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LIGHTWEIGHT CONCRETE BASED ON BIO-AGGREGATES AND GYPSUM BINDER FOR CONSTRUCTION PRODUCTS

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Abstract

Selecting the optimal composition of gypsum concrete with a two-component organic aggregate and glass fiber is a complex task, which in this work was solved using desing of experiment. Adequate mathematical models of tensile strength in bending, compressive strength and water absorption are determined. Based on the mathematical planning of the experiment, the composition of gypsum concrete with the maximum value of tensile strength in bending, which is used in the manufacture of gypsum concrete slabs, was determined. It is shown that gypsum concrete slabs made using casting technology from the developed gypsum concrete composition have a thermal conductivity coefficient K = 0,256 W/(m·K) and provide a noise level reduction to 29,55 dB in the frequency range from 100 to 300 Hz.

Keywords: gypsum binder, organic fillers, sawdust, flax fire, glass fiber, gypsum concrete, physical and mechanical properties, optimization of gypsum concrete composition, mathematical planning, gypsum concrete slabs.

ЛЕГКИЕ БЕТОНЫ НА ОСНОВЕ БИОЗАПОЛНИТЕЛЕЙ И ГИПСОВОГО ВЯЖУЩЕГО ДЛЯ ИЗДЕЛИЙ СТРОИТЕЛЬНОГО НАЗНАЧЕНИЯ

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Реферат

Подбор оптимального состава гипсобетона с двухкомпонентным органическим заполнителем и стеклянной фиброй является сложной задачей, которая в данной работе решена с помощью метода математического планирования эксперимента. Определены адекватные математические модели прочности на растяжение при изгибе, прочности на сжатие и водопоглощения. На основе математического планирования эксперимента определен состав гипсобетона с максимальным значением предела прочности на растяжение при изгибе, который использован для изготовления гипсобетонных плит. Показано, что гипсобетонные плиты, изготовленные по литьевой технологии из разработанного состава гипсобетона, имеют коэффициент теплопроводности K = 0,256 Вт/(м·K) и обеспечивают снижение уровня шума до 29,55 Дб в диапазоне частот от 100 до 300 Гц.

Ключевые слова: гипсовое вяжущее, органические заполнители, древесные опилки, костра льна, стеклянная фибра, гипсобетон, физико-механические свойства, оптимизация состава гипсобетона, математическое планирование, гипсобетонные плиты.

Introduction

The development and implementation of environmentally friendly materials into construction practice is one of the priorities of modern construction science. So-called “green” materials can reduce the negative impact on the environment during the construction and operation of buildings, on the one hand, and solve the problem of providing the population with affordable, environmentally friendly housing, on the other hand. In this regard, research aimed at expanding the scope of application of lightweight concrete based on gypsum binder and environmentally friendly organic aggregates is relevant for the development of “green” construction.

Organic aggregate are used for the production of heat-insulating, as well as heat-insulating structural and structural materials and products: wood concrete, cement fiberboard, xylolite, reed concrete, peat boards, heat-insulating boards made from flax, wood fiber and particle boards, etc. [1]. Research on the development of compositions of cement concrete with organic aggregate of various plant species is widely presented in scientific publications. The analysis shows that wood as an organic aggregate is used in the form of crushed wood, machine shavings, sawdust, and wood fiber [2–5]. Flax is used in the form of flax shives and tow [6, 7]. Stems, fibers, husks, cakes of cereal crops, cotton, hemp, reeds, sunflowers, and rapeseed are used as aggregates [8–12]. In terms of the number of publications, the most widely presented in research is the use of organic aggregates based on wood, flax and cereals in concrete. Some scientific studies show the possibility of using beet pulp [13], cactus fibers [14], coconut shells [15], horsetail fibers [16], eucalyptus fibers [17].

The purpose of this research is to develop the composition of a raw material mixture for light-weight concrete based on environmentally friendly and safe materials, such as gypsum, sawdust, flax shives and glass fiber, for the production of gypsum concrete slabs with high thermal and acoustic characteristics. The research was carried out as part of the research work “Lightweight concrete based on bioaggregate and complex gypsum binder for wall structures” (number of state registration 20230695 dated 16.05.2023, grant from the Ministry of Education of the Republic of Belarus).

