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Thermal Insulation Materials with High-porous Structure Based on the Soluble Glass and Technogenic Mineral Fillers

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1. Statement of the problem

Alkali-silicate porous materials obtained by means of thermal or cold foaming of alkali metals silicates aqueous solutions (soluble glass) or solid alkali silicate hydrogels (Pavlenko & Koshlak 2015a,b, Koshlak et al. 2016, Leonovich 2012, Pavlenko & Pietrowski 2017, Fei et al. 2007), are referred to the present-day, efficient inorganic insulants, promising due to the ability to achieve low values of the relative density and thermal conductivity while maintaining sufficient structure strength and easy handling of foaming and induration processes within a wide range of composition formulations. The above benefits are based on the equilibrium and homogeneity of the main raw mixture component: soluble glass and hydrogels based on it.

Composite alkaline-silicate porous thermal-insulating materials, both granulated and block-type, contain significant amounts of the gas phase. There are various technological approaches to obtaining such materials at gas development directly in the strata of the formed composition. Moreover, the process of gas development at high temperatures can be based both on the special additives reactions, and on the crystallization and chemically bound water vapors liberation.

2. Recent research analysis

To manufacture foam glass, special gas forming agents are used. Normally, the process of making the foam glass lies in preparing the batch, consisting of 95-97% of powdered glass and 5-3% of the gas forming agents (carbonate, such as limestone, or carbon, such as charcoal, coke, carbon dust), heating the batch to the temperature of silicates' pyroplastic state. At this temperature glass grains are sintered and gases formed as a result of the gas-forming agents decomposition, blow highly viscous glass melt. After annealing and cooling, porous material is formed with high thermal insulation properties and high mechanical strength (Koshlak 2017a). General issues to obtain the foam glass, including granular one, are described in monographs (Koshlak 2017b, Demidovich 1975). The foaming temperature of foam glass usually lies between 750°C and 900°C.

Another method is the heat processing of glassy silicates containing water, which gasifies at high temperatures and foams the silicate base. Raw material in this process can be both natural (Meizel & Sandler 1988) and synthetic water-containing materials.

To obtain blocks of heat-insulating material, the granular thermal insulating silicate filler can be used, as suggested by the authors (Patent No. 2161142). In this case, the use of a silicate binding component permits forming blocks of the required size and shape, and dehydration of the latter occurs at temperatures within 100-350°C.

The feed silicate composition can be obtained by artificial means. In this case, it is often possible to avoid energy-intensive and technologically costly operation of obtaining highly dispersed silicate powders. The raw materials basis for such technical solutions, are water soluble silicates, most frequently sodium silicates. Obtaining of sodium silicates solutions is performed in compliance with the schemes of the technical product synthesis: soluble glass, or by means of silicon oxide dissolution in a strong caustic, or by autoclave dissolution of pre-fused silicate (silicate-blocks). Further, aqueous solution of sodium silicate in one way or another is converted into a gel, for example by the adding acids or strong electrolytes, and the resulting material is accessible to heat treatment, when water is removed from it and the product foams, increasing its volume significantly. In this case, if heat treatment of the material is performed in a rigid metal form, then while foaming, the material fills the entire free volume of the form, forming blocks of the given configuration.

Amorphous silica is frequently used to produce sodium silicate with the required Na_2O/SiO_2 ratio. Normally, microsilica-wastes from the production of crystalline silicon are used for these purposes (Patent No. 2097362).

Another option to obtain light porous silicate blocks is mixing the finished granulated lightweight silicate with any binding material, followed by hardening of the composition and obtaining the required blocks. Both of the described approaches to obtaining light silicates have been implemented in numerous technical solutions. At the same time, examples of the particular lightweight products manufacture may have some differences both in the composition of the starting materials and in their processing technology.

As it was noted above, one of the ways to obtain foamed silicate in the form of blocks or slabs is heat treatment in rigid forms of sodium silicates pre-transformed into the gel state with various additives.

For the raw material transformation from the fluid to the thickened pasty state and the subsequent granulation, it is possible to add not only the hydrophobic agent, but also the acidic components to it. Thus, in (Patent No. 2220927), the option of adding boric acid is suggested. In (Patent No. 2220928), it is suggested to increase the content of acid oxides in the composition due to adding not only mineral acid, but dispersed acid oxides as well, preferably SiO_2 and Al_2O_3, due to adding burnt clay: naturally burnt clay (which constituents content is close to that of the TPP fly ash); in (Patent No. 2246463) – fly ash of thermal power plants is directly suggested.

