Properties of Fine Graded Perlite-Based Lightweight Cement Mortars Subjected to Elevated Temperatures

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Abstract: The present research compared the behaviours of lightweight mortars based on ordinary Portland cement (OPC), calcium sulphoaluminate cement (CSAC), and calcium aluminate cement (CAC) containing expanded perlite and subjected to elevated temperatures. The perlite substituted natural sand in amounts of 25, 50, 75, and 100% by volume. The mortars were subjected to heating at up to 300 °C, 650 °C, and 1000 °C at a rate of 20 °C/min. The consistency and density of fresh mortars, compressive strength and density of hardened mortars after heating and cooling, and absorbability were assessed. Such a holistic testing approach is the main novelty of this research, which is related to the aforementioned mixtures and elevated temperatures. The main contribution of this article is a comparison of various cement types coupled with variations in the level of sand replacement with expanded perlite. In previous studies, comparisons were made in pairs of OPC-CSAC and OPC-CAC for normal-weight concrete. There is a gap in our knowledge of triple comparisons and lightweight cement composites which is filled by the current study. The use of OPC at up to 650 °C is recommended because it is the most common solution, its performance is similar to that of CAC, and it is cheaper than other solutions. Above 650 °C and up to 1000 °C, CAC is the only solution because it performs better than other cements. CSAC is not suitable for use at elevated temperatures because of its poor strength performance, even if it is the best solution from an environmental point of view. Sand replacement with perlite does not increase the strength performance under elevated temperatures, but its efficiency is different for various types of cement.

Keywords: Portland cement; calcium sulphoaluminate cement; calcium aluminate cement; expanded perlite; lightweight mortars; lightweight aggregate; refractory uses; elevated temperatures; compressive strength; cement composites properties

1. Introduction

One of the most important challenges of the modern world is to implement the idea of sustainable development in as many fields as possible. There are many opportunities for innovation in this respect. Such efforts may involve the use of materials that are optically adapted to work under particular conditions. The second possibility is to replace expensive and environmentally unfriendly materials with their equivalents in terms of properties [1,2]. The third is energy savings, which can be achieved by using alternative fuels or replacing primary raw materials with by-products or waste [3–5], and energy efficiency in terms of energy savings [6,7]. All these aspects are key to this publication. The first manifests itself in the use of lightweight perlite cement and geopolymer composites as a material that works at high temperatures [8,9]. This is a very promising material for such an application due to its insulating properties and light weight [10,11]. The second involves an attempt to replace expensive calcium aluminate cement (CAC) with cheaper
but less environmentally friendly ordinary Portland cement (OPC) or more environmentally friendly cement and similarly priced calcium sulphate alumina cement (CSAC) [12–14]. The third is related to the lower heat transfer coefficient for mortars with a higher content of lightweight aggregates [15–17]. As a result, these composites can be used as heat-insulating cladding for rooms and equipment where high temperatures are present.

Lightweight cement composites are used in the production and construction of thermal insulation cladding, furnaces, fireplaces, etc. The aggregates most commonly used for the production of lightweight aggregate mortars (LAM) are expanded perlite [18], expanded clay [19], vermiculite [19,20], pumice [19], and foam glass [21]. Current research focuses on the use of expanded perlite (EP). EP in building materials provides good thermal and sound insulation, as well as good fire resistance. It also possesses one of the lowest densities among other lightweight materials suitable for aggregate use [22], and it has the potential to effect internal self-curing in cement composites due to its water retention abilities [23,24]. It is manufactured by grinding and firing natural rock at 800–1200 °C. Under these conditions, the rock softens and the water in it turns into steam and causes expansion [25,26]. Perlite rock is an amorphous material which consists mainly of silicon dioxide [26]. Expanded perlite is used alone as a granular thermal insulation material. It is used for horizontal insulation, i.e., mainly ceilings and attics. It is also used as a component of mortars, plasters, and paints with insulating properties, and it is used under normal temperature conditions [27,28]. Its favourable properties are its lightness, with a bulk density of 30–190 kg/m³, and its low thermal conductivity, i.e., in the range of 0.04–0.05 W/m·K [29].

LAMs consist of a cement matrix that bonds the aggregate grains together. The type of binder used in such mortars depends on the operating temperature of the particular object. A common choice is high-alumina cement (HAC) or calcium alumina cement (CAC), but mixtures of these compounds with Portland cement, or Portland cement alone or in blends, can also be used in a limited temperature range [30,31]. The binder can also be enriched with fly ash or silica fume [32].

OPC is the most widely used cementitious material. This is the most basic cementitious material, but there are other variations in Portland cement, i.e., in phase composition. For example, there is low-heat Portland cement, that is richer in belite [33]. Total cement production was 4.2, 4.1, and 4.3 Gt in the years 2019–2021, respectively [34–36]. The cement industry is responsible for about 5–8% of global CO₂ emissions [37,38]. OPC is used in general constructions but rarely in applications that require high temperatures. The behaviour of this material at elevated temperatures has been the subject of several studies [39–42]. The main products of the hydration process of OPC are the C-S-H phase and portlandite. These products are subjected to deterioration at elevated temperatures to form dicalcium and tricalcium silicates (2CaO SiO₂–C·S and 3CaO SiO₂–C·S), although the exact temperature varies significantly [43,44]. A comprehensive overview is given in Table 1.

