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ORIGINAL ARTICLE

Maximizing strength and durability in wood concrete (arbolite) via innovative additive control and consumption

Aleksandr Yagubkin[1] · Dmitry Shabanov[1] · Aleksandr Niyakovskii[1] · Valentin Romanovski[2]

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Abstract
A new approach for assessing the effectiveness and determining the consumption of additives to regulate the structural and mechanical characteristics of wood concrete is proposed, which allows rapid assessment in a short time and reduces the consumption of materials. The period is reduced from 28 to 1 day, and the sample sizes are reduced from 150 × 150 × 150 to 20 × 20 × 20 mm compared to those of the standard method. The results obtained are comparable using both methods within an error of up to 7%. The thermal conductivity of wood concrete with the addition of potassium sulfate was 20.8% less than that with the addition of calcium chloride. This reduction will reduce wall thickness, material consumption, and cost by 20.8%. In this regard, potassium sulfate, which does not form crystalline hydrates and makes it possible to obtain a material with lower thermal conductivity than other additives, all other things being equal, has a new advantage for wood concrete. In addition, potassium sulfate reduces the risk of corrosion of cement stone because one of the main causes of corrosion is crystalline hydrates. Reducing the risk of corrosion will increase the durability of the material.

Keywords Wood concrete · Additive · Calcium chloride · Potassium sulfate · Wood filler · Cement · Thermal conductivity

1 Introduction

Waste recycling is part of sustainable development. When choosing a recycling technology, it is important to know the composition of the waste [1–4]. The use of waste in the production of building materials is widely known [5, 6]. At the same time, there are many known areas for using industrial waste in the production of building materials for various purposes. For example, walnut shells are used in the production of building materials [7, 8], biochar and ash after thermal processing of plant raw materials [9, 10], foundry send [11], red gypsum [12], banana fibers [13, 14], glass-fiber [15], water treatment wastes [16, 17], wood fibers [18], bamboo fibers [19], waste paper [20], plating electrolytes [21], and paper industry slag [22]. The latest researches demonstrate the potential of using alternative materials in concrete to enhance its mechanical properties and sustainability. The incorporation of glass fibers improves tensile and flexural strength, making concrete more durable and resistant to cracking [23]. Using recycled concrete and rice husk ash contributes to sustainability while maintaining satisfactory mechanical performance [24]. Residual wood ash and secondary aluminum chips also enhance the strength of concrete, offering environmentally friendly alternatives to traditional materials [25, 26]. Coconut fiber improves mortar properties in masonry walls, highlighting the benefits of organic material integration [27]. Agricultural ashes and HDPE show promise in stabilizing low plasticity clay soils, contributing to sustainable construction practices [28]. Wood sawdust serves as an effective replacement for fine aggregates, enhancing the sustainability of concrete production [29], and the use of recycled concrete aggregate demonstrates viability in maintaining concrete's physical and mechanical properties [30].

Arbolite (wood concrete) is a lightweight structural and heat-insulating concrete based on a cement binder, wood chips (up

✉ Valentin Romanovski
rvd9ar@virginia.edu

Aleksandr Yagubkin
a.yagubkin@psu.by

Dmitry Shabanov
d.shabanov@psu.by

Aleksandr Niyakovskii
a.m.niyakovski@psu.by

[1] Department of Construction Industry, Polotsk State University, Blokhina 29, 211440 Novopolotsk, Belarus

[2] Department of Materials Science and Engineering, University of Virginia, Charlottesville, VA 22904, USA

to 80–90% of the volume), and chemical additives. Arbolite is used for residential, commercial, and industrial purposes. It is usually used to build walls, internal partitions, or formwork for 2–3-storey buildings. In Europe, wood concrete began to be actively used in the 1930s. Its use is associated with the Durisol group of companies, which had its own representative offices in the Netherlands, Switzerland, and Germany. In its volume, wood concrete consists of 80–90% coniferous wood chips treated with mineral additives using Portland cement as a binder. Currently, Durisol has representative offices in 14 countries around the world [31]. Etex Building Performance GmbH in Germany produces wall panels made of wood concrete. The panel has a three-layer structure, a rigid base inside, and a smooth top layer on both sides. The panel is made of Portland cement, water, wood fibers, and mineral additives [32]. In Austria, the Velox company has been producing permanent formwork from wood chips and cement slabs for 50 years. The operational properties of the formwork determine the quality characteristics of the house. The slabs are environmentally friendly, produced by pressing from mineralized wood chips (95%) and cement, with the addition of aluminum sulfate (catalyst) and liquid glass (mineralizer, antiseptic, binder). Non-commercial wood is used for the production of slabs—spruce balance with a low sugar content [33]. In Japan, Permax wood-cement slabs are produced. Softwood blanks and plywood production waste are used as filler, from which longitudinal shavings are made on planing machines. The shavings are dried, after which the wood fiber is spread in an even layer on a special distributing machine and impregnated with cement paste with the addition of mineralizers. In addition to wood fiber, wood chips are also used for Permax boards. In Japan, about 20 million pieces of such boards are produced per year; their production is also developing in neighboring countries (Thailand, the Philippines, etc.) [34]. In the USA, the company "Faswall" produces blocks that consist of Portland cement, wood chips, and fly ash. The blocks meet all American standards and have been widely used for 60 years [35]. The company "Lignacite ltd" (Great Britain) has developed building blocks based on sawdust of coniferous wood, sand, and cement. The blocks are hollow, have good heat and sound insulation properties, and are water, fire, frost, and bio-resistant. They are used for the construction of low-rise buildings as a material for external and internal walls [36].

Published works [37–39] note that the main difficulty in the production of wood concrete products is reducing the harmful effect of wood filler on the processes of strengthening the cement binder. This is because the strength of wood concrete is negatively affected by many substances contained in wood filler. These primarily include hemicelluloses, starch, and extractives [40–42]. The processes of formation of the structure of wood concrete differ from those of conventional concrete. When preparing the wood-concrete mixture, fairly high water-to-cement ratios (W/C) of 1.1 are used. This is because the wood filler is very hygroscopic. More than half of the mixing water is absorbed by the cell walls, saturates the fibers, and fills the pores and capillaries of the wood filler.

