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Structural Formation and Properties of Eco-Friendly Foam Concrete Modified with Coal Dust

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Abstract: Foam concrete is a popular energy-efficient construction material with a fairly wide range of usage in buildings and structures. Increasing ecological efficiency and reducing construction costs by the application of different types of industrial waste in the manufacturing technology of this composite is a promising direction. The main goal of this study is to investigate the possibility of coal dust (CD) waste inclusion in the technology of energy-efficient cellular concrete produced by foam concrete technology. Test samples of foam concrete were made using coal dust by partially replacing cement in the range of 0–10% in increments of 2%. The following primary characteristics of foam concrete were studied: fluidity of mixtures; compressive strength; density; thermal conductivity of foam concrete. An X-ray diffraction analysis of foam concrete composites was performed, which showed changes in their phase composition when using coal dust as a modifier. Coal dust in rational quantities from 2% to 6% improves the physical and mechanical characteristics of foam concrete and increases the structure uniformity. The optimal values of the foam concrete characteristics were recorded at a dosage of coal dust of 6%. At the same time, the density decreased by 2.3%, the compressive strength increased by 15.6%, and the thermal conductivity coefficient decreased by 8.9% compared to the ordinary composition. The use of the resulting foam concrete is advisable in enclosing structures to create high energy efficiency of buildings and structures due to the improved structure and properties.

Keywords: foam concrete; coal dust; waste in concrete; compressive strength; thermal conductivity

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1. Introduction

The urgent character of this research is due to the fact that, currently, construction and urban and economic management require technologies of energy-saving and energy-efficient building materials [1–3]. Energy efficiency is necessary in the stage of manufacturing building materials, as well as in the stage of construction of buildings. That is, civil engineers and scientific developers in the field of construction are faced with the task of maximizing the optimization of the technology of building material production and structure erection considering environmental friendliness and energy efficiency [4]. In this regard, approaches to comprehensively solving the voiced problems through the application of different types of waste for the purpose of greening the environment in the technology of new energy-efficient and energy-saving construction materials are seen as interesting and important [5–10]. One example of such building materials that are most efficient in terms of energy saving is cellular concrete [11–14]. A number of works are known in the study of industrial, fuel, and energy waste as components in the composition of cellular concrete [15–19].

In [20], foam concrete compositions with fly ash were developed that have acceptable characteristics in terms of compressive strength and lower thermal conductivity. The compositions of foam concrete with fly ash, developed and studied in [21], are characterized by lower density and have less shrinkage. However, their strength is within acceptable limits. It was found in [22] that the use of fly ash instead of part of the cement in an amount of 10–40% is acceptable and helps to reduce the density and thermal conductivity of the material with an acceptable drop in compressive strength. The addition of ash of more than 40% leads to a fairly strong loss of strength and a significant deterioration in other characteristics. In general, the use of fly ash in foam concrete is justified and, with the correct selection of the formulation, allows one to obtain composites with improved thermal insulation characteristics and lower density while maintaining an acceptable reduction in compressive strength, which is also confirmed by a number of the following studies [23–27].

Instead of fly ash, other types of waste are used in foam concrete, for example, various types of slag. In the study [28], compositions of foam concrete with slag were developed. It has been established that with the introduction of slag from 25% to 55%, with increasing its dosage, the characteristics of the composite deteriorate. However, by optimizing the recipe parameters and with a 35% slag content, it is possible to obtain foam concrete with parameters that meet the requirements of engineering applications. In [29], by replacing part of the cement with 30% slag and adding 1% basalt fiber to the composition of foam concrete, the authors were able to obtain composites with the best characteristics in terms of compressive and flexural strength in comparison with control samples. A study of the resistance of slag foam concrete to sulfate and chloride environments carried out in [30] showed that the blast furnace slag inclusion instead of part of the binder increases the resistance of foam concrete to these aggressive environments by up to 50%. The effective slag introduction as a partial replacement for cement in foam concrete technology has also been investigated in a number of subsequent works [31–34].

Microsilica is a popular type of waste used in concrete technology, including foam concrete. Research carried out in [35] showed that the use of microsilica together with basalt fiber in the composition of foam concrete is quite promising, and the correct selection of the recipe makes it possible to obtain strong and lightweight insulating foam concrete. Silica smoke in the composition of foam concrete acts as a mineral stabilizer and increases the stability of foams, which is confirmed by research [36,37]. In [38], the introduction of microsilica instead of part of the cement up to 10% helps to increase the compressive strength of foam concrete. Research [39–41] also confirms the positive effect of silica fume introduction on the stability of foam concrete mixtures and their physical and mechanical characteristics.

An effective solution is to use several types of waste in foam concrete technology. For example, in [42], the compositions of foam concrete with fly ash and microsilica were studied, and with rationally selected recipe parameters it is possible to obtain foam concrete with acceptable characteristics. In the study [43], the optimal compositions of foam concrete with steel slag and fly ash were developed. The use of waste such as marble powder in an amount of 25% instead of a part of fine aggregate and rice husk ash in an amount of 10% by weight of the binder in [44] in the composition of foam concrete allows us to obtain a composite with the lowest drying shrinkage value and good strength characteristics.

Based on these research sources, it can be noted that, among the line of cellular concrete produced in the global industry, foam concrete occupies a special place. Foam concrete produced using non-autoclave technology has a number of advantages in terms of ease of production, as well as minimizing energy costs in its production, and the possibility of conducting experiments and pilot testing of new recipes and technological solutions regarding its composition and technology [45]. At the same time, for numerous countries, especially those where coal mining is widely developed, there is a problem of the accumulation of coal dust in large quantities near populated areas. This problem increases the risk of environmental pollution and hinders the achievement of sustainable development goals [46,47].

Thus, the purpose of this study is to investigate the possibility of coal dust waste application in the technology of energy-efficient cellular concrete produced using foam concrete technology.

Research objectives:

- Analysis of the existing research, regulatory, and technological base to manufacture non-autoclaved foam concrete using various types of waste;
- Identification of scientific deficits and prospects from the point of view of theory and practice for the use of coal dust as components of such foam concrete;
- Setting up an experiment, selecting basic components, and determining technological parameters to obtain the most effective foam concrete based on coal dust;
- Conducting pilot experiments and analyzing the results obtained in comparison with existing analogs to determine the effectiveness of the suggested solutions;
- Determination of fundamental relationships between the composition, structure, and properties of the resulting foam concrete;
- Scientific substantiation of the result obtained, determination of the qualitative and quantitative picture of structure formation, and properties of foam concrete using coal dust.

The scientific novelty of this research lies in obtaining experimental data and identifying, on their basis, fundamental and applied dependencies between the composition, structure, and properties of foam concrete based on coal dust, identifying the best recipe-technological ratios of such foam concrete. The specificity and explanation of ongoing processes are based on graphic, physical, and technological dependencies.

