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Research of the Effect of the Concrete Reinforcement Structure on the Stress-Strain State of Structures

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Abstract
The results of the research of concrete with dispersed fibers of various materials are presented in the paper. Since, till present, fiber reinforced concrete has not been sufficiently studied as a material of structures, the main emphasis is placed on the consideration of strain characteristics at different stages of loading and the variable reinforcement percentage. The factors of the influence of physical and chemical properties of saturating media on strain properties and the concrete breaking strength were shown. It was substantiated that the conventional mixtures used for the laying of underground cavities have a great strain capacity, as well as insignificant strength, which ultimately predetermines the shifts in the rock massifs after the cavities are eliminated. It has been proved that strong concrete structures cannot provide for long operative conditions in complex hydrogeological conditions. Metal fiber, as a component, contributes to a significant improvement in the backfill strain indexes, but during surface works, for example, through wells, the situations with plugging of the latter are possible because of the possible formation of "hedgehogs" while mixing the mixture. The information on the dosage of metallic and synthetic fibers recommended for the use of dispersed-reinforced concrete is presented. A qualitative and quantitative assessment of the stress-strain state of fiber-reinforced concrete structures is made.

Keywords: fiber-reinforced concrete, laying of underground cavities, reinforcement of concrete with dispersed fibers, strain characteristics.

INTRODUCTION

The use of dispersed-reinforced concrete and shotcrete is becoming increasingly widespread in the practice of building tunnels, massive structures, road surfaces, in floors construction in commercial and warehouse premises, as well as in the manufacture of conventional building structures (columns, foundations, slabs, etc.), which makes it possible to increase their resistance to mechanical effect both at the concrete hardening stage and during operation. However, despite the high enough interest in this material during production, the normative literature regulating the definitions of the mechanical properties of dispersed reinforced concrete has not been fully developed, and the determination of individual indicators required during the design of structures made of dispersed reinforced concrete and shotcrete has not been described in the normative literature.

The important indicators characterizing the concrete operation, such as the material for laying underground cavities or the support structure element, are the following: ultimate strength upon uniaxial compression; ultimate strength upon uniaxial tension; ultimate tensile strength upon bending; Young modulus upon uniaxial compression. The values of these indicators depend on the dosage of the additives, as well as their type and composition of the concrete mix, and should be determined on the basis of laboratory tests. The existing regulatory framework and documents regulating the definition of basic indicators characterizing the mechanical operation of dispersed-reinforced concrete were reviewed in the paper. Based on the results of the research work, the existing approaches to testing were summarized.

METHODOLOGY

Analysis of the processes affecting the change in the strain state of concrete structures

As the studies [1-19] show, the formation of fracture nucleus is associated with plastic strain, and the macro-destruction of materials is preceded by complex microscopic processes of accumulation of damages. Concretes are classified as materials with a so-called "imperfect" structure: A large number of pores, inclusions, cracks, and composition variety. This determines a wide range of manifestations of creep and fracture processes physics. For concrete with good adhesion between composite components, the main feature is the microcracks appearance and development.

At the stage of transformation of microcracks into the main crack, during the concrete behavior in compression, the internal friction forces play an important role. Like fittings, they restrain local transverse strains, distributing them more evenly throughout the cross section of the model and preventing the avalanche-like development of the first crack. Many small cracks are formed instead of it. In appearance, this manifests itself in the form of plastic strain of concrete. During axial tension or bending of unreinforced concrete, there are no restraining and distributing forces, so the load-bearing capacity of concrete is underutilized because of an early development of cracks in any section.

The production and operation of concrete structures are accompanied by cracking caused by a complex of causes (Table 1).

Cracks, strains or fractures may be caused by the action of various loads; errors in the calculations; the use of poor-quality materials; the disturbance of heat treatment and installation technology; heterogeneity of strength, elasticity and rigidity of the materials used; loss of strength of the substrate.

