Heat-insulating lightweight concretes and composite materials on the basis of inorganic binders with application in construction

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Abstract: *A general overview of a number of thermal insulation materials and products made on the basis of inorganic binders (mainly Portland cement) is presented. The technological methods of production, the main operational indicators and the application in construction of various heat-insulating and structural-heat-insulating lightweight concretes are examined. The structure of various cellular concretes (foam concretes and aerated concretes), composite materials and lightweight aggregate concrete was analyzed. The role of the origin, technological processing, characteristics and composition of different types of light additive materials for the formation of the final operational properties of the products has been traced.*
Keywords: *COMPOSITE MATERIALS, INORGANIC BINDERS, LIGHTWEIGHT CONCRETE*

1. Introduction

One of the main priorities in the renovation of the existing building stock (built according to different construction systems) and the construction of new buildings is the provision of optimal energy efficiency [1-5], sound insulation and fire safety.

In modern construction, they find various applications materials with heat and sound insulation characteristics [1-4,6-19]: expanded polystyrene (EPS), extruded polystyrene (XPS), polyurethane, depron, rubber sheets, wood-fiber boards, cork boards, insulation wallpaper, mineral wool (stone, glass, slag), various composite materials and lightweight concretes with various structures and other materials.

The construction of external thermal insulation is a widely applied approach that provides a number of advantages [2,3]: protection of the building from cyclical climatic effects of the environment during the different seasons, lowering the necessary energy consumption to maintain a favorable microclimate and comfortable living environment in the living spaces during the heating period and summer months, preserving the volume of the interior space of the premises (in contrast to interior insulation), soundproofing effect, aesthetic renewal of building facades and others.

The design and construction of thermal insulation systems using some of the materials that have gained considerable popularity in recent decades (EPS, XPS etc.) does not provide an optimal solution in the long term within the entire service life of the building. Significant disadvantages of a large part of the various modifications of the mass-applied products are insufficient reliability in the conditions of fires, aging of the material, limited shelf life and other.

In a number of cases, a more expedient approach is the use of various thermal insulation materials obtained on the basis of inorganic binders [1,9,18-25], providing better complex performance indicators. In this aspect, products made of lightweight concretes [6,9,18,19,26-29], which are characterized by a bulk density of up to 1800 kg/m^3, represent a promising possibility. Various types of heat-insulating (compressive strength > 0.5 MPa, thermal conductivity coefficient < 0.3 W/mK), structural-heat-insulating concretes (compressive strength > 3.5 MPa, thermal conductivity coefficient < 0.75 W/mK) have been developed) and structural lightweight concretes (compressive strength > 15 MPa). Typical representatives of lightweight concretes are foam concretes [9,18,26], aerated concretes (made mainly by the autoclave method) and concretes with the presence of a significant amount of lightweight aggregates [6,25,27,28]. The main advantages of the use of lightweight concrete are the lightening of the built structures [19,20], the increase of heat and sound insulation characteristics, the use of long-lasting, non-flammable and non-combustible products (in the absence of organic lightweight aggregates).

The aim of the present overview is the presentation in a summarized form of part of the results of a preliminary study conducted in connection with the implementation of scientific-applied project financed by NIF of BSMEPA. A full opportunity to apply the obtained data is the development, based on the existing experience, of an innovative material that meets the requirements for installation around doors and windows of buildings, according to Ordinance No. I_3/1971 of 2009, amended in 2015, concerning construction technical rules and norms for ensuring fire safety.

2. Heat-insulating lightweight concrete and composite materialsbased on hydraulic inorganic binders

2.1. Heat-insulating lightweight concretes with a cellular structure

Foam concrete and aerated concrete refer to cellular concrete [6,24], which are characterized by the presence of pores uniformly distributed in the volume and are prepared from a binder, a quartz component, water, a suitable pore former (foam-forming and gas-forming additives), etc.

The technological methods used to obtain the cellular concretes allow the regulation of porosity and the preparation of products with different volumetric mass, appropriate thermal conductivity, sufficient strength and various purposes [1,29]. The increase in bulk density from 600 to 1200 kg/m^3 is accompanied by an increase in strength and thermal conductivity. There are different brands (15, 25, 35, 50, 75, 100, 150) of cellular concrete determined by compressive strength. Water absorption and frost resistance depend to a significant extent on the distribution, characteristics and stability of the formed porous structure [20].