Raw materials and research methods

In order to carry out experimental research, the building gypsum «Tayfun Master № 35» grade G–5 III A by GOST 125 was used. The setting time of gypsum is determined by GOST 23789: initial setting time is 9 minutes and 30 seconds, final setting time is 15 minutes. The normal density coefficient is 0.6. The mixing water for binder and gypsum concrete met the requirements of GOST 23732. For fiber reinforced lightweight concrete glass fiber 12 mm long in accordance with TS BY 691581903.001-2018 was used. Sawdust and flax shives were used as organic aggregate. Sawdust is a waste of forestry production "Ostrovetsky Experimental Forestry Enterprise". For experimental studies, sawdust with a particle size of up to 5 mm was used. The bulk density of sawdust was 0,258 kg/m^3, humidity 4 %. Flax shives with particle sizes up to 20 mm in length was used. The bulk density of flax shives was 0,154 kg/m^3, moisture was 0.5 %.

The studies using the methods and tests set out in national standards were carried out. Beam samples 40 × 40 × 160 mm in size were made with different contents of organic aggregate and tested for tensile strength in bending, compressive strength, water absorption, water resistance according to GOST 23789, porosity – according to GOST 12730.4, density – according to GOST 12730.1.

Samples-cubes with an edge of 70 mm to determine the physical and mechanical characteristics of optimized composition gypsum concrete were made. The compressive strength of gypsum concrete was determined on a hydraulic press PGM-1000MG4 A according to GOST 10180, water absorption – according to GOST 12730.3. The samples at a temperature of 50 ± 5 °C to constant weight in a SNOL60/300 LFN drying cabinet were dried. The thermal conductivity coefficient was measured using an ITP-MG4 device on slab samples measuring 250 × 250 × 30 mm according to STB 1618. The sound insulation properties of gypsum concrete were studied using a training acoustic chamber according to STB EN ISO 10140-414. Mathematical processing of the research results was carried out in the computer program "PlanExp B-D13", developed in the Microsoft Visual Basic 6.0 programming environment.

Optimization of organic aggregate compositions using desing of experiment

When creating lightweight concrete, considerable attention is paid to selecting the composition of the initial mixture. The quality of the resulting material depends on the quality of the raw materials and the correct composition of the mixture. Optimization of the composition of organic aggregates for gypsum concrete was carried out using desing of experiment and processing of factorial experiment data using the computer program "PlanExp B-D13". The content of the following components was considered as factors influencing the physical and mechanical properties of gypsum concrete: glass fiber (X1), sawdust (X2), flax shives (X3). The water-gypsum ratio remained constant in all compositions and was equal to W/G = 0.6.

To carry out the experiment, sample beams 40 × 40 × 160 mm were made, which were tested 2 hours after mixing with water, 7 days and after drying the samples to constant weight at a temperature of 50 ± 5°C. The following physical and mechanical properties of gypsum concrete with organic aggregates were determined as output parameters: tensile strength in bending (Rben), compressive strength (Rcs), water absorption (W_m). The levels and intervals of variation of factors are given in Table 1. The experimental plan and the obtained results are shown in the Table 2.

Table 1 – Levels and intervals of factor variation

Factors		Variation Levels			Variation Interval
Natural Value, % by weight of gypsum binder	Code	–1	0	+1	
Glass fiber	X1	0,2	0,4	0,6	0,2
Wood sawdust	X2	4	6	8	2
Flax shives	X3	2	4	6	2

Table 2 – Plan of experiment and Experimental results

№	Plan of Experiment						Rben, MPa, age			Rcs, MPa, age			W_m %
	Coded Factors Values			Natural Factors Values			2 hours	7 days	dry concrete	2 hours	7 days	dry concrete	
	X1	X2	X3	X1	X2	X3							
1	–1	–1	-1	0,2	4	2	2,16	2,91	3,04	2,75	3,21	5,91	26,0
2	+1	–1	-1	0,6	4	2	1,73	2,48	3,26	2,60	2,82	5,74	26,2
3	–1	+1	-1	0,2	8	2	1,95	2,70	3,13	2,50	2,69	5,73	27,1
4	–1	–1	+1	0,2	4	6	2,01	2,76	3,13	2,56	2,52	5,06	26,5
5	–1	0,19	0,19	0,2	6,38	4,38	2,01	2,76	3,24	2,66	2,59	5,45	26,1
6	0,19	–1	0,19	0,438	4	4,38	1,92	2,67	3,56	2,77	2,83	5,08	26,7
7	0,19	0,19	-1	0,438	6,38	2	1,94	2,69	3,53	2,75	3,07	6,31	36,1
8	–0,29	+1	+1	0,342	8	6	1,78	2,53	2,72	2,43	2,63	5,16	27,9
9	+1	–0,29	+1	0,6	5,42	6	1,54	2,29	2,39	2,60	2,40	5,27	28,3
10	+1	+1	–0,29	0,6	8	3,42	1,94	2,69	3,01	2,49	2,61	5,28	27,1

