5 mm, 15 times in 15 seconds; (10) measure the diameter of the concrete spread about its 2 perpendicular directions and find the mean value.

Consistency of the mixture was analyzed for water to cement ratio 0.3 (Fig.2). The results of flow table test depend on propagation of flow of fresh composite mix. Flow table tests demonstrated that smaller aggregate particles (size fraction 0-1 mm) absorbed much more water as compared with others size fractions, therefore consistency of fresh mixture was thicker, workability was also lower as compared with mixtures that contained larger particles of expanded perlite aggregate, thus filling molds required more attention. As size fraction of expanded perlite aggregate increased, the spread diameter on flow table tests had increasing trend; similarly, the workability was also improved. Conducted flow table tests also demonstrated that adding silica aerogel by cost of expanded perlite aggregate affected consistency and workability of the mix. This occurred because of the reduced amount of porous expanded perlite aggregate, and owing to hydrophobicity of silica aerogel particles that repel water molecules, resulting in increased degree of wetness of the mix. Flow table tests demonstrated that degree of wetness and workability of the mix was affected by water/cement ratio, size fractions and amount of porous expanded perlite aggregate particles.

2.4. Methods

The main point of the study was to investigate effects of grain size of expanded perlite aggregate and silica aerogel content on compressive strength and thermal conductivity of the cementitious composite. For this reason, measurements specified in further paragraph were taken on all specimens after 28 days