Modification of additives to soluble glass is also proposed in the study (Patent 2134668). In the invention described, soluble glass is mixed with portland cement and sodium hexafluorosilicate. The resulting mass is filled in the forms and undergoes heat treatment in the furnace, where the raw mass is additionally blown up and acquires the necessary properties.

Currently, the two technologies for thermal insulating materials manufacturing of rare-glass compositions are suggested. The main difference between them is the method of the starting rare-glass composition preparation. These are process flow diagrams with the use of liquid (Patent No. 2268248) and mechanical granulation. The both technologies are two-staged and include stages of the prepared rare-glass composition granulation and the subsequent granules heating in a closed form at the temperatures within 400-450°C.

With the use of technologies for liquid granulation of composite systems, there arise difficulties connected with the large fillers granulation, which are difficult to pass through the bushing openings; with maintaining the necessary concentration of Al, Ca, Mg chlorides solutions and their mixtures in the operation cycle and with the worked-out brine utilization. The indicated problems do not occur at the use of mechanical granulation, it is possible to use standard equipment. At the moment, the processing technical procedure, which includes mechanical granulation, is the most processable, promising and used in our suggested developments.

An interesting technical solution of the set assignment is the suggested variant of using the starting raw materials mix and the technology used in the production of alkaline-silicate insulation material: "aerated glass" TOV "Stroyevolutsia" (Żelazna 2012). Under its regulations, heat treatment of the soluble glass mixture, a creaming agent (slightly hydrated sodium silicate) and hydrophobe agents are provided. The process of obtaining a granulated "aerated glass" includes homogenizing by mixing the components of the above starting mixture and subsequent heat treatment at 110-115°C. In the course of the transformation, the mass viscosity is significantly growing and the initial liquid system is transformed into a plastic-solid mass. Cooled to the room temperature, the product is completely solidified and acquires fragility, necessary for the subsequent crushing into pieces. After crushing, it is fractionated and "beads" are obtained. The air-entrainment to such "beads" is performed in a boiling layer or in a drum oven at 350-600°C.

The use of such a procedure causes a number of technological problems connected with rheological and environmental difficulties of introducing in this way hydrophobe agents into the composite system, with the possibility to reproduce the dimensions and regularity of pores, the granules macrostructure strength in general and the reduction of internal tension in the products.

3. Identification of previously unsettled parts of the general problem

Analysis of the existing suggested raw mixtures formulations and methods of obtaining thermal insulating materials proves that introducing a significant gel formers amount has a serious drawback: the gelling agent breaks the soluble glass structure to form hydrosilicic acid gel, which is capable of retaining less water than soluble glass. This adversely affects the porosity of the resulting rare glass compositions. Therefore, there is a need to introduce such substances that are inert to soluble glass at the normal temperature.

In addition, a significant drawback of the known methods is performing air-entrainment at fixed temperatures in the furnace within the range of 300-700°C. Such a mode of heat treatment reveals several contradictory trends. At relatively low temperatures, the air-entrainment process is complicated due to the low warming-up rate of the raw mass internal areas, resulting in the increased duration of its air-entrainment process.

At the same time, the slow warming up of rare-glass mixtures also leads to significant losses of chemically bound water, due to which air-entrainment of the mixtures occurs. The high rate and unevenness of their heating is manifested in the size, regularity of the pores and the strength of the entire porous structure, in the internal tensions of the products. Therefore, an important prerequisite for obtaining the expanded material possessing a set of required properties and their reproduction is compliance with the principle of correspondence between the rate of crystallization and chemically bound water isolation and the rate of new solid silicate structures formation.

In all of the above-described methods, the first stage is to obtain a solid or plastic composition from soluble glass which can then be subjected to heat treatment. At the same time it is not necessary to use different additives that cause coagulation of silicates. It is possible to obtain a plastic composition using soluble glass simply by means of adding an inert disperse component.

4. Statement of assignment and methods of its solving

The study performed is aimed at the search and development of an optimized raw material mixture variant of the silicon oxide containing technogenic component: fly ash of thermal power plants and methods of obtaining the fly ash based porous alkaline-silicate composite thermal insulating materials of extended application, differing from the analogues by their composition, the content of the starting raw mass, the sequence and modes of the target product formation, the applied technological equipment.