2. Materials and Methods

2.1. Materials

To manufacture experimental foam concrete samples, the following initial raw materials were used:

- Portland cement CEM I 52.5N (C) (CEMROS, Stary Oskol, Russia).
- Quartz sand (S) (RostStroyMix, Rostov-on-Don, Russia).
- Coal dust (CD) (IMPEX-GROUP, Krasny Sulin, Russia).
- Synthetic foaming agent Rospena (F) (Rospena, Mordovia, Russia).

The characteristics of raw materials are presented in Tables 1–4.

Table 1. Portland cement properties.

Property	Value
Specific surface area (m^2/kg)	335
Soundness (mm)	0.4
Fineness, passing through a sieve No 008 (%)	98.1
Setting times (min)	
- start	150
- end	240
Compressive strength (MPa):	
- 2 days	24.6
- 28 days	56.1

The bulk density of coal dust was 545 kg/m^3. Figures 1 and 2 show XRD analysis and size distribution curve of coal dust particles.

Table 2. Characteristics of quartz sand.

Sieve Diameter (mm)					Content (% by Weight) of Grains with a Particle Size of Less than 0.16 mm	Fineness Modulus
Partial Residues on Sieves (%)						
Total Residues on Sieves (%)						
2.5	1.25	0.63	0.315	0.16		
1.6	4.3	7.9	39.7	43.7	2.8	1.72
1.6	5.9	13.8	53.5	97.8		
Bulk density (kg/m^3)					1421	
The content of dust and clay particles (%)					0.12	
Content of clay in lumps (%)					0.06	

Table 3. Chemical composition of coal dust.

SiO_2 (%)	Al_2O_3 (%)	Fe_2O_3 (%)	CaO (%)	MgO (%)	TiO_2 (%)	P_2O_5 (%)	SO_3 (%)	Loss on Ignition (%)
30.83	15.74	6.22	2.92	3.43	0.64	0.07	2.81	37.34

Table 4. Characteristics of Rospena foam concentrate.

Property	Value
General view	Clear liquid
Composition:	
- protein (%)	25
- mineral salts (%)	4
Density (g/cm^3)	1.10
Stability (h)	1.5
Multiplicity	85

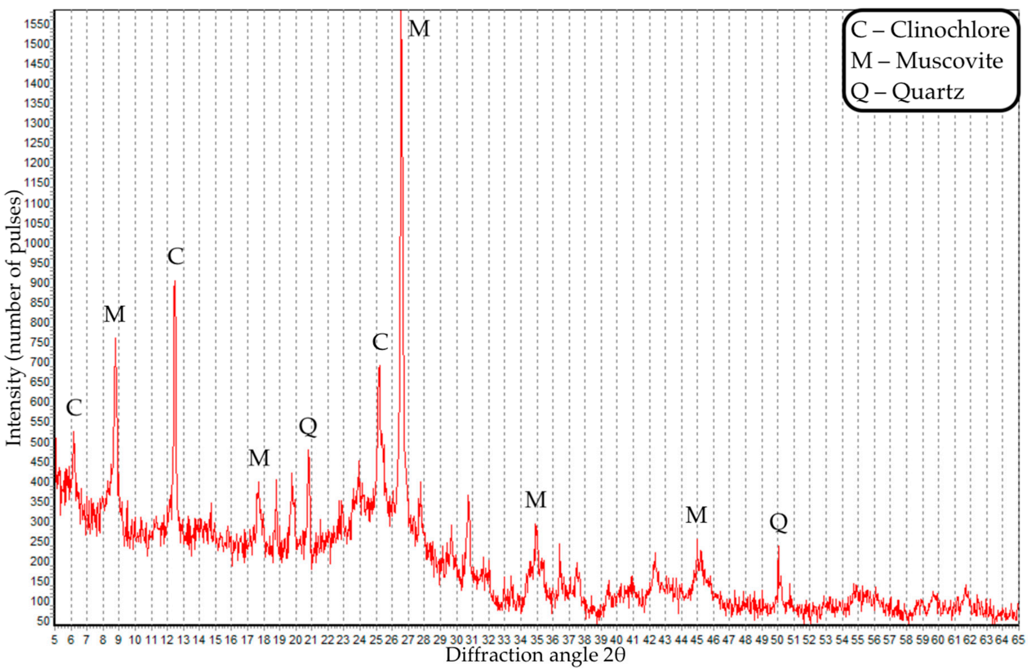

Figure 1. XRD of coal dust.

X-ray diffraction analysis of coal dust (Figure 1) revealed the phases of quartz, muscovite, and chlorite with the presence of an amorphous carbon phase.

Figure 2 shows that the largest proportion of coal dust particles (64%) is ranges from 20 to 70 microns. The proportion of particles smaller than 20 microns is 12.4%. Particles larger than 70 μm in size were distributed in an amount of 23.6% of all particles.

The photographs of materials used as raw materials for the production of foam concrete are presented in Figure 3.

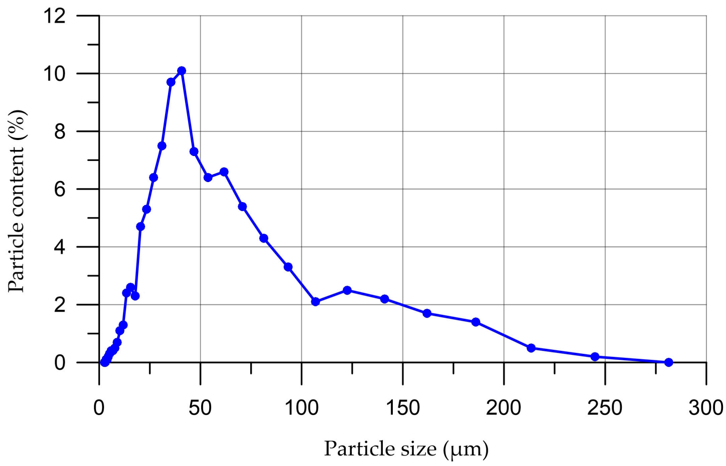

Figure 2. Distribution curve of coal dust particles.


(**a**) (**b**) (**c**) (**d**)

Figure 3. Raw materials: (**a**) sand; (**b**) cement; (**c**) foaming agent; (**d**) coal dust.

2.2. Methods

Table 5 presents the compositions of experimental foam concrete mixtures used in the current study.

Table 5. Compositions of experimental foam concrete mixtures.

Mixture Type	Proportion per 1 м^3				
	C (kg/m^3)	W (L/m^3)	S (kg/m^3)	CD (kg/m^3)	Foaming Agent (L)
0CD	408	230	326	0	1
2CD	400	230	326	8	1
4CD	392	230	326	16	1
6CD	384	230	326	24	1
8CD	375	230	326	33	1
10CD	367	230	326	41	1

In laboratory conditions, the creation of foam concrete samples was carried out in the following order:

- Initial materials were dosed under the formulation of the compositions;
- Dry components (sand, cement, and coal dust) were added to water and mixed for 2 min at a speed of 600 rpm on a turbulent laboratory foam concrete mixer CA 400/500 (DSTU, Rostov-on-Don, Russia) with a capacity of 50 L using one-stage technology without the use of a special foam-forming installation;
- A foaming agent was introduced into the resulting mixture and all components were intensively mixed for 4 min;
- The foam concrete mixture, brought to a homogeneous state, was poured into molds and compacted by tapping the metal molds 15 times with the mixture on the concrete surface;
- Foam concrete samples were kept in natural conditions for 3 h and then placed in a steaming chamber;
- Steaming of foam concrete samples was carried out according to the following regime: temperature rise—3 h; exposure—12 h; cooling—2 h. The maximum steaming temperature was 80 °C;
- Before stripping, steamed samples were kept for 2 h in laboratory conditions at a relative air humidity of 55% and an air temperature of 25 °C and then removed from the molds.