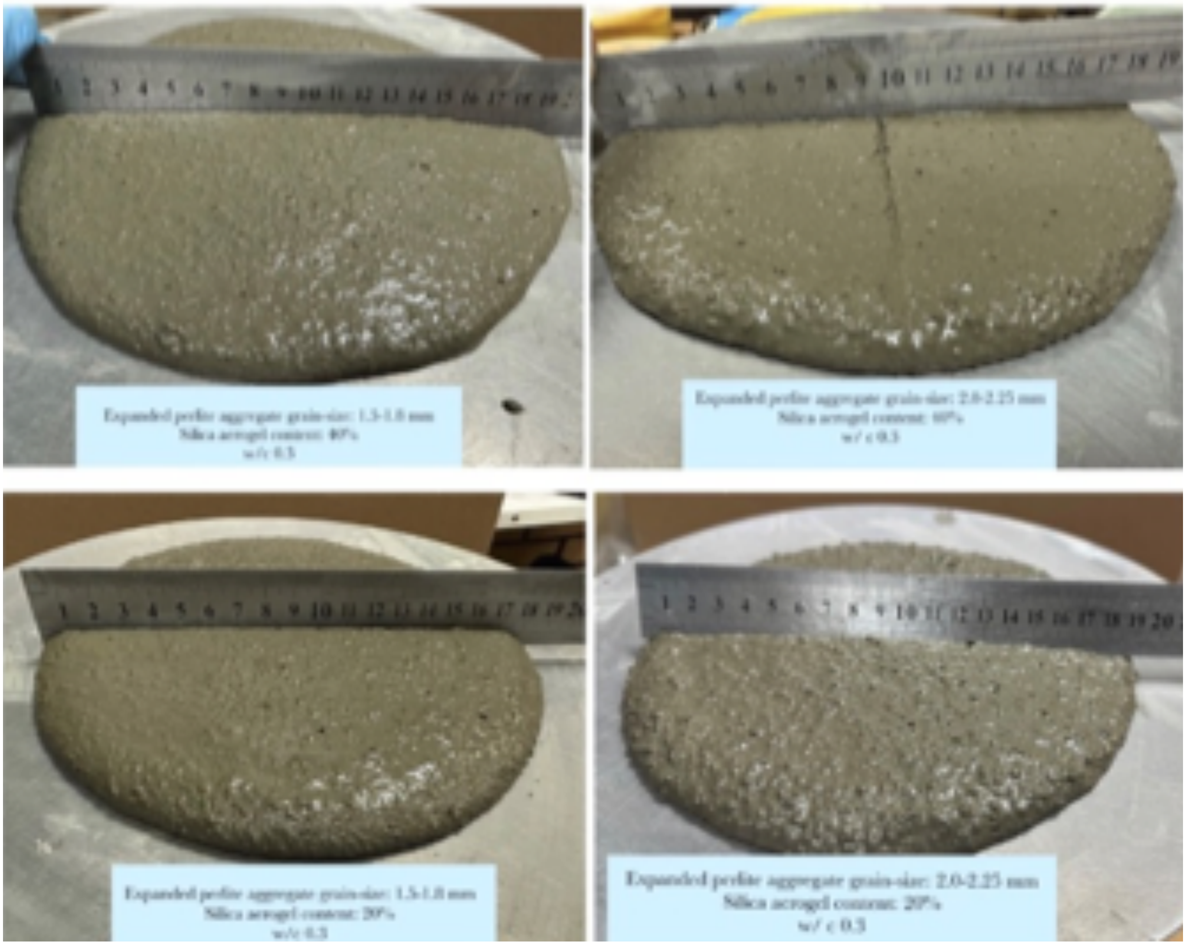

Fig. 1. Flow table test experiment setting

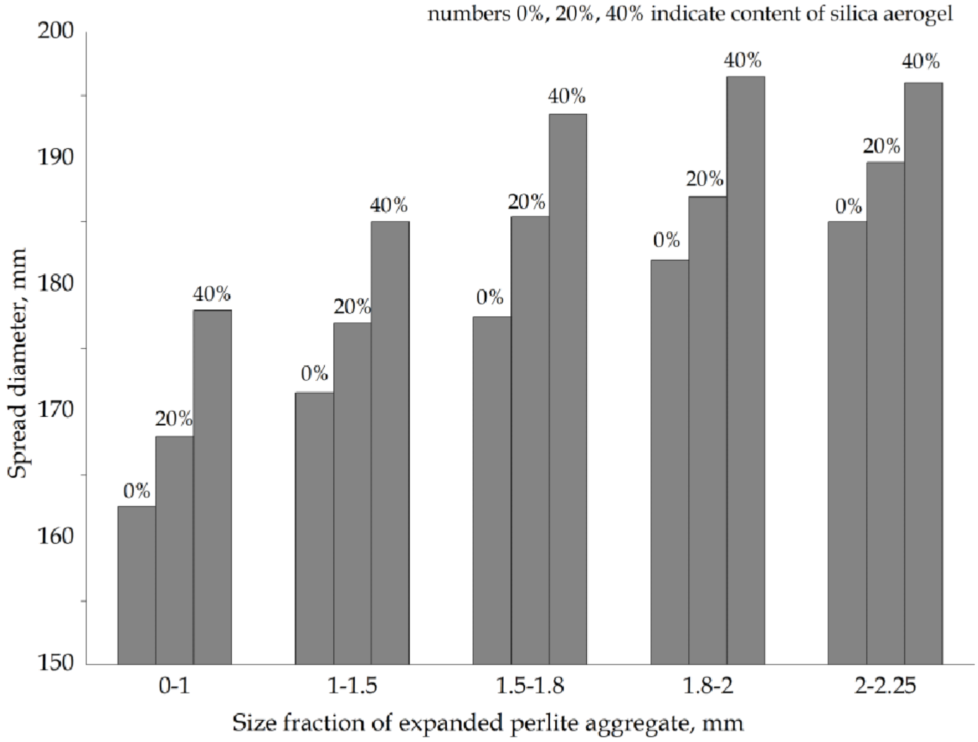

Fig. 2. Flow table test results, water to cement ratio 0.3

of curing. Density was measured according to PN-EN 12390-7 and calculated by dividing quantity of the dry mass of sample by it volume. Samples for density measurements were dried to constant weightin the dryer at temperature 70°C.

Compressive and flexural strength tests were performed on portions of cubic prisms 40x40 mm, according to PN-EN 12390-3 on automatic machine MATEST 183N.

Thermal conductivity was measured on samples 300x300x50 mm using heat flow meter Fox 314 with accuracy of ±1%. Prior to the launch of the test, samples were dried to constant weight at temperature 70°C and stored in the dryer's chamber at ambient temperature 25°C. Each specimen was positioned in a heat flow meter between two temperature-controlled plates which establish temperature difference **Δ**T across the sample. The resulting heat flux from steady-state heat transfer through the specimen was measured by heat flux transducers covering area 100x100 mm of upper and lower sample surfaces. Thermal conductivity coefficient was calculated according to Fourier's Law:

$$\lambda=\frac{Q}{A}\frac{L}{\Delta T} \tag{1}$$

where, Q/A is a heat flux; L stays for sample thickness; ΔT stays for temperature difference across the sample. Thermal conductivity coefficient was measured at three pairs of temperature: -10^{o}-0 ^{o}, 0 ^{o}-10 ^{o}, 10 ^{o}-25 ^{o} and final result was given as arithmetic mean of three measurements.

Optical method for microstructure analysis was applied. Investigation was conducted on scanning electron microscope TESCAN3VEGA using high-energy electrons for obtaining high-resolution images at x200, x500 and x1000 magnifications. Experiment was conducted with purpose to investigate:

- porous structure of expanded perlite aggregate embedded in the composite and bond between expanded perlite aggregate and cement matrix
- adhesion of silica aerogel with cement matrix with criterion such as air gap between silica aerogel particle and cement matrix.