The saturation of wood filler with water can occur within several hours. At this time, hydration processes occur in the cement paste. At a certain point, cement becomes insufficient for the water that has not been absorbed into the wood filler and is in the cement paste. Therefore, the cement begins to draw water from the wood aggregate. However, in the cell walls, fibers, pores, and capillaries, water washes out the extractable substances: sucrose, glucose, fructose, and starch. These substances, which enter the cement before it begins to set, slow the process of strength development from several days to several months and worsen the adhesion of the cement stone to the wood filler because they create films on the surface of the alite and aluminates and isolate the cement particles from the water. Therefore, it is important that the reaction with the additive begins before hemicellulose, starch, and tannins enter the cement from the wood filler along with the mixing liquid. The hemicellulose component of wood is composed of complex organic substances—polysaccharides [43]. The negative role of hemicellulose is that it can be hydrolyzed by alkali and turn into sugars that are soluble in water [44]. The negative role of starch manifests itself in the winter season when it turns into sugars and oils, which are nutrient media for the plant. Oils (a mixture of palmitine and stearin fats) are capable of forming thin films on the surface of wood particles that prevent the adhesion of the aggregate to the cement paste [45]. Extractive substances include tannins, soluble monosaccharides, fatty and resin acids, and mineral salts. Some of the tannins that can be extracted from wood with water are called tannins and gallotannins. They slow the setting of cement [46]. When making wood concrete, tannins and sugary substances, organic acids, and mineral salts are mainly extracted from wood with water. The intensity of the supply of extractive substances weakens by the time the cement begins to set and stops at the end of the setting period. Therefore, if, due to the additive, the processes of setting and hardening the cement paste are accelerated, then the harmful substances that will come along with water from the wood filler will not be able to significantly affect the strength gain of the cement.

One of the most effective and low-cost ways to neutralize such substances is to modify the cement binder with solutions of chemical compounds [47, 48]. The most common additives for neutralizing such harmful substances released from wood filler are hardening accelerators. Other techniques and methods are also used to solve this problem [49–51]: mineralization of wood filler and electrical stabilization. However, these methods are quite expensive and complex and therefore are not widely used.

Currently, a large number of hardening accelerator additives are known. The composition of most additives is hidden by manufacturers' patents. The most well-known substances used in the manufacturing of wood concrete that accelerate the setting and hardening processes are calcium chloride, aluminum sulfate, sodium liquid glass, copper sulfate, etc. The most common additive for regulating the structural and mechanical characteristics of wood concrete is calcium chloride. Calcium chloride acts as a plasticizer on the concrete mixture, as it improves its workability with a slight reduction in water consumption. At the same time, even at small doses, it noticeably accelerates the setting and hardening of concrete. The use of calcium chloride facilitates and accelerates the heating of concrete and reduces the optimal temperature for heat treatment of concrete at normal pressure and makes it possible to reduce the voltage when heating products with electric current [52].

However, there are also known negative aspects when using calcium chloride as a wood concrete modifier: (i) it is sensitive to the composition of cement, and therefore, its dosage must be selected for a specific cement only experimentally; (ii) it has strong hygroscopicity and maintains a high constant moisture content of concrete, which leads to a decrease in the strength of wood concrete and impairs the thermal insulation ability; (iii) it produces efflorescence on the concrete surface; and (iv) it impairs the chemical resistance of wood concrete.

Other additives are inferior to calcium chloride and have their own disadvantages [53]. Aluminum sulfate reduces the strength of wood concrete by 10–12% compared to wood concrete modified with the addition of calcium chloride, which attracts up to 18 water molecules; liquid glass is inferior to the addition of calcium chloride because, when used, wood concrete has a 50% lower strength. Copper sulfate attracted up to 5 water molecules, and blue salt efflorescence was observed on the surface of the samples. The addition of potassium sulfate, according to [54, 55], increases the rate of dissolution of alite disks by 2 times, and more than 60% of the disks dissolve within 20 min. In addition, potassium sulfate accelerates the hydration of anhydrite. In the presence of sulfates, the hydration process strongly shifted toward the formation of calcium hydrosulfoaluminate. By acting as an accelerator for the hardening of wood concrete, potassium sulfate allows the cement paste to set and harden in the early stages, thereby protecting the cement stone from the aggressive effects of wood filler. An effective additive will provide the compressive strength of wood concrete at the level of wood concrete with the addition of calcium chloride and will not attract water.

Therefore, the choice of the type and consumption of an additive to regulate the structural and mechanical characteristics of wood concrete, which does not have the disadvantages of calcium chloride, is an urgent task. Additionally, in the published sources, we did not find methods for assessing the effectiveness and selecting the dosage of chemical additives for wood concrete. The standard method suggests testing samples of size $150 \times 150 \times 150$ mm on the 28th day of curing; this requires a long time and a large consumption of materials, incl. chemical additives. Calcium chloride, aluminum sulfate, sodium liquid glass, copper sulfate, and potassium sulfate were used for heavy concrete and subsequently used for wood concrete. At the same time, for heavy concrete, strength is important, and thermal conductivity is not as important (the heavy concrete is insulated with mineral wool, expanded polystyrene, etc.). Wood concrete is a structural and thermal insulation material; therefore, in addition to its strength, its low thermal conductivity is important. Therefore, it is also important to assess the influence of crystalline hydrates on the thermal conductivity of wood concrete.

The references cited above show that the main direction for improving the physical and mechanical properties of arbolite is the use of chemical additives; a review of both individual and complex modifying additives for improving the physical and mechanical characteristics of arbolite is provided. It is shown that additives provide a positive effect, but they also have certain disadvantages. In addition, to date, there is no method for assessing the effect of additives on the strength of arbolite with minimal costs of materials, time, and labor. The study of additives-modifiers in the studies presented above is carried out by direct methods—by making a large number of arbolite samples. Therefore, an express method is needed (presented in the article) for developing new arbolite modifiers with minimal costs of materials, time, and labor.

The objectives of this work were as follows: (i) to develop a new quick approach for assessing the effectiveness of additives for regulating the structural and mechanical characteristics of wood concrete, which will allow rapid assessment in a short time and will reduce the consumption of materials compared to the standard method; and (ii) to select the type and consumption of additives for modifying the wood-concrete mixture, which will allow for obtaining a material with the desired properties and will not have the disadvantages of other known additives.

2 Materials and methods

2.1 Materials and reagents

To prepare the arbolite, the following were used: wood chips (mixed species of pine needles and deciduous (birch, poplar, alder)) with sizes up to 30 mm, Portland cement CEM I 42.5 N, and tap water. The following additives were used to regulate the structural and mechanical characteristics of wood concrete: calcium chloride hexahydrate ($CaCl_2 \cdot 6H_2O$, 98%, Sigma−Aldrich), potassium sulfate (K_2SO_4, 99%, Sigma−Aldrich), sodium liquid glass (40% concentration), copper(II) sulfate pentahydrate ($CuSO_4 \cdot 5H_2O$, 98%, Sigma−Aldrich), and aluminum sulfate ($Al_2(SO_4)_3 \cdot 18H_2O$, 98%, Sigma−Aldrich).

2.2 Sample preparation

The standard method for assessing the effectiveness and consumption of additives (GOST 30459–96, GOST 19222–84, and EN 480–14) suggests the production of arbolite cube samples with an edge size of 150 mm with a known additive, such as calcium chloride (control composition) and the studied additive (tested composition). Then, the samples were kept for 28 days at a temperature of 18–20 °C and an air humidity of 60%. After this, the compressive strength is determined. Then, the compressive strength of the control and the studied composition was compared. Composition of wood concrete for testing according to standard methods is as follows: cement consumption, 350 kg/m^3; chip consumption, 230 kg/m^3; and W/C = 1.1.

