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Research of technological parameters for producing thermal insulating arbolite based on developed slag alkali binders

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Abstract. The paper presents the results of studies of an arbolite block made from rice husks. Granulated blast furnace slag of «Qarmet» OJSC and Dzhambul phosphorus slag were used as slag-alkali binders. The resulting material was examined for basic thermal and mechanical characteristics. As a result, it was found that the adhesion strength of the developed slag-alkali binders with rice husks exceeds the adhesion strength of Portland cement with the latter by 1.40 - 4.08 times, where slag-alkaline arbolite was obtained based on rice husks with an average density of 450-800 kg/m^3 and a strength of 0.6 – 3.41 MPa. The frost resistance of the developed wood concrete compositions ranges from 15 to 30 cycles of alternating freezing and thawing. The results of this study can be used in the future when designing energy-efficient buildings.
Keywords: arbolite, rice husks, strength, slag, binders, slag-alkaline arbolite.

1. Introduction

Recently, cheaper construction methods have begun to be introduced in the construction industry, characterized not only by low cost, but also by relatively quick installation, minimal use of lifting equipment, a minimum range of materials used, and most importantly, low heat loss through the building envelope [1], [2], [3]. Such materials also include arbolite i.e., wood concrete [4], [5], [6].

A great contribution to the study and improvement of wood concrete production was made by domestic and foreign scientists, who, based on their research, emphasized the positive qualities of this material. The author Matyeva A.K. in her work [7] considers the technology of obtaining weather-resistant arbolite from chopped straw, where as a result arbolite was obtained with thermal conductivity qualities of the thermal interface thermal conductivity index equal to 0.07–0.09 W/(M K)*, which is 5 times better compared to burnt brick and strength from 1.8 to 4.0 MPa. In work [8], the authors carried out a simulation using the ANSYS software package of the effect on the thermal conductivity value of the pore content in arbolite blocks, where pores with content from 1.5% to 20% and the structure of the fibers in various directions were considered. However, the fiber structure also showed a significant difference from 8.16% to 15.33% depending on the direction of the fibers. In [9], the authors studied the effect of humidity on the strength characteristics of wood concrete, where they showed that wood concrete shows the greatest strength in its natural state. Thus, the previously conducted studies highlight the relevance of the direction, as well as the need to continue research in this direction.

The purpose of the work is to develop a technology for obtaining arbolite and its efficient production based on the optimization of the composition of slag-catching binders by processing granulated phosphorus and blast furnace slags with various technogenic modifiers.

2. Methods

The following were used as the main raw materials of slag-alkaline binders.

2.1 Aluminosilicate component of the slag-alkaline binder

The granulated blast furnace slag of JSC “Qarmet” (GBFS) was used (Table 1) [10].

The granulated blast furnace slag (GBFS) used in the research had the following chemical composition, with mass proportions of, %: CaO – 40.46; Al_2O_3 – 14.12; MgO – 7.97; SiO_2 – 36.08; TiO_2 – 0.99; BaO – 0.32; MnO – 0.33.

The Dzhambul phosphorus slag (PGS) was used (Table 1) [10]. Phosphorus slag had the following chemical composition, with mass proportions of, %: SiO_2 – 42.71; Al_2O_3 – 2.54; Fe_2O_3 – 0.25; CaO – 45.92; MgO – 3.24; P_2O_5 = 2.25; SO_3 – 0.5; puncture loss – 0.07.

Table 1 – Main physical characteristics of starting materials

Physical characteristics	Unit of measurement	PGS	GBFS
Bulk Density	kg/m^3	1210	1190
Density	g/cm^3	2.8	2.92
Basicity module	M_b	1.09	0.96
Activity module	M_a	0.06	0.39
Quality coefficient	C_q	1.2	1.68

2.2 Alkaline component of slag-alkaline binder

The following were used as an alkaline component:

- an aqueous solution of sodium silicate (liquid glass) with a silicate module M_s= 3, with a density of 1.1÷ 1.3 g/cm^3;
- sodosulfate mixture, a waste from the production of caprolactam, the chemical composition of which is given in Table 2;
- sodium sulfide sludge, a waste product from the production of metallurgical chromium oxide (chrompic), the chemical composition of which is given in Table 3;
- caustic soda (NaOH).