3. Results and discussion

3.1. Density, flexural and compressive strength

For density measurement all samples were oven-dried to the constant weight at temperature 70°C. Experimental results showed, that density of cementitious composites was influenced by the grain size of expanded perlite aggregate, without regard to content of silica aerogel (Fig.3). The density was stretched between specimen as follows: 1.5 g/cm^3 for grain size 0-1mm, 1.3 g/cm^3 1-1.5 mm, 1.25 g/cm^3 for grain size 1.5-1.8 mm, 0.95 g/cm^3 for grain size 1.8-2 mm, 0.85 g/cm^3 for grain size 2-2.25 mm. As grain size of expanded perlite aggregate was increasing, dry bulk density was decreasing. The observation can be attributed to high porosity and surface area of coarser grains of expanded perlite aggregate, especially 1.8-2 mm and 2-2.25 mm. Results also showed, that dry bulk density of the composite was reduced after embedding silica aerogel. According to the results, observed decrease of density was between 20% and 33% for samples with 20% of silica aerogel as compared with reference samples without silica aerogel; as for samples with 40 % of silica aerogel, the percentage of decrease oscillated between 34.7% and 64 % when compared with reference samples. Results showed, that samples with 20% of silica aerogel obtained dry bulk density between 1.2 g/cm^3 and 0.57 g/cm^3. As for the samples with embedded 40% of silica aerogel, dry bulk density changes from 0.98 g/cm^3 to 0.3 g/cm^3.

Obtained density of the composites are consistent with results of related studies regarding effects of expanded perlite on properties of ultra-light cementitious composites. For example, in paper of Różycka, et al. (2016), for autoclaved aerated concrete samples with 20% and 40% of expanded perlite powder, density was between 0.55 and 0.45 g/cm^3. In studies of Chen et al., (2020) and Jiu & Li, (2021), obtained density of the lightweight concrete with expanded perlite aggregate was between 0.5 and 0.9 g/cm^3, which corresponds with density of the composites with expanded perlite aggregate of grain size 1.5-2.25 mm. Results proved, that samples with expanded perlite aggregate grain size 1.8-2 and 2-2.25 mm, in contrast to smaller grains of expanded perlite aggregate, obtained relatively low density below 1 g/cm^3 at the beginning even without silica aerogel.

