

# Effect of perlite waste addition on the properties of autoclaved aerated concrete



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## HIGHLIGHTS

- The EPW can be used as a quartz sand replacement in the production of AAC.
- The EPW has positive influence on the formation of calcium silicate hydrates.
- Replacing the quartz sand by EPW has a positive effect on the thermal conductivity of AAC.

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## ABSTRACT

In presented paper, the influence of expanded perlite waste on the properties of autoclaved aerated concrete (AAC) was investigated. Expanded perlite waste was used as a quartz sand replacement in conventional AAC mixtures at 5%, 10%, 20%, 30% and 40% by weight. Results show that use of expanded perlite waste in AAC caused a unit weight decrease in the produced AAC, it is connected with the changes in the properties of AAC. The thermal conductivity coefficient and compressive strength of specimens decreased as the amount of expanded perlite waste increased in AAC. The introduction of perlite waste up to 10% by weight reduced the thermal conductivity about 15% without significant reduction of compressive strength. Further improvement of thermal conductivity may be obtained by the addition of perlite waste up to 30%, but it caused reduction compressive strength about 20%. The minimum thermal conductivity value was 0.074 W/m·K, observed at 40% expanded perlite waste replacement. The structural and microstructural investigations showed that expanded perlite waste has a positive influence on the formation of calcium silicate hydrates (1.1 nm tobermorite) in AAC. From this result, it was concluded that expanded perlite waste can potentially be used as quartz sand replacement in the production of AAC.

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## 1. Introduction

Perlite is naturally occurring aluminosiliceous amorphous volcanic rock. Raw perlites when heated to a suitable temperature (above 870 °C) expand and transform into a cellular material of low bulk density. This expansion process is due to the presence of two to six percent combined water in the crude perlite rock. Upon rapid heating, water held within the perlite vaporizes and creates bubbles in the heat softened rock. During this process perlite expands up to 15–20 times of its original volume and produce frothy-like microstructure [1]. This microstructure gives the material a set of favourable properties such as excellent insulation properties, low density and high porosity causing the expanded perlite one of the most popular lightweight mineral filler [2–13]. In 2012,

the global perlite production registered was 2.66 million tons [14]. China accounted for just over 27% of the world's total perlite production volume and was the dominant perlite manufacturer. China was followed by Greece, the USA and Turkey [14]. The global perlite production is expected to post stable growth in the years ahead and to exceed 3.05 million tons in 2016 [14]. This growth is predicted to be stimulated by the constantly increasing demand worldwide along with new capacity introductions.

One of the main problems associated with the production of expanded perlite is a formation of relatively large quantities of the fine fraction (about 5–10%) with a particle size below 200 μm. The resulting lightweight waste due to a large specific surface area and dustiness is very difficult to dispose, especially in dry conditions and so far didn't find effective applications. Expanded perlite waste has a volume character and in most cases storage capacity in the areas of production has been exhausted; therefore, it has become necessary to develop a method for its utilization.

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Expanded perlite waste contains in its chemical composition significant amounts of  $\text{SiO}_2$  (65–75%), and therefore can be an attractive addition replacing part of the raw materials in autoclaved aerated concrete (AAC) technology. Autoclaved aerated concrete is widely used as building material because of excellent insulation properties and relatively high compressive strength despite a very low bulk density. Generally, aerated concrete is usually made from a mix of quartz sand and/or fly ash, cement, lime, gypsum and aluminum powder which acts as a pore forming agent. The specific surface area of the quartz sand plays an important role in the production of autoclaved concrete, in most cases the quartz sand is ground to the required fitness by ball milling. This process is energy consuming. Many studies have been reported that the hydrothermal reactions in the  $\text{CaO-SiO}_2\text{-H}_2\text{O}$  system are controlled by the dissolution of quartz; the results showed that finer sand reduces AAC processing time [15–17]. The amorphous expanded perlite waste can be considered as an alternative siliceous material for ground to the relatively high specific surface area quartz sand. It should be noticed that in AAC technology, sand is wet milled which provides a practical solution to the problems with occurring during utilization of perlite waste dusting.

