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Eco-Friendly Foam Concrete with Improved Physical and Mechanical Properties, Modified with Fly Ash and Reinforced with Coconut Fibers

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Abstract. The development of new types of environmentally friendly and cost-effective building materials is currently a relevant topic and is actively developing throughout the world. In modern construction materials science, the most popular direction is the development of new concrete compositions using waste of various origins. The objective of this study is to develop new compositions of foam concrete using local waste from the fuel and energy complex and plant natural fibers. To determine the optimal amount of the modifying additive fly ash (FA), 7 experimental concrete compositions with different percentages of cement replacement by FA were made. The content was established as optimal. Foam concrete with 15% FA has the lowest density of 1075 kg/m^3 and a minimum thermal conductivity coefficient of 0.248 W/m × °C, as well as increases in compressive and bending strength of 23.3% and 21.7%, respectively. The effect of coconut fiber (CF) was assessed on the composition of foam concrete modified with the optimal amount of FA 15%. The optimal dosage of CF was 0.6%. As a result of FA modification and CF dispersed reinforcement, a complex effect was obtained. The increase in compressive and bending strength was 30.14% and 72.83%, respectively, compared to conventional foam concrete. The density and thermal conductivity coefficient decreased by 9.8% and 8.34%, respectively. The results obtained during the experimental studies prove the effectiveness of the proposed formulation solutions and allow obtaining an energy-efficient foam concrete composite with improved characteristics.

Keywords: foam concrete, fly ash, coconut fiber, compressive strength, flexural strength, thermal conductivity

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1. INTRODUCTION

Currently, the environmental problem is particularly acute all over the world and requires the search for ideas aimed at solving it. As for the construction industry, the undisputed leader among all building materials is concrete [1]. As is known, the main component of concrete is Portland cement, the production of which requires large energy costs and leaves a large carbon footprint [2]. Accordingly, the search for solutions that will make concrete more environmentally friendly and economical is relevant [3, 4 ,5]. Various types of waste can improve the environmental friendliness of cement composites when used in their manufacture. For example, if replacing part of the Portland cement is considered, then such types of waste as fly ash, microsilica, ground blast furnace granulated slag and other types of slag are well suited for this. Such types of waste have binding properties and, with the correct selection of the concrete composition, have a positive effect on the final properties of the composite [6, 7]. Waste from dismantling and demolition of buildings and structures in the form of broken brick and concrete can be used as part of the replacement of small or large aggregate [8, 9]. For example, the use of ash from the combustion of solid municipal waste in the form of finely ground powder in the manufacture of lightweight wall panels made it possible to obtain products with improved performance properties [10]. Replacing up to 25% of cement with ash in the manufacture of foam concrete ensured an increase in its initial strength by 12% [11]. The use of sand from civil construction waste made it possible to obtain economical and environmentally friendly foam concrete blocks with the required performance characteristics [12]. In general, the use of demolition waste in the manufacture of foam concrete makes it possible to obtain composites with the required or improved properties [13]. In [14], the authors developed energy-efficient lightweight foam concrete with 50% of cement replaced with phosphogypsum. The addition of fly ash allows to increase the stability of foam and to obtain lightweight foam concrete with a density of up to 600 kg/m^3 and compressive strength of up to 3.42 MPa [15]. The use of fly ash as sand ensured the production of an improved composition of foam concrete suitable for 3D printing [16]. The positive effect of modification of foam concrete with fly ash is confirmed by several other studies [17, 18].

Another popular formulation solution that improves the properties of foam concrete composites is the use of various dispersed reinforcing fibers. Polypropylene fiber is most often used for dispersed reinforcement of foam concrete, as it is strong and lightweight enough. Introducing up to 3% polypropylene fiber improved the mechanical properties of foam concrete composites [19]. In addition, dispersed reinforcement with polypropylene twisted bundle fibers from 1.5% to 2.0% ensured an increase in such properties as compressive strength, bending and splitting [20]. The positive effect on the physical and mechanical properties of foam concrete when introducing polypropylene fiber is also confirmed by studies [21, 22]. Using natural fibers of plant origin as a dispersed reinforcing component also seems promising. Currently, much attention is paid to plant fibers in the development of environmentally friendly composite materials. Plant fibers have low cost, low density, high strength and are a renewable and easily processed product [23-27]. For example, including sisal fibers in the amount of 0.15% improved the mechanical properties of concrete and its durability [28]. Introducing wood fibers in the amount of 0.4% increased the mechanical strength of the cellular composite [29]. Using fibers from sugar cane bagasse up to 5% improved the strength properties of the composite and its durability and reduced shrinkage during drying [30]. Based on the results of a study of the possibility of using rice straw as a reinforcing fiber, it was found that this formulation solution has a positive effect on the properties of the composite [31]. The combination of coir and sisal fibers improved the compressive and flexural strength of foam concrete and increased its resistance to freeze-thaw and moistening-drying cycles [32]. Coconut fiber also has a positive effect on the final properties of the cellular composite, which is confirmed by studies [33-35]. The results of studies of foam concrete reinforced with coconut fiber showed a change in the destruction mode and an increase in bending strength, compressive strength and tensile strength when splitting from 10% to 45% depending on the type of strength. In general, the results of the review revealed a shortage of studies on the use of coconut fibers in foam concrete technology. In addition, the chemical composition of waste from the fuel and energy complex varies greatly depending on the raw material and the region where it is produced. Accordingly, in order to establish an ash utilization system, it is necessary to work out a number of issues, including conducting research on its use in cement composites. The novelty of the study lies in obtaining new compositions of foam concrete with fly ash and coconut fiber and new dependencies of the composite properties on the dosages of ash and fiber, describing the complex effect of modification and dispersed reinforcement.

The purpose of this study is to obtain environmentally friendly, economical and energy-efficient foam concrete modified with local waste from the fuel and energy complex and reinforced with vegetable coconut fiber. The objectives of the study are:

- study of the local raw material base, selection of man-made waste and assessment of the possibility of its application in the technology of cement composites (chemical analysis, density, granulometric composition);
- calculation and selection of experimental compositions of foam concrete taking into account the actual properties of the raw materials used;
- production of experimental samples of foam concrete modified with fly ash and dispersedly reinforced with coconut fiber, and assessment of their properties (fluidity of the mixture, density, compressive and bending strength, thermal conductivity coefficient).
– practical recommendations for the use of the obtained foam concrete in the construction industry.

2. MATERIALS AND METHODS

Portland cement CEM I 42.5N (CEMROS, Moscow, Russia), quartz sand (Don Resource, Kagalnik, Russia), fly ash (Novocherkassk State District Power Plant, Novocherkassk, Russia), synthetic foaming agent (Rospena, Mordovia, Russia) and coconut fiber (Auriki Gardens, Yaroslavl, Russia) were used to produce foam concrete samples. The main properties of foam concrete components are presented in Tables 1 and 2.

Table 1. Properties of foam concrete components.