Cellular concretes are classified into three main groups [6]: heat-insulating (with a volume density of not more than 500 kg/m^3), structural-heat-insulation for enclosing structures (with a volume density of 500 to 900 kg/m^3) and structural applicable to reinforced concrete (with a volume density from 900 to 1200 kg/m^3).

Portland cement is usually used to make cellular cement concrete. Developed cement-free aerated concretes (gas silicate and foam silicate) by using lime-quartz mixtures and applying autoclave hardening.

Foam concrete is obtained by mixing separately prepared cement dough and mechanically resistant foam, previously obtained in the form of an aqueous solution of a foaming agent (rosins, sulfonates, natural proteins, hydrolyzed animal blood). The air bubbles formed in the binding dough form the characteristic "cellular" structure of concrete with air pores evenly distributed throughout the volume [9,18,29]. An essential technological requirement is that the formed foam exhibits resistance in the alkaline environment of the hydrating cement and does not break before the end of the bonding [26]. To increase its stability, stabilizers and mineralizers (iron and aluminum salts or hydrophilic substances such as water glass, glue, gelatin, etc.) are introduced into the aqueous solution of the foaming agent.

With the direct introduction of air-entraining additives into the cement dough, a controlled increase in the presence of a certain amount of air in the form of small bubbles distributed evenly in the product, which ensures a decrease in thermal conductivity, an increase in volume and a decrease in the mass of the products [1]. This allows the preparation of filled, frost-resistant and other concretes. Acidol, hydrophobic surfactants, abietic acid and others are used as air-entraining agents.

Foam concrete is non-combustible (class A1), an ecological material characterized by the presence of evenly distributed spherical closed pores, less water absorption, high frost resistance, wear ability, low thermal conductivity, good heat and sound insulation properties [9]. The spherical shape of the pores, which is characteristic of foam concrete, provides a more favorable distribution of the forces under load and the same properties in different directions. The volume weight, quantity and size of the formed pores vary widely in the case of foam concretes, providing an appropriate combination of the necessary thermal insulation and strength characteristics, which are consistent with the intended functional use of the product [18]. Foam concrete is used in the construction of partition walls, load-bearing walls (in accordance with its load-bearing capacity), heat and sound insulation of walls and ceilings, floor screeds and others. Significant opportunities are provided by the application of mobile units for the preparation and laying of foam concrete directly on construction sites, which speeds up the execution of construction activities and allows the preparation of concrete masses with the necessary indicators. Foam concrete mixtures are characterized by low density, very good workability, self-leveling and self-compacting properties and the possibility of applied through pumping equipment and installations [9,18]. The material is applicable for monolithic casting in formwork forms, leveling of floor surfaces, as filler (for cavity filling and hard-to-reach areas), etc.

Aerated concrete is cellular concrete prepared by the autoclave method from mixtures of Portland cement, quartz component (fine fraction) and gas-forming additives, forming a characteristic structure with evenly distributed holes in the volume of the finished product [6]. The formation of pores is carried out by the introduction of gas-forming additives, in which gas is released as a result of chemical reactions [1].

According to the type of gas-forming chemical reaction, gas-forming additives are classified into three types [6]:

- entering into a chemical interaction with the binder or the products of its hydration (for example, aluminum powder - most often a degassing agent). The aluminum powder interacts with the calcium hydroxide $Ca(OH)_2$ obtained during the hydration of the cement, during which hydrogen is released. In this interaction, the particles of aluminum powder become the centers of the formation of gas bubbles, which gradually increase and form pores in the cement paste;
- decomposing additives with gas release (perhydrol H_2O_2 when interacting with CaClOCl);
- interacting and releasing gas as a result of exchange reactions - ground limestone and hydrochloric acid.

In the production of aerated concrete, cement, quicklime, gypsum dihydrate, ground quartz sand, aluminum powder and water are used as raw materials [6]. The prepared mixture is sieved and left in a heat tunnel for up to 3 hours at a temperature of 50-60°C. The hardening of aerated concrete blocks takes place in the process of autoclaving at a pressure of 20 Bar and a steam temperature of 180-190°C (with a technological downtime in the autoclave of 10 h).