Mechanical properties and durability of AAC significantly depend on a major constituent in autoclaved concrete, calcium silicate hydrate –1.1 nm tobermorite. A decisive influence on the synthesis of calcium silicate hydrates has a  $\text{SiO}_2$  modification. Amorphous expanded perlite waste due to higher solubility than quartz, can have a positive effect on the synthesis of calcium silicate hydrates formed in the AAC and consequently on the mechanical properties the material. On the other hand, synthesis of calcium silicate hydrates besides  $\text{CaO/SiO}_2$  molar ratio,  $\text{SiO}_2$  modification, reaction time and temperature is strongly influenced by the presence of small amounts of admixtures [18–22], so the other important factor to consider is influence of available  $\text{Al}_2\text{O}_3$ ,  $\text{Fe}_2\text{O}_3$  and alkalis contributed by expanded perlite waste on the synthesis of calcium silicate hydrates. Much literature concerning the use of expanded perlite in the technology of building materials, investigates the effects of expanded perlite on the properties of lightweight concrete [2–4,23]. In concrete, expanded perlite is used instead of fine aggregate with various replacement ratios depending on required strength. The test results indicate that compressive strength and modulus of elasticity decrease with increasing perlite content in the concrete mixture. Moreover, water absorption and sorptivity coefficient, increase with the higher perlite contents [4]. Replacing normal aggregate by the expanded perlite reduced the thermal conductivity of the mixtures as a result of the porous structure of the perlite [4]. Yu et al [24], investigated the influence of raw perlite powder on the strength of concrete, using perlite powder as cement replacement. Their results showed that perlite powder has a significant pozzolanic effect and improved the strength of concrete.

Although extensive studies of the use of expanded perlite in lightweight concrete technology have been reported, the possibility of using this material in AAC technology has not been investigated. In recent years, the tendency to replace the traditional raw materials in AAC production by industrial wastes has been appeared [25–40]. Wastes were considered as partial replacements for the binder or quartz sand. The objective of present work was to investigate the effect of expanded perlite waste used as a substitution of ground quartz sand on the properties of autoclaved concrete. Perlite waste was used to replace part of quartz sand at 5, 10, 20, 30 and 40% by weight, respectively. Potential advantages of the use expanded perlite waste in AAC technology are primarily environmental and economic benefits. Utilization of perlite waste in AAC, could enable reduce production costs of AAC attributed to the reduction of energy consumption during the milling process, and moreover, reduce the amount of residual waste in landfills.

## 2. Materials and methods

### 2.1. Materials

Samples of autoclaved concrete with different amount of perlite waste were obtained on a laboratory scale, according to Polish technology of AAC production – UNIPOL. Characteristic for the UNIPOL technology is activation part of quartz sand (in an amount of about 20% relative to the total amount of sand) by milling to relatively high specific surface area i.e. about 4000–6000  $\text{cm}^2/\text{g}$  (Blaine'a), what accelerates reaction of silica with the binder. In presented work, standard quartz sand was ground in laboratory mill to specific Blaine surface area of 5000  $\text{cm}^2/\text{g}$  and 2000  $\text{cm}^2/\text{g}$ , respectively. The surface area of the ground quartz sand corresponds to the typical surface area sand used in the production of autoclaved concrete in industrial scale, i.e. 5000  $\text{cm}^2/\text{g}$  (activated quartz sand) and about 2000  $\text{cm}^2/\text{g}$  in the wet ground slurry. The cementitious material used in this study was Ordinary Portland Cement (OPC) CEM I 42.5R. Pure p.a. calcium carbonate from POCH (Poland) was used as CaO source. It was calcined at 1000 °C for 2 h. The efficiency of decarbonation was tested by XRD method. In the concrete production network water was used. Commercially available aluminum powder with mating surface 6200  $\text{cm}^2/\text{g}$  was used as pores producing agent. Table 1 presents the chemical compositions of the expanded perlite waste. The chemical composition of the waste is mainly  $\text{SiO}_2$ . Specific Blaine surface area of the expanded perlite waste was 13,000  $\text{cm}^2/\text{g}$ .

The particle size distribution of expanded perlite waste and ground quartz sand determined by laser particle size analyzer is presented in Fig. 1. Quartz sands are characterized by smaller particle size compared to expanded perlite waste, which contains particles with size up to 1000  $\mu\text{m}$ .