As a result of statistical processing of experimental data, assessment of the significance of the coefficients of mathematical models using the Student t-test and the adequacy of mathematical models using the Fisher criterion, the corresponding regression equations in coded form were obtained (1) – (7). Regression equations show the influence of two-component organic aggregate and glass fiber on the physical and mechanical properties of gypsum concrete:

Tensile strength in bending at the age 2 hours:

$$Rben_{2\,hour} = 1{,}948 - 0{,}135 \cdot x_1 - 0{,}107 \cdot x_3 - 0{,}106 \cdot x_3^2 + 0{,}096 \cdot x_1 \cdot x_2 - 0{,}026 \cdot x_1 \cdot x_3 . \quad (1)$$

Tensile strength in bending at the age 7 days:

$$Rben_{7\,day} = 2{,}722 - 0{,}132 \cdot x_1 - 0{,}109 \cdot x_3 - 0{,}119 \cdot x_3^2 + 0{,}112 \cdot x_1 \cdot x_2 - 0{,}035 \cdot x_1 \cdot x_3 . \quad (2)$$

Tensile strength in bending dry concrete:

$$Rben_{dry} = 3{,}547 - 0{,}106 \cdot x_1 - 0{,}125 \cdot x_2 - 0{,}277 \cdot x_3 - 0{,}369 \cdot x_1^2 - 0{,}339 \cdot x_3^2 - 0{,}156 \cdot x_1 \cdot x_3 - 0{,}168 \cdot x_2 \cdot x_3 . \quad (3)$$

Compressive strength at the age 2 hours:

$$Rcs_{2\,hour} = 2{,}811 - 0{,}106 \cdot x_2 - 0{,}077 \cdot x_3 - 0{,}113 \cdot x_1^2 - 0{,}126 \cdot x_2^2 + 0{,}083 \cdot x_3^2 + 0{,}045 \cdot x_1 \cdot x_3 . \quad (4)$$

Compressive strength at the age 7 days:

$$Rcs_{7\,day} = 2{,}85 - 0{,}063 \cdot x_1 - 0{,}084 \cdot x_2 - 0{,}222 \cdot x_3 - 0{,}219 \cdot x_1^2 + 0{,}091 \cdot x_1 \cdot x_2 + 0{,}041 \cdot x_1 \cdot x_3 + 0{,}096 \cdot x_2 \cdot x_3 . \quad (5)$$

Compressive strength dry concrete:

$$Rcs_{dry} = 5{,}605 - 0{,}053 \cdot x_1 - 0{,}429 \cdot x_3 - 0{,}094 \cdot x_1^2 - 0{,}442 \cdot x_2^2 + 0{,}31 \cdot x_3^2 + 0{,}081 \cdot x_1 \cdot x_2 + 0{,}059 \cdot x_2 \cdot x_3 . \quad (6)$$

Water absorption:

$$W_m = 34{,}682 + 0{,}525 \cdot x_1 + 0{,}132 \cdot x_2 - 0{,}784 \cdot x_3 - 7{,}466 \cdot x_1^2 - 1{,}736 \cdot x_2^2 + 1{,}018 \cdot x_3^2 + 0{,}235 \cdot x_1 \cdot x_2 + 0{,}152 \cdot x_1 \cdot x_3 - 1{,}037 \cdot x_2 \cdot x_3 . \quad (7)$$

Analysis of the coefficients of the regression equation for the output parameter of compressive strength shows that a higher content of flax shives (X3) leads to a decrease in compressive strength. The combined use of sawdust with glass fiber and flax shives with glass fiber in the composition of gypsum concrete has a positive effect on compressive strength. With an increase in the amount of flax shives, the water absorption of concrete decreases, as indicated by the negative value of the coefficient of factor (X3) in the mathematical model (7). On the contrary, an increase in the amount of glass fiber leads to an increase in water absorption of gypsum concrete.

