На багатьох підприємствах гірничо-металургійної галузі використовуються насоси, що перекачують агресивні рідини і пульпи, містять абразивні частки. Для виготовлення корпусів насосів з урахуванням умов їх роботи використовують дорогі леговані сталі з підвищеною товщиною стінки корпусу.

В результаті досліджень проведено аналіз можливих матеріалів для виготовлення фібробетону з необхідними характеристиками міцності. Проведено вибір оптимального співвідношення компонентів, що забезпечують, з одного боку, мінімізацію витрат на фібробетон, а з іншого боку – раціональну технологію виготовлення корпусних деталей з фібробетону без додаткової механічної обробки.

Встановлено, що найбільшою мірою заданим умовам відповідають суміші, що містять бутовий щебінь, кварцовий пісок і кварцове борошно як заповнювач, сталеву фібру анкерного типу, а також смолу і затверджувач.

Теоретичні та експериментальні дослідження показали, що заповнювач повинен відповідати наступним вимогам: по гранулометричному складу він повинен бути трикомпонентним, причому розмір часток кожного компонента повинен на порядок відрізнятися від попереднього. Це дозволяє отримати щільні суміші за рахунок заповнення пустот в великих фракціях частинками менших розмірів.

В результаті лабораторних досліджень встановлено, що міцність таких затверділих сумішей на стиск становить 230…240 МПа.

Експериментально встановлено, що оптимальна добавка фібри (сталевої анкерного типу) повинна знаходитися в межах 3…5 % по масі.

Отримані результати досліджень дозволяють здійснити розрахунки параметрів корпусних деталей насосів зі зниженою товщиною стінки, меншою масою, а також розробити технологію відливання таких деталей з високим ступенем готовності їх до використання

Ключові слова: фібробетон, фібра, корпусні деталі, зносостійкий матеріал, композиційні матеріали, характеристика міцності, наповнення з полімеру

UDC 691.342

DOI: 10.15587/1729-4061.2018.151038

STUDYING FIBER-REINFORCED CONCRETE FOR CASTING HOUSING PARTS OF PUMPS

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1. Introduction

Pumps are units used in many technological processes for transferring liquids and slurries. Often these are aggressive liquids, as well as slurries with a high content of solid abrasive particles. As a result, pump housings have to be made of wear-resistant materials (e. g. alloy steels) with a large wall thickness in order to prolong pump housing service life. The above shows that pumps become metal-consuming, heavyweight and also very expensive products.

At the same time, the world practice of mechanical engineering shows that one of the general directions in equipment upgrading is the replacement of metals with composite materials. Therefore, replacement of metal with another material, for example, fiber-reinforced concrete, which will make it possible to obtain fundamentally new characteristics and manufacturing technologies of pump housing parts is of practical interest.

As in traditionally reinforced structures, fiber reinforcement is based on the fact that the material of the fiber-reinforced concrete mix transfers the applied load to the fibers through tangential forces acting on the interface. If the modulus of the fiber is higher than that of the mix, the main part of the stresses are perceived by fibers.

The range of manufactured fibrous materials is very extensive, but not all fibers meet the requirements that apply to fiber-reinforced concrete. Here, such characteristics as stability of the reinforcing material, its adhesion to concrete, coefficient of linear expansion, etc. are taken into account. Also important is the cost of reinforcing materials, the volume of their production.

The possibility to use fiber-reinforced concrete for the manufacture of pump housings will solve a number of topical issues. Among them, rejection to use expensive high-quality metal, possibility to exclude machining of products, use cheap components and significantly reduce pump housing weight.

The problem of obtaining structural materials with low cost, high wear and acid resistance is relevant due to the high cost of high alloy steels, which are used for the manufacture of pump housings in the mining and metallurgical industry. Currently, the development of a hydrometallurgical method of metal production is observed. In this regard, the need to use hydrodynamic pump units has increased. Therefore, the application of fiber-reinforced concrete as structural materials for the manufacture of pump housings is one of the priorities today.