Fig. 2 shows XRD analysis expanded perlite waste. X-ray diffraction study indicated the presence of amorphous glassy matrix as well as some amounts of aluminum silicate and calcium aluminum silicate. Fig. 3 presents SEM observations of expanded perlite waste and quartz sand. As shown in Fig. 3(c), expanded perlite waste exhibit a frothy-like structure with numerous open pores, that gives it a great specific surface area. SEM observations confirm the results of particle size distribution analysis; expanded perlite waste (Fig. 1 c) is characterized by coarser grains compared to ground quartz sand (Fig. 1a and b).

### 2.2. Mix proportion

The reference mix was composed of OPC, lime, quartz sand and water. The sand was replaced by expanded perlite waste at levels of 5%, 10%, 20%, 30% and 40% by weight. Aluminum powder was added at 0.3% by weight of the binder (OPC + lime). The mix proportions are summarized in Table 2. While mixing the dry mixes with water, it was observed that along with increased content of expanded perlite additive in the mix (at the same consistency), the water to solids ratio (w/s) was also increased from 0.48 to 1.40. The increase in w/s is attributed to porous microstructure and high specific surface area of expanded perlite what is associated with higher water demand. The AAC samples were prepared by the following procedure. First, the weighed raw solid materials were mixed with water for 2 min. Next, aluminum powder was added and mixed with the slurry for another 20 s. The obtained slurry was casted into preheated steel molds of 100 × 1000 × 100 mm and hardened at the temperature of 60 °C for 2 h. In the next step, samples were put into laboratory autoclave. Hydrothermal synthesis was carried out in the saturated steam pressure at a temperature 180 °C; the duration of isothermal curing was 12 h.

### 2.3. Testing procedure

After autoclaving the samples were dried and examined. Phase composition of samples was investigated using XRD. Powder XRD patterns were carried out using a Philips X-ray diffractometer X'pert system with monochromatic  $\text{CuK}_\alpha$  radiation. The microstructure of synthesized samples was observed using SEM. Low vacuum FEI NanoSEM 200 microscope was used. In order to avoid charging of the samples, a thin layer of carbon was deposited onto observed surfaces. The bulk density and compressive strength tests were conducted according to EN 772-13 [41] and EN 772-1 [42], respectively. For each mix proportion, a set of six samples were used to determine the compressive strength and the bulk density. The thermal conduc-

**Table 1**  
Chemical composition of expanded perlite waste.

| Composition                                | %, (by weight) |
|--|----------------|
| $\text{SiO}_2$                             | 70             |
| $\text{Al}_2\text{O}_3$                    | 14             |
| $\text{K}_2\text{O} + \text{Na}_2\text{O}$ | 7.6            |
| MgO  | 0.2            |
| $\text{Fe}_2\text{O}_3$                    | 2.4            |
| CaO  | 3              |
| LOI  | 1.7            |

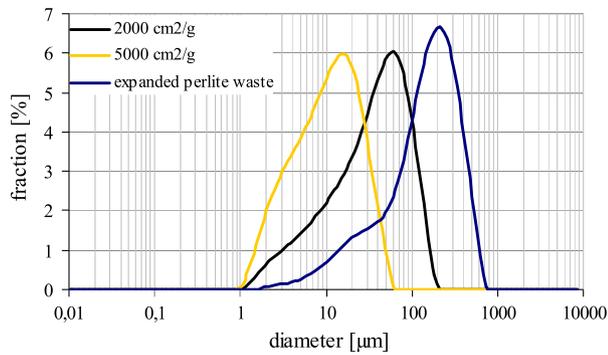


Fig. 1. Size distribution of expanded perlite waste and ground quartz sands.

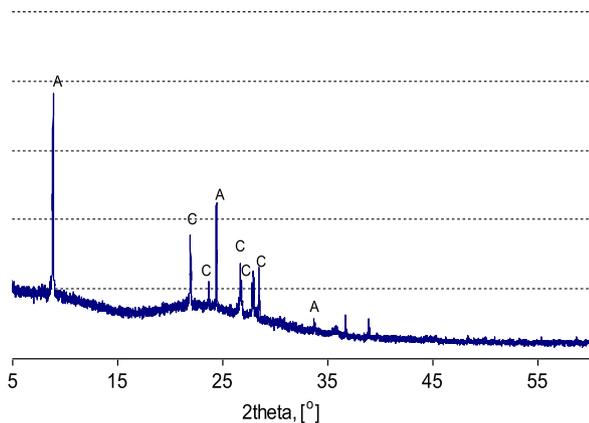


Fig. 2. XRD analysis of expanded perlite waste (A – aluminum silicate, C – calcium aluminum silicate).

tivity of samples was measured using ISOMET 2104 (Applied Precision, Ltd.) heat transfer analyzer based on unsteady heat transfer method [43]. The measurements were performed on samples at room temperature.

