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Review papers

Review of selected aspects of shaping of physical, mechanical and thermal properties and manufacturing technology of lightweight and ultra-lightweight autoclaved aerated concrete

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Abstract: The paper provides an overview of selected scientific articles presenting research carried out in recent years on methods for producing autoclaved aerated concrete. Traditional technologies are briefly presented, together with innovative solutions for the production of low-density and ultra-low-density materials. In addition to the presentation of the manufacturing methods themselves, the results of research into the properties of the autoclaved aerated concrete obtained and their dependence on the technology used are also presented. A subjective selection and review of articles covering research into the thermal conductivity of concrete, the technological factors influencing them and the ways in which they can be shaped was also carried out. A significant number of the cited articles do not function in the world scientific circulation due to the language barrier (they are mainly in Ukrainian). In the meantime, they contain interesting research results which can inspire further research into the issues discussed concerning the production technology and the thermal and strength properties of autoclaved aerated concrete, with particular emphasis on lightweight and ultra-lightweight concrete.

Keywords: autoclaved aerated concrete, inorganic binders, manufacturing technology, thermal conductivity

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1. Introduction

At the present stage of society's development, conserving resources and reducing pollution of the earth's atmosphere, primarily by carbon dioxide, is of great importance. One of the most polluting industries is the construction industry. Therefore, there is a need for new cost-effective and bio-friendly materials, as well as for a wider implementation of resource-saving technologies.

One of the main functions of building materials is to enclose part of the space and create comfortable living conditions in it. These tasks are most fully met by highly efficient porous materials: cellular glass and ceramics, autoclaved aerated concrete, foamed concrete and materials based on porous aggregates. Paper [1] describes a developed technology for production of glass-crystalline foam ceramics. Glass-crystalline foam ceramics and products made of it are the latest achievement of the construction and manufacturing industry. The material is obtained by firing at 1150°C, using titanium carbide with a particle size up to 1 µm as a pore former. Foam materials based on glass-crystalline compositions have a density of 350÷600 kg/m^3 and are characterised by low thermal conductivity (0.2÷0.4 W/m·K) as well as reduced strength which is still higher than 15 MPa [1].

One of the effective building materials is light and ultralight aerated concrete based on non-organic binders [2–6]. Gunasekaran et al. [7] note that the thermal resistance requirements for wall constructions are becoming increasingly stringent every year. In Poland, for example, in 2014 the U-value was 0.25 W/(m^2·K), in 2017 it was lowered to 0.23 W/(m^2·K), and from 2021 the U-value must not exceed 0.20 W/(m^2·K) [8]. These requirements are met by structures made of aerated concrete.

Reduction of density and at the same time heat conductivity of such concrete can be achieved by various methods [9–13]; however, the main way is the introduction of a large number of air pores into the concrete structure. As research of many authors show, the crucial characteristics of such concrete are influenced both by the number of pores and their size and distribution, and by properties of the matrix i.e. the material of which the concrete is made. Regarding the thermal insulation properties of autoclaved aerated concrete, many authors also paid attention to the equilibrium of moisture content of the materials during their use.

Hamad [14] provides a classification of aerated concrete which is divided into two groups: non-autoclaved aerated concrete (foamed concrete) and autoclaved aerated concrete. Two types of foaming agents are used for the production of autoclaved aerated concrete: organic and synthetic. The main way to produce pores in autoclaved aerated concrete is by using aluminium powder (Fig. 1).

Research in the field of development of efficient wall structures and products made of aerated concrete, which is characterized by high both mechanical and performance characteristics, is developing in the following directions [15]:

– use of dispersed reinforcement by non-metallic fibres;
– improvement of methods of optimal calculation of aerated concrete mixtures composition with different mineral and chemical additives;

– development of new methods of mathematical planning of experiments which allow to provide optimal parameters of structure and properties of autoclaved aerated concrete at micro level;
– development of methods to optimise the structure and properties of aerated concrete at a macro level by using structural modelling methods;
– development of methodological basis for optimal calculation of autoclaved aerated concrete composition at different levels of design.

