Construction and Building Materials 302 (2021) 124385

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Recycling of rice husks ash for the preparation of resistant, lightweight and environment-friendly fired bricks

Aleksandr Ketov [a,*], Larisa Rudakova [a], Iakov Vaisman [a], Iurii Ketov [a], Viktors Haritonovs [b], Genadijs Sahmenko [c]

[a] Department of Environmental Engineering, Perm National Research Polytechnic University, Perm 614990, Russia
[b] Department of Roads and Bridges, Riga Technical University, Riga LV-1658, Latvia
[c] Department of Building Materials and Products, Riga Technical University, Riga LV-1658, Latvia

ARTICLE INFO

Keywords:
Rice husks ash
Cellular structure
Foam collapse
Lightweight clay brick

ABSTRACT

Rice husks ash was previously shown as a raw material for the foamed silicates production. This article is devoted to the use of the foamed silicates as an aggregate for the manufacture of lightweight cellular clay bricks. The coalescence of the foamed silicate structure inside a ceramic matrix leads to obtaining cellular lightweight ceramics in the process of firing. The present study has shown that on decreasing the ceramic brick density while using the foamed silicate filler the mechanical strength is not significantly decreased as opposed to the bricks with inert fillers. This effect is explained by obtaining a high strength glass layer on the inside surface of the cells. The lightweight cellular bricks demonstrate good heat insulation properties. Using rice husks ash as a raw for foamed granulated silicates in the manufacture of lightweight ceramic bricks not only solves the problem of rice husks as a large-tonnage waste, but also provides an environment-friendly building material with strength and heat insulation.

1. Introduction

1.1. Origin

Clay brick is probably the oldest building material, which is used unchanged from the moment of its invention to the present day. However, the current level of technology development urgently requires a responsible attitude to natural resources. One of the problem solutions is using renewable resources and reducing the consumption of primary natural resources. In the case of ceramic bricks, it can be practically implemented by reducing the weight of products and replacing natural clay as a raw material with renewable resources. Such renewable resources include rice husks, which are annually produced in significant quantities.

Secondary use of rice husks is quite limited in practice due to the high content of silica in it, which reaches up to 18–22 wt%. As a result, rice husks burn and assimilate poorly in the environment. As a result, although the amount of this silica-containing raw obtained annually is comparable to commercially produced silicate raw materials, the use of rice husks to create industrial products is very limited.

In our opinion, the contradiction between the significant amount of renewable silica resource and its very low consumption can be overcome by creating a special technology for processing silica obtained from rice husks ash into a competitive valuable product on the market.

1.2. Objective

This article presents the results of studies on the production of lightweight cellular ceramic bricks using rice husks ash as one of the sources of raw materials. In general, the addition of plant waste, including rice husks, to the original clay prior to molding raw bricks is the most obvious solution for making lightweight bricks. Burnout of plant residues during firing leads to the formation of porosity and a decrease in the density of the ceramic material. However, the negative consequence of this technical solution is a decrease in the strength of the resulting products. It is usually not possible to reduce the density of a ceramic product below 1500 ÷ 1600 kg/m^3 due to a catastrophic drop in its strength. The reason for this phenomenon is the lack of interaction between an aluminosilicate matrix and an organic filler. As a result, after the aggregate burns out, a smaller amount of the solid phase with

* Corresponding author.
E-mail address: alexander_ketov@mail.ru (A. Ketov).

https://doi.org/10.1016/j.conbuildmat.2021.124385
Received 10 February 2021; Received in revised form 7 July 2021; Accepted 26 July 2021
Available online 3 August 2021

unchanged properties remains in the bulk of the material, and this solid phase cannot provide acceptable strength.

In this work, a foam-silicate granular aggregate based on rice husks ash has been prepared for an aluminosilicate matrix. Lightweight cellular bricks are made by mixing aluminosilicate brick clay with the foam silicate granular aggregate, pressing and subsequent firing. During the firing of such composite brick, the aggregate granules collapse as a result of melting and coalescence of the silicate foam and form a glassy crust on the inner surface of the cells in the ceramic material. The resulting cellular glass-like structure has its own stiffness, independent of the stiffness of the clay matrix.

According to the results of the experiments, the processes of appearance and destruction of the cellular structure inside the composite bricks are considered; the influence of various parameters on the engineering properties of the obtained lightweight bricks is evaluated. The objectives of the study are:

1. To understand the conditions of growth and high-temperature fracture of the silicate foam produced from rice husks ash and to investigate the possibility of using granulated foam silicate as an aggregate in the manufacture of ceramic bricks.
2. To investigate the processes occurring during the firing of composite raw bricks made of clay and granulated foam silicate aggregate.
3. To study the influence of the fraction and fractional composition of the granulated foam silicate aggregate on the properties of lightweight bricks and to evaluate the best ratio of the raw mixture components.
4. To offer the technology in order to simultaneously solve the problems of efficient utilization of rice husks waste and to create lightweight and environment-friendly cellular ceramic bricks.

Within the concept of sustainable development we hope to find a technical solution to use waste not as an additive to existing raw materials, but as an independent raw material having its own properties and value, as well as to develop the technology of processing this raw material into a valuable product with a certain consumer market. By this study we hope to increase the value of waste as a renewable raw material resource, to propose a technical solution for reducing trace carbon and improving the environmental situation while producing simultaneously a cost-effective environment-friendly product and, thereby, to contribute to the creation of conditions for sustainable development.

2. Literature review

The world's annual rice production is estimated at 700 million tons, with rice husks accounting for about 20% of the rice mass [1] and it consists of cellulose (50%), lignin (25% −30%), silica (15% −20%) and moisture (10% −15%). The bulk density of rice husks is small and lies in the range of 90–150 kg / m^3. The annual amount of waste generated in the form of rice husks reaches 150 million tons [2]. The main features that distinguish rice husks from other waste products of plant origin are a high proportion of ash residue and the composition of the ash, which is silica. One can state that every year about 30 million tons of renewable silica is formed on the earth when rice husks are assimilated into the environment in one way or another. Due to the natural feature of rice husks, consisting of organic and inorganic parts, numerous solutions are proposed for the integrated use of this waste, which imply obtaining energy from combustion and using ash in the manufacture of various materials and products, such as silica gel, ingredients for lithium ion batteries, graphene, activated carbon, catalysts, zeolites, nanotubes and many other things [3].

Due to the significant volumes of rice husks ash produced, the technologies of making multi-tonnage products used in construction are of the greatest interest from the point of view of utilizing this waste. Some studies have been undertaken in this direction to obtain pozzolanic additives that improve the properties of cements [4], binding compositions [5,6], as well as materials obtained at high temperatures, such as aerogels [7], glass [8] and ceramics [9]. It should be noted that it is possible to use silica from rice husks ash to produce foamed silicate glasses. In this case, the ash of rice husks can be an additive to glass cullet as the main type of raw material [10] or be the basis of the composition [11]. The undoubted advantage of using rice husks ash, in particular, and ash from plant waste, in general, is the reduction of manufacturing costs due to the use of cheaper raw materials [12]. However, for a deeper economic analysis, it is necessary to take into account a variety of technical and economic factors [13].

One of the most common methods of utilization of rice husks in Southeast Asian countries is addition of rice husks to the raw mixture when forming clay bricks [14]. In this case, rice husks do not differ from the plant waste of some other origin, any such additive burns out on firing, which increases the porosity of a brick, but reduces its strength. Therefore, it is not recommended to add a filler of plant origin in excess of 5 wt% The use of pore-makers in the brick production reduces the consumption of clean clay resources as well as weight of a baked brick body. Many organic or inorganic additives have been used as pore-makers in brick production for improving thermal performance. In addition to traditional sawdust [15], tea waste [16], olive oil production waste [17,18], sorghum waste [19], and sugar cane processing waste [20] are known to be used as additives.

The reduction of linear shrinkage on drying can be considered as a technological advantage of adding rice husks ash to the raw mixture in the production of clay bricks, but even in this case the addition of an aggregate over 5 wt% rests on the problems of strength of the resulting products [21].

The addition of rice husks ash to the raw mixture results in a smaller pore volume in the finished product compared to the addition of unburned rice husks. But even in this case, it is not possible to achieve the resulting products density below 1600 kg/m^3 versus 2000 kg/m^3 for pure ceramics [22] due to a critical decrease in the strength of the products.

Besides the addition of burn-out additives, lightweight ceramics can be obtained by swelling during rapid firing. For example, the research [23] showed the ability of high-temperature swelling for most of the traditional South-European clays commonly used for the production of bricks and tiles. At firing temperatures of 1175–1300 °C, an aggregate with loose bulk density of 470–1320 kg/m^3 and apparent density of 890–2390 kg/m^3 was obtained in a rotary kiln. The use of this aggregate for brick clay matrix is not discussed, possibly due to the high density of foamed aggregate granules. However, the use of a lightweight refractory aggregate for the manufacture of lightweight bricks can be realized with the help of diatomite [24] or expanded perlite [25]. The granules of the filler remain intact after firing of the bricks because of the high thermal stability. As a result, the porous structure of the aggregate is also observed in the resulting ceramic product.

One can state that the main methods for producing lightweight porous ceramic bricks are the addition of burn-out additives and the introduction of a granular lightweight refractory aggregate.

In the case of a burn-out aggregate, we see a fundamental contradiction between the decrease in the density of the resulting ceramic porous material and the need to maintain its high strength. The sufficiently high density of refractory lightweight aggregates, such as the aforementioned diatomite or expanded perlite, when they are used as clay brick aggregates, leads to a sufficiently high density of the resulting brick. The density of the finished product is usually higher than 1400–1500 kg/m^3. In our opinion, the existing contradictions in the production of lightweight clay bricks with the density below 1000 kg/m^3 and the acceptable strength maintained can be eliminated only by changing the mechanism of creating a porous material. In our research, we use light foam silicate aggregates, which on firing bricks create a new spatial structure inside the material having its own strength.