Composition component	Indicator	Actual value
Portland cement CEM I 42.5N (PC)	Specific surface area (m^2/kg)	343
	Setting times (min) - start - end	 190 240
	Standard consistency of cement paste (%)	28.6
	Compressive strength at 28 days (MPa)	49.5
	Bending strength at 28 days (MPa)	5.7
	C_3S (%)	72.8
	C_2S (%)	11.9
	C_3A (%)	6.8
	C_4AF (%)	7.6
	$CaO_{fr.}$ (%)	0.9
Quartz sand (QS)	Bulk density (kg/m^3)	1375
	Apparent density (kg/m^3)	2568
	The content of dust and clay particles (%)	0.09
	Content of clay in lumps (%)	0

Continuation of Table 1

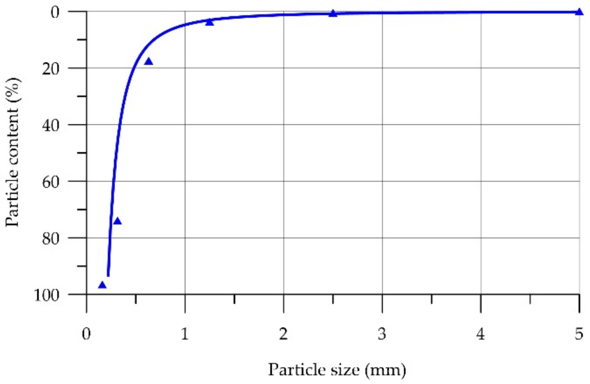
Coconut fiber (CF)	Diameter (μm)	21 ± 1.1
	Length of fiber (mm)	20 ± 5
	Density (kg/m^3)	895
	Tensile strength (MPa)	175
Synthetic foaming agent Rospena (R)	General view	Clear liquid
	Density (g/cm^3)	1.15
	Stability (h)	1.5
	Multiplicity	85

Table 2. Properties of fly ash.

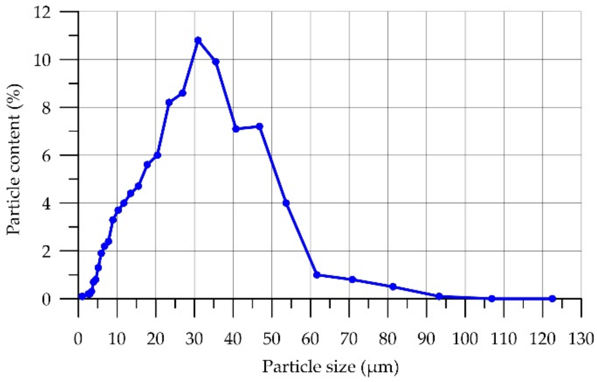
	SiO_2 (%)	TiO_2 (%)	Al_2O_3 (%)	Fe_2O_3 (%)	CaO (%)	MgO (%)	K_2O (%)	Na_2O (%)	P_2O_5 (%)
Fly ash (FA)	52.3	0.87	24.5	11.1	6.43	2.3	0.15	2.09	0.26
	Bulk density (kg/m^3)								1078
	Apparent density (kg/m^3)								2660

Before being introduced into foam concrete, coconut fibers were treated with a 5% NaOH solution to increase their resistance to the aggressive alkaline environment formed during the hydration of Portland cement clinker.

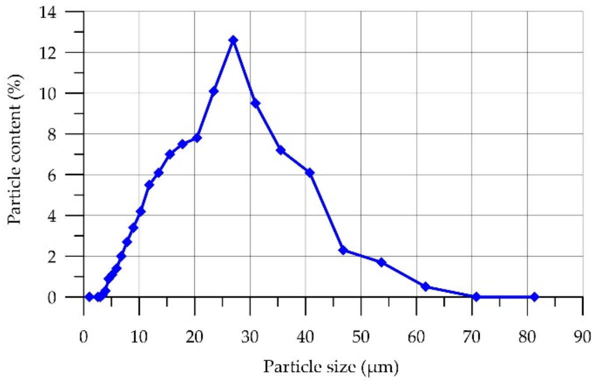
The distribution curves of sand and fly ash particles by size are shown in Fig. 1.



a) Quartz sand



b) Fly ash



c) Portland cement

Fig. 1. Particle size distribution curves.

According to the sieving curve of sand shown in Figure 1a, its fineness modulus is 1.92. Fly ash particles are predominantly (87.5%) in the size range from 8 to 60 μm (Figure 1b). The main amount of ash particles (10.8%) has a size of 30 μm. Portland cement particles have a predominant size of 8 to 47 μm (89.3%). The distribution peak of 12.6% falls on particles of 27 μm.

The effect of partial replacement of cement with fly ash and dispersed reinforcement with coconut fiber on the final properties of experimental foam concrete samples was assessed according to the experimental research program shown in Fig. 2.

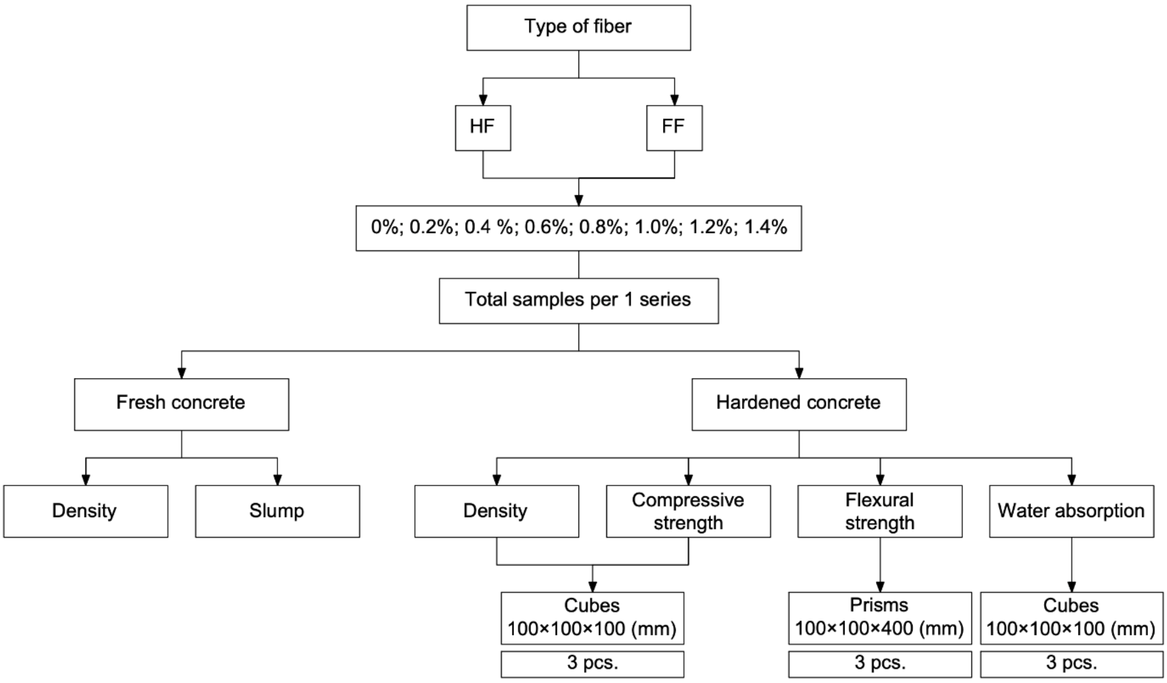


Fig. 2. Test program.

