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Optimization of concrete composition with polypropylene fiber to improve their crack resistance in road construction conditions

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Abstract. The study included a detailed examination of the crack resistance of heavy concrete and foam concrete that were not subjected to autoclave curing. An important aspect of this study was the use of polypropylene fiber as a reinforcing material, which made it possible to identify differences in the characteristics between reinforced and unreinforced samples. The purpose of the work was to evaluate the mechanical properties of the materials under study, as well as their behavior during destruction. For this purpose, the criteria of fracture mechanics were used, which made it possible to establish not only the strength and deformation characteristics, but also the force and energy indicators of crack resistance. The experimental results showed that the addition of polypropylene fiber significantly improves the strength characteristics of both heavy concrete and foam concrete. This improvement was especially noticeable in the case of foam concrete, which, due to reinforcement, demonstrated increased crack resistance. This is due to the fact that polypropylene fiber promotes a more uniform distribution of stress in the material, which in turn reduces the likelihood of cracking and improves resistance to destruction. In addition, the study confirmed that the use of polypropylene fiber not only increases strength, but also improves the durability of concrete, making them more suitable for use in construction, especially in conditions where materials are subject to significant mechanical loads and adverse environmental factors.
Keywords: concrete, polypropylene fiber, crack resistance, dispersed reinforcement, road pavement, construction, composite, cement matrix, durability

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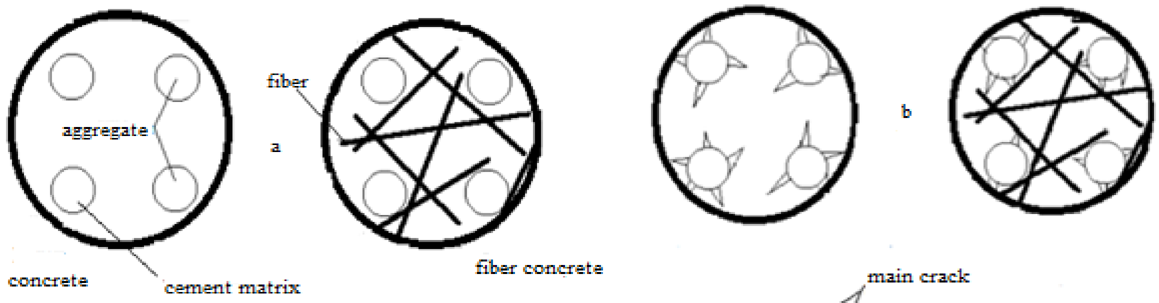
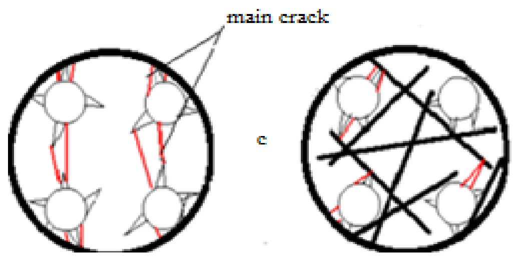
1. INTRODUCTION

The rapid development of road infrastructure, caused by the growth of traffic intensity and freight traffic, places ever higher demands on the strength and durability of road surfaces. Cement concrete, despite its widespread use, remains a material subject to significant drawbacks that limit its potential in road construction [1, 2]. The main problem is the formation of cracks, which significantly reduce the service life of road surfaces and lead to the need for expensive repairs. The main reason for early cracking in concrete structures is shrinkage resulting from cement hydration and water evaporation. This process is most intense in the first 24 hours after concrete is laid, when its strength is not yet high enough to withstand internal stresses. The formation of cracks not only reduces the load-bearing capacity of the structure, but also promotes the penetration of water, chlorides and other aggressive substances, accelerating the corrosion of reinforcement (in the case of reinforced concrete structures) and the destruction of the concrete itself. Cracks also worsen the adhesion between the layers of the road surface, reducing its resistance to the impact of dynamic loads from motor vehicles. The nature and depth of cracks depend on many factors: the composition of concrete (cement grade, water-cement ratio, type and amount of aggregates), climatic conditions (temperature, humidity), laying and compaction technology, and the presence and type of reinforcement. Traditional methods of combating cracking include the use of high-quality cements with low heat of hydration, reducing the water-cement ratio (which, however, may impair the ease of laying the mixture), adding plasticizers to increase the mobility of concrete, and using various types of reinforcement. Dispersed reinforcement with fiber (steel, polypropylene, fiberglass, basalt) is one of the most effective methods [3, 4]. Fibers, uniformly distributed in the concrete matrix, prevent the spread of cracks, forming microcracks that do not violate the integrity of the structure [5, 6].