2. Literature review and problem statement

Fiber-reinforced is widely used in the manufacture of building structures instead of normal concrete. Enough works [1–13] are devoted to the study of the mechanical characteristics of fiber-reinforced concrete. There are also works [3–5, 7], which consider various methods for producing fiber-reinforced concrete. The authors of [1, 2] believe that concretes with disperse fibers (fiber-reinforced concretes) have high crack resistance and impact strength, possess the best compressive and bending tensile strengths. In [3, 4], the conveyor and shuttle technology for the preparation of fiber-reinforced concrete mix is proposed. The technology lies in the layer-by-layer mixing of the fiber-reinforced concrete components inside the formwork of the manufactured product. In [5], the influence of the method of fiber-reinforced concrete preparation on the strength characteristics was investigated. As a result of the research, it was found that the best characteristics are provided by the samples prepared in a flexible-body mixer, and the use of a gravity mixer does not provide a high-quality homogeneous mix.

The paper [6] presents the results of the study to determine the strength of disperse fiber-reinforced fine concrete, depending on the method of mixing, which was carried out in a paddle or muller mixer. Basalt fiber with a content of 0.25 to 1 % by volume was used as a reinforcing fiber. According to the results of the study, the optimum method of mixing the fiber-reinforced concrete components in terms of the distribution orientation and volume content of fibers was obtained.

The author of [7] investigated the possibility of using technogenic raw materials in the production of high-quality fiber-reinforced concrete used for monolithic construction. The optimum composition of binding components of the mix and the type of fiber were determined. As a result, it was found that fiber-reinforced concrete with wavy fiber as a reinforcing material has the best strength and deformation characteristics.

The results of the experimental study of the effect of elevated temperatures on the strength of the modified fine concrete and axial compression deformation are presented in [8]. The study found that short-term heating to 200 °C, unlike normal heavy concrete, practically does not reduce the strength of the modified fine concrete compared with the strength at normal temperature.

In [9], data on the compressive and tensile strengths of fiber-reinforced concrete with basalt and polypropylene fibers are presented. The results show that the optimum dose for basalt fiber, providing high tensile strength is about 0.6 % of the total volume. While the optimum dose for polypropylene fiber is about 0.3 %. The study of the effect of ground basalt materials on the mechanical properties of fiber-reinforced concrete is given in [10]. The results of the experiments showed that an increase in the content of ground basalt fiber significantly increases the bending strength. It was also noted that brittleness was significantly reduced, and viscosity and plasticity were steadily improved. Therefore, it can be assumed that the ground basalt fiber is a suitable reinforcing material for the production of high-strength concrete.

The study [12] addressed the issues of improving the mechanical properties of basalt fiber composite material with the addition of high-density maleic anhydride grafted polyethylene (MAPE). The maximum values of specific tensile and bending strengths are achieved with the MAPE content of 5–8 %.

Experimental studies of the mechanical properties of basalt reinforced concrete with different fiber proportions from 0 to 2.5 kg/m^3 show that basalt fiber has little effect on compressive strength, but can significantly increase impact strength [12]. Improvement of the mechanical properties of composite materials was also considered in [13]. The main objective of this study was to investigate the role of various types of fiber impregnation, such as steel, polyvinyl alcohol (PVA) and ground basalt fibers in fresh and cured properties of self-compacting concrete. The effect of the fibers was observed in improved bending and tensile strengths, as well as plasticity. PVA and basalt fibers showed better performance than steel fibers in this regard.

The review of the literature on this issue [1–13] showed that the technology used for the preparation of fiber-reinforced concrete and the proposed methods for determining the mechanical characteristics of fiber-reinforced concrete are suitable only for building products. No works related to the use of fiber-reinforced concrete as a material for the manufacture of pump housing parts were revealed. Selection of the optimum composition of components and the technology of preparation of fiber-reinforced concrete meeting the operating conditions of pump equipment require additional research. The mechanical characteristics of fiber-reinforced concretes, in principle, satisfy the possibility of using them in the manufacture of pump housings, but it is necessary to investigate the effect of aggressive media on the properties of fiber-reinforced concrete.