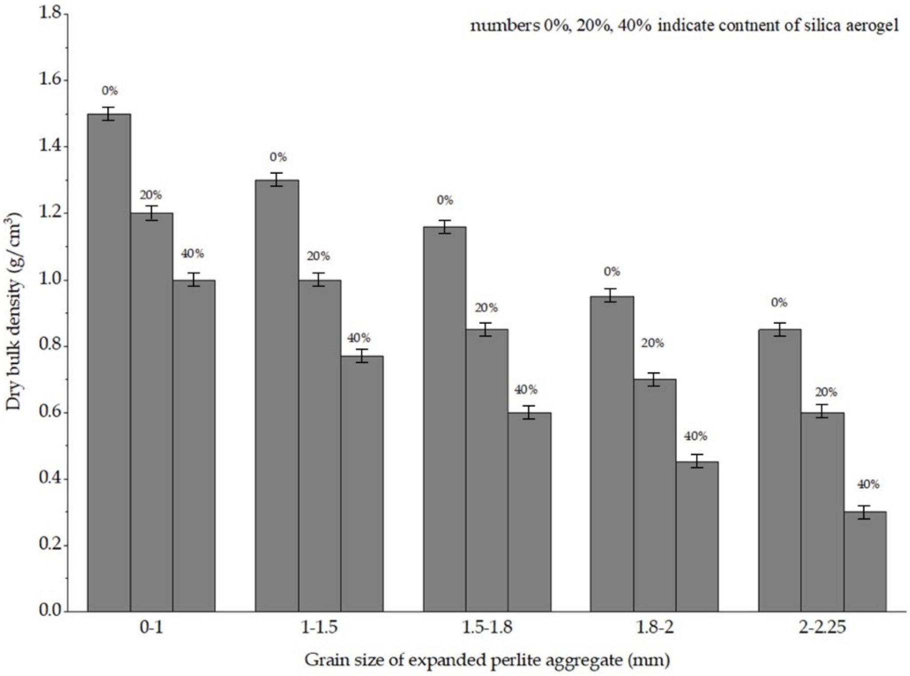

Fig. 3. Dry bulk density of the composites

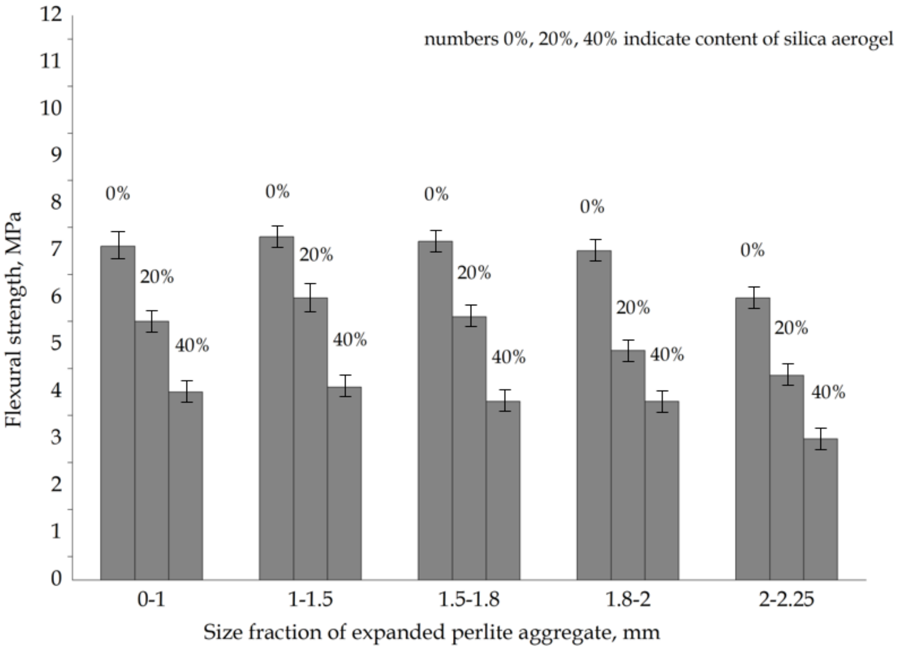

Fig. 4. Flexural strength of the composites

The results of the flexural strength at 28 days are presented in Fig.4. Results demonstrated, that flexural strength for samples without silica aerogel was nearly similar for all size fractions of expanded perlite aggregate and was in the range between 6.6 MPa and 7.3 MPa; the lowest value of flexural strength was observed for grain-size 1.5-1.8 mm and 2.0-2.25 mm. As content of silica aerogel was increased, flexural tensile strength was reduced. The lowest flexural tensile strength demonstrated samples with 40% of silica aerogel. The possible reason for this decrease was the low adhesion between silica aerogel particles and cement matrix and minimal mechanical strength of silica aerogel particles.

According to experimental results, the compressive strength of the composites after 28 days of curing was between 55 and 13 MPa (Fig. 5). Composites with grain size of expanded perlite aggregate 0-1 and

1-1.5 mm had compressive strength 55 and 45 MPa, whereas for samples with 1.5-1.8 mm, 1.8-2 mm and 2-2.25 mm, compressive strength was 31 MPa, 27.5 MPa, 25 MPa, respectively. Results revealed, that compressive strength of the composites was influenced by the grain size of expanded perlite aggregate. The samples with expanded perlite aggregate of 0-1 and 1-1.5 mm maintained higher compressive strength than samples with expanded perlite aggregate of grain size 1.5-1.8 mm, 1.8-2 and 2-2.25 mm. This can be acknowledged to higher compressive strength of small particles of expanded perlite aggregate as compared with larger grains. This observation was also confirmed in study of Adhikary et al. (2020). Incorporating smaller grain-size of expanded perlite aggregate in cementitious composite with silica aerogel probably can be adopted to overcome problem of declining mechanical strength resulting from incorporating 20% and higher content of silica aerogel. Others authors, that investigated the effects of small grain-size of expanded perlite aggregate on mechanical properties of the cementitious composites, indicated pozzolanic reaction of fine size fractions of expanded perlite powder Kramar, Bindiganavile, (2011), Gao et. al (2014), Khamidi et al., (2014), Fickler et al., (2015), Jia & Li, 2021.

Decreasing trend of the compressive strength for the samples with expanded perlite aggregate of grain size 1.5-1.8 mm, 1.8-2 mm and 2-2.25 mm can be associated with high surface area and porosity of expanded perlite aggregate, that also influenced density of the composites (Różycka et al., 2016; Chen et al., 2020; Jiu & Li, 2021).