The appearance of experimental samples of foam concrete of the control composition and with the addition of coal dust is presented in Figure 4.

The samples presented in Figure 4 differ in color: the foam concrete sample with coal dust (Figure 4b) has a dark gray or even black color, in contrast to the lighter sample of the control composition (Figure 4a). In addition, the surface of the sample in Figure 4a has, upon visual inspection, a larger number of pores and voids visible to the naked eye, as well as some heterogeneity in different areas.

The fluidity of the mixtures was determined on a Suttard viscometer in the form of a cylinder (GEO-NDT, Moscow, Russia). The fluidity of the mixtures was characterized by the diameter of the mixture's spread. The diameter of the spread on the viscometer was determined as follows. The Suttard viscometer and glass were prepared, previously wiped with a damp cloth. Then, the cylinder was installed on the glass, filled with the mortar mixture flush with the edges, and quickly raised to a height of up to 20 cm and moved to the side. The diameter of the spread was measured immediately after lifting the cylinder using a ruler in two mutually perpendicular directions with an error of no more than 5 mm, and the arithmetic mean was calculated.

The requirements [48,49] regulate the procedure for determining the average density of foam concrete, in accordance with which the mass and volume of dried samples were assessed. The average density was calculated using the following formula:

$$\rho = \frac{m}{V} \times 1000 \quad (1)$$

Here, m is the mass of the sample, g; V is the sample volume, cm^3.

(**a**) (**b**)

Figure 4. Foam concrete: (**a**) control composition; (**b**) contains coal dust.

The compressive strength of foam concrete was assessed in accordance with the requirements provided in [50–54] on samples dried to constant weight. The compressive strength of foam concrete was determined using the following formula:

$$R = \alpha \times \frac{F}{A} \times K_w \quad (2)$$

Here, F is the breaking load (N); A—sample working section area (mm^2); α—scale factor; K_w is a correction factor for cellular concrete.

The appearance of the destroyed foam concrete samples after the strength test is shown in Figure 5.

The nature of the destruction of foam concrete samples of both the control composition and that containing coal dust, visible in Figure 5, is identical, and the destroyed samples resemble an hourglass shape. The similarity revealed during the analysis of the nature of destruction indicates the following. The demonstrated similarity of these processes in the two samples proves the structural validity and mechanically confirms the feasibility of using coal dust as a component of foam concrete. An important aspect is not only good physical and mechanical properties but also the nature of the destruction of the material sample. In this regard, directions are visible for the effective standardization of new material and its introduction into mass production.

The structure of foam concrete samples was analyzed using a stereoscopic microscope MBS-10 (Measuring equipment, Moscow, Russia) with a magnification of 10 times.

The granulometric composition of the starting materials for the production of foam concrete was analyzed using a Microsizer model 201C (VA Insol, St. Petersburg, Russia).

X-ray diffraction analysis of the concrete structure was carried out using an ARLX'TRA diffractometer. The characteristic radiation of the copper anode was used (wavelengths

CuKα11.5406 Å, CuKα21.5444 Å). The identification of serpentinite phases and minor minerals was carried out using the PDF-2 X-ray database.

(**a**) (**b**)

Figure 5. Foam concrete samples destroyed after compressive strength testing: (**a**) control composition; (**b**) composition with coal dust.

The thermal conductivity coefficient of foam concrete was determined in accordance with the requirements of the method in [55] using the ITP-MG4 device (Figure 6). Before testing, foam concrete samples were dried to constant weight, and the deviations of geometric parameters were monitored. The edges of the sample in contact with the working surfaces of the device plates were made flat and parallel.

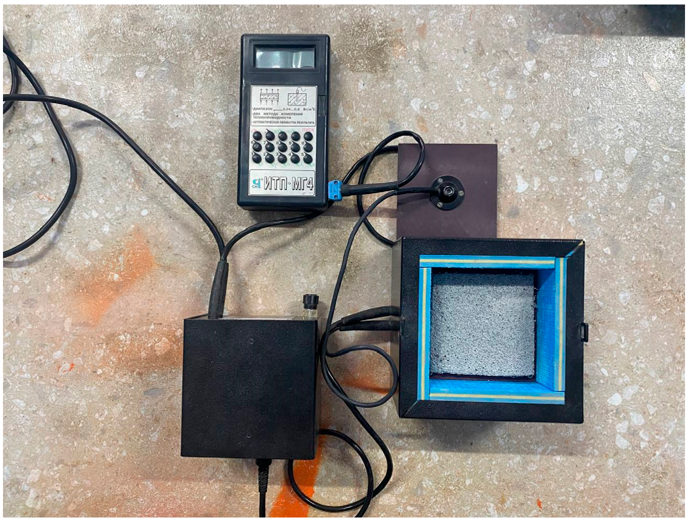

Figure 6. The process of determining the thermal conductivity coefficient of foam concrete.

Since the experimental part included several stages of sample preparation and testing, it is advisable to present the research program in the form of a block diagram presented in Figure 7.

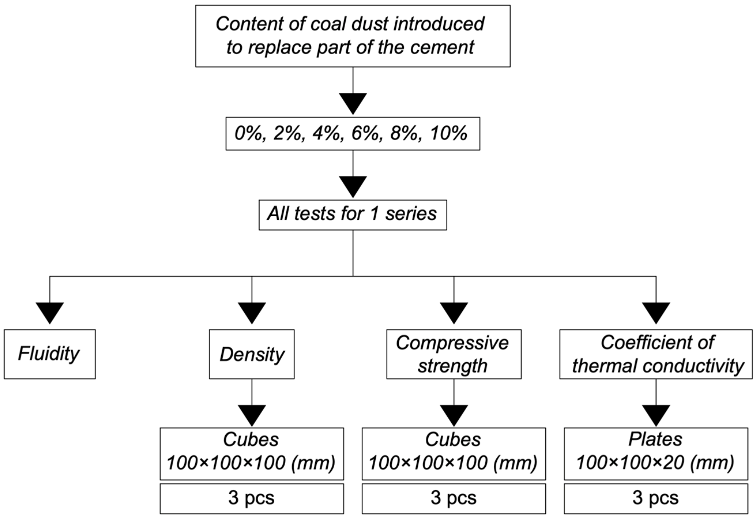

Figure 7. Experimental research program.

3. Results and Discussion

The results of determining the fluidity of mixtures are presented in Figure 8.