Alkaline components were used in the form of an aqueous solution. The density of the alkaline component was changed by adding water, and the silicate module of sodium silicate was changed by adding an aqueous solution of sodium hydroxide.

Table 2 – Chemical composition of alkaline components

Name	Content of oxides and salts, mass%							
	SiO_2	Na_2O	Al_2O_3	Fe_2O_3	Na_2CO_3	Na_2SO_4	NaCl	Impurities
Sodium silicate	73.2	24.4	1.5	0.07	-	-	-	0.82
Sodosulfate mixture	-	1-3	-	-	40-46	25-40	5-14	0.5-1

Table 3 – Chemical composition of chrompic

$Na_2S_2O_3$	Na_2SO_3	Na_2CO_3	Na_2S	Cr_2O_3
82.5-85.4	6.8-8.1	6.0-7.2	1.0	1.0

2.3 Organic filler

Rice husk was used as an organic filler, which is a waste of Akmarzhan JSC in Kyzylorda, formed during the technological processing of raw rice and meeting the requirements of [11] (Figure 1). The physical properties of rice husk are given in Table 4, and the fractional composition in Table 5.

Figure 1 – Rice husk

Table 4 – Physical properties of rice husk

Properties	Unit of measurement	Indicators
Bulk Density	kg/m^3	120
Natural humidity	%	9
Water absorption by mass	%	up to 160
Compaction coefficient		up to 2.5

Compared to wood, rice husks contain higher levels of inorganic substances and protein compounds, while at the same time, only pentosans are present among hemicelluloses. In addition, the equilibrium humidity values are low, but the smoldering and combustion temperatures are elevated (800-1000 ^{o}C). Strength characteristics are presented in Table 6.

Table 5 – Fractional composition of rice husks

Name of organic filler	Residue type	Residues on a sieve with a hole, mm%				Bottom
		20	10	5	2.5	
Rice husk	partial	0	10	9	69	22
	full	0	10	19	88	

The water absorption value of rice husk as a function of time is shown in Figure 2.