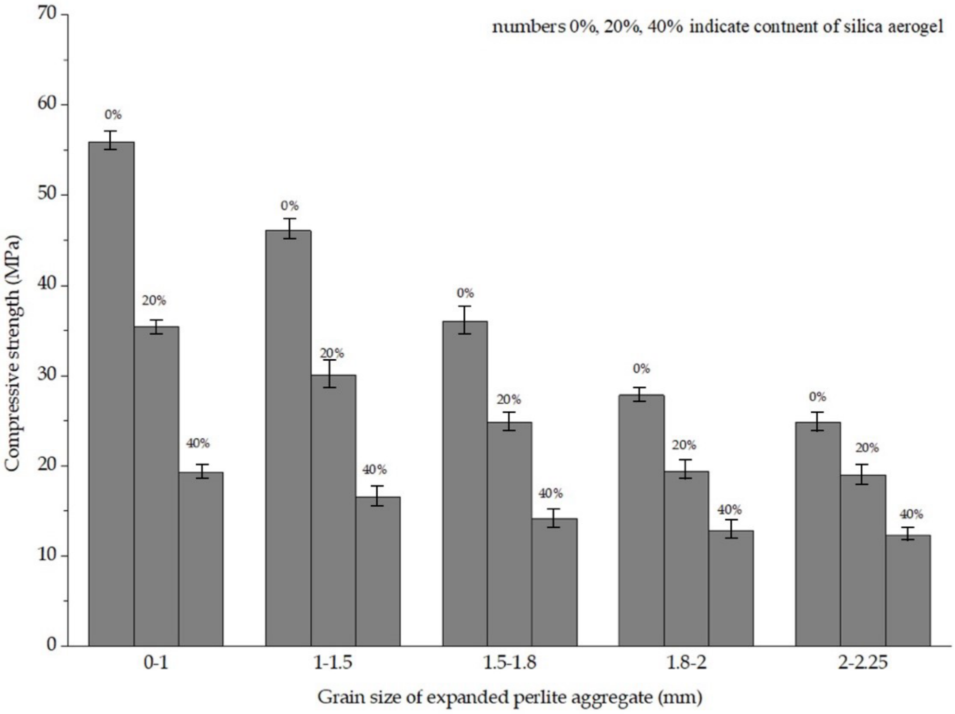

Fig. 5. Compressive strength of the composites

As for samples with silica aerogel, results showed, that composites with 20% of silica aerogel obtained compressive strength between 19 MPa and 35.4 MPa, whereas composites with 40% of silica aerogel had compressive strength between 12.3 MPa and 19.3 MPa. Results showed, that compressive strength of the samples with 20% and 40% of silica aerogel was also influenced by grain size of expanded perlite aggregate. For composites with grain size of expanded perlite aggregate 0-1 mm compressive strength was 35 MPa and 25 MPa, for 1-1.5 mm compressive strength was 30 MPa and 16 MPa, for 1.5-1.8 mm compressive strength was 25 MPa and 14.1 MPa, for 1.8-2 mm compressive strength was 19.4 MPa and 12.8 MPa, for 2-2.25 mm compressive strength was 19 MPa and 12.3 MPa. The effect of silica aerogel varied between the samples. For example, embedding 20% of silica aerogel reduced compressive strength of the samples with expanded perlite aggregate of grain size 0-1 mm by 36.7%, of grain size 1-1.5 mm by 34.7%, of grain size 1.5-1.8 mm by 20%, of grain size 1.8-2 mm by 29%, of grain size 2-2.25 mm by 23%. Similar trend was observed when 40% of silica aerogel was used.

Obtained results are consistent with the results of related studies, however composites with grain size of expanded perlite aggregate 0-1 and 1-1.5 mm proved better performance as compared with other authors. For example, compressive strength of the samples with expanded perlite aggregate 0-1 mm and silica aerogel was 35 MPa and 19.3 MPa, whereas in study of Gao et. al (2014) obtained compressive strength was 30 MPa and 13 MPa for samples with 20% and 40% of silica aerogel. In studies of Khamidi et al., (2014), Fickler et al., (2015) samples with 20% and 40% of silica aerogel had compressive strength 34.3 MPa and 17 MPa, which corresponds to experimental results of this study.

Results showed, that proposed methodology can be used as a tool for reaching better mechanical characteristics of the lightweight composite. Study provided a closer look to the topic of lightweight composites with different grain sizes of expanded perlite aggregate and silica aerogel. It was found, that different size fractions of expanded perlite aggregate had various impacts on density and compressive strength. Results indicated, that problem of reduction of the compressive strength when embedding silica aerogel can be solved by using fine grain size of expanded perlite aggregate. Proposed approach provided more data, one of the designing lightweight cementitious composites with expanded perlite aggregate and silica aerogel.