The presence of sawdust (X2) in gypsum concrete has a greater effect on compressive strength than on tensile strength during bending. The factor (X2) has the greatest influence on compressive strength at the age of 2 hours; for gypsum concrete at the age of 7 days and for dry gypsum concrete, the influence of this factor becomes less significant, as indicated by the small value or absence of the linear coefficient of the factor (X2) in regression models (4) and (5) respectively.

The effect of factors on the concrete tensile strength in bending are different as can be observed in Figures 1–3. For the tensile strength in bending, the glass fiber content (X1) is one of the most important factors. At an early age influence glass fiber content (X1) is higher, compared to flax shives content (Figure 1, 2). Flax shives content (X3) is the second by its influence on tensile strength in bending. As the concrete dries, the influence of (X3) is increased.

Using regression equations, for a given output parameter, it is possible to determine the composition and predict the physical and mechanical properties of fiber-gypsum concrete with organic aggregates.

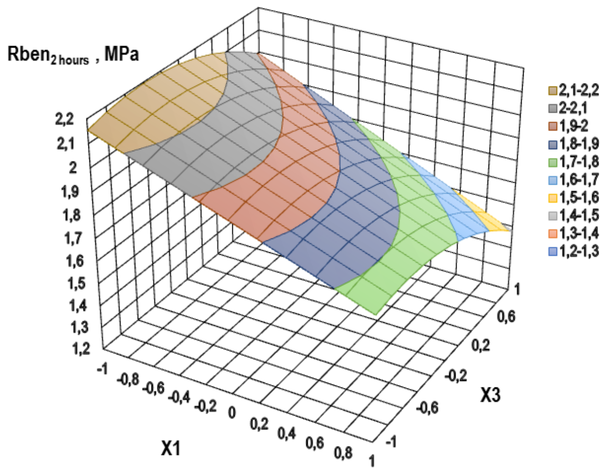

Figure 1 – Response surfaces for tensile strength in bending at 2 hours vs. glass fiber content (X1), flax shives content (X3), sawdust content (X2 = –1)

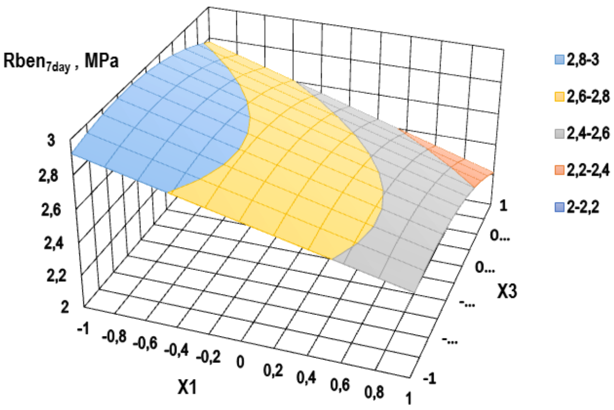

Figure 2 – Response surfaces for tensile strength in bending at 7 days vs. glass fiber content (X1), flax shives content (X3), sawdust content (X2 = 1)

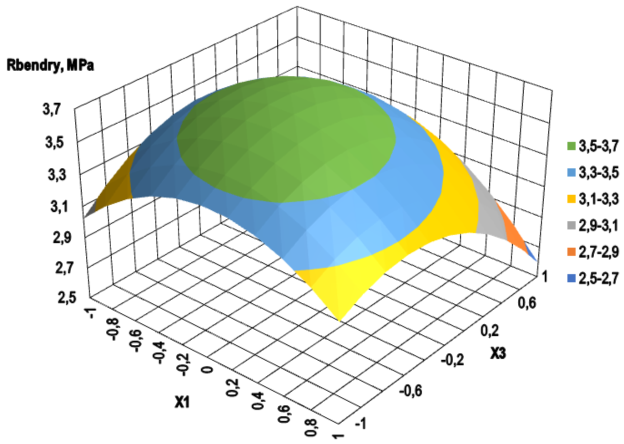

Figure 3 – Response surfaces for tensile strength in bending dry concrete vs. glass fiber content (X1), flax shives content (X3), sawdust content (X2 = –1)