The compositions of foam concrete mixtures modified with fly ash and dispersedly reinforced with coconut fiber are presented in Tables 3 and 4, respectively.

Table 3. Compositions of foam concrete mixtures modified with FA.

Mixture type	Concrete mixture proportion per 1 m^3				
	PC (kg/m^3)	Water (L/m^3)	QS (kg/m^3)	FA (kg/m^3)	R (L)
0FA	385	240	416	0	0.78
5FA	366	240	416	19	0.78
10FA	347	240	416	38	0.78
15FA	327	240	416	58	0.78
20FA	308	240	416	77	0.78
25FA	289	240	416	96	0.78
30FA	269	240	416	116	0.78

Table 4. Compositions of foam concrete mixtures, dispersion-reinforced CF.

Mixture type	Concrete mixture proportion per 1 м^3					
	PC (kg/m^3)	Water (L/m^3)	QS (kg/m^3)	FA (kg/m^3)	CF (kg/m^3)	R (L)
15CF/0.2	327	240	416	58	0.65	0.78
15CF/0.4	327	240	416	58	1.31	0.78
15CF/0.6	327	240	416	58	1.96	0.78
15CF/0.8	327	240	416	58	2.62	0.78
15CF/1.0	327	240	416	58	3.27	0.78
15CF/1.2	327	240	416	58	3.92	0.78
15CF/1.4	327	240	416	58	4.58	0.78

Foam concrete mixtures and foam concrete samples were manufactured in laboratory conditions using the following method. First, the raw materials were dosed according to the formula presented in Tables 3 and 4. Then, the cement-sand mortar and foam were prepared. Intensive mixing of the cement-sand mortar with foam and fiber was performed until a homogeneous mixture was obtained. Then, the finished mixture was poured into cube molds (100 × 100 × 100 mm) and prisms (100 × 100 × 400 mm). Plates (100 × 100 × 20 mm) were manufactured in cube molds with special inserts. Freshly prepared samples were kept in molds for two days, then removed from the molds and hardened for the remaining 26 days under normal conditions at a temperature of 20±2 °C and a relative humidity of 95±5%.

The fluidity of the freshly prepared foam concrete mixture was determined using a Suttard viscometer in the form of a cylinder (GEO-NDT, Moscow, Russia). Before determining the fluidity, the viscometer and glass were wiped with a damp cloth. Then the cylinder was installed on the glass and filled to the brim with foam concrete mixture. The cylinder with the foam concrete mixture was raised up by 20 cm and moved to the side. The diameter of the foam concrete mixture spread was measured using a ruler in three places and the average spread value was calculated according to GOST 23789-2018 and EN 13279-2:2024.

The density of the experimental samples of hardened foam concrete was determined according to the method according to EN 12390-7:2019. Before determining the density, the foam concrete samples were dried to a constant mass. The average density value was calculated using the formula:

$$\rho = \frac{m}{V} \times 1000, \tag{1}$$

there: m –mass of the sample, g;

V – volume of the sample, cm^3.

The compressive and flexural strength of foam concrete was determined using the methods according to GOST 10180-2012, EN 12390-1:2021, EN 12390-2:2019, EN 12390-3:2019, EN 12390-4:2019 and EN 12390-5:2019.Before testing, the foam concrete samples were inspected for defects in the form of cracks and rib fractures and dried to a constant mass. When determining the compressive strength, the sample was loaded until failure at a constant rate of load increase (0.6 ± 0.2) MPa/s. The compressive strength of the foam concrete sample was determined using the formula:

$$R = \alpha \frac{F}{A} K_{\omega}, \tag{2}$$

there: F – breaking load, N;

A – area of the working cross-section of the sample, mm^2;

α are the scaling factors for converting the concrete strength to the concrete strength in samples of the basic size and shape;

K_w – correction factor for cellular concrete, taking into account the humidity of the samples at the time of testing.

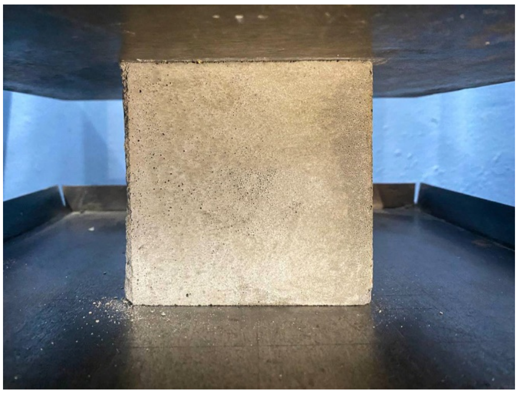
When determining the bending strength, the sample was loaded at a rate of (0.05 ± 0.01) MPa/s. The bending strength was determined by the formula:

$$R_{bt} = \delta \frac{Fl}{ab^2}, \tag{3}$$

there: F – breaking load, N;

a, b, l – width, height of the prism cross-section and the distance between the supports, respectively, when testing samples for tensile strength under bending, mm.

The appearance of the experimental fiber-reinforced foam concrete sample before and after the compressive strength test is shown in Fig. 3.



a) Before failure.

b) After failure.

Fig. 3. Foam concrete sample reinforced with coconut fiber under load.

As can be seen from Fig. 3, the failure of the foam concrete sample occurred in a standard manner. The failed sample has a pronounced trapezoid shape. The failure of the fiber-reinforced foam concrete sample was viscous.

The thermal conductivity of the foam concrete samples was determined according to the method according to GOST 7076-99 using the ITP-MG4 device (Stroypribor, Chelyabinsk, Russia). Before testing, the plate samples were dried to a constant weight. The edges of the sample that were in contact with the ITP-MG4 device plates were additionally leveled by grinding. The appearance of the foam concrete sample for determining the thermal conductivity coefficient is shown in Fig. 4.

Fig. 4. General view of the foam concrete sample for determining the thermal conductivity coefficient.

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

3. RESULTS AND DISCUSSION

The results of determining the fluidity of the mixture, density, compressive strength and flexural strength of foam concrete modified with FA in various dosages are shown in Fig. 5-9. Fig. 5 shows the dependence of the fluidity of the foam concrete mixture on the amount of fly ash introduced instead of part of the cement.