3. The aim and objectives of the study

The aim of the study was to reveal the possibility of manufacturing pump housings, transferring aggressive liquids and abrasive slurries, of fiber-reinforced concrete, which has a number of advantages compared to alloy steel.

To achieve the aim, the following objectives were set:

– to find rational materials for the manufacture of fiber-reinforced concrete;

– to develop a method of selection of the optimum composition of fiber-reinforced concrete;

– to develop a technology of mixing components and forming a mix;

– to determine the strength characteristics of fiber-reinforced concrete.

4. Method of selection of rational composition of fiber-reinforced concrete

Currently, the most common types of reinforcing materials are as follows: fibers in the form of short pieces of a thin steel wire, mineral fibers (glass, quartz, basalt) and polypropylene fibers (Fig. 1, 2).

Elementary basalt fibers with a diameter of 8–10 mm correspond in strength to the high-carbon cold-drawn wire (1.8...2.5 thousand MPa), and the density is 3.5 times lower. The elasticity modulus of these materials is lower than that of steel, but twice the elasticity modulus of concrete. This predetermines real opportunities of using basalt fibers as an effective reinforcing material for fiber-reinforced concrete.

Fig. 1. Steel fibers

Fig. 2. Basalt fiber

Synthetic polypropylene fibers, like many other materials of organic origin, are characterized by increased deformability, and the elasticity modulus of such fibers is no more than 1/4 of the elasticity modulus of normal concrete. Therefore, polypropylene fibers can hardly fulfill the role of effective bearing bars for fiber-reinforced concrete.

The effectiveness of fiber-reinforced concrete with reinforcing fibers depends on their location and orientation in the array. Two options of reinforcement can be distinguished: with a clear orientation of the fibrous filler in the direction of the acting forces and reinforcement with fibers (mainly of limited length) with an arbitrary orientation in the product. The increase in tensile strength in the latter case is due to the fact that the fibers with free orientation and sufficient uniformity of distribution in the material are able to perceive forces of practically any direction and thereby prevent crack formation and propagation in the product. Fibers inhibit the movement of microdefects in fiber-reinforced concrete. If crack formation still occurred, then, blocking the crack from almost all sides, fibers prevent its further growth and propagation. This occurs until the tensile strength of fiber reinforcement is overcome or its adhesion to the cement matrix is disturbed.

In the production of fiber-reinforced concrete mixes, there is a need for the correct selection, rational combination of the initial components related to the preparation technology.

To obtain a steel-fiber-reinforced product, it is necessary to observe the following technological operations: first, it is needed to perform a dry-mix of aggregate with the required number of fibers. After that, a binder is added to the mix and mixing is performed to obtain a homogeneous composition of the fiber-concrete mix.

5. Study of fiber-reinforced concrete characteristics and selection of rational composition

The volume fraction of fiber in the product must be large enough to ensure that the share of the load perceived by the fiber is as large as possible. However, if the fiber content in the material exceeds a certain level, this will lead to a deterioration in the material properties due to the fact that the mix is not able to impregnate all the fiber bundles. As a result, the adhesion of the fibers to the mix decreases, and voids can be formed in the product.

The ultimate goal of fiber-reinforced concrete manufacture is to obtain an isotropic material with the necessary physical and mechanical characteristics.

Of practical interest is the study of the effect of fiber consumption on the strength characteristics of fiber-reinforced concrete. For this, according to the method of rational experimental design, experimental compositions were developed, in which consumption of the components varied. The composition of fiber-reinforced concrete used for casting the housing parts of centrifugal pumps was taken as the control composition.