Among light aggregates there is foam glass known for having a bulk density of 150–400 kg/m^3. Foam glass can be produced from glass waste, but when used as filler it is usually considered only as an aggregate in concrete [26] and asphalt mixtures [27], which excludes high-temperature processing of the mixture of foam glass with the matrix material. Despite the risks of alkali silica reactions (ASR) between the foam glass aggregate and the cement matrix [28], options for granular foam glass to create composite materials with a cement matrix, and not with a ceramic one, are considered. It may be due to the risks of softening the foam glass material inside the ceramic matrix on firing and destroying the entire composite material. However, it was previously shown [29] that high-temperature coalescence of foam silicate granules can be used to create voids in a ceramic matrix.

3. Materials and methods

Ceramic brick is one of the most widely used materials in modern construction. Reducing the weight of bricks leads to an increase in its thermal insulation properties and a decrease in construction labor costs, while saving resources in its production and reducing the trace carbon.

3.1. Materials

3.1.1. Rice husks ash

Rice husks produced in the Krasnodar region of Russia were used. Preparation of the foamed silicate material from rice husks ash was described by us earlier [30]. At the same time, it was shown that the combustion of rice husks in air leads to incomplete oxidation of organic compounds and the residual carbon concentration in the ash is up to 6.5 wt%. Rice husks for the experiments were burn in the column furnace with the free air convection from down and moving of burning front from down to up. In the proposed case of a repeated heat treatment of rice husks ash in the production of bricks, it is assumed that the residual carbon will not have a significant impact on the quality of the resulting brick. Therefore, all experiments were carried out with the ash containing residual carbon in the above amount. The appearance of the ash used in the experiments is shown in Fig. 1.

3.1.2. Preparation of an aggregate from rice husks ash

It is known that hydrated sodium silicate is able to foam and form cellular structures at temperatures lower by 250–300 °C than in the synthesis of standard foam glass. For example, the authors [31] show that geopolymer paste, obtained from microsilica and sodium hydroxide solution, cures at 60–100 °C and foams at 200–500 °C, forms inorganic foams with a density of 85 kg/m^3. In our experiments, rice husks ash was mixed with 2.5 M sodium hydroxide solution to form a paste. The resulting paste was heat-treated for 24 h at the temperature of 90 °C. The resulting gel was crushed to a particle size of less than 2 mm in a jaw crusher and the obtained granules were heat-treated in a drum furnace at 550 °C and sieved into fractions. To prepare cellular ceramics, seven sieves with the size of cells 0,160; 0,212; 0,425; 0,85; 1,4; 2,0 and 5.0 mm were used. The appearance of the obtained foam silicate granules is shown in Fig. 2. Data on the bulk density of foam silicate granules, depending on the fraction, are presented in Table 1.

Fig. 1. Rice husks ash.

3.1.3. Lightweight bricks preparation

It is assumed that in the composite material made of clay and foam silicate granules, in the process of heat treatment there occurs coalescence of the foam silicate granules to form voids in the places where they are located, inlaid from the inside with glassy material.

For the manufacture of bricks, the standard clay of the plant "Ceramic brick's production of Zakamenoi" of the Perm Region (Russia) was used (https://l.pkk.perm.ru/). The clay chemical composition is given in Table 2. Dispersed composition of the clay is presented in Table 3.

The standard procedure is supposed to use the maximum firing temperature of 1030 °C for eight hours, with the total duration of the products in the furnace of 24 h.

An example of preparing clay bricks with the addition of rice husks is described in detail [32]. The finished products minimum density of 1300 kg/m^3 was achieved by adding rice husks in an amount of 15 wt%. At the same time, the compressive strength did not exceed 2–6 MPa for the ground rice husks and 1–2 MPa for the coarse rice husks. And the thermal conductivity coefficient of the samples was higher than 0.2 W/(m·K). We can assume that the standard procedure of adding the rice husks as a filler to clay fails to obtain clay bricks of acceptable strength with the density lower than 1300–1400 kg/m^3. That is why it is difficult to expect thermal conductivity lower than 0.2 W/(m·K) of such products.

For testing this assumption, in order to prepare lightweight bricks, standard clay was mixed with a given amount of the aggregate and pressed at a load of 2.0 MPa. The obtained blanks were dried at 90 °C for 24 h and heat-treated in a muffle furnace according to a given program. The addition of husks ash makes it difficult to sinter clay due to inertia and refractoriness of silica contained in rice husk. The view of the surface of the brick, shown in Fig. 3, obtained from standard clay with the addition of 10 wt% of rice husks according to the standard firing procedure used at the plant suggests that there is no interaction between the amorphous silica of the rice husks and the clay matrix material. The heat treatment of the sample included the maximum firing temperature of 1030 °C for eight hours, with the total duration of the products in the furnace of 24 h. As a result, the strength of the resulting brick was below 0.5 MPa, which made it possible to exclude the research with the addition of rice husks to clay from the program of further experiments.

In the course of preliminary experiments, it was discovered that heat treatment of the blanks with a foam silicate aggregate used according to the standard program of the factory furnace leads to deep sintering of the material, accompanied by partial vitrification of the samples and changes in geometric dimensions. This effect confirms the change in the sintering mechanism of the material, when the silicate melt formed from foam silicate granules begins to play a key role in the sintering process. Therefore, in the further experiments, all the samples of composite blanks with the foam silicate filler were fired at temperatures lower than under the factory conditions, namely at 980 °C, with an exposure at the maximum temperature for three hours.

As a result of the proposed method of preparing bricks, a ceramic material with a cellular internal structure is obtained, shown in Fig. 4. In the process of the heat treatment, the brick blanks do not change their shape.

3.2. Methods

Thermal analysis of the samples TG-DSC-MS was carried out in the air atmosphere of 20 °C to 1000 °C with the heating rate of 10 °C/min. with the Netzsch device (Germany) synchronously with the mass spectral analysis. Compression strength was determined with the PGMMG4

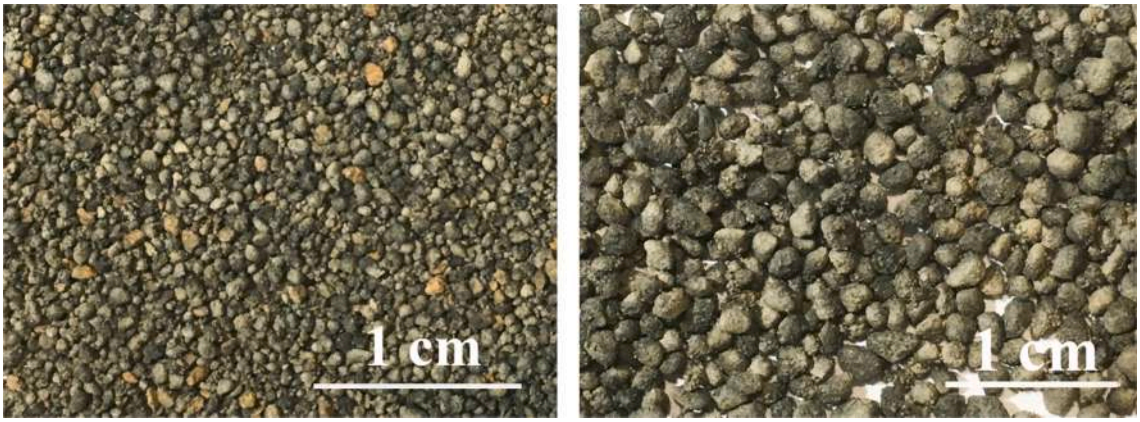

Fig. 2. Foam silicate granules from rice husk ash: fraction 0,425–0,85 mm (left), fraction 1,4–2,0 mm (right).

Table 1
Bulk density of foam silicate granules.

Fraction (mm)	Bulk density (kg/m^3)
2,0 ÷ 5,0	321
1,4 ÷ 2,0	370
0,85 ÷ 1,4	435
0,425 ÷ 0,85	512
0,212 ÷ 0,425	583
0,160 ÷ 0,212	627

Table 2
Average chemical composition of the clay.

Oxide	Average content (wt. %)
SiO_2	61,74
Al_2O_3	12,57
Fe_2O_3	5,06
TiO_2	0,71
CaO	3,46
MgO	1,95
K_2O	1,79
Na_2O	1,26
MnO	0,11
SO_3	0,61

Table 3
Dispersed composition of the clay.

Dispersed composition	Average content (wt. %)
Clay particles (less than 0.005 mm)	18 ÷ 25
Dust particles (0,005 ÷ 0,05 mm)	48 ÷ 52
Sand particles (0,05 ÷ 2,0 mm)	27 ÷ 32

press (Priborkomplekt, Russia).

To study the structure of the resulting material, a Hitachi S-3400 N scanning electron microscope was used. The thermal conductivity coefficient was measured using the PIT-2.1 device (Russia) under the stationary thermal conditions.

4. Results and discussion

4.1. Transformation of the aggregate

The foam silicate aggregate is made in advance, and its heat treatment is carried out at temperatures several hundred degrees lower than when it is subsequently heat treated as part of the composite material during the firing of ceramics. Under normal conditions, foam silicate fillers are heat treated at 550–800 °C, and not higher, in order to avoid softening and destruction of the material. Studies of foam silicate materials are usually limited to the temperatures at which the cellular structure arises and grows. It seems logical, since high-temperature destruction of foam is not of interest from a practical point of view. In the case in question, however, it is the destruction of the foam silicate aggregate that leads to the formation of a new structure inside the ceramic matrix. Therefore, it is of interest to consider the high-temperature destruction of the foam silicate material, both in its free state and inside the ceramic matrix.

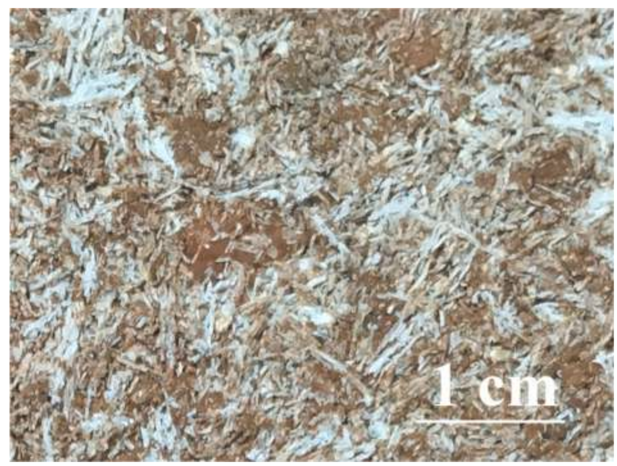

Fig. 3. The surface of the composite brick with the addition of 10 wt% rice husks to the original composition.