5. Study results and their discussion

In the present project, the set task of making the targeted porous thermal insulating material is achieved by means of the raw mass hot foaming technology, which procedure includes the four main stages:

1) preparation of the starting raw mixture components and homogenization of the latter;
2) the composite system "gaging" by soluble glass and formation of a persistent gel; fragmentation of the hardened raw mass and placement of the granulate into lined dismountable molds;
3) heating and transferring of the workpieces' substance into the pyroplastic state (110-115°C);
4) further hot foaming and reproduction of the regular porous macrostructure of composite systems (130-220°C) and formation of the targeted processed product's properties (500-550°C).

The blowing agent in this case is water (mainly silanol or molecular, strongly bound by hydrogen bonds with unbridged oxygen atoms), which is released during heat treatment of composite systems.

In the raw mixture, the industrial soluble glass, thermal power plants fly ash of the mixed chemical composition (see Table 1), sticky portland cement and, additionally, a thickener (pre-staged partially dehydrated hardened "dry glass") are used.

Table 1. Chemical composition of the thermal power plants fly ash, % mass
Tabela 1. Skład chemiczny popiołu lotnego elektrowni, % mas.

SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	Na_2O	K_2O	Mn_3O_4	TiO_2	SO_3	P_2O_5
51,68	16,75	14,47	0,88	4,38	0,35	2,58	0,04	0,86	4,24	0,49

In the prepared samples, the fly ash is manifesting good reinforcing properties, high thermal stability, sufficient resistance to aggressive media, has a small bulk density. At the same time, the results of the authors' studies (Breck 1976, Ovcharenko 2000) (on the ability of alkaline-silicate systems with Al_2O_3 in alkaline media to form insoluble products of $Na_2O \cdot Al_2O_3 \cdot 2Si_2O_3 \cdot nH_2O$) permit to consider aluminum oxide contained in ash to be a modifying component that provides the raw mix with the properties necessary for the targeted product formation.

In forming the raw mix, the results were taken into account on improving the water resistance of alkali silicate composition by means of replacing the two-calcium silicate (belit) hydrophobe components with the sticky Portland cement; the results are presented in (Maliavsky & Zvereva 2015).

The "setting" rate control of the suggested raw mix during the formation of hydrosilicic acid xerogel (depending on the executed tasks purposes) was performed by means of varying properties of the thickener used and by means of regulating the hardened processed mass fragmentation in the further processes and its subsequent hot foaming.

The raw mix prepared according to the optimized formulation, in contrast to the previously considered analogues, starts hardening at the usual temperature from the moment of its "gaging" with soluble glass and forms a plastic cake with the properties necessary for further fragmentation.

The suggested raw mix also permits to overcome the difficulties associated with drying of viscous rare-glass mix to remove a large output amount of water (56-62%) to the water content of 33-38% needed to obtain a rigid hydrogel capable of thermal blowing.

The optimized formulation of the raw mix allows processing of the compositions in various ways, with the formation of thermal insulating materials of extended application. An important prerequisite for their reproduction with the necessary properties system is strict compliance with the regulatory requirements established by the previous empirical studies.

In parallel with the formulation development, the technology of samples manufacturing was being tried. Thereat, the decisive factor, in contrast to the regulations, the exclusion of the raw mix granulation stage after heat treatment 110-115°C and the use of sealed closed forms at their temperature annealing.

The suggested hot air entrainment of the silicate compositions structure "blowing" of the systems in a xerogel form passes quickly, avoiding the viscous-adhesive state. The determining factor in the process of the systems thermal activation was the technical performing of their heating reproduced rate (Pat. 43549).

The conscious choice of its optimal mode is motivated by empirical data to determine the thermal foaming features of composite systems obtained by the method of differential-thermal analysis (DTA) presented in Fig. 1.