Table 1

Studied fiber-reinforced concrete compositions

No.	Components	Composition 1		Composition 2		Composition 3	
		Consumption, %	Consumption, g	Consumption, %	Consumption, g	Consumption, %	Consumption, g
1	Crushed granite	51	1000.0	52	1040.0	–	–
2	Crushed rubble	–	–	–		51	1000.0
3	Quartz sand	25.5	502.0	–	–	25.5	502.0
4	Ground quartz	11	220.0	–	–	11	220.0
5	Ground andesite	–	–	33.6	620.0	–	–
6	Fiber:						
6.1	Steel wire	3.5*	70*	–	–	–	–
6.2	Glass	–	–	3.5*	70*	–	–
6.3	Steel anchor	–	–	–	–	3.5*	70*
7	Resin	10.6	200.0	12	240.0	10.6	200.0
8	Hardener	2.0	40.0	2.4	50.0	2.0	10.0

*Note: * – “±” to the total mass*

The first step of the technology of casting fiber-reinforced concrete specimens was the preparation of raw components. The moisture content of the fillers and aggregates of polymer concrete should be no more than 0.5...1 %. This is explained by the fact that the strength and other properties of fiber-reinforced concrete fall sharply when using wet aggregate: the thinnest water layer on the aggregate particles worsens the hardening of the polymer binder and reduces its adhesion to them. Therefore, aggregates and fillers were dried in a drying cabinet at 80...110 °C and always cooled before dosing to normal temperature.

Fine ground granite (black and white, rubble stone, and also quartz sand) was used as a filler (Table 1).

Synthetic resin and hardener were brought to the desired viscosity before use by heating and introduction of 646 solvent, acetone.

Preparation of fiber-reinforced concrete mix was carried out in the following order. First, the binder was prepared, and then aggregates were introduced into the prepared mix. The binder was prepared for 30...60 s. The finished mix was immediately loaded into a special container, where there were already the pre-mixed and treated modifying additives (with a small amount of binder) of the aggregate. Mixing of the aggregates with the binder was carried out for 1.5...2 minutes.

Introduction of a portion of the resin (monomer) into the container with the aggregates was aimed at creating thin resin films on the surface of the aggregates. With the subsequent introduction of the binder, the aggregate will not adsorb the resin from the binder, and the strength of the binder contact layers will not decrease, as is the case with the introduction of the binder into the raw aggregate.

Two-stage preparation of the mix has several advantages: the total duration of the mixing cycle, as well as the resin (monomer) consumption, is reduced. The binder is more homogeneous and can be heated or cooled during preparation to control viscosity and pot life. Vacuuming can also be carried out to remove air and increase strength.

Due to the significantly higher viscosity and stickiness of fiber-reinforced concrete mixes, a vibrating table with an increased frequency of vibration compaction and overloading was used during molding.

Square prisms with a cross-section of 40×40 mm and a length of 160 mm were used as control specimens (Fig. 3).

Fig. 3. Control specimens

Tests to determine the short-term compressive strength, tensile strength and bending tensile strength were carried out in accordance with GOST 10180-78 (BRITISH STANDARD. BS EN 12390-1-2000).

Bending tests were carried out on control specimens – prisms of L=160 mm, cross-section in the middle part 40×40 mm. The height and width of the specimen in its middle part were determined with a caliper with an accuracy of 0.1 mm, and tests of the specimens were performed on a manual hydraulic press with a maximum force of 100 kN. For research, attachment to the press was developed, consisting of a steel disk, on which two guides of the d=10 mm bar were fixed. To control the loading parameters of the specimens, a standard pressure gauge was used, and to calculate P_{bend}, the diameter of the press piston d_{pist}.

P_{bend} force was determined by (1)

$$P_{bend}=d_{pist}\cdot p, \text{ N}, \quad (1)$$

where p is the pressure in the working cavity of the press, MPa.

Bending strength was calculated by (2)

$$\sigma_{bend}=\frac{M_{bend}}{\frac{c\cdot h^2}{6}}, \text{ MPa}, \quad (2)$$

where σ_{bend} is the bending strength, MPa; c is the specimen width at the break point, m; h is the specimen height at the break site, m; P_{bend} is the load in the middle part of the specimen, N; $W_{x\text{-}x}$ is the section modulus of the specimen, m^2; l is the distance between the bearings, m.

The layout of the specimen on the bearing elements, their shape, dimensions and relative position are shown in Fig. 4.