According to GOST 32614 Gypsum construction boards. Technical conditions, GOST 6266 Plasterboard sheets Technical conditions the tensile strength in bending is the main characteristic for gypsum boards. According to the obtained regression equation (formula 3), the maximum flexural tensile strength dry concrete $Rben_{dry}$ = 3,67 MPa will be achieved at a value of factor X2 = -1, which corresponds to a sawdust content of 4 % by weight of the gypsum binder, and at value of factors: X1 = - 0,084 (glass fiber content 0,383 % by weight of gypsum binder), X3 = - 0,141 (flax shives content 3,718 % by weight of gypsum binder).

Thus, the composition of gypsum concrete with organic aggregates with a maximum tensile strength in bending, includes the following content of components, wt. %: gypsum binder – 59,49; glass fiber – 0,23; sawdust – 2,38; flax shives – 2,21; water – 35,69.

To experimentally confirm the adequacy of the mathematical models, sample beams 40 × 40 × 160 mm were made from gypsum concrete with an optimized composition of organic aggregates. The water-gypsum ratio corresponded to the standard consistency of the gypsum binder W/G = 0.6. The density of the dry samples was 1117 kg/m^3.

The obtained actual and calculated values of the physical and mechanical characteristics of gypsum concrete are presented in Table 3.

Table 3 – Experimental and theoretical values the physical and mechanical characteristics of gypsum concrete with an optimized composition

The value of gypsum concrete characteristics	Rben, MPa, age			Rcs, MPa, age			W_m, %
	2 hours	7 days	dry concrete	2 hours	7 days	dry concrete	
Experimental value	2,10	2,90	3,58	2,87	3,05	5,46	31,4
The value, calculated with equation (1) – (7)	2,01	2,78	3,67	2,80	2,98	5,24	32,7
Deviation, %	4,5	4,3	2,5	2,5	2,3	4,2	4,0

Deviations of experimental and theoretical values do not exceed 5 %, which indicates high convergence with the calculation result and confirms the reliability of the obtained mathematical models.

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Physico-mechanical, sound-proofing and heat-insulating properties of concrete slabs with lightweight fiber-gypsum with organic aggregates

The samples gained strength under natural humidity conditions at a temperature of 18–20 °C. The tests at the age of 7 days, after drying the samples to constant weight at a temperature of 50±5 °C and in a water-saturated state were carried out. The experimental results are presented in Table 4.

Table 4 – Physical and mechanical properties of gypsum concrete for gypsum concrete slabs

Density, kg/m^3 age		Compressive strength, MPa, age			Softening coefficient	Water absorption, W_m, %	Porosity, %
7 days	dry concrete	7 days	dry concrete	Saturated with water			
1388	1120	4,28	5,42	3,94	0,73	30,6	34,1

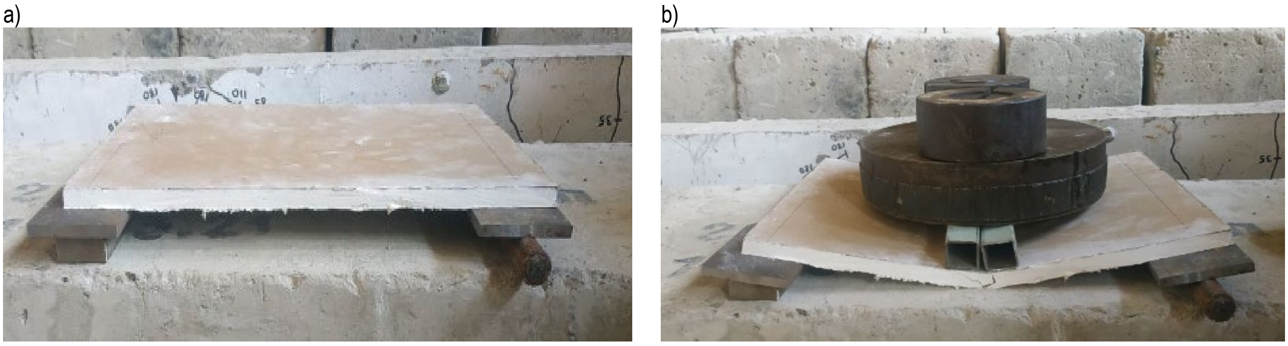
To determine the class of compressive strength and grade of average density, sample-cubes 70 × 70 × 70 mm were made and tested from optimized composition gypsum concrete.