The choice of fiber type depends on the required concrete characteristics and operating conditions. Steel fiber provides high tensile strength, but is susceptible to corrosion, polypropylene is not susceptible to corrosion, but has lower strength [7]. Glass fiber and basalt fiber occupy an intermediate position in terms of strength and corrosion resistance. However, even with the use of dispersed reinforcement, it is almost impossible to completely eliminate cracking in concrete [8]. Therefore, research into new methods aimed at modifying the properties of cement stone and increasing its resistance to shrinkage stress is relevant. The use of additives that modify the cement hydration process, allowing you to control the kinetics of hardening and reduce the level of internal stresses. Such additives include various superplasticizers, mineral additives (fly ash, microsilica, metakaolin), and nanomodifiers [9, 10].

Concrete reinforcement with dispersed fibers is a revolutionary approach in the construction industry, allowing the creation of composite materials with fundamentally new properties [11]. Unlike traditional reinforcement using steel reinforcement, where the process of product manufacturing and reinforcement are separated in time and space, the technology of dispersed reinforcement involves the simultaneous formation of a matrix (cement mortar) and the uniform distribution of reinforcing fibers in it. This "synchronous" approach to creating a composite results in a unique combination of properties that go beyond the characteristics of individual components [12]. The key factor determining the improved properties is the heterogeneous structure of the composite and, as a result, the huge area of the phase interface between the fibers and the cement matrix. This extensive contact surface plays a decisive role in the mechanism of increasing strength and deformation characteristics. Fibers, be they steel, polypropylene, glass or basalt, prevent crack propagation by absorbing the energy of destruction [13]. When a crack propagates through the matrix, it encounters resistance from the fibers, which either bend or break, dissipating the energy and preventing failure. This phenomenon is especially effective in the case of short, randomly oriented fibers, which create a three-dimensional reinforcing network. According to research by A.V. Parfenov, the crack resistance of concrete with the introduction of (1–3%) fiber fibers increases by 1.2–3 times, and the viscosity of the system – by more than 30 times.





a) the initial state of the composite structure of concrete;
b) the effect of dispersed fiber on strengthening concrete under load to form cracks;
c) the influence of dispersed fiber on the strengthening of concrete in the presence of main cracks.

Fig. 1. Illustration of the effect of fiber on the strengthening of concrete under loading.

Road pavement, which is the top layer of the road surface, is subject to significant impacts from both traffic loads and natural and climatic factors. These operating conditions significantly complicate the operation of road structures compared to other types of structures, such as bridges or buildings. As a result, the choice of material for the road surface becomes critical to ensure durability and reliability. One of the most effective solutions for such difficult conditions is the use of concrete pavement, especially if it is reinforced with dispersed reinforcement. This reinforcement method involves uniform distribution of reinforcing fibers throughout the entire volume of concrete, which significantly increases its strength characteristics.

According to GOST R 59120-2021, road pavement layers must not only withstand mechanical loads, but also affect the change in the freezing depth of the subgrade. The depth of penetration of 0 °C into the soil does not always coincide with the actual freezing depth, which means that the freezing depth is usually less than the depth to which the 0 °C temperature penetrates. This phenomenon is especially noticeable under asphalt pavements of highways, motorways and city streets, where the freezing depth significantly exceeds that under the grass cover, which is usually covered with snow in winter. Research in the field of dispersed reinforcement of concrete is focused on its increased strength characteristics compared to unreinforced analogues. However, it is worth noting that cement concretes can exhibit insufficient crack resistance and a high degree of brittleness, which makes them vulnerable to various mechanical and temperature influences. This emphasizes the importance of choosing the right materials and technologies to ensure the durability of road structures. The temperature regime of the soil located under the road surface is formed under the influence of two key factors: solar radiation falling on the surface and the flow of radiogenic heat emanating from the depths of the Earth. Seasonal and daily fluctuations in the intensity of solar radiation, as well as the outside air temperature and the level of solar radiation, directly affect the change in soil temperature. Depending on the specific soil-climatic and hydrological conditions, the soil temperature can fluctuate at a depth of several tens of centimeters to one and a half meters. It is important to note that at a depth of more than 10 meters, the soil is practically not affected by seasonal temperature fluctuations. This is due to the fact that at such depths the soil is in a state of thermal inertia, and changes in surface temperature have a minimal effect on its condition [14].

