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Research Article

Lightweight Cement Mortars with Granulated Foam Glass and Waste Perlite Addition

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This article presents the influence of granulated foam glass (GFG) on thermal insulation and mechanical properties of lightweight cement mortars. The mortars were additionally modified with addition of ground perlite dust. Ground expanded perlite waste was introduced into the cement matrix in the amounts of 10%, 20%, and 30% of cement mass. The results show that application of this waste increases the strength of the mortars as well as decreases their thermal conductivity coefficient. A series of mortars were prepared with introduction of granulated foam glass with mass per unit filler/cement ratio equal to 0.6, 0.9, and 1.2. The aggregate composition of GFG was combined from different monofractions in the range 0–2 mm so that it filled the mortar volume to the maximum. Additionally, mortars were made, in which 20% of 0–0.25 mm GFG volume was replaced with quartz sand with the same granulation. Each mortar series was modified with addition of ground perlite waste in the amount of 20% of cement mass. The results indicate an improvement of thermal insulation properties along with greater participation of perlite in the mortars. The increase of the thermal conductivity coefficient was observed in the mortars, where the GFG was replaced with quartz sand. Greater amount of GFG results in decrease of compressive strength, but it can be improved by replacing part of the lightweight filler with sand or by introducing the addition of ground expanded perlite to the matrix. This also results in lower water absorption of mortars. Research proved that in most cases, the addition of ground expanded perlite decreased the capillary sorption of mortars, as well as the water absorption coefficient by capillary action, with growing proportion of the lightweight filler.

1. Introduction

The development of energy-saving building enforces using construction materials with increasingly better thermal insulation properties. The most often used materials are blocks from autoclaved aerated concrete, porous ceramic, and lightweight concrete with porous aggregates. Due to the need for elimination of thermal bridges on the seams, thin-layer mortars are applied, which demands a high precision, both during production of the blocks and during the bricklaying. For that reason also, the heat insulating mortars are often used. Such mortars should be compatible with walls. Designing mortars is, in a way, a compromise, since the improvement of thermal insulation properties via introduction of lightweight filler causes deterioration of strength properties. Popular lightweight fillers applied in mortars and concretes are as follows: expanded perlite [1–4], cenospheres from coal ash [5–8], granulated foam glass [9–11], fine clay aggregate fractions [12–14], and aggregates achieved from fly ashes [15–17], and also styrofoam and polyurethane foam aggregates [18, 19]. Thermal conductivity coefficient of mortar mostly depends on its porosity, thus mostly on the amount and porosity of lightweight filler and less (but still) on the thermal conductivity coefficient of cement matrix. Mechanical properties of the mortars are defined by strength and volume of the cement matrix in the mortar.

The aim of the research presented in this work was to design a cement mortar, in which granulation of the applied filler was matched in such a way, so as to minimise the volume of empty spaces between grains, which would be filled with cement matrix. The granulated foam glass (GFG) was used as a lightweight filler due to its very good insulation properties, spherical shape of grains, and relatively low water absorption.

The GFG aggregate may react expansively with alkalis in the cement, and the possibility of ASR and risk of high expansion must always be taken into account [20–22]. However, in other studies where the foamed glass was used, a limited expansion was observed [23, 24].

In this research, the cement matrix was modified by the introduction of pozzolanic additive such as ground expanded perlite dust. Expanded perlite is commonly used as lightweight filler; however, waste in the form of dust after additional grinding is characterised by exceptionally good pozzolanic properties. Those properties are connected with its amorphous structure, high content of silica, and very-high surface area, which is an effect of lamellar shape of grains after grinding [25]. Also, ground raw perlite has smaller but still good pozzolanic properties [26]. The use of pozzolanic additives including ground expanded perlite powder is also one of the most effective methods of suppressing the ASR reaction [27–29].

2. Materials and Methods

Research was conducted in two stages: in the first stage, the properties of the cement matrix modified with addition of ground expanded perlite waste in order to improve its strength are tested; in the second stage, mortars with addition of GFG grains smaller than 2.0 mm were prepared with optimal aggregate composition for maximum thermal insulation effect. Mortars, where part of the lightweight filler was replaced with quartz sand, were also prepared in this stage.