3.2. Effects of expanded perlite aggregate grain size and silica aerogel content on thermal conductivity

The thermal conductivity coefficient was obtained for samples that contain expanded perlite aggregate of grain size 1.8-2.0 mm and 2-2.25 mm, for which the cement composites presented the lowest densities. Thermal conductivity results are given in Table 5. According to the results, samples with expanded perlite aggregate of grain size 1.8-2 mm showed thermal coefficient 0.174 W/mK, whereas for 2-2.25 mm thermal conductivity was 0.180 W/mK. This can be attributed to higher porosity and surface area of coarse grains of expanded perlite aggregate. When amount of silica aerogel in the samples was increased from 0 % to 20 %, thermal conductivity decreased. As for samples with expanded perlite aggregate of grain size 1.8-2.0 mm, the decrease was equal to 8.3 %. Similar decrease of 8.0 % was observed for samples with grain size 2.0-2.25 mm. In further experiment as silica aerogel content was increased to 40%, thermal conductivity was reduced by 21.1 % for samples with expanded perlite aggregate of grain size 1.8-2.0 mm and by 25.3% for the samples with expanded perlite aggregate of grain size 2.0-2.25 mm, presented decrease was calculated in relation to the reference samples without silica aerogel. Considerable effect of silica aerogel on thermal conductivity of the composite can be associated with highly porous structure of silica aerogel particles and high surface aera.

Table 5. Thermal conductivity of the composites with expanded perlite aggregate of and silica aerogel

Grain size of expanded perlite aggregate (mm)	Thermal conductivity coefficient (W/mK) in relation to silica aerogel content (%)		
	0	20	40
1.8-2.0	0.180	0.165	0.142
2.0-2.25	0.174	0.160	0.130

The analysis of results indicated, that the grain size of expanded perlite aggregate had reducing effect on thermal conductivity of the composite. Embedding silica aerogel had also decreasing effect. Obtained results correspond to the results of related studies. For example, in study of Gao et. al (2014) concrete samples with 20% and 40% of silica aerogel had thermal conductivity coefficient 0.40 W/mK and 0.3 W/mK, which was higher than thermal conductivity of the composites in experimental study. In study of Khamidi et al., (2014) samples of cement paste with 20% silica aerogel had thermal conductivity 0.16 W/mK, which is consistent with experimental results of this study. In studies of Chen et al., (2020) and Jia & Li, (2021) thermal conductivity was between 0.10 W/mK and 0.19 W/mK, which corresponds to the experimental results.

3.3. Regression analysis

The linear regression analysis confirmed, that correlation coefficient R^2 was between 0.93 and 0.99, and proved strong correlation between variables (Fig. 6 - Fig. 8). As for the grain size of expanded perlite aggregate and dry bulk density, correlation was proved by high values of coefficients R^2 = 0.99 and R^2 adj. = 0.98 for samples with 0%, 20% and 40% of silica aerogel (Fig. 6); as for the adjusted coefficient R^2 (R^2 adj.) one independent regressor was adopted. Relationship between dry bulk density and grain size of expanded perlite aggregate proved, that changing grain size of expanded perlite aggregate from fine to coarse indeed influences the density of the composites and allows to reduce it. Results also proved high correlation between compressive strength of the composites and grain size of expanded perlite aggregate with R^2 between 0.93 and R^2 adj. between 0.91 and 0.95 (Fig. 7).

Presented in Fig. 6 relationship between dry bulk density of the composites and grain size of expanded perlite aggregate indicates, the importance of the conducted study which objective was to investigate the effects of grain size of expanded perlite aggregate on chosen characteristics of the lightweight cementitious composites with silica aerogel. The regression analysis proved, that there is a relationship between the grain size of expanded perlite aggregate and dry bulk density of the composites. Which indicates, that density of the composites can be changed by embedding different grain sizes of the expanded perlite aggregate.

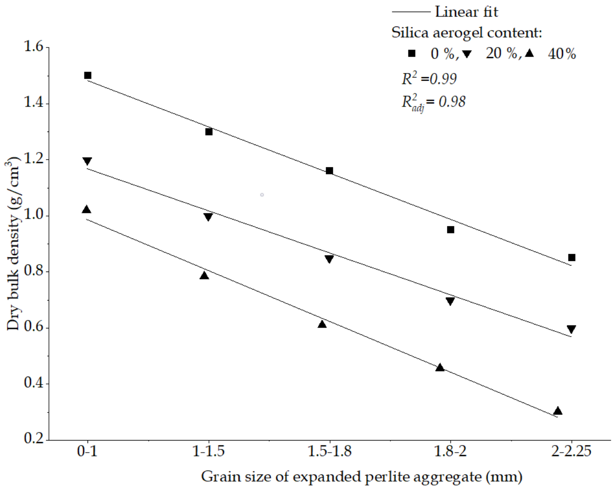

Fig. 6. Correlation between grain size of expanded perlite aggregate and dry bulk density of the composites