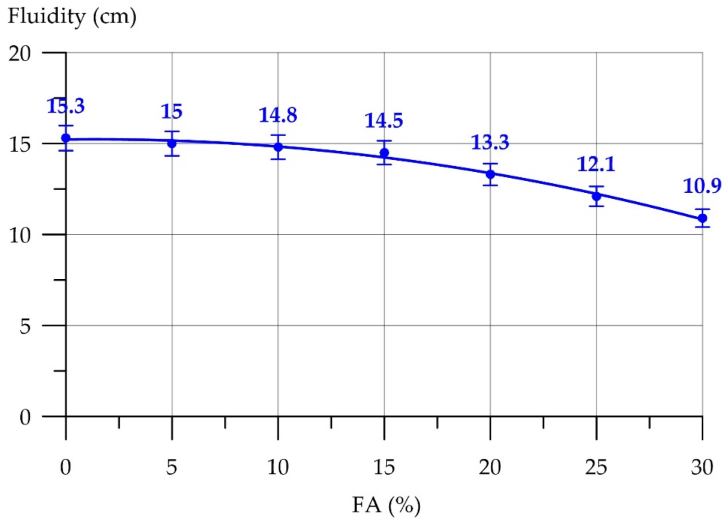


Fig. 5. Change in the fluidity of foam concrete mixture with an increase in the amount of FA.

Fig. 5 shows that partial replacement of cement with FA reduces the fluidity of foam concrete mixtures. The dependence of the fluidity (FFA) on the amount of FA (x in equation) can be approximated by formula:

$$F_{FA} = 15.22 + 0.015x - 0.00538x^2, R^2 = 0.992, \tag{4}$$

The dependence is direct: with an increase in the FA content, the decrease in the fluidity of the foam concrete mixture is more intense. With a maximum FA content of 30%, the fluidity of the mixture was 10.9 cm, which is 28.76% less than the fluidity of the control mixture. FA particles have a porous structure and when introduced into the foam concrete mixture, they absorb part of the free water, which inevitably leads to a decrease in the fluidity of mixtures on a cement binder [36]. Figure 6 shows the dependence of the density of the foam concrete mixture (ρ) on the amount of fly ash introduced instead of part of the cement.

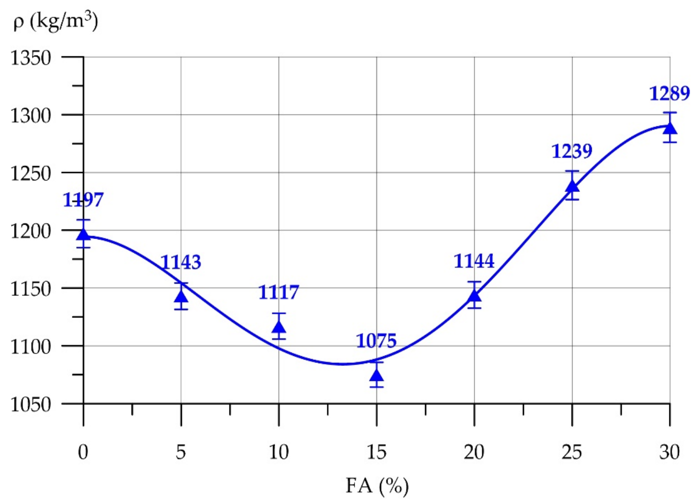


Fig. 6. Change in the density of foam concrete mixture with an increase in the amount of FA.

Dependance of the density (ρ) on the amount of FA is in a good agreement with the polynomial of the 4th degree:

$$\rho = 1194.5 + 0.1958x - 2.448x^2 + 0.1767x^3 - 0.00306x^4, R^2 = 0.978, \quad (5)$$

The dependence of the change in the density of foam concrete on the amount of FA, shown in Figure 6, has the following character. In the section of the curve where the amount of FA varied from 5% to 15%, a decrease in density is observed. The minimum value of the density of foam concrete of 1075 kg / m^3 was recorded at 15% FA. The decrease in this indicator in comparison with the control composition was 9.44%. Further, with an increase in the dosage of FA from 20% to 30%, an increase in density is observed. When replacing cement with FA in an amount of 30%, the density value was 1289 kg / m^3, which is 8.59% more than that of the control samples. The decrease in density when replacing cement with FA to 15% is explained by the fact that FA in the foam concrete mixture plays the role of a mineral stabilizer and to some extent increases the stability of the foam. Accordingly, with a greater number of stable foam bubbles, the composite acquires a more uniform structure with a greater number of pores and lower density [37]. Fig. 7 shows the dependence of the compressive strength (R) of foam concrete on the amount of fly ash introduced into the foam concrete mixture.

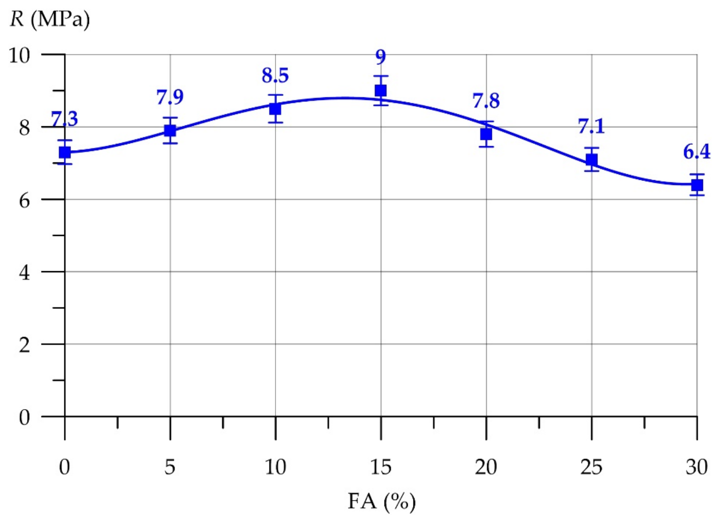


Fig. 7. Change in the compressive strength R of foam concrete with an increase in the amount of FA.

Dependance of the compressive strength (R) on the amount of FA is in a good agreement with the polynomial of the 4th degree:

$$R = 7.298 + 0.020x + 0.0293x^2 - 0.00219x^3 + 3.878 \times 10^{-5}x^4, R^2 = 0.963, \quad (6)$$

The compressive strength of foam concrete with different FA content introduced to replace part of the cement changed as follows. In the range of FA content of 5-15%, a stable increase in compressive strength is observed with a peak value at 15% FA. The maximum compressive strength was 9.0 MPa, which is 23.3% higher than that of the control composition of foam concrete. At a higher FA dosage of 20%, a decrease in the positive effect is observed, and at 25% and 30% FA, the foam concrete composite has compressive strength values lower than that of the control composition. At the maximum FA content of 30%, the compressive strength of foam concrete is 6.4 MPa, which is 12.3% lower than that of the control samples of the composite. Fig. 8 shows the dependence of the flexural strength (R_{tb}) of foam concrete on the amount of introduced fly ash.

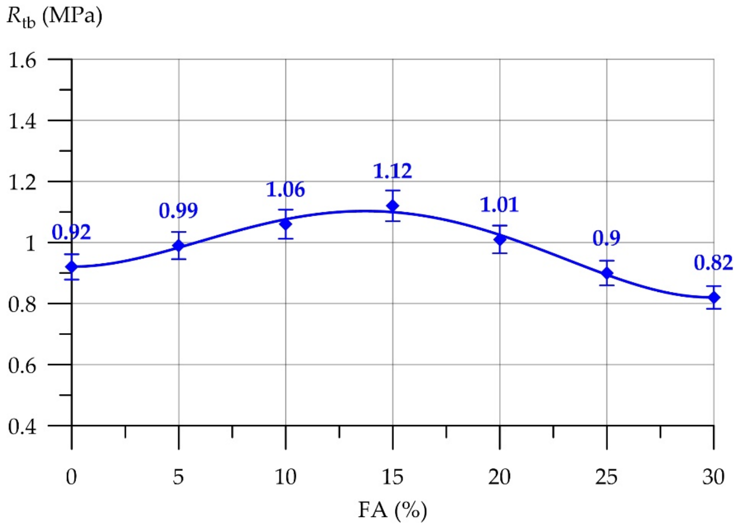


Fig. 8. Change in the flexural strength of foam concrete with increasing amount of FA.

