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Study of physico-mechanical properties and methods for increasing the strength of concrete shaft supports under the influence of aggressive environmental factors

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Abstract. There are various methods of supporting underground mine workings, each of these methods has a number of advantages and disadvantages. The most versatile method has proven to be the support that includes a concrete mixture (shotcrete and gunite – concrete support, reinforced concrete support, etc.). Today, many mines and mining operations use concrete mixtures to construct various structures in the conditions of underground mining, while mining enterprises often face the problem of concrete losing its strength characteristics during operation. The purpose of the study is to provide the most accurate assessment of concrete behavior under various aggressive environmental factors, such as thawing of the rock mass and the presence of aggressive waters at the support installation site. The paper also discusses possible methods for increasing strength and resistance to various destructive factors. The research included testing concrete for frost resistance, conducting electrolysis tests, adding various components to increase the strength of concrete samples, as well as comparing different concrete grades. The obtained results allowed to provide a more accurate assessment of the influence of negative factors on the physical and mechanical properties of concrete support, as well as to select an integrated approach to increasing the stability of support under various conditions of underground environment.

Keywords: concrete, concrete samples, M400, aggressive environment, thawing of rock mass

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Исследование физико-механических свойств и методы повышения прочности бетонной шахтной крепи при влиянии агрессивных факторов внешней среды

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Резюме. Существуют различные способы крепления подземных горных выработок, каждый из этих способов имеет ряд преимуществ и недостатков. Наиболее универсальным себя зарекомендовало крепление, в составе которого имеется бетонная смесь (набрызг и торкрет – бетонная крепь, железобетонная крепь и т. д.). На данный момент множество рудников и шахт используют бетонную смесь для сооружения различных упрочняющих конструкций в условиях подземной разработки месторождения, требующих очень тщательного подхода, при всем этом горнодобывающие предприятия зачастую сталкиваются с такой проблемой, как потеря бетоном своих прочностных характеристик в процессе эксплуатации. Целью данного исследования являлась наиболее точная оценка поведения бетона при различных агрессивных факторах внешней среды, таких как растепление массива горных пород и наличие агрессивных вод в месте установки крепления. Также в работе рассмотрены возможные методы повышения прочности и устойчивости к тем или иным разрушающим факторам. Исследования включали в себя испытания бетона на морозостойкость, а также проведение «электролизных» испытаний, добавление различных компонентов для повышения прочности бетонных образцов, а также сравнение различных марок бетона. Полученные результаты помогли дать более точную оценку влияния негативных факторов на физико-механические свойства бетонной крепи, дали возможность подобрать комплексный подход к повышению устойчивости крепления в различных условиях подземной среды.

Ключевые слова: бетон, бетонные образцы, М400, агрессивная среда, растепление массива горных пород

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Introduction

Ensuring safety during underground mining operations is one of the most important aspects in the putting mining enterprises engaged in the development of mineral deposits by underground mining method into commission. One of the stages in ensuring the safety of mining operations in the conditions of underground mining is the construction of mine supports [1]. In modern practice, the mine support has proved to be the most versatile, which includes concrete (shotcrete and gunite – concrete support, reinforced concrete support, concrete support), such a support can be used for horizontal, inclined, and vertical workings of various cross-sections [2]. Concrete support has a low cost compared to other types of support, as well as higher strength characteristics, which make it the most versatile compared to other support methods [3]. However, there are a number of negative factors that have a negative impact on the strength characteristics of concrete, and over time completely destroy it. The most pronounced aggressive factors affecting the destruction of concrete are aggressive waters containing various chemical elements [4–6] and temperature fluctuations, especially in mines located in permafrost conditions [7, 8]. Due to the increasing trend of switching from rail to self-propelled transport, which is mostly equipped with diesel engines (the temperature of the exhaust gas being emitted into the atmosphere from such a unit can reach 400 °C), a significant temperature drop occurs, which subsequently causes the thawing of the rock mass [9]. Such negative factors can lead to significant destruction and damage to materials, equipment and load-bearing structures, which will prevent timely work performance in mining, significantly increase the risk of injury to workers at the workplace, and also lead to additional costs for the restoration of these structures [10].

Materials and methods

To study the influence of negative factors of the mining environment on concrete support, as well as to identify possible methods to increase resistance to negative factors, the following tests were carried out:

– freeze-thaw resistance of concrete;

– the use of different grades of cement;

– the addition of building fiber to the concrete composition;

– the effect of corrosion on reinforced concrete samples;

– the use of composite mesh in the concrete composition.