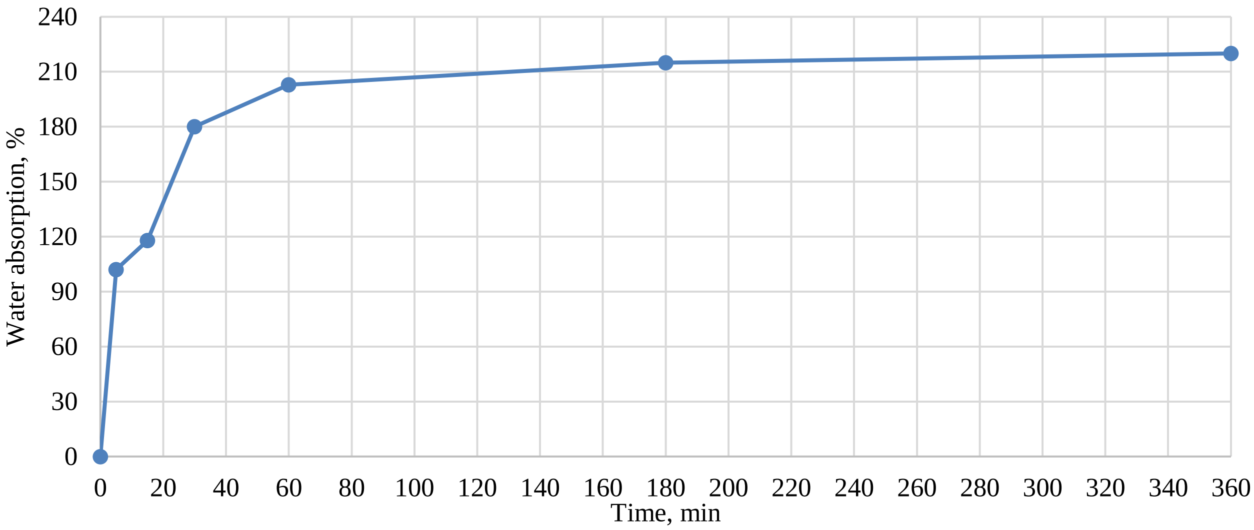

Figure 2 – Water absorption of rice husk as a function of time

Table 6 – Compositions and strength of the studied slag-alkaline binders

No.	Aluminosilicate component		Aqueous solution of alkaline component, %			ρ, g/cm^3	$R_{compr,}$ MPa
	Type of slag	Portland cement, %	Liquid glass	Chrompik	Sodosulfate mixture		
1	GBFS	-	8.8	1.95	-	1.28	90.9
2		-	5.9	3.9	-	1.25	66.0
3		-	5.9	-	3.33		84.4
4		-	-	7.8	-	1.2	20.0
5		5	-	4	-	1.1	15
6		5	-	-	3.5	1.25	26.5
7	PGS slag	-	5.9	-	3.33		87.2
8		-	-	7.8		1.2	30
9		5		4	-	1.1	65
10		10	-	4	-	1.1	67
11*		6	-	-	8	1.0	36.9

Determination of technological parameters for their production and study of properties, where the main characteristics of the slag-alkali binder were determined in accordance with [12], [13], [14], [15], [16].

3. Result and Discussion

3.1 Study of the influence of technological parameters on producing arbolite

Existing technological lines for the production of arbolite structures are mainly based on standard equipment for the production of concrete using lightweight porous aggregates. However, organic filler of plant origin, due to its specific features, requires the introduction of adjustments to the technological stages of production. Rice husk, like other organic fillers, also has specific features, such as a loose and fragile structure, heterogeneity in the structure of the spatial frame, and high water absorption. It is also distinguished by its still low bulk density, significant anisotropic properties, high elastic-plastic, and many other characteristics. These listed properties must be taken into account when designing the composition and production technology of wood concrete, since the macro- and microstructure of the resulting material, which determine the strength indicators, depends on them.

In addition to the factors listed above, the strength of the wood-concrete largely depends on the properties and quantity of the starting materials for the preparation of the wood concrete mixture, on the methods of its preparation and installation, as well as on the hardening conditions and the environment in which the wood concrete will work.

Based on the above, our further research was aimed at studying the technological factors influencing the production of wood concrete with the proper quality in terms of strength, such as consumption of the alkaline component specific pressing pressure, and hardening conditions.

3.2 Effect of compaction coefficient on strength

When forming the structure of wood concrete, the compaction process plays an important role, since the strength and average density of the resulting material depends on the degree of compaction.

Due to the anisotropy of the properties and the low average bulk density of the organic filler, compaction of the wood-concrete mixture cannot be carried out by conventional vibration. In the practice of producing arbolite products, to compact the arbolite mixture, methods of power vibration rolling, roller vibrating rolling, pressing, and vibrating under load are used. Manual tamping is also used, but the latter is very labor-intensive. Of the listed methods, vibration with a weight has found wide application. This method allows, due to vibration, to reduce the specific pressing pressure, and on the other hand, the use of molds with locking lids, since after removing the load, the compacted arbolite mixture is deformed back, which leads to disruption of the structure of the material.

Also, the progressive technology for manufacturing arbolite products includes the press method of molding an arbolite mixture with subsequent batch formation on a vertical conveyor of a molding station.

One of the important technological factors that determine the properties of a material is the coefficient (degree) of compaction, i.e., the ratio of the volume of the mixture in the loosely poured state to the volume of the molded material.

When studying the effect of the compaction coefficient of the wood-concrete mixture on strength, we used the composition of the wood concrete mixture in the ratio of components, mass, part: aluminosilicate component: rice husk: alkaline component = 1: 0.69: 0.71. In order to prevent reverse deformation of the samples, we used forms that allowed us to fix the volume of the sample. Fixation in a stationary state improves the contact interaction of the filler components with the binder, thereby developing the effect of contact hardening of the wood-concrete mixture.

The results obtained (Fig. 3) show that the strength of arbolite samples depends on the compaction coefficient of the mixture. Accordingly, with an increase in the compaction coefficient, the strength of the samples increases. Whereas, the samples molded without load had a strength of only 0.047 MPa (at $C_{compaction} = 1$), increasing $C_{compaction}$ to 1.5 made it possible to obtain wood concrete with a strength of 0.55 MPa, while the specific pressing load was equal to 0.012 MPa. A further increase in the specific pressing pressure by 0.076 MPa (at $C_{compaction} = 2$) led to an increase in the strength of the wood-concrete by 0.95 MPa. In this case, a dense packing of the constituent components of the arbolite mixture occurs, since the filler particles, being suspended in the arbolite mixture, during compaction tend to occupy a position in which the direction of the large size of each particle becomes parallel to the layers of the mixture.