Today, frost protection layers consisting mainly of coarse and medium-grained sands, which can make up to 95% of the total volume of materials used, are actively used in the construction of highways, especially those with monolithic concrete and asphalt concrete pavements. These layers are designed to protect the road structure from the negative impact of low temperatures and prevent the formation of ice plugs, which helps to increase the service life of the road. However, despite the use of such frost protection layers, there are a number of problems that can negatively affect the durability and reliability of the road surface. In particular, such a design cannot guarantee complete protection against blowing away, which can occur when the soil located under the road surface freezes. Freezing can lead to the formation of voids, which, in turn, causes deformation and destruction of the pavement. In addition, during the period of thawing of the soil, precipitation is possible, which can also negatively affect the condition of the roadway.

Research and use of various thermal insulation materials in road construction began to actively develop in the middle of the 20th century. This is due to the fact that the problem of freezing of the roadbed has always remained relevant for highways.

A feasibility study of the construction of pilot sites conducted at the end of the 20th century and the beginning of the 21st century revealed important aspects related to the design of road pavement. The results of the study demonstrated that designs using alternative materials were more cost- effective than traditional solutions, where construction sand was used as a frost-protective layer. This fact is of great importance for the design and construction of highways, as it allows for cost optimization and increased resource efficiency. Road pavement is a key element in highway infrastructure. It not only ensures the strength and durability of the pavement, but also affects traffic safety. It is important to note that the cost of road pavement construction can account for up to 70% of the total cost of road construction.

Experience of both domestic and foreign road construction has confirmed the high efficiency of using thermal insulation materials in road pavement construction. In recent years, Russia has seen a growing interest in the use of non-autoclaved foam concrete, which has proven itself not only in the construction of residential and public buildings, but also in road construction. This modern thermal insulation material has unique properties that make it ideal for use in road pavement construction. Foam concrete in a road structure can perform two important functions: firstly, it serves as a thermal insulation layer, preventing the formation of ice and maintaining an optimal temperature in the road structure, and secondly, it distributes the loads arising from passing cars over the entire surface of the road pavement. This reduces the risk of deformation and damage, which is especially important in conditions of variable climate and high loads. When designing road structures, building materials are arranged according to the principle of decreasing strength. This is due to the fact that the stress from temporary loads fades along the depth of the structure. However, despite this principle, the critical values of the stress-strain state parameters must be determined both for the base concrete used for the coating and for the foam concrete, which acts as a heat-insulating layer [15, 16].

Although many researchers have focused on the dispersed reinforcement of concrete and its increased strength characteristics compared to unreinforced analogues, it is worth noting that cement concretes often have low crack resistance and a high degree of brittleness of destruction. These shortcomings can become critical during road operation, especially under conditions of significant temperature fluctuations and mechanical loads. To date, research in this area remains insufficiently deep, especially when it comes to cellular concretes such as foam concrete.

3. METHODS AND MATERIALS

The production and testing of concrete samples of pilot batches was carried out in strict accordance with the requirements of current regulatory documents, which is an important stage in assessing the quality and characteristics of concrete. For this study, each series of concrete samples consisted of six cubes measuring 100 × 100 × 100 mm and four prisms measuring 100 × 100 × 400 mm. Such sample sizes allow obtaining representative data on the strength characteristics and crack resistance of concrete. Crack resistance of concrete is a critical characteristic that determines the durability and reliability of structures. To assess it, equilibrium mechanical tests were carried out on prisms that initially had a pre-created normal tear crack. The tests were carried out using a three-point bending scheme, which allows for a more accurate assessment of the material's behavior under load. During the tests, a complete load-deflection (FV) diagram was recorded on a special testing rig, which made it possible to analyze in detail not only the strength characteristics, but also the behavior of concrete during destruction.

The general appearance of the test setup is shown in Fig. 2, the diagram of the measuring part of the setup is shown in Fig. 3, and the diagram of the bending tests of the prism sample with an initiated normal rupture crack is shown in Fig. 4.

Fig. 2. Press for testing concrete strength by destructive method.

During the tests, state diagrams of materials were developed, which allowed a more detailed analysis of the behavior of heavy concrete and foam concrete under the influence of various loads. These diagrams serve as an important tool for visualizing the process of destruction and determining the key characteristics of crack resistance. To calculate the tensile strength of concrete in bending, the maximum load values \u200b\u200bobtained from the diagrams shown in Fig. 5 and 6 were used. These values \u200b\u200bare critical, since they help to determine how the material will behave under real operating conditions, where bending and stretching can lead to cracking. The compressive strength of concrete, in turn, was determined in accordance with the requirements of national standards of the Russian Federation.