4.1.1. Microstructure of the foamed silicate granules

In the considered case, the filler is light silicate foam. The appearance of a granule and its surface are shown in Fig. 5. The surface of the granule is covered with pores having a diameter of mainly 1 ÷ 20 µm.

The internal structure of the material is shown in Fig. 6. It should be noted that the internal foam structure and cellular structure is uniform even in fairly thin internal structural elements. Besides, the above-mentioned pores can be observed not only on the external surface of a granule, but also on all the internal surfaces.

As a result of the available cellular uniform structure, foam silicate granules provide the strength sufficient for the stability of the aggregate when forming the raw mass. The formation of the foam silicate granule cellular structure is possible only in the case of the thermoplastic state of the material in a sufficiently wide temperature range, typical for glasses.

In the finished ceramic material, it is not possible, however, to observe the cellular structure of the granules. In fact, in Fig. 4, the cell sizes correspond to the sizes of the foam silicate granules used as (a)

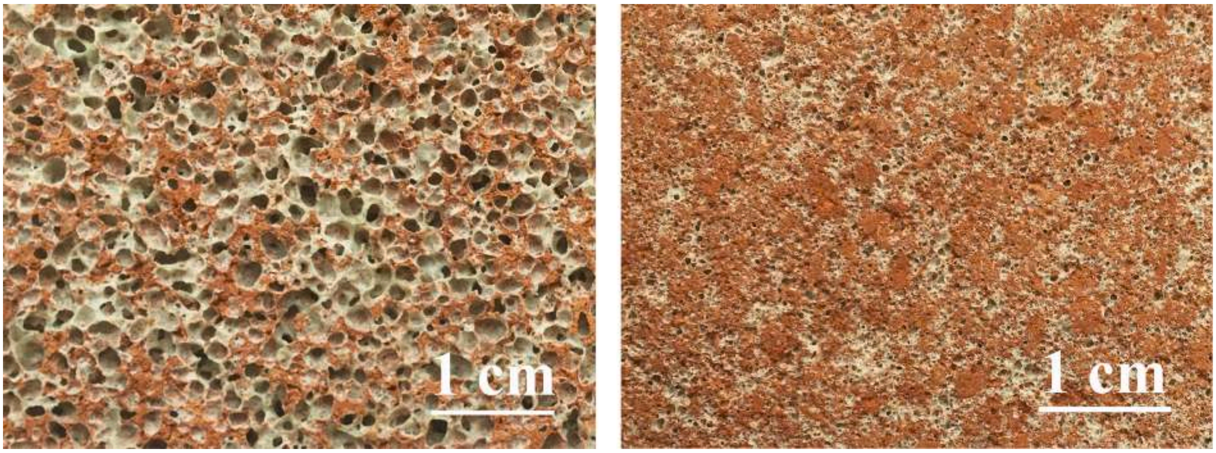

Fig. 4. Typical structure of the cellular material obtained from clay and an aggregate in the form of foam silicate granules: the granule fraction 1,4 ÷ 2,0 mm (left); the granule fraction 0,425 ÷ 0,85 mm (right).

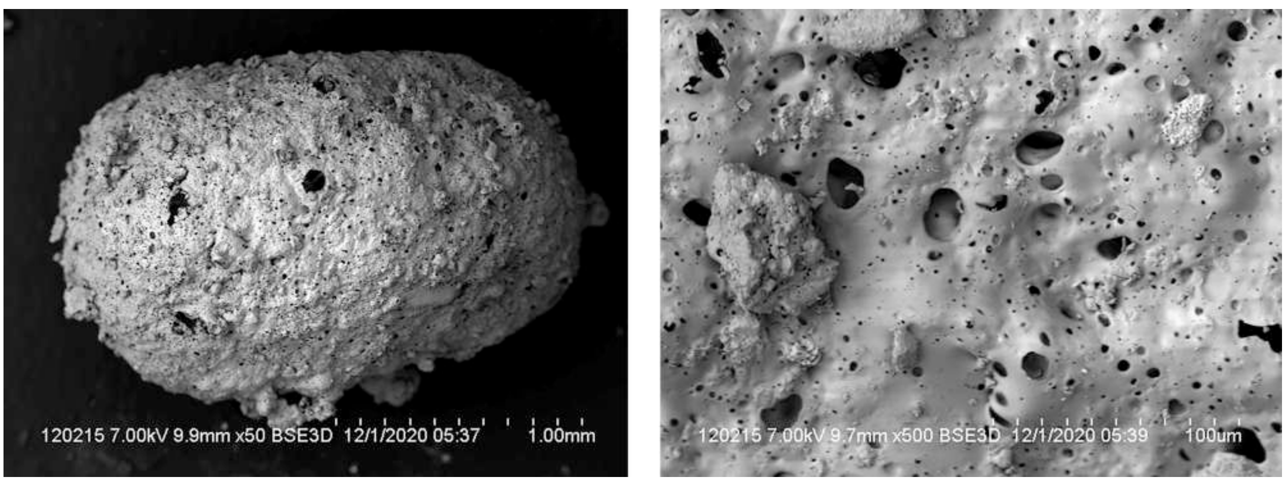

Fig. 5. SEM images of a foamed silicate granule: a whole granule (left); the surface of a granule (right).

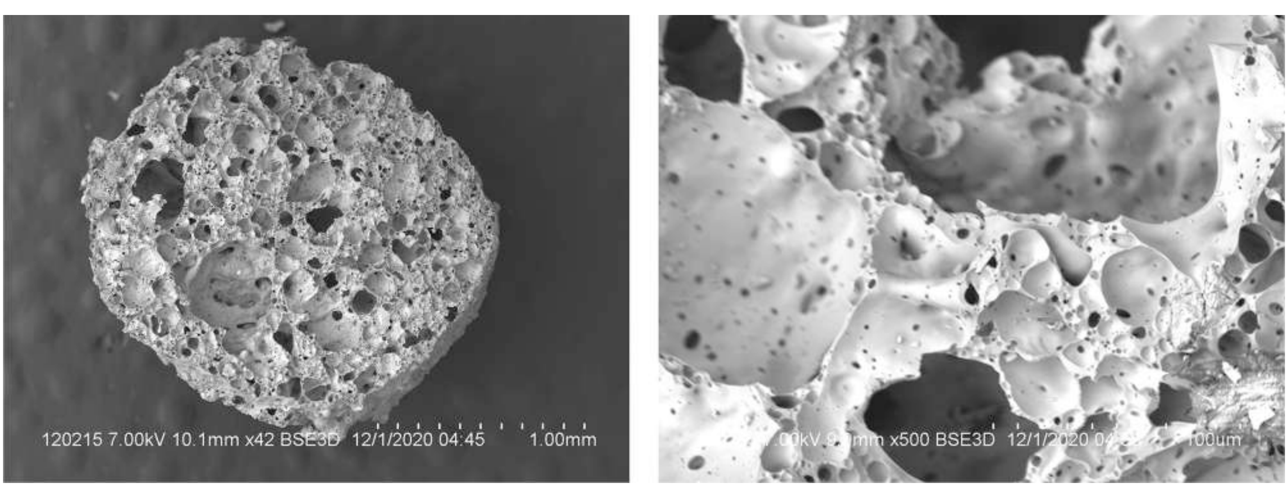

Fig. 6. SEM images of a crushed foamed silicate granule.

filler. At the same time, the granules themselves with a characteristic cellular structure and a cell size of 10–100 μm, as in Fig. 6, are absent. One can assume that the granules of the foam silicate aggregate melted and the foam coalesced in the process of the clay matrix firing. As a result, formed inside the ceramic matrix were the cells covered from the inside with a layer of silicate glass derived from the foam silicate.

The resulting structure is close to syntactic foams. Syntactic composite materials are usually obtained by introducing hollow spheres into three types of matrices [33]: polymer [34], metal [35], or ceramic [36]. In addition to monocellular spheres, poly-cellular aggregate granules can also be used for the production of synthetic composite materials. In this case, the structure of the foam silicate filler remains unchanged at low temperatures of preparation of the syntactic material, for example, when the stir casting method of mixing aluminum alloy with the expanded glass filler is used [37]. The authors [38] show the identity of the macrostructure of the aluminum alloy syntactic foam with the filler made from expanded glass particles and the aluminum alloy foam obtained by dissolving salt granules poured in the same aluminum melt. If in the first case the internal structure of the poly-cellular aggregate remains unchanged, in the second case the voids in place of the dissolved salt granules repeat their shape and location at the moment of the aluminum alloy solidification.

In the composite materials obtained, we observe the presence and at the same time the development of the syntactic foams technology. On the one hand, the filler granules disappeared, but on the other hand, they were not washed out of the matrix, as the salt in the above case, and the filler material remained on the walls of the formed cells. The internal structure of the aggregate was destroyed, and that may be due to the high-temperature coalescence of the foam structure.

4.1.2. *High-temperature coalescence of foamed silicate*

In general, foams as macroheterogenic systems formed by liquid and gas inevitably collapse over time in accordance with the known patterns [39]. Coalescence implies the rupture of films between drops/bubbles and involves contributions from hydrodynamics, surface rheology, surface forces, and thermal fluctuations [40]. Silicate foam is no exception, and when at high temperatures the transition to the molten state occurs, the viscosity of the melt decreases and the silicate foam breaks down like any other foam. Despite the experimental difficulties of studying the process, using evolved gas analysis and combining the temperature-dependent melt viscosity with x-ray data, we describe the evolution of foam structure during the foam growth and subsequent collapse [41]. To study the behavior of silicate foam obtained from rice husks ash, the appearance of the material obtained from a billet of the same mass at different temperatures was considered at the first stage.

Examples of the silicate material samples obtained from rice husks ash by heat treatment for 30 min at various temperatures are shown in Fig. 7.