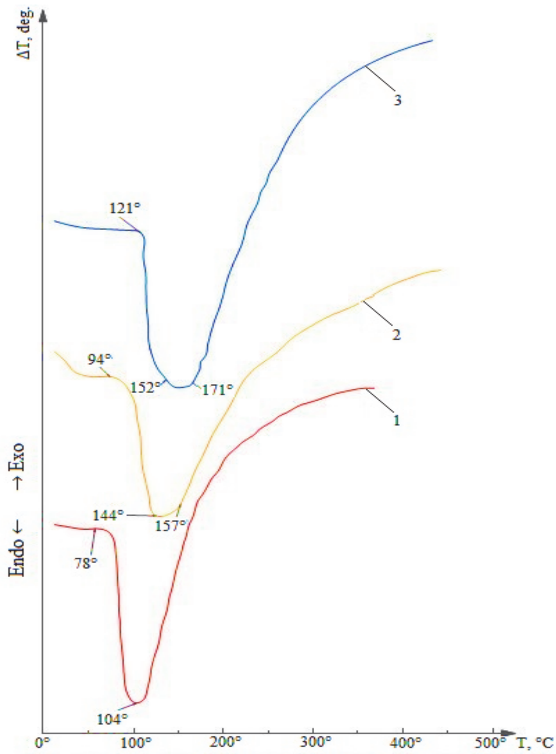


Fig. 1. DTA thermograms of sodium rare-glass composites xerogels in coordinates ΔT–T, recorded at heating the samples in adequate conditions at different rates: curve 1 – 4 deg./min.; curve 2 – 7 deg./min.; curve 3 – 20 deg./min.

Rys. 1. DTA termogramy kserożeli kompozytowych z metali ziem rzadkich we współrzędnych ΔT–T, zapisany podczas grzania próbek w tychże warunkach przy różnej przędkości: krzywa 1 – 4ºC/min.; krzywa 2 – 7ºC/min.; krzywa 3 – 20ºC/min.

The air entrainment process includes the three main stages, the duration and nature of which depends on the type and amount of water containing the raw mix:

– within the range of 100-110°C, the hardened composite system partially transforms into the pseudopyroplastic state and begins to deform with increasing volume;
– within the range of 130-147°C, an intensive release of free and adsorbed water and intensive air entrainment of the sample mass occurs;
– at the temperature values above 147°C, the removal of constitutional moisture, the completion of restructuring, physical and chemical transformations of composite systems are observed.

Based on the analysis of the thermographic data and the macrostructure of the samples obtained, it can be concluded that the greatest contribution to the formation of the product's structure with maximum homogeneity is made by the constitutional water, while removal of the excess adsorption moisture at the initial stages leads to the formation of large through pores and capillary channels in the raw mass. Therefore, the initial rare-glass composition should contain a minimum amount of free and adsorbed water.

As the efficient ways to reduce the free water's effects, the following ones can be recommended:

– direct thermal dehydration and transformation of soluble glass into xerogel (the basis of the present variant of the suggested technical solution);
– liquid granulation of composite systems (for example, in Al, Ca, Zn, Mg chlorides solutions or their mixtures);
– introducing of mineral fillers or chemical additives into the rare-glass composite system, which leads to the development of gelation processes.

According to the results of the study (Bohdal 2013), alkaline-silicate compositions in solutions at heating form a number of hydrated associates with differing properties. This permits modifying the properties of the raw mix thickener – grated "dry glass" – by means of the partial unwatering of the purchased product in a liquid state at different temperature values, in the conditions of the technological cycle for the target product formation, simultaneously with the same equipment, without the use of additional equipment. Meanwhile, the empirically determined physicochemical behavior of composite silicate systems, the features of unwatering and the viscosity state passing, strong adhesion of the intermediate transformation products to metals, ceramics, glass allow to suggest technological regulations, stages, sequence of operations during processing, development and selection of the equipment materials, variations in the methods of obtaining and using porous targeted composites.

Laboratory practice proves that the excess amount of the soluble glass introduced in a liquid state during the "gaging", on the one hand improves the rheological properties, the plasticity of the treated raw mix, and on the other hand, during the subsequent heat treatment, causes additional viscosity of the system, deteriorates the heat transfer conditions, requires more prolonged temperature holding at higher temperature values and leads to the increased energy costs. Therefore, a necessity arises to find an efficient way of regulating the rate of gelling, using the method of shifting the equilibrium of physical and chemical processes of the disperse systems dehydration by adding less hydrated forms of the dried soluble glass; with the degree of the grated "dry glass" dispersion, with its dosage and regulating the processes of the hardened processed mix fragmentation during the granulate formation and the subsequent hot air entrainment.

The improved formulation of the raw mix preparing allows processing compositions in various ways with the formation of insulating materials of extended application: granular insulating filler (Fig. 2), materials for thermal insulation for the structures complicated in the form (Fig. 3), the plate and film-like types of insulating materials (Fig. 4) This task (depending on the purpose and features of the performed tasks) is solved by the capability of performing the final stages by means of several different ways of the products obtaining.

The use of the two stages procedure of the suggested renovation in the technology of preparing the porous thermal insulating materials determines: 1) the nature and the behavior peculiarities of the rare-glass composite systems components during the heat treatment, their strong adhesion manifestation related to most structural materials; 2) the necessity to solve the problem of easy workpieces removal from the formation molds; 3) the choice of the method for lining the internal surfaces of dismountable equipment molds; 4) thermophysical and chemical properties of the used lining material.