### 3. Results and discussion

#### 3.1. Bulk density

One of the most important properties of AAC is bulk density. Physical properties of autoclaved concrete depend on their bulk density and the properties of materials are qualified with density. Bulk density, compressive strength and thermal insulation properties of AAC are related to each other. In general, while the unit weight of concrete increases, the strength of concrete also increases. However, the thermal conductivity coefficient also increases, because of the increasing unit weight of concrete. Bulk density of the samples is presented in Fig. 4.

According to the obtained data, the bulk density of AAC can be reduced substantially by replacing quartz aggregate by expanded perlite waste. Replacement of quartz sand by perlite waste in an amount of 5% by weight reduces the bulk density about 12% compared to the reference sample. The replacement of quartz sand by perlite waste in an amount of 40% by weight reduces density about 45%, therefore, the amount of perlite waste has a significant influence on the bulk density of specimens and therefore it affects the properties of concrete. As is known, the specific gravity of the expanded perlite waste is lower than the specific gravity of quartz sand, therefore, the bulk density of the concretes produced with waste were consequently lower. Moreover, reduction of bulk density may be attributed to a high porous microstructure of expanded perlite (Fig. 3) and coarser compared to ground quartz sand grains (Fig. 1). A similar effect of expanded perlite on bulk density was observed in many scientific papers regarding the influence of expanded perlite on properties of lightweight concrete [2–4].

#### 3.2. Compressive strength

The changes in mechanical properties of specimens are given in Fig. 5. Generally, compressive strength is related to bulk density, while the bulk density of AAC decreases the strength of concrete decreases. The analysis of the results showed that the values of

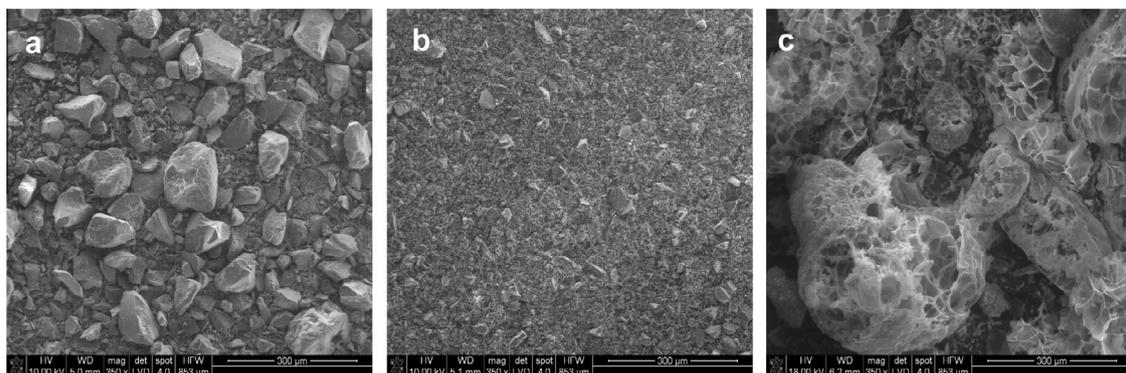


Fig. 3. SEM microphotograph of: a) ground quartz sand 2000 cm<sup>2</sup>/g, b) ground quartz sand 5000 cm<sup>2</sup>/g, c) expanded perlite waste.

Table 2

Mix proportions of aerated concrete with expanded perlite waste, (wt%).

| Sample | OPC | CaO | Quartz sand             |                         | Perlite waste | Aluminum powder<br>(wt% of binder) | w/s  |
|--------|-----|-----|-------------------------|-------------------------|---------------|------------------------------------|------|
|        |     |     | 2000 cm <sup>2</sup> /g | 5000 cm <sup>2</sup> /g |               |                                    |      |
| 0      | 13  | 16  | 54                      | 17                      | 0             | 0.3                                | 0.48 |
| 5      | 13  | 16  | 51                      | 17                      | 3             | 0.3                                | 0.52 |
| 10     | 13  | 16  | 48                      | 17                      | 6             | 0.3                                | 0.58 |
| 20     | 13  | 16  | 42                      | 17                      | 12            | 0.3                                | 0.66 |
| 30     | 13  | 16  | 36                      | 17                      | 18            | 0.3                                | 0.83 |
| 40     | 13  | 16  | 30                      | 17                      | 24            | 0.3                                | 1.40 |