The applied perlite dust was a waste from expanded perlite production, which additionally was ground in the laboratory ball mill to the Blaine surface area of about 7700 cm^2/g. Milling time was 3 hours, which is enough for total destruction of the remaining porous microstructure of the expanded perlite grains in the form of single perlite plates. Moreover, grain distribution of the perlite waste was tested before and after milling with the use of a laser particle size analyser (MasterSizer 2000). The influence of perlite grain size on the content of active components SiO_2 and Al_2O_3 was also tested with the chemical method. The JEM1011 (JEOL) transmission electron microscope was used for observation of the perlite grains after milling. The chemical composition of the applied perlite dust, cement, and GFG is presented in Table 1. First, the influence of ground perlite on the properties of cement matrix was defined; then, the properties of lightweight mortars were tested. Portland cement CEM I 42.5R was used for making the matrix. A reference sample without perlite addition and a series with variable amount of addition of ground expanded perlite (10, 20, and 30% of cement mass) and water/cement coefficient equal 0.40 were prepared. The influence of increasing water amount by 5% on the properties of matrix with addition of 30% ground expanded perlite ($w/c = 0.42$) was also tested. From the pastes, beams were formed ($25 \times 25 \times 100$ mm) for tests on mechanical properties, and puck-shaped samples (diameter 50 mm and height 10 mm) were used for tests on thermal conductivity coefficient. After demoulding, the samples were kept in a climatic chamber under 100% RH and at temperature 20°C until the tests are conducted.

Compressive strength tests after 1, 2, 7, and 28 days of curing were conducted with the use of a universal testing machine (QC-508B1, Cometech) with loading force increase corresponding to a tension increase of 0.40 MPa/s. Samples intended for defining thermal conductivity coefficient were kept in the climatic chamber for 28 days, and before measurements, there were dried. Puck-shaped samples after drying were polished to reduce thermal contact resistance between sample and plates of instrument. Measurements were made by the steady-state heat flow method by TA Instruments FOX 50 (conforms ISO 8301 standard [30]) at an average temperature of 10°C. The temperature of sample surface was maintained as 5°C and 15°C, respectively, and after the heat flux stabilized, the measurement was made. The result was calculated from heat flux value, height of sample, and temperature differences on both surfaces of each of the samples, and it was the mean value of three independent measurements.

To define the pore size distribution, the mercury intrusion porosimetry technique was applied (Quantachrome Poremaster 60).

Commercially available aggregates of GFG were used as the lightweight filler. For mortar preparation, the aggregate composition was composed of different monofractions within the range 0–2 mm in order to maximise filling of empty spaces, which approximately correlates to the content of respective grain fractions in standard sand for mortars. Content of grain fractions equalled: 0.10–0.30 mm, 23%; 0.25–0.50 mm, 10%; 0.5–1.0 mm, 35%; and 1.0–2.0 mm, 32%, respectively. For tests of thermal conductivity coefficient of grain fractions of GFG and the mixture, the same method was used as that for the cement pastes, but aggregate samples after they were dried were put in polypropylene rings (diameter 50 mm and height 10 mm) before tests.

A series of cement mortars were made in the form of beams ($40 \times 40 \times 160$ mm) and pucks (diameter 50 mm and height 10 mm) for tests on thermal conductivity, which were kept before tests at the temperature of 20°C and relative humidity of 100%. A compressive strength test was conducted after 2 and 28 days of curing, and for samples after 28 days of conditioning, the bulk density was defined according to EN 1015-10 [31], water absorption according to the Polish standard PN-B-06250 [32], and water capillarity according to EN 1015-18 [33]. Tests were conducted in a similar way as in the case of measurements of cement pastes in the previous step. Mass per unit of GFG for cement in the mortar equalled 0.6, 0.9, and 1.2, respectively. A series of mortars were prepared with addition of ground expanded perlite in the amount of 20% of cement mass. The water/cement ratio equalled 0.50, and for series with greater amount of aggregate, in order to correct the rheological properties, a

Table 1: Chemical composition of used materials.