CAC is a relatively expensive material which is produced at approximately 0.1% of the OPC volume due to the limited availability of the main raw material, bauxite [45]. However, it is also more environmentally friendly: CO₂ emissions are 48% of OPC CO₂ production [12]. It is used to prepare blended cements with rapid strength development and as an ingredient in refractory concretes and mortars [46–48]. It is also used for pipe and installation linings [45] and heat-insulating concrete [49]. The main properties of CACs are rapid strength development and high resistance to high temperatures [45]. Good durability in terms of acid, chloride, and sulphate attack has been reported [50]. Good thermal properties are the effect of hydrate sintering and the production of a refractory matrix [48,49]. At 100 °C, C₃AH₆ is formed by the dehydration of the CAH₆ phase. At a temperature of 450 °C, the formation of a new phase, i.e., C₁₂A₇, occurs. This is related to the dehydration of C₃AH₆ and AH₃. A further increase in temperature to 800 °C causes the formation of a calcium aluminosilicate gel (C-S-H) [51]. Above 1000 °C, there are further thermally induced transitions. The following phases are formed: CA (up to 1300 °C); CA₂ (above 1040 °C) and CA₆ (above 1060 °C) [52]. A summary of a study in the literature
on the thermal decomposition of cements is given in Table 1. CAC is manufactured from bauxite and limestone. The process consists of calcination and grinding [12]. It consists mainly of fast-hydrating monocalcium aluminate (CaO Al₂O₃–CA), which is responsible for the early strength, and slower-hydrating calcium dialuminate (CaO 2Al₂O₃–CA₂), which has excellent long-term strength [12,46,48]. The secondary phases are gehlenite, mayanite, and brownmillerite [50,53]. Sulphates are not present in CAC. It mainly produces hydrated calcium aluminates. The C-S-H phase and portlandite are absent [54]. CAC has a bad reputation due to several collapses of CAC-based beam structures in the 1970s [47]. There is one big drawback of CAC as a structural material: hexagonal phases are transformed over time into cubic ones. This results in significant strength loss. Chemical resistance can also be decreased after such conversions [46,48,50].

**Table 1.** Decomposition temperatures for various hydrates and compounds present in hydrated OPC, CSAS, and CAC.

<table>
<thead>
<tr>
<th>Hydrate/Compound</th>
<th>Occurrence in Cement Type</th>
<th>Temperature [°C]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ettringite</td>
<td>OPC, CSAC</td>
<td>120–130 [55]; 160–173 [56]; 80 [57]; &lt;180 [58]; 100–110 [59]</td>
</tr>
<tr>
<td>C-S-H phase</td>
<td>OPC, CSAC</td>
<td>690 [57]; &lt;660 [58]</td>
</tr>
<tr>
<td>C-S-H gel water</td>
<td>OPC, CSAC</td>
<td>&lt;150 [55]; &lt;180 [58]</td>
</tr>
<tr>
<td>CH</td>
<td>OPC, CSAC</td>
<td>420–550 [55]; 480–490 [56]; 430 [57]</td>
</tr>
<tr>
<td>CaC₃</td>
<td>OPC, CSAC</td>
<td>650–800 [55]; 660–740 [58]; 710–730 [59]</td>
</tr>
<tr>
<td>AFm</td>
<td>OPC, CSAC</td>
<td>200–210 [59]</td>
</tr>
<tr>
<td>AH₃</td>
<td>CSAC, CAC</td>
<td>276–282 [56]; 250 [57]; 180–280 [58]; 240 [59]; 280–310 [60]; 266–310 [61]; 210–300 [46]</td>
</tr>
<tr>
<td>AH₃ gel water</td>
<td>CSAC, CAC</td>
<td>&lt;150 [60]; &lt;120 [62]; 100 [46]</td>
</tr>
<tr>
<td>CAH₁₀</td>
<td>CAC</td>
<td>&lt;150 [60]; 110–120 [61]; 120 [46]</td>
</tr>
<tr>
<td>Ca₂AH₈</td>
<td>CAC</td>
<td>&lt;150 [60]; 170–230 [61]; 170–195 [46]</td>
</tr>
<tr>
<td>Ca₂ASH₈</td>
<td>CAC, CSAC</td>
<td>&lt;150 [60]; 220–240 [61]</td>
</tr>
<tr>
<td>Ca₂AH₆</td>
<td>CAC</td>
<td>280–310 [60]; 290–350 [61]; 240–370 [46]</td>
</tr>
<tr>
<td>Ca₂AH₁₀</td>
<td>CAC</td>
<td>440 [61]</td>
</tr>
<tr>
<td>Ca₄AH</td>
<td>CAC</td>
<td>280–310 [60]</td>
</tr>
<tr>
<td>C₆AH</td>
<td>CAC</td>
<td>183 [60]</td>
</tr>
</tbody>
</table>