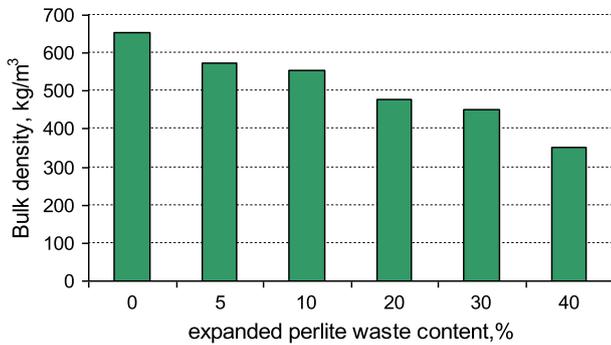


Fig. 4. Effect of expanded perlite waste content on bulk density AAC.

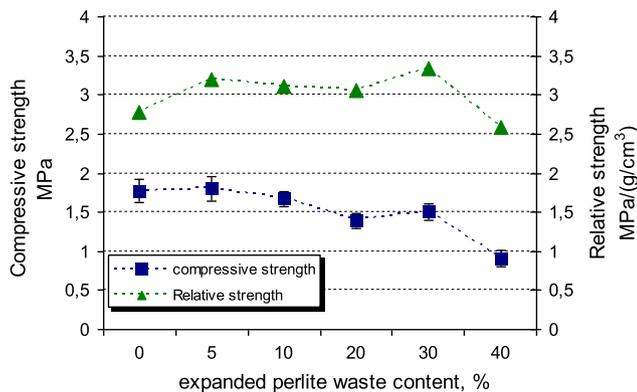


Fig. 5. Effect of expanded perlite waste content on the compressive and relatively strength AAC.

compressive strength samples with 5% and 10% of perlite waste are comparable with references sample, despite the bulk density reduction by 12% and 16%, respectively, compared to the reference sample. At higher proportions of perlite waste, a slight decrease in compressive strength was observed; however, it hardly changes when the perlite waste content ranges to 40%. Results of numerous studies have indicated that expanded perlite reduces the unit weight and compressive strength of lightweight concrete. Topcu [3] and Sengul [4] reported that substantial reductions in compressive strength were observed with increasing substitution of sand with expanded perlite. A complete replace of normal aggregate by the expanded perlite corresponds to a reduction of compressive strength from 28.8 MPa to 0.1 MPa [4].

A possible explanation for the drop in strength of AAC can be that an approximately 70% of AAC volume is occupied by aggregate and the properties of aggregate have a great effect on the properties of concrete [4]. As the quartz sand is replaced by the porous expanded perlite aggregate, compressive strength is reduced due to lower strength of the perlite than crystalline quartz sand [4,44,45]. The compressive strength of AAC is not only governed by the strength of aggregate but also by the porosity of the material. As shown in Table 1, the substitution of quartz sand with expanded perlite waste caused a significance increase in the mixing water requirement, which also had a negative effect on strength performance. A higher w/s ratio results in the formation of capillary pores that reduce the compressive strength of the AAC.

### 3.3. Thermal conductivity

Autoclaved aerated concrete is a type of material that combines two functions: construction and insulation, combining in this way the two contradictory features – relatively high strength and high