Since harmful substances released from wood filler during the production of wood-concrete mixtures affect the setting time and the rate of strength gain of the binder during the hardening of wood concrete [56], it is advisable to determine the effectiveness of the additive on cement stone and not on wood concrete. This eliminates the influence of the quality of compaction of the wood-concrete mixture and moisture deformations of the wood filler on the strength (standard criterion for the effectiveness of the additive). The advantages of this method include reducing research time and material consumption. However, when implementing this method, it is necessary to extract harmful substances from the wood filler and add them to the cement paste. To do this, we have proposed a new method for assessing the effectiveness and consumption of additives.

In the first stage, it is necessary to obtain an aqueous concentrate (AC) of water-soluble components of wood filler (wood chips). AC is obtained by boiling, followed by recalculating the content of dissolved substances. With increasing temperature, the release of substances from wood filler increases, which negatively affects the setting time and strength of cement. The higher the temperature is, the less time is required to release the maximum amount of “cement poisons” [57]. In this work, an aqueous concentrate was obtained by boiling 500 g of wood filler in 2 L of water and determining the quantity of dry matter in the solution (the amount of water, wood chips, and boiling mode were selected based on published research results [58, 59]). Additional experiments were performed to determine the required boiling time. The task was to determine the minimum time during which the amount of soluble substances released by wood would be maximal. To do this, an average sample of 500 g of wood filler was poured with 2 L of water and weighed along with the container. The container was placed on an electric stove and boiled. After boiling, the container with the sample was weighed again, water was added to the original weight, and the sample was mixed. Then, the solution was drained from the container, allowed to cool, and filtered. A 100 mL aliquot of solution was evaporated on an electric hotplate, and the amount of extractives was determined. The data on the amount of substances released by wood depending on the boiling time are presented in Table 1.

Table 1 shows that 40 min is the minimum boiling time at which the maximum amount of extractives is released.

Then, the samples are made from Portland cement (or other binder that will be used to make wood concrete), water, the resulting aqueous concentrate, a known (calcium chloride), and a studied additive (in this work, we studied sodium liquid glass, copper sulfate, aluminum sulfate, and potassium sulfate). To test the additive, two batches must be made. For the first batch (reference), 400 g of cement, 2% calcium chloride (a known additive) of the mass of cement (8 g), and 70 g of water and water concentrate were added, corresponding to the percentage of dry residue. For the second batch (with the additive being tested), 400 g of cement, the additive whose influence needs to be determined, 70 g of water, and water concentrated in an amount corresponding to the % of dry residue were used. Cement and water were mixed for 5 min; AC was added, and the mixture was mixed for another 5 min. The cement paste was placed in 6-cavity molds to produce cube samples measuring 20 × 20 × 20 mm, followed by vibration compaction. Then, the forms are installed in the steaming chamber. The heat and humidity treatments were carried out under the following conditions: the relative humidity in the chamber was 90–100%, the temperature rise rate was 15–20 °C per hour for 4–6 h to a temperature of 80–90 °C, and the temperature was held at this temperature for 3–4 h. After this, the samples were removed from the chamber, kept at an air temperature of 18–20 °C and air humidity of 50–60% for 1–2 h, and tested for strength. Based on the results of testing the compressive strength of

Table 1 Amount of substances after the evaporation of 100 mL of sample, mg

Boiling time, min							
5	10	15	20	30	40	50	60
19 ± 2.3	206 ± 12	357 ± 21	504 ± 36	608 ± 30	1011 ± 48	1018 ± 27	1021 ± 42

individual samples, the average strength of a series of samples is determined, for which anomalous test results are first rejected. Based on the test results, a conclusion is drawn about the influence of the studied additive on the strength of cement paste in comparison with the reference composition (performance criterion). This method allows the evaluation and comparison of the effectiveness of various additives.

Samples for analysis were made from cement paste with aqueous concentrate. We studied samples aged for 28 days, obtained using composition No. 1 with an aqueous concentrate without a modifier, composition No. 2 with the addition of calcium chloride (2% by weight of cement), and composition No. 3 with the addition of potassium sulfate (2% by weight of cement).

The criterion for effectiveness, as in the standard method, is the strength obtained using known additives. The reference efficiency (1) is taken to be the strength of the main, most powerful calcium chloride accelerator. The strength of the additive-free composition is taken as zero efficiency. The standard method involves making samples of 150 × 150 × 150 mm wood concrete with the additive being studied and determining the compressive strength. The equation for calculating the efficiency criterion (*Ef*) is as follows:

$$Ef = R_{\mathrm{add}}/R_{\mathrm{CaCl2}}$$

where R_{CaCl2} is the compressive strength of the sample with calcium chloride (MPa), and R_{add} is the compressive strength of the sample with the additive; the effectiveness and consumption of which should be determined (MPa).

2.3 Sample analysis

The compressive strength was determined on a testing machine (hydraulic press) Testing Servicetronic with a load of up to 2000 kN.

Microscopic analysis of the cement compositions was carried out using an Axiovert-10 optical microscope (Germany) and a JSM-5610 LV scanning electron microscope (Japan).

The phase composition of the cement stone hydration products was studied using X-ray diffraction and differential thermal analysis methods. For differential thermal analysis, the thermoanalytical system "TGA/DSC-1/1600 HF Mettler Toledo Instruments" (Switzerland) was used. The sample weight for each sample was approximately 100 mg. The temperature increased from 20 to 1000 °C at a rate of 10 °C/min. To carry out X-ray phase analysis, a D8 Advance Bruker AXS X-ray diffractometer (Germany) was used. The results were processed using the Panalytical X'PERT PRO diffractometer software package (Netherlands).

The thermal conductivity coefficient of the wood concrete was determined using an ITP-MG4 250 device (Russia). The temperature of the lower plate of the device was 40 °C, and that of the upper plate was 10 °C. The sample dimensions were 250 × 250 × 40 mm. The test was carried out when the device reached a stationary thermal regime. The thermal conductivity coefficient of the wood concrete was determined by the following parameters: cement consumption, 350 kg/m^3; chip consumption, 165 kg/m^3; and W/C = 1.1.

The process flow of the experimental part is shown in Fig. 1.

3 Results and discussion

3.1 Comparison of the standard and proposed approaches

As noted earlier, to exclude the influence on the strength (a standard criterion for the effectiveness of an additive) of the compaction quality of the wood-concrete mixture and moisture deformations of the wood filler, it is more advisable to conduct research on cement stone rather than on wood concrete. Therefore, according to the proposed method for assessing the effectiveness of additives on cement stone (cube samples measuring 20 × 20 × 20 mm), hardening accelerator additives were investigated. At the same time, cube samples were made from a 150 × 150 × 150 mm arbolite mixture to evaluate the effectiveness of the additives using standard methods. The average density of the samples obtained from cement stone was 2278–2369 kg/m^3, and that obtained from wood concrete was 640–672 kg/m^3. The research results are presented in Table 2.