Dependance of the flexural strength (R_{tb}) on the amount of FA is in a good agreement with the polynomial of the 4th degree:

$$R_{tb} = 0{,}921 - 0{,}000795x + 0.00390x^2 - 0.000274x^3 + 4.727 \times 10^{-6}x^4, R^2 = 0.984, \quad (7)$$

The curve of the dependence of the flexural strength on the amount of FA has a similar character to the previous dependence. The introduction of FA in the amount of 5%, 10% and 15% has a positive effect on the flexural strength. The maximum value of the flexural strength was 1.12 MPa, which is 21.74% higher than that of the control composition of foam concrete. With an amount of 20% FA, the flexural strength decreases, and at 25% and 30%, a negative effect is observed with a decrease in the flexural strength to 10.9%.

Thus, having analyzed the dependences of the change in the strength properties of the foam concrete composite modified with FA, it can be established that the replacement of Portland cement up to 15% is optimal. FA contains 52.3% silicon dioxide, which actively enters into hydration reactions with Portland cement and promotes the formation of additional calcium hydrosilicates (CSH). The additional presence of CSH helps to strengthen the interpore partitions [38]. Due to stronger interpore partitions, the strength properties of foam concrete also increase. At 20% FA and more, a negative effect is observed, which is explained by the supersaturation effect. Too many FA particles reduce the fluidity of the foam concrete mixture and lead to the collapse of foam bubbles, due to which the pore structure of the composite deteriorates and becomes non-uniform [37]. Figure 9 shows the graphical dependence of the thermal conductivity coefficient (λ_0) of foam concrete.

As can be seen from Figure 9, modification of foam concrete with fly ash also has a positive effect on its thermal conductivity. A gradual decrease in the thermal conductivity coefficient is observed on the section of the curve from 5% to 15% FA. The minimum value of the thermal conductivity coefficient was recorded at 15% FA and amounted to 0.248 W/m×°C, which is 14.78% less than that of the control composition of foam concrete. With an increase in the FA content from 20% and more, an inverse relationship is observed. The maximum value of the thermal conductivity coefficient of 0.325 W/m×°C was recorded at 30% FA. The increase in the value was 11.68%.

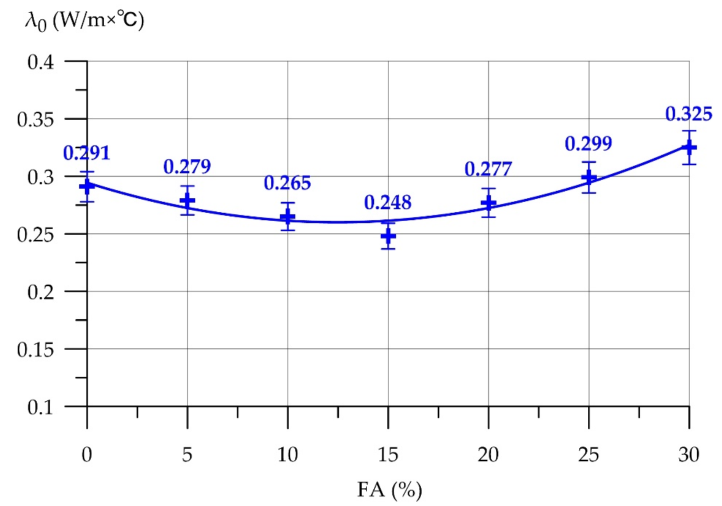


Fig. 9. Change in the thermal conductivity coefficient of foam concrete with an increase in the amount of FA.

Dependance of the thermal conductivity (λ_0) on the amount of FA is in a good agreement with the polynomial of the 2nd degree:

$$\lambda_0 = 0.294 - 0.0055x + 0.00022x^2, R^2 = 0.919, \tag{8}$$

The results of modification of foam concrete with fly ash have good convergence with the studies of other authors. For example, in [39], foam concretes with FA content from 25% to 35% and improved performance properties were developed, namely increased compressive strength up to 38% and thermal conductivity reduced by 3.4%. The FA modification made it possible to obtain energy-efficient foam concrete with reduced thermal conductivity and reduced indoor temperature fluctuations [40, 41, 42]. The positive effect of FA on the physical and mechanical properties of foam concrete has also been proven in studies [43, 44]. In terms of strength characteristics, the foam concrete obtained in this study is only slightly inferior to the foam concretes obtained in some other studies, but this shortcoming is compensated by a better effect on the thermal conductivity of the composite.

Thus, based on the results of the conducted experimental studies, the following was established. Modification of foam concrete with FA in an optimal dosage of no more than 20% has a positive effect on its physical and mechanical properties. The best properties are possessed by a foam concrete composite with 15% FA. Accordingly, for further studies to assess the effect of dispersed reinforcement with vegetable coconut fiber on the properties of foam concrete, a composition of the 15FA type was adopted as a control composition.

The results of determining the fluidity of the mixture, density, compressive and flexural strength of foam concrete with FA, dispersedly reinforced with CF in various dosages, are shown in Figures 10-14. Fig. 10 shows the dependence of the fluidity of foam concrete with fly ash on the amount of added coconut fiber. The dotted line shows the confidence limits of the regression.

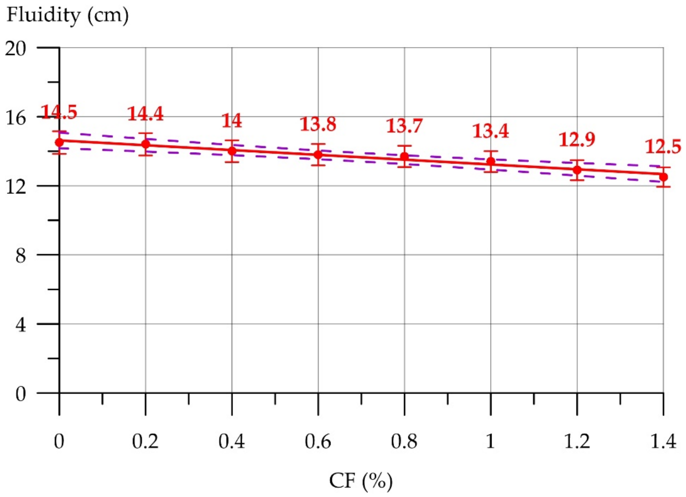


Fig. 10. Change in the fluidity of foam concrete mixture with FA with increasing amount of CF.