thermal insulating properties. The thermal conductivity coefficients are shown in Fig. 6. Replacing the quartz sand by expanded perlite waste has a positive effect on the thermal conductivity coefficient and its values were found to be strongly dependent on the bulk density (Fig. 4). As expected the thermal conductivity decreased with decreasing bulk density. Replacement quartz sand by perlite waste in amounts of 5, 10, 20, 30, 40% by weight reduces thermal conductivity by 10, 13, 15, 30, 40%, respectively, according to the reference sample ( $\lambda = 0.127$  W/m·K). Kurama et al. [27], Wongkeo et al. [28], Kunchariyakun et al. [32] and Huang et al. [20] reported similar observations on the effect of density on the thermal conductivity of AAC. It is well known that the thermal conductivity of AAC besides density depends on the porosity and pore size distribution, moisture content and the phase composition [46]. The thermal conductivity of porous materials decreases rather uniformly with a reduction of bulk density; however, the thermal conductivity of material is not only controlled by porosity but also by the thermal conductivity individual components of the material. The main phase in the composition of AAC is residual quartz which has a high thermal conductivity. Perlite waste causes lowering thermal conductivity coefficient of AAC in two ways, first, by decreasing the bulk density of the material and second, by the reduction of residual quartz in phase composition of AAC. Replacing quartz aggregate by the expanded perlite waste reduces the thermal conductivity of the mixtures as a result of the porous microstructure [4] and lower thermal conductivity of the amorphous expanded perlite (0.04 W/m·K [47]) compared to crystalline quartz (6.8–12 W/m·K [48]). The minimum thermal conductivity of AAC was 0.074 W/m·K, observed at 40% expanded perlite waste replacement. This value is very difficult to achieve in the case of AAC products, so expanded perlite waste is promising material, which can have a positive influence on insulating properties of AAC.

### 3.4. XRD analysis

XRD analyses were performed to investigate the phase changes in the AAC samples. The major minerals in the phase compositions of AAC are calcium silicate hydrate phases, especially 1.1 nm tobermorite and residual quartz grains [46,49]. The phase compositions of AAC can be in a large extent influenced by the phase composition of materials used as cement replacement material or as partial replacements for aggregates. For example Huang et. al [26], who used copper tailings and blast furnace slag as main raw materials to prepare AAC observed in the final AAC products besides tobermorite and quartz, residual minerals including dolomite, augite, phlogopite, amphibole, clinochrysolite and albite.

As mentioned before calcium silicate hydrates, especially 1.1 nm tobermorite, is the main product evolving during the

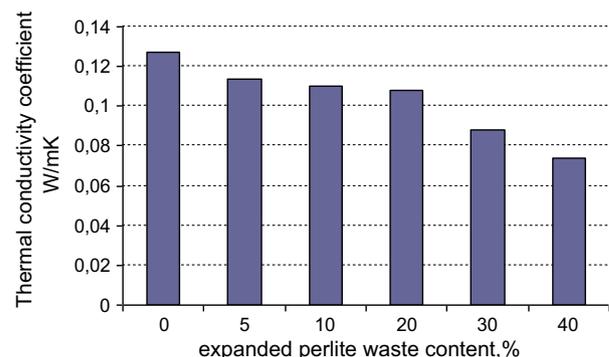


Fig. 6. Effect of expanded perlite waste content on the thermal conductivity AAC.

hydrothermal hardening of AAC, causing the good compressive strength of the final product. It is commonly known that small amounts of inorganic admixtures can affect substantially the kinetics and mechanism of calcium silicate hydrates synthesis. For example,  $\text{Al}^{3+}$  ions accelerate the formation of 1.1 nm tobermorite.  $\text{Na}^+$  ions accelerate a formation of poorly crystallized calcium silicate hydrates, and further transformation of this intermediate product into well-developed crystalline 1.1 nm tobermorite can be distributed [18]. XRD analysis (Fig. 7a) showed mainly the presence of crystalline 1.1 nm tobermorite in AAC phase composition. The presence of 1.1 nm tobermorite was accompanied by a typical for AAC phases; unreacted quartz and calcite. The foreign ions introduced with the perlite waste do not interfere with the synthesis of calcium silicate hydrates. It can be seen in Fig. 7b that intensity of diffraction reflections of 1.1 nm tobermorite ( $d$ -spacing 1.1 nm,  $2\Theta = 7.8^\circ$ ) increase with increasing amount of expanded perlite waste. It is probably related to differences in the reactivity of  $\text{SiO}_2$  in expanded perlite waste and quartz sand. The replacement of lower reactive silica (quartz sand) by highly reactive silica had a positive effect on the formation of calcium silicate hydrates. Similar results were also observed by Kunchariyakun [32] who used rice husk as a partial replacement for quartz sand. The intensity of the tobermorite peak increased with increasing rice husk dosage, which could indicate that the high reactivate  $\text{SiO}_2$  in rice husk quickly consumed the calcium hydroxide to form calcium silicate hydrates [32]. The influence of coal fly ash from circulating fluidized bed combustion boiler which contains active  $\text{SiO}_2$  on AAC properties was investigated by Song et al. [31]. It was found that the  $\text{CaO}/\text{SiO}_2$  ratio affects the properties of AAC containing coal fly ash by altering the hydrates and also has marked effect on the diffraction intensity of tobermorite.