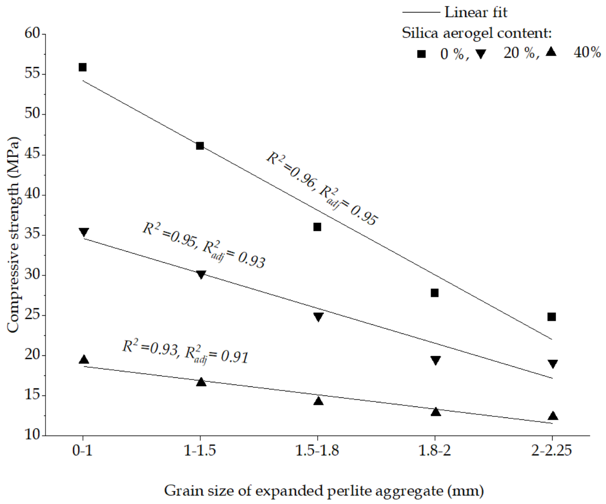

Fig. 7. Correlation between grain size of expanded perlite aggregate and compressive strength of the composites

The relationship between the grain size of expanded perlite aggregates and the compressive strength is presented in Fig. 8. According to the results, correlation coefficients for samples with 0 % of silica aerogel were $R^2 = 0.96$ and R^2 adj. = 0.95, for samples with 20 % of silica aerogel: $R^2 = 0.95$ and R^2 adj. = 0.93, for samples with 40 % of silica aerogel: $R^2 = 0.93$ and R^2 adj. = 0.91. The relationship between the variables indicates, that compressive strength of the composite can be increased or decreased by changing the grain size of expanded perlite aggregate without regards to the content of silica aerogel.

Statistical analysis indicated high correlation between thermal conductivity of the samples and content of silica aerogel (Fig.8). According to obtained correlation coefficients R^2=0.99 and R^2 adj.=0.98 showed very high correlation. The relationship between silica aerogel content and thermal conductivity indicates, that thermal conductivity of the composites can be reduced, by means of embedding silica aerogel.

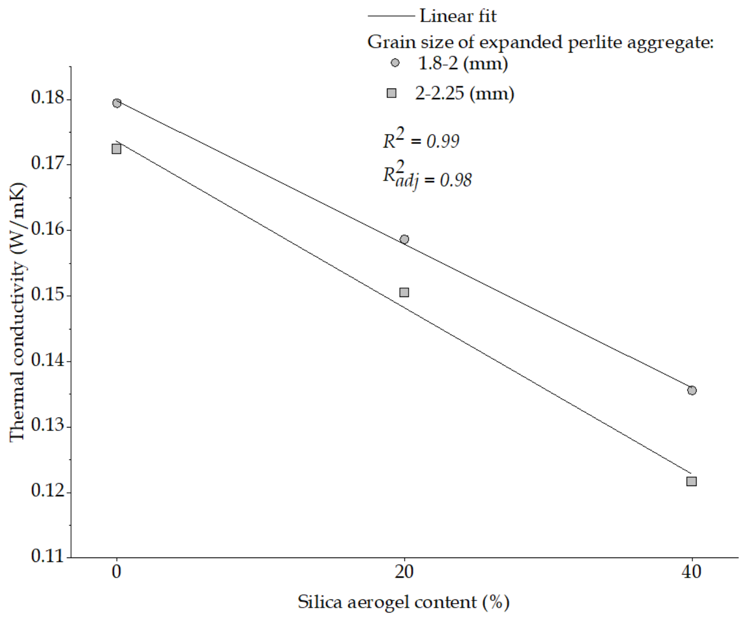

Fig. 8. Correlation between silica aerogel content and thermal conductivity of the composites

3.3. Microstructure of the composite

Samples for microstructure analysis were taken from specimen group prepared with expanded perlite aggregate of grain size 1.8-2 mm and 40% of silica aerogel. Microstructure images were taken at x200, x500 and x1000 magnifications are presented in Fig. 9. The microstructure results showed that expanded perlite aggregate developed good chemical bond around transition zone with cement matrix. Microstructure images related of expanded perlite aggregate suggested, that grains of expanded perlite did not collapse during mixing process and preserved their three-dimensional porous structure.

Microstructure images showed, that silica aerogel particles were fairly distributed within cement matrix. Microstructure images also proved fragmentation of certain particles of silica aerogel that took place during mixing process. This can be attributed to brittleness and low mechanical strength of silica aerogel. Similar observation was also mentioned in studies of Adhikary et al., (2021). The presence of visible space in transition zone between silica aerogel particle and cement matrix which can be associated with reduced adhesion, owing to hydrophobic surface of silica aerogel and hydrophilic cement matrix. Surface observations correspond with studies of Jia & Li, (2021), Zhang et al. (2023).