Freeze-thaw resistance of concrete. The test was carried out in accordance with Russian State Standard 10060-2012[1] [11]. To obtain optimal strength of the concrete sample, it is necessary to take into account the proportions proposed by the manufacturer of the cement used. The following proportions were used to produce one sample with dimensions of 100×100×100 mm [12]:

– cement M400 – 492 g;

– sand – 661 g;

– water – 207 ml.

Subsequently, 12 experimental concrete samples were made. After pouring (to achieve maximum strength characteristics), the samples gained strength at room temperature for 28 days. Next, freeze-thaw cycles were carried out by placing them in an environment with a negative temperature for 2 hours, after which the samples were placed in water at room temperature for the same time (Fig. 1). A total of 50 freeze-thaw cycles were carried out.

After 50 freeze-thaw cycles, uniaxial compression strength tests were carried out on an IP-500M brand testing press. The comparison results are shown in Fig. 5, *a.*

The use of various grades of cement. During the test, cement grades M400 and M600 were used, then the samples obtained were also tested for freeze-thaw resistance. To obtain a concrete sample M600 with dimensions of 100×100×100 mm, the proportions proposed by the manufacturer were used [13]:

– cement M600 – 528 g;

– sand – 456 g;

– water – 265 ml.

Proportions for obtaining concrete samples of the M400 grade:

[1] State Standard 10060-2012. *Concrete. Methods for determining freeze-thaw resistance.* Moscow: Standartinform; 2018, 25 c.

a *b*

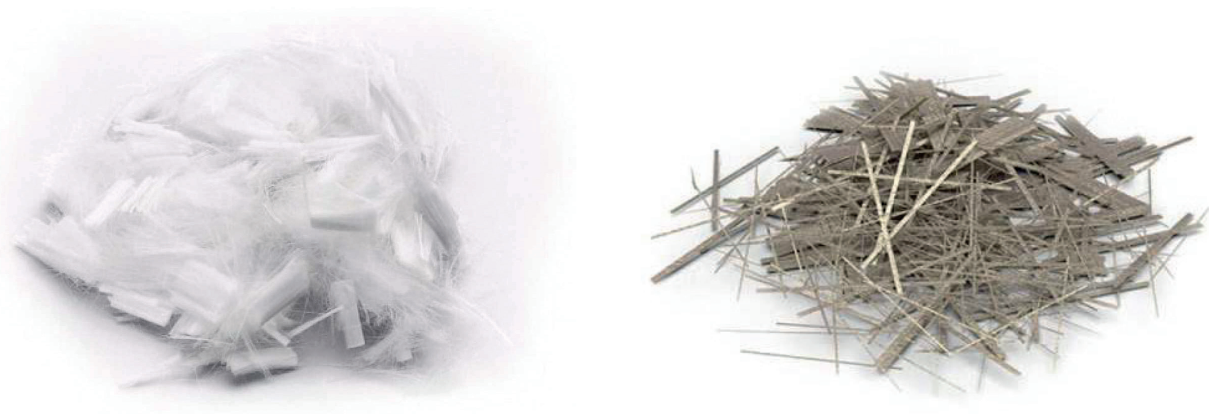
Fig. 1. Freeze-thaw cycle with concrete samples:
a – concrete samples kept in water at room temperature;
b – concrete samples kept under subzero temperatures
Рис. 1. Цикл морозостойкости с бетонными образцами:
a – бетонные образцы находятся в воде комнатной температуры;
b – бетонные образцы находятся в условиях отрицательной температуры

– cement M400 – 492 g;
– sand – 661 g;
– water – 207 ml.

To achieve their maximum strength properties, the samples gained strength within 28 days. Next, the concrete samples were tested for freeze-thaw resistance in the amount of 50 cycles. The comparison results are shown in Fig. 5, *b*.

Adding construction fiber to concrete composition. Two types of construction fiber were used for the test: basalt fiber and polypropylene fiber (Fig. 2).