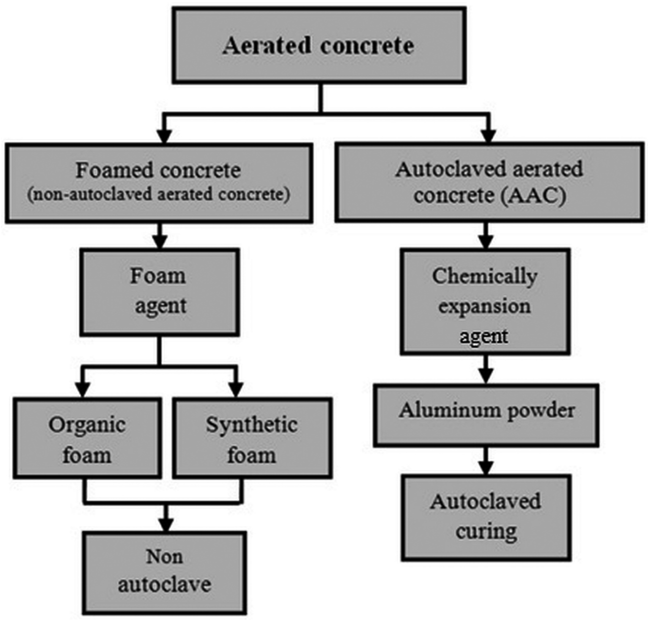

Fig. 1. Classification of aerated lightweight concrete [14]

2. Autoclaved aerated concrete technology research

At present, three basic technologies of aerated concrete production are implemented at the factories: pouring, vibrating and hammering [16, 17]. The pouring technology is connected with the use of a forming mixture with a sufficiently high water content ($w/s = 0.5 \div 0.6$), which affects the main characteristics of the final product. More preferable vibration technology, which allows reducing the water consumption ($w/s = 0.3 \div 0.4$), and due to the occurrence of the effect of thixotropic reduction, it also decreases viscosity and increases the rate of plastic strength of the concrete mass.

When using foaming agents, it is possible to produce foamed concrete with densities from 400 to 1600 kg/m^3. The consumption of protein foaming agents is about 80 g/l of concrete mixture, while the consumption of synthetic foaming agents is only 40 g/l. For the production of autoclaved aerated concrete, aluminium powder with a particle size of 50 to 100 μm is used. Depending on the required density of aerated concrete, the consumption of aluminium powder ranges from 0.2 to 0.5% of the dry weight of the cement. Fig. 2 shows a typical scheme of autoclaved aerated concrete production, which includes an additional process – autoclaving at pressure of 4÷16 MPa and processing time of 8÷16 hours. Autoclave treatment has a strong effect on the strength because high temperature and pressure produce a stable tobermorite form. The final strength depends on the pressure and the duration of autoclaving.

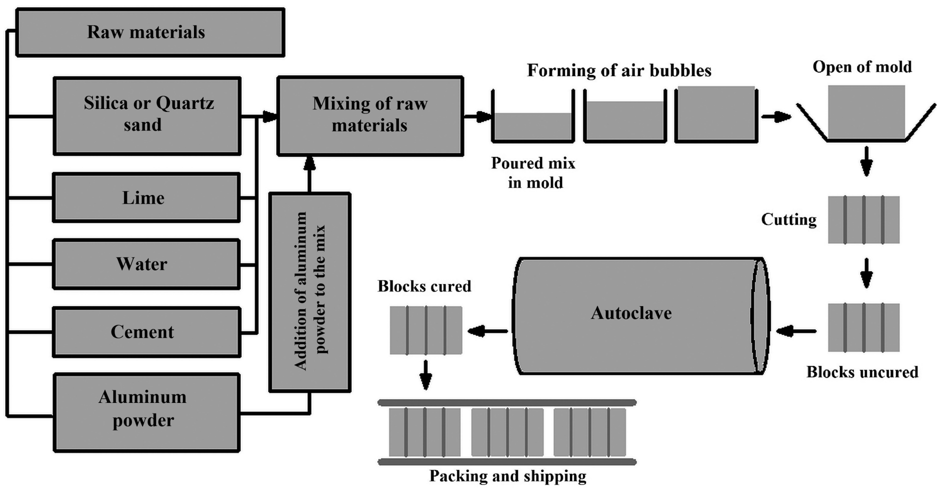

Fig. 2. Process phases of aerated concrete production [14]

During the process of autoclaving, new mineral phases are formed in the structure of aerated concrete: hydrated calcium silicates with a variable CaO/SiO_2 ratio and with different degrees of crystallinity from amorphous C–S–H(I) to crystalline tobermorite with a size of 1.1 nm. The presence of these phases and the ratio between them affects not only the strength and durability of aerated concrete but also its thermal conductivity.

In recent years, there has been a steady trend towards increased demand for autoclaved aerated concrete products, which are characterised by low thermal conductivity with sufficient density and strength due to the presence of a significant number of artificially created pores. The main problem of autoclaved aerated concrete technology is the multi-component composition and instability of the porization process which can result in lowering of the compressive strength [14–16, 18–21]. The analysis of literature sources showed that to obtain light and ultra-light concrete, two ways of obtaining cells are mainly used: the introduction of gas formers into the concrete mass (aluminium powder or aluminium paste) or the foam formers mainly based on an organic compounds.