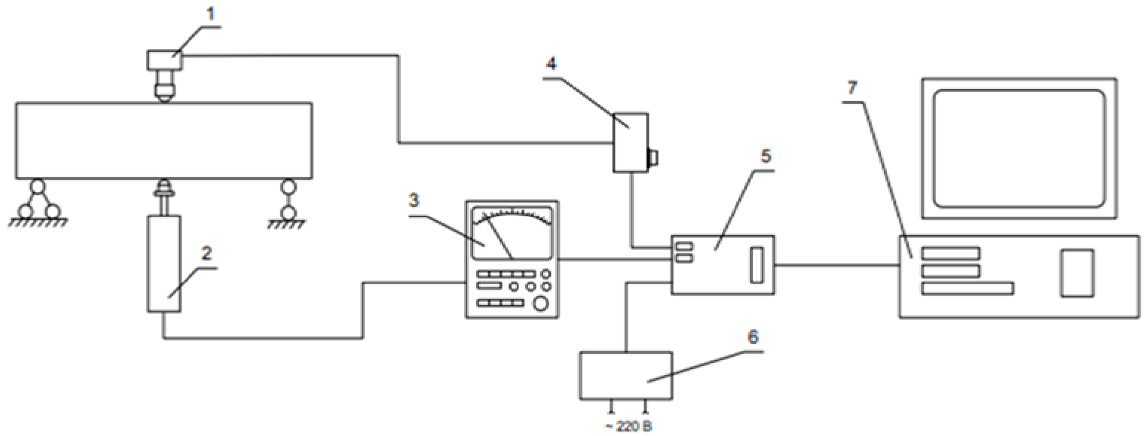


Fig. 3. Scheme of the measuring part of the installation for determining the characteristics of crack resistance: 1 – strain gauge; 2 – inductive displacement sensor; 3 – amplifier-converter of the signal from the displacement sensor; 4 – resistor bridge; 5 – interface board; 6 – power supply; 7 – computer.

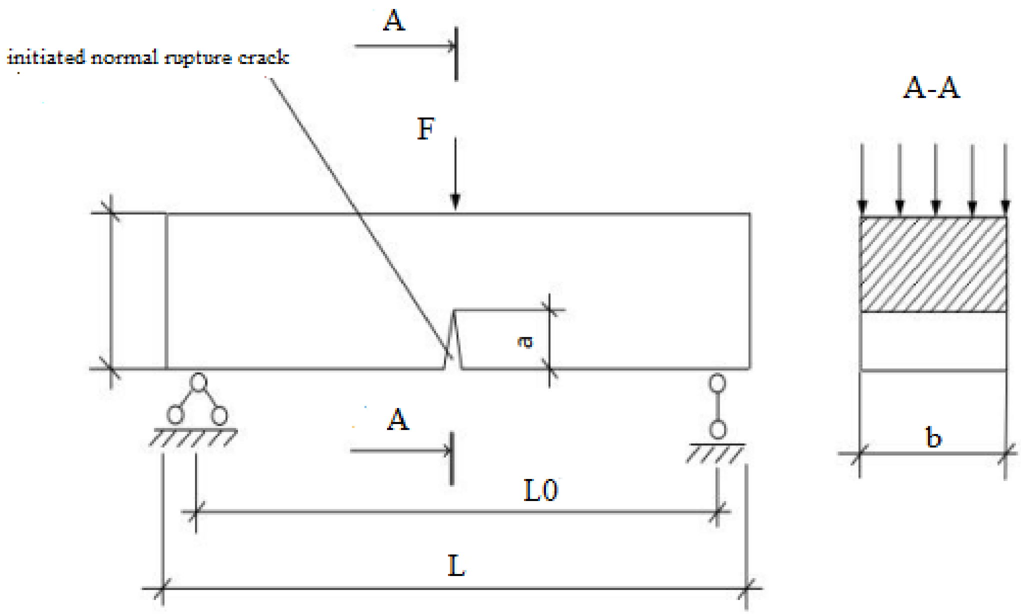


Fig. 4. Scheme of bending tests of a prism specimen with an initiated normal tensile crack: a – length of the initial notch (m); b. l, l 0 – specimen dimensions (m); F – load (kN).

In the production of heavy concrete mixtures, we used various components that provide the required physical and mechanical properties of the final product. Portland cement II / A-P PC-500 for general construction purposes was used as the main binder; this type of cement is characterized by high strength and resistance to environmental influences, which makes it ideal for use in construction. Dry quartz sand with a fineness modulus of Mk = 1.3, which provides good homogeneity and strength. In addition, crushed stone screenings of fraction 1.25-5.0 mm are added to the composition. This component plays an important role in improving the structure of the mixture, filling the voids between large grains and increasing the overall density. Large filler in heavy concrete mixtures is represented by granite crushed stone of fraction 5-32 mm. Granite crushed stone is characterized by high strength and durability.