Basalt fiber consists of short basalt fibers, its immediate advantage over other types of construction fiber is its resistance to aggressive environments, including extreme temperature drops [14]. Polypropylene fiber, on the contrary, is made in the form of polypropylene thread fibers, also of short length. This type of fiber is most resistant to plastic deformations [15, 16]. During the test, M400 grade cement was also used, the propor-



a *b*

Fig. 2. Types of construction fiber:
a – basalt fiber; b – polypropylene fiber
Рис. 2. Виды строительной фибры:
a – базальтовая фибра; b – полипропиленовая фибра

tions of concrete and the construction fiber added into its composition were taken in accordance with the manufacturer:

– cement M400 – 492 g;
– sand – 661 g;
– water – 207 ml;
– polypropylene/basalt fiber – 5 g.

The proportions were taken to produce one unit of a concrete sample with dimensions of 100×100×100 mm. As before, the samples gained strength properties for 28 days and were tested for uniaxial compressive strength using an IP-500M test press. The comparison results are shown in Fig. 5, *c*.

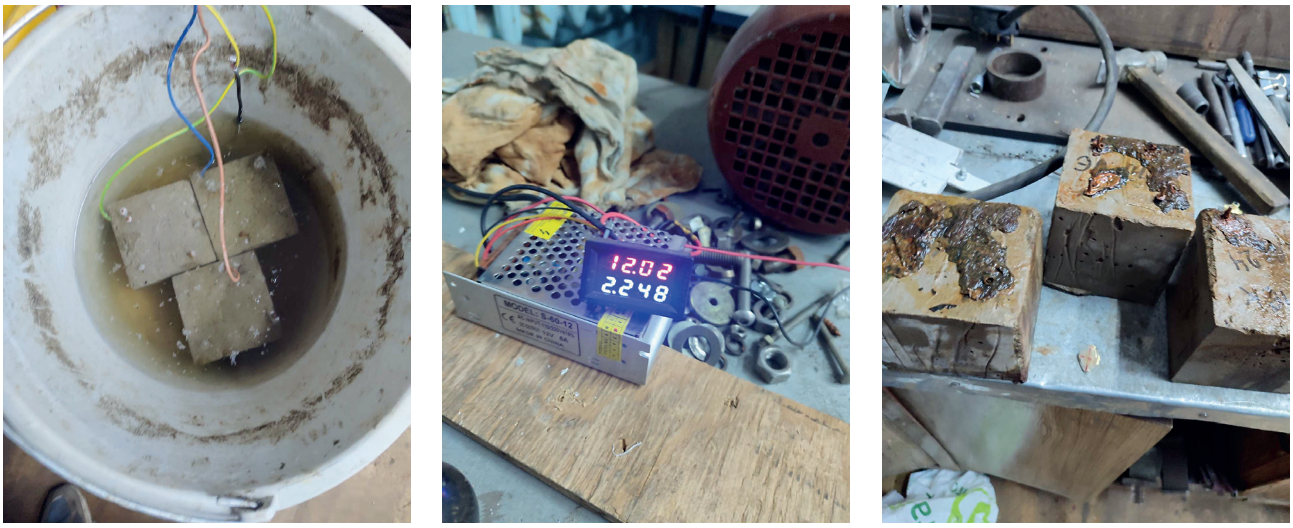
The effect of corrosion on reinforced concrete samples. Corrosion is a process that occurs over a long time, even in the presence of aggressive conditions. It takes several weeks or months to detect any changes, and electrolysis tests have been conducted to accelerate the corrosion process [17]. Electrolysis is a physical and mechanical process in which an electric current passing through an electrolyte causes decomposition of a substance into its components. In this test, electrolysis helps to increase the rate of the corrosion process several times.

Electrolysis tests were carried out as follows. Experimental concrete samples containing steel reinforcing mesh were placed in a vessel with a solution of water and salt (40 g/L ratio). A copper wire is attached to the protruding ends of the steel, through which electric current flows (the applied current was 2–3 A, and the applied voltage was around 12 V). The second copper wire, also coming from the current source, is attached to a metal plate, which is also located in a prepared solution of water and salt. In this design, the metal plate is the cathode, and the reinforcing mesh in the concrete sample is the anode. Due to redox reactions, the reinforcing mesh becomes covered with a corrosion coating in a short period of time [18, 19] (Fig. 3).

After a certain time (2 and 4 hours), the samples were tested for uniaxial compression strength, the tests were carried out using an IP-500M brand press.