Fylatov et al. [17] considered the specifics of making aerated concrete with additional porosity. Foam concrete and autoclaved concrete are very similar in terms of functionality in buildings, technological methods of production and a set of standardized technical indicators, but there are some differences in the values of these indicators. These differences are mainly due to the different composition of the raw mixes, the particular nature of their porosity, as well as the curing conditions. Taking into account the positive and negative sides of foam and gas porization of concrete mixtures, combination of the two methods of porization into one technological process is a promising option. This means that it is advisable to supplement gas porization in the production of autoclaved gas concrete with foam porization (gas foam concrete), and in the production of non-autoclaved concrete to supplement foam porization with gas porization (foam-gas concrete).

The technology of three-stage porization of raw mix, including two foam and one gas porization has been developed [17]. The first stage is carried out by porization of sandy slurry in a wet mill by means of air entrainment agents. In the second stage, the raw mix is porated by air entrainment through intensive mixing of the raw materials in a high-speed mixer. In the third and final stage, the pores appear in the mixture as a result of gasification. The structure obtained this way has larger gas pores surrounded by a shell of more stable small foam pores of two orders of magnitude, which ensures increased stability of the porous system after foaming. Industrial tests have shown high efficiency of the developed technology.

In [22], a technology of foam concrete production is developed which uses a physical method of foaming of the concrete mass. In this case, ultra-lightweight foamed concrete with density lower than 250 kg/m^3 was obtained. The main components of the presented foam concrete are: Portland cement, building plaster, slaked lime and inorganic fibre. For the foam production, a foam generator was used, in which an organic based foaming agent suspension was processed (dilution coefficient 1:50). The foam density was 45 kg/m^3. Examination of the foam concrete by scanning microscopy showed that the structure walls thickness ranges from 100 µm to 500 µm. Small closed pores have been observed in the wall structure, in addition perfect crystal formations have been observed in the pores, which strengthen the foam concrete structure.

Lightweight foamed concrete with densities from 160 kg/m^3 to 1600 kg/m^3 has been developed and investigated in [23]. The microstructure of such concrete was investigated using an electron scanning microscope. The study showed that foamed concrete with high permeability is characterised by pores with the size of 100÷800 µm, and most of them are open pores. It has also been found that the strength of foamed concrete depends not only on density but also on its microstructure. The highest strength is achieved when there is a sequential alternation of small and large pores. On the other hand, the irregularly distributed large pores and open pores lead to low durability and high water permeability.

Lapovska et al. [24] investigated a heat insulating autoclaved aerated concrete reinforced with basalt fibre. Basalt fibre was introduced into concrete with a density of 150 kg/m^3 in order to increase its tensile and bending strength. It has been stated, that basalt microfibers modified with zirconium silicide a have higher corrosion resistance in autoclaved aerated concrete curing environment in comparison with ordinary fibres. Thus, modified microfibers have a four times higher resistance in an 2N NaOH environment. Samples without fibre have a compressive strength of 0.120 MPa after 4 hours and reinforced samples have a compressive strength from 0.122 MPa to 0.147 MPa after hardening time of 3.5 hours. The compressive strength of the autoclaved concrete in the case of the fibre reinforced samples was up to 0.425 MPa and for the control samples (without fibres), it was 0.371 MPa. The average density of aerated concrete was practically the same irrespective of the presence or absence of fibres.

Another way of application of synthetic microfibers in cellular concrete technology was presented by Mydin in his work [25]. Synthetic microfibers in the form of a mesh were used in one, two or three layers as an external confinement of specimens made of lightweight foamed concrete (LFC). In the study, LFC of three different densities was prepared: 600, 1100 and 1600 kg/m^3. Although there was no direct effect on the structure of the concrete prepared in this way, the use of synthetic microfiber mesh made it possible to achieve a reduction in concrete parameters such as porosity, water absorption and shrinkage by a maximum of 25.6%, 29.6 and 76.8%, respectively. There was also a very significant increase in compressive, flexural and tensile strength.

Kanstad [26] tested prefabricated beams made of lightweight concrete with a density 1100÷1200 kg/m^3 reinforced with different types of fibres: polymer fibres of different composition as well as steel fibres. All types of fibres significantly improved the concrete's ability to withstand tensile forces, so this type of fractures did not occur in fibre-reinforced beams. The best results were obtained with hooked steel fibres. In beams without fibre reinforcement, failure started with a major horizontal crack near the support which further developed and resulted in shear failure. Kanstad states that fibre reinforcement can be used for different types of lightweight concrete, but preliminary experiments are needed to establish the optimum type of fibre.