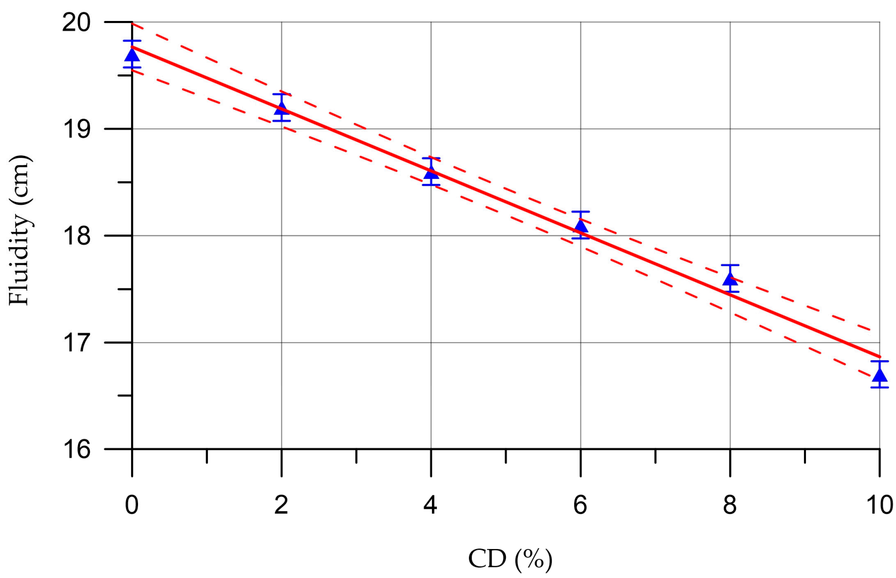

Figure 8. Changes in the fluidity of mixtures in different CD dosages (the dotted line shows the confidence limits).

Alteration in the fluidity of mixtures on different CD dosages is approximated by Equation (3) with a coefficient of determination R^2.

$$D_f = D_0 - 0.29\,x, \quad D_0 = 19.76, \qquad R^2 = 0.989 \tag{3}$$

Here D_f is the spread diameter, cm; x is the CD dosage, %; D_0 is the spread diameter when CD = 0.

As can be seen from Figure 8, with the introduction of CD from 2% to 6%, a smooth decrease in fluidity is observed. At a CD dosage of 2%, the fluidity was 19.2 cm, which is 2.5% less than the similar indicator of the control composition. At dosages of 4% and 6%, the fluidity values were 18.6 cm and 18.1 cm, which is 5.6% and 8.1% less than the control composition. At 8–10% CD, a sharp decrease in fluidity is observed. Thus, the fluidity values at these dosages were 17.6 cm and 16.7 cm, which is 10.7% and 15.2% less in comparison with the control composition.

In general, the decrease in the fluidity of mixtures when administered with CD is primarily due to its high dispersion and high water demand. Note that when adding 2–6% CD, the decrease in the fluidity of the mixture is not so critical and will not have a significant effect on the process of formation of the porous structure of the composite. Also, during the formation of the porous structure of the foam concrete composite, part of the SiO2 contained in the coal dust will actively react with calcium hydroxide and form highly dispersed crystals of calcium hydrosilicates, which will subsequently participate in the formation of interpore partitions and perform the function of a reinforcing strengthening material [36,37,56]. However, when CD is added in an amount of 8–10%, the fluidity of the mixtures decreases more significantly than with 0–8%. A decrease in the fluidity of mixtures indicates a deterioration in the rheological characteristics of the solution, including increased viscosity. An increase in the viscosity of the medium will negatively affect the formation process of the porous structure of foam concrete. The uneven porosity of foam concrete directly affects its physical and mechanical characteristics [56].

The results of determining the density of foam concrete are presented in Figure 9.

Alteration in the density of mixtures at different CD dosages is approximated by Equation (4) with a coefficient of determination R^2.

$$D = D_{m0} + 4.74\,x - 7.38\,x^2 + 1.449\,x^3 - 0.0729\,x^4,\ \ D_{m0} = 824.43,\quad R^2 = 0.960 \tag{4}$$

Here, D is density, kg/m^3, x is the CD dosage, %; D_{m0} is the mixture density when CD = 0.

In CD dosages ranging from 2% to 6% (Figure 9), there is a small decrease in the density of foam concrete. At 2% CD, the density of the foam concrete was 812 kg/m^3; at 4%, it was 805 kg/m^3 at 6–800% kg/m^3, and the drop in the density of these foam concrete compositions in comparison with the control sample was 0.9%, 1.7%, and 2.3%, respectively. At 8% and 10% CD, an increase in the density of foam concrete is observed to be 836 kg/m^3 and 853 kg/m^3, respectively. And the values of density increased in comparison with the control composition are 2.1% and 4.2%.

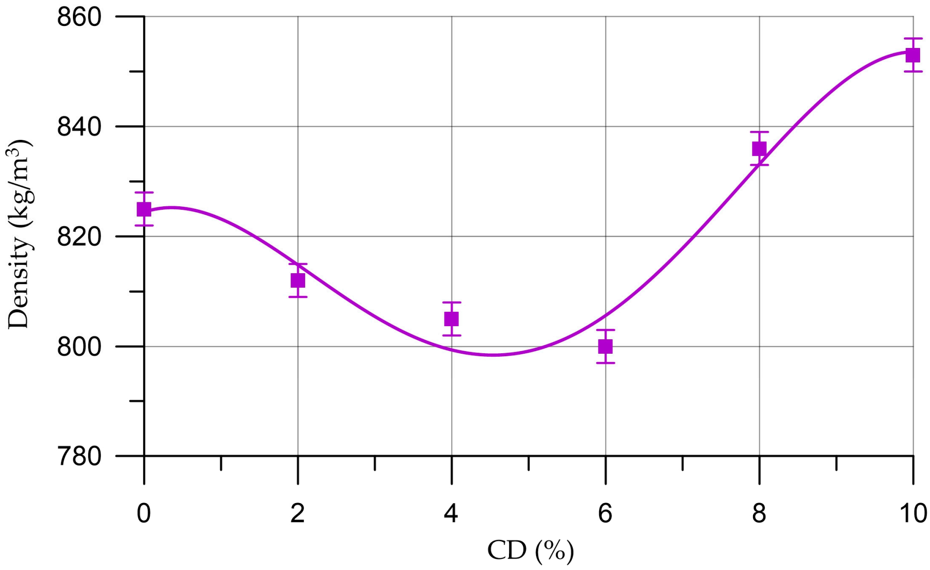

Figure 9. Changes in the density of foam concrete at different CD dosages.