In the presented study, despite positive effect of expanded perlite waste on tobermorite formation, samples with a dosage of perlite waste of 40% leads to gradual reductions in the strength of AAC (Fig. 5). It may be concluded that for the higher expanded perlite contents, compressive strength is more affected by replacement ratio of waste and related reduction of bulk density than 1.1 nm tobermorite formation. Porosity and the pore structure are the most important factors influence on the compressive strength of AAC, therefore, density reduction and the related increase in porosity are found to cause a significant strength drop [46].

### 3.5. Microstructure analysis

The microstructure of AAC depends upon a number of parameters such as type, amount, and phase composition of constituent materials or temperature of hydrothermal treatment. The

microstructure of concrete is also influenced by the rate of hydration, type of reaction products formed, and their distribution in the AAC [46,50,51]. It is well established that reaction products can be substantially modified by the application of industrial by-products or waste residues in AAC [26,32–34]. The SEM images of the AAC sample are shown in Fig. 8. The results show, that the perlite waste additive has a positive impact on the formation of AAC microstructure during AAC hardening. It can be seen that the major phase in the final AAC products is generated during hydrothermal treatment 1.1 nm tobermorite. The foreign ions introduced with perlite waste do not effect significantly on the morphology of 1.1 nm tobermorite. The replacement of quartz sand by expanded perlite waste increases the formation of 1.1 nm tobermorite, which is observed in the whole volume of the samples. Lathlike thin plates of 1.1 nm tobermorite crystals positively effect the mechanical properties of AAC up to 10% of waste. As the percentage of perlite waste in the replacement increased up to 40%, the AAC structure became more porous (Fig. 8c), it might be the main cause in reducing the compressive strength values with an increase in the waste replacement ratio. The observed porous microstructure has a positive effect on the insulation properties of AAC by reduction thermal conductivity coefficient value.

## 4. Conclusions

The results show that the expanded perlite waste can be considered as an alternative siliceous source to reduce the consumption of natural quartz sand used as micro-aggregate in AAC production. Replacement of quartz sand by perlite waste reduces substantially the bulk density of AAC, which has a significant influence on the properties of the material. The introduction of perlite waste up to 10% by weight reduced the thermal conductivity about 15% without significant reduction of compressive strength. Further improvement of thermal conductivity may be obtained by addition of perlite waste up to 30%, but it caused reduction of mechanical properties about 20%. The lowest value of conductivity was obtained for the 40% perlite waste replacement amount, but the decreased strength values of this concrete limited the usability. The structural and microstructural investigations showed that the foreign ions introduced with perlite waste have positively influence on the formation of calcium silicate hydrates in AAC. It is worth noting that disposal and use of waste products such as expanded perlite waste is difficult due to the problem of dusting during its treatment in the dry state but the introduction of waste at the stage of wet grinding quartz sand allows to eliminate that problem. The use of expanded perlite waste to replace quartz sand