Among aerated concrete products, the YTONG trademark has gained exceptional popularity. The Autoclaved aerated concrete (AAC) is fire-resistant, non-combustible (class A1), ecological, long-lasting product with low density, good vapor permeability, suitable sound and heat insulation properties. Various construction products are made from the material [1,6]: bricks, blocks, slabs, panels, vaults, roofing and flooring. The appropriate complex operational characteristics of aerated concrete products ensure their wide application in modern construction. The low weight of the products facilitates transport and their application on construction sites. The diverse assortment, the concrete sizes, the easy workability, allow accelerated implementation of the planned construction activities. Foam concrete products are applicable for the construction of external walls, internal partition walls, internal insulation and others. The strength indicators of some products allow their application in the construction of load-bearing structures. The material is resistant to the impact of various weather conditions and their cyclical changes. At the same time, the use of aerated concrete products reduces the risk of condensation and the development of mold and mildew.

2.2. Thermal insulation composite materials and lightweight aggregate concrete

Products obtained on the basis of light additive materials and matrix frominorganic binders**,** are composite materials [30-32]. A variety of heat-insulating composite materials and various lightweight concretes, applicable in modern construction, have been developed [30]. Different fractions lightweight aggregates find application [33-36]: volcanic pumice, volcanic slag, limestone tuff, swollen vermiculite, diatomite, obsidian, perlite, clay mica, slate, ceramsite, fireclay, slag ashes, slag pumice, granulated blast furnace slag (GBFS), clinker, ash from TPS, carbon-containing waste, wood waste, expanded polystyrene granules, etc. According to their origin and degree of technological processing, lightweight aggregates are classified as natural and artificial [33]. Natural lightweight aggregates are obtained by partial crushing and screening of natural porous rocks (volcanic tuff, pumice, shelly limestone, etc.). Artificial lightweight aggregates are products obtained during the heat treatment of various mineral raw materials. With these materials, two groups of lightweight aggregates are distinguished: specially prepared (swollen perlite, vermiculite, clays and mica) and secondary products from industry (ash from TPS, metallurgical slag, etc.).

When developing various composite materials (in particular lightweight concrete), the pre-planned operating characteristics (thermal conductivity, mechanical parameters, manufacturability, processability, cost) determine the selection and use of specific lightweight aggregates materials [33]. For products in which high structural resistance is not required, but the priority characteristic is the presence of thermal insulation properties, it is recommended to apply a highly porous, especially light additive material [1]. At the same time, due to the significantly lower bearing capacity of these composites, their functional application is limited.

The most favorable complex combination of the main indicators (bulk mass, thermal conductivity, strength) of the final products and the negligible consumption of cement for their preparation is achieved with maximum saturation with lightweight aggregates and their compact distribution in the volume [6]. Effective saturation with lightweight aggregates is possible only with appropriate selection of the particle size composition of the introduced small and large fractions and the application of some technological factors (intensive compaction, use of plasticizing additives, etc.). This minimizes the presence of cement stone, which is the heaviest part of the composite [30].

The most important characteristics of lightweight aggregates are their bulk density and compressive strength, which largely determine the performance of the products [33]. Perlite and vermiculite are most often used for the preparation of heat-insulating composite materials. Volcanic tuff is applicable in the production of structural-heat-insulating composites and lightweight concretes with a bulk mass of 1300-1800 kg/m^3 and a strength of 5-20 MPa. Swollen clays and micas (type expanded clay), sintered ash fine gravel and agglomorite are considered suitable lightweight aggregates for the preparation of structural lightweight concrete.

The sizes, the number, the local distribution and the geometric shape of the pores in the grains have a significant influence on the strength indicators of the lightweight aggregates, as the smaller volume of the pores provides higher strength. The reduction of the porosity of the shell of the aggregates allows an increase in the strength [33]. For swollen clays and micas, this is accomplished by applying heat treatment in an appropriate temperature range. The presence of a coated shell of the grains lowers water absorption, while lightweight aggregates are characterized by significantly higher water absorption [1,20,30].