The composition of the aggregate mixture for non-autoclave curing foam concrete mixtures was developed using the absolute volume method, which allows for continuous granulometry. Portland cement grade PC-500, which complies with general construction standards, was used as a binder. An important component of the mixture is quartz sand obtained from a manufacturer in the city of Nizhny Novgorod, with a fineness modulus of Mk = 1.18, this sand provides the necessary grain structure, which has a positive effect on the homogeneity and strength of concrete, and to achieve the necessary lightness and improve the thermal insulation properties of foam concrete, the foaming additive BLAIZER MB was added to the composition.

For reinforcement heavy and cellular concrete used polypropylene fiber, the characteristics of which are presented in Table 1.

Table 1. Technical characteristics of polypropylene fiber.

Parameter name	Meaning
Fiber diameter, μm	18-20
Linear density, dtex	3.3
Length, mm	12
Specific gravity, t/m3	0.91
Young's modulus , N/mm2	3500
Melting point, ºC	145
Tensile strength, N/mm2	350

Continuation of Table 1

Fiber surface	It is coated with a special composition – a lubricant – which promotes dispersion and adhesion to cement solution
Appearance	Separate fibers of white color in in bulk homogeneous mass
	

4. RESULTS AND DISCUSSION

The results of the study of the strength and deformation characteristics of heavy and cellular concrete are presented in Table 2. For clarity, the state diagrams of these concretes can be seen in Fig. 5 and 6.

The compressive strength of both heavy reinforced and unreinforced concretes demonstrates almost identical values. This indicates that traditional reinforcement methods do not have a significant effect on this characteristic. However, in the case of foam concretes that were reinforced with dispersed fibers, a noticeable improvement in compressive strength is observed. This is due to the fact that dispersed fibers help strengthen the interpore partitions, which makes the material more resistant to compressive loads. However, it is worth noting that compressive strength is not the only characteristic for fiber concrete. An important aspect of the use of dispersed reinforcement is its effect on tensile strength in bending. This characteristic is one of the key problems that are solved with the help of dispersed reinforcement.

Table 2. Strength and deformation characteristics of the studied concretes.

Series	Average density of concrete, kg/m3	Availability fibers in composition concrete	Strength for compression, R_b, MPa	Tensile strength at bending, R_{tb}MPa	Fragility criterion, $X_{tb} = (G_f E_{tb}/R_t b_2) \times 10^{-3}$ м
D600f	600	+	1.75	0.45	140
D600	600	-	1.63	0.37	122
D700f	700	+	1.91	0.61	226
D700	700	-	1.82	0.41	216
D1200f	1200	+	8.51	0.65	259
D1200	1200	-	7.88	1.47	106
Bf	2400	+	62.3	10.81	343
B	2400	-	58.5	5.11	86

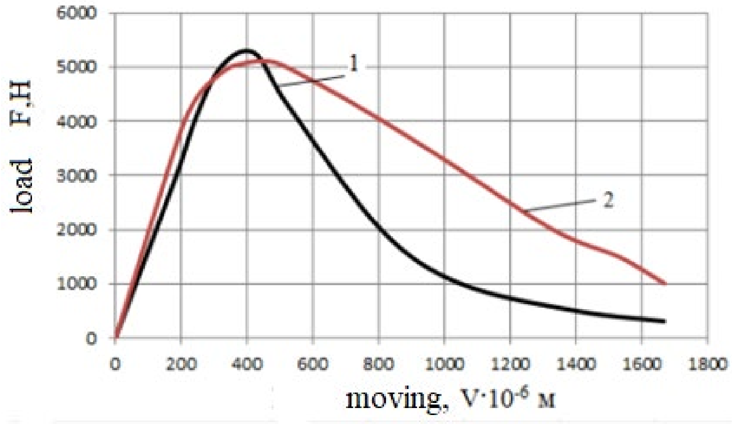


Fig. 5. Condition of heavy concrete 1-concrete series B, 2-concrete series Bf.