From Table 2, it follows that the efficiency criteria of the standard and proposed methods differ by no more than 7% (the standard method allows deviations in the strength of wood concrete up to 20%). The proposed method allows, in comparison with the standard method, a reduction in the time for determining the effectiveness and dosage

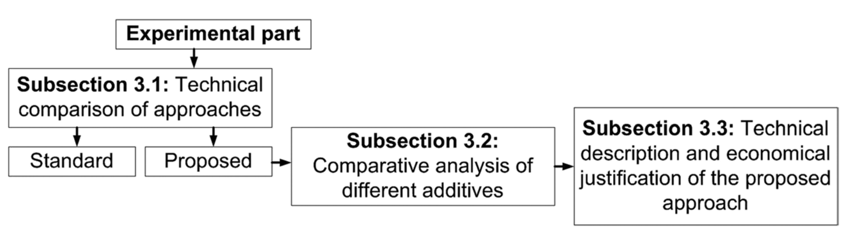

Fig. 1 The process flow of the experimental part

Table 2 Comparison of the results obtained using the standard and proposed methods

Additive	Additive consumption, % by weight of cement	Suggested method			Standard method			Notes
		Average density of cement stone, kg/m^3	Compressive strength of cement stone (increase in strength) according to the proposed method, MPa (%)	Performance criterion (*Ef*)	Average density of wood concrete, kg/m^3	Compressive strength (increase in strength) of wood concrete, MPa (%)	Performance criterion (*Ef*)	
Calcium chloride	1.0	2290	30.60 (0.00)	0.82	647	2.191 (0.00)	0.85	White discolorations on the surface of the sample
	2.0	2310	37.50 (22.55)	1.00	651	2.587 (18.07)	1.00	
	3.0	2329	37.50 (22.55)	1.00	659	2.607 (18.99)	1.01	
Sodium liquid glass	3.0	2330	24.76 (0.00)	0.66	648	1.780 (0.00)	0.69	–
	4.0	2349	27.63 (11.59)	0.74	652	2.095 (17.70)	0.81	
	5.0	2369	27.25 (10.06)	0.73	656	2.000 (12.36)	0.77	
Copper sulfate	0.4	2278	35.49 (0.00)	0.95	638	2.277 (0.00)	0.88	Blue discolorations on the surface of the sample
	0.8	2286	36.73 (3.49)	0.98	639	2.354 (3.38)	0.91	
	1.2	2294	28.73 (− 19.05)	0.77	641	1.837 (− 33.14)	0.71	
Aluminum sulfate	1.0	2291	27.54 (0.00)	0.73	657	1.852 (0.00)	0.72	–
	2.0	2312	33.75 (22.55)	0.90	662	2.510 (26.94)	0.97	
	3.0	2332	33.75 (22.55)	0.90	672	2.365 (27.70)	0.91	
Potassium sulfate	1.0	2288	34.58 (0.00)	0.92	640	2.360 (0.00)	0.91	–
	2.0	2307	37.47 (8.36)	1.00	644	2.472 (4.75)	0.96	
	3.0	2325	37.52 (8.51)	1.00	648	2.480 (5.08)	0.96	

from 28 days to 1 day and a reduction in material consumption by more than 400 times (3 samples measuring 20 × 20 × 20 mm for the proposed method and 3 samples measuring 150 × 150 × 150 mm for the standard method).

The best doses of additives obtained coincided with the optimal ranges for concrete. For the addition of calcium chloride, the optimal consumption was determined to be 2 wt% by weight of cement, the compressive strength of the wood concrete was 2.587 MPa (the efficiency criterion for the standard and proposed methods according to Section 2.2 is taken to be equal to 1), and the average density of the samples was 651 kg/m^3. When the additive concentration is reduced to 1%, its efficiency drops by 18% when tested using the proposed method and by 15% using the standard method. Increasing the concentration to 3% does not increase efficiency either using the proposed or the standard method. When liquid glass was added, the optimal consumption was 4 wt% by weight of cement, the compressive strength of the wood concrete was 2.38 MPa, and the average density of the samples was 652 kg/m^3. At the same time, the compressive strength is 19% less than that of arbolite with the addition of calcium chloride (the criteria for the efficiency of the additive according to the proposed and standard methods differ by 7 percentage points). When the concentration of the additive decreases to 3%, its efficiency drops by 8% when tested according to the proposed method and by 12% according to the standard method. Increasing the concentration to 5% leads to a slight decrease in efficiency according to both the proposed (− 1%) and standard methods (− 4%). For the addition of copper sulfate, the optimal consumption is 0.8 wt% by weight of cement, the compressive strength of the wood concrete is 2.354 MPa, and the average density of the samples is 639 kg/m^3. And the compressive strength decreases compared to arbolite with the addition of calcium chloride by 9% (the criteria for the efficiency of the additive according to the proposed and standard methods differ by 7 percentage points). When the concentration of the additive decreases to 0.4%, its efficiency drops by 3% when tested according to the proposed method and the standard method. Increasing the concentration to 1.2% leads to a significant decrease in efficiency according to both the proposed (− 12%) and the standard method (− 20%). For the addition of aluminum sulfate, the optimal consumption is 2 wt% by weight of cement, the compressive strength of wood concrete is 2.51 MPa, and the average density of the samples is 662 kg/m^3. Compressive strength is almost not reduced (– 3%) compared to calcium chloride arbolite (the additive efficiency criteria for the proposed and standard methods differ by 7 percentage points). When the additive concentration is reduced to 1%, its efficiency drops by 17% when tested using the proposed method and by 25% using the standard method. Increasing the concentration to 3% does not change the efficiency using the proposed method, while the efficiency drops by 6% using the standard method. For the addition of potassium sulfate, the optimal consumption is 2 wt% by weight of cement, the compressive strength of wood concrete is 2.472 MPa, and the average density of the samples is 644 kg/m^3. Compressive strength, as well as that of the aluminum sulfate additive, is almost not reduced (– 4%) compared to arbolite on calcium chloride (the criteria for the effectiveness of the additive according to the proposed and standard methods differ by 4 percentage points). When the concentration of the additive is reduced to 1%, its effectiveness drops by 8% when tested according to the proposed method and by 5% according to the standard method. Increasing the concentration to 3% does not lead to an increase in effectiveness according to either the proposed or standard method.

Thus, the efficiency criteria for the proposed and standard methods differ by no more than 7 percentage points, which indicates the efficiency of the method proposed in the article.

3.2 Comparison of additives

The main advantage of adding potassium sulfate over the main, most powerful accelerator (calcium chloride) is that the addition of potassium sulfate allows one to maintain a lower operational humidity of the wall and, accordingly, a lower thermal conductivity. Calcium salts have small cation radii, so they easily attract significant amounts of water dipoles. Calcium chloride exists in the form of crystalline hydrates with variable structures. Calcium chloride attracts up to 6 water molecules to form crystalline hydrates ($CaCl_2 \cdot 6H_2O$). Aluminum sulfate is also hygroscopic and is characterized by the formation of the crystalline hydrate $Al_2(SO_4)_3 \cdot 18H_2O$. The K_2SO_4 additive does not attract water and does not form crystalline hydrates. Thus, 1 kg of calcium chloride attracts up to 0.973 kg of water, which leads to a deterioration in the thermal conductivity, water absorption, and other properties of wood concrete (Tables 2 and 3, Fig. 2). Salt K_2SO_4 is not hygroscopic; therefore, its use will provide a lower thermal conductivity under the operating conditions of the wall enclosure (Table 3). This is also confirmed by the differential thermal analysis (Fig. 2a–c).