It is obvious that the dehydration of hydrosilicate at temperatures of 200 ÷ 550 °C leads to an increase in the size of the samples due to the formation of a foamy structure. However, at temperatures above 800 °C, the viscosity of the melt decreases, the films are destroyed under the influence of the surface tension of the melt, and the foam begins to coalesce. The process externally looks like sagging of the foam, decreasing in its volume.

The destruction of the silicate foam structure at temperatures above 800 °C was confirmed by the thermogravimetry data synchronized with the mass spectroscopy of gaseous products. Instrumental observation of the silicate foam coalescence process at high temperatures is difficult. However, it is possible to record the destruction of individual bubbles in the case of the reaction of the gas medium of the bubbles with the surrounding atmosphere.

It was previously shown [42] that in the case of the carbon presence in the raw mass, preparation of the foam silicate materials by the hydrate mechanism is accompanied by the formation of carbon (II) oxide and hydrogen:

$$C + H_2O \rightarrow H_2 + CO \quad (1)$$

The gases formed as a result of the reaction foam the composition being in the pyroplastic state. As a result, some of the gases are trapped inside the silicate cells. Foam glass is usually not heated above the temperature range of its foaming, but with a further increase in temperature, the cells are destroyed and the released gases are oxidized by air oxygen:

$$H_2 + O_2 \rightarrow H_2O \quad (2)$$

$$CO + O_2 \rightarrow CO_2 \quad (3)$$

In this case, it is difficult to record the formation of water molecules against the general high background of water vapor. But the oxidation reaction of carbon monoxide (II) to carbon monoxide (IV) is fixed by analyzing the resulting carbon monoxide (IV). Besides, the oxidation reaction of carbon monoxide (II) to carbon monoxide (IV) is exothermic and accompanied by a thermal effect on the DSC curve. Therefore, during the high-temperature destruction of the silicate foam, one can observe a synchronous behavior of the mass spectroscopy current curve $m/z = 44$ and the DSC thermal effect curve (Fig. 8). In the Figure, gray arrows show correspondence of the three strongest thermal effects to the corresponding peaks of the ion currents. A careful comparison of the DSC and ion current curves allows us to conclude that not only the marked three peaks have a corresponding response to the second curve, but also all the visible peaks. This effect is connected with the destruction of the silicate cells and silicate bubbles, the release and oxidation of carbon (II) oxide. The larger is the collapsing bubble, the more carbon (II) oxide is released into the carrier gas stream, and the greater effects are observed on the DSC and MS curves. The moments of collapsing definite silicate bubbles are unpredictable and chaotic, but sooner or later each silicate bubble collapses with increasing temperature, and such destruction is necessarily accompanied by a synchronous effect on the DSC and MS curves.

It should be particularly noted that the effect of synchronous behavior of the DSC curves and the ion current $m/z = 44$ is observed for all the studied samples at temperatures above 800 °C, but the number and intensity of the peaks in all the made experiments were different, that corresponds to the idea of the random nature of the appearance and destruction of silicate foam cells.

In addition to the observed effect of the silicate foam destruction at temperatures

above 800 °C, thermogravimetric analysis allows us to observe the process of removing water from the hydrosilicate throughout the studied temperature range. At the initial stage, the process is endothermic with the extremum at 152 °C and is connected with evaporation of mainly free water. Two exothermic effects with the maxima at 434 °C and 616 °C are further recorded on the DSC curve. Coincidence of the exothermic effects with the maxima on the ion current curve $m/z = 44$, that is, with the maxima of forming carbon dioxide, indicates the processes of oxidation of the carbon contained in the ash of rice husks. The presence of two maxima is probably associated with the oxidation of carbon by water vapor (steam) and air oxygen.

One can state that the silicate foam is obtained from hydrosilicate at

Fig. 7. Results of the silicate material heat treatment at various temperatures (from left to right): Original silicate; 250 °C; 550 °C; 920 °C.

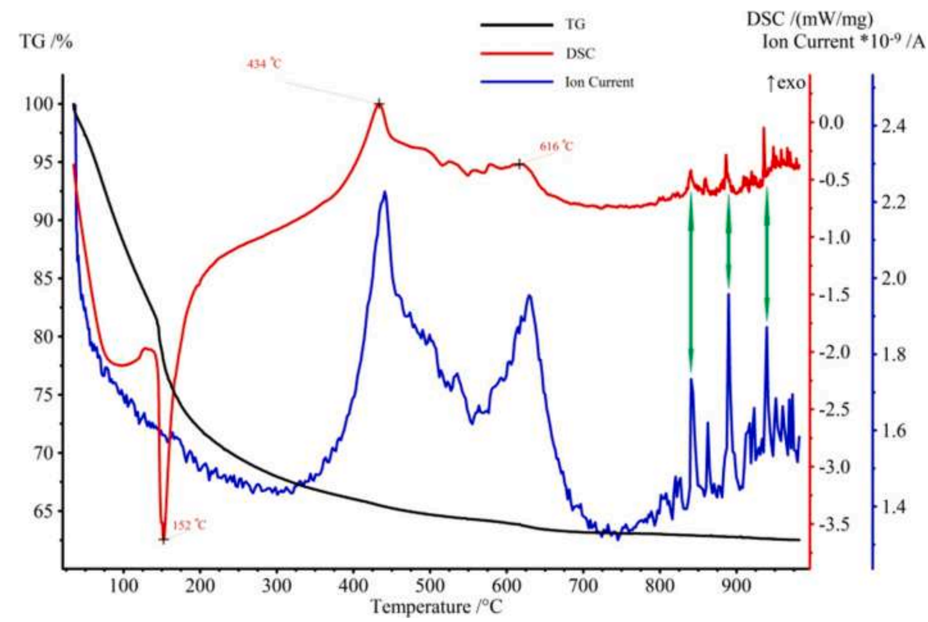

Fig. 8. Thermogravimetric analysis synchronous with the mass spectroscopy ($m/z = 44$) of the raw silicate material.

temperatures of 200 ÷ 550 °C and the foam is destroyed at temperatures above 800 °C.

4.1.3. High temperature collapse of the foamed silicate granules

To create cells in a ceramic matrix, it was proposed to use granules of the foam silicate material, so the behavior of the finished foam silicate granules synthesized at 550 °C to the sintering temperatures of ceramics was studied by the method of thermogravimetry. The results are shown in Fig. 9.

Once again one can observe the correspondence of DSC and ion current peaks. The most intensive four pair of peaks are marked with green arrows. Granules of the foam silicate material contain a significant amount of carbon, which was transferred to their composition from the original rice ash and could not be oxidized during the preparation of the granules at a relatively low temperature. The black color of the initial granules presented above also indicates that they contain a significant amount of carbon. Part of the carbon from the silicate material or carbon (II) oxide from the open cells is oxidized by air oxygen, which is recorded as an exothermic effect with the maximum at 445 °C and the synchronous maximum with it on the ion current curve $m/z = 44$.

Above the temperature of 800 °C, as in the case of the raw hydrosilicate, an effect of the appearance of small and narrow peaks is observed, chaotic in intensity and time, but synchronous for the ion current and DSC curves. One can state that the effect of collapsing the bubbles/cells of the silicate foam is observed not only in the continuous process of nucleation and collapse of the foam cells, but also in the case of high-temperature destruction of the pre-produced foam silicate. Therefore, during the heat treatment of a composite preform made of granules of the foam silicate material, at the sintering temperature of ceramics, the cellular structure of the granules collapses and voids form at the locations of the granules. This effect is used to produce a cellular ceramic material.

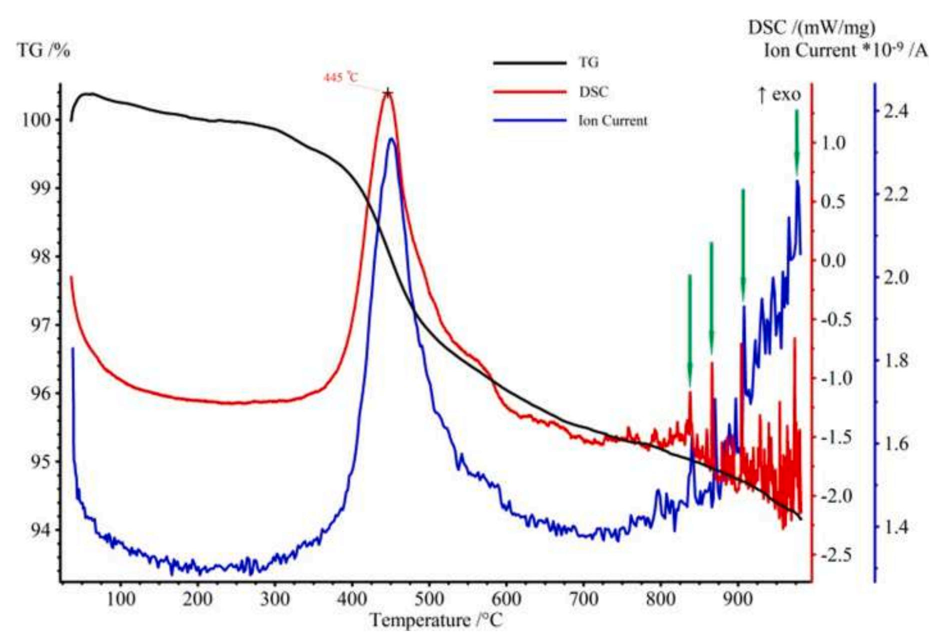

Fig. 9. Thermogravimetric analysis synchronous with the mass spectroscopy ($m/z = 44$) of foam silicate aggregate granules.

4.2. Transformation of cellular ceramics

Acceptable concentration limits for the production of cellular ceramics were determined by manufacturing samples with different ratios of aggregate and matrix materials. It was found out that cellular ceramics is formed at low concentrations of the aggregate in the matrix material. When the proportion of foam silicate granules in the initial composition is more than 55 ÷ 60 wt%, there is a gradual inversion of the dispersion medium: the ceramic matrix of clay is replaced by a glassy matrix of sodium silicate.