Compound (%)	Cement CEM I 42.5R	Waste expanded perlite (WEP)	Granulated foam glass (GFG)
SiO_2	19.4	71.1	72.0
Al_2O_3	6.3	13.0	—
Fe_2O_3	2.7	1.6	—
CaO	62.9	1.6	6.0
MgO	1.2	0.5	4.0
SO_3	3.5	1.6	—
K_2O	0.1	3.8	—
Na_2O	0.7	4.2	15.0
Others	6.8	—	3.0

superplasticizer based on polycarboxylate ethers was used. Before the cement was mixed, the GFG aggregates were moistened with part of water in order to limit the capillary action during mixing.

Additional series of six mortars was also prepared, where 20% of volume of GFG (<0.25 mm) was replaced with quartz sand with the same granulation. The composition of used mortars is presented in Table 2.

3. Results

Figure 1 shows the change of grain distribution of perlite waste before and after grinding. Perlite waste contains grains of size 1–1000 μm, where the bigger ones are porous as normal expanded perlite, whereas after grinding, the grain distribution is bimodal with the second maximum at about 0.15 μm.

Porous microstructure of grains is destroyed during grinding, which can be observed in the maximum on the distribution curve below about 10 μm, which is approximately the transverse dimension of perlite plates.

Figure 2 presents the microstructure of waste expanded perlite grains after grinding. Second maximum below 150 nm refers to the thickness of perlite plates, but as is presented on Figure 2, it also refers to relatively high content of very fine grains. This material is characterised also by large surface area which results in its high reactivity. Perlite pozzolanic activity strongly depends on the grain size, which is presented in Table 3.

Content of active oxides (SiO_2 and Al_2O_3) increases along the decreasing diameter of perlite grains. Grains with diameter lower than 10 μm result in almost three times higher pozzolanic activity of the ground perlite waste, in comparison to the unground one, which can be related to the significant increase of the surface available for reaction. Perlite after grinding was used as pozzolanic addition modifying the cement matrix in the amounts of 10, 20, and 30% of cement mass, respectively.

Figure 3 presents the change of bulk density of the paste in the function of the addition of ground expanded perlite. As the addition was introduced into the matrix, its porosity decreased which is observed in the increase of density and also in the size of the pores. Local maximum is moved in the direction of pores with smaller dimension (Figure 4). Ground perlite contains active silica, and thus, in the pozzolanic reaction with calcium hydroxide, new amounts of C-S-H phase are formed, which leads to additional condensing of the cement matrix. Ground perlite is introduced as an additive, not as a substitute of cement, which results also in physical effect of filling empty spaces, i.e., filler effect. This effect is especially visible in the pore distribution curve for sample with 30% of perlite. Paste with water/cement ratio increased by 5% shows lower bulk density, because the surplus of used water after evaporation leaves more pores. Local maximum in the pore size distribution equals around 1 μm, analogously as for the sample without the addition of ground perlite waste.

Mechanical properties of the pastes improved after short time of curing and after 28 days (Figure 5). After one day of hydrating, the difference in strength between reference sample and the sample with 30% of ground expanded perlite equalled 56%. After 28 days of curing, the strength difference was also significant, around 46%. Compressive strength increase can be caused by a few factors. Since the expanded perlite was an addition and not a substitute of cement, by classification of perlite as part of the binder, the water/binder factor decreased.

Ground perlite has a pozzolanic character; in pozzolanic reaction, active SiO_2 binds calcium ions, and thus additional amounts of C-S-H phase are produced replacing the portlandite. Due to the fine granulation of the used perlite, the cement matrix was compacted. Addition of more water ($w/c = 0.42$) causes an obvious decrease of compressive strength, due to evaporation of water which does not take part in the process of hydration and creates pores which weaken the microstructure of the cement matrix. Nevertheless, the strength is still higher than that in the sample without the addition of ground perlite.

Figure 6 presents the influence of expanded perlite addition on the thermal conductivity coefficient of the paste. All samples with addition of expanded perlite are characterised by lower thermal conductivity coefficient than that of the reference. The lowest coefficient value was observed for the mix with 20% addition of ground perlite. The result is a projection of simultaneously competing factors. Decrease of the thermal conductivity coefficient is related to the amorphous character of the introduced filler (decrease of heat conductivity) and to moving the maximum of the porosity in the direction of smaller pores as the addition of perlite grows. That implicates the decrease of convection effect in the heat transport through the material. On the other hand, however, the cement matrix

Table 2: Composition of mortars.

Sample	GFG (g)	Cement CEM I 42.5R (g)	GFG/ binder ratio	Ground expanded perlite (g)	Sand (g)	Water (g)	Superplasticizer (g)
0.6/0-P	270	450	0.6	90	—	225	—
0.6/0-0	270	450	0.6	0	—	225	—
0.9/0-P	405	450	0.9	90	—	225	1.13
0.9/0-0	405	450	0.9	0	—	225	1.13
1.2/0-P	540	450	1.2	90	—	225	2.25
1.2/0-0	540	450	1.2	0	—	225	2.25
0.6/S-P	217	450	0.6	90	180	225	—
0.6/S-0	217	450	0.6	0	180	225	—
0.9/S-P	314	450	0.9	90	260	225	1.13
0.9/S-0	314	450	0.9	0	260	225	1.13
1.2/S-P	443	450	1.2	90	367	225	2.25
1.2/S-0	443	450	1.2	0	367	225	2.25

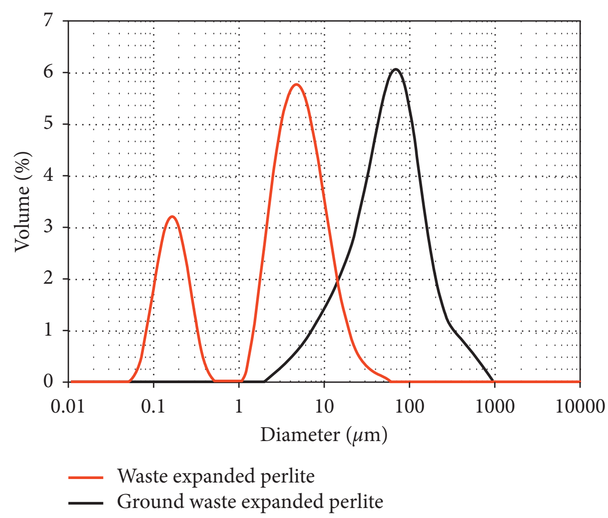

Figure 1: Grain size distribution of ground waste expanded perlite before and after the grinding.

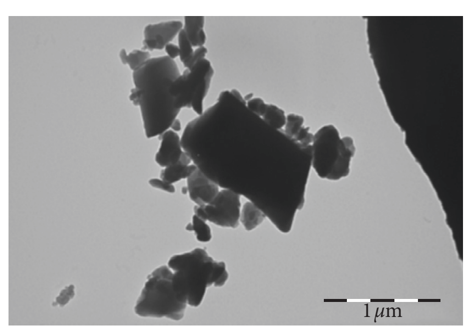

Figure 2: TEM observation of ground waste expanded perlite.

Table 3: Content of active oxides in relation to the perlite grain size.

Expanded perlite	$SiO_{2(act)}$ (%)	$Al_2O_{3(act)}$ (%)	Sum of active oxides (%)
Normal < 1 mm	17.0	2.8	19.8
Waste powder < 100 μm	31.1	5.5	36.6
Ground waste powder < 10 μm	48.2	6.6	54.8

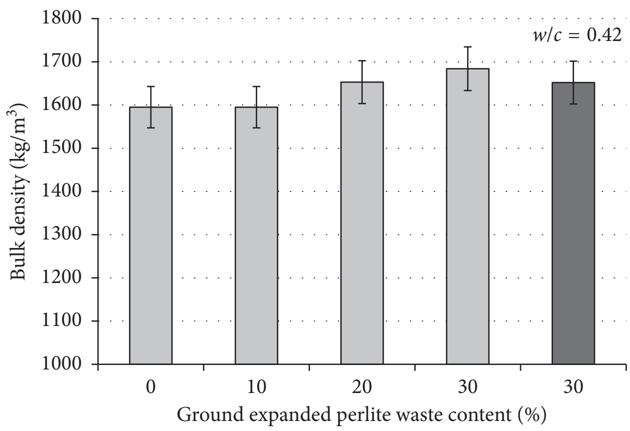

Figure 3: Bulk density of cement pastes.