The thermogram characterizing the use of the calcium chloride additive (Fig. 2b) has a bifurcated endothermic effect on the removal of adsorbed water (91 and 116 °C). In the thermograms of compositions 1 and 3 (Fig. 2a, c), this effect is indicated by a single peak in the temperature range of 114 and 103 °C, respectively. This can be explained by the fact that the addition of calcium chloride attracts

Table 3 Results of determining the thermal conductivity and strength of wood concrete modified with additives

Type and consumption of additive	Average density of wood concrete, kg/m^3	Thermal conductivity coefficient of wood concrete according to experimental data, W/(m °C)
Calcium chloride, 2% by weight of cement	558 ± 6	0.120 ± 0.004
Potassium sulfate, 2% by weight of cement	550 ± 4	0.095 ± 0.002

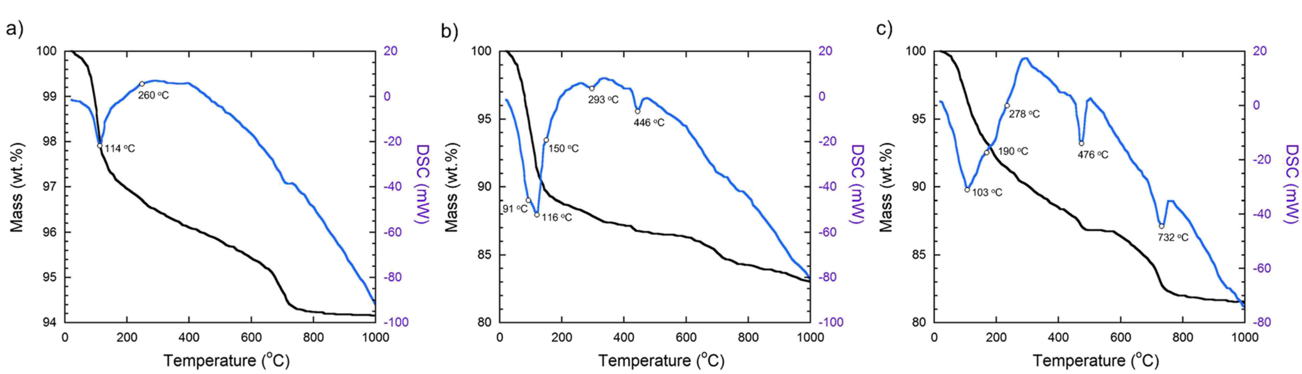

Fig. 2 TGA and DSC of cement stone with AC (**a** without additives, **b** with the addition of calcium chloride, **c** with the addition of potassium sulfate)

up to six molecules of water to form crystalline hydrates ($CaCl_2 \cdot 6H_2O$). The K_2SO_4 additive does not attract water and does not form crystalline hydrates. Consequently, the use of a potassium sulfate additive ensures a low operational humidity during the operation of the wall fence and guarantees a lower thermal conductivity. The slight endothermic effect of composition 2 (Fig. 2b) at a temperature of approximately 150 °C indicates an accelerating effect of the additive on the hydration process of C3A [60]. The endothermic effect of composition 3 (Fig. 2c) at a temperature of 190 °C indicates the accelerating effect of the additive on the process of C3S hydration. The second endothermic effect in composition 1 (Fig. 2a) is observed in the temperature range of 260 °C and is associated with the onset of C3S hydration and the formation of a C-S–H gel. For compositions 2 and 3 (Fig. 2b, c), this effect is observed at temperatures of 293 and 278 °C, respectively. This indicates an increase in the amount of C-S–H phase and an increase in the strength of the concrete with the addition of calcium chloride and potassium sulfate, in contrast to the additive-free composition. Another confirmation of the increase in the strength of wood concrete with the addition of potassium sulfate and calcium chloride is the endothermic effect of compositions 2 and 3 (Fig. 2b, c) in the temperature range of 446 and 476 °C, respectively. This can be attributed to the dehydration of $Ca(OH)_2$. During the first 8 h, $Ca(OH)_2$ accounted for approximately 25% of the total calcium hydroxide formed after 30 days. The bifurcated endothermic peak for composition 2 (Fig. 2b) in the temperature range 700–760 °C indicates the accelerating effect of calcium chloride on the hydration of C3A and the possibility of its chemisorption on the surface of C-S–H. Additionally, the second peak can be attributed to the effect of the introduction of a certain amount of chloride ions into the hydrosilicate lattice. For composition 3 (Fig. 2c), the effect in the temperature range of 700–760 °C manifests itself in the form of a larger single peak. This indicates that the addition of potassium sulfate is an effective accelerator but does not contain chloride ions. A small endothermic effect in the temperature range of 675 °C for composition 3 (Fig. 2) indicates the transformation of potassium sulfate into a uniaxial negative form.

Based on the analysis presented above, we can conclude that the addition of potassium sulfate, like the addition of calcium chloride, accelerates the hydration of C3S. However, at the same time, the addition of potassium sulfate attracted less adsorbed water than did the addition of calcium chloride.

The mechanism of action of additives, as well as the negative impact of substances released by wood on the hydration of cement paste, can be observed using optical and electron microscopy methods (Figs. 3 and 4).

In samples with an aqueous concentrate (Fig. 3a), a distribution of reducing substances (yellow) is observed throughout the entire volume of the cement stone. In samples with the addition of calcium chloride (Fig. 3b), reducing substances are blocked in the form of large yellow clusters. This allows us to conclude that due to this, the harmful effect of reducing substances on the processes of setting and hardening cement stone is reduced. In samples with the addition of potassium sulfate (Fig. 3c), reducing substances are also blocked in the form of yellow accumulations, which allows us to conclude that the proposed addition of potassium sulfate is effective.