The last of the cements used in the current research is calcium sulphaaluminate cement (CSAC). It is much more environmentally friendly than OPC because of the lower calcination temperature required, i.e., CO₂ emissions are lower by about 40% [38]. This kind of cement is also more expensive due to the high price of raw materials containing alumina. Its applications are limited to special uses, mainly repair mortars, but 3D printing mix as well as waterproof, decorative, and insulating mortars have been reported. It is also used in blends with OPC, mainly to limit the expansion of CSAC [63]. There are few reports on its behaviour at elevated temperatures; those that do exist have mainly focused OPC-CSAC blends (and not in combination with a lightweight aggregate) [39,64]. The main products of CSA hydration are ettringite, monosulphate, and alumina hydrate, but the C-S-H phase and portlandite also exist [39,55,57]. Those phases obviously decompose under elevated temperatures; the ranges are given in Table 1.

**Motivation for and Novelty of the Present Research**

The properties of OPC, CSAC, and CAC normal-weight composites have been widely researched, but most often in comparisons of pairs: OPC–CAC or OPC–CSAC. The compressive strength and other mechanical and physical properties of normal and lightweight mortars have also been tested. The behaviour of perlite-based OPC mortars is known in the normal operating temperature range. The novelty of the present research is a comparison of the behaviours of different types of cement with lightweight perlite-based
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mortars subjected to elevated temperatures. The main questions raised are: (1) Which cement should be used in the preparation of lightweight composites according to their different costs, availability, and environmental impact? And (2) Does the perlite content enhance performance at elevated temperatures?

2. Materials and Methods

2.1. Materials

Tests were carried out using mortars. Mortars were produced from a cementitious material, water, aggregate in the form of sand, expanded perlite in various volumetric ratios, and superplasticizer (SPF) for the improvement of consistency.

The cementitious material used was a mixture of 90% cement and 10% silica fume (SF). The binders involved in the investigation were commercially available ordinary Portland cement (OPC–CEM I 42.5R), calcium sulfoaluminate cement (CSAC), and calcium aluminate cement (CAC). The OPC and CSAC were provided by Heidelberg Materials; CAC was manufactured by the Polish manufacturer Górka Cement. The perlite originated from a Czech supplier. Silica fume is a product of the Sika company. The specific surface area of Blaine was measured to be 4550 cm$^2$/g, 5610 cm$^2$/g, and 3530 cm$^2$/g for OPC, CSAC, and CAC, respectively. An important cementitious material that is part of a variety of high-performance concrete mixtures is silica fume. Its inclusion in this study was inspired by one sentence: “The combined use of calcium aluminate cement and microsilica is an important part of modern refractory technology”, found in [45]. The phase composition is given in Table 2. All materials were tested using X-ray diffraction analysis (XRD) method. The water used for the tests was tap water. The superplasticizer (SPF) used was a solution of modified polycarboxylates.

The aggregate mix was composed of natural sand (NS) and expanded perlite (EP). Sand replacement levels were 0, 25, 50, 75, and 100%. The perlite replaced the sand by volume. The granulation of both sand and perlite was 0–1 mm. The physical properties of the aggregates are given in Table 3. The chemical characteristics of EP are presented in Table 4. An XRD analysis of the perlite indicated that 94.0% was in an amorphous phase.

Table 2. Phase composition of cements [%].

<table>
<thead>
<tr>
<th>Cement</th>
<th>C_3S</th>
<th>C_3A</th>
<th>C_3AF</th>
<th>C_4S</th>
<th>C_4A_3_S</th>
<th>C_MgO</th>
<th>C_MgS</th>
<th>C_CaO</th>
<th>C_Ca_3_S</th>
<th>C_MgO</th>
<th>C_MgS</th>
</tr>
</thead>
<tbody>
<tr>
<td>OPC</td>
<td>71.1</td>
<td>5.6</td>
<td>3.9</td>
<td>12.7</td>
<td>0.15</td>
<td>4.3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CSAC</td>
<td>4.8</td>
<td>2.6</td>
<td>43.5</td>
<td>16.4</td>
<td>3.7</td>
<td>5.9</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CAC</td>
<td>5.2</td>
<td>19.1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>59.9</td>
<td>1.7</td>
</tr>
</tbody>
</table>

Table 3. Physical parameters of aggregates.

<table>
<thead>
<tr>
<th></th>
<th>Bulk Density [g/dm$^3$]</th>
<th>Real Density [g/dm$^3$]</th>
<th>Fractions [mm] [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.0–0.063</td>
<td>0.063–0.125</td>
<td>0.125–0.25</td>
</tr>
<tr>
<td>NS</td>
<td>1651.2</td>
<td>2652.0</td>
<td>0.5</td>
</tr>
<tr>
<td>EP</td>
<td>90.2</td>
<td>2320.0</td>
<td>0.7</td>
</tr>
</tbody>
</table>
The maximum amount of EP was established on the basis of mortar consistency in such a way as to not exceed the maximum dose of SPF to obtain a radius of $14 \pm 1$ cm in the flow table consistency test for OPC mortars. For the sake of simplicity, the perlite:sand ratio is a volume ratio. The exact composition of the mortars is presented in Table 5. Cross sections of the samples containing different cements and amounts of EP are given in Figure 1. Samples prepared with other cements differed only in colour. The EP was hardly visible due to its fineness.