To prepare samples with a different ratio of foam silicate granules and clay, the fraction of foam silicate granules of 0.16–2.0 mm was used. In the field of composite materials with a clay dispersion medium (Fig. 10) and in the transition area (Fig. 11), the products do not change shape during the firing process and are identical in appearance to ordinary clinker bricks. The residual carbon of rice husks ash, the presence of which is observed in foam silicate granules, is completely oxidized during the firing of composite bricks.

The inversion of the dispersion medium leads to significant changes in the physical and chemical properties of the composite material. At firing temperatures, in the region of the foam silicate aggregate high concentrations, sodium silicate passes into a thermoplastic state and is not able to provide structural rigidity. As a result, the preforms lose their shape in the process of heat treatment and cannot be fired according to the standard procedure for ceramics. In this case, the samples in their appearance obviously resemble the foam-glass material, which, in fact, they are, as shown in Fig. 12. In this case, the clay particles are dispersed in the glass melt and the behavior of the composition in the process of heat treatment becomes identical to the behavior of foamed silicate, as described above for the sodium foam silicate.

The use of different foam silicate aggregate fractions allows us to shift the boundary of the dispersion medium inversion. Thus, the use of narrow fractions of the aggregate makes it possible to obtain cellular ceramic materials to higher concentrations of the aggregate in the initial composition, which may be due to a lower proportion of the volume filling with the monodisperse aggregate. Only the clay matrix, which has a significantly higher softening temperature than the material of the foam silicate aggregate, can be a basis for maintaining a rigid cellular structure in the process of heat treatment. Therefore, compositions with the ceramic dispersion medium and low content of granular foam silicate aggregate in the initial composition are of interest for practical use. It can be assumed that in this case, the foam silicate granules coalesce and the resulting melt additionally binds the clay matrix. Such mechanism of forming cellular lightweight ceramics is confirmed by the electron microscopy data.

4.2.1. Microstructure

A section of the cellular ceramic material is shown in Fig. 13. The material of the initial foam silicate granules has melted in the process of preparation and formed glassy crusts on the inner surface of the cells. A part of the cells contact each other, forming a continuous frame inside the resulting composite material. This circumstance significantly distinguishes the material from the ordinary syntactic composite in which the hollow spheres cannot touch each other in order to avoid destruction during its manufacture. Therefore, it is impossible, for example, to have the filler content of more than 20 wt%, which corresponds to 56 vol%, for the synthetic composite material based on a cement matrix and hollow glass microspheres [43]. As a result, it is impossible to synthesize composite material with the density below 1390 kg /m^3.

In the case described, the resulting composite material consists of an aluminosilicate phase in the form of baked clay and a glass phase formed from the foam silicate of the filler granules with the filler fraction in the initial mixture of up to 55 wt%. Scanning electron microscopy data confirm this two-phase structure of the material. Fig. 14 shows a micrograph of the cellular material cross-section obtained by the method of scanning electron microscopy. In the left part of the micrograph there is a section of the glass phase, and in the right part – of the aluminosilicate phase. The glass phase is the continuous material melted during the preparation process, and the aluminosilicate phase consists of the particles, mainly less than 50 μm, which is typical for clay.

Taking into account the microscopy data, one can assume that the resulting composite material will have higher strength than the materials similar in density, but having no internal cellular framework made from the glassy material.

4.2.2. X-ray analysis

At all the stages of cellular ceramics preparation, the crystal phases were identified by the X-ray diffraction (XRD). The phase composition of the analyzed sample was determined using the database "ICDD PDF-4 + 2018″. The results of studying the raw materials, clay and foam silicate granules, are shown in Fig. 15.

The untreated X-ray image of the foam silicate aggregate sample shows a high background level, which indicates the presence of a high proportion of amorphous matter in the sample. The sample also contains a single crystalline phase in the form of quartz.

Raw clay is characterized by high intensity of the quartz peaks, which makes it difficult to decipher the weakly expressed peaks of silicate compounds. In addition to the mentioned quartz, sodium calcium aluminum silicate Anorthite $(Ca,Na)(Si, Al)_4O_8$ can be reliably identified. The remaining crystal impurities form insignificant signal excesses relative to the background and cannot be reliably determined.

In the case of the fire materials (Fig. 16), besides the quartz and anorthite signals, the formation of cristobalite is observed. Moreover, while for a standard brick made of fire clay the signal looks weak, for the cellular material the signal becomes comparable to the characteristic peaks of quartz.

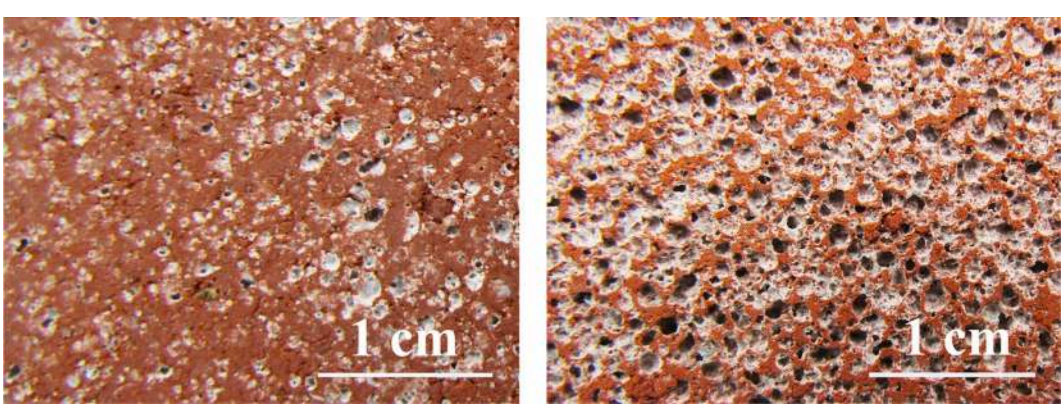

Fig. 10. The outer surface (left) and the section (right) of the composite material with the clay dispersion medium, the content of foam-ceramic granules in the initial composition is 12.5 wt%

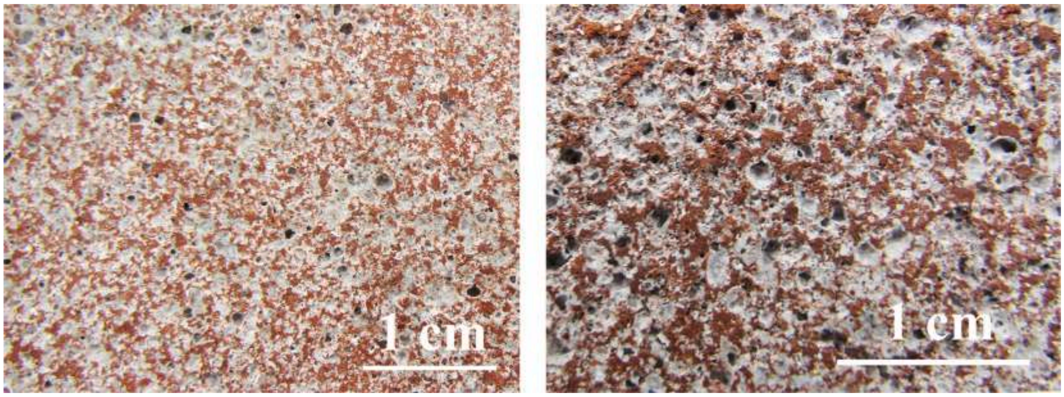

Fig 11. The outer surface (left) and cross-section (right) of the composite material with the transition dispersion medium, the content of foam-ceramic granules in the initial composition is 33.3 wt%

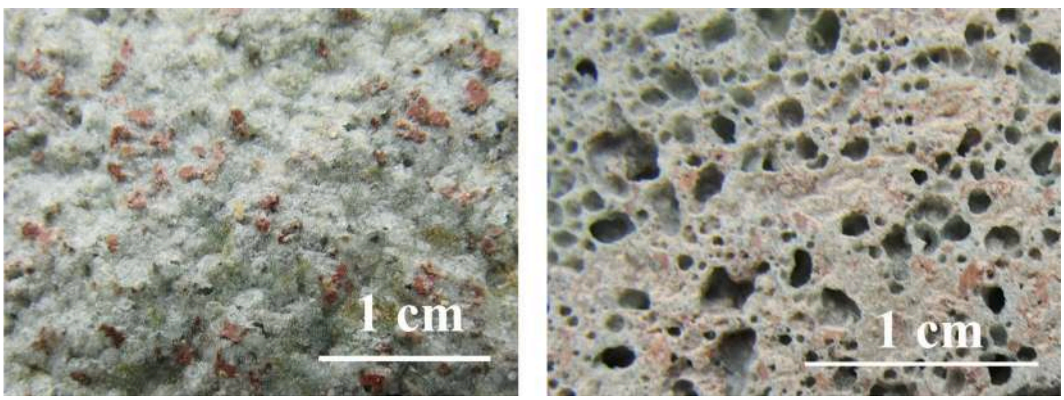

Fig.12. The outer surface (left) and the cross-section (right) of the composite material with the glassy dispersion medium; the content of foam-ceramic granules in the initial composition is 57.1 wt%

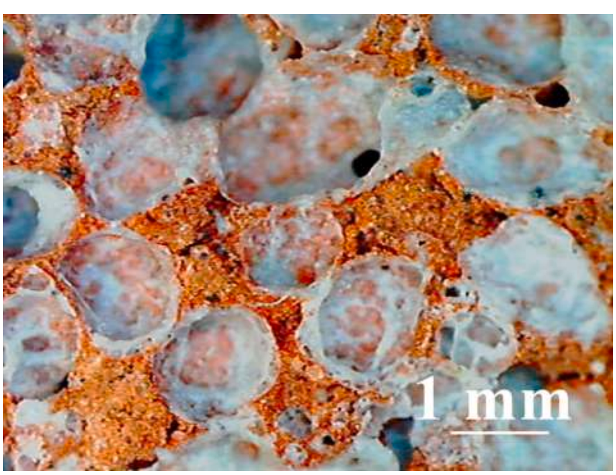

Fig. 13. Cross-section of the cellular ceramic material, optical microscopy.

Fig. 14. Cross-section of the cellular ceramic material, scanning electron microscopy.

Another feature of the X-ray image of a cellular sample is an increase in the general background, which is characteristic of the glass phase presence.

4.3. Characteristics of the cellular ceramics

Taking into account the structure of the resulting ceramic material, determined by the cellular frame made of the composite ceramics, it can be assumed that the main consumer properties of the material, such as density, strength and thermal conductivity, will be determined by the proportion in the cellular frame in material and by the fractional composition of the initial foam silicate granules.

4.3.1. Density

Dependence of the cellular ceramics density on the amount of the foam silicate granular aggregate in the initial mixture was determined at a fraction of 0.16–2.0 mm. The results are shown in Fig. 17.

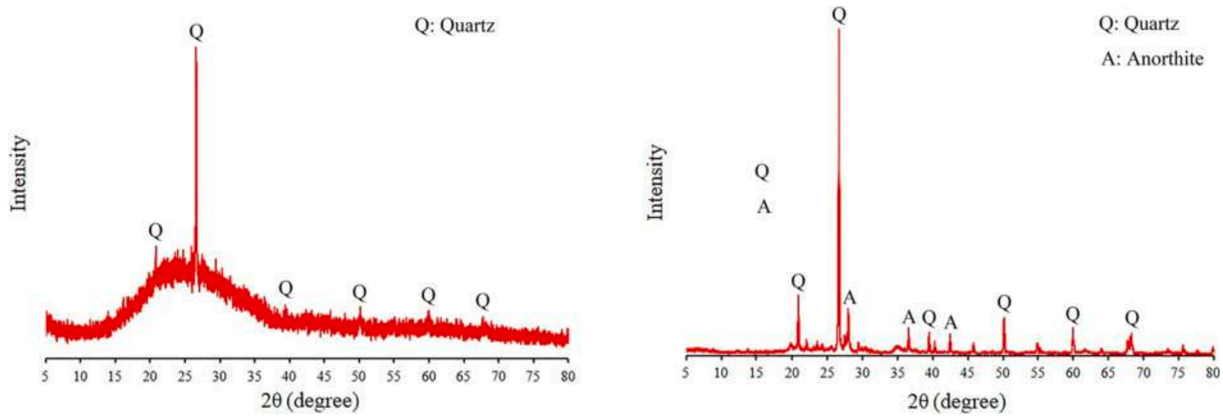

Fig. 15. XRD patterns of the raw materials: foamed silicate filler (left); raw clay (right).

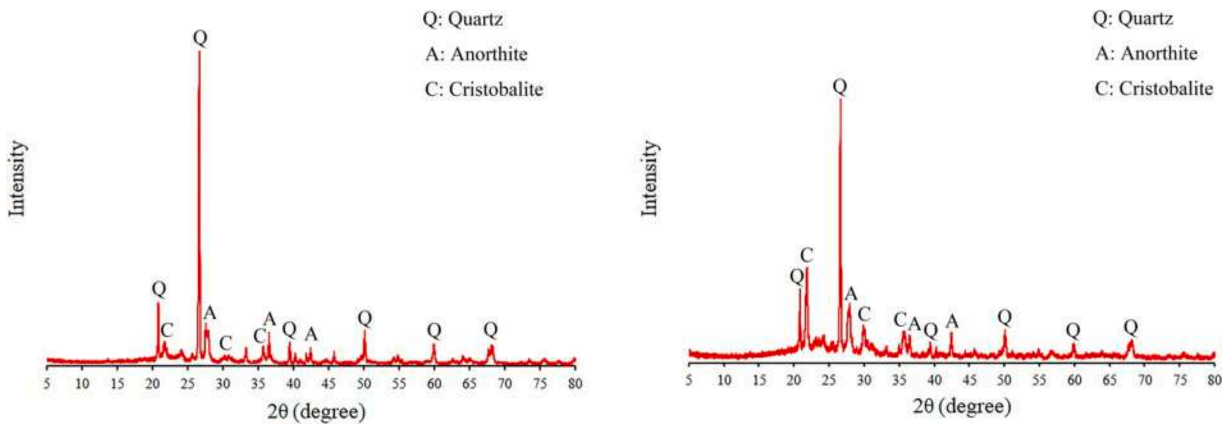

Fig. 16. XRD patterns of the clinker bricks: standard clay brick (left); cellular brick (right).

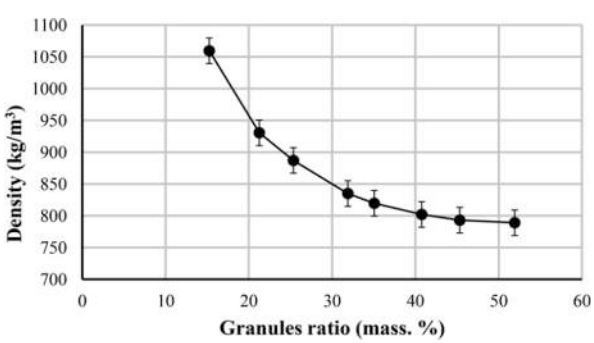

Fig. 17. Dependence of the resulting cellular ceramics density on the amount of the granular foam silicate material in the initial mixture with clay.

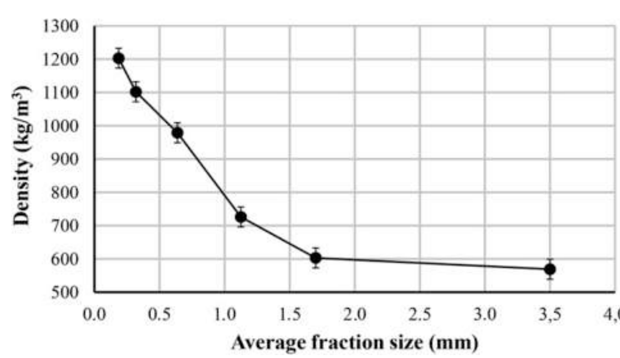

Fig. 18. Dependence of the resulting cellular ceramics density on the fractional composition of the granulated foam silicate material in the initial mixture with clay.

It was shown above that the bulk density of the granulated foam silicate significantly depends on the size of the granules. The dependence of the density of the resulting cellular material on the size of the granules also remains for the cellular ceramic material obtained from these granules. To reveal this pattern, samples of the cellular ceramics with the same content of granules in the original composition of 49.4 wt % and various fractions of the aggregate were made. This ratio of components in the samples was chosen due to the technical feasibility of dosing the initial components in an equal mass ratio and taking into account the moisture content of the initial clay powder. Based on the results obtained (Fig. 18), one can conclude that the fractional composition has a significant influence on the density of the resulting cellular material.

4.3.2. Thermal conductivity

Lightweight materials usually have good thermal insulation properties due to the significant amount of air inclusions in their volume. The silicate cellular materials of low density are characterized by the linear dependence of their thermal conductivity on density [44]. Therefore, it is of interest to consider thermal insulation properties of the resulting cellular ceramics as a material with low density. For this purpose, the thermal conductivity coefficient was determined for all the cellular ceramics samples described above. The corresponding dependence of the thermal conductivity coefficient on the density of the samples is shown in Fig. 19.

Thus, the resulting cellular ceramics has thermal insulation

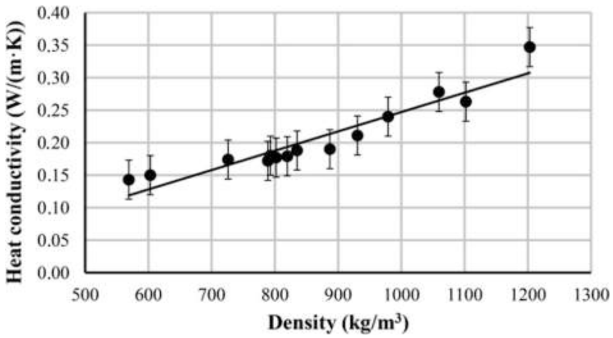

Fig. 19. The dependence of the thermal conductivity coefficient of the resulting cellular ceramics on the density.

properties comparable to aerated concrete or ceramic thermoblocks, which, combined with the low density, makes the material promising for construction. However, the possibility of using cellular ceramics in building structures will be determined by its strength characteristics.

4.3.3. Compression test

It is found that the increase in the proportion of the granulated aggregate in the composition while using a wide fraction of 0.16–2.0 mm leads to a uniform increase in strength, as it can be concluded from the relationship shown in Fig. 20. This fact is difficult to explain considering the aggregate as an inert material. The seemingly anomalous dependence is explained by the appearance in the composite material of the cellular structure made of glass formed from the foam silicate during coalescence of the latter. The spherical hollows that occur at the locations of the initial granules are covered from the inside with a layer of clay with the glass melt from the foam silicate absorbed into it. Therefore, with an increase in the proportion of the foam silicate aggregate in the initial composition, the connectivity of the formed spheres with each other in the resulting material increases, and the strength of the composition increases, accordingly. In the observed case, the structural elements of the material that determine the strength of the structure are replaced, and instead of solid-phase sintering of clay aluminosilicate particles, a spatial packing of spheres bonded by liquid-phase sintering occurs.

The fact of the fundamental influence of emerging cellular structure on the strength of the resulting material is confirmed by the study of the dependence of the obtained material strength on the size of granules fraction in the original composition. Thus, Fig. 21 shows the dependence of the compressive strength of the cellular material on the average size of the granules used in the initial composition. The samples of cellular ceramics with the same content of granulated foam silicate of different fractions in initial mixture were used the same as described above.

Reducing the size of the granules leads to obtaining a fine-grained

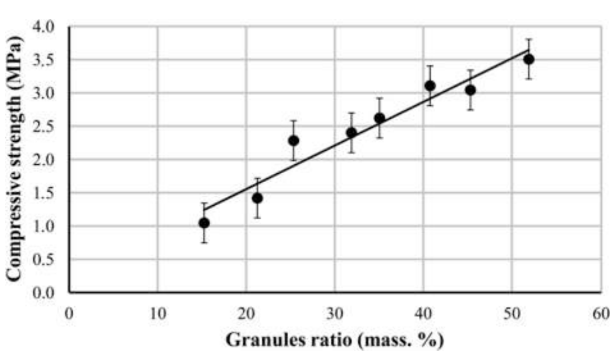

Fig. 20. Dependence of the compressive strength of the resulting cellular ceramics on the proportion of the foam silicate aggregate in the initial composition.

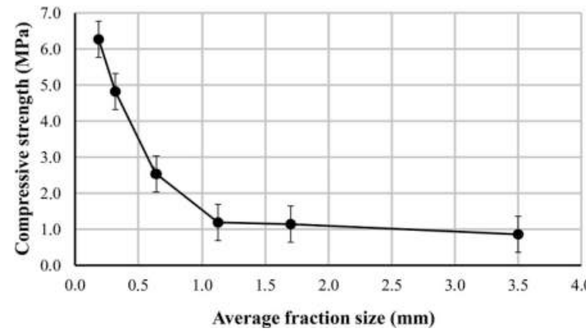

Fig. 21. Dependence of the compressive strength of the resulting cellular ceramics on the fractional composition of the granulated foam silicate material in the initial mixture with clay.

material with a higher strength. The effect is associated with an increase in specific surface area of the filler granules and, accordingly, an increase in the specific contact area between the granules in the original composition and areas in the formed material.

For the production of cellular ceramics, it is preferable to use the granulated aggregate of fractions below 1.2 mm. It is possible to crush foam silicate granules and to use the resulted product as a filler for clay bricks but the quality of such bricks would be low because of filling of opened pores on the granules surface with glue.

4.4. General assessment of rice husks ash suitability for lightweight fired bricks production

The utilization of rice husks is a real problem because of high content of silica in material complicates natural consummation as “fertilizer” and also burning. However bioenergy from burning of plants wastes including rice husks in addition to solar, hydrothermal and wind energy is considered will play an important role to enable sustainable development [45]. Biomass needs to fulfill the following criteria as a sustainable resource of energy: it should be readily available; arable land for food resources should not be affected by biomass for energy generation and it should produce zero waste and have no negative impact on the environment [46]. In this regard, rice husk as by-product in rice production can fulfill these criteria but the main task is appeared transformation of produced rice husks ash into ecological friendly product. So using of rice husk ash in brick industry is possible to consider environmentally friendly.

Using the filler with fractions of 0.5–0.8 mm for the production of cellular ceramics, it is possible to produce the cellular ceramics with the density of 850–1000 kg/m^3, the strength of 2.0–3.5 MPa, and the thermal conductivity coefficient of 0.2–0.3 W/(m * K). The material meets the basic requirements of the national standard [47] and is classified as a high-efficiency product in terms of its thermal characteristics.

The question about economical efficiently depends on the specific economic conditions in various countries and even in regions. In common case the high level of taxes on wastes land filling and the extraction of clay as natural mineral resource leads to increasing of the economic efficiency of replacing clay into filler on the base of renewable resources as rice husk ash and vice versa. Undoubtedly, transport costs make it economically feasible using of the described technology in the areas of rice production.

The ratio of foam silicate filler can be reached up to approximately half of mass. Taking into account that production of one kilogram of foam silicate filler needs about 0.8 kg of rice husks ash one can conclude that production of one kilogram of cellular ceramic according the proposed technology leads to utilization of 0.4 kg of rice husk ash.

Ceramic bricks are known as one of the most popular construction material. Therefore, we hope that the significant manufacture of ceramic bricks in the world and the possibility of using high amount of rice husk ash in proposed process will solve the problem of this waste recycling.

5. Conclusions

From the point of view of sustainable development, the feasibility of using secondary resources, in particular silica from rice husks ash has been known for a long time and is not in doubt. Various solutions are also known for the use of silica as an additive and filler in the production of various ceramic materials. However, in most technical solutions, rice husks, like other organic waste, is added to the raw clay to increase the porosity of the product and does not interact with the ceramics formed in the firing process. The proposed technical solution differs from the known solutions in a fundamentally different view of the recycled material. Rice husks ash is considered as a unique type of raw material that has its own properties and these properties are what the technological solution is based on. As a result, the ash of rice husks allows us to create a rigid cellular structure inside the ceramic material and obtain the products that are not only acceptable in the existing brick market, but also have the advantage of low density and good thermal insulation properties.

1. The results of the study showed that the foam silicate granulated aggregate made from the rice husks ash can be used for the production of lightweight ceramic bricks.
2. In the process of the raw bricks firing, the foam silicate granules melt and collapse to form hollow cells at the locations of the aggregate granules. During the firing of bricks, the silicate material of the aggregate forms a coating on the inner surface of the cells, and the set of cells reinforced with such a coating forms a continuous three-dimensional frame inside a brick. As a result, the resulting composite brick has a strength that exceeds that of materials with the similar density. Cellular ceramic lightweight bricks can be used in construction in accordance with the national standard of Russia, and at the same time such bricks have thermal insulation properties at the level of ceramic thermo blocks and aerated concrete.
3. It is established that the increase in the proportion of the foam silicate filler in the raw composition leads to an increase in the strength of the obtained porous material and is limited by the conditions of the dispersion medium inversion from an aluminosilicate one of the raw clay material to a silicate one of the foam silicate filler material. Therefore, the proportion of the granulated foam silicate aggregate in the raw material composition should not exceed 55–60 wt%. For the production of cellular ceramics, it is preferable to use the granulated aggregate of fractions below 1.2 mm.
4. The proposed technology will solve the problem of rice husks utilization and provide the market with lightweight and environment-friendly cellular ceramic bricks having additional thermal insulation properties.

The development of the lightweight and environment-friendly cellular ceramic bricks technology will in the future permit to use a renewable resource and to meet the requirements of the concept of sustainable development and the transition to green building materials and technologies.

CRediT authorship contribution statement

Aleksandr Ketov: Conceptualization, Investigation, Writing - review & editing, Writing - original draft. **Larisa Rudakova:** Software, Data curation. **Iakov Vaisman:** Validation, Formal analysis. **Iurii Ketov:** Visualization. **Viktors Haritonovs:** Investigation, Supervision. **Genadijs Sahmenko:** Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgment

The authors would like to thank specialists Vladilen Avtukhovich and Konstantin Varaksin from the Limited Liability Company “Ceramic brick’s production of Zakamenoi” of the Perm Region (Russia) for raw clay and testing of the technology. The authors would like to thank Vladimir Korotaev, Andrei Baiankin and Natalia Rossomagina for their assistance with this project.

References

[1] B. Singh, Rice husk ash, Waste and Supplementary Cementitious Materials in Concrete (2018) 417–460, https://doi.org/10.1016/b978-0-08-102156-9.00013-4.
[2] V. Jittin, A. Bahurudeen, S.D. Ajinkya, Utilisation of rice husk ash for cleaner production of different construction products, J. Cleaner Prod. 263 (2020), 121578, https://doi.org/10.1016/j.jclepro.2020.121578.
[3] R. Pode, Potential applications of rice husk ash waste from rice husk biomass power plant, Renew. Sustain. Energy Rev. 53 (2016) 1468–1485, https://doi.org/10.1016/j.rser.2015.09.051.
[4] C. S. Rodrigues, K. Ghavami, K., P. Stroeven, Rice Husk Ash as a Supplementary Raw Material for the Production of Cellulose–Cement Composites with Improved Performance, Waste and Biomass Valorization. 1(2) (2010) 241–249, 10.1007/s12649-010-9017-7.
[5] A. Hajimohammadi, J.S.J. van Deventer, Solid Reactant-Based Geopolymers from Rice Hull Ash and Sodium Aluminate, Waste Biomass Valorization 8 (6) (2016) 2131–2140, https://doi.org/10.1007/s12649-016-9735-6.
[6] H.K. Tchakouté, C.H. Rüscher, S. Kong, E. Kamseu, C. Leonelli, Thermal Behavior of Metakaolin-Based Geopolymer Cements Using Sodium Waterglass from Rice Husk Ash and Waste Glass as Alternative Activators, Waste Biomass Valorization 8 (3) (2016) 573–584, https://doi.org/10.1007/s12649-016-9653-7.
[7] Ö. Başgöz, Ö. Güler, The unusually formation of porous silica nano-stalactite structure by high temperature heat treatment of SiO_2 aerogel synthesized from rice hull, Ceram. Int. 46 (1) (2020) 370–380, https://doi.org/10.1016/j.ceramint.2019.08.271.
[8] F. Bondioli, L. Barbieri, A.M. Ferrari, T. Manfredini, Characterization of Rice Husk Ash and Its Recycling as Quartz Substitute for the Production of Ceramic Glazes, J. Am. Ceram. Soc. 93 (1) (2010) 121–126, https://doi.org/10.1111/j.1551-2916.2009.03337.x.
[9] S.K.S. Hossain, R. Pyare, P.K. Roy, Synthesis of in-situ mullite foam using waste rice husk ash derived sol by slip-casting route, Ceramics International. 46 (8A), 10871-10878, 10.1016/j.ceramint.2020.01.099.
[10] P. Chakartnarodom, P. Ineure, Foam Glass Development Using Glass Cullet and Fly Ash or Rice Husk Ash as the Raw Materials, Key Eng. Mater. 608 (2014) 73–78, https://doi.org/10.4028/www.scientific.net/KEM.608.73.
[11] S.S. Hossain, L. Mathur, P.K. Roy, Rice husk/rice husk ash as an alternative source of silica in ceramics: A review, J. Asian Ceram. Soc. 6 (4) (2018), https://doi.org/10.1080/21870764.2018.1539210.
[12] D. Eliche-Quesada, M.A. Felipe-Sesé, J.A. López-Pérez, A. Infantes-Molina, Characterization and evaluation of rice husk ash and wood ash in sustainable clay matrix bricks, Ceram. Int. 43 (1) (2017) 463–475, https://doi.org/10.1016/j.ceramint.2016.09.181.
[13] S. Demis, J.G. Tapali, V.G. Papadakis, Plant Design and Economics of Rice Husk Ash Exploitation as a Pozzolanic Material, Waste Biomass Valorization 6 (5) (2015) 843–853, https://doi.org/10.1007/s12649-015-9412-1.
[14] S.M.S. Kazmi, S. Abbas, M.A. Saleem, M.J. Munir, A. Khitab, Manufacturing of sustainable clay bricks: Utilization of waste sugarcane bagasse and rice husk ashes, Constr. Build. Mater. 120 (2016) 29–41, https://doi.org/10.1016/j.conbuildmat.2016.05.084.
[15] G. Cultrone, I. Aurrekoetxea, C. Casado, A. Arizzi, Sawdust recycling in the production of lightweight bricks: How the amount of additive and the firing temperature influence the physical properties of the bricks, Constr. Build. Mater. 235 (2020), 117436, https://doi.org/10.1016/j.conbuildmat.2019.117436.
[16] S. Ozturk, M. Sutcu, E. Erdogmus, O. Gencel, Influence of tea waste concentration in the physical, mechanical and thermal properties of brick clay mixtures, Constr. Build. Mater. 217 (2019) 592–599, https://doi.org/10.1016/j.conbuildmat.2019.05.114.
[17] M.D. La Rubia-García, Á. Yebra-Rodríguez, D. Eliche-Quesada, F.A. Corpas-Iglesias, A. López-Galindo, Assessment of olive mill solid residue (pomace) as an additive in lightweight brick production, Constr. Build. Mater. 36 (2012) 495–500, https://doi.org/10.1016/j.conbuildmat.2012.06.009.
[18] L. Pérez-Villarejo, D. Eliche-Quesada, J. Martín-Pascual, M. Martín-Morales, M. Zamorano, Comparative study of the use of different biomass from olive grove in the manufacture of sustainable ceramic lightweight bricks, Constr. Build. Mater. 231 (2020), 117103, https://doi.org/10.1016/j.conbuildmat.2019.117103.
[19] H.-Y. Liu, H.-S. Wu, C.-P. Chou, Study on engineering and thermal properties of environment-friendly lightweight brick made from Kinmen oyster shells & sorghum waste, Constr. Build. Mater. 246 (2020), 118367, https://doi.org/10.1016/j.conbuildmat.2020.118367.

[20] O.T. Maza-Ignacio, V.G. Jiménez-Quero, J. Guerrero-Paz, P. Montes-García, Recycling untreated sugarcane bagasse ash and industrial wastes for the preparation of resistant, lightweight and ecological fired bricks, Constr. Build. Mater. 234 (2020) 117314, https://doi.org/10.1016/j.conbuildmat.2019.117314.
[21] F. Andreola, I. Lancellotti, T. Manfredini, F. Bondioli, L. Barbieri, Rice Husk Ash (RHA) Recycling in Brick Manufacture: Effects on Physical and Microstructural Properties, Waste Biomass Valorization (2018), https://doi.org/10.1007/s12649-018-0343-5.
[22] C.-L. Hwang, T.-P. Huynh, Investigation into the use of unground rice husk ash to produce eco-friendly construction bricks, Constr. Build. Mater. 93 (2015) 335–341, https://doi.org/10.1016/j.conbuildmat.2015.04.061.
[23] J.M. Moreno-Maroto, M. Uceda-Rodríguez, C.J. Cobo-Ceacero, T. Cotes-Palomino, C. Martínez-García, J. Alonso-Azcárate, Studying the feasibility of a selection of Southern European ceramic clays for the production of lightweight aggregates, Constr. Build. Mater. 237 (2020), 117583, https://doi.org/10.1016/j.conbuildmat.2019.117583.
[24] R.J. Galán-Arboledas, M.T. Cotes-Palomino, S. Bueno, C. Martínez-García, Evaluation of spent diatomite incorporation in clay based materials for lightweight bricks processing, Constr. Build. Mater. 144 (2017) 327–337, https://doi.org/10.1016/j.conbuildmat.2017.03.202.
[25] A.G. Celik, T. Depci, A.M. Kılıc, New lightweight colemanite-added perlite brick and comparison of its physicomechanical properties with other commercial lightweight materials, Constr. Build. Mater. 62 (2014) 59–66, https://doi.org/10.1016/j.conbuildmat.2014.03.031.
[26] M. Limbachiya, M.S. Meddah, S. Fotiadou, Performance of granulated foam glass concrete, Constr. Build. Mater. 28 (1) (2012) 759–768, https://doi.org/10.1016/j.conbuildmat.2011.10.052.
[27] A. Mohajerani, J. Vajna, T.H.H. Cheung, H. Kurmus, A. Arulrajah, S. Horpibulsuk, Practical recycling applications of crushed waste glass in construction materials: A review, Constr. Build. Mater. 156 (2017) 443–467, https://doi.org/10.1016/j.conbuildmat.2017.09.005.
[28] G. Bumanis, D. Bajare, J. Locs, A. Korjakins, Alkali-silica reactivity of foam glass granules in structure of lightweight concrete, Constr. Build. Mater. 47 (2013) 274–281, https://doi.org/10.1016/j.conbuildmat.2013.05.049.
[29] A. Ketov, V. Korotaev, L. Rudakova, I. Vaisman, L. Barbieri, I. Lancellotti, Amorphous silica wastes for reusing in highly porous ceramics, Int. J. Appl. Ceram. Technol. 18 (2) (2021) 394–404, https://doi.org/10.1111/ijac.v18.210.1111/ijac.13654.
[30] I. Glushankova, A. Ketov, M. Krasnovskikh, L. Rudakova, I. Vaisman, Rice hulls as a renewable complex material resource, Resources. 7 (2) (2018) 31, https://doi.org/10.3390/resources7020031.
[31] S. Shakouri, Ö. Bayer, S.T. Erdoğan, Development of silica fume-based geopolymer foams, Constr. Build. Mater. 260 (2020) 120442, https://doi.org/10.1016/j.conbuildmat.2020.120442.
[32] G. Görhan, O. Şimşek, Porous clay bricks manufactured with rice husks, Constr. Build. Mater. 40 (2013) 390–396, https://doi.org/10.1016/j.conbuildmat.2012.09.110.
[33] L.O. Afolabi, Z.M. Ariff, S.F.S. Hashim, T. Alomayri, S. Mahzan, K.-A. Kamarudin, I. D. Muhammad, Syntactic foams formulations, production techniques, and industry applications: a review, J. Mater. Res. Technol. 9 (5) (2020) 10698–10718, https://doi.org/10.1016/j.jmrt.2020.07.074.
[34] M.L. Jayavardhan, B.R. Bharath Kumar, M. Doddamani, A.K. Singh, S.E. Zeltmann, N. Gupta, Development of glass microballoon/HDPE syntactic foams by compression molding, Compos. B Eng. 130 (2017) 119–131, https://doi.org/10.1016/j.compositesb.2017.07.037.
[35] B. Katona, G. Szebényi, I.N. Orbulov, Fatigue properties of ceramic hollow sphere filled aluminium matrix syntactic foams, Mater. Sci. Eng., A 679 (2017) 350–357, https://doi.org/10.1016/j.msea.2016.10.061.
[36] S. Ren, X. Tao, X. Ma, J. Liu, H. Du, A. Guo, J. Ge, Fabrication of fly ash cenospheres-hollow glass microspheres/borosilicate glass composites for high temperature application, Ceram. Int. 44 (1) (2018) 1147–1155, https://doi.org/10.1016/j.ceramint.2017.10.089.
[37] M. Su, H. Wang, H. Hao, T. Fiedler, Compressive properties of expanded glass and alumina hollow spheres hybrid reinforced aluminum matrix syntactic foams, J. Alloy. Compd. 821 (2019), 153233, https://doi.org/10.1016/j.jallcom.2019.153233.
[38] D. Cheneler, A.R. Kennedy, A comparison of the manufacture and mechanical performance of porous aluminium and aluminium syntactic foams made by vacuum-assisted casting, Mater. Sci. Eng., A 789 (2020), 139528, https://doi.org/10.1016/j.msea.2020.139528.
[39] A. Bhakta, E. Ruckenstein, Decay of standing foams: drainage, coalescence and collapse, Adv. Colloid Interface Sci. 70 (1997) 1–124, https://doi.org/10.1016/S0001-8686(97)00031-6.
[40] D. Langevin, Coalescence in foams and emulsions: similarities and differences, Curr. Opin. Colloid Interface Sci. 44 (2019) 23–31, https://doi.org/10.1016/j.cocis.2019.09.001.
[41] S.A. Luksic, R. Pokorny, J. George, P. Hrma, T. Varga, L.R. Reno, A.C. Buchko, A. A. Kruger, In situ characterization of foam morphology during melting of simulated waste glass using x-ray computed tomography, Ceram. Int. 46 (11) (2020) 17176–17185, https://doi.org/10.1016/j.ceramint.2020.02.215.
[42] I. Vaisman, A. Ketov, I. Ketov, Cellular glass obtained from non-powder preforms by foaming with steam, Ceram. Int. 42 (14) (2016) 15261–15268, https://doi.org/10.1016/j.ceramint.2016.06.165.
[43] H. Wang, F. Hou, C. Chang, Experimental and computational modeling of thermal conductivity of cementitious syntactic foams filled with hollow glass microspheres, Constr. Build. Mater. 265 (2020), 120739, https://doi.org/10.1016/j.conbuildmat.2020.120739.
[44] J. Königa, A. Lopez-Gilb, P. Cimavilla-Romanb, M.A. Rodriguez-Perezb, R. R. Petersenc, M.B. Østergaardc, N. Iversenc, Y. Yuec, M. Spreitzera, Synthesis and properties of open- and closed-porous foamed glass with a low density, Constr. Build. Mater. 247 (2020), 118574, https://doi.org/10.1016/j.conbuildmat.2020.118574.
[45] H.B. Dizaji, T. Zeng, I. Hartmann, D. Enke, T. Schliermann, V. Lenz, M. Bidabadi, Generation of High Quality Biogenic Silica by Combustion of Rice Husk and Rice Straw Combined with Pre- and Post-Treatment Strategies—A Review, Applied Science 9 (6) (2019) 1083, https://doi.org/10.3390/app9061083.
[46] P, McKendry, Energy Production from Biomass (Part 1): Overview of Biomass, Bioresour. Technol. 83 (2002) 37–46, 10.1016/S0960-8524(01)00118-3.
[47] GOST 530-2012 (Russian Federation). Ceramic brick and stone. General specifications.