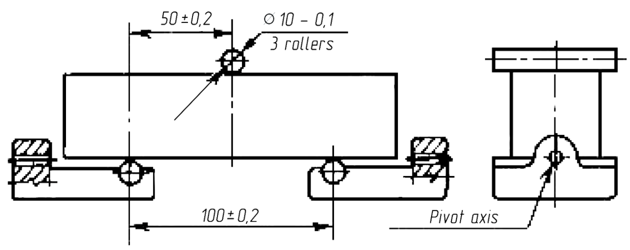

Fig. 4. Layout of the specimen on the bearing elements

The test results are shown in Table 2.

Table 2

Bending strength of fiber-reinforced concrete specimens

Specimen No.	Dimensions		Pressure in the working cavity of the press P, MPa	Section modulus of the specimen, $W_{x\text{-}x}$, cm^3	Bending load P_{bend}, kN	Bending strength, MPa
	c, cm	h, cm				
1.1	4.0	4.2	51	11.76	1.62	73.6
1.2	4.0	4.0	45	10.67	17.31	81.12
1.3	4.1	4.3	51	12.63	19.62	77.67
2.1	3.9	4.2	51	11.47	19.62	85.53
2.2	4.2	4.2	53	12.35	20.38	82.55
2.3	4.2	4.1	50	11.77	19.23	81.71
3.1	4.0	4.4	55	12.91	21.16	81.95
3.2	4.0	4.2	53	11.76	20.39	86.69
3.3	4.0	4.5	52	13.5	20.00	74.07

To determine the compressive strength of the specimens, a hydraulic press with a maximum load of 1,000 kN, which provides specimen loading in the mode of pure compression was used.

To compensate for the spatial deviation from the non-parallelism of the specimen bearing faces, the press must have a movable ball bearing and a device for centered mounting of pressure plates transferring the load on the specimen.

To carry out a compression test, the specimens were placed between two plates so that the side faces, which were adjacent to the mold walls during manufacture, were on the plate planes, and the plate guides were adjacent to the end smooth plane (Fig. 5). The specimen with the plates is centered on the bearing plate of the press. The average speed of loading during the tests was (2.0±0.5) MPa/s.

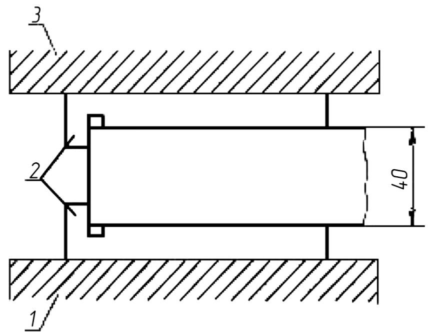

Fig. 5. Specimen position between the pressure plates in the compression test: 1 – lower press plate; 2 – plates; 3 – upper press plate

The compressive strength of an individual specimen was calculated as the quotient of failure load (kN) and the working area of the plate S_{area} (cm^2), i. e. 4.0 cm^2, as the arithmetic mean of the four largest test results of six specimens (Table 3).

The calculation of P_{comp} was performed according to the formula

$$\sigma_{comp} = \frac{P_{comp}}{S_{area}}, \text{ MPa}, \quad (3)$$

where S_{area} is the bearing area of the pressure plates.

The test results are shown in Table 3.

Table 3

Compressive strength of fiber-reinforced concrete specimens

Specimen No.	Pressure gauge readings *p*, MPa	Breaking load, kN	Compressive strength, MPa
1.1	80	30.77	136.76
1.2	82	31.55	140.22
1.3	81	31.16	138.49
2.1	131	50.40	224.00
2.2	130	50.01	222.67
2.3	128	49.24	218.84
3.1	138.0	53.09	235.96
3.2	136.0	52.31	232.49
3.3	140.0	53.85	239.33

As follows from the analysis of Table 3, the type of fiber has a great influence on the strength characteristics. Anchor steel fiber should be considered the most promising.

6. Results of studies of fiber-reinforced concrete characteristics

Theoretical studies and laboratory experiments confirmed the possibility of obtaining a new composite material – fiber-reinforced concrete. It has the following characteristics: density of the new material is 2,200...2,300 kg/m^3, compared with 7,600...8,000 kg/m^3 for alloy steel. The bending strength of fiber-reinforced concrete is 80...87 MPa, and the compressive strength is 230...240 MPa. This can significantly reduce the weight, as well as wall thickness, of the pump housing.