A slight drop in the density of foam concrete at CD dosages of 2–6% is due to the fact that CD has a lower density compared to Portland cement. Accordingly, replacing part of the cement with coal dust in an amount of 2–6% leads to a slight decrease in the mass of the composite. A sharp increase in the density of foam concrete with a CD of 8–10% is associated with the following factors. An increased CD content negatively affects the stability of the foam and its dispersibility. As is known, foam films in a foam concrete mixture function as a frame on which solid particles are concentrated. Subsequently, solid particles attached to the elements of the foam structure enter into hydration reactions and turn into a solid phase, thereby forming a closed-cell foam concrete composite. To form a foam concrete structure of a given density, it is important to maintain a certain ratio between the specific surface area of the foam and the specific surface area of solid particles [57]. And as noted earlier, CD has high dispersion and an increased water demand, and it negatively affects the fluidity of mixtures. Accordingly, with an increased content of CD, an excess of solid particles will appear, and the amount of foam to resolve these particles will not be enough, and when the film surface is oversaturated with solid particles and the viscosity of the mixture is increased, foam bubbles begin to burst and collapse. All this leads to a heterogeneous porous structure with a large number of dense zones and fewer pores [56,57]. Consequently, foam concrete composites containing 8–10% CD of coal dust have a slightly higher density.

Figure 10 shows a graphical dependence of compressive strength on the amount of coal dust added to the foam concrete mixture.

Alteration in the compressive strength (R) of mixtures at different CD dosages is approximated by Equation (5) with a coefficient of determination R^2.

$$R = R_0 + 0.0233\,x + 0.0365\ x^2\ -\ 0.00434\ x^3,\ R_0 = 4.075,\ \ R^2 = 0.944 \tag{5}$$

Here, R is compressive strength, MPa; x is the CD dosage, %; R_0 is the compressive strength when CD = 0.

From Figure 10, it can be seen that when replacing part of the cement in the composition of foam concrete mixtures with CD in an amount of 2–6%, an increase in compressive strength is observed. At dosages of 2%, 4%, and 6%, the compressive strength values are 4.21 MPa, 4.43 MPa, and 4.73 MPa, and the increment values compared to the control composition were 2.9%, 8.3%, and 15.6%, respectively. With a CD amount of 8% and 10%, a decrease in compressive strength is observed, the values of which were 4.26 MPa and 3.65 MPa, respectively. Compared to the control composition, the compressive strength increased by 4.2% and decreased by 10.8%, respectively.

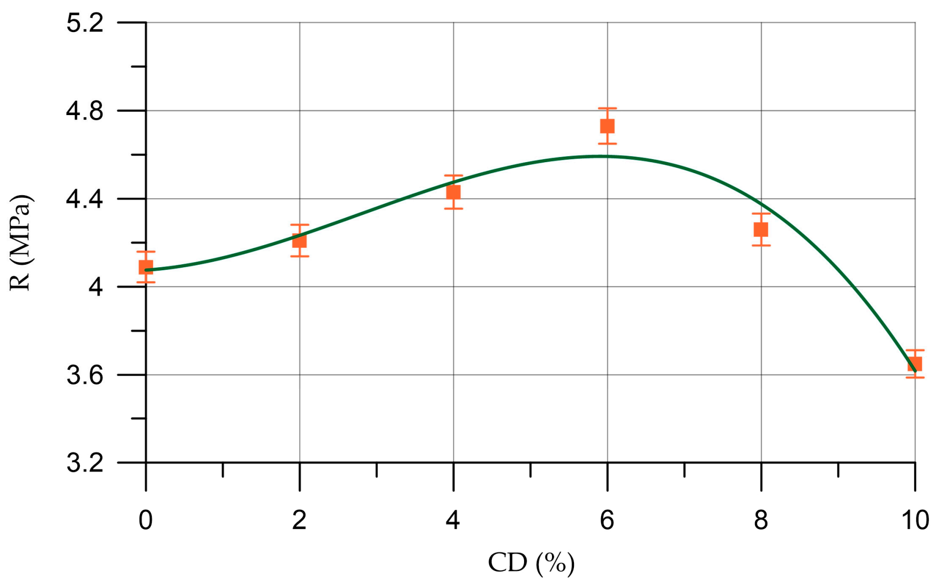

Figure 10. Changes in compressive strength of foam concrete at different amounts of CD.

The increase in compressive strength of foam concrete at 2–6% CD can be explained by the following facts. The foam formed during the production of foam concrete mixtures is characterized by a polyhedral structure. The foam consists of gas bubbles, predominantly in the shape of polyhedra, the faces of which are flat and curved films, the edges are

Plateau-Gibbs channels, and the vertices are channel nodes. In foam, gas bubbles are pressed against each other by a thin layer of dispersion medium—foam films. This foam structure is also described by Plato's rule [56,57]. In this study, coal dust, introduced into the foam concrete mixture instead of part of the binder in an amount of 2–6%, acts as a mineral stabilizer. CD increases the elasticity and stability of the film, which in turn will prevent liquid from flowing down to the Plateau boundary. In addition, the interaction of silicon dioxide in CD with calcium hydrosilicates reduces the pH of the liquid medium, which means that the possibility of carbonization with simultaneous shrinkage is reduced. Thus, replacing part of the cement in the composition of foam concrete in a rational amount is justified and helps to obtain a cellular composite with a more uniform porous structure and increased strength [58].

When replacing part of the cement with 8–10% CD, destruction and collapse of foam bubbles are observed, which is associated with the supersaturation of the foam concrete mixture with fine CD particles and a significant deterioration in rheological characteristics. This process will include the following main stages. The first stage is expressed in the flow of interfilm fluid through channels under the influence of gravity. Next, the process of gas diffusion between gas bubbles begins. Due to the pressure difference in the bubbles, gas is transferred from an area of high pressure (small bubbles) to an area of low pressure (large bubbles). And ultimately, at the end of the diffusion process, the films reach a critical thickness and break. Consequently, the zones of reduced strength with an increased value of the water–cement ratio are formed in the volume of the foam concrete composite, which are the centers of destruction and reduce the strength of the entire composite [56–58].

Figure 11 shows the dependence in the form of a graph of the thermal conductivity of foam concrete with different amounts of coal dust in it.

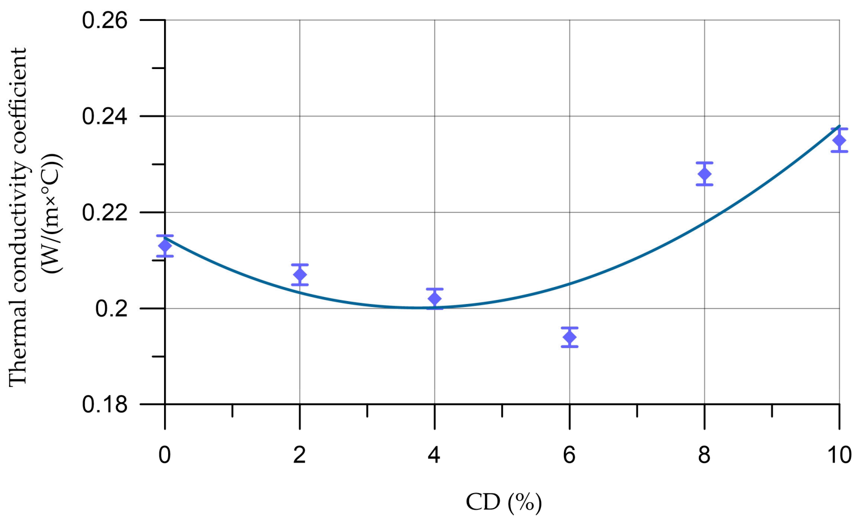

Figure 11. Changes in the thermal conductivity coefficient of foam concrete with different amounts of CD.