From the results obtained it follows that an increase in the specific pressing pressure from 0.088 to 0.29 MPa led to an increase in the strength of arbolite samples by only 0.64 MPa.

When conducting research, it was revealed that with an increase in the liquid added to the mixture, it is also possible to reduce the specific pressing pressure, but at the same time, excess liquid flows out of the mold and, due to this, the homogeneity of the material is disrupted.

Based on the results obtained, we can make a preliminary conclusion that with increasing $C_{compaction}$, the strength of the arbolite samples increases, as a result of which the density also increases, since although the ratio of the components of the wood-concrete mixture was constant, the actual consumption of materials per $1m^3$ of products also increases.

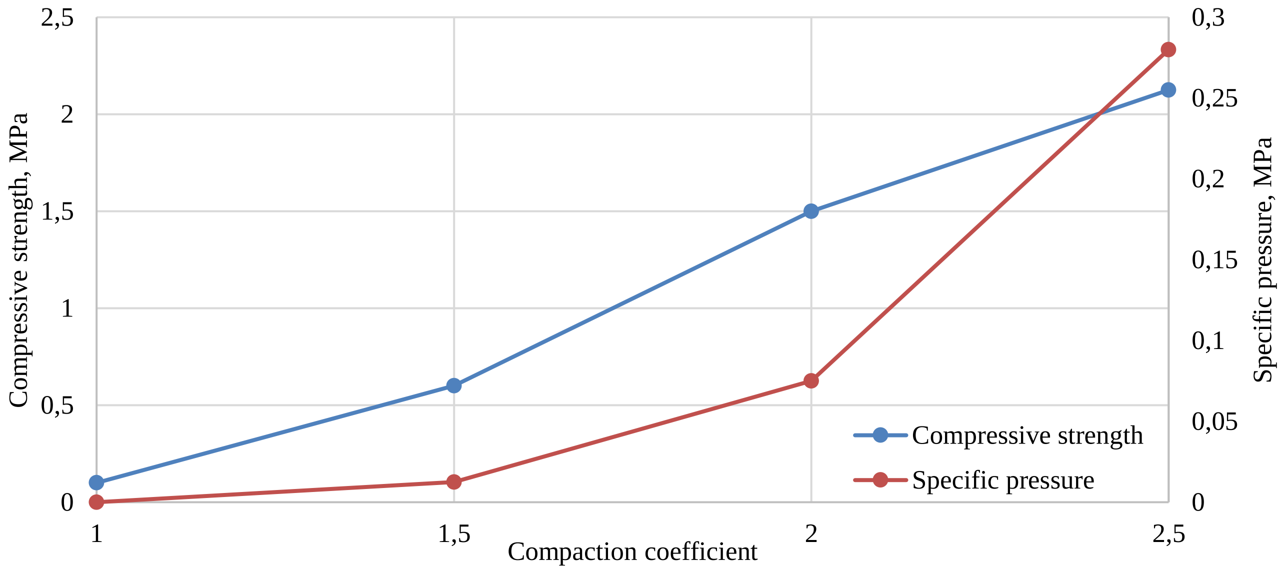

Figure 3 – The influence of the compaction coefficient on the strength of arbolite and on the specific compaction pressure of the mixture

3.3 Influence of hardening conditions on strength

Wood concrete consists mainly of two materials that are opposite in nature, the first is an organic aggregate that requires dry conditions and the second is a mineral binder that requires moisture and a certain temperature for the hydration reaction to occur. Therefore, the hardening of wood concrete products is an important technological operation in its production. Finding the optimal heat treatment regime for products will largely determine the strength and other indicators of products. Therefore, studying hardening processes and choosing optimal ways to accelerate them is a necessary task.

In the traditional technology for the production of wood concrete based on Portland cement, to accelerate its hardening, it is recommended to carry out heat treatment at a temperature of 40°C and a relative humidity of 50-60%. To accelerate the hardening of arbolite samples and determine the optimal heat treatment modes, staged experiments were carried out. The results obtained were analyzed and the following were established:

- that for the developed compositions, slag-alkali wood concrete on rice husks, the optimal heat treatment temperature is 70°C with isothermal exposure according to the 3+3+8+3 scheme. In further studies, to accelerate the hardening of arbolite samples, we used this heat treatment mode.