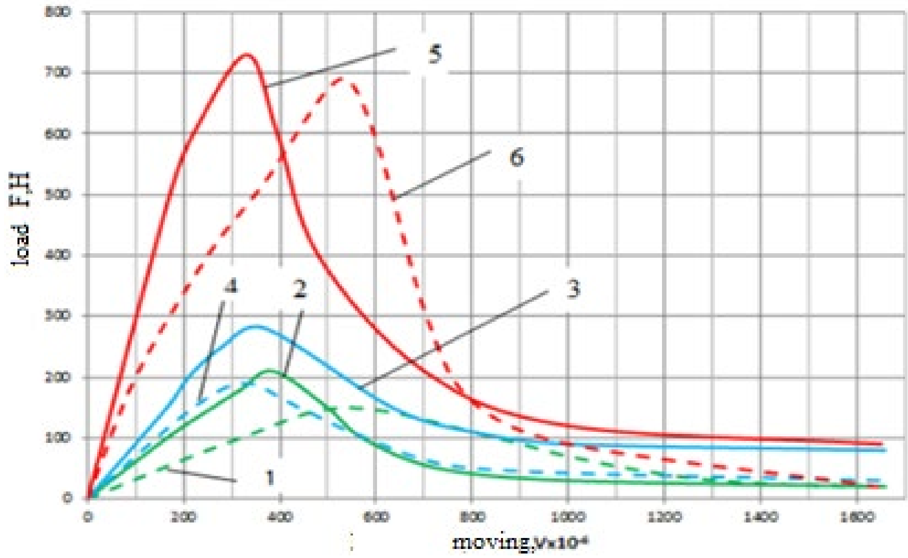


Fig. 6. States of foam concrete series: 1 – foam concrete series D600f; 2 – foam concrete series D600; 3 – foam concrete series D700f; 4 – foam concrete series D700; 5 – foam concrete series D1200f; 6 – foam concrete series D1200.

Table 3 presents the strength and energy characteristics of crack resistance of the studied concrete and foam concrete samples, both reinforced and unreinforced with polypropylene fiber. Comparative graphs reflecting specific energy consumption during static destruction are presented in Fig. 7, 8, diagrams showing the critical stress intensity factors Ki, which characterize the fracture toughness, are given in Fig. 9, 10.

Table 3. Power and energy characteristics of crack resistance of the studied concretes.

Series	W_i, 10^{-2}Н · м	W_l, 10^{-2}Н · м	G_i, J/м^2 ·	G_F, J/м^2 ·	G_{ce}, J/м^2	J_i, J/м^2	K_i, МПа·$^{1/2}$	K_c, МПа·$^{1/2}$
D600f	4.45	6.11	7.73	16.21	0.93	4.59	0.04	0.01
D600	10.58	4.02	19.23	15.82	0.41	15.08	0.04	0
D700f	6.11	15.98	9.81	34.11	3.33	6.18	0.05	0.03
D700	3.41	8.41	5.73	17.98	1.09	3.57	0.03	0.01
D1200f	16.69	25.65	27.91	53.42	12.03	23.01	0.18	0.12
D1200	20.62	15.73	34.42	52.68	1.22	21.15	0.12	0.02
Bf	157.35	182.21	261.6	745.23	72.97	205.32	0.99	0.64
B	134.92	204.56	228.49	482.59	119.12	158.02	0.96	0.75

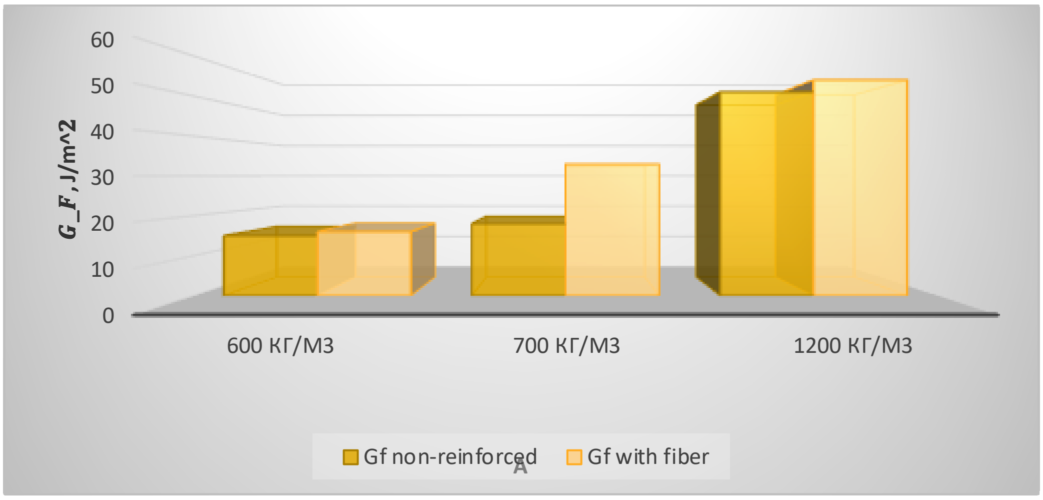


Fig. 7. Comparative graph of specific energy consumption during static destruction $G_F$of foam concrete.