Table 1. Types of cracks and their causes

Causes of cracks															
Prior to hardening (up to 6 hours)					After hardening (up to 28 days)										
Concrete pouring		Shrinkage strain			Volume strain			Structure, design strain			Physicochemical processes				
Casting and pouring	Form irregular surface	Plastic shrinkage	Contractional shrinkage	Surface shrinkage	Moistening, drying	Thermal expansion	Plastic flow	Overload (rated load)	Uneven base	Fatigue cracks	Interaction of cement alkalis with aggregates	Formation of the ettringite-thaumasite system	Cyclic freezing / thawing		

Each of these factors is most intensively manifested at different stages of hardening of concrete, and therefore their effect on the durability of concrete elements is not the same. The greatest role is played by strains, occurring in hardened concrete, where the bulk falls on those that are associated with stretching or bending loads, internal stresses during cyclic freezing and thawing, environmental effects, and corrosion processes. The development of defects over time has a significant effect on the stress-strain state of structural elements.

It is known from [2,6,20-21] that the strength of any stone materials is reduced in case of water saturation. The reason for this is that microcrack formation is facilitated by adsorption of a polar liquid by a solid body. This is also true for concrete used in the laying.

The volumetric stress state of compression, temperature, physicochemical properties and pressure of saturating fluids, tectonic stresses and loading conditions (speed and duration of the process) are one of the main factors determining the behavior and properties of concrete under the conditions of the backfill massif.

Firstly, the influence of the saturating liquid pressure is expressed in the decrease in the value of the uniform compression, and, consequently, in the decrease in the effect of repulsion at the lying depth.

Secondly, in the case of anomalously high pressure, its effect can be expressed in the natural rupture of concrete structures and the formation of cracks.

Research of the properties of concrete and factors affecting its stress-strain state

A number of works [1,7,20-21] are devoted to the influence of physical and chemical properties of saturating media on the strain properties and resistance of concrete to fracture, the main conclusions of which include the following:

- under the effect of active media (mineralized water, aqueous solutions of surface-active substances, etc.), the resistance of concrete to shear and the magnitude of residual strain are sharply reduced;
- the physicochemical effect of saturating media on the strain behavior of concrete consists mainly in stimulating strain along the grain boundaries, owing to the adsorption effect (the phenomenon of adsorptive facilitation of strains and lowering the strength of solids, that since 1928 is known as the "Rebinder effect", has an extremely broad generality of manifestation on any solid of crystalline and amorphous, solid and porous bodies);
- strain microcracking promotes the growth of permeability;
- in places where the strain is most developed and is accompanied by microfractures, the development of destruction (separation or shear) cracks of different orders is most likely, to which, according to modern concepts, the filtration properties of any stone materials are related;
- with an increase in the degree of water saturation of the samples, a regular decrease in the strength of concrete occurs and a significantly larger effect of excess water in the pores on the strength of the concrete;
- drying of concrete is also one of the factors weakening its structural bonds and, therefore, contributing to the formation of repulse cracks in the marginal part of the laying massif.

As is known, the concrete as a material has low strength properties for bending and stretching – the main destructive stresses in any mine structure.

To improve the effective performance of the mechanical operation of concrete, for example, as a shotcrete support structure, its dispersed reinforcement with metallic, synthetic or other types of fibers is performed. Fibers used for shotcrete reinforcing allow increasing the concrete tensile strength in bending and partially retaining the ability to resist external loads after the formation of a crack. Upon reaching the limiting state, a redistribution of forces takes place, and the maximum stress values move from the crack formation to the edge zones. The main difference in the mechanical behavior of dispersed-reinforced concrete and shotcrete from unreinforced concrete is manifested in the superlimiting strain zone. In the limiting zone, the nature of their strain is similar. In this regard, the value of the ultimate bearing capacity of the support material is taken to be the value at which the section of the structure completely loses its ability to resist the load, and its destruction occurs with the loss of the ability to resist further loading.