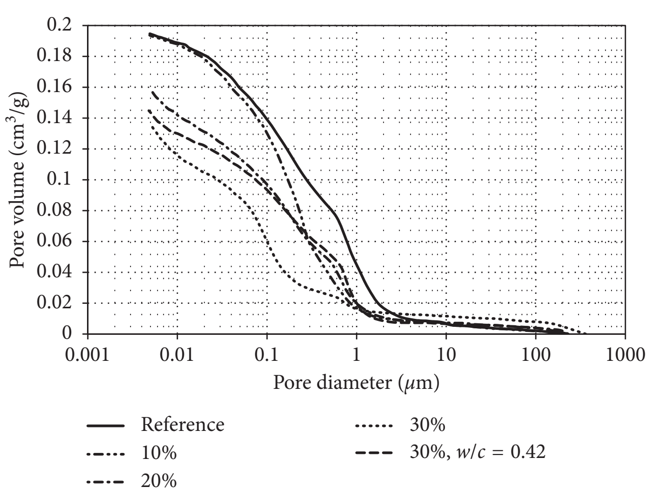

Figure 4: Cumulative pore size distribution of pastes with different ground perlite addition after 28 days of hydration.

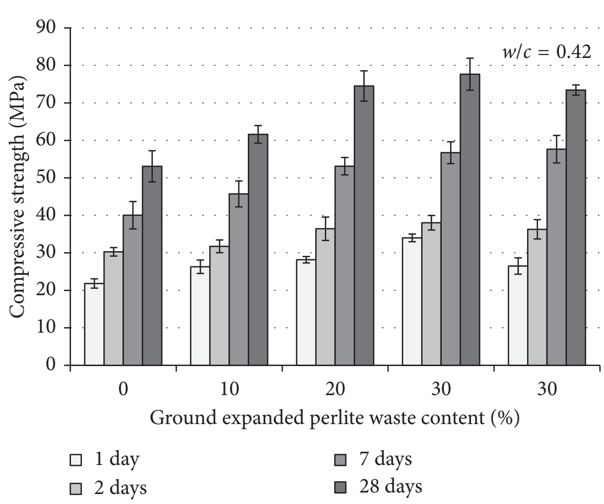

Figure 5: Compressive strength of pastes with ground expanded perlite waste addition.

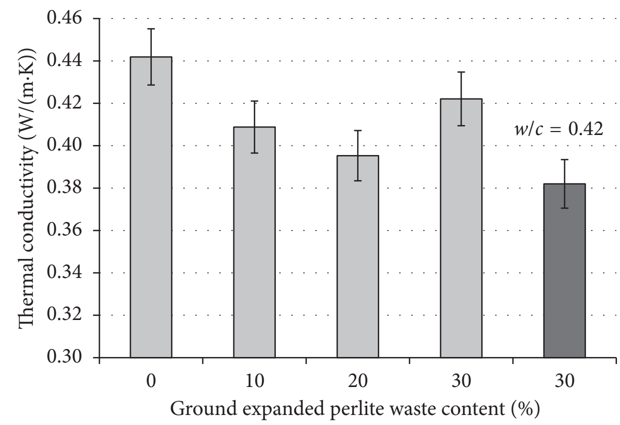

Figure 6: Thermal conductivity of pastes with ground expanded perlite waste addition.

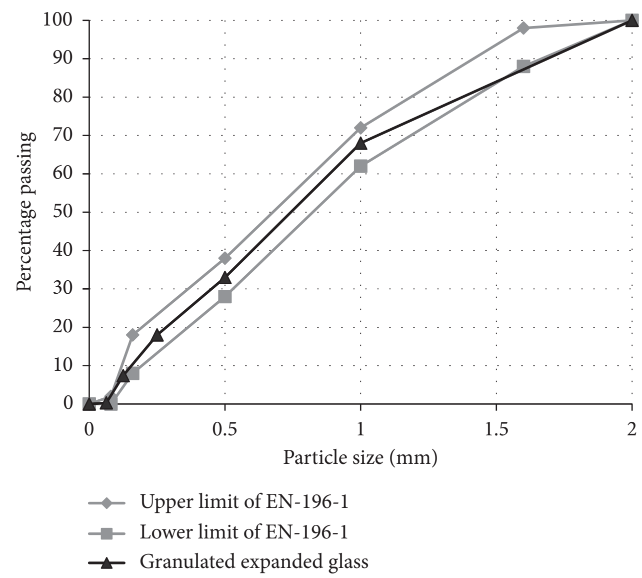

Figure 7: Cumulative grain size distribution of GFG and limits for sand according EN-196-1 standard [34].

gets condensed (new amounts of C-S-H as a result of pozzolanic reaction and additional filling with perlite grains), which leads to decrease in total porosity and thus to increase in the thermal conductivity coefficient. Macroscopic observation of thermal conductivity coefficient change in cement matrix is then a resultant of those components.