3.4 Study of the construction and technical properties of slag-alkali wood concrete on rice husks

The basic properties of slag-alkali wood concrete on rice husks, including strength, water absorption and swelling, and frost resistance, have been studied.

3.4.1 Change in strength over time

Studies of these properties were carried out on the developed compositions of slag-alkaline wood concrete on rice husks (Table 7).

Table 7 – Compositions and properties of slag-alkali wood concrete on rice husks

Slag-alkali binder's composition No.	Material consumption per 1 m^3 of wood concrete							Average density of wood concrete, kg/m^3
	Binder components					Rice husk,	Compressive strength, 28 days, MPa	
	Aluminosilicate		Alkaline component					
	Type of slag	Quantity, kg	Type	Density, g/cm^3	Quantity, l	kg		
1	Karaganda granulated blast furnace slag	250	Liquid glass + chrompic	1,28	200	150	0.5	465
2		350			225	150	1.6	572
3		350			270	240	2.8	678
4		500			315	240	3.6	825
5		350			225	150	1.4	552
6		500			315	240	3.4	805
7	Electrothermal-phosphorus slag	250	Liquid glass + Sodosulfate mixture	1,25	200	150	1.1	459
8		500			315	240	1	800
9		350	Chrompic	1,1	225	150	1	442
10		500	Sodosulfate mixture	1	315	240	2	785
11		350			315	240	1.8	635

Note: In compositions 10-11, the aluminosilicate component contains 5% Portland cement. Composition 11 was mixed with water.

The tests were carried out on samples that had hardened under natural conditions after heat treatment at the age of 1; 28; 90; and 180 days. It should be noted that the heat treatment was carried out at high humidity of the environment, created due to the release from moisture filler at a temperature of 70 ºC. To do this, the forms with the samples were tightly closed.

In this mode, a kind of "microclimate" is created inside the mold, which has a beneficial effect on the hardening processes of the binder, which, as is known, is hydraulic.

Tests have shown that with prolonged hardening, the strength of wood concrete increases, which indicates the continuation of hydration processes and an increase in the strength of the slag-alkaline binder stone.

The research results showed that the most intensive increase in the strength of wood concrete based on slag-alkaline binder is observed up to 28 days of age (Figure 4). At the same time, the increase in strength ranges from 12 to 25%. This increase can be explained by the fact that during this period the wood concrete is still in a wet state. The existing alkali in the alkaline component, extinguished by the organic filler, along with evaporating water, gradually migrates from the filler, as a result of which the hydration processes of the slag-alkaline binder deepen during subsequent hardening. At the same time, the density of the binding frame of the slag-alkali wood concrete increases, moisture losses decrease, and an increase in strength is observed over time. During the hardening period from 28 to 180 days, the moisture content of the wood-concrete is stabilized and its strength is also stabilized for almost all compositions, with the increase in strength ranging from 2 to 13%.

3.4.2. Water absorption and swelling

The water absorption test of arbolite samples was carried out on samples with rib dimensions of 10x10x10 cm, at normal atmospheric pressure.

The results obtained show (Figure 5) that the water absorption rate strongly depends on the density of wood concrete, which is associated with the content of binder and rice husk. Moreover, the lower the average density of wood concrete, the greater its water absorption rate. An increase in average density leads to a decrease in water absorption. Thus, arbolite samples with an average density of 500 kg/m^3 have this indicator equal to 89% by weight. This is explained by the fact that the organic filler - rice husk - has high water absorption. An increase in the density of wood concrete by 350 kg/m^3 led to a decrease in water absorption by 57% and amounted to 32%, respectively. It should be noted that the samples containing sand have the lowest water absorption.