Based on the review of technical literature and scientific publications [2-3, 20-21] concerning the degree of influence of the standard dosage of fiber (30-40 kg of metal fiber per 1 m^3 of concrete mixture; 6-7 kg of synthetic fiber per 1 m^3 of concrete mixture) on the concrete mechanical characteristics, the following conclusions may be drawn:

- The compressive strength of dispersed-reinforced concrete can increase up to 20%, at a dosage of steel fiber of 40 kg per 1 m^3 of concrete mix;
- Straight tensile tests have shown that the strength of standard concrete and dispersed-reinforced concrete is not significantly different. It was noted that with a standard dosage of fiber, the compression and tensile strength of dispersed-reinforced concrete insignificantly increases, and in some cases it does not differ. However, concrete becomes more plastic, and its crack resistance increases;
- Depending on the type of fiber used, the tensile strength of dispersed-reinforced concrete at standard dosages may increase by 150-180% in comparison with unreinforced concrete;
- The results of tests of dispersed-reinforced concrete under the influence of dynamic loads showed that it is capable of withstanding compressive and tensile loads 3-10 times exceeding the loads perceived by unreinforced concrete.

With an increase in the fiber dosage, the strength, rigidity and crack resistance can significantly increase. The paper [4] shows that in the case of fiber consumption four times exceeding the standard one, it is possible to obtain more than threefold increase in the bending strength of concrete and more than fourfold increase in resistance to cracking.

The analysis of scientific and technical publications led to the conclusion that dispersed-reinforced concrete allows improving the performance of ordinary concrete in the following cases:

- in the case of the decrease in the number and size of microcracks during the concrete hardening;
- in the case of an increase of concrete hardness upon formation and development of macrocracks;
- in the case of an increase in the waterproofness of solid supports, due to the reduction in the number of cracks and their opening width in comparison with conventional concrete;
- in the case of the concrete resistance to destruction in local areas, for example, the formation of chips;
- in the case of an increase in the durability as compared to unreinforced concrete;
- in the case of an increase of corrosion resistance;
- in the case of an increase in the concrete fracture resistance upon thermal influence;
- in the case of loading implementation in the form of specified strain (interaction scheme). If the scheme of specified loads is implemented, the behavior of dispersed-reinforced concrete practically does not differ from that of unreinforced concrete;
- in case of a decrease in the complexity of work.

The main advantages that are obtained when using dispersed-reinforced shotcrete are the following:

- There is no need to install the reinforcing cages, which makes it possible to increase the safety of work at the construction site and reduce the work labour input;
- The cohesion of the shotcrete with the rock contour increases;
- The lining thickness is reduced as compared to the conventional shotcrete;
- A higher quality for the shotcrete lining is achieved; the presence of cavities that can be formed between the rock contour and the shotcrete is excluded in case the reinforced mesh is used;
- Reinforcement is performed throughout the volume of the lining and in all directions. The resistance of the lining to the formation of cracks and chips is increased in case of a complex loading of the lining;
- The rate of the compression and tensile strength development of the disperse-reinforced shotcrete is higher as compared to conventional concrete;
- The residual strength of the dispersed-reinforced shotcrete is considerably higher than the strength of conventional concrete.

It should be noted that all of the above conclusions are made for disperse-reinforced concrete, the volume of fiber in which does not exceed the standard dosage.

Upon the consumption of 150-250 kg of metal fiber per 1 m^3 of concrete and the use of high-strength concretes, the uniaxial tensile strength of dispersed-reinforced concrete is increased. However, the cost of such disperse-reinforced concrete is significantly increased.

Below is summary information of the dosage of metallic and synthetic fiber (**table**) recommended for fixing the mine workings with dispersed-reinforced shotcrete. As it is shown in the table provided, the minimum recommended consumption of synthetic fiber for fixing mine workings with disperse-reinforced shotcrete is 6.5 kg.

Table 2. The relationship between the tunneling or mining realization conditions and the mechanical behavior of dispersion-reinforced shotcrete [6,19]

Conditions for tunneling or mining realization		The standard criterion for estimating the structural deflection		An increased criterion for estimating the structural deflection		
TPL	Stability category according to Q-system	ENFARC test (25 mm deflection), J	Round Panel Test (40 mm deflection), J	Round Panel Test (80 mm deflection), J	Estimated consumption, kg/m^3	
					metal fiber	macro synthetic fiber
IV	F	> 1,400	> 560	> 840	55	11.5
	E	> 1000	> 400	> 600	40	9
III	D	> 700	> 280	> 420	27.5	7.5
II	C	> 500	> 200	> 300	20	6.5
I	B					
0	A	-	-	-	0	0

Note: TPL – concrete category by destructive energy

RESULTS

The research of the stress-strain state of concrete structures based on steel fibre filler

The purpose of the first stage of the study was to determine the physico-mechanical properties of fiber-reinforced concrete with various types of fiber and the change in its amount in the mixture. The physical and mechanical properties of sand-cement samples without reinforcement and samples with wire reinforcement were also defined during the tests.