To control the loss of strength, as well as a visual comparison of the reinforcing mesh in the concrete, reference samples of reinforced concrete and samples of reinforced concrete for electrolysis tests were made, a total of 12 pieces. Cement of the M400 grade was also used to make the reinforced concrete sample:

– cement M400 – 492 g;
– sand – 661 g;
– water – 207 ml;



a **b** **c**

Fig. 3. Electrolysis tests:
a – reinforced concrete samples in NaCl solution; b – voltage and current applied to the samples; c – reinforced concrete samples undergoing corrosion

Рис. 3. Электролизные испытания:
а – железобетонные образцы, находящиеся в растворе NaCl; b – напряжение и ток, подаваемые на образцы; c – железобетонные образцы, подверженные коррозии

– steel reinforcing mesh – 47 g.

Tables 1 and 2 show the values of dimensions, loads and voltages in reinforced concrete samples.

The use of composite mesh in concrete. The use of composite materials as a concrete mixture for the construction of mine supports is currently not widely used in the mining industry and requires additional research, since the behavior of composites under high loads and prolonged exposure to rock pressure has not been sufficiently studied [20]. However, in recent decades, modern polymer composites, as well as structures and products made from them, have found wider application in the construction industry. A standard composite mesh made of polymer materials was used to make the samples (Fig. 4).

M400 grade cement, sand and water were used as components in the following proportions:

– M400 cement – 492 g;
– sand – 661 g;
– water – 207 ml;
– composite mesh – 25 g.

For the test, 6 concrete samples were made, which contain a composite. Composite mesh has the lowest specific gravity compared to steel reinforcing mesh, while it is worth noting that the composite is not susceptible to corrosion, as steel is susceptible. The test results are presented in Table 3.

Results and discussion

The study of concrete freeze-thaw resistance. The pressure value is calculated in accordance with Russian State Standard 10180-2012[2]. The reference sample size is 100×100×100 mm. The average load on concrete samples of the M400 grade is 146.3 kN, the average value of the stress acting on the samples is 13.5 MPa. The average load on concrete samples of the M400 brand after frost resistance cycles was 90.28 kN, the average pressure was 8.58 MPa, while the indicator after freeze-thaw resistance tests fell by almost 39%.

Comparison of two different grades of concrete. The reference sample size was

a b

Fig. 4. Composite mesh in concrete composition:
a – type of composite mesh added to the concrete mix; b – composite mesh in the destroyed sample
Рис. 4. Композитная сетка в составе бетона:
a – вид композитной сетки, добавляемой в раствор бетона; b – композитная сетка в разрушенном образце

[2] State Standard 10180-2012. *Concrete. Methods for determining strength from control samples.* Moscow: Standartinform; 2013, 31 p.