Bubeníka & Zacha [19] proposed a technology for producing lightweight soundproof concrete based on the introduction of a lightweight aggregate, cellular glass, into the aerated concrete. Studies have shown that with the introduction of such an aggregate, the average density of concrete ranged from 390 kg/m^3 to 550 kg/m^3, and the compressive strength from 0.84 to 1.55 MPa. It is claimed that such concrete can be used not only as an acoustic barrier but also as structural and thermal insulation concrete.

A system of thermal insulation structures has been proposed in [27]. The principle is to manufacture compression zones of optimum shape out of a strong material, e.g. high-strength concrete, and then fill the rest of the structure with lightweight concrete. Special chain reinforcement is used for the tensile zones of the concrete elements. This reinforcement opens up the possibility of using ultra-lightweight concrete in such structures. The lightweight concrete forms the shape of the structure, stabilises the compression zones and protects the high-strength concrete against physical influences such as impacts, fire, cracking and weathering.

A mixture of lime, Portland cement and finely ground quartz sand is often used as a composite binder in the production of autoclaved aerated concrete. One of the directions for improving the quality of products of cellular structure is the management of the hydration process of the components of the composite binder. The conditions of the binder hydration affect the properties of the obtained products. Obtaining and preserving the activity of the components of the composite binder during preparation of the mixture is an important factor in obtaining high quality products [6, 7, 14, 17, 28]. Therefore, much attention in theory and practice is paid in the technology of autoclaved aerated concrete production to the optimisation of the composition of binder mixture and to choosing the best parameters of concrete hardening to ensure products of maximum strength available for the material with given density.

Binders containing materials which exhibit pozzolanic activity or hidden binding properties are also used in the manufacture of autoclaved aerated concrete. It is assumed that the use of such a complex binder in autoclaved aerated concrete manufacture will reduce the sedimentation deformations of the formed mass and provide an increase of quality of the materials with a porous structure.

Different industrial wastes can be used in the production of aerated concrete. Introduction of fly ash from Polish power plants as a fine aggregate replacement to produce autoclaved aerated concrete with a density of 350 kg/m^3 has been proposed [7]. Compositions presented in Table 1 were tested and as a result, aerated concrete with a density of 400÷600 kg/m^3, which meets the requirements of the standard in terms of durability, was obtained.

Table 1. Mix proportions of series tested in [7] (in relation to cement mass)

Series number	Cement	Fine aggregate	Fly ash	Gypsum
1	1	3.00	0.00	0.5
2	1	2.25	0.75	0.5
3	1	1.50	1.50	0.5
4	1	0.75	2.25	0.5
5	1	0.00	3.00	0.5

Othman et al [29] used the waste material processed spent bleaching earth (PSBE) in the production of foamed concrete. It is derived from processing deoiled spent bleaching earth used in refining of crude palm oil. This material exhibits pozzolanic properties and was used as a replacement for 30% cement. The resulting foam concrete was characterised by increased strength and better durability parameters than a material with the same proportions of components, in which all the binder was cement.

Serdiuk et al. [18] proposed a method of activating ashes which are used as aerated concrete aggregates with acid solutions. Depending on the chemical composition of the fly ash, it can be considered as an analogue of blast furnace slag, the particles of which are covered with a glassy film. Products of the interaction of ash and acids: $Al_2(SO_4)_3$, $(Ca,Mg)SO_4$, $Fe_2(SO_4)_3$, $(K,Na)SO_4$ and others are intensifiers of mineral binder hydration. Destruction of the glassy shell of the fly ash ensures its high reactivity. The use of chemically activated fly ash in ash-cement binder can reduce the consumption of Portland cement by 30% and obtain a strength gain of up to 15% [18].

The influence of aluminium powder dosage on selected properties of aerated concrete containing 30% of fly ash was researched in [20]. Aluminium powder was introduced into the composition of foamed concrete in the amount from 0.25 to 1.00% of cement mass.

The results of physical and mechanical tests showed that the increase of aluminium powder reduces by 1.5÷4.4 times the modulus of elasticity compared to the control specimens. The introduction of fly ash into foam concrete allowed for 25÷30% reduction of cement use in the developed compositions without compromising the strength properties.

To obtain efficient autoclaved aerated concrete, Strokova et al. proposed a nanostructured binder (NB) [21]. Nanostructured binder is a promising type of cementless binder of non-hydration type of hardening. This is a binding material with significant functional and structure-forming role of nano-system component, obtained by the technology of high-concentration binder systems (HCBS). Specificity of the NB technology allows using a wide range of silica-containing rocks as the main raw material component.

When using such a binder, the porosity of interstitial partitions is reduced, which is explained by the presence of nanodispersed particles in NB. When obtaining cellular composites using NB, the particles of minimum size are located in the gaps between the relatively large particles of the matrix system, which contributes to the creation of a thin film of mineralizer on the surface of the air bubble. This allows obtaining a material with a low density (300÷400 kg/m^3) and a relatively high strength (3÷4 MPa).

The use of micro reinforcement enhances the effect of NB on the strength properties of autoclaved aerated concrete [21]. In addition, micro reinforcement of NB-based cellular composites through the introduction of fibre contributes to improving the surface quality of products and to reducing the time required for the implementation of the technological cycle of their production.

The technology for the production of autoclaved aerated concrete using nanostructured binder (NB) has been also proposed in [28]. To increase the strength of autoclaved aerated concrete based on NB, the hardening principle based on the effect of "cold sintering" is applied. In this case, the dried material is exposed to aging in chemically active liquid media (alkalis, acids, salts, etc.) with subsequent drying. The chemically active solution acts as a cold mineralising agent. The hardening of such treated autoclaved aerated concrete can be explained by the insignificant dissolution of the solid matrix phase during the curing process and the occurrence of the ionic exchange phenomenon between the components of the raw mass and the solution.

In order to improve the performance properties of gas concrete, the method of their saturation with organosilicon substances of different origin has been used [30]. The best results in terms of improving hydrophobicity and the degree of filling of open pores were shown by concretes saturated with agents based on polymethylphenylsiloxane compounds.

Drochytka et al. [6] tested high-quality aerated concrete produced using fly ash from the Czech Republic. Chemical composition of the fly ash is provided in Table 2. As a reference, autoclaved aerated concrete (AAC) based on quartz sand with the density of 500 kg/m^3 was used. Regarding mechanical properties, both kinds of AAC based on fly ash showed standard strength classes P4 (f_c = 4.0 MPa) and P2 (f_c = 4.0 MPa) at a density in the range of 400÷600 kg/m^3. The hygroscopic sorption properties were examined according to the EN ISO 12571 [31] standard method. For the construction of adsorption curves, the specimens were dried to a constant weight. The dried specimens were placed in containers with solutions which maintained relative humidity of 33, 55, 75 and 98%, respectively.

The analysis of the results showed that the moisture content of the fly ash based concrete was higher than that of the material based on silica sand. At the same time, the thermal conductivity of fly ash concrete was lower than that of quartz sand concrete [6].

Table 2. Chemical composition of fly ash [6]

Component	Percentage contents [%]
SiO_2	45
Combustion loss	7
Total sulphur as SO_3	0.2
MgO	2
Al_2O_3	35
Fe_2O_3	18

The composition of Portland cement based foam concrete was developed and presented in [32]. Thirteen batches of the concrete were tested. The air content varied from 6 to 35%. Foaming agents were used, one of which was protein based and the other two were synthetic. The amount of air in the foam mass and its sludge, as well as the density, compressive strength and static modulus of elasticity of each batch of concrete were measured. The main results showed that porous concrete has a good potential for use in lightweight structures due to the fast evolution of the mechanical properties and the high thermal resistance. However, it is very sensitive to the type of foaming agent. The results showed that the type of the agent has a significant effect on thermal resistance and sorption coefficient but less effect on the mechanical properties.

In papers [4, 33], properties of autoclaved aerated concrete of different composition are considered and the phase composition as well as mechanism of hydration of binders are provided. It is observed that specimen size and shape, method of pore formation, location, load direction and age are all factors that strongly influence the strength test results. In general, compressive strength increases linearly with density. Table 3 shows the compressive strength values for different densities of concrete.

Table 3. Properties of AAC aerated concrete [4]

Dry density (kg/m^3)	Compressive strength (MPa)	Static modulus of elasticity (kN/mm^2)	Thermal conductivity ($W/(m\cdot K)$)
400	1.3–2.8	0.18–1.17	0.07–0.11
500	2.0–4.4	1.24–1.84	0.08–0.13
600	2.8–6.3	1.76–2.64	0.11–0.17
700	3.9–8.5	2.42–3.58	0.13–0.21

The compressive strength is inversely proportional to the moisture content. Thus, an increase in strength is observed after the specimens are dried to an equilibrium state. The highest strength is observed in the absolutely dry state. Therefore, a correction factor for the transition from the state of specimens with a certain moisture content to specimens in an absolutely dry state has been proposed in [34].

The dependences of moisture diffusion coefficient at different values of relative air humidity and porosity of samples of autoclaved aerated concrete on the concentration of water-repellent additives were investigated and presented in [35]. It is shown that water retention characteristics can be used to determine the frost resistance of autoclaved aerated concrete. It was found that at concentrations of water-repellent additives of 1÷2%, the increase in frost-resistance occurs due to an increase in the number of closed reserve pores of small diameter. The decrease of frost resistance in the concentration range of 2÷3% is connected with the increase in open porosity due to the wedging effect of water-repellent molecules in depressions on the surface of large pores. At additive concentrations above 3%, the frost resistance increases due to a significant hydrophobic effect preventing the penetration of water into the pores.

Vylegzhanin & Pinsker [36] proposed a model of autoclaved aerated concrete that allows taking into account of the characteristic indicators of its porous structure (density coefficients, porosity, pore diameters and the distance between them), as well as the dependence of these indicators on the density factor of aerated concrete. The coefficient of porosity of aerated concrete R_g/R_k is proposed, which determines the proportion of microporous cement stone (MCS) per unit volume of aerated concrete, where R_k is the density of MCS, R_g is the density of aerated concrete. The porosity of aerated concrete $P = 1 - R_g/R_k$ determines the fraction of pores in a unit volume of aerated concrete. The main result of the research is that the main characteristics of aerated concrete as a porous material depend on the pore size and the distance between them. With an increase in the density of aerated concrete R_k with a constant density of aerated concrete R_g, the distance between pores decreases, resulting in a reduced influence of MCS, and vice versa, with a decrease in R_k, the influence of MCS increases [36].

3. Research on thermal conductivity of autoclaved aerated concrete

Autoclaved aerated concrete is a building material that can fulfil two roles, sometimes simultaneously. It is used to construct load-bearing structures, mainly walls, but it is also used as an insulating material to reduce the transport of heat between the inside of a building and the external environment. Because of this dual use, and some other insulating applications, the thermal performance of autoclaved aerated concrete, mainly its thermal conductivity, is the subject of research. Some of these studies are discussed in this section.

The research of Zapotoczna-Sytek et al. [37] on the thermal conductivity of autoclaved aerated concrete showed that the way of measuring the thermal conductivity is of great importance. So is the thickness of the specimen, which is related to the "thickness effect" known from the literature for low density materials. The apparent thermal conductivity, measured under stationary heat flow conditions, clearly differs with differing specimen thickness, which is mainly influenced by the density of the material and the emittance of the measuring apparatus plates [38].

It was shown in [37] that the thickness of the specimen strongly affects the measurement of the thermal conductivity for different reasons as well. It was observed that at a very low thickness of the specimen, the measured thermal conductivity was 0.04 W/(m·K), while at the same time when the thickness of the specimen was enlarged to 30 mm, the measured value increased to 0.14 W/(m·K). This is not the aforementioned "thickness effect", as this is observed in the case of specimens with the thickness of approximately 30 mm and more. The difference resulted from the ratio of pore size to specimen thickness. In thinner layers of porous materials heat is transported more by less efficient mechanisms of radiation and possibly convection and less by conduction.

The thermal properties of autoclaved aerated concrete depend largely on its moisture content [16]. The water absorption of autoclaved aerated concrete depends on the type of binder, the nature of porosity and a variety of other factors. The increase in the thermal conductivity of autoclaved aerated concrete for each percent increase in moisture content is 6 to 8 percent. The influence of moisture on thermal conductivity measurements was another issue investigated in [37]. The thermal conductivity of autoclaved aerated concrete with a density of 500 kg/m^3 was measured. It was found that the effect of humidity on the heat transfer process is evident only for specimens thicker than 30 mm. For specimens from 5 to 30, mm the influence of humidity on the thermal conductivity is negligible.

Garbalińska & Bochenek [39] present the results of two multi-step experiments in which measurements were made on specimens of autoclaved aerated concrete with a density of 400 kg/m^3. One part of the experiment was to determine the empirical dependence of the thermal conductivity coefficient of autoclaved aerated concrete as a function of its moisture content. The relationship defined in this part was used to determine the thermal conductivity coefficient of specimens of concrete initially fully immersed in water and then during drying out under laboratory conditions for 1, 2 and 3 months. It was found that the equilibrium moisture content of the concrete structure was reached only after three months of drying [39]. The results obtained prove the indisputable necessity to take into account the moisture content of partition structures when drawing up energy balances of buildings, because moisture processes have a strong influence on the thermal parameters of walls.

For insulating porous materials, the heat transfer by means of a gas layer adsorbed on the surface of the solid phase has a great influence on the value of the thermal conductivity coefficient [40]. The thermal boundary layer concept helps to understand the reason why materials with the same pore structure of different compositions have different thermal characteristics. Conversely, materials with similar properties but a different shape and size of pores have little difference in thermal conductivity. Anikanova & Rakhimbaev [40] have shown that the heat transfer coefficient of air increases more than twice if the void size exceeds 8 mm. At air layer thickness of 1÷2 mm the effective heat transfer coefficient of air changes insignificantly, and at an increase of this parameter up to 5 mm, it increases 1.5 times [40]. In the case of porous building materials, such as aerated concrete and foamed concrete, with a pore diameter of 1÷3 mm, the effect of the thermal boundary layer on the overall thermal conductivity coefficient of the material is of great interest and importance.