Straight lengths of wire of 25-40 mm long and 1.6 mm in diameter, as well as metal chips (metalworking waste), were used as fiber. At the same time, the percentage of fiber in the sample was changed. The applied loads and elastic and plastic strains with fixation of destructive cracks and safety after testing the coherence of the samples were measured during the test.

The results of the tests are given in Table 3 (bending) and Table 4 (strain).

The experimental studies were carried out on the IP-500 press, the strains were measured with the help of the IHS-5 clock-type indicator with a 0.01 mm dividing point. The tests have shown that placement of curvilinear, volumetric metal segments as fiber in the concrete provides for a significant increase in the physical and mechanical properties of concrete products as compared to conventional concrete or straight metal segments.

The purpose of the following set of studies was to determine the effect of the percentage of fibers on the strength of concrete during compression and stretching.

The following percentages of fiber reinforcement by weight were adopted: 0 ... 10% with 1% increments. For the experimental studies of the strength of fiber-reinforced concrete, 22 samples were made in the form of a cube with a side of 100 mm and 22 samples in the form of beams with dimensions of 40:40:160 mm.

The composition of the solution and the laboratory tests were based of the above regulatory documents.

The sand size module was adopted as equal to 1.5; the water-cement ratio – 0.45; the cement to sand ratio – 1:3; the diameter of steel fiber – 0.5 mm, and its length – 20 mm.

The results of the tests for axial compression of cubes are given in Table 5.

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Table 3. Results of the bend test of samples

Item No.	Sample characteristics	Bending stress σ, MPa / Relative strain ε 10^{-3}					
1	2	3					
1	Cement-sand mixture 1:3 (free of foreign matter)	0.3 / 0	0.625 / 0.5				
2	Cement-sand mixture 1:3 (lower edge reinforcement)	0.3 / 1.0	0.75 / 2.1	1.56 / 3.5	2.3 / 4.8	3.12* / 5.2	3.4 / 6.25
3	Cement-sand mixture 1:3 (upper edge reinforcement)	0.3 / 0.75	0.75 / 3.75	1.25* / 5.5	0.75 / 6.25	—	—
4	Cement-sand mixture 1:3 (wire sections 10%)	0.5 / 2.5	0.75* / 5.0	0.75 / 6.25	—	—	—
5	Cement-sand mixture 1:3 (chip scrap 10%)	0.75 / 2.25	1.0* / 5.0	1.0 / 6.75	—	—	—
6	Cement-sand mixture 1:3 (chip scrap 20%, upper edge)	0.75 / 2.75	1.25* / 6.5	1.25 / 7.0	—	—	—
7	Cement-sand mixture 1:3 (chip scrap 20%, lower edge)	0.75 / 4.0	1.25* / 6.25	1.25 / 7.25	—	—	—

Table 4. Results of the tensile test of samples

Item No.	Sample characteristics	Tensile stress σ, MPa / Unit strain ε 10^{-3}				
1	2	3				
1	Cement-sand mixture 1:3 (clear)	0.68 / 0	1.37* / 1.0	—	—	—
2	Cement-sand mixture 1:3 (wire sections 10%)	0.68 / 0	1.37* / 12	1.37 / 15	—	—
3	Cement-sand mixture 1:3 (chip scrap 20%)	0.98 / 0	1.47 / 12	1.47 / 32	1.67 / 48	1.76* / -
4	Cement-sand mixture 1:3 (reinforcement)	0.98 / 0	1.47 / 16	2.42 / 52	2.95 / 72	2.95* / 100

*Note: * – sample destruction point. The samples with fibroids retained connectivity during bending tests after the appearance of cracks.*

Table 5. Axial compression test results

Reinforcement percentage, n, %	0	1	2	3	4	5	6	7	8	9	10
Compression strength, σ_{comp}	13.2	17.4	17.6	16.3	16.0	15.6	15.3	13.8	13.7	12.3	12.6

The analysis of the results obtained shows that the strength of fiber-reinforced concrete samples, practically, does not depend on the percentage of reinforcement with steel fibers. The growth of ultimate strain with an increase in the reinforcement percentage should also be noted.

The fiber-reinforced concrete tensile strength was determined according to the three-point bending loading scheme (Table 6).

Table 6. Results of the tensile test of prisms

Reinforcement percentage, n, %	0	1	2	3	4	5	6	7	8	9	10
Tensile strength, σ_{tens}	1.22	1.18	1.19	1.2	1.33	1.94	2.05	2.3	2.82	3.36	4.12

As can be seen from Table 6, with an increase in the percentage of steel fiber reinforcement, the tensile strength of fiber-reinforced concrete is increased (by 3.3 times with respect to unreinforced specimens) with a reinforcement percentage of 6 or more.

With a small percentage of reinforcement, the effect of strength increasing is not observed. This can be explained not only by the small number of fibers, but also by their random arrangement, in which the orientation does not coincide with the action of tensile stresses. With a greater number of fibers this probability decreases, and the results become more predictable.

With a sufficient degree of accuracy (correlation coefficient R = 0.99), the obtained dependence can be described by the equation:

$$\sigma_{tens} = 0.0395n^2 - 0.1166n + 1.2747 \quad (1)$$

Further compression testing of the halves of beams showed an increase in strength at high reinforcement percentages (6 ... 10). Apparently, this is explained by a large-scale effect: The ratio of the length of the fibers to the transverse dimensions of the prisms is 20/40 = 0.5, and for cubes, this ratio is 20/100 = 0.2. The increase in the axial compression strength of the halves of the prisms is explained by the restraining effect of steel fibers on transverse strains.

The test results are shown in Table 7.

Table 7. Compression tests results of halves of prisms

Reinforcement percentage, n, %	0	1	2	3	4	5	6	7	8	9	10
Tensile strength, σ_{tens}	6.12	6.10	6.15	6.6	6.8	7.4	7.35	7.12	7.22	13.8	13.1

The use of fibers in bent reinforced concrete elements is advisable only in the stretched zone, which will lead not only to an increase in the moment of cracks formation, but also to a decrease in the width of its opening.

In order to determine the feasibility of the industrial application of fiber-reinforced concrete, the development of technology for its production and use, at the building materials factory the authors carried out experimental work on the manufacture and testing of reinforced concrete units for the protection of excavations.

The technology and organization of work for the production of BZHBT series blocks according to TU 7-5-91 was adopted as a basis. The concrete 30 MPa grade and hot-rolled steel with a diameter of 6.5 mm and 3 mm were used for their manufacture.

The consumption of reinforcement, which is made in the form of a W letter with a cross bar, amounted to 450 g per unit. In the experimental units, the reinforcement was not used, and the crushed metal shavings were introduced into the concrete mix up to 2.5 kg per unit. The ordinary metal shavings were shred using manual snip-cutters. The shredding process did not cause any special difficulties and could well be mechanized.

Fiber-reinforced concrete was manufactured using the same technology of preparation of ordinary concrete for units. Shredded shavings at the rate of 100 kg per 1 m^3 were added in the concrete mixer, in addition to all components. The process of mixing, feeding and filling the molds on the vibrating table took place according to the conventional scheme. At the same time, the properties of fiber-reinforced concrete for the cone slump were investigated, with the purpose of analyzing its technological qualities.

After molding and steaming, the ready-made units of fiber-reinforced concrete and serial units were subjected to the compression load tests and crack resistance against dynamic loads.

The research performed at the plant laboratory in accordance with GOST 29167-91 showed that the technological properties of fiber-reinforced concrete do not differ from that of ordinary concrete. The units of fiber-reinforced concrete have increased compressive strength – up to 10% and crack resistance – up to 30%. At the same time, if under the influence of dynamic load the serial units split and lost performance, the fiber-reinforced concrete units did not lose their volume integrity and could be used for their intended purpose in the appearance of cracks.

The research of the stress-strain state of concrete structures with the polypropylene-based filler

The conventional mixtures used for the laying of underground cavities have a great strain capacity, as well as insignificant strength, which ultimately predetermines the shifts in the rock massifs after the indicated cavities are eliminated. As a consequence of the above reasons, strong concrete structures also cannot provide long-term operation modes in complex hydro-geological conditions. Metal fiber contributes to a significant improvement in the backfill strain indexes, but during surface works through wells, the situations with plugging of the latter are possible because of the possible formation of "hedgehogs" while mixing the mixture. There is a need to use dispersion-reinforced plugging mixtures, the fibers of which have greater flexibility and plasticity than the metallic ones.

Such mixtures include compositions containing, for instance, polypropylene fibers. Polypropylene fiber (PPF) is clean, safe, easy to use, chemically neutral fiber compatible with all binders and additives. In cross section, these fibers have both round and close to rectangular shapes.

The number, type and length of fibers used in mixtures for construction works on surfaces depend on the project requirements. The volume of fibers less than 0.1% lowers the plastic shrinkage during cracking, and, consequently, prevents cracking of the material. It has been established [4,21-24] that the presence of polypropylene fiber in concretes and solutions eliminates the formation of shrinkage cracks at the early stage by 60-90% (during the use of a reinforcing mesh – only by 6%).

The dosage of 0.1% and more by volume or 0.6-0.9 kg/m^3 of solution predetermines the possibility of its mixing in an auto-mixer during 5 minutes for uniform dispersion without formation of lumps and clumps [21].

A higher dosage, especially that of fibrous fibers, is used in prefabricated concrete, shotcrete and other types of concrete where strength and splitting resistance are important.

At a dosage of 0.1-1.0%, PPF does not provide for a primary reinforcement. The theory shows [4,25-27] that the amount of fiber that withstands the load after cracking – the critical volume of fiber – for PPF is about 2.0% by volume. However, even a dosage of 0.1-1.0% PPF by volume gives certain advantages to the solution, both in the plastic and in the hardened state. Fibers exert an immediate effect, increasing the mixture cohesion, preventing sedimentation of large, heavy particles during compaction and facilitating the feeding of the mixture by a pump [2,4,10,21,27-28].

The following studies were carried out to analyze the effect of reinforcement with polypropylene fibers on the strength of the composite. As base samples simulating the properties of thin-walled solution polymeric structures, the plates of d×9×40 cm in size were adopted, where the thickness of the plates d = 1 cm or equal to the thickness of the walls or shelves of the structure. In our studies, such samples were tested with the help of special devices for axial tension, for bending in the "flat" and "on the rib" positions. Hollow prisms glued from the indicated plates were subjected to compression tests. Shrinkage was also determined on the samples.

Samples were made from the fine-grained concrete of A group of B25 ... B40 classes with a content of polypropylene fiber n = 0.5; 1.0; 1.5 and 2.0% of the composite volume. The fiber (FIBRIN X-T) produced in the form of lengths of 14 mm was used for fiber reinforcement. The tensile strength of fibers with a diameter of 0.2 mm is 450-600, and the modulus of elasticity is 4,000-6,000 MPa. The cement-sand matrix had a composition of C:S=1:1 on the cement of 400 and 500 grades in the consumption of up to 800 kg/m^3, F:C=0.45, and sand with a size module up to M_s=1.5.

The load that caused the appearance of the first cracks in specimens with reinforcement 1.0-2.0%, during the tensile and bending tests, was 10-12% greater than that which formed cracks in samples with a smaller reinforcement percentage. At the same time, the limiting relative strains of the solution stretching by the time of detection of the first cracks with the opening width of 3-5 μm amounted to $20 \cdot 10^{-5} - 30 \cdot 10^{-5}$, which is 2-2.5 times higher than the ultimate extensibility of the matrix solution.