Alteration in the thermal conductivity (λ) of mixtures at different CD dosages is approximated by Equation (6) with a coefficient of determination R^2.

$$\lambda = \lambda_0 - 0.00782\,x + 0.001073\,x^2 - 5.787 \times 10^{-6} x^3, \;\; \lambda_0 = 0.215, \;\; R^2 = 0.8 \tag{6}$$

Here, λ is the coefficient of the thermal conductivity, W/m $\times$ °C; λ_0 is the thermal conductivity coefficient when CD = 0.

Figure 11 shows that the results of determining the thermal conductivity coefficient of foam concrete are in good agreement with the results of determining the density and compressive strength. At CD 2–6%, the thermal conductivity coefficient of the material decreased. At 2%, 4%, and 6% CD, the values of the thermal conductivity coefficient were, respectively, 0.207 W/m × °C, 0.202 W/m × °C, and 0.194 W/m × °C, which is 2.8%, 5.2%, and 8.9% lower compared with the thermal conductivity coefficient of the control composition. At 8–10% CD, there is an increase in the thermal conductivity coefficient to 0.228 W/m × °C and 0.235 W/m × °C, which is higher than the values of the control composition by 7.0% and 10.3%, respectively.

Foam concrete containing coal dust, which is introduced instead of part of the cement in a rational amount of 2–6%, has lower values of the thermal conductivity coefficient than the control composition of foam concrete made only with cement. This is primarily due to the fact that coal dust contributes to a slight decrease in the density of the composite and an increase in its strength due to the formation of a more uniform porous structure and strengthening of the interpore walls due to the formation of additional calcium hydrosilites [56–58].

Figure 12 shows a comparative analysis of the pore structure of foam concrete of the control composition 0CD (Figure 12a), the composition with the best physical and mechanical characteristics 6CD (Figure 12b), and the composition with the worst physical and mechanical characteristics 10CD (Figure 12c).

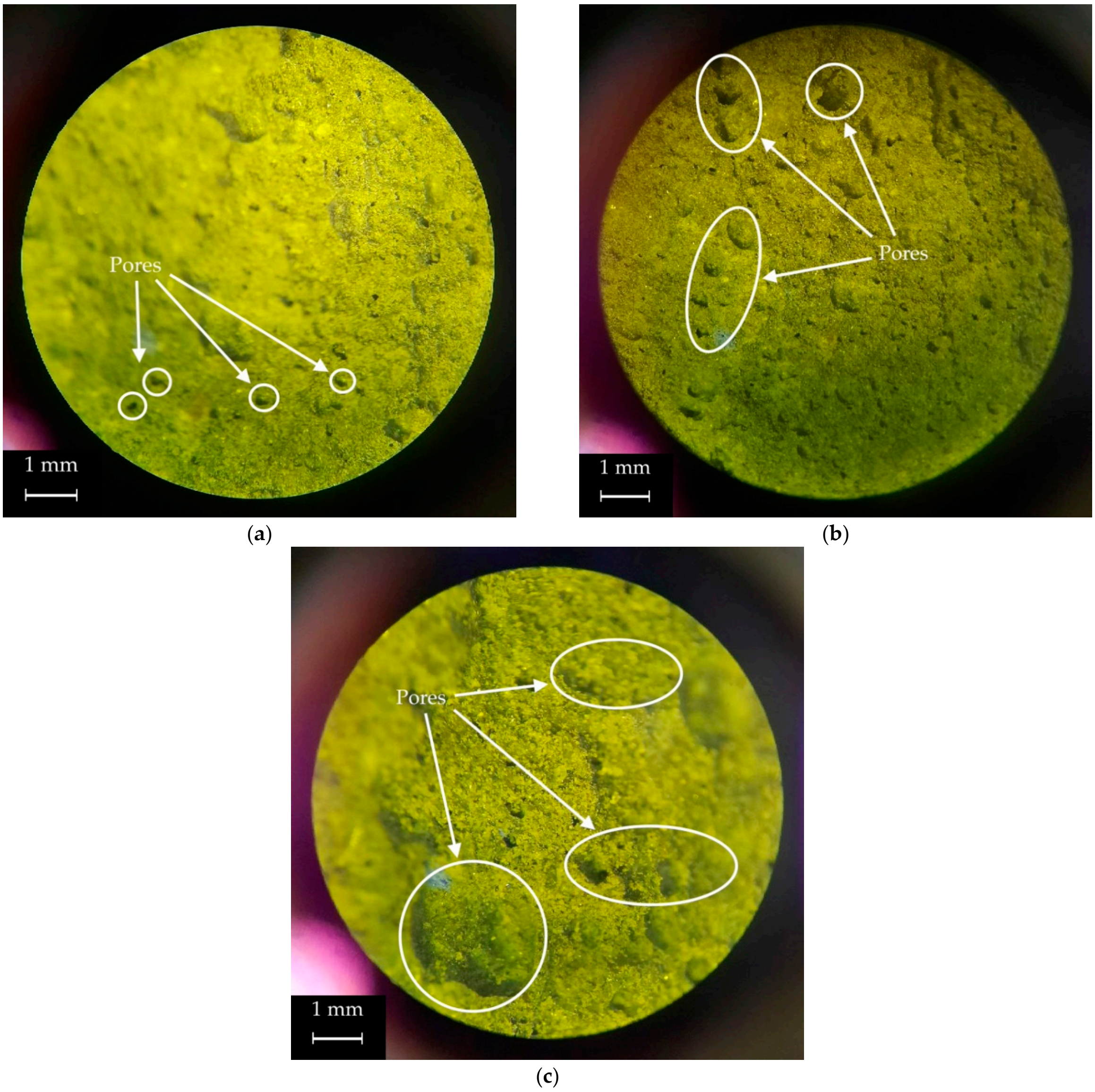

Figure 12. Photographs of the pore structure of foam concrete: (**a**) control composition; (**b**) composition with 6% CD; (c) composition with 10% CD.

Photographs of the pore structure presented in Figure 12 demonstrate that foam concrete with 6% CD (Figure 12b) is characterized by the most uniform structure and uniform distribution of pores, which are predominantly spherical in structure compared to the structure of the control sample. As for the structure of foam concrete with 10% CD (Figure 12c), it differs significantly from the control composition and the composition with 6% CD and is characterized by uneven porosity, and the pores themselves have strong differences in size and shape.

A comparative analysis of the presented images is also intended to confirm the previously established thesis about the structural and recipe-technological reliability of introducing coal dust into the composition of foam concrete. The general structure of samples of all types shows that significant destruction does not occur with the introduction of coal dust in various dosages. Thus, microscopic analysis at the micro level confirms the test results in compliance with the fundamental principle “composition—structure—properties”.