A cement matrix with 20% addition of ground perlite characterised by the best insulation properties and slightly smaller strength in comparison with sample with 30% of perlite was chosen for mortar preparation. To make the aggregate composition of GFG, individual grain fractions were mixed in such a way that spaces were filled maximally (Figure 7).

On the basis of percentage of grain fractions in the aggregate and their thermal conductivity coefficients, the resultant value of this coefficient was defined for the mixture. This value of the thermal conductivity coefficient equalled

0.073 W/(m·K); for comparison, measured coefficient of the mixture equalled 0.078 W/(m·K). The difference between the measured and estimated thermal conductivity coefficient can be caused by more intensive (than in theory) filling of empty spaces in the mixture and additional bridging of heat transport on the contact points, where the heat can be easily transported.

It was assumed, on the basis of rule of mixtures, that bulk density of mortars would not exceed 1000 kg/m^3. Mortars were prepared, where the mass of lightweight aggregate and binder ratio equalled, respectively, 0.6, 0.9, and 1.2. Mortar bulk density decreases along the increasing ratio of filler/cement, and for series with partial substitute of GFG with sand, values are, respectively, higher due to higher density of sand (Figure 8). Higher density of mortar with sand and matrix with addition of ground expanded perlite results from densifying of matrix.

Compressive strength decreases with increased participation of the lightweight filler which results mainly from low strength of grains of GFG (Figure 9). With higher filler/cement ratio, the amount of cement matrix is not enough to fill the spaces between the porous grains, which implies an increase of intergranular porosity. Additionally, with the highest aggregate/cement ratio, there can be areas of direct contact of aggregate grains, creating in this way a very weak contact zone. After 28 days, a compressive strength decrease was observed, which equalled from 14 to 33% of samples with the filler/cement ratio equal to 0.9 in comparison with samples, with the ratio equal to 0.6. In case of samples with the smallest amount of cement matrix, the strength decreases about 50% in comparison with samples from series 0.6. The addition of ground expanded perlite improves the compressive strength of all mortars. This results from reduction of porosity of the matrix. Replacing a part of the lightweight filler with quartz sand generally caused an increase of compressive strength (slight decrease was observed only in case of the filler/cement ratio equal 1.2).

As expected, the deterioration of insulation properties of mortars where part of GFG was replaced with quartz sand was observed. This is caused by a much higher thermal conductivity coefficient in quartz than in the aggregate of foamed glass. Figure 10 presents the influence of aggregate/cement ratio on the thermal conductivity coefficient of mortars. It was observed that the addition of ground expanded perlite caused in most cases an increase of thermal conductivity coefficient (except for series 06/0-P). Presumably, contrary to the pastes, in this case, the mechanism related to physical densifying of microstructure prevails, and the effect related to better properties of the very cement matrix is only visible in case of its greatest content; in other cases, it is masked. Active silica present in perlite reacts with calcium ions which are released during the process of hydration, making additional amount of C-S-H phase, and at the same time reducing the total porosity of the mortar.

Possible pozzolanic reaction of foam glass aggregate can also cause the change of porosity on the interfacial transition zone. Greater content of lightweight filler causes improvement of thermal insulation of mortars. Nevertheless, differences in values of thermal conductivity coefficient of mortars with smaller amount of binder are relatively little. Moisture absorption of mortars decreases in case of partial replacement of aggregate with quartz sand, which is caused by lower absorption of sand in comparison with GFG. Addition of ground perlite causes the absorption to fall by physical sealing of the matrix and higher level of cement reacting, which leads to production of additional amount of C-S-H phase filling the pores in the matrix. For mortars with GFG, where filler/cement ratio equalled 0.6 and 1.2, the differences are slight. A more visible difference occurred by the filler/cement ratio equal to 0.9, where the addition of ground perlite caused an 18% decrease of moisture absorption of the mortar (Figure 11(a)). Comparing the results presented in Figure 11(b) for all the types of mortars, it can be stated that the addition of ground expanded perlite limits the capillary sorption in mortars. Pozzolanic addition in the form of ground expanded perlite seals the cement matrix and thus capillary pores responsible for water absorption can be filled and the action is limited. For most mortars, the water absorption coefficient expressed by capillary action decreases with greater amount of GFG in the mortar.