As a rule, the first force bending cracks were formed near surface pores. Upon increasing the load on the surface of the specimen, a large number of dashed cracks appeared, that in the limiting stage were joining together into continuous cracks with a step from 3 to 8 mm at n = 0.5 %, and from 20 to 30 mm at n = 1.0 %. A method of various strain gauges, a microscope and a Brinell tube were used to determine the fracture toughness of prototypes.

The greatest compressive strength of polypropylene fibrous solution (at absolute values of 29 ... 32 MPa) was obtained at n = 1.5%; it exceeded the strength of the matrix solution by only 10%.

An increase in the fiber content to 2.0% somewhat complicated the compaction of the mixture, and the strength remained close to the strength of the concrete matrix. The Poisson's ratio of the polymer-fiber solution is in the range from 0.20 to 0.23.

The tensile strength of a solution with dispersed fibers from polypropylene was σ_{tens} at experimental values of 3.7 ... 6.04 MPa and was increasing with the increase in the matrix strength and the content of fiber therein. At n =

2.0%, it is 2 to 2.3 times greater than the strength of the matrix solution. Upon transition from class B20 to B40, the tensile strength increased by 20%.

Taking into account that the destruction of bent or stretched elements from the polymer-fiber solution occurs mainly at a load exceeding the cracking load, then the following formula [2] may be used in determining the tensile strength of a solution with a fibrous polymer filler:

$$\sigma_{tens} = nmC\sigma_b \quad (2)$$

where n – coefficient of reinforcement, determined by the ratio of the fiber volume to the composite volume; σ_b – breaking strength of monofiber; m – coefficient that takes into account the effect of the matrix strength on the composite strength; C – a complex coefficient that takes into account the orientation of the fibers, the influence of the fiber length, the effect of the aggregate state of the reinforcing fiber, etc.

The use of the presented dependencies allows solving the problem of destruction of concrete or mortar with fibrous filler as a result of the action of tensile loads.

DISCUSSION

The analysis of the above studies allows drawing the following conclusions:

On the use of metallic fiber:

1) The use of metallic fibers in concrete structures significantly improves the strength properties of the structure. In comparison with pure concrete elements, the bending stress increases by 50%, and the tensile strength – by 37%.
2) The presence of fiber provides for an increased crack resistance of the product, since after the appearance of destructive cracks such samples retain coherence.
3) The use of curled wire segments instead of rectilinear ones improves the physical and mechanical properties of the structure.
4) Samples of fiber-reinforced concrete have equivalent physico-mechanical properties in contrast to reinforced concrete structures, regardless of the load application scheme.
5) Increasing the percentage of filling concrete with fiber increases the strength characteristics of the samples.
6) The cost of filler made from metal chips is many times less than that from calibrated wire, which reduces the cost of the product.

A concrete reinforced with steel fibers of various lengths is characterized by high fire resistance, low creep, and high deformation characteristics. In general, dispersed reinforcement of steel fibers from 1 to 3% increases compressive strength up to 40% and bending strength up to 150%, sharply increases resistance to mechanical and thermal shocks, and improves wear resistance.

On the use of polypropylene fiber:

1) With a higher dosage of longer fiber, its strength can be compared with concrete containing 25-30 kg of steel reinforcement. The current tests show encouraging results – when using polypropylene fibers in an amount of 1% by volume, the shear strength of concrete increases, which can provide an alternative method for designing joints of structural elements from mortars and concrete.
2) Polypropylene fiber in an amount of 0.1% by volume provides resistance to water protrusion, subsidence, plastic shrinkage cracking, abrasion, freeze/thaw cycles, impact resistance, as well as fire resistance, residual strength, antimicrobial protection and reduced permeability.
3) The advantages described above mean that PPF can be used in all applications of mortar and concrete. The advantages of the solution with PPF are in the better adhesion of the mixture (compared to other non-metallic fibers), which accelerates the laying.
4) Polypropylene fiber increases the ability of the mortar to deform without fracture during the critical setting period, which prevents the formation of microcracks inside the frozen body and also inhibits the expansion of visible surface cracks that occur during plastic shrinkage.
5) PPF prevents the movement and subsequent evaporation of water, increasing the hydration of cement on the surface, but does not replace the proper procedures for aging the mortar.
6) Short fibers reduce the number of microcracks, allowing to avoid significant stress dislocations. Long fibers, which significantly reduce the workability of the concrete mix, are necessary to reduce the number of discrete microcracks at high loads. However, it is important that the volume of long fibers is less than the volume of short fibers. Fiber, which is contained in an amount of less than 1%, is used primarily to increase the crack resistance in slabs of road surfaces that are subject to surface abrasion and high rates of shrinkage cracks. The presence of fibers in the volume of 1 to 2% increases the tensile strength, resistance to cracking, impact strength, which makes it possible to use this composite for shotcrete-concreting. A high fiber content of more than 2% is intended for strain hardening, and creating an ultra-strong concrete.