This nature of the structure confirms the previously stated positions on the influence of CD on the rheological and physical–mechanical characteristics of foam concrete:

- At an optimal content (2–6%), coal dust introduced into the foam concrete instead of part of the cement acts as a mineral stabilizer and increases the stability of the foam, and due to the presence of silicon dioxide in the CD composition, it promotes the formation of additional hydrosilicates that strengthen the interpore walls;
- When the amount of coal dust increases by more than 6%, a negative effect is observed, expressed in the deterioration of rheological and physical–mechanical characteristics, which is associated with the supersaturation of the foam concrete mixture with too many highly dispersed particles of coal dust, with a high water requirement.

The XRD analysis of foam concrete of the control composition (Figure 13) and foam concrete with 6% CD (Figure 14) only confirms the identified differences between them.

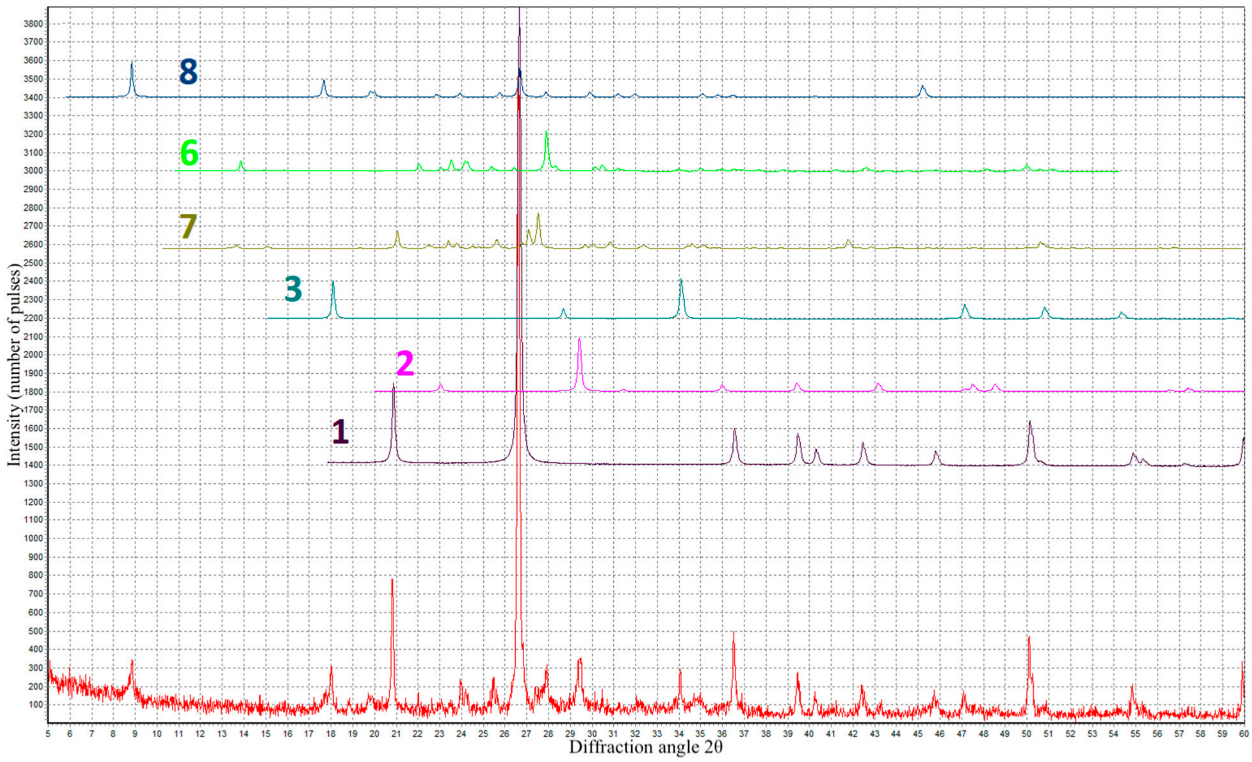

Figure 13. X-ray image of foam concrete of the control composition: 1—quartz; 2—calcite; 3—portlandite; 6—albite; 7—microcline; 8—illite.

Based on the results of XRD analysis of foam concrete of the control composition, the main phases were identified as quartz, calcite, portlandite, albite, microlin, and illite. As for foam concrete with the addition of coal dust, it differs from the control and mainly contains phases such as quartz, calcite, portlandite, and larnite.

Analyzing the results obtained, a number of important aspects should be noted. First, it is necessary to analyze the nature of the interaction of the coal dust additive with the other components of the foam concrete mixture in the stage of the beginning of its formation, in the stage of hardening of the foam concrete mixture, and finally, in the stage of the final structure formation of the foam concrete mixture. In the stage of introducing a finely dispersed additive of coal dust into the composition of the foam concrete mixture, it is integrated into the composition of the cement mortar, which implies its interaction with the active component—cement and the inert component—filler, in particular, sand [59].

At the same time, to understand the complex structure of the emerging foam concrete conglomerate and the creation of a porous system, it is important to strictly adhere to the requirements for the ratio between the specific surface area of the foam and the specific surface area of solid particles. The introduction of a rational amount of coal dust instead of part of the binder makes it possible to achieve the most ideal relationship between these parameters [60].