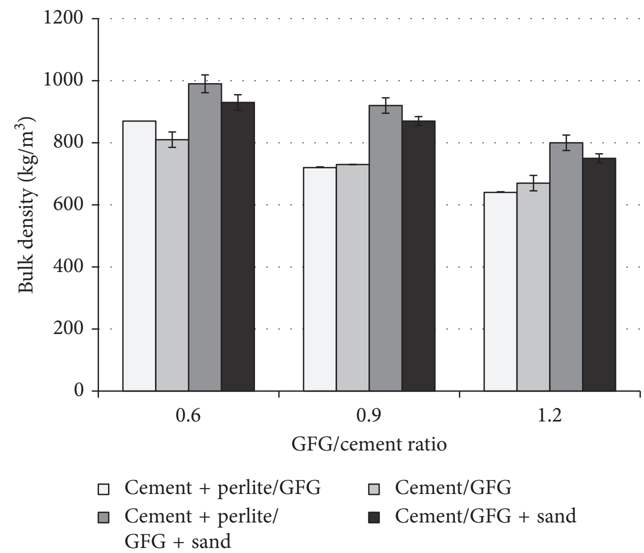

Figure 8: Bulk density of mortars.

A series where GFG was partially replaced with sand and 20% of ground expanded perlite was added to the cement is an exception. The capillary sorption decrease along with an increase of lightweight filler may be caused by smaller amount of paste in the composite volume. Capillary pores are mainly distributed in the cement matrix between the filler grains, but in the aggregate grains, the closed pores are prevailing.

4. Conclusions

The results show that ground expanded perlite is characterised by good pozzolanic properties and can be applied as an addition improving the mechanical properties, especially in lightweight mortars with decreased amount

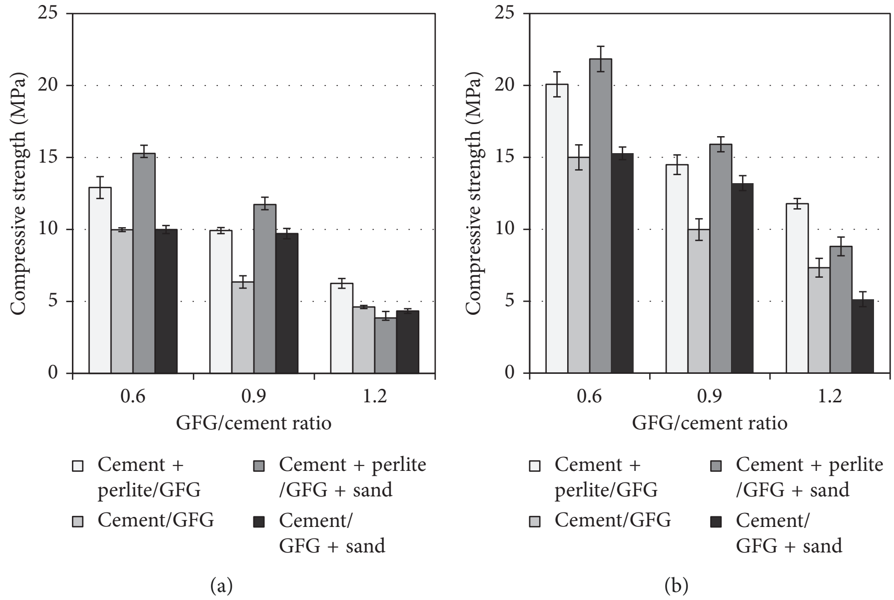

Figure 9: Compressive strength of mortars after 48 h (a) and 28 days (b) of hardening.