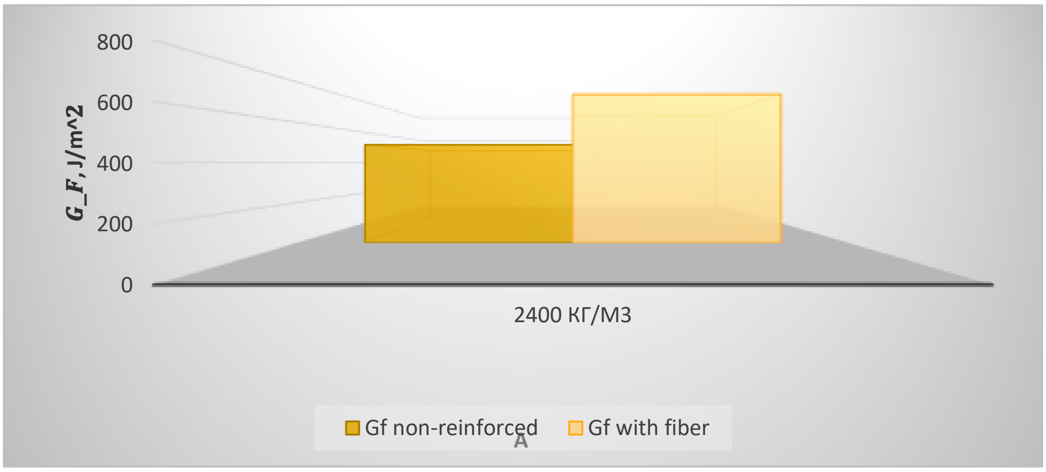


Fig. 8. Comparative graph of specific energy consumption during static destructionG_F heavy concrete.

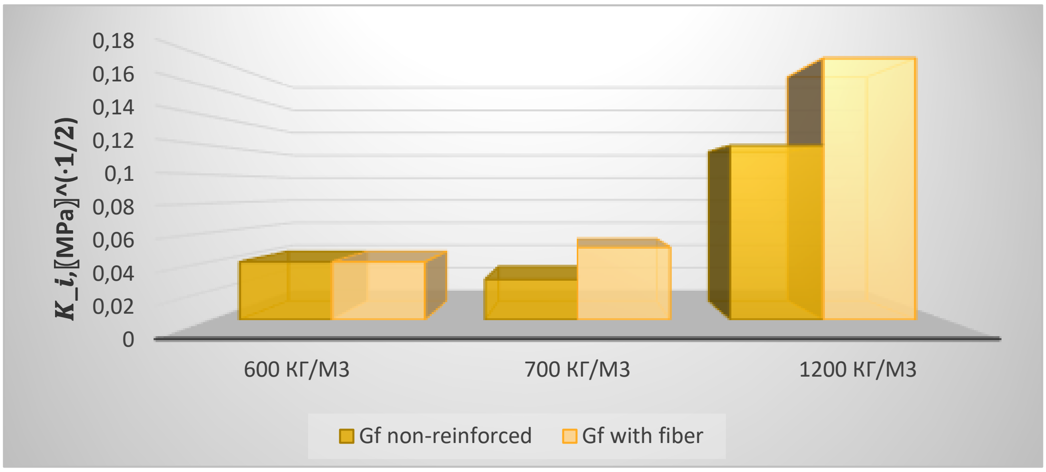


Fig. 9. Comparative graph of critical stress intensity factors$\boldsymbol{K_i}$ cellular concrete.