Table 5. Mortar compositions.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Binder</th>
<th>Water [ml]</th>
<th>Extruded Perlite [g]</th>
<th>Sand [g]</th>
<th>Superplasticizer [% c.m.]</th>
</tr>
</thead>
<tbody>
<tr>
<td>OPC REF</td>
<td>Ordinary Portland Cement (1620 g), silica fume (180 g)</td>
<td>0</td>
<td>700</td>
<td>70</td>
<td>0.83</td>
</tr>
<tr>
<td>OPC P25</td>
<td>Sulphoaluminate Cement (1620 g), (w/b ratio 0.5)</td>
<td>1075</td>
<td>3225</td>
<td>1775</td>
<td>1.00</td>
</tr>
<tr>
<td>OPC P50</td>
<td>Calcium Aluminate Cement (1620 g), (w/b ratio 0.5)</td>
<td>2150</td>
<td>2150</td>
<td>1775</td>
<td>1.28</td>
</tr>
<tr>
<td>OPC P75</td>
<td>Calcium Silicate Cement (1620 g), (w/b ratio 0.5)</td>
<td>3225</td>
<td>291</td>
<td>1775</td>
<td>1.61</td>
</tr>
<tr>
<td>OPC P100</td>
<td>Calcium Silicate Cement (1620 g), (w/b ratio 0.5)</td>
<td>4300</td>
<td>388</td>
<td>0</td>
<td>2.00</td>
</tr>
<tr>
<td>CSAC REF</td>
<td>Calcium Silicate Cement (1620 g), (w/b ratio 0.5)</td>
<td>1075</td>
<td>2150</td>
<td>2150</td>
<td>0.39</td>
</tr>
<tr>
<td>CSAC P25</td>
<td>Sulphoaluminate Cement (1620 g), (w/b ratio 0.5)</td>
<td>2150</td>
<td>2150</td>
<td>2150</td>
<td>0.72</td>
</tr>
<tr>
<td>CSAC P50</td>
<td>Calcium Silicate Cement (1620 g), (w/b ratio 0.5)</td>
<td>3225</td>
<td>3225</td>
<td>3225</td>
<td>1.00</td>
</tr>
<tr>
<td>CSAC P75</td>
<td>Calcium Silicate Cement (1620 g), (w/b ratio 0.5)</td>
<td>4300</td>
<td>4300</td>
<td>4300</td>
<td>1.39</td>
</tr>
<tr>
<td>CSAC P100</td>
<td>Calcium Silicate Cement (1620 g), (w/b ratio 0.5)</td>
<td>1075</td>
<td>1075</td>
<td>1075</td>
<td>1.78</td>
</tr>
<tr>
<td>CAC REF</td>
<td>Calcium Aluminate Cement (1620 g), (w/b ratio 0.5)</td>
<td>0</td>
<td>0</td>
<td>70</td>
<td>0.89</td>
</tr>
<tr>
<td>CAC P25</td>
<td>Calcium Silicate Cement (1620 g), (w/b ratio 0.5)</td>
<td>1075</td>
<td>1075</td>
<td>1075</td>
<td>1.06</td>
</tr>
<tr>
<td>CAC P50</td>
<td>Calcium Silicate Cement (1620 g), (w/b ratio 0.5)</td>
<td>2150</td>
<td>2150</td>
<td>2150</td>
<td>1.44</td>
</tr>
<tr>
<td>CAC P75</td>
<td>Calcium Silicate Cement (1620 g), (w/b ratio 0.5)</td>
<td>3225</td>
<td>3225</td>
<td>3225</td>
<td>1.72</td>
</tr>
<tr>
<td>CAC P100</td>
<td>Calcium Silicate Cement (1620 g), (w/b ratio 0.5)</td>
<td>4300</td>
<td>4300</td>
<td>4300</td>
<td>2.11</td>
</tr>
</tbody>
</table>

Figure 1. Cross-sections of (a) OPC, (b) CSAC, and (c) CAC, containing samples with various EP amount, increasing from left (0%) to right (100%).
2.2. Methods

2.2.1. Fresh Mixes Properties

Each mortar was prepared in the same way and under the same conditions. Mortars were mixed with an amount of SPF that was sufficient to allow for an equal diameter (14 ± 1 cm) in the flow table test. It was necessary to obtain the same mortar compaction for further tests. The trial batches were prepared at the beginning to establish a proper dose of SPF. At first, cement and water were mixed together. SPF was added after 1 min and the mix was mixed for another minute. The sand was placed in a bowl and mixed with cement paste for 1 min. Eventually, EP was added; the mixing time was in a range of 1.0–1.5 min to obtain a homogeneous mixture with proper consistency. The EP was added at the end of the mixing procedure to avoid crushing its grains and excessive absorption of water from the mix. The flow table tests were conducted according to EN 1015-3 [65]. The measure of differences in consistency was the SPF dose. The density of fresh mixtures for the mortars in the plastic state was established according to EN 1015-6 [66].