Introducing CF in a range between 0.2% and 1.4% into the composition of a foam concrete mixture reduces its fluidity. The dependance of the fluidity (F_{cf}) of foam concrete mixture with FA with increasing amount of CF can be approximated by linear function:

$$F_{CF} = 14.625 - 1.393x, R^2 = 0.964, \quad (9)$$

Coconut fibers have a porous structure and, when introduced into cement composite mixtures, they absorb part of the mixing water, reducing their fluidity [45, 46]. However, in the considered ranges of reinforcement, there is no significant decrease in the fluidity of the mixture. For the control composition mixture of type 15FA, the fluidity value was 14.5 cm, and with a maximum CF content of 1.4%, the fluidity of the mixture was 12.5 cm, which is 13.79% lower. Fig. 11 shows the dependence of the density of foam concrete mixture containing FA on the amount of added coconut fiber.

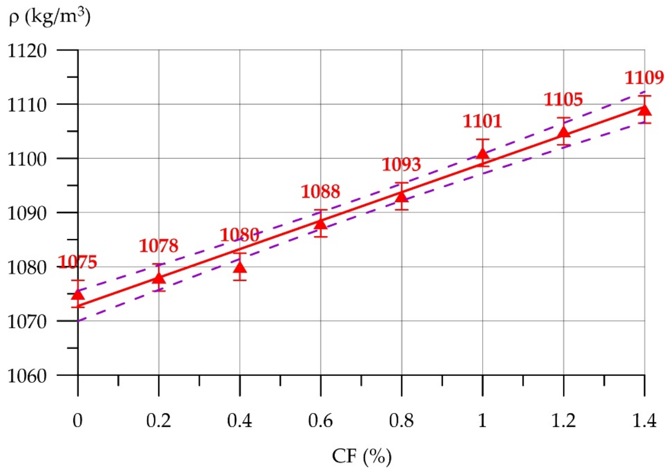


Fig. 11. Change in the density of foam concrete mixture with FA with increasing amount of CF.

Figure 11 shows that dispersed reinforcement of foam concrete with CF does not have a significant effect on the change in its density. The dependance of the density (ρ_{CF}) of foam concrete mixture with FA with increasing amount of CF can be approximated by formula:

$$\rho_{CF} = 1072{,}75 + 26{,}25x, R^2 = 0.982, \quad (10)$$

With an increase in the CF dosage, the density of concrete increases. With the maximum CF content, the density of foam concrete was 1109 kg/m^3, which is 3.16% higher than that of the control composition of foam concrete without fiber. CF has a low density and a porous structure, so a slight increase in density can be associated with the mechanism of interaction between the fiber and the foam concrete mixture during its hardening. At the interface between the "solution part and coconut fiber" phases, a zone of increased density is formed and a strong bond is formed. The presence of such zones leads to an increase in the density of the composite [38].

Fig. 12 shows the dependence of the compressive strength of foam concrete with FA on the amount of added coconut fiber.

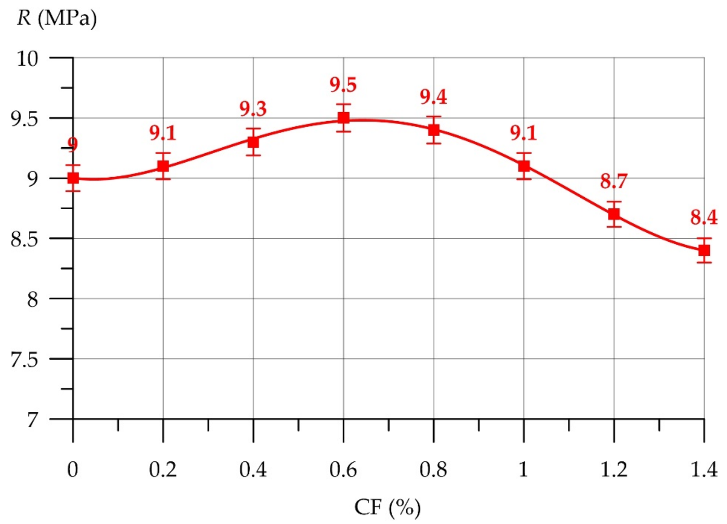


Fig. 12. Change in compressive strength of foam concrete with FA with increasing amount of CF.

The dependance of the compressive strength (RCF) of foam concrete mixture with FA with increasing amount of CF can be approximated by a polynomial of 4th degree with coefficient of determination R^2:

$$R_{CF} = 9.003 - 0.538x + 6.446x^2 - 8.941x^3 + 3.137x^4, R^2 = 0.998, \qquad (11)$$

The introduction of CF into the composition of modified FA foam concrete in optimal quantities increases the compressive strength. With a CF content of 0.2%, 0.4%, and 0.6%, an increase in compressive strength is observed with a peak value of 9.5 MPa at 0.6% FA, an increase of 5.56%. Then, with an increase in the CF content, the compressive strength begins to decrease. The minimum value of compressive strength at 1.4% CF was 8.4 MPa, which is 6.67% less than the control.

Fig. 13 shows the dependence of the flexural strength of foam concrete with FA on the amount of added coconut fiber.

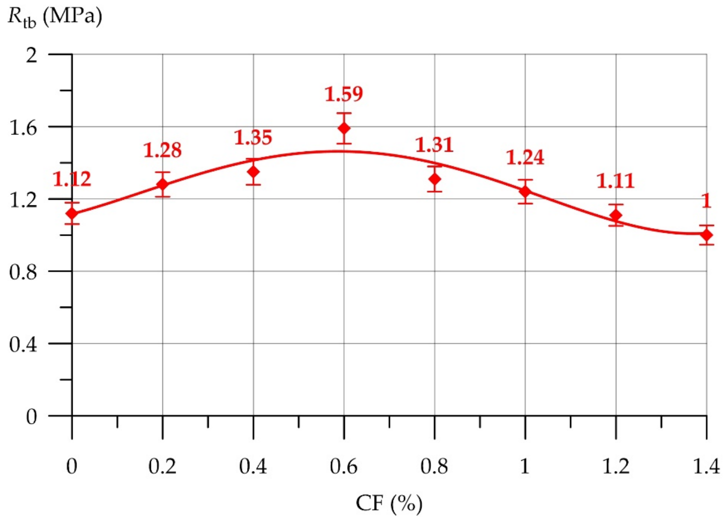


Fig. 13. Change in the flexural strength of foam concrete with FA with increasing CF amount.

The dependance of the flexural strength (RtbCF) of foam concrete mixture with FA with increasing amount of CF can be approximated by a polynomial of 4th degree with coefficient of determination R^2:

$$R_{tbCF} = 1.1167 + 0.6603x + 1.1946x^2 - 2.968x^3 + 1.243x^4, R^2 = 0.872, \quad (12)$$

The curve of the flexural strength dependence on the CF amount has a similar character to the previous dependence. The introduction of CF in an amount from 0.2% to 0.6% provides a gradual increase in flexural strength. The maximum flexural strength was recorded at 0.6% CF and amounted to 1.59 MPa, which is 41.96% higher than that of the control composition of foam concrete. Then the effect of dispersed reinforcement begins to deteriorate. With a CF dosage of 0.8% to 1.2%, the flexural strength of fiber-reinforced foam concrete is higher or comparable to the flexural strength of 15FA foam concrete samples. At 1.4% CF, the minimum flexural strength of 1.07 MPa was recorded, which is 4.46% lower than the value of the 15FA composition. Fig. 14 shows the dependence of the thermal conductivity of foam concrete with FA on the amount of added coconut fiber.