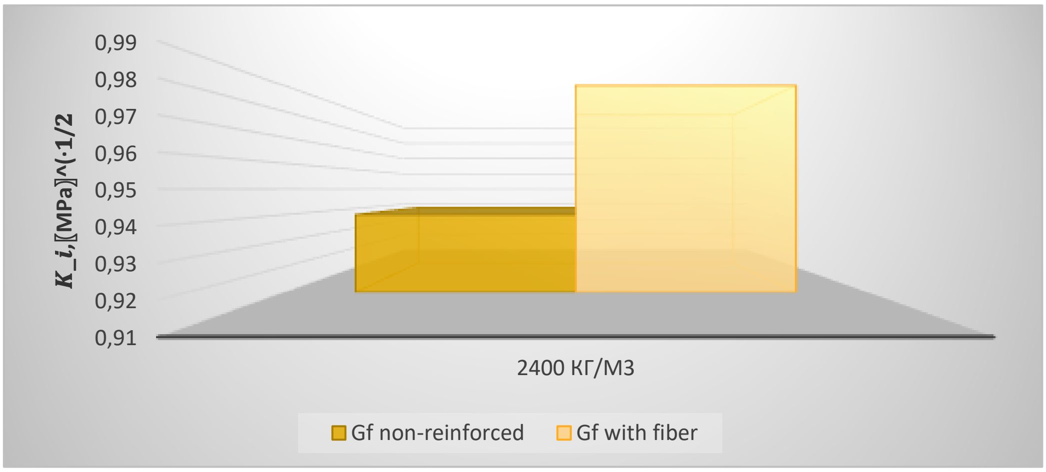


Fig. 10. Comparative graph of critical stress intensity factors $\boldsymbol{K_i}$of heavy concrete.

According to the conducted studies, the addition of polypropylene fiber to concrete and foam concrete leads to a noticeable increase in crack resistance indices, which are studied according to the criteria of fracture mechanics. Analysis of the phase diagrams presented in Fig. 5 and 6 demonstrates that foam concrete with a density of 600 kg/m³, reinforced with polypropylene fiber (designated as D600f), has significant advantages in the subcritical stage of deformation, that is, before the appearance of the first macrocracks. It is important to note that at this stage, the addition of fiber does not always lead to an equally significant increase in the specific energy consumption for static deformation, which is recorded before the moment the main crack begins to move ($\boldsymbol{G_i}$). The most noticeable effect of reinforcement with polypropylene fiber is observed in the closed stage of destruction. At this stage, the fiber effectively restrains the process of destruction of samples, starting from the moment when the main crack develops and until complete defragmentation of the material. The indicator characterizing this effect is the specific energy consumption for static failure ($\boldsymbol{G_F}$), presented in Table 3 and Fig. 7, 8. Specific energy consumption $\boldsymbol{G_F}$ is higher in all series of concrete with dispersed reinforcement compared to unreinforced samples, which confirms the efficiency of this approach. The most pronounced reinforcement effect is observed in heavy concrete and cellular concrete with a density of 700 kg / m³, where the indicators $\boldsymbol{G_F}$ are 1.5 and 1.8 times higher than the values of unreinforced samples. In the D600f and D1200f series, high values are also recorded, but the difference in values between reinforced and unreinforced samples is somewhat smaller compared to the previous series. The critical stress intensity factor, which is also called fracture toughness ($\boldsymbol{K_i}$), demonstrates similar trends. In reinforced concretes of the D700f and D1200f series, the indicators $\boldsymbol{K_i}$ are significantly higher, indicating their increased resistance to destruction under the influence of external loads. These results highlight the importance of using polypropylene fibres to improve the strength properties of concrete, especially in conditions where materials are subject to significant mechanical loads.

4. CONCLUSIONS

During the tests of pilot series of concrete and foam concrete samples, as well as the analysis of the obtained results, the high efficiency of reinforcing heavy concrete and non-autoclaved foam concrete with polypropylene fiber was established. Such reinforcement significantly increases the strength characteristics, as well as the power and energy indicators of crack resistance of these materials. The expediency of using polypropylene fiber for reinforcing foam concrete is manifested both at the initial stage of deformation and in conditions when the main crack has already formed, which indicates its ability to improve resistance to destruction. The reinforced material is capable of withstanding large deformations before and after the formation of the main crack, which is critically important for ensuring the durability and reliability of structures made of these concretes. The positive effect of dispersed reinforcement of heavy cement road concretes also manifests itself in an increase in tensile strength at bending, which increases by 22% on average. All this affects the overall efficiency of concrete, especially in the closed stage, when fiber fibers begin to actively participate in the process of formation and development of cracks. They not only slow down the process of destruction, but also allow to maintain the integrity of the structure for a longer period. With an increase in the density of foam concretes, a direct proportional relationship is observed between the growth of specific energy consumption for static destruction and the density of the material. Denser foam concretes require greater efforts for destruction, which also indicates their increased strength. The introduction of polypropylene fiber into the composition of concrete and foam concrete leads to a noticeable effect, especially in the closed stage of destruction. Fiber effectively restrains the process of destruction of samples from the moment of the appearance of the main crack and until the complete destruction of the material. The indicator characterizing this effect – as specific energy consumption for static destruction, denoted by $\boldsymbol{G_F}$ – is significantly higher in all series of concretes with dispersed reinforcement compared to unreinforced samples. This confirms that polypropylene fiber not only improves strength characteristics, but also contributes to a more efficient distribution of loads in the material, which reduces the likelihood of sudden destruction.

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