When producing low density aerated concrete (100÷300 kg/m^3), it is necessary to use MCS stone with a density R_k lower than 800 kg/m^3 in order to ensure an acceptable pore spacing concerning grain sizes resulting from the grinding of the raw materials of the aerated concrete [36]. Calculations show that increasing or decreasing the pore diameter in aerated concrete at constant porosity has no effect on the thermal conductivity of concrete. This conclusion is contrary to results of some other research.

It has been noted [16, 41, 42], and this conclusion seems quite obvious, that a decisive factor in reducing the thermal conductivity of autoclaved aerated concrete is an increase in overall porosity. Thus, a reduction in average density by 100 kg/m^3 results in a 20% reduction in the thermal conductivity. The calculation shows that reducing the average density of aerated concrete to 200 kg/m^3 decreases the thermal conductivity to 0.06 W/(m·K) and lower, that corresponds to the thermal conductivity of highly efficient insulating materials, such as mineral wool and cellular glass. The thermal conductivity of porous materials with an equal amount of the solid phase depends mainly on the volume of porosity, type and characteristics of the cellular structure.

It has been shown in [13] that the pore size has a great influence on the thermal conductivity and bearing capacity of the material. It is necessary to strive for a minimum pore size. However, in this case, the thickness of inter-pore partition decreases, which should be taken into account when optimizing this parameter. Reduction of pore size is achieved by: regulation of porization processes and rheological properties of the mass, reduction of dispersion of solid components.

Zhukov et al. have carried out calculations [43], and have also provided techniques for determining true, average and open porosity. The true porosity of insulating materials is usually determined by calculation based on the true and average density of the material. The open porosity is estimated by experimental methods based on the volume of pores filled with water or other fluid (as mercury in the mercury intrusive porosimetry procedure). Closed porosity is calculated from the true and open porosity values.

Cheylitko et al. [44] have shown that for a porous insulation material or structural element, the heat energy transfer is characterised by an effective thermal conductivity coefficient. In determining the thermal energy as a fluid, the heat flux through a porous structure can be broken down into a set of elementary heat fluxes of which lateral boundaries are formed by projection onto the pore surface. It is shown that the reduction of the heat transfer coefficient of porous materials depends on the thermal permeability and the geometric characteristics of the porous structure. Thus, if the geometric characteristic of the porous structure of insulating materials is known, the thermal conductivity of that material can be theoretically calculated.

The shape of pores is a parameter which characterises the degree of deformation of spherical pores into regular polyhedrons [41]. The degree of pore deformation can be judged by the volume of cellular porosity: if its value exceeds 75÷80%, it indicates the possibility of transition of spherical pores into polyhedrons. The higher the porosity, the more regular the polyhedrons should be. To achieve optimum parameters of aerated concrete, the technologists strive to achieve a dense and smooth pore surface.

The thermal conductivity studies of porous materials with microfibers [45] have shown that three main parameters (cell diameter, porosity and microfibre diameter) contribute to the hydrodynamic processes in the porous structure. When the cell diameter and porosity are fixed, the fibre diameter contributes to the vapour pressure variation. With a fixed fibre diameter, the highest value of pressure drop take place by the lowest porosity. But still the shape and size of the fibres in the highly porous structure model have a greater influence on the thermal resistivity of the medium than the cell diameter and porosity itself, which ultimately has a significant impact on the thermal conductivity of the highly porous materials.

The thermal conductivity of various insulating materials which are used in the manufacture of solar collectors has been measured and discussed in [46, 47]. The thermal conductivity as well as some other measurements were carried out on three different insulating materials. The measurements were made at temperature of 85°C and a relative humidity of 85%. These regimes are justified by the fact that these materials work under these conditions. One material that has a great promise is lightweight concrete. The lightweight concrete was prepared by a special technology in which lightweight claydite sand was used as a fine aggregate. A great advantage of lightweight concrete is that the density can be adjusted very precisely to obtain the required thermal conductivity. Another advantage of lightweight concrete in such an application is its great durability [46]. Ultimately, the authors recommended lightweight concrete on keramsite sand as an effective material for the construction of solar collectors.