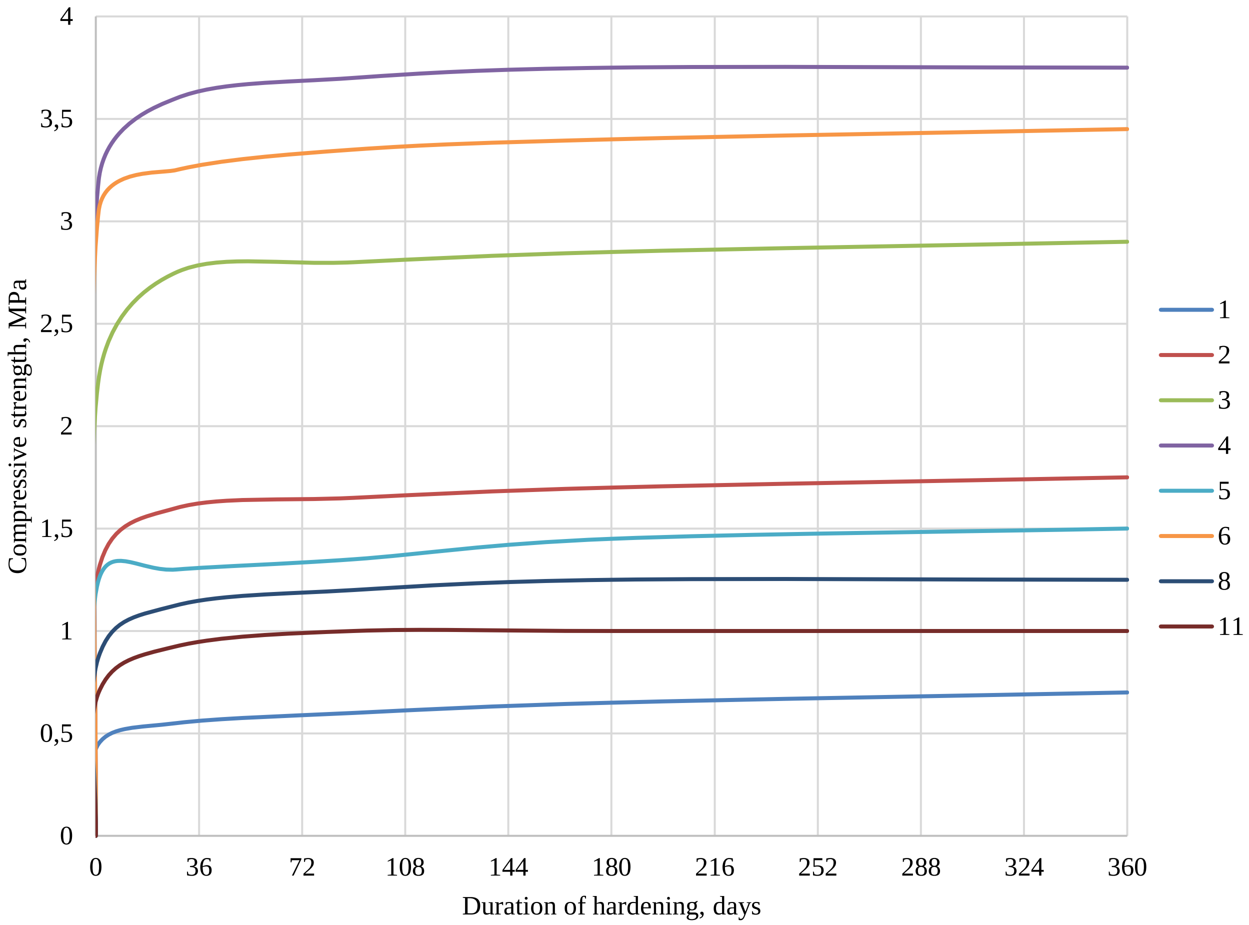

Figure 4 – Change in the strength of slag-alkali wood concrete on rice husks by time (the numbers of the compositions are according to the Table 7)

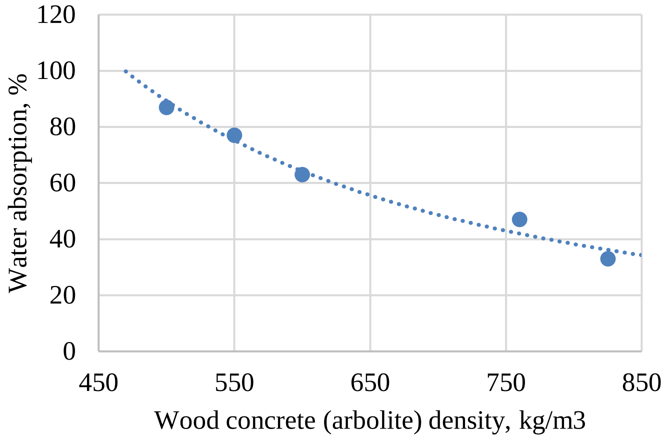

Figure 5 – Dependence of water absorption of slag-alkaline wood concrete on average density