4. Conclusions

In this study, based on five grain size of expanded perlite aggregate and different content of silica aerogel, cementitious composites were prepared and the effect of the grain size of expanded perlite aggregate as well content of silica aerogel on the density, compressive strength and thermal conductivity were studied. In addition, microstructure of the composite was analyzed. The principal

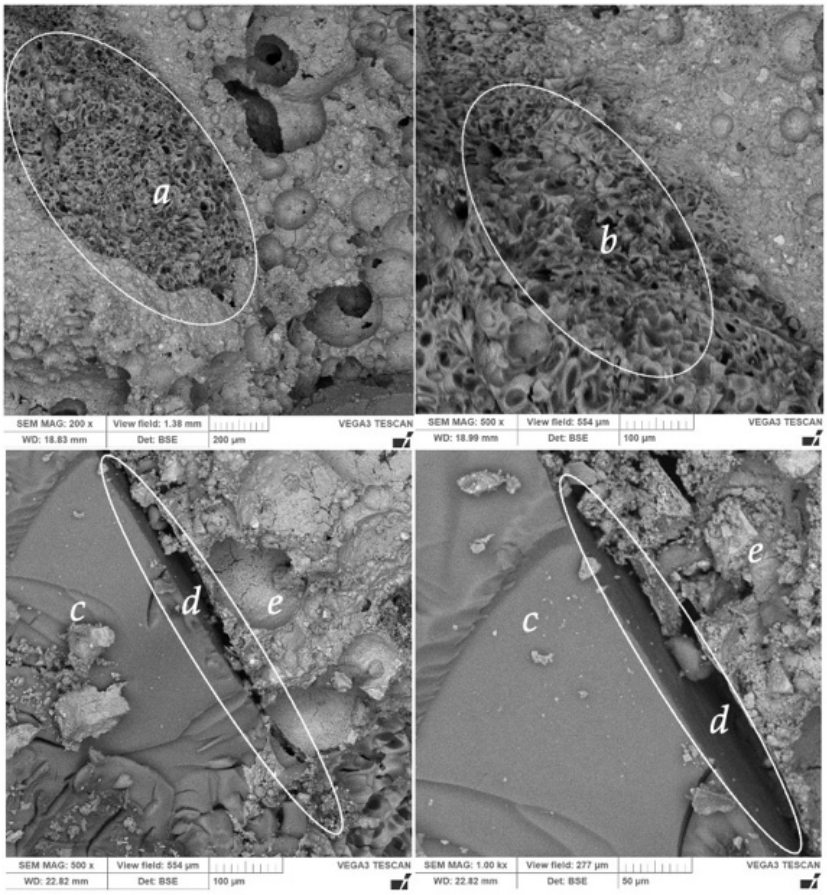

Fig. 9. Scanning electron microstructure of the sample with expanded perlite aggregate and silica aerogel; a, b) grain of the expanded perlite aggregate c) silica aerogel particle, d) air void between silica aerogel and cement matrix, e) cement matrix

conclusions from the study are as follows:

- Using of expanded perlite aggregate of different grain sizes demonstrates good compatibility between cementitious composite with silica aerogel. Composite samples that contained smaller grains of expanded perlite aggregate demonstrated higher compressive strength, owing to higher strength of lightweight aggregate; incorporation of larger particles of expanded perlite aggregate led to decline of compressive and flexural strength of the composite. Study indicated that the strength of the lightweight composite with 20% and 40% of silica aerogel might be improved by means of incorporation small-grain particles of expanded perlite aggregate.
- Obtained compressive strength of the composite samples was in the range between 15 MPa and 55 MPa, flexural strength was in the range between 3.4 MPa and 7.4 MPa. Incorporating 20% and 40% of silica aerogel declined compressive and flexural strength. Incorporating small grain-size of expanded perlite aggregate allowed to obtain higher compressive strength as compared with samples that contained larger grain-size of expanded perlite aggregate.
- Using expanded perlite aggregate of the grain size 1.8-2.25 mm has higher potential for decreasing density, and thermal conductivity coefficient, however also reduce compressive strength of the composite.
- Regression analysis proved strong correlation between grain size of expanded perlite and dry bulk density $R^2 = 0.99$ and compressive strength R^2 was between 0.93 and 0.96.
- Silica aerogel can considerably reduce dry bulk density and thermal conductivity coefficient of the composite, however also leads to reducing mechanical parameters of composite. The obtained thermal conductivity of the chosen composites was between 0.130 W/mK and 0.180 W/mK.

- Expanded perlite aggregate developed strong chemical bond with cement matrix of the lightweight composite and preserved three-dimensional porous structure after mixing process. The presence of air voids between silica aerogel and cement matrix in the interfacial transition was confirmed, indicating reduced adhesion of silica aerogel with cement matrix.

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