In order to determine the regularity of the effect of fiber content on fiber-reinforced concrete strength, laboratory experiments were conducted. Fibers ranging from 1 % to 6 % were introduced into the rationally selected composition of the mix with an interval (step) of 1 %.

Beams with the dimensions listed in Table 2 were made. After hardening, the beam specimens were tested for strength on the hydraulic press as described above.

According to the results of studies of fiber-reinforced concrete specimens with various fillers-fibers, it was concluded that they satisfy the requirements for centrifugal pump housings, both in terms of mechanical strength and chemical resistance. The plot of fiber-reinforced concrete strength versus fiber percentage is shown in Fig. 6.

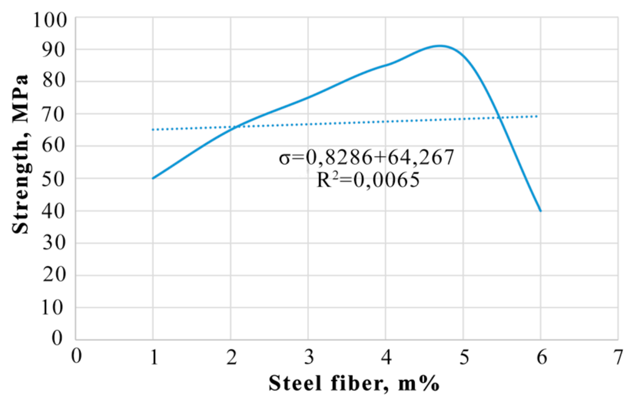

Fig. 6. Plot of fiber-reinforced concrete strength versus steel fiber content

Manufacturing of pump housings of fiber-reinforced concrete can be carried out by casting without additional machining, which is a significant advantage compared to existing technologies for the manufacture of pump housings.

7. Discussion of the results of fiber-reinforced concrete study

The studies and the results showed that it is technically and technologically possible to obtain a composite material with improved characteristics. This is due to the use of discontinuous aggregate and introduction of anchor steel fiber into the mix. The acquisition of new properties is also contributed by the two-stage technology for the preparation of fiber-reinforced concrete.

The advantages of the proposed fiber-reinforced concrete are a significant increase in the material strength, high resistance to aggressive and abrasive media and durability. This expands its scope.

The studies also showed some difficulties in the implementation of the proposed technology.

When forming the composition of the fiber-reinforced concrete mix, the ratio of the components by size and percentage should be strictly observed, the fiber content, as well as vibration parameters during the mix finishing, should be controlled. These requirements can be met in conditions of complete mechanization and automation of dosing and casting of housing parts.

For a full assessment of the effectiveness of fiber-reinforced concrete, it is necessary to estimate its wear resistance, as well as economic aspects.

8. Conclusions

1. It was found that from the point of view of obtaining fiber-reinforced concrete with the required technological, strength and economic characteristics, the most expedient are: aggregate – crushed granite or rubble, quartz sand, ground quartz or andesite; fiber – steel wire or anchor, fiberglass; binder – resin and hardener.

2. The developed method of selecting the optimum composition of fiber-reinforced concrete involves the use of three aggregate fractions, which ensures the filling of voids in larger fractions with smaller particles to ensure a high density of the mix. It was found that the composition of fiber-reinforced concrete with the following contents: crushed rubble – 51 %, quartz sand – 25.5 %, ground quartz – 11 %, steel anchor fiber – 3.5 %, resin – 10.6 %, hardener – 2 % should be considered rational.

3. The two-stage technology of fiber-reinforced concrete preparation was proposed. At the first stage, the components are prepared – resin and hardener preheating and mixing to the required viscosity, drying and mixing of the dosed aggregate and fiber. At the second stage, the aggregate, fiber and binder are mixed in the mixer.

4. The strength characteristics of fiber-reinforced concrete are 230...240 MPa, which is an order of magnitude higher than normal polymer concrete.

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