The water absorption of lightweight aggregates with closed pores and an uneven surface depends on the amount of water in the cement paste, the consistency of the cement paste, the presence of plasticizers, the duration of the stay of the grains in the mixture until it is compacted [1,6].

The process of swelling or agglomeration of the raw material (clays, mica, various waste products and others) is a basic technological step in the production of artificial [33]. The swelling of the material during heat treatment to the tempering temperature is carried out under the action of the formed gas phase. To ensure effective swelling [6], the choice of raw materials is consistent with the requirements for the content of gas-forming substances and the simultaneous progress of pyroplastic processes and the release of gases during thermal treatment.

The formation of the gas phase can be the result of various chemical reactions [6]: thermal decomposition and combustion of organic compounds at temperatures above 400°C, separation of water from clay minerals at a temperature of about 600°C, release of CO_2 from carbonates at temperatures of about 900°C, reduction of Fe_2O_3 at a temperature of about 1100^{o}C with release of free oxygen.

After drying, the raw materials (clays, mica, etc.) are crushed and sorted into fractions with a certain maximum size [6]. If necessary, the materials are subjected to additional finer grinding. In the presence of water and special additives, the ground raw material is granulated. Clays with a plastic consistency are molded into cylindrical or other shapes. Swelling processes are mainly carried out in rotary kilns and on sinter conveyors.

The composition of composite materials is determined based on several main factors [33]: set density, influence of the characteristics of the lightweight aggregates on the properties of the final product, water absorption of the porous lightweight aggregates used.

The lightweight aggregates used are usually characterized by lower strength and stiffness than the cement matrix, therefore the maximum achievable strength of the composite is determined by the strength and deformability of the lightweight aggregates [30,33]. The use of very lightweight aggregates is accompanied by increased consumption of cement, and the use of heavy water leads to an increase in density. As the density of the lightweight aggregates increases, the strength indicators of the composite increase.

The granulometric composition of the lightweight aggregates is determined according to the planned strength and density of the composite materials, the necessary compaction of the mixture and the possibility of providing and separately storing different fractions of the lightweight aggregates [33]. The use of lightweight aggregates with a continuous granulometric composition reduces the risk of delamination during the preparation of the products. When preparing heat-insulating and structural-heat-insulating concretes with low bulk density and moderate strength, it is advisable to use lightweight aggregates with a larger share of coarse fractions [6].

The consumption of cement for the preparation of various composites with a given strength varies within wide limits according to the strength of the grains of the lightweight aggregates and the content of free water necessary to compact the resulting mixture [30-33]. The necessary recommended amount of cement is determined with sufficient accuracy experimentally by preparing individual trial mixes with lightweight aggregates with a certain granulometric composition.

An essential characteristic of the materials with the considered structure is the deformation [6] caused by external loads, fluctuations in moisture content and temperature. Deformation under the influence of prolonged static loading in a number of cases reduces the internal stresses in the material (result of shrinkage or temperature fluctuations), which reduces the risk of cracks. But in most cases, this effect is unfavorable, due to an increase in the general deformation of the material.

The preparation of various composites with a porous structure or porous lightweight concrete [6] is carried out from a binder, lightweight aggregates, with or without the introduction of sand, a pore-forming additive, water and in some cases with the introduction of additives regulating the bonding and hardening time. Similar compositions allow reducing the volume density of materials and are used to obtain products containing ceramsite or ceramsite gravel [1,30]. The volume density of the obtained products varies from 700 to 1400 kg/m^3 and depends primarily on the bulk density of the expanded clay lightweight aggregates, the specificity of the pore-forming additive and the presence or absence on sand. In construction practice, various heat-insulating (ceramsite-perlite concrete) and structural-heat-insulating light concretes obtained on the basis of Portland cement and the joint presence of ceramsite and other inorganic porous fillers are used.

A specific technological approach to forming a highly porous construction of the products involves the construction of a fibrous skeleton by introducing and interweaving kaolin, slag, glass, mineral or other fibers [1]. The operational characteristics and density of the resulting products depend on the size and flexibility of the fibers used and their placement in the volume. Air pores of different shapes and sizes are present in the resulting fibrous structure, and with directed orientation of the fibers, samples with higher strength are prepared.