In addition, the direction and uniformity of fiber distribution in the material further enhances its operational reliability. Concrete, in which the fiber is distributed evenly and is aligned in the direction of the main perceived forces, best resists the acting load. Ideally, the fibers should be located in each section of the structural elements making up the concrete.

CONCLUSION.

The effect of moisture in the presence of various salts activates the physico-chemical interactions of the phase constituents of the material. Such conditions intensify the internal mass transfer processes and promote the migration of substances in the structure of concrete, which causes a change in the composition of the pore fluid and a decrease in the concentration of water-soluble alkalis. This leads to an increase in the concentration of migratory substances in certain areas. The existence of such active sites causes the uneven development of stresses in the body of concrete and the development of large cracks, the mouths of which are the active sites. In this case, the crack formation process is characterized by the rapid destruction of structural elements.

In the case of using fiber, the growth of microdefects at the initial stage can be prevented or stopped. As a result, the design does not break up into pieces, preserving its integrity.

Thus, the use of dispersed reinforcement makes it possible to reduce the concentration of stresses, to prevent the development of opposing cracks and to impede the process of crack formation. By selecting the types of mixed fibers and adjusting the ratio of the volume of these fibers to each other and concrete, it is possible to steadily regulate the properties of the material, increasing its crack resistance, which in turn ensures a qualitative improvement of not only the durability of the material under load, but also increases the corrosion resistance caused by the growth of internal stresses, as well as weather resistance, resistance to variable wetting – drying, freezing – thawing and other cyclic processes.

Industrial experiments are consistent with theoretical data and show that the destruction of fiber-reinforced concrete does not occur immediately, but gradually. At first, microcracks are formed in the concrete, the number of which gradually increases. The formation of a continuous crack occurs at a higher strain value than in conventional concrete. Fiber, somewhat, supports the concrete, helping it resist tensile stresses.

The results of the studies conducted indicate the possibility of using fiber-reinforced concrete structures in various areas of construction with a full analysis of the structure operation work, both qualitatively and quantitatively:

- the properties of fiber-reinforced concrete are determined by the type of fibers and concrete used, their quantitative ratio, and in many respects depend on the state of contacts at the interface;
- a significant increase in the strength characteristics of the composite in comparison with the initial concrete, while maintaining the achieved level in time, is ensured by the use of high-tech fibers that are chemically stable with respect to the matrix and with a greater modulus of elasticity than the matrix;
- the type of fibers, their relative length and percentage in the mixture should be assigned based on the requirements for products and structures, taking into account the adopted technology. A deviation from the optimal values of the indicated parameters reduces the effectiveness of dispersed reinforcement to a greater or lesser extent;
- with optimal reinforcement parameters, the introduction of fibers contributes to improving the structure and properties of the initial concrete, increasing its hardness and durability.

The studies conducted during the last decade convincingly show that dispersed reinforcement improves the mechanical characteristics of concrete: increases crack resistance, impact resistance, tensile and bending strength; contributes to the resistance of concrete to the influence of an aggressive environment; allows to reduce effective sections of structures and in some cases to refuse using rod reinforcement or to reduce its consumption. Thus, the conditions are created to reduce the material consumption and labor intensity of construction, as well as increase its nomenclature.

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