The optimal structure is considered to have a porosity that is evenly distributed throughout the volume of the material in the form of pores that are polydisperse in size, closed, deformed into regular polyhedra, and separated by thin and dense interpore partitions of equal cross-sections with a glossy pore surface. Due to the lack of clear criteria for assessing the state of the pore surface, the following conventional gradations are used [40]: torn (loose), smooth (dense), and glossy (high density). From the photographs (Fig. 4a), we can conclude that large crystals are observed in the samples of cement with aqueous concentrate, and the pore surface is more loose and felt-like; as a result, a significant decrease in strength is observed. Images of the cement

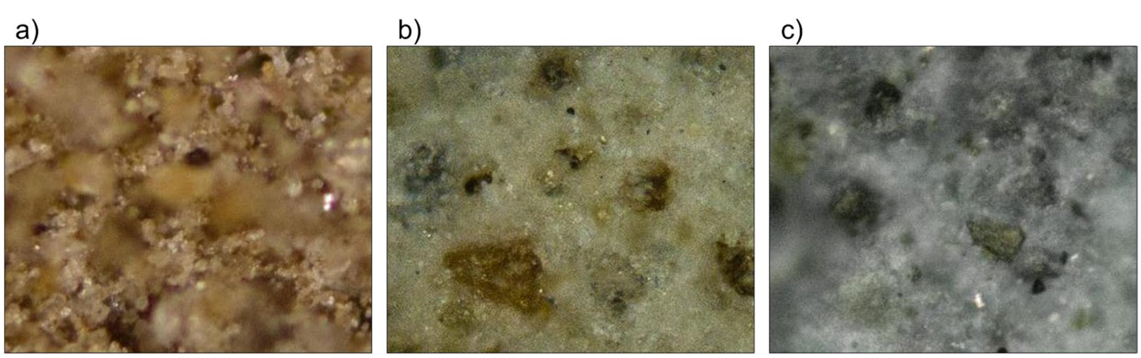

Fig. 3 Optical microscopy images (magnification × 100) of cement stone with AC **a)** without additives, **b)** with the addition of calcium chloride, **c)** with the addition of potassium sulfate)

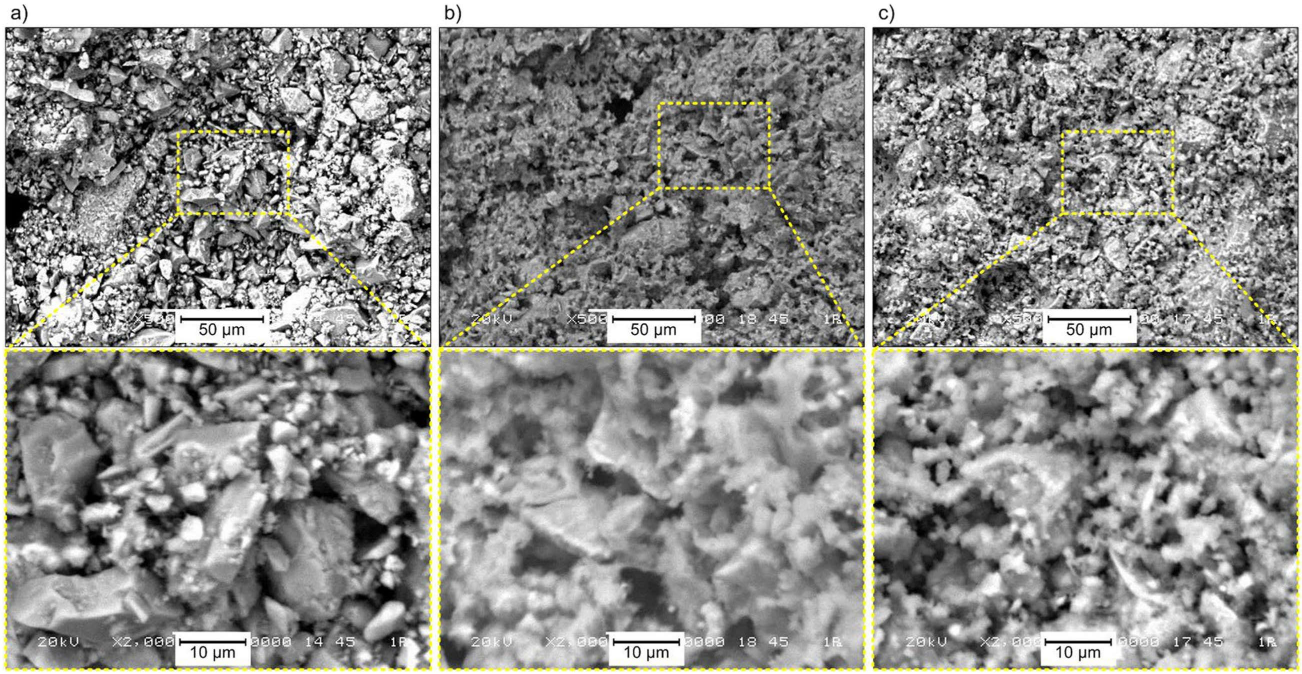

Fig. 4 SEM images of cement stone with AC without additives **a)**, AC and calcium chloride **b**), and AC and potassium sulfate **c**)

stone with the addition of calcium chloride (Fig. 4b) show a smooth surface and medium-sized pores. In photographs of cement stone with the addition of potassium sulfate (Fig. 4c), a smooth surface is observed, and the proportion of small pores increases.

The results obtained for assessing the structure and porosity generally coincide with the results of other researchers [40, 61, 62]. Thus, the research carried out allows us to say that when potassium sulfate is added, it is possible to obtain a smooth porosity that is uniformly distributed throughout the volume of the material with a large proportion of small pores.

To assess the phase composition of the obtained samples, XRD analysis was used. For composition No. 1 (Fig. 5a), the following minerals were identified: a high-temperature stable form of anhydrite, a stable form of calcium orthosilicate, and semiaqueous calcium sulfite. This indicates that substances released from wood filler ($C_{12}H_{22}O_{11}$—sucrose, $C_6H_{12}O_6$—fructose, $C_6H_{12}O_6$—glucose, $C_6H_{10}O_5$—starch) bind calcium ions, converting them into substances that have stable forms. Moreover, as indicated in [40, 53, 62], these substances do not contribute to the setting and hardening of cement. The presence of calcium carbonate was determined from the X-ray diffraction pattern of composition No.

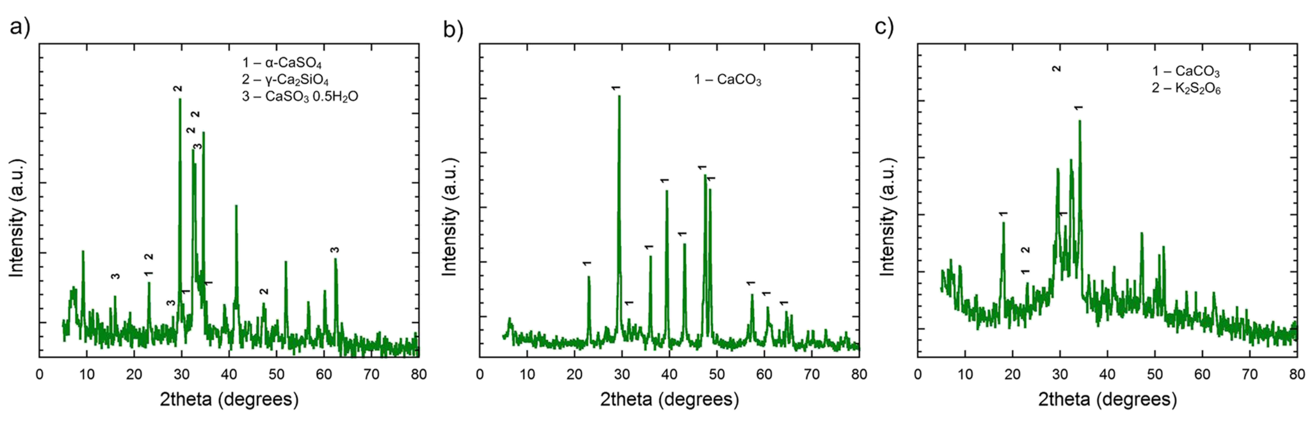

Fig. 5 XRD diffractogram of cement stone with AC **a)** without additives, **b)** with the addition of calcium chloride, **c)** with the addition of potassium sulfate)