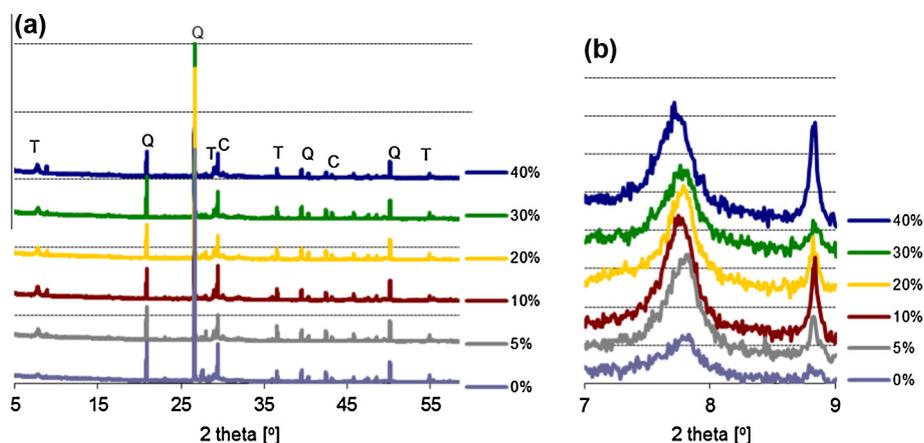
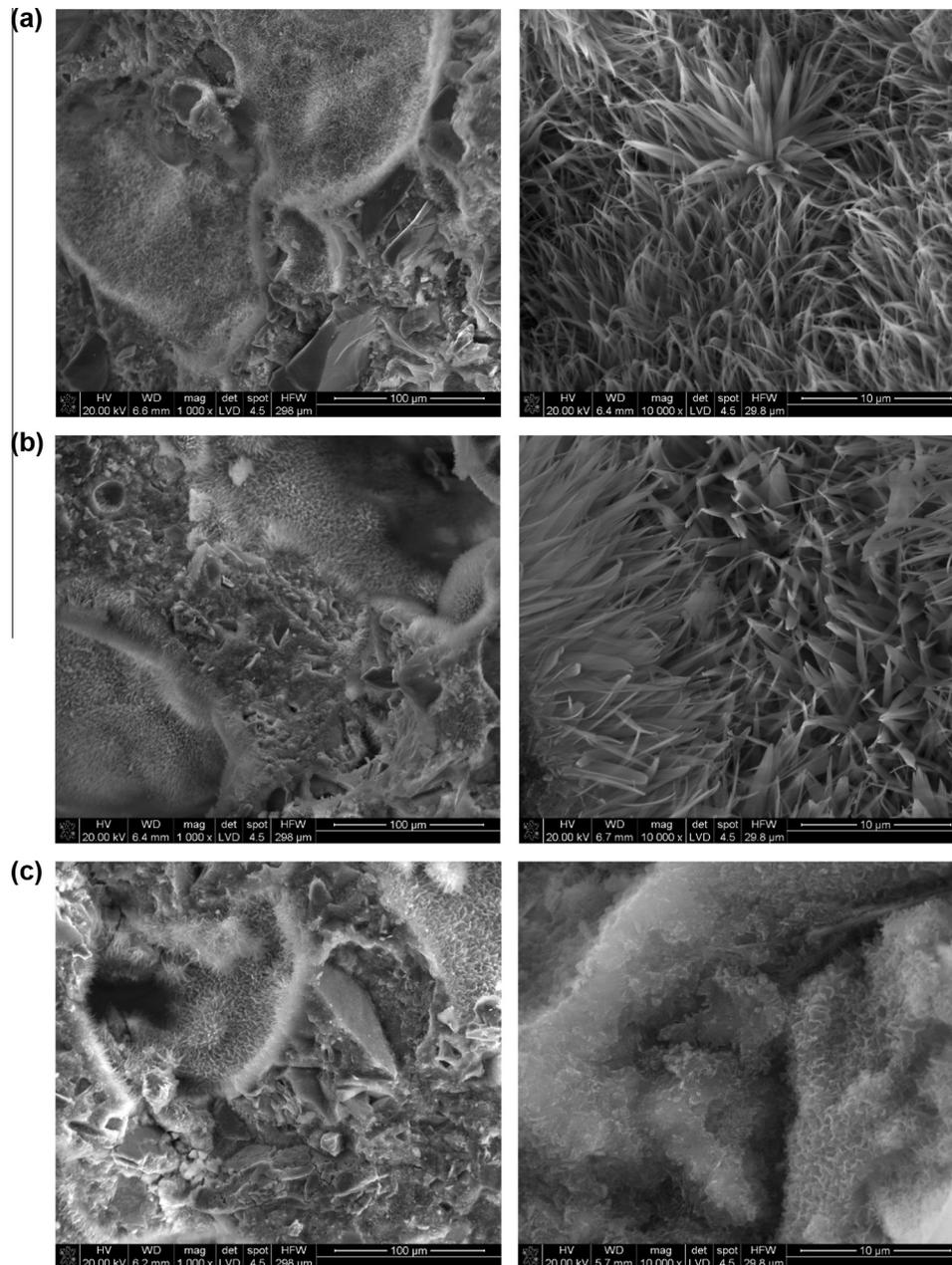


Fig. 7. XRD analysis of AAC samples (T – 1.1 nm tobermorite, C – calcite, Q – quartz).



**Fig. 8.** SEM observations of samples: a) reference sample, b) quartz sand was replaced by 5% of expanded perlite waste; c) quartz sand was replaced by 40% of expanded perlite waste.

consumes less natural minerals and reduces the amount of waste stored in the landfill.

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