![Figure 2. Mixer and flow table test setup.](image)

2.2.2. Hardened Mortar Preparation

Samples of hardened mortars with dimensions 160×40×40 mm for compressive strength, density, and absorbability tests were prepared, cured, and tested according to standard EN 196-1 [67]. Mortars were stored in a 20 °C water bath for 28 days, then removed and dried to a constant mass at 65 °C to avoid the dehydration of gypsum. After being dried, the samples were placed in an electric furnace. The samples were separated by chamotte dividers to avoid merging. The samples were heated to 300 °C, 650 °C, and 1000 °C at a rate of 300 °C/h. The isothermal conditions at the selected temperatures were maintained for an hour. The cooling rate was non-linear, and the samples were cooled with a furnace. The preparation and heating procedure is illustrated in Figure 3.
Temperature choice is as described in Table 1; an explanation for our choice of these temperatures is presented below:

- 300 °C—above or at the end of AH3 and most hydration products of CAC decomposition, above AFm, ettringite decomposition
- 650 °C—above CH, above or at the end of C-S-H decomposition
- 1000 °C—above CaCO3 decomposition, in range of softening of typical perlite (871–1093 °C) but below melting point (~1260–1343 °C) [68].

2.2.3. Hardened Mortar Properties

After cooling, the dimensions of the samples were measured. All samples were weighed, photographed, and their compressive strength was tested (six samples of each type). Confidence intervals are presented in the diagrams. The compressive strength was tested according to EN 196-1 [67]. The setup of the compressive strength test is presented in Figure 4. The dry density was tested according to EN 1015-10 [69] for samples that reached constant mass after drying at 65 °C (for samples before heating) and after cooling to room temperature for samples after heating. Absorbability was tested according to EN 13755 [70] (only for samples before heating). This parameter was tested on three samples of each type. Confidence intervals are presented in the diagrams. The samples were photographed after heating to 650 °C and 1000 °C before the strength test to show the thermal cracks visible on the surface. There were no changes visible to the naked eye after heating to 300 °C.
Figure 4. Compressive strength machine.

3. Results and Discussion

3.1. Properties of the Fresh Mixes

Immediately after mixing, the consistency was tested. Figure 5 indicates that the amount of SPF needed to obtain a flow diameter of 14 ± 1 cm was almost exactly the same for the OPC and CAC mortars. The amount of SPF needed increased from 15 and 16 g for mortars with sand as aggregate for OPC and CAC cements, respectively. The dose increased with EP content up to 36 and 38 g for mortars with 100% perlite for OPC and CAC cements, respectively. For CSAC, it was lower, disregarding the amount of EP added. The decrease was in the range of 12% for 100% perlite content, up to 50% for mortars that contained only sand. This shows that the main factor shaping consistency is the perlite content. Such behaviour of the CSAC, CAC, and OPC-based cements used in this research related to consistency, viscosity, and rheology, as observed in the current study is dependent on the exact type, specific surface area and composition of both cements. This means that taking different OPC, CSAC, and CAC, varying in phase composition or specific surface area, the results of consistency may be different [71]. This is connected to the very fast setting of CSAC, and difficulties in proper conducting of tests. There is research showing better consistency of concrete-based concrete and the opposite is also reported [72–74]. CAC rapidly loses workability over time [75]. In addition, no results of CSAC-SF or blends have been reported. CAC-SF may be of improved consistency [76].
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Figure 5. Superplasticizer dosage for stable consistency of mortars (column bars and left axis) flow diameter (polylines and right axis).

Figure 6 gives an overview of the densities of mortars with various cements and different EP replacement ratios. It is clearly visible that the density drops together with the perlite content. For mortars containing sand only, the highest density was recorded for CAC and the lowest for CSAC, for 100% EP it was opposite, and other variations were observed in between. Although the differences are very small and should not be treated as statistically important. Although a greater than observed decrease in density was expected with increasing amount of EP, the results were double checked, and it seems that the absorbability of the perlite itself is a reason. Water fills the pores of EP, which otherwise would be occupied with air, and the volume of the mixture would be greater. The method to avoid it may be prewetting of perlite (with part of the water used to produce mortars, not the additional one), which will also serve as an additional source of water for cement hydration and allow the consistency to be stable [77].

Figure 6. Density of fresh mortars.