According to GOST 25820-2014 the compressive strength class of gypsum concrete corresponds to B3,5; medium density grade – D1100.

Determination of the breaking load and deflection of sheets made of gypsum concrete with optimized composition of organic fillers was carried out according to the GOST 6266 method. The essence of the method is to destroy the sample-slab with a concentrated load applied in the middle of the span according to a single-span pattern. For testing, slabs with dimensions of 400 × 300 mm and thicknesses of 10 mm, 12,5 mm, 15 mm were made. To compare the results, a plasterboard board (GSP-A), 12,5 mm thick, manufactured at JSC BelGips was taken as a control sample.

These slabs are used for constructing partitions and cladding wall surfaces. To conduct the experiment, a sample measuring 400 × 300 mm was cut out of a plasterboard sheet. The device and testing process are presented in Figure 4. The test results are presented in Table 5.

a) b)



a) location of the slab on supports located at a distance of 350 mm; b) destruction of the slab under load applied in the middle of the span

Figure 4 – Procedure for testing sample-slabs for bending

Table 5 – The value of the breaking load when testing sample-slabs for flexural

Name of samples	Thickness, mm	Breaking load, N	Deflection, mm
Slab JSC BelGips	12,5	300	2,0
Slab №1	10	160	3,0
Slab №2	12,5	240	2,08
Slab №3	15	320	3,6

Analysis of the test results shows that, with the same thickness, the gypsum slab of JSC BelGips has higher flexural strength than gypsum concrete slab № 2 with an optimized composition of organic aggregate. In the experiment, a sheet of plasterboard with glued layers of cardboard was used; board № 2 was not glued with cardboard. All other things being equal, the experiment did not take into account the influence of the adhesion strength of the gypsum core and cardboard, which can provide an increase in the flexural strength of gypsum plasterboard sheets of JSC BelGips. When the slab thickness increased to 15 mm (slab № 3), the value of the destructive load exceeded that for a 12,5 mm thick gypsum plasterboard.

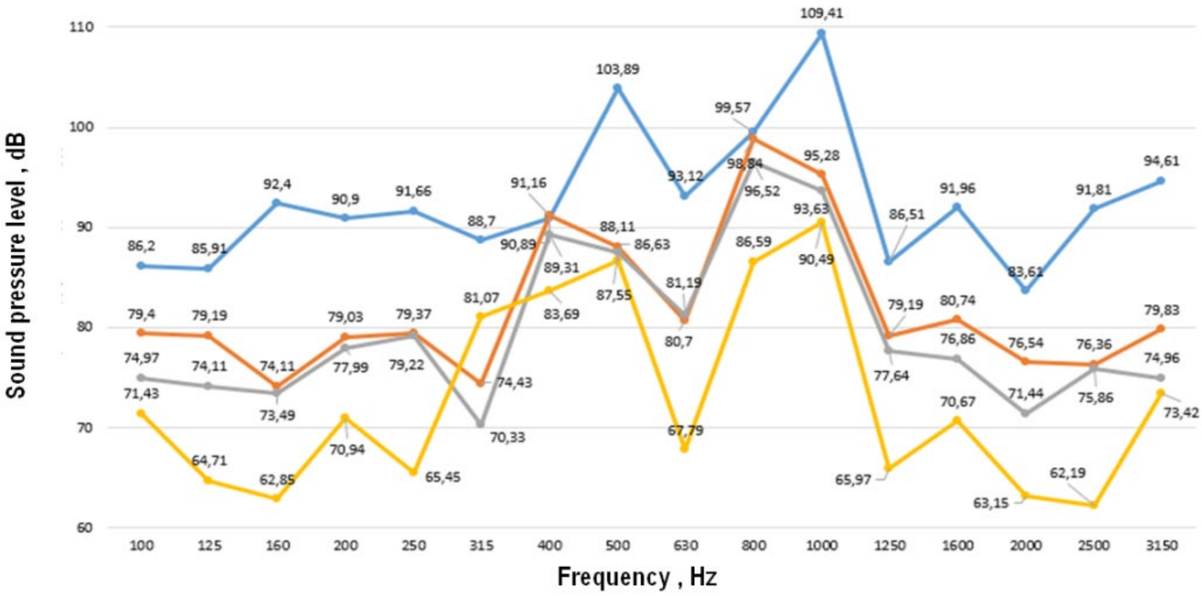
To conduct research to determine thermal conductivity, a slab measuring 250 × 250 × 30 mm was made from a gypsum concrete mixture with an optimized composition of organic aggregates and dried to constant weight. Measurements performed on the ITP-MG4 device showed that the thermal conductivity is 0,256 W/(m·K) with density of gypsum concrete 1120 kg/m^3. According to GOST 6266, the thermal conductivity of plasterboard boards should be in the range of 0,22–0,35 W/(m·K).