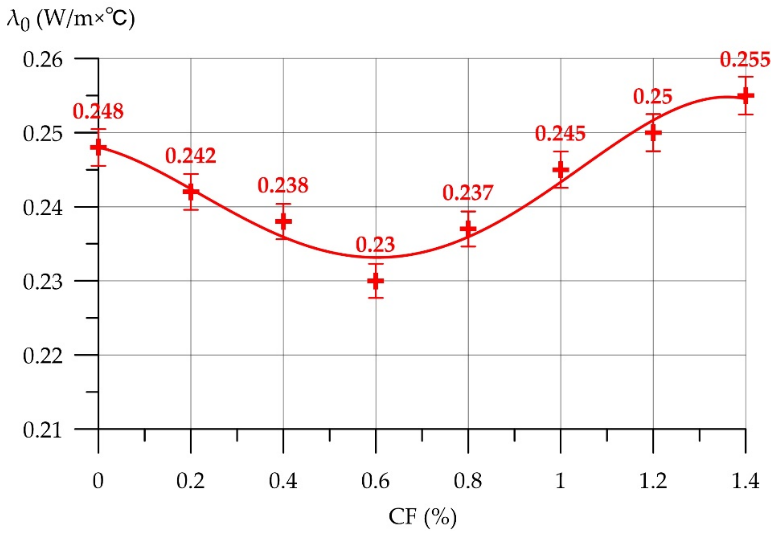


Fig. 14. Change in the thermal conductivity coefficient of foam concrete with FA with increasing amount of CF.

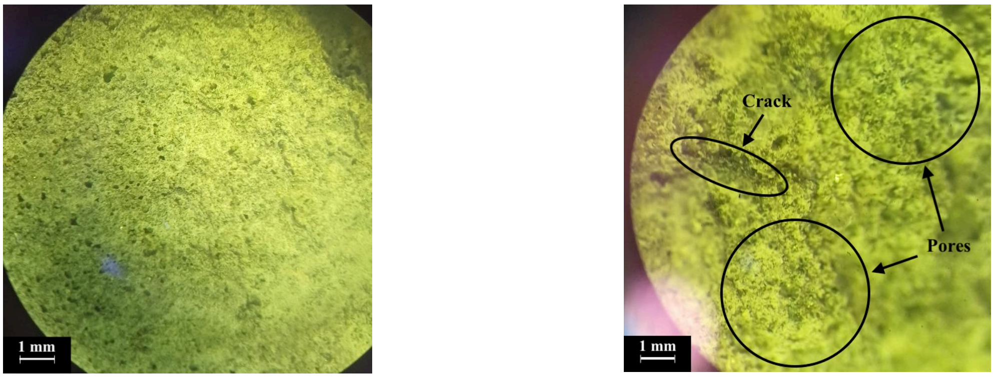
The dependance of the thermal conductivity (λ_{0CF}) of foam concrete mixture with FA with increasing amount of CF can be approximated by a polynomial of 4th degree:

$$\lambda_0 = 0.248 - 0.0150x - 0.0994x^2 + 0.1813x^3 - 0.0716x^4, R^2 = 0.953, \tag{13}$$

Dispersed reinforcement with coconut fiber has a positive effect on the thermal conductivity of foam concrete. The dependence of the change in the thermal conductivity coefficient on the percentage of CF has the following nature. At 0-0.6% CF content, there is a decrease in the thermal conductivity coefficient with a minimum value of 0.230 W/m×°C at the point of 0.6% CF, which is 7.26% lower than that of the control composition of foam concrete. Then there is an increase in the value of the thermal conductivity coefficient. Its maximum was recorded at 1.4% CF and amounted to 0.255 W/m×°C, which is 2.82% higher than that of the samples of the control composition of foam concrete.

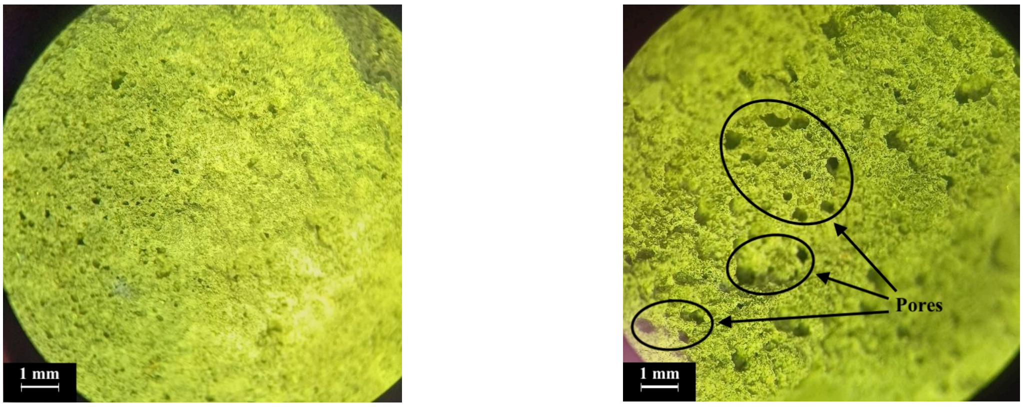
Improvement in compressive strength with dispersed reinforcement with coconut fibers is explained by the fact that the fibers block the propagation of cracks in the structure of the foam concrete composite. Coconut fibers have a porous and rough structure, due to which improved interphase adhesion between them and the mortar part is formed. Cracks in the structure of the foam concrete composite are blocked due to the fact that part of the destructive load is absorbed and damped by CF [38, 47, 48]. If the amount of fibers introduced into the foam concrete composition is excessive, then a phenomenon called "agglomeration" is observed. With too high a content, coconut fibers are not able to distribute normally and evenly throughout the volume, they become tangled and intertwined, forming weakened zones. The presence of weakened zones in the form of crumpled CF negatively affects the strength properties. A decrease in thermal conductivity is associated with the properties and structure of CF and the additional macrostructural cells formed by them [39]. The positive effect of dispersed reinforcement with coconut fiber on the properties of various cement composites with both cellular and dense structures is confirmed by a number of other numerous studies [49-60]. For example, the use of natural fibers, including coconut fibers, improved the bending strength by up to 37.6% and reduced the shrinkage of the solution during drying [49]. The inclusion of 0.5% coconut fiber in the composition of self-healing concrete improved their strength properties: compressive strength by up to 6% and flexural strength by up to 40%, and corrosion resistance was also increased [50]. Modification of concrete with 5% microsilica and 1.5% CF improved tensile and shear strength by 47% and 70% compared to the control mixture [51]. Coconut fibers in the composition of high-strength concrete also showed good results, improving its penetration properties and impact toughness [52]. The inclusion of CF in the composition of foam concrete in studies [53,54] improved their strength properties. Similar positive effects from dispersed CF reinforcement are presented in a number of other studies [55-60]. Thus, a comparative analysis of the results obtained in this study with the results obtained by other authors showed that they have good convergence and are not inferior to those previously obtained in terms of values characterizing the improvement of the physical and mechanical characteristics of foam concrete due to the addition of coconut fiber.