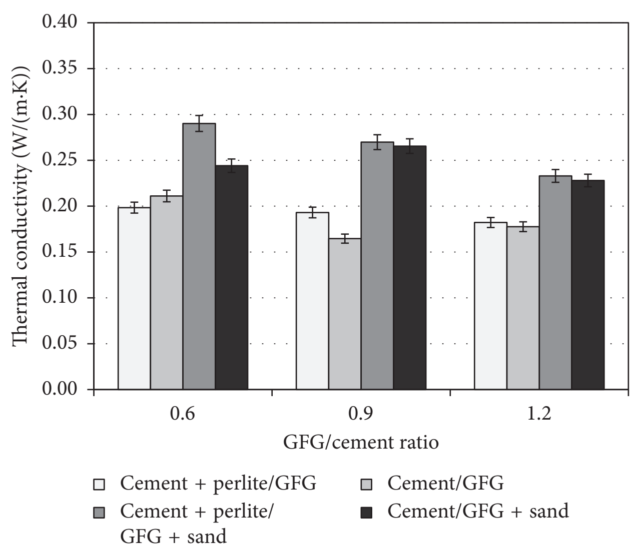

Figure 10: Thermal conductivity of mortars.

of binder. Their activity strongly depends on the size of the perlite grains. Ground expanded perlite applied as an additive also decreases the water absorption and capillary sorption of mortars. The thermal conductivity coefficient of lightweight mortars depends on many factors and is not a simple result of filler and matrix properties. Competing processes of matrix caulking and increasing the component of heat conductivity, as well as decreasing the average pore diameter and thus decreasing the convection component in a cumulative heat transport mechanism may have different participation, and it is difficult to predict the resultant effect. It may be however stated simplistically that in combinational circuits, the factor that increases the thermal insulation coefficient will be decisive, which results from a decrease in total porosity and not from decrease of pore size. Application of GFG as a lightweight filler, especially with optimised granulation, enables obtaining mortars with good thermal insulation properties and relatively high mechanical properties. These properties can be additionally improved when part of the aggregate is substituted with quartz sand, where the greatest strength after 28 days is about 20 MPa (for series 06/S-P) and the thermal conductivity coefficient equals 0.29 W/(m·K). Compressive strength decreases along with increasing the amount of GFG, which results from low strength of the very grains of GFG. For most mortars, the water capillary sorption decreases along with the increasing amount of GFG in the mortar and is lower for

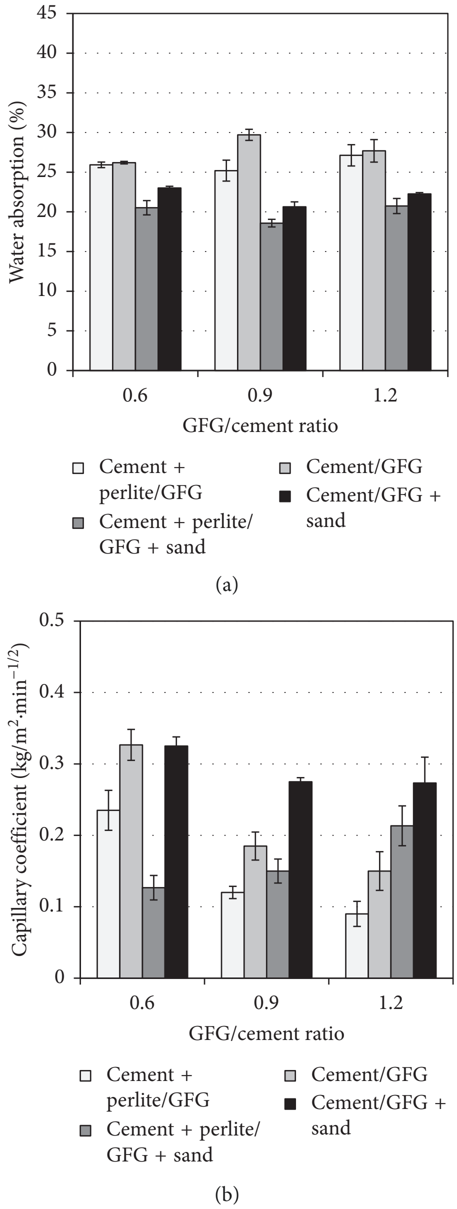

Figure 11: Water sorption of mortars.

samples with addition of ground expanded perlite. The risk of expansion of mortars due to ASR reaction can be limited by that additive.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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