The features of the suggested project are:

– ease and availability of obtaining components and preparing the raw mix,
– formation of the raw mix directly at its "gaging" with soluble glass under the normal conditions,

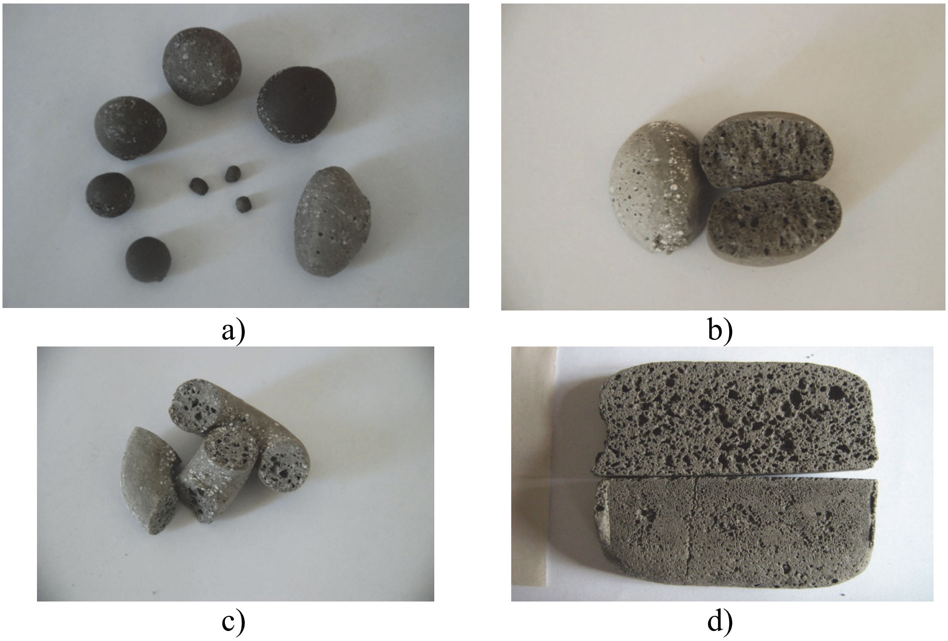


Fig. 2. Illustration of the granular thermal insulating fillers' samples, obtained in the lined molds without limitation of formation volume: a), b) – cutting of iso-sized elements; c) – cutting elements of plastic hardened raw cake of the set preformed thickness; d) – of workpieces, formed in separate dismountable molds

Rys. 2. Wygląd próbek granulowanych wypeiniaczy termoizolacyjnych, otrzymanych w formach z wykiadziną bez ograniczania objętości formacji: a), b) – przekroje elementów izometrycznych; c) – przekroje elementów w plastykowych foremkach z utwardzoną powierzchnią o wstępnie ustalonej grubości; d) – przekroje elementów, uformowanych w oddzielnych rozbieralnych formach

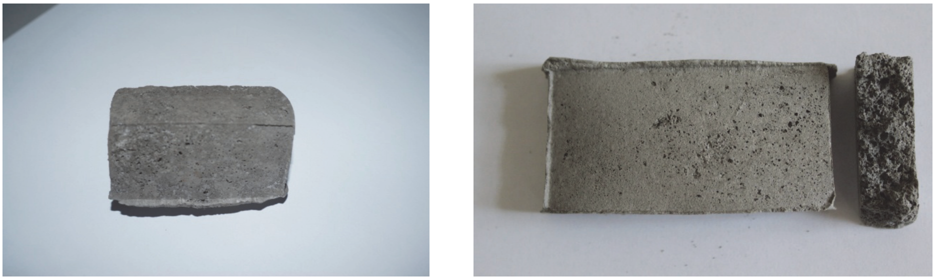
– the thermal insulation method is fast,
– the possibility of easy formation and fragmentation of the raw workpieces, their inherent properties makes it possible to spread in time and space separate stages of thermal insulation: the stage of preparation, formation of granulate (possibly, in a specialized site); storage; transportation; technological packing in the working area complying with the increased resistance requirements to the heat transfer (possibly, in the construction site),

a) b)

Fig. 3. Illustration of fragments of thermal insulation zones sections in complicated form structures performed by the working zone filling with fragmented elements and the subsequent heat treatment in dismountable equipment of varying complexity: a) - without limiting the free volume of formation; b) - with restriction of formation space