Next, a comparative analysis of the structure of conventional foam concrete, foam concrete modified with FA (composition type 15FA), and foam concrete modified with FA and dispersedly reinforced with CF (composition type 15CF/0.6) was performed. Fragments of test samples were selected to study the structure of foam concrete. Photographs of the structure of foam concrete fragments are presented in Fig. 15-17.



a) Without marking. b) After failure.

Fig. 15. Photographs of the structure of conventional foam concrete with a 10-fold increase.



a) Without marking. b) After failure.

Fig. 16. Photographs of the structure of foam concrete modified with 15% FA, magnified 10 times.

a) Without marking. b) After failure.

Fig. 17. Photographs of the structure of foam concrete modified with 15% FA and 0.6% CF, magnified 10 times.

The performed analysis of the foam concrete structure is in good agreement with the experimental data. Foam concrete modified with fly ash (Figure 16) has a more uniform pore structure compared to the control foam concrete (Fig. 15). The photographs of foam concrete with FA and CF (Fig. 17) show structural zones formed by dispersed reinforcement, and there are no noticeable defects in the form of cracks, voids and fused pores at the interface between the coconut fiber and foam concrete matrix phases [21, 61]. The combined effect of 15% FA modification and 0.6% CF dispersed reinforcement made it possible to significantly improve the physical and mechanical properties of foam concrete compared to conventional foam concrete. The density of the hardened composite decreased by 8.34%, while a decrease in the thermal conductivity coefficient of 20.96% was recorded. The increases in compressive and flexural strength were 30.14% and 72.83%, respectively. It is worth noting that these formulation solutions reduce fluidity by 9.80%. The results of improving the properties of foam concrete due to the complex effect of using fly ash and coconut fiber are already in many ways superior to the results obtained in other studies that used various formulation solutions to strengthen the cellular composite [42-44, 49-60]. Thus, based on the results of this study, an environmentally friendly composition of foam concrete with improved strength and thermal insulation properties was developed. The positive effect was achieved by selecting the optimal range of modifying additive and fiber content. FA acts on foam concrete as a stabilizer and as a mineral pozzolanic additive. After formation, foam bubbles begin to gradually merge and enlarge under the action of gravity and van der Waals forces, which ultimately leads to gas diffusion and foam rupture [15]. FA particles are adsorbed at the Plateau boundaries and delay the process of foam bubble merging due to surface tension, thereby increasing the foam stability. Due to the stabilizing properties of FA, the foam concrete composite acquires a stable network of voids. Silicon dioxide contained in FA particles enters into chemical reactions with free Ca(OH)2, and additional CSH are formed at the Plateau boundaries, which subsequently strengthen the interpore partitions and increase the overall strength of the composite [18]. CFs in the body of the foam concrete composite perform the function of a skeleton and restrain the propagation of cracks throughout the structure, both under the action of destructive loads and during shrinkage [39].

The environmental friendliness of foam concrete lies in its production with fly ash, which allows for rational disposal of accumulated waste. By saving cement, the carbon impact on the environment is reduced [62]. Plant fibers are a renewable raw material component and their use in cement composite technology is a rational formulation solution that allows for increasing the environmental friendliness of foam concrete. However, despite the high environmental friendliness and cost-effectiveness of the foam concrete with improved properties developed in this study, there are some limitations. Firstly, the unstable chemical composition of fly ash can lead to the fact that when producing foam concrete based on this waste, difficulties may arise with adjusting the compositions of foam concrete mixtures and it will be necessary to introduce additional modifying or chemical additives that will ultimately allow obtaining a composite with the required characteristics. In addition, it will be necessary to further develop the logistics processes for delivering waste to plants producing cellular concrete and products made from them. In the technological process of producing foam concrete mixtures, it may be necessary to equip the technological line with additional equipment for cleaning and preparing fly ash for introduction into the foam concrete mixture. Secondly, there is a problem concerning the properties of foam concrete dispersedly reinforced with coconut fiber. Plant fibers in foam concrete may lose their properties over time and their positive effect on the characteristics of foam concrete may decrease. Hence, there is a need for additional research aimed at studying the durability properties of foam concrete modified with fly ash and dispersedly reinforced with coconut fiber. Evaluation of the durability properties of the improved foam concrete composite is the direction of further research.

4. CONCLUSIONS

The properties and structure of foam concrete modified with fly ash and dispersedly reinforced with vegetable coconut fiber were studied. The following conclusions were made based on the obtained results.

(1) Modification of foam concrete with FA up to 30% by weight, replacing part of the cement, reduces the composite flowability. A similar effect was recorded with the introduction of CF. The decrease in the flowability of foam concrete when using these formulation techniques is explained by the sufficiently high water demand of FA particles and the porous structure of CF.

(2) Modification of foam concrete with FA in an optimal amount of up to 20% has a positive effect on their physical and mechanical properties. Foam concrete composite modified with 15% FA has the best properties. In comparison with the foam concrete of the control composition, it has a density value reduced by 9.44% and a thermal conductivity coefficient reduced by 7.26%. The maximum values of compressive and flexural strength increases were 23.29% and 21.74%, respectively. A large amount of silicon dioxide (52.3%) in FA reacts with free calcium hydroxide during hydration reactions, forming additional CSH, which helps strengthen interpore partitions and, as a result,

increases the strength of foam concrete. FA also acts as a mineral stabilizer, thereby reducing the density and thermal conductivity of foam concrete and improving its pore structure. (3) Dispersed reinforcement of foam concrete modified with 15% FA with coconut fiber in optimal dosages of up to 1% by weight of cement has a positive effect and improves the properties of the composite. The maximum increase in compressive and flexural strength by 5.56% and 41.96%, respectively, was recorded at 0.6% CF. Thermal conductivity decreased by 7.26%. CFs in the composition of foam concrete form structural zones that strengthen the material, and at the interface between the phases "coconut fiber - foam concrete matrix" there are no noticeable defects in the form of cracks, voids and fused pores; they take on part of the destructive load and block the propagation of cracks. All these factors together give a positive effect.

(4) Structural analysis of the pore structure proves the effectiveness of the formulation solutions used in this study. Foam concrete modified with 15% FA and dispersedly reinforced with 0.6% CF has the best structure and uniform porosity without noticeable defects.

Thus, the main result of this study is a new optimal composition of energy-efficient, environmentally friendly and economical foam concrete using waste from the fuel and energy complex - fly ash and vegetable coconut fiber. This foam concrete has improved properties compared to conventional foam concrete. This composite can actively serve as a structural and thermal insulation material in the construction of buildings and structures for various purposes. The resulting material meets the requirements of the sustainable development agenda.

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