The dependence of the thermal conductivity of metal oxides on the electronegativity of the chemical elements in their composition is shown in [40]. The greater the electronegativity of a metal, the lower the thermal conductivity of its oxide. For example, the thermal conductivity coefficient decreases by a factor of 4 when going from magnesium oxide to silicon dioxide. Thus, the thermal conductivity of dense materials is greatly influenced by the nature of chemical bonds and coordination numbers in their structure. The findings on the influence of the electronegativity of metal oxides may be particularly useful in composing the raw material composition for the production of aerated concrete using fly ash or industrial waste (e.g. metallurgical slags).

The transfer of heat deep into a composite heat insulating coating (under high-intensity heat exposure) depends not only on the composition and structure of the material but also on the nature of its fracture [48]. Thus, the formation of pores in the surface layer, which breaks down, is able to block part of the heat fluxes directed into the depth of the material. At the same time, pore walls, while receiving radiation energy, simultaneously emit it bringing radiation component to heat conductivity of the material.

In [49], a study was carried out to reduce the thermal conductivity of a thin layer mortar while maintaining the same compressive strength. The aim of the work was to reduce the thermal conductivity as much as possible with maintaining the required mortar strength. The effect of greatly reducing the thermal conductivity was achieved by adding colloidal silica. The thermal conductivity of the thin-layer mortar was lowered to the range of 0.15÷0.21 W/(m·K) while maintaining the compressive strength class M10. By performing finite element calculations, the results were transferred to the whole wall. Monolithic walls built with appropriately modified, thin-layer mortar are characterised by an improved thermal insulation of up to 2.0%. If the effect is transposed to a wall with a thick mortar joint, the improvement in thermal insulation is between 3.2 and 5.2%.

Adilkhodjaev et al. [15] used a computer software package to determine the relationship between porosity, strength and thermal conductivity of non-autoclaved aerated concrete using image analysis to determine the properties of aerated concrete. Optimising the pore structure allowed to develop compositions of high porosity aerated concrete with a density of 500 kg/m^3 and 700 kg/m^3 which strength increased by 20÷25% in relation to materials in which pore structure was not optimised.

It has been shown that the main factor which affects the thermal conductivity of autoclaved aerated concrete is the average density of the concrete. At the same time, the presence of mechanically bound water in the cement stone structure as well as the nature of porosity (pore diameter distribution, shape of pores) also perform an important role. Some authors also point out the influence of convection phenomena and the presence of a wall effect, which make certain corrections to the thermal conductivity of developed autoclaved aerated concrete.

4. Conclusions

The following conclusions can be drawn from the literature data:

- The phase composition of hydration products varies depending on curing conditions. The most acceptable conditions under which a stable tobermorite gel is formed is autoclave treatment at high pressure and temperature.
- The method of pore formation plays a significant role in the formation of micro- and macrostructure, and also affects the strength of autoclaved aerated concrete.
- The thermal conductivity of autoclaved aerated concrete are affected not only by its density, but also by the moisture content. Thus, this kind of concrete should to be classified according not only to its density, but also taking into account its thermal conductivity, which is significantly influenced by the composition of the raw materials used in production of the concrete.

Although autoclaved aerated concrete has been a fairly well-known and researched material for many years, there is still space for further research into, among other things, the thermal properties of the material and the improvement of production methods to obtain a material with lower density and relatively higher strength.

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Przegląd wybranych aspektów kształtowania właściwości fizycznych, mechanicznych i cieplnych oraz technologii wytwarzania lekkiego i ultralekkiego betonu komórkowego

Słowa kluczowe: beton komórkowy, spoiwa nieorganiczne, technologia wytwarzania, przewodność cieplna

Streszczenie:

W artykule dokonano przeglądu wybranych artykułów naukowych prezentujących prowadzone w ostatnich latach badania nad metodami wytwarzania betonu komórkowego. Przedstawiono skrótowo tradycyjne technologie oraz innowacyjne rozwiązania pozwalające uzyskać materiał o niskiej i bardzo niskiej gęstości. Poza prezentacją samych metod wytwarzania materiału przedstawiono także wyniki badań właściwości uzyskiwanego betonu komórkowego i ich zależność od zastosowanej technologii. Dokonano również subiektywnego wyboru i przeglądu artykułów obejmujących badania właściwości cieplnych betonu, czynników technologicznych mających na nie wpływ oraz sposobów ich kształtowania. Znaczna liczba cytowanych artykułów nie funkcjonuje w światowym obiegu naukowym ze względu na barierę językową (są one głównie w języku ukraińskim). Tymczasem zawierają one interesujące wyniki badań, które mogą być inspiracją do dalszych badań nad omawianymi zagadnieniami dotyczącymi technologii produkcji oraz właściwości cieplnych i wytrzymałościowych betonu komórkowego ze szczególnym uwzględnieniem betonu lekkiego i ultralekkiego.

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