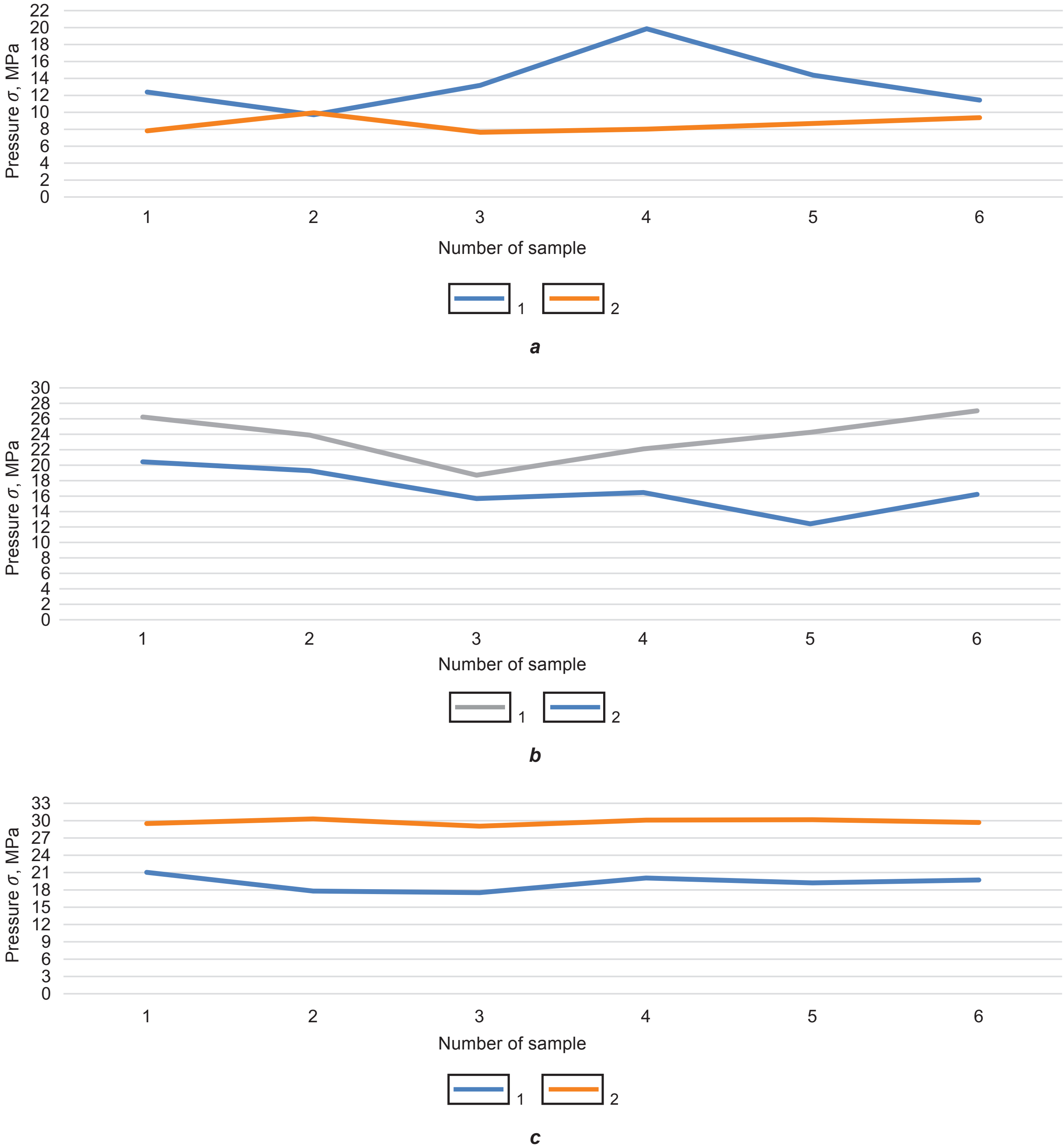


Fig. 5. Dependence diagrams of the pressure acting on concrete samples:
a – grade M400 before (1) and after (2) freeze-thaw resistance tests;
b – grades M400 (1) and M600 (2);
c – grade M400 with polypropylene (1) and basalt (2) fibers added in the mix
Рис. 5. Графики зависимости давления, действующего на образцы бетона:
а – марки М400 до (1) и после (2) испытаний на морозостойкость;
b – марки М400 (1) и М600 (2);
с – марки М400 с добавлением в состав полипропиленовой (1) и базальтовой (2) фибры

100×100×100 mm. According to the results of comparing the strength of two grades of concrete, M600 grade concrete turned out to be the most durable, the samples of this grade withstood an average load of 299.5 kN, while the average stress in the samples is 23.7 MPa, which is 74% higher. Also, M600 grade concrete proved to be the most frost-resistant compared to M400 grade concrete. After carrying out freeze-thaw cycles, the average load on concrete samples of this grade was 219.5 kN, and the average pressure was 16.75 MPa, compared with reference samples, the strength decreased by 27%.

The use of construction fiber in the concrete composition. A reference sample size of 100×100×100 mm was taken. According to the results of the tests, M400 grade concrete using basalt fiber turned out to be the most durable. These samples were able to withstand an average load of 313.13 kN, the average pressure per sample was 29.8 MPa. The basalt fiber helped to increase the strength by almost 2.5 times compared to the reference concrete samples, which did not contain any additional additives.

The effect of corrosion on reinforced concrete samples. During the comparison of the strength of the tested samples, it was found that the average compressive stress in reinforced concrete samples is 26 MPa, which is almost 1.5 times more than the stress in the reference samples, the average value of which was 18 MPa. It should be noted that the reinforcing mesh did not allow the sample to split into parts even after its destruction.

Electrolysis tests helped to achieve the formation of corrosion on the surface of the reinforcing mesh in a short period of time, while the samples were divided into two parts: these are samples that were in solution for 2 and 4 hours. As a result of compression tests, it was found that the average strength of samples in solution for 2 hours decreased by almost 1.3 times (the average pressure was 19.28 MPa), and the strength of samples in solution for 4 hours decreased by 1.5 times (the average pressure was 17.58 MPa).

The use of composite material in the concrete composition. A comparative strength analysis showed that reinforced concrete samples demonstