

Structure and properties of a porous wood-mineral composite based on slag-silicate binder with a finely dispersed aluminosilicate additive

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ABSTRACT

Introduction. The extension of the range of binders, aggregates, and fillers as well as functional additives and structural modifiers for concrete and composite materials currently allows for the production of innovative materials with enhanced mechanical, physical, and physico-chemical properties. Lightweight structural and functional materials derived from binders of different natures with fillers derived from vegetable raw materials, such as sawdust concrete, arbolite, fibrolite, or xylolite, are of particular interest. The aim of this research was to develop and investigate the properties of a wood-mineral cement-free composite material with a porous structure that has been stabilized using a finely dispersed aluminosilicate additive. **Materials and methods of research.** A cement-free slag-based silicate binder was utilized in the study, comprising ground blast furnace slag and a curing agent – a solution of sodium silicate (sodium liquid glass). A synthetic foam-forming agent with a finely dispersed additive (bentonite) was employed to create the porous structure of the material. Crushed softwood was used as an aggregate. A range of samples were produced, varying the composition within the following parameters: slag 330–440 kg/m³, crushed wood 120–160 kg/m³, and solution-to-slag ratio 0.5–0.7. Several samples were subjected to thermal treatment by heating in a temperature-controlled environment at 80–90 °C and at humidity of at least 90% for 6–12 hours. Samples were examined using mechanical testing methods, thermogravimetric analysis, X-ray diffractometry, porometry, and thermal conductivity measurements. **Results and Discussion.** A cement-free porous wood-mineral composite material (an analogue of arbolite) was obtained. It is shown that the introduction of ground blast furnace slag (330–440 kg/m³) and crushed softwood (125–160 kg/m³) into the mixture at optimal ratios of liquid glass/slag 0.7 and foaming mixture/slag 0.0035 (3.5% foaming agent + 4% bentonite) makes it possible to obtain a composite material with a density of 550–680 kg/m³, compressive strength of 1.35–3.65 MPa, an open porosity of 45–50%, and an average thermal conductivity of 0.08 W/(m·K). The heat and humidity treatment of the composite at 80–90 °C contributes to the achievement of ultimate strength within 10–12 h. The presence of a finely gel-forming additive (bentonite) with particle sizes of 1–5 μm in the foaming mixture helps to stabilize the homogeneous porous structure of the composite material (spherical pore sizes less than 1 mm).

Conclusion. The porous wood-mineral composite material obtained in the work can be used for the production of lightweight non-load-bearing structural elements, as a noise and thermal insulation material.

KEYWORDS: wood-mineral porous composite, slag-silicate binder, finely dispersed structure stabilizer, heat and moisture treatment, strength, water absorption, thermal conductivity

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Структура и свойства пористого древесно-минерального композита на основе шлакосиликатного вяжущего с высокодисперсной алюмосиликатной добавкой

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АННОТАЦИЯ

Введение. Расширение перечня вяжущих, заполнителей и наполнителей, функциональных добавок и модификаторов структуры бетонов и композитов позволяет в настоящее время получать инновационные материалы с улучшенными механическими, физическими и физико-химическими характеристиками. Представляют интерес легкие конструкционные и функциональные материалы на основе вяжущих различной природы с заполнителями из растительного сырья (опилкобетон, арболит, фибролит, ксилолит и др.). Целью работы являлось получение и исследование свойств бесцементного древесно-минерального композиционного материала с пористой структурой, стабилизированной с использованием высокодисперсной алюмосиликатной добавки. **Материалы и методы.** В работе использовали бесцементное шлакосиликатное вяжущее, включающее молотый доменный шлак и активатор твердения – раствор силиката натрия (натриевое жидкое стекло). Для формирования пористой структуры материала применяли синтетический пенообразователь с высокодисперсной добавкой (бентонит). В качестве заполнителя использовали дробленку хвойных пород. Была получена серия образцов, в которых варьировали компоненты в следующих интервалах: шлак 330–440 кг/м³, древесная дробленка 120–160 кг/м³, отношение затворитель/шлак 0,5–0,7. Часть образцов подвергали термической обработке путем нагрева в термостате при температурах 80–90 °С и относительной влажности воздуха не менее 90% в течение 6–12 ч. Образцы изучали с использованием методов механических испытаний, термогравиметрии, РФА, определяли пористость, теплопроводность. **Результаты.** В работе получен бесцементный пористый древесно-минеральный композиционный материал (аналог арболита). Показано, что введение в смесь молотого доменного шлака (330–440 кг/м³) и древесины (125–160 кг/м³) при оптимальных соотношениях жидкое стекло/шлак 0,7 и пенообразующая смесь/шлак 0,0035 (3,5% пенообразователя + 4% бентонита) позволяет получить композиционный материал плотностью 550–680 кг/м³, прочностью при сжатии 1,35–3,65 МПа, открытой пористостью 45–50%, средней теплопроводностью 0,08 Вт/(м·К). Тепловлажностная обработка композита при 80–90 °С способствует достижению марочной прочности в течение 10–12 ч. Присутствие в пенообразующей смеси ультрадисперсной гелеобразующей добавки (бентонит) с размерами частиц 1–5 мкм способствует стабилизации однородной пористой структуры композиционного материала (размеры сфероидных пор менее 1 мм). **Заключение.** Полученный в работе пористый древесно-минеральный композиционный материал может быть использован для производства легких несущих конструктивных элементов, в качестве шумо- и теплоизоляционного материала.

КЛЮЧЕВЫЕ СЛОВА: древесно-минеральный пористый композит, шлакосиликатное вяжущее, высокодисперсный стабилизатор структуры, тепловлажностная обработка, прочность, водопоглощение, теплопроводность

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INTRODUCTION

Concrete is a versatile building material with a wide range of compositions, structures, and practical uses. The increasing number of binders, aggregates, additives, and structural modifiers allows for the creation of innovative materials with improved mechanical, physical, and physico-chemical properties [1, 2]. A current trend in the construction industry is the reduction of energy and resource consumption at all stages of the production process

through complex raw material processing, the use of waste materials, the widespread adoption of additive technologies, and the development of green technologies for material production and disposal [1]. In this context, lightweight concrete based on various binders and aggregates derived from plant materials (such as sawdust concrete, arbolite, fibrolite, and xylolite) is of particular interest [2]. Wood-mineral composites combine the properties of materials based on mineral binders (strength, thermal resistance, fire resistance) and vegetable raw materials

(low specific gravity, porosity, low thermal conductivity, corrosion resistance) [2, 3]. Despite the long history of obtaining and using these materials, there is still a large number of ongoing studies aimed at improving their performance by varying the binder composition (cement-based and cement-free), the content and composition of organic aggregates (wood chips, shavings, sawdust), and the introduction of additives such as mineralizers, pore-forming agents, and hydrophobizing agents [4–15]. In this regard, the investigation of the mechanisms that govern the formation of wood-mineral composite structures and their properties has significant scientific and practical importance.

There are few studies on the production of wood-mineral composite materials based on alkali-activated slag-containing binders, despite the fact that these materials have great potential for implementation in terms of resource conservation and environmental protection during their production [2, 4]. The binding agents in these materials are aluminosilicate compounds, both natural (clay) and man-made (fly ash and metallurgical slag), and the activators for the setting and hardening processes are alkaline reagents such as caustic alkalis and liquid glass [4]. The highly alkaline nature of these binders promotes better adhesion between the wood aggregate and the mineral matrix, as the solution penetrates the cell walls of the wood and leads to mineralization and hardening at the interface between the binder and wood [16, 17].

In most of the studies on the properties of composites based on alkali-activated binders, fine wood waste was used as an aggregate [16–18]. For example, a high proportion of 2.36 mm wood fibers (10–50 wt.%) mixed with a binder based on fly ash and a mixed $\text{Na}_2\text{SiO}_3 + \text{NaOH}$ activator (2.5:1) leads to a decrease in density (1720–1300 kg/m^3), an increase in porosity and water absorption (0.5–3.5%), a decrease in compressive strength (33–5 MPa) for composite material obtained under heat treatment conditions (60 °C, 24 h) [18]. Pressing of alkali-activated mixtures containing fly ash, methakaolin (20 wt.%) and lignocellulose waste (20 wt.%) in the presence of $\text{Na}_2\text{SiO}_3 + \text{NaOH}$ activator followed by heat treatment (60–100 °C) makes it possible to obtain lightweight composite boards (1.1 kg/m^3), the characteristics of which allow us to consider such materials as replacements for chipboard and fiberboard based on organic binders [19]. It has been demonstrated in [20] that the addition of sawdust up to 6.3% to a slag-alkaline mixture (ground slag, sodium hydroxide activator 4.9–7.1%) results in a two-fold increase in flexural strength and a reduction in compressive strength compared to the control sample. This increase in strength can be attributed to the formation of an optimized reinforced microstructure in the material, which manifests itself in a reduction of cracking. An increase in the amount of sawdust used in the composite up to 10% leads to a

reduction in the strength and density of the samples (from 1.836 to 1.027 kg/m^3) and an increase in their apparent porosity by more than two times. Features of the composite's structure formation include the formation of C–S–H and C–A–S–H hydrate phases with a fibrous, needle-like, or lamellar morphology. One of the factors that contributes to the composite material's enhanced resistance to cracking is the improved adhesion of sawdust particles to the cement matrix, which is achieved by filling micropores within the sawdust using a binder. This leads to a significant reduction in thermal conductivity (from 0.553 to 0.203 $\text{W/m}\cdot\text{K}$) when the sawdust content in the material increases to 10 wt.%.

It was shown in [21] that the introduction of 10 wt.% of wood aggregate (sawdust, fiber, flour) in a slag-alkali binder (70% fly ash + 30% methakaolin, alkaline activator $\text{NaOH} + \text{Na}_2\text{SiO}_3$) helps to reduce the compressive strength of the composite by 2–3 times compared with the control sample. At the same time, an increase in the dispersion of the filler has a positive effect on the strength of the composite material. Adding a sufficiently large proportion of pine sawdust to calcined clay (mass ratio 3:1) using sodium liquid glass as an activator under heat treatment conditions (75 °C, 24–38 h) makes it possible to obtain a lightweight composite material (density 610–760 kg/m^3) with high flexural and compressive strength and modulus of elasticity [22]. This material is characterized by more than 3 times lower thermal conductivity compared to the control material. The possibility of manufacturing shaped products for masonry from mixtures containing fly ash, ground metallurgical slag, alkaline activator $\text{NaOH} + \text{Na}_2\text{SiO}_3$ and wood chips (up to 68 vol.%) is shown [23].

An analysis of the available literature has revealed that there is a lack of systematic studies on the properties of cement-free, porous wood-based mineral composite materials. In this regard, the aim of this study was to develop and investigate the properties of composite materials based on a silicate binder derived from slag, with a porous structure that has been stabilized using a finely dispersed aluminosilicate additive.

MATERIALS AND METHODS

To obtain the composite material, a slag-silicate binder was used, which included ground blast furnace slag and a hardening activator (sodium silicate solution, sodium liquid glass). Ground granular blast furnace slag ('Mechel Materials' LLC, Chelyabinsk, Russia) had a specific surface area of 550 m^2/kg and a bulk density of 1.5 g/cm^3 . The composition of the slag was determined in accordance with GOST 3476–2019, the results of determining the chemical composition are shown in Table 1. Based on the chemical composition, the slag quality coefficient is 1.57.

Table 1. Chemical composition of slag

Content of oxides (wt. %)								
SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	MgO	K ₂ O	Na ₂ O	SO ₃	TiO ₂
34.1	11.7	0.6	36.5	10.8	0.7	0.8	2.6	2.2

Table 2. Characteristics of the foaming agents used in the work

Foaming agent	Density, g/cm ³	pH
PB-Lux (JSC 'RHZ Nordiks', Voskresensk, Russia)	1050–1100	8–10
Etalon ('Aist' LLC, Chelyabinsk, Russia)	1120	6.5–8

A solution of sodium silicate (sodium liquid glass Na₂Ox_nSiO₂, ρ = 1.5 g/cm³) of the SNZH1 brand ('PromKeramika' LLC, Shchekino, Russia) according to GOST 13078-2021 was used for curing the composite material, it composed of 29 wt.% SiO₂ and of 10.4 wt.% Na₂O with silicate modulus *n* = 2.8.

Synthetic anionactive ('PB-Lux') and protein ('Etalon') foaming agents were used to form the porous structure of the material, the characteristics of which are given in Table 2.

The foam was prepared using a portable pneumatic foam generator IK FOAM Pro2+ from solutions with a different ratio of water and foaming agent. For the resulting foam, the multiplicity was determined by the ratio of the volume of foam and the initial solution and the stability index for liquid separation when holding the foam for 30 min. Preliminary tests have shown that the optimal foaming agent content for obtaining foam with a sufficient multiplicity is 3.5%. To increase the stability of the foam in the slag-alkali mixture, a finely dispersed gel-forming aluminosilicate additive (bentonite clay powder PIT1 according to GOST 28177-89, 'Bentholding' LLC, Moscow, Russia) with a particle size of 1–5 microns and with a content of the main clay mineral montmorillonite of at least 70 wt.% was used.

Crushed softwood according to GOST 19222-2019 ('Smolenskiy Les', Dorogobuzh, Russia) with needle-shaped or flat particles measuring 2–20 mm, with bulk density 120–140 kg/m³ and humidity 10–15% was used as aggregate in the production of wood-mineral composite material.

To determine the characteristics of the material studied in the work, samples were formed in the shape of 40×40×160 mm³ prisms and of 10×10×10 cm³ cubes. The concrete mix was prepared using a CONTROLS 65-L0006/AM laboratory mixer by sequentially loading crushed wood, ground slag, a finely dispersed additive, a sodium silicate solution and foam from a foam generator into a bowl while stirring. To determine the optimal ratio of binder and aggregate components, which can produce a composite material that meets the requirements for self-

supporting structural and thermal insulation blocks (dry density grade D600, compressive strength class B1.5), a series of samples was obtained in which the components varied in the following ranges: slag 330–440 kg/m³, crushed wood 120–160 kg/m³, the aggregate/slag ratio 0.5–0.7. The total mixing time of the concrete mixture from the moment of loading of all components was 5 min. The samples were formed by layering and final compaction of the mixtures in molds on a vibrating pad. The samples were kept in molds at a temperature of 20±2 °C and at relative humidity of at least 90% for 1 day, then removed from the molds and stored under normal laboratory conditions. Some of the samples were subjected to heat treatment by heating in a thermostat at temperatures of 80–90 °C and at relative humidity of at least 90% for 6–12 hours.

The strength characteristics of the obtained samples (compressive and flexural strength) were determined after 28 days of storage using a universal testing machine UPB 86/200 Form + Test (Germany). The tests of samples of the same composition were repeated six times, and the average strength values were calculated based on the results obtained. The determination of water absorption (by weight and volume) of a porous composite was carried out in accordance with GOST 12730.3-2020 by weighing samples in a water-saturated state. Thermal analysis (DTA + TG) of the materials was performed using an SDT Q600 (USA) thermal analyzer, the samples were heated to 1000 °C with a heating rate of 10 K/min, the air purge rate through the analyzer furnace was 100 ml/min. Heat release during binder hydration was measured using isothermal calorimetry (TAM Air 3116-2, TA Instruments, USA). The phase composition of the materials was determined by X-ray phase analysis, X-ray diffractograms were recorded using a SHIMADZU XRD 6000 (Japan) diffractometer with a copper anode ($\lambda_{\text{K}\alpha 1} = 1.54056 \text{ \AA}$; tube voltage 40 kV, current 40 mA) in the angle range $2\theta = 5\text{--}70^\circ$ with a scanning step of 0.02°. The specific surface area of the materials was determined using the Brunauer-Emmett-Teller method using the Quantachrome NOVA 2200e (USA) device by low-temperature

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nitrogen adsorption-desorption at 77 K. The thermal conductivity of the samples was measured using an ITP-MG4 (Russia) type meter in accordance with GOST 7076-99. A multifunctional scanning electron microscope JEOL JCM-6000 Plus (Japan) was used to study the morphology and structure of the samples.

RESULTS AND DISCUSSION

For the formation of a porous structure in a wood-mineral composite material, it is essential to produce foam with a controllable multiplicity. The stability of this foam must be maintained in order to ensure high dispersion and uniform distribution of air bubbles throughout the volume of the initial mixture prior to the setting of the binder. Preliminary experiments with various foam agents (Table 2) revealed that a protein-based foam agent in an alkaline sodium silicate environment produces a less stable foam with lower multiplicity than a synthetic foam agent. Therefore, further optimization of the component ratios for foam generation was performed using a synthetic foam agent. Figure 1 illustrates the results of determining the foam multiplicity and amount of separated liquid based on the composition of the initial foam mixture.

It can be seen from the data presented (Fig. 1) that the inclusion of sodium silicate and bentonite into the foaming mixture has various effects on the properties of the resulting foam. While the foam multiplicity appears to be largely unaffected by the presence of either additive at concentrations up to 4% (Fig. 1a), the water separation during foam stratification is significantly reduced in the presence of bentonite over an extended period of time (Fig. 1b). This stabilizing effect is attributed to the

sorption of bentonite particles at the air-liquid interface, which hinders the coalescence of individual bubbles and prolongs the duration of the foam's stable state. Increasing the bentonite concentration (above 4%) further enhances foam stabilization, although it also leads to a decrease in foam multiplicity (Fig. 1a). Therefore, the addition of bentonite at a concentration of 4% to the liquid phase is sufficient to produce a foam with the highest degree of multiplicity and stability during the formation of the porous structure of the composite material.

Important factors determining the technological characteristics of a concrete mix are workability, density, delamination, and the start and end time of setting of the binder. For the slag-silicate binder used in the work, the parameters were determined to achieve the required strength class of the stone to obtain a composite material (Table 3).

Rather short setting times combined with high strength are characteristic of cement-free slag-alkali binders [2], which is explained by the intense interaction of the alkaline activator with amorphous (glass phase) slag components to form a dense polymerized aluminosilicate matrix (the so-called 'geopolymer concrete'). To determine the effect of foam injection on the interaction between the binder components, the kinetics of heat release in a slag-alkali mixture of a given composition was studied (Table 3) in the presence of foaming agent and bentonite using isothermal calorimetry. According to the temperature measurements of the control mixture (without foaming agent) and a mixture containing 0.35% of the foaming solution based on the mass of slag, the dependences of the heat flux on the reaction time (up to 240 h) are shown in Fig. 2.

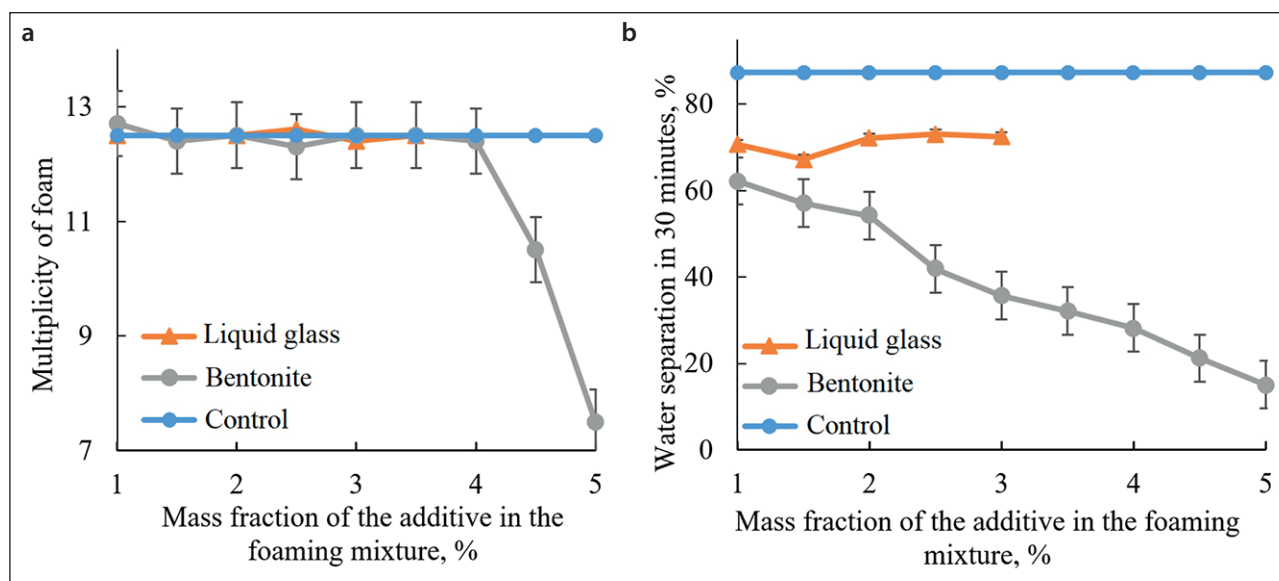
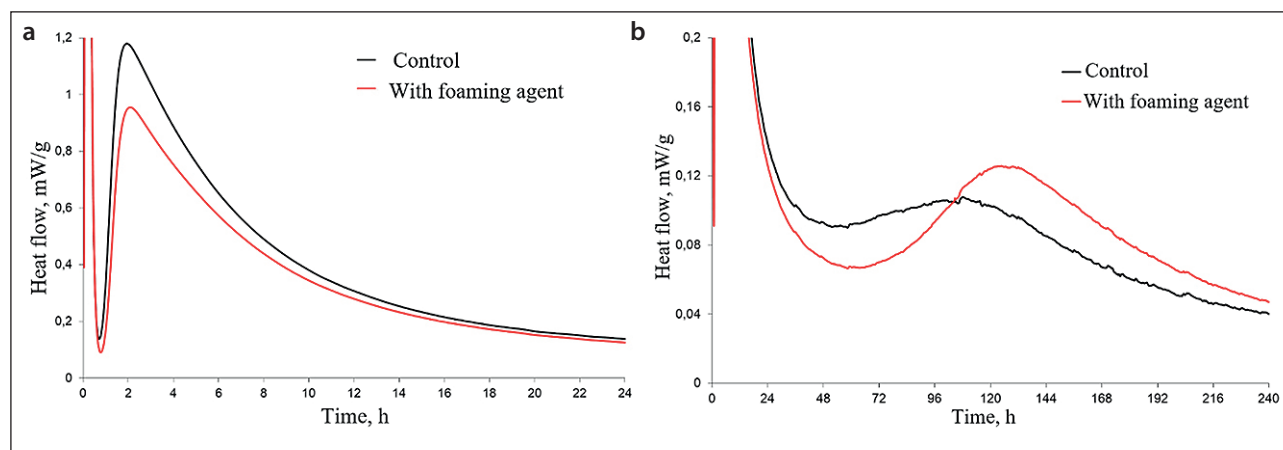


Fig. 1. The effect of the presence of liquid glass and bentonite in a foaming solution (PB-Lux foaming agent) on (a) the multiplicity and (b) the stability of the foam

Table 3. Composition and characteristics of the slag-silicate binder

Liquid glass/slag ratio	Setting time, min		Normal density, %	Strength grade
	Start	End		
0.7	30	50	46	M300

**Fig. 2.** The dependences of the heat flow on the exposure time of the slag-silicate mixture in the presence and absence of a foaming agent at (a) the initial and (b) the final stage of the formation of the structure of the slag-silicate stone

It follows from the calorimetry results (Fig. 2) that several periods of heat release are observed for the control sample of the mixture and the sample with the foaming agent. The initial period with a maximum at a time of ~ 10 min is typical for both samples, the magnitude of the heat flux practically does not depend on their composition. The second period with a maximum heat release after about 2 h is characterized by a lower thermal effect for the sample with a foaming agent, which can be explained by the sorption of surfactants on the surface of slag particles and the associated slowdown in the formation of products in the hardened material (Fig. 2a). With an increase in the duration of interaction in the slag-silicate system, a shift in the maximum heat release in the case of a porous sample (by ~ 18 h) and its narrowing on the time scale compared with the control sample is observed (Fig. 2b). This effect is also explained by the inhibition of the processes of structure formation in a solid material, which are diffusive in nature. Nevertheless, the sum of the heat fluxes in the entire studied range of structure formation for both samples practically coincides and amounts to about 105 J/g. Consequently, foaming of the slag silicate mixture does not significantly change the intensity of hydration processes, especially in the early stages of hardening.

It is known that slag-alkali binders quickly set and gain brand strength during heat treatment [2, 20]. To determine the effect of temperature on the phase composition of the products formed during the curing of the binder,

two series of experiments were performed when samples were heated at 80 and 90 °C and at relative humidity of at least 90% for 6–12 h. The obtained X-ray diffraction data were compared with those for samples that hardened under normal conditions for 1 and 28 days. A typical X-ray diffraction pattern of a slag stone is shown in Fig. 3.

From XRD results (Fig. 3), the main crystalline phases formed during hardening, both under normal conditions and upon heating, are okermanite (calcium-magnesium silicate) and calcite, the total content of which does not exceed 10 wt.%. The predominant component (up to 90%) in slag silicate stone is an amorphous phase. Calcite is formed due to carbonation of an alkali-containing material, calcium-magnesium silicate is formed due to the interaction of liquid glass with slag components. Obviously, the temperature conditions of the hardening of the material are insufficient for the crystallization of silicates prone to amorphization in the system. Thus, heat treatment of slag silicate stone does not lead to a significant change in the composition of crystalline products and an increase in their proportion in the material.

Due to the predominantly X-ray amorphous structure of the interaction products in the slag-liquid glass system, the composition of the products formed when wood was introduced into the system was evaluated using thermal analysis. The sample for analysis had the following initial composition: slag 385 kg/m³, crushed wood 138 kg/m³, liquid glass solution 270 kg/m³, foaming agent 1.35 kg/m³, bentonite 1.54 kg/m³. Average weight loss when heated

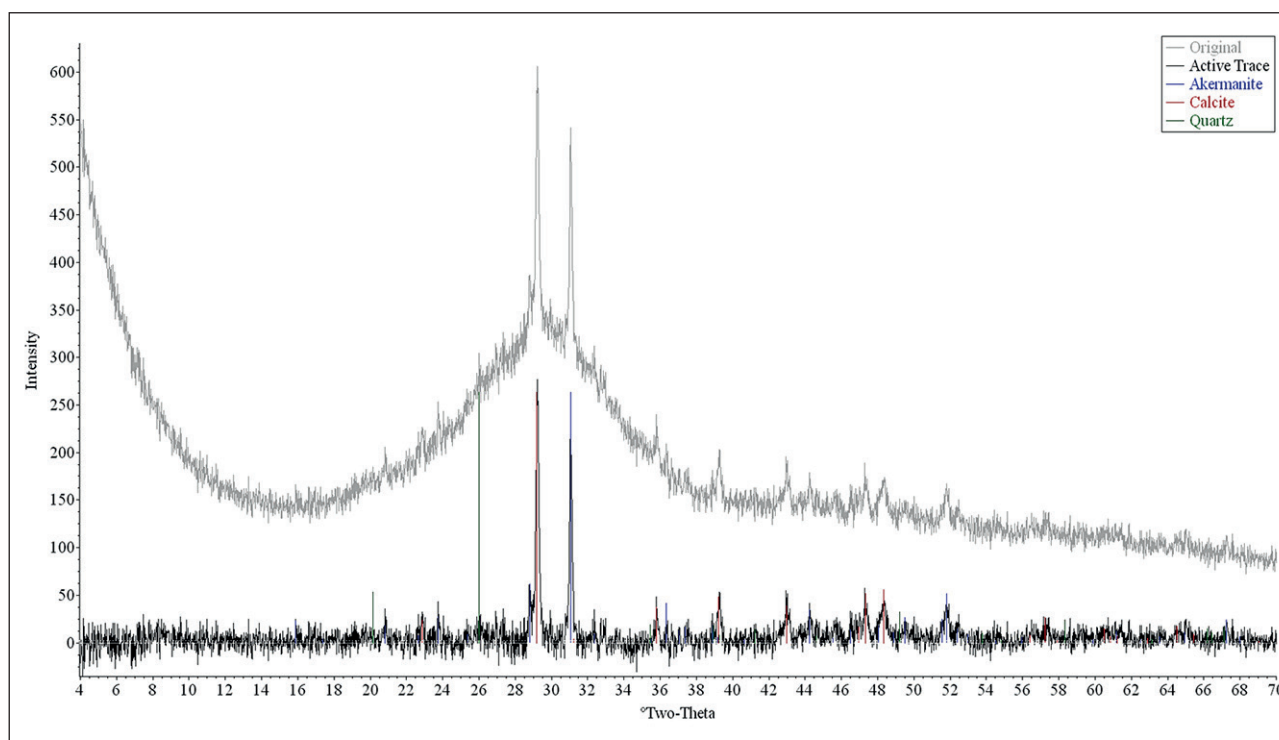


Fig. 3. XRD pattern of a sample of slag-silicate stone (liquid glass/slag ratio 0.7) subjected to heat treatment at 90 °C for 10 h.

to 1000 °C for samples obtained under normal hardening conditions is 15%, after heat treatment – 10%. Typical TG-DTG curves of linear heating of samples are shown in Fig. 4.

The TG curves of the material are characterized by four main stages of weight loss and their corresponding endothermic effects in the temperature ranges 75–150, 225–375, 450–650 and 720–830 °C. In the temperature range of 75–150 °C, weakly bound water (capillary, sorption, interlayer) is removed from sodium hydrosilicates $\text{Na}_2\text{O}\cdot\text{SiO}_2\cdot n\text{H}_2\text{O}$. When the temperature rises to 225–375 °C, a decrease in the mass of the samples occurs due to the dehydration of calcium hydrosilicates such as tobermorite. A weakly expressed broad endothermic effect in a wide temperature range of 450–650 °C reflects the thermal decomposition (charring) of wood in the material. In parallel, complete dehydration of tobermorite and gyrolite, as well as decomposition of residual portlandite, occurs at these temperatures. The effects caused by the presence of these phases are more pronounced on the thermograms of samples with long periods of hardening. An increase in temperature to 720–830 °C is accompanied by the decomposition of calcite CaCO_3 , the presence of which in the samples is confirmed by XRD data (Fig. 3), as well as calcium and sodium hydroaluminosilicates. The presence of calcite is explained by carbonization of lime and calcium hydrosilicates. Thus, the thermal analysis data show a high degree of transformation during the

interaction of the binder components, since the greatest mass loss occurs at $T > 150$ °C due to the decomposition of complex hydrate phases. The increase in decomposition temperatures of the wood aggregate is due to the mineralizing effect of the alkali-silicate components of the binder.

The features of the pores and the structure of the contact zone between the aggregate particles and the mineral matrix were studied using electron microscopy (Fig. 5).

Microscopy data shows that the material is characterized by closed-type pores, which are predominantly spherical in shape and have dimensions of the order of 1 mm or less (Fig. 5a). The pore walls are solid and have a thickness of the order of tens of micrometers (Fig. 5b). The products of the interaction of the binder components differ in morphology; the bulk particles of lamellar and prismatic shapes are calcium hydrosilicates with colloidal bentonite particles deposited on their surface (Fig. 5c). A special feature of the contact zone at the boundary of wood particles and the mineral matrix is its dense and relatively homogeneous structure (Fig. 5d). The surface of the wood particles due to the mineralizing effect of the sealer is also covered with the products of the interaction of the binder components, which are also observed in the mineral matrix of the material. The mineralizing effect of liquid glass has a positive effect on the stabilization of the properties of wood aggregate and its thermal stability, which is consistent with the results of thermal analysis (Fig. 4). In addition, the hydrolytic effect of the alkaline

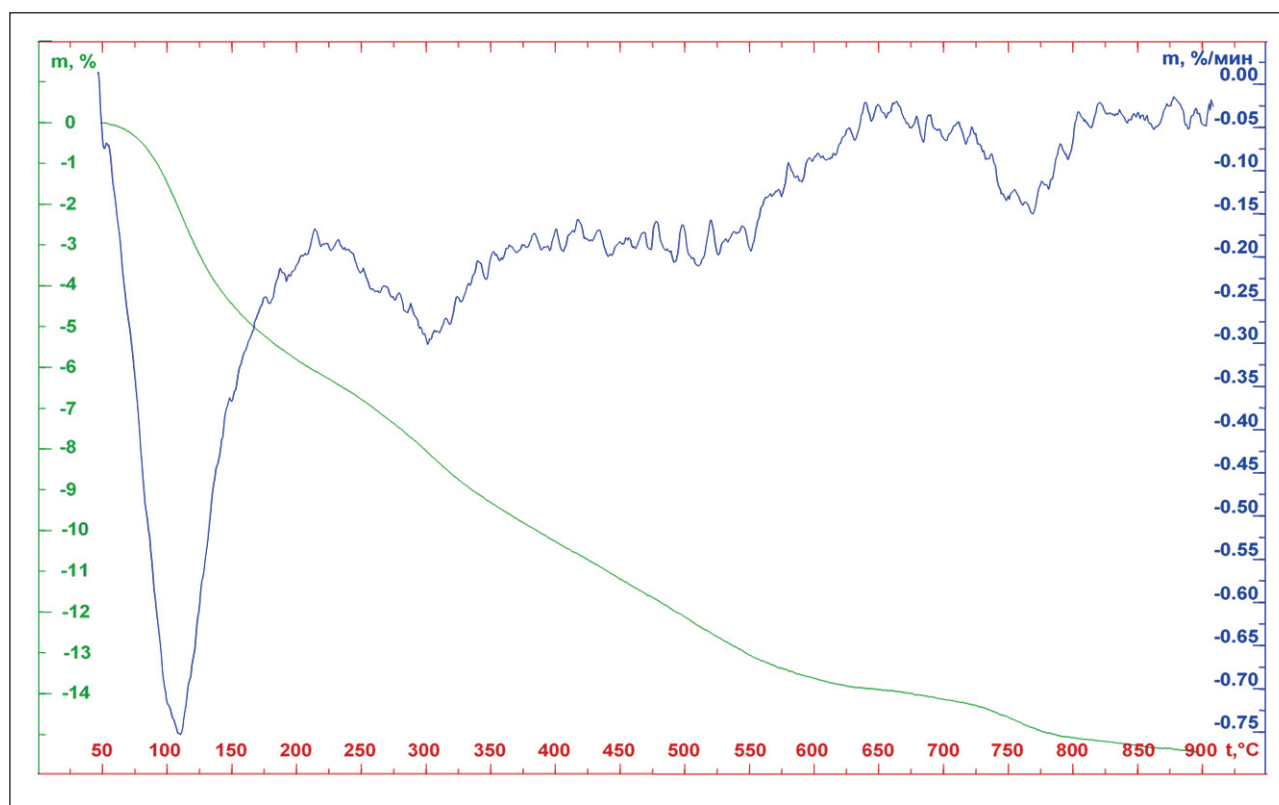


Fig. 4. TG (green) and DTG (blue) curves obtained by linear heating of a porous wood-mineral composite sample after 28 days of its hardening under normal laboratory conditions

binder medium on the wood components contributes to the formation of a more dense contact with the mineral matrix (Fig. 5d).

From the point of view of practical application, the most important characteristics for a porous wood-mineral composite material are strength, porosity, water absorption and thermal conductivity. To determine the nature of the effect of the ratio of the initial components on the compressive strength of the material, a series of samples was obtained under normal hardening conditions. The weights of the raw materials and the strength values are given in Table 4.

The research results have shown that the compressive strength and density of the composite are more correlated with the proportion of slag in the initial mixture. The dependence of strength characteristics on the content of crushed wood in the material is less pronounced. For example, the proportion of wood in sample No. 3 is the largest (wood/slag ratio 0.43) among all the presented variants, while compressive strength takes an intermediate value (Table 4). Samples No. 4 and 6 with high strength contain average amounts of wood, sample No. 7 with a low proportion of wood (wood/slag ratio 0.3) has the lowest strength. The amount of hardening agent can vary within narrow limits: with a liquid glass/slag ratio of 0.5 or less, the mixture is characterized by low workability

and the resulting material has a heterogeneous structure; with a ratio greater than 0.7, separation of the liquid and stratification of the sample are observed. The most reproducible characteristics of material samples with uniform porosity are obtained with an optimal liquid glass/slag ratio of 0.7.

Heat treatment of the composite material leads to a regular increase in its strength. Figure 6 shows the results of measuring the compressive strength of samples of composition No. 3 with the largest proportion of wood (Table 4) after their isothermal heating at 80 and 90 °C with different durations.

An increase in the strength of the material during heat treatment (Fig. 6) occurs due to an increase in the depth of interaction of the components of the slag silicate binder, to an increase in the binding strength of wood particles with the mineral matrix, and to the reinforcing function of the aggregate. A comparison of the data in Fig. 6 and Table 4 shows that during heat treatment, an increase in the strength of the material can be achieved by 15–20% compared with the samples obtained under normal hardening conditions. Heat treatment at 90 °C during 8–10 h is sufficient to achieve the highest strength, an increase in the heating time is impractical (Fig. 6). The use of lower temperatures reduces the efficiency of the material production process by increasing the heating

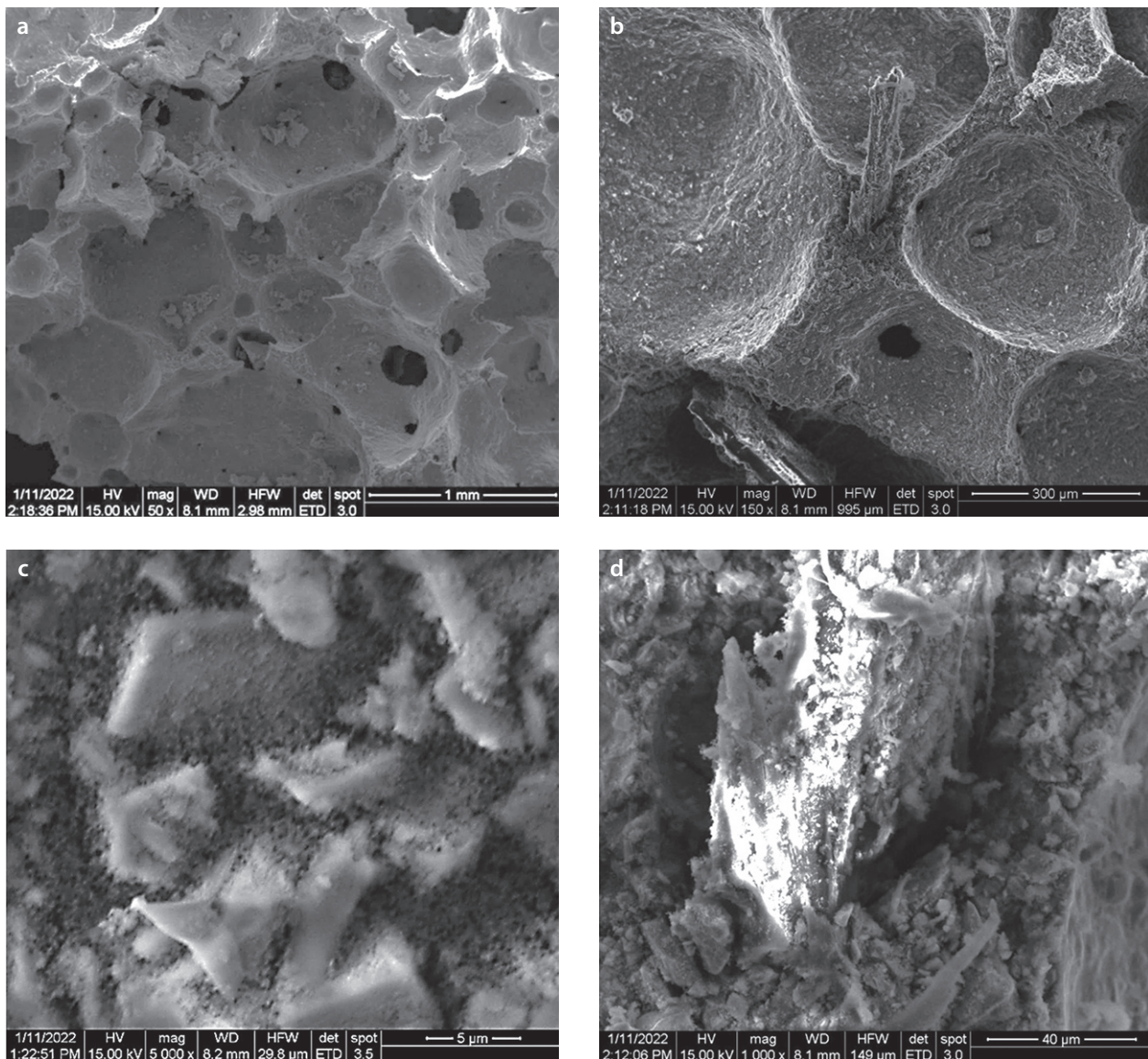


Fig. 5. Micrographs of cross-section of a porous wood-mineral composite based on a slag silicate binder aged 28 days during hardening under normal conditions: (a) pores of various diameters; (b) distribution of pores and wood in the volume of the material; (c) hydroaluminosilicate distributed among slag particles; (d) the contact zone of wood with mineral the matrix

time, temperatures above 90 °C lead to increased removal of water, contribute to the destruction and softening of the material.

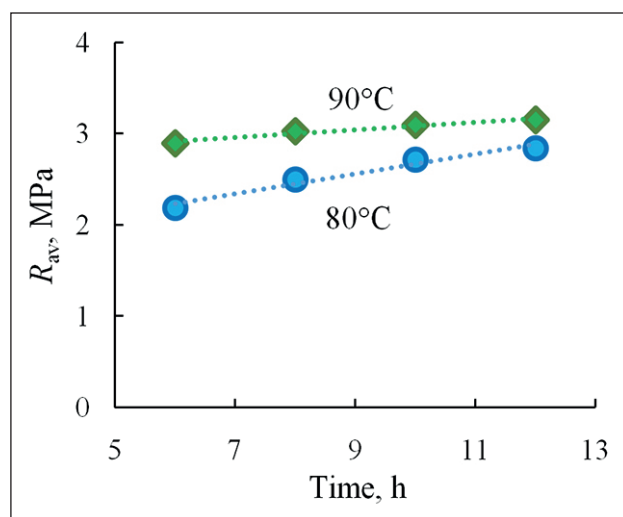
The water absorption of a wood-mineral composite is directly related to its porosity and can significantly reduce the strength of the material, primarily due to the swelling of wood particles and the associated softening of the material. To assess water absorption, samples with average binder and aggregate contents were weighed (sample No. 9, Table 4) in the initial mixture, and then were hardened under normal conditions for 28 days. Based on the results of determining the compressive strength of samples in a water-saturated state, the softening coefficient of the

material was calculated as the ratio of the strengths of wet and dry samples. The results of the water absorption determination are shown in Table 5.

It follows from the characteristics of water absorption that the resulting composite material has low water resistance, and in a humid environment, the strength and frost resistance of such a material will decrease significantly. In addition to penetrating into the open pores, water is absorbed by wood particles, which, due to swelling, will also cause softening of the material. In fact, the observed trend is typical for all porous and wood-containing materials, therefore, such materials are recommended to be used in conditions of low humidity or to protect them

Table 4. The content of raw materials for obtaining a porous composite material and its characteristics at the age of 28 days (hardening under normal conditions, liquid glass/slag ratio 0.7)

Sample	Slag, kg/m ³	Crushed wood, kg/m ³	Foaming agent, kg/m ³	Bentonite, kg/m ³	Dry density, kg/m ³	Compressive strength R_{av} , MPa
1	347	124	1.21	1.38	552	1.38
2	424	124	1.48	1.69	640	2.78
3	347	152	1.21	1.38	575	2.38
4	424	152	1.48	1.69	668	3.33
5	331	138	1.16	1.32	546	1.40
6	439	138	1.54	1.75	680	3.65
7	385	118	1.35	1.54	593	1.34
8	385	158	1.35	1.54	627	1.75
9	385	138	1.35	1.54	607	1.50

**Fig. 6.** Dependence of compressive strength (R_{av}) of wood-mineral composite samples (composition No. 3, Table 4) on the duration of their isothermal heating at different temperatures (relative humidity of at least 90%)**Table 5.** Water absorption of porous wood-mineral composite material

Indicator	Value
Water absorption by weight W_m , %	74
Water absorption by volume W_v , %	45
Softening coefficient K_s	0.63

from moisture (surface hydrophobization, impregnation with special compounds).

Measurements of thermal conductivity of porous composite material samples with average values of density and strength (compositions Nos. 3, 8, 9; Table 4) showed

that the average value of thermal conductivity is about 0.08 W/(m·K). The obtained values of thermal conductivity are close to those for arbolite based on Portland cement, and they are significantly lower than those for foam and aerated concrete, which confirms the good thermal insulation properties of the material.

CONCLUSION

1. The possibility of producing a porous composite wood-mineral material, analogous to arbolite, based on a slag-silicate binder, wood aggregate, synthetic foaming agent, and fine aluminosilicate foam stabilizer (bentonite), has been experimentally confirmed. By varying the content of raw materials, consisting of 330–440 kg/m³ blast furnace slag and 125–160 kg/m³ wood, at optimal ratios of liquid glass to slag 0.7 and foaming agent mixture to slag 0.0035 (composed of 3.5% foaming agent and 4% bentonite), it is possible to produce a composite material with following characteristics: density 550–680 kg/m³, compressive strength 1.35–3.65 MPa, an open porosity 45–50%, and an average thermal conductivity 0.08 W/(m·K). It is shown that the heat and humidity treatment of the composite at 80–90 °C for 10–12 h helps to gain strength, which, with normal hardening, is achieved within 28 days.

2. Stabilization of the homogeneous porous structure of the resulting composite material (spherical pore sizes less than 1 mm) is achieved by introducing a fine gel-forming additive (bentonite) with particle sizes of 1–5 μm into the foaming mixture. Bentonite particles are distributed in the walls of foam bubbles, reduce their ability to coalesce and strengthen the pore walls in the mineral binder matrix during setting due to gelation.

3. During setting and hardening of the slag-silicate binder, mainly amorphous products (hydrosilicates and hydroaluminosilicates of calcium and sodium) are formed, the proportion of crystalline products (calcite, okermanite) does not exceed 10%. The hydrolytic effect

of the alkaline binder medium on the wood components contributes to the formation of a more dense contact with the mineral matrix. The contact zone of the slag-silicate matrix with wood particles has a dense homogeneous structure, it contains calcium hydroaluminosilicate particles in the form of petals, which are formed in areas

of accumulation of colloidal bentonite particles at the interface of the contacting phases.

4. The porous wood-mineral composite material obtained in the work can be used for the production of light-weight non-load-bearing structural elements, as a noise and thermal insulation material.

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ADDITIONAL INFORMATION

The authors state that neither generative artificial intelligence nor artificial intelligence-based technologies were used in the preparation of this article.

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