Vermiculite (most often with aggregate size up to 0-6 mm) is used as a thermal insulation lightweight aggregates [1,6]. For the preparation of composite materials based on vermiculite, Portland cement is used, and when preparing different solutions - lime or a combination of cement and lime. Vermiculite concrete is characterized by good thermal insulation properties and at the same time is applicable as a refractory material at temperatures of 900-1100°C.

Swollen perlite (fig. 1) is applicable for the preparation of heat-insulating screeds, various heat-insulating composite materials, etc. paerlite concrete [33]. Due to the low strength of pearlite, the preparation of building structures with pearlite content requires a significant consumption of cement.

Fig. 1. *Perlite for construction (fraction up to 3 mm).*

Agglomerated ash gravel is lightweight aggregates, suitable for the preparation of composite materials and lightweight concrete (with a single-fraction structure or with a continuous granulometric composition) with a relatively low bulk density (1050-1550 kg/m^3) and high strength (5-30 MPa). Grains from agglomerated ash are characterized by a diameter of about 10-40 mm, which is why in some cases crushing is necessary, worsening the surface properties of the lightweight aggregates [34].

For the preparation of various composite products and lightweight concrete (slag pumice concrete and others) slag pumice and granulated blast furnace slag are suitable lightweight aggregates [6,34].

In connection with the growing trend for the utilization of various waste materials, a promising lightweight additive material with thermal insulation characteristics is the granular foam glass (fig. 2 and 3), obtained after thermal foaming (in the presence of a foaming additive) of waste silicate glass [37,38]. Fractions of foamed glass granules with a fine-grained structure are suitable lightweight aggregates for preparing thin-walled heat-insulating screeds and insulating plasters for walls of different types. A standard application of various fractions of granular foam glass is their use as bulk insulating and filling material. A current opportunity for the use of foam glass granules is their introduction as lightweight aggregates in the preparation of lightweight heat-insulating concrete for construction [39], therefore, they can be considered as a suitable substitute for a number of traditional lightweight additive materials (ceramsite, agloporite, expanded perlite, vermiculite, etc.).

Fig. 2. *Foam silicate specimens obtained from foamed waste glass.*

Fig. 3. *Foam silicate specimen (horizontal and side section).*

Based on foam glass granules, hydraulic inorganic binder (Portland cement) and technological additives, an innovative non-flammable, non-combustible, waterproof and long-lasting composite material was obtained [40-42].

A laboratory technological methodology has been developed for the preparation of various experimental prototypes. The method allows obtaining finished products or blanks subject to additional technological processing. The application of suitable coatings (putty and others) on the external surfaces of the samples increases the operational characteristics of the products [40]. The composite is potentially applicable for the preparation of heat and sound insulation boards and panels, cladding of walls and ceilings, construction of internal non-bearing partition walls, external insulation of buildings, etc. Another possibility of using various composite boards and various profiles is insulation of various production facilities, aggregates, installations and others [39]. The composite material allows further modification and development, according to the planned specific functional role of the products in construction.

3. Conclusions

A significant priority in the reconstruction of old and the construction of new buildings is the provision of optimal energy efficiency, sound insulation and fire safety.

Some of the used standard thermal insulation materials (EPS, XPS, etc.) widely applicable for the construction of thermal insulation systems do not provide a complete solution in a long-term aspect for the entire life cycle of a building.

In a number of cases, the use of materials and products based on hydraulic inorganic binders and other inorganic components is justified. There is a significant variety of heat-insulating and structural-heat-insulating lightweight concretes with a cellular structure (foam concretes and aerated concretes), various composite materials and lightweight concretes obtained on the basis of inorganic lightweight aggregates of various origins, characteristics and fractional composition.

Due to the annually increasing amounts of waste products and existing environmental problems, the development of effective technologies for their utilization is of considerable interest. In this aspect, a promising lightweight additive material with thermal insulation characteristics is granular foam glass obtained after thermal foaming (in the presence of a foaming agent) of waste silicate glass. A full opportunity for the application of different fractions of foam glass granules is their introduction in the role of lightweight aggregates in the preparation of lightweight heat-insulating concretes for construction. On the basis of granular foam glass and inorganic binders (Portland cement), experimental composite materials have been obtained, applicable for the preparation of various insulating boards, profiles and others.

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