The water absorption of wood concrete and structures can be reduced by protecting its open surfaces with various films and coatings. A protective layer of cement-sand mortar with a composition of 1:5 and a thickness of up to 10 mm reduces the water absorption of wood concrete by up to two times.

The results obtained from the study of linear swelling of samples made of slag-alkali wood concrete on rice husks in a water-saturated state show that they also depend on the density of wood concrete and range from 0.98 to 1.75%. It should be noted that the lowest swelling rate is characteristic of samples with the lowest content of organic filler.

3.4.3. Frost resistance

The frost resistance of slag-alkali arbolite on rice husks was determined on sample cubes with edge dimensions of 10x10x10 cm. The duration of freezing at a temperature of -20 °C was 4 hours. Thawing time at a temperature of 20 °C is 4 hours.

Tests of the frost resistance of slag-alkaline arbolite have shown (Table 8) that the frost resistance of the latter depends on its composition and ranges from 15 to 30 cycles of alternating freezing and thawing. The developed wood concrete meets the requirements in terms of frost resistance.

Table 8 – Frost resistance of slag-alkaline arbolite

Composition No. according to table. 7	Frost resistance coefficient through, cycles				Frost resistance, cycle
	15	25	30	40	
2	0.83	0.65	0.35		15
3	0.86	0.78	0.71		15
6	0.94	0.85	0.75		25
7	0.98	0.92	0.87	0.76	30
12	0.97	0.87	0.78	0.69	25

4. Conclusions

This paper presents technological solutions for obtaining slag-alkali arbolite on rice husks, allowing the use of industrial and agro-industrial waste, which lead to savings in expensive raw materials and the solution of economic and environmental issues.

The main results, practical recommendations obtained personally by the author, in the course of research work are as follows:

1. The possibility of obtaining slag-alkali arbolite on rice husks, with an average density of 450-800 kg/m^3 and a strength of 0.6-3.41 MPa, is theoretically substantiated and experimentally

proven due to the implementation of the properties of highly reactive slag-alkali binder and optimization of the technology for its production, ensuring high technology and construction and technical properties.

2. It was established that the adhesion strength of the developed slag-alkali binders with rice husks exceeds the adhesion strength of Portland cement with rice husks by 1.40 - 4.08 times. The highest adhesion strength values are demonstrated by binders sealed with a sulfate-containing alkaline component in combination with liquid glass, which are 0.18-0.21 MPa.

3. It has been established that the amount of the alkaline component introduced during the preparation of the arbolite mixture depends on the ratio of rice husk and aluminosilicate component. A graphical dependence of the effect of the alkaline component consumption on the ratio of rice husk and aluminosilicate component has been experimentally determined and derived.

4. The developed arbolite compositions on a slag-alkaline binder increase their strength over time. A more intensive gain in strength is observed up to the age of 28 days. In this case, the strength increase is from 12 to 25%. The linear swelling of slag-alkaline arbolite on rice husk in a water-saturated state depends on the density of the arbolite and is from 0.98 to 1.75%. The lowest swelling value is characteristic of samples with the lowest content of organic filler. The frost resistance of the developed arbolite compositions is from 15 to 30 cycles of alternating freezing and thawing. They have high weather resistance.

5. A technology for the production of slag-alkaline arbolite on rice husks has been developed, which allows, due to the use of the developed slag-alkaline binder compositions, to save time and energy costs of production due to accelerated hardening of arbolite products. At the same time, the production cycle of products is reduced to 3 times, and energy costs to 1.3-1.4 times compared to the traditional technology of arbolite production on Portland cement binder. In addition, the production of slag-alkaline binders also allows saving energy and natural mineral raw materials.

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Erzhan Kuldeyev – resources, drafting, editing.
Elmurad Yunusaliyev – analysis, visualization, data processing.
Zhambul Aymenov – methodology, drafting, interpretation.

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