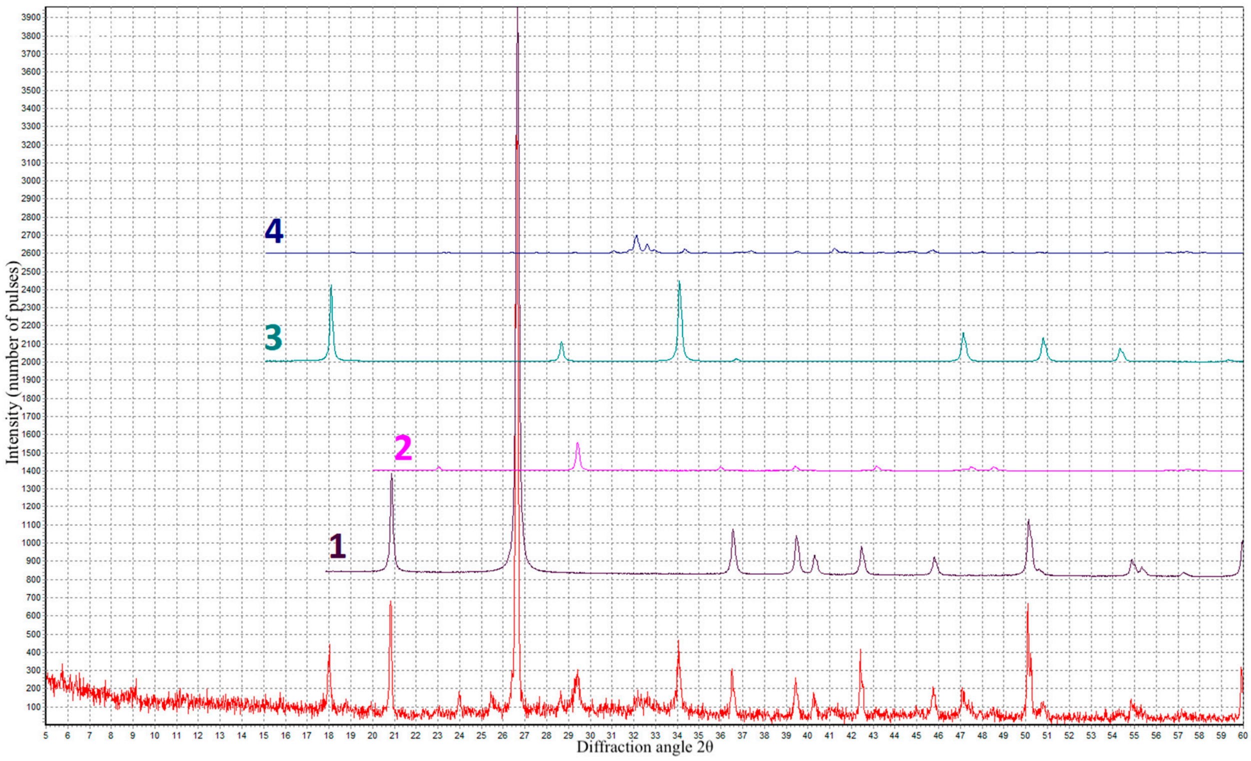

Figure 14. X-ray image of foam concrete with 6% CD: 1—quartz; 2—calcite; 3—portlandite; 4—larnite.

An important aspect is also the process of mixing the components, which determines the maximum homogeneity of the mixed, unhardened foam concrete solution. This is due to the fact that it is necessary to achieve the most uniform distribution of modifying particles in forming a conglomerate of the foam concrete mixture. The uniform distribution of coal dust particles makes it possible to achieve the creation of so-called crystallization centers, which at the micro level will include a collection of sand, that is, granular aggregate and fine coal dust around sand particles embedded in the cement mortar [61]. Ultimately, going through the hardening life cycle stage, the foam concrete mixture acquires a porous appearance with the most uniform distribution of pores. This approach, subject to the exact formulation and dosage of the components, the order of introducing the components into the mixture, their compatibility with each other, and the correct conditions for keeping the foam concrete mixture during maturation and hardening, ultimately provides possible efficiency in achieving the optimal structure and increasing or maintaining performance characteristics of the resulting foam concrete using coal dust [55–60,62,63].

Thus, these experimental studies show that it is possible to use coal dust as a partial replacement for cement in a rational amount. It has a positive effect on the physical and mechanical characteristics of foam concrete, which is also confirmed by a number of other studies [62–65]. For example, in [64], when replacing part of the cement with coal dust of up to 5% in heavy concrete technology, an increase in mechanical strength is observed due to a decrease in overall porosity and increased formation of hydration products. Similarly, in [62–66], the use of coal dust in the technology of heavy concrete in a rational amount helps to improve performance characteristics. As for the use of coal dust specifically in the technology of cellular concrete, as was mentioned earlier, it functions as a mineral stabilizer similar to silica smoke, fly ash, and slag. And the content of silicon oxide in the composition of these wastes is the main factor responsible for improving the properties of cellular concrete [20–41,67].

As for the significance of the applied construction industry, this technology, which involves modifying foam concrete products and structures with coal dust, can become a promising direction for improving the quality of construction in a number of regions of the world. In particular, the use of coal dust, provided that the recipe and technological parameters are observed at a rational level, allows, as has already been proven above, us to obtain structures and products with high-quality structure and high-performance characteristics.

Taking into account the fact that non-autoclaved foam concrete, in comparison with analogs (for example, aerated concrete), has a relatively simple technology, it seems that the production of such products will not be difficult for the construction industry, both large and small scale.

Equipment for such products and structures is inexpensive and available to a wide range of manufacturers. At the same time, taking into account the fact that the raw materials for foam concrete are also quite accessible to manufacturers and builders, we can say that such technology and formulation will be in demand in the construction sector.

The scientific value of the research is expressed by the new dependencies obtained, both in terms of the rheological characteristics of foam concrete mixtures modified with coal dust and the physical and mechanical interpretation of the nature of structure formation and the formation of properties of foam concrete composites based on coal dust.

The experimental studies carried out allowed us to obtain a number of important results in sufficient quantity to form the basis of a big database for the creation of new smart methods for monitoring and regulating the properties of manufactured products in concrete production. In particular, artificial intelligence methods and the development of directions for introducing such methods into the construction industry can serve as an example.

4. Conclusions

The rheological and physical–mechanical characteristics of foam concrete with different contents of coal dust additive introduced instead of part of the cement were studied. Based on the results obtained, the following conclusions were made.

(1) The introduction of CD into the foam concrete mixture instead of part of the cement has a negative effect on fluidity. When replacing 2–6% of cement with CD, the effect on fluidity is not critical, and the deterioration of this indicator in comparison with the control composition does not exceed 8.1%. With the introduction of CD more than 6%, a deterioration in the fluidity of mixtures is observed, which is primarily associated with the high water requirement of CD particles.

(2) Replacing part of the cement with CD in the composition of foam concrete mixtures in an amount of 2–6% has a positive effect on the physical and mechanical characteristics of the foam concrete composite. The best characteristics were recorded for foam concrete with 6% CD. For this foam concrete composition, in comparison with the control, the density decreased by 2.3%, the compressive strength increased by 15.6%,

and the thermal conductivity coefficient decreased by 8.9%. The improvement in the physical and mechanical characteristics of foam concrete is due to the fact that CD, introduced in an optimal amount into the composition of the foam concrete mixture, acts as a mineral stabilizer, and silicon dioxide in the composition of CD promotes the formation of additional hydrosilicates and thereby strengthens the interpore walls.

(3) The introduction of more than 6% CD into foam concrete mixtures negatively affects the physical and mechanical characteristics of the composite. With the introduction of CD in an amount of 10%, the density of foam concrete increased by 4.2%, the compressive strength decreased by 10.8%, and the thermal conductivity coefficient increased by 10.3%, respectively. This is due to the fact that the foam concrete mixture solution is supersaturated with CD particles and the optimal ratio between the specific surface area of the foam and the specific surface area of solid particles is violated, and also because the water requirement of CD particles is too high. As a result, the foam bubbles collapse, and the hardened composite has a heterogeneous pore structure.

(4) The phase composition of foam concrete containing coal dust has distinctive features compared to the phase composition of the control sample of foam concrete and is characterized by the presence of four main phases, such as quartz, calcite, portlandite, and larnite.

Thus, the use of coal dust in the composition of foam concrete with a carefully selected recipe makes it possible to obtain economically, environmentally, and energy-efficient foam concrete with improved physical and mechanical characteristics, as well as solve the problem of disposal of accumulated waste.

Recommendations for the use of such foam concrete include proposals for the construction of buildings and structures for various purposes, mainly in areas rich in waste such as coal dust. It should be noted that, first of all, such concrete can be used in enclosing structures to create high energy efficiency of buildings and structures due to the improved structure and properties.

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