The sound insulation properties of gypsum concrete slabs were determined using a training acoustic chamber on samples measuring 250 × 250 × 30 mm and 250 × 250 × 12,5 mm. A comparison of sound insulation properties was carried out with plasterboard boards of JSC BelGips, 12,5 mm thick and 250 x 250 mm in size.

Measurements were carried out on sound pressure levels in octave frequency bands with geometric mean frequencies of 100; 125; 160; 200; 250; 315; 400; 500; 630; 800; 1000; 1250; 1600; 2000; 3150 Hz in accordance with SN 2.04.01-2020 Noise protection. Construction standards of the Republic of Belarus. At the first stage, measurements of the sound pressure level were carried out in an empty acoustic chamber ("radiating" compartment). At the next stage, the acoustic chamber was divided into two compartments by a polystyrene foam partition, and the gypsum concrete sample under study was installed in the "window" of the partition. Next, the frequency was changed and the sound pressure level was recorded in the compartment separated from the source of the sound signal by a partition with the material under study ("receiving" compartment).

The efficiency of the soundproofing properties of the material was assessed by the decrease in the sound pressure level in the "receiving" compartment compared to the sound pressure level in the "emitting" compartment. The results of measuring the sound insulation properties of plasterboard slabs and gypsum concrete slabs with organic aggregates are presented in Figure 5.

Analysis of the results obtained shows that gypsum concrete with organic aggregate is superior in its soundproofing properties to the gypsum plasterboard board of JSC BelGips with the same thickness in the frequency range from 100 to 160 Hz. At a sound pressure level exceeding 250 Hz, the samples have comparable values in the amount of reduction in the sound pressure level in the "receiving" compartment. The results obtained show that the sound insulation ability of gypsum concrete slabs with organic aggregate increases with increasing slab thickness. Thus, in the frequency range from 100 to 300 Hz with slab thicknesses of 12,5 mm and 15 mm, the magnitude of the decrease in sound pressure level is, respectively, from 11,23 dB to 18,91 dB, from 14,77 dB to 29, 55 dB. In general, the results obtained allow us to draw a conclusion about the effective sound-proofing ability of gypsum concrete slabs with organic aggregate.



1 – empty chamber (blue line); 2 – BelGips slab 250 × 250 × 12,5 mm (orange line); 3 – gypsum concrete slab with organic aggregate 250 × 250 × 12,5 mm (gray line); 4 – gypsum concrete slab with organic aggregate 250 × 250 × 30 mm (yellow line)

Figure 5 – Dependence of the sound pressure level in the “receiving” chamber on the frequency of sound when passing through the partition

Conclusion

Mathematical dependences of the physical and mechanical properties of gypsum concrete on the amount of organic aggregate have been obtained, which make it possible to optimize and calculate the compositions of gypsum concrete with given properties. A raw material mixture composition has been developed for structural and thermal insulation dispersed-reinforced light-weight gypsum concrete with two-component organic aggregate based on local raw materials of the average density grade D1100, strength class B3,5, thermal conductivity K = 0,256 W/(m·K). Gypsum concrete slabs, made using casting technology from the developed gypsum concrete composition, provide a noise level reduction of up to 29,55 dB in the frequency range from 100 to 300 Hz.

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