3.2. Physical Properties of Mortars

The dry density of mortars containing lightweight aggregate is obviously lower, and the decrease is proportional to the EP content. The results are given in Figures 7–9 for OPC, CSAC, and CAC, respectively. The drop in density for OPC-based mortars with sand replacement level at 0, 25, 50, 75 and 100% by EP is 1.94, 1.91, 1.76, 1.58 and 1.26 kg/m$^3$ which is 1.5, 9.3, 18.6, 35.1%, respectively (percentage difference to non-perlite mortar). This drop is the result of replacement of the sand with EP that is of lower density.
This is only an example; other mortars based on various cements exhibit a similar behaviour. The full list of percentage differences is presented in tabular form in Table 6. The comparison of results is referred to the mortar density at 20 °C, for various cements separately. There are slight exceptions, but the rule is that the density decreases together with perlite content, but also with temperature to which mortars were subjected. This is obvious because of the loss of chemically bound water and thermal decomposition of hydrates in various cement pastes. It was thoroughly described in the Introduction, together with the temperature choice (i.e., [39,55,56,62]). The differences are visible when comparing various cements, but are not very significant. It is connected with shrinking of samples subjected to heating, which means that, together with mass loss, volume loss is present.

Figure 7. Dry density of OPC containing mortars with different sand replacement level.

Figure 8. Dry density of CSAC containing mortars with different sand replacement level.

Figure 9. Dry density of CAC containing mortars with different sand replacement level.
Table 6. Percentage decrease of dry density for OPC, CSAC, CAC with 0–100% EP and after heating to 20–1000 °C. The reference is always 0% of perlite at 20 °C.

<table>
<thead>
<tr>
<th></th>
<th>OPC</th>
<th>CSAC</th>
<th>CAC</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>20 °C</td>
<td>300 °C</td>
<td>650 °C</td>
</tr>
<tr>
<td>REF</td>
<td>0.0</td>
<td>1.5</td>
<td>3.1</td>
</tr>
<tr>
<td>P25</td>
<td>1.5</td>
<td>4.1</td>
<td>4.6</td>
</tr>
<tr>
<td>P50</td>
<td>9.3</td>
<td>12.4</td>
<td>14.4</td>
</tr>
<tr>
<td>P75</td>
<td>18.6</td>
<td>22.7</td>
<td>25.8</td>
</tr>
<tr>
<td>P100</td>
<td>35.1</td>
<td>40.7</td>
<td>42.8</td>
</tr>
</tbody>
</table>

The absorbability of mortars is strictly related to their density. The results are presented in Figure 10. Obviously, increasing the perlite content produces an increased absorbability due to the higher porosity of the composites. However, although the density of mortars containing various cements is similar at 20 °C, the relations of absorbability are different. The OPC-based mortar has an absorbability raising from 6.5% for no perlite content to 26.2% for 100% perlite-based sand replacement. The largest increase in the amount of absorbed water is between 75 and 100% EP content. CSAC has greater initial absorbability at a level of 12.6% and reaches 28.5% for 100% EP, but the greatest increase is observed between 50 and 75%. Moreover, CAC mortars behave similarly to those with OPC but with a greater substitution of sand for perlite. The initial absorbability is 5.1%, 6.1% is for 25% EP—a value similar to OPC without EP at all. CAC mortar with 100% perlite instead of sand exhibits almost the same absorbability. Similar relations are for intermediate replacement levels. Since the density of CAC and OPC mortars is almost the same, the reason has to be the open/close porosity ratio. The former must be greater for OPC based composites. Lower permeability was reported for CAC, which may support the present results [78]. There are no other works found dealing with CAC or CSAC lightweight mortars that can confirm this further.

Figure 10. Mass absorption of mortars after 28 days.

3.3. Mechanical Properties of Mortars

Figures 11–13 show the results of the compressive strength tests for OPC, CSAC, and CAC mortars, respectively. Sand perlite replacement was found to not improve concrete performance at elevated temperatures. Samples of mortars manufactured using CSAC, which were not subjected to elevated temperatures, have the highest compressive strength (67.2 MPa–39.5 MPa for 0% and 100% EP content, respectively) compared to those based on OPC and CAC. Both latter are comparable reaching, respectively: 57.6 MPa and 55.4 MPa for samples without perlite and 33.2 MPa and 29.2 MPa for 100% of perlite content.
The general behaviour of mortars is predictable: a higher perlite content produces a lower compressive strength, and the higher temperature at which the samples were heated has the same effect. The interesting part of it is the similarity of the OPC and CAC strength up to 650 °C. After heating to 300 °C, the strength is 55.2 MPa and 53.1 MPa for samples without perlite and 26.6 MPa and 23.4 MPa for 100% perlite content. Heating the samples without perlite up to 650 °C resulted in a strength of 32.4 MPa and 28.4 MPa, while for samples with a 100% EP content it is 7.5 MPa and 8.5 MPa. Both OPC and CAC lose most of the strength between 300 °C and 650 °C. The difference is visible after heating.
at 1000 °C For OPC-based mortar, the residue strength is 7.4 MPa for the sample without perlite and 2.7 MPa for the sample with 100% substitution of sand by perlite. CAC the residue strength is higher and the values are 17.4 MPa and 5.4 MPa, respectively. It is due to the high heat resistance and refractory properties of CAC composites [47]. Such properties are mainly caused by CA as the main phase of CAC. It should be mentioned that CAC above 1000 °C is sintered and its strength increases [46].