Rys. 3. Wygląd przekrojów elementów izolacji termicznej o złożonym kształcie, wykonanych przez wypełnianie strefy roboczej fargmentowanymi elementami z następną obróbką termiczna, w rozbieralnym sprzęcie o różnych złożonościach: a) – bez ograniczenia objętości formacji; b) – z ograniczeniem objetości formacji

– processing of complicated working areas: selection of the raw mix cake thickness, the size and shape of the starting fragmented elements (depending on the target task and in order to provide more tight packing),
– the versatility of the thermal insulation method (based on the manifestation of significant adhesion ability of alkaline-silicate composite systems in relation to most structural materials: metals, ceramics, glass, wood),



a) b)

Fig. 5. Illustration of the items fragments formed: a) – in the form of plates; b) – in the form of films
Rys. 5. Wygląd fragmentów próbek ukształtowanych: a) – w postaci płyty; b) – w postaci folii

- low shrinkage with the suggested formulation of the raw mix and the method of treatment,
- indifference to most components and stability of the thermal insulation material properties, high thermal and chemical resistance, noncombustibility, ability to withstand significant temperatures;
- combination of the valuable properties set: low thermal conductivity factor, thermal stability, incombustibility, durability, low cost.

6. Conclusions

The raw mix of silica-containing technogenic component – fly ash of thermal power plants – and the methods of preparing waterproof porous thermal insulating materials of extended application on its base according to the powder low-temperature technology has been developed using multifunctional properties of soluble glass as: a) a binding component; b) blowing agent; c) the raw mix hardening rate regulator. The physical and chemical, technological aspects of obtaining and using the suggested alkaline-silicate compositions have been considered.

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Izolacja termiczna o strukturze wysokoporowatej na bazie szkła wodnego i wypełniaczy mineralnych o pochodzeniu poprodukcyjnym

Streszczenie

Przekazujemy wyniki badań procesów powstawania porowatej struktury metodą termicznego wzdęcia żelowej mieszaniny surowców. Badaliśmy przemiany fizyko-chemiczne surowej mieszaniny po jej ogrzaniu, co umożliwiło określenie początkowej zawartości wody w surowej mieszaninie, optymalnej dla tworzenia się kserożelu i resztkowej zawartości żelu, wystarczającej do skutecznego pęcznienia. Surowa mieszanina zawiera lotny popiół z elektrowni cieplnej, jak również sposoby wytwarzania porowatych materiałów wodoodpornych, wytrzymałych materiałów izolacyjnych na bazie technologii proszek o niskiej temperaturze zostały opracowane przy użyciu właściwości wielofunkcyjnych szkła wodnego jako: a) element łączący; b) środek porotwórczy; c) regulator szybkości utwardzania dla surowej mieszaniny. Uwzględniono fizyko-chemiczne, technologiczne aspekty wytwarzania i stosowania proponowanych kompozycji alkaliczno-krzemianowych. Zaproponowaliśmy zoptymalizowany skład surowej mieszaniny, która wykorzystuje maksymalną dopuszczalną ilość popiołu jako wypełniacza mineralnego; rozważane są tryby obrzęku termicznego. Na podstawie uzyskanych danych opracowano nową technologię produkcji porowatych materiałów termoizolacyjnych.

Abstract

We report results of research into processes of formation of porous structure by the method of thermal bloating of the gel-like mixture of raw materials. Regularities of the course of physical-chemical transformations are considered in the material when it is heated; as a result, we established the initial water content in the raw mixture, optimal for the formation of xerogel, and the residual water content in gel, sufficient for effective bloating. The raw mix of silica-containing technogenic component – fly ash of thermal power plants – and the methods of preparing waterproof porous thermal insulating materials of extended application on its base according to the powder low-temperature technology has been developed using multifunctional properties of soluble glass as: a) a binding component; b) blowing agent; c) the raw mix hardening rate regulator. The physical and chemical, technological aspects of obtaining and using the suggested alkaline-silicate compositions have been considered. We proposed the optimized composition of the raw mixture that employs maximally permissible amount of ash as a mineral filler; the thermal modes of bloating are studied. Based on the data obtained, a new technology for the production of porous thermal insulation materials is created.

Słowa kluczowe:
popiół lotny, szkło wodne, kompozytowe materiały termoizolacyjne, krzemiany alkaliczne, termiczne wzdęcia

Keywords:
fly ash, soluble glass, composite insulation materials, alkaline silicate, thermal bloating