2 (Fig. 5b). This may explain the rapid strength gains in cement stone with the addition of calcium chloride [40]. In the X-ray diffraction pattern of composition No. 3 (Fig. 5c), calcium carbonate and potassium dithionate are clearly visible. According to [40, 53], $CaCO_3$ affects the average density, water resistance, and strength of cement. According to [53], $K_2S_2O_6$ increases the strength of cement. The presence of calcium carbonate and potassium dithionate indicates that the addition of potassium sulfate provides high-strength cement stone and, consequently, wood concrete.

At the final stage, the thermal conductivity of the samples with the addition of calcium chloride and potassium sulfate was determined (Table 3).

Table 3 shows that the thermal conductivity of wood concrete with the addition of potassium sulfate is 20.8% less than that with the addition of calcium chloride. This finding is completely consistent with the above studies. This reduction will reduce wall thickness, material consumption, and cost by 20.8% (which will amount to $15 per 1 m^3 of wall).

A comparison of the advantages and disadvantages of the most well-known additives in wood concrete is presented in Table 4.

3.3 Proposed approach

The proposed method for assessing the effectiveness of additives for the manufacture of wood concrete is described below and presented in the diagram (Fig. 6).

Stage 1 (aqueous concentrate preparation):

- Sampling of 500 g of wood filler
- Adding 2000 mL of water to the wood filler sample
- Boiling the resulting mixture at 100 °C for 40 min
- The mixture was filtered after boiling through a sieve with a mesh size of 12–15 μm to obtain AC.

Stage 2 (preparation of cement paste):

- Preparation of a control mixture by mixing cement (400 g), AC (100 mL), and water (70 mL) with calcium chloride (8 g)
- Preparation of the test composition by mixing cement (400 g), AC (100 mL), and water (70 mL) with the test additive (preliminary consumption or range is taken from the literature sources or by expert assessment)
- Vibration compaction of the control and test compositions in 6 nested molds with cube sample rib dimensions of 20 × 20 × 20 mm
- Heat and humidity treatment of the control and test compositions according to the following regime: relative humidity in the chamber 90–100%, rate of temperature increase of 15–20 °C per hour for 4–6 h to a temperature of 80–90 °C, and then holding at this temperature for 3–4 h
- Removal of the control and test composition from the chamber, exposure at an air temperature of 18–20 °C and air humidity of 50–60% for 1–2 h
- The evaluation method allows one to select effective additive modifiers and determine their dosage while ensuring less labor intensity, test duration, and lower material consumption.

Stage 3 (determining the effectiveness of the additive):

- Determination of average density, compressive strength for the control and test compositions, and performance criteria for the test composition.

An economic comparison of the cost of determining the effectiveness of additives for arbolite using the standard and proposed methods is shown in Table 5. The comparison was performed in current prices as of 08/07/2024 in US dollars for the territory of the Republic of Belarus (Table 5).

As can be seen from the table, the testing method proposed in the article is more than 60% cheaper than the standard one.

Research limitations Instrument errors are as follows: scales for determining the mass of samples and the amount of materials for their manufacture, ± 0.015 g; digital caliper for measuring the size of samples, ± 0.03 mm; Testing Servicetronic hydraulic press, ± 2%; and device for determining thermal conductivity ITP-MG4 “250,” ± 5%. Statistical indicators are as follows: when testing samples from cement stone, the variation coefficient is 10% (average density and compressive strength); when testing samples from arbolite, the variation coefficient is 10% (average density); and the variation coefficient is 15% (compressive strength, thermal conductivity coefficient).

The main direction of development of the method and additive proposed in the article is to test the possibility of their use with materials on other organic fillers: plant and agricultural waste (wheat and rye straw, coconut fiber, etc.), ash (rice husk, wood, etc.).

4 Conclusion

Based on the results of this work, a method has been proposed for assessing the effectiveness of additives for regulating the structural and mechanical characteristics of wood concrete, which allows rapid assessment in a short time and reduces the consumption of materials compared to the standard method (testing using the method proposed in the

Table 4 Summary of the advantages and disadvantages of various additives in wood concrete

Additive	Advantages	Disadvantages
Calcium chloride	1. Accelerates the setting and hardening of concrete. Due to this, substances released from wood filler are prevented from having a harmful effect on cement 2. Acts on the concrete mixture as a plasticizer (reduces water consumption) 3. Reduces the optimal temperature 4. Allows you to reduce the voltage when heating products with electric current	1. Is sensitive to the composition of cement; therefore, its dosage must be selected for a specific cement only experimentally 2. It has strong hygroscopicity and maintains a high constant moisture content of concrete, which leads to a decrease in the strength of wood concrete and impairs the thermal insulation ability 3. Forms salt efflorescence on the concrete surface 4. Deteriorates the chemical resistance of wood concrete
Potassium sulfate	1. Accelerates the setting and hardening of concrete. Due to this, it prevents the harmful effects on cement of substances released from wood filler 2. Successfully neutralizes substances released from wood that slow down the processes of setting and hardening, reducing the strength of cement stone and causing corrosion of cement stone 3. Reduces the thermal conductivity coefficient and, accordingly, the wall thickness by 20.8% 4. Reduces the risk of cement stone corrosion 5. Does not form salt efflorescence on the concrete surface	1. Is sensitive to the composition of cement; therefore, its dosage must be selected for specific cement only experimentally 2. At a temperature of 20 °C, it has a solubility of 11%, which limits its maximum dosage, which may be needed, for example, when using freshly cut wood
Sodium liquid glass	1. Creates a film on the surface of wood filler and prevents the penetration of harmful substances from wood into cement 2. Does not form salt efflorescence on the concrete surface 3. Does not impair the chemical resistance of concrete 4. Works as an antiseptic for wood filler	1. Reduces the strength of wood concrete by up to 50% compared to wood concrete modified with the addition of calcium chloride 2. Requires a different technological sequence for the manufacture of wood concrete (first, you need to soak the wood filler with liquid glass for a certain time, and then add it to the wood-concrete mixture)
Copper sulfate	1. Accelerates the setting and hardening of concrete. Due to this, it prevents the harmful effects on cement of substances released from wood filler 2. Works as an antiseptic for wood filler 3. Does not impair the chemical resistance of concrete	1. Reduces the strength of wood concrete by up to 15% compared to wood concrete modified with the addition of calcium chloride 2. It has strong hygroscopicity and maintains a high constant moisture content of concrete, which leads to a decrease in the strength of wood concrete and impairs the thermal insulation ability 3. Is sensitive to the composition of cement; therefore, its dosage must be selected for a specific cement only experimentally 4. Forms salt efflorescence on the concrete surface
Aluminum sulfate	1. Accelerates the setting and hardening of concrete. Due to this, it prevents the harmful effects on cement of substances released from wood filler 2. Does not form salt efflorescence on the concrete surface 3. Does not impair the chemical resistance of concrete	1. Reduces the strength of wood concrete by up to 12% compared to wood concrete modified with the addition of calcium chloride 2. It has strong hygroscopicity and maintains high constant moisture content of concrete, which leads to a decrease in the strength of wood concrete and impairs the thermal insulation ability 3. Is sensitive to the composition of cement; therefore, its dosage must be selected for a specific cement only experimentally

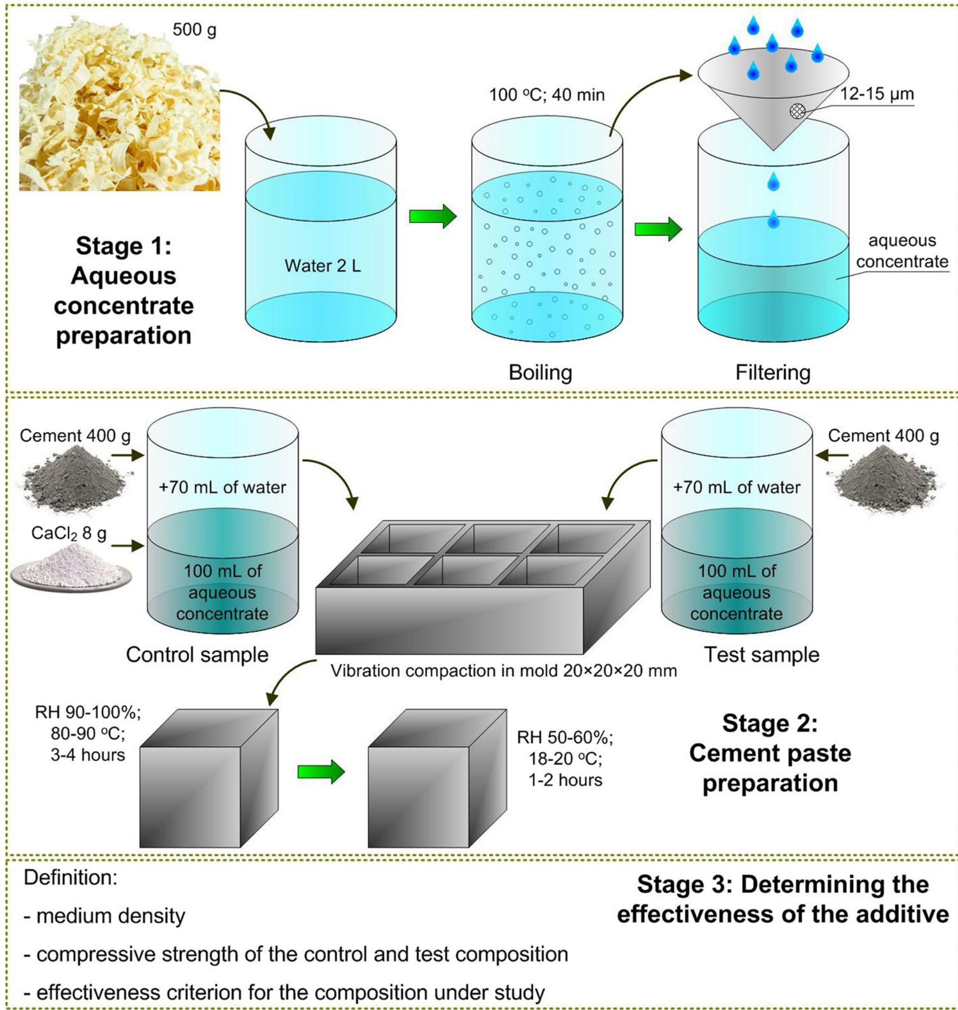

Fig. 6 Method for assessing the effectiveness of additives for the manufacture of wood concrete

Table 5 Comparative analysis of cost using standard and proposed methods (1 test)

Методика	Standard	Proposed
Cost of cement, $	0.50	0.12
Cost of wood chips, $	0.05	0.01
Cost of additive (calcium chloride or potassium sulfate—price the same), $	0.08	0.02
Cost of water (for sample preparation and for equipment rinsing), $	1.00	0.30
Cost of laboratory testing, $	40.00	15.00
Total, $	41.63	15.45

article is more than 60% cheaper than using the standard method). It is proposed to use potassium sulfate as an additive to regulate the structural and mechanical characteristics of wood concrete, which, compared to the most common additive, calcium chloride, holds 7 L less water per 1 m^3 of a wood concrete wall; therefore, its use will provide a lower thermal conductivity under operating conditions such as wall fencing. The mechanism of action of the additive was confirmed using modern methods of physicochemical analysis. The thermal conductivity of wood concrete with the addition of potassium sulfate is 20.8% less than that with the addition of calcium chloride. This reduction will reduce wall thickness, material consumption, and cost by 20.8% (which will be $15 per 1 m^3 of wall).

As a result of the analysis of the disadvantages of calcium chloride and other additives for regulating the structural and mechanical characteristics of wood concrete, the advantages of adding potassium sulfate as a modifier in wood concrete were shown:

- Works as a hardening accelerator, as in concrete
- Successfully neutralizes substances released from wood that slow the processes of setting and hardening, reducing the strength of cement stone and causing corrosion of cement stone
- Due to the small size of the cationic radii, it does not form crystalline hydrates, which reduces the thermal conductivity coefficient and, accordingly, the wall

thickness by 20.8% (no one has studied this for wood concrete, and for concrete, it is not so important, since concrete structures are usually used with insulation, for example, with mineral wool, and it is the insulation, not the concrete, that provides the thermal insulation properties)
- Reduces the risk of cement stone corrosion because one of the main causes of corrosion is crystalline hydrates (they are present in cement minerals, and nothing can be done about them, but in addition, they are mixed with additives, and since they are not present in potassium sulfate, the likelihood of corrosion decreases)
- Did not form salt efflorescence on the surface of the samples.

Author contribution Aleksandr Yagubkin: conceptualization, formal analysis, investigation, methodology, resources, supervision, data curation, validation, visualization, writing—original draft, writing—review and editing. Dmitry Shabanov: methodology, resources, supervision, data curation, validation, writing—original draft, writing—review and editing. Aleksandr Niyakovskii: formal analysis, investigation, validation. Valentin Romanovski: formal analysis, data curation, validation, visualization, writing—original draft, writing—review and editing.

Data availability All data, models, and code generated or used during the study appear in the submitted article.

Declarations

Ethics approval and consent to participate Not applicable.

Consent for publication Not applicable.

Competing interests The authors declare no competing interests.

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