CSAC mortars exhibited different behaviour (Figure 12). The main decrease in compressive strength is visible below 300 °C. It is related to a much higher ettringite content in hydrated CSAC than in OPC. Ettringite shapes the strength of CSAC, and in OPC, the C-S-H phase is responsible for it. In case of CSAC the ettringite originates from ye’elimite in the presence of gypsum, while in case of OPC it is a product of the C3A reaction with water in the presence of sulphates [79–81]. Ettringite is thermally decomposed below 180 °C and C-S-H phase over 600 °C [56–58]. Although there is a similarity visible in the behaviour of OPC and CSAC—the residual strengths after heating up to 1000 °C are very close–7.4 MPa and 4.3 MPa for samples without perlite and 3.7 MPa and 2.7 MPa for 100% perlite content. For CAC, the residue strength is higher (5.4 MPa).

For clarity of presentation, the percentage of residual strength is presented in Figure 14. It is important to note that the general residual strength is higher for samples with a lower amount of perlite. The smallest differences are present in the case of CSAC (6–9% at 1000 °C, 17–21% at 650 °C and 28–30% at 300 °C). The strength of the cement-aggregate composite is a function of the strength of the cement matrix, the strength of the aggregate and the bond between these phases [82]. In case of heating in the studied range, the sand and perlite generally remain unchanged [26,83]. Changes are present in the cement matrix. Its strength decreases due to the thermal decomposition of hydration products [55,56,62]. The strength decreases to a specific level that may be above or below of the aggregate strength level. If there is more sand and less perlite than the composite, it is of greater strength because the sand strength is greater than that of the perlite. Therefore, if the strength of the cement matrix and its bond to the aggregate is satisfactory, the composites with a higher amount of sand will perform better.

The similarity of the behaviour of OPC and CAC is visible for all perlite contents at temperatures up to 300 °C (80–96% for both cements) and up to 650 °C (23–56% for OPC and 29–51% for CAC). The CSAC behaviour is very different.

The greatest residual strength (18–31%) is present at 1000 °C in the case of CAC. For OPC and CSAC, it is 8 to 13% and 6% to 9%, respectively. The perlite content has little influence on the percentage of residual CSAC strength at different temperatures and even slightly increases with the increase in the perlite content at 1000 °C. The loss of strength for CSA cement itself is so huge that the cement matrix plays a small role in shaping the strength. Its deterioration is so significant that it cannot longer hold the aggregate together and destruction is through the cement matrix and not through the perlite particles. The residual strength is presented as a percentage, and in absolute terms it is in the range of 3.7 to 4.3 MPa, so the difference is very small.
3.4. Photography of surfaces of mortars after heating

The samples were photographed after heating up to 650 °C (Figure 15) and 1000 °C (Figure 16) and cooling to ambient temperature to show the thermal cracks visible on the surface. No changes were visible to the naked eye after heating to 300 °C.

Cracks are visible after heating up to 650 °C, but they are very thin and hardly visible. There are only single cracks on surfaces of reference mortars without perlite, and only in the edge areas. The length does not exceed 4 mm. More cracks are visible on the surfaces of mortars containing EP. They are longer and, although they are a bit thicker than in reference mortar, they are also very thin. The most visible cracks are visible on the surface of the OPC mortar.

In case of heating up to 1000 °C the differences are visible in color in case of OPC an CSAC. The OPC became more yellowish/beige, and the CSAC became lighter. No color change is observed in CAC mortars. Cracks are visible on all surfaces of the samples. Surprisingly, compared to the compressive strength, which is the highest for CAC mortars after heating to 1000 °C, the CAC mortar exhibits the thickest and densest crack net, both in the sample with and without perlite. The effect of higher cracking intensity for CAC samples compared to OPC and CSAC heated to 1000 °C deserves further attention. Mortars containing OPC and CSAC are cracked, but the thickness and length are lower. Additionally, in case of reference sample, the cracks are hardly visible. Similar observations have been reported for composites, but for alkali activated slag mortars [84] and normal-weight cement mortar containing waste steel slag and waste clay brick [85].
Figure 15. Macroscopic view on samples (OPC/CSAC/CAC; REF/P100) heated up to 650 °C. Height and width of the sample part visible are 40 mm, as is the height of the sample.

Figure 16. Macroscopic view on samples (OPC/CSAC/CAC; REF/P100) heated up to 1000 °C. Height and width of the sample part visible are 40 mm, as is the height of the sample.

3.5. Correlations

Both the amount of SPF and the density of the mortar in the plastic state are highly correlated with the EP content. In case of SPF dosage, linear trend lines were used for the description of the determination coefficient and polynomial ones for the density, because
the linear model was not fitting. R² for the amount of perlite content—SPF were in the range of 0.979–0.996, which shows that the correlation is strong. The equations given in Figure 17 showing the relations of perlite content and density should be treated as a possible solution to predict mortar density for intermediate perlite content. The graphs are shown in Figure 17.

![Graph showing linear correlation perlite content - SPF amount and polynomial correlation perlite content - density of fresh mortar](image)

**Figure 17.** Correlation of (a) SPF amount and (b) density of fresh mortar to EP content.

The increased water demand for lightweight cement composites containing perlite is strictly related to its porosity, the basic property of lightweight aggregate. It was reported by several researchers for various lightweight products [86,87].

In Figure 18 the correlation between density and absorbability is shown for the three types of cement. All relations are linear with a fair R² factor between 0.969 and 0.994. Since the absorbability is the lowest for CAC, the possibility of entering aggressive chemical compounds is slightly lower than in case of OPC, therefore, durability should also be slightly enhanced [88].

![Graph showing linear correlations of density to absorbability according to cement type](image)

**Figure 18.** Linear correlations of density to absorbability according to cement type.

Figure 19 presents the correlation between compressive strength and perlite content. For all cements, the correlations are strong. The exponential correlation was chosen for presentation, as it fits the results better than the linear one. All R² coefficients are in the range 0.961 and 0.989. Only two exceptions are present: R²=0.431 and R²=0.873 for CSAC and OPC after heating at 1000 °C. In these cases, the linear correlations resulted in a similar R² factor. It is caused by very small and similar values of compressive strength. It is hard to predict the behaviour of cement composites under such conditions. For CAC, R² after heating up to 1000 °C is 0.987, so the correlation is strong and may be used to estimate the
strength of intermediate perlite content. The correlation between compressive strength and dry density is a result of the one mentioned above and the correlation between perlite content and density presented previously in Figure 18.

![Figure 19. Correlations of EP content to compressive strength according to cement type.](image)

4. Summary of Results

The increase in the amount of perlite results in a decrease in the compressive strength. The best correlation model for compressive strength–perlite content is exponential correlation in all cases at 650 °C. It is very difficult to establish the correlation equation for results at 1000 °C, due to the very small values.

There is a linear correlation between consistency (in terms of SPF amount) and perlite content. Linear correlation is also observed for the density-absorbability relationship. The correlation between the density of fresh mortar and the content of perlite is not linear. Exponential correlations of EP content and compressive strength were observed. The $R^2$ values show that the relationships found are reliable.

Absorbability is the lowest for CAC based mortars and the greatest for CSAC based ones. Absorbability is linearly correlated with perlite content.

Macroscopic observations gave an overview of surfaces. Cracks were observed after heating up to 650 °C for mortars with expanded perlite content. At 1000 °C, cracks were present in all samples, regardless of the presence of perlite.

5. Conclusions

The aim of the present research, and its strength, is a holistic approach and comparison of the behaviours of lightweight mortars based on OPC, CSAC, and CAC containing expanded perlite, subjected to elevated temperatures.

The question was raised at the beginning: Which cement should be used in the preparation of lightweight composites according to their different costs, availability, and environmental impact? May now be answered as follows: The OPC and CAC mortars show similar performance up to 650 °C. CSAC-based ones gained worse compressive strength after heating to any of the presented temperatures. The best performance in terms of compressive strength was found after heating to the maximum temperature of 1000 °C for CAC. The mortars based on OPC and CSAC behaved similarly; the residual strength was comparable. Only in the case of CAC, the $R^2$ factor indicates that the compressive strength of mortars with intermediate perlite content is predictable.

Therefore, it is recommended to use OPC up to 650 °C, because it is the most common solution, its performance is similar to CAC, and it is cheaper than other solutions. Above 650 °C, up to 1000 °C, CAC is the only solution because it performs better than other cements. CSAC is not suitable for use at elevated temperatures because of its poor strength
performance, even if it is the best solution from an environmental point of view. This is an unfortunate answer to the second sustainability issue presented in the Introduction.

The second question was raised: Is the perlite content increasing the performance at elevated temperatures and has to be answered adversely. This is an answer to the first sustainability issue stated in the introduction: perlite replacement does not increase strength performance at elevated temperatures, but its efficiency is different for various types of cements.

The idea of addressing the sustainability of presented is not addressed in this paper, but will be part of future research. The other parameters and studies that will enhance the knowledge in the topic will be a part of the future research, which will include, among others, the study of microstructure by SEM, porosity tests, analysis of thermal properties, and volume changes caused by the heating of mortars. Moreover, future research shall also include expanded perlite with a larger grain size.

Author Contributions: Conceptualization, J.P. and P.K.; methodology, J.P.; validation, J.P. and P.K. and M.M.; formal analysis, J.P.; investigation, J.P., M.M. and V.B.; resources, J.P.; data curation J.P.; writing—original draft preparation, J.P.; writing—review and editing, J.P., P.K. and M.M.; visualization, J.P.; supervision, P.K.; project administration, J.P.; funding acquisition, J.P. All authors have read and agreed to the published version of the manuscript.

Funding: Part of this research was performed during internship funded by Polish National Agency for Academic Exchange, decision number PPN/WYM/2019/1/00190/DEC/1. Moreover, the finalization of the article was also financially supported by the Ministry of Education, Youth and Sports of the Czech Republic via VŠB–Technical University of Ostrava (project SGS SP2023/056).

Data Availability Statement: Data available on request. The data are not publicly available due to privacy.

Conflicts of Interest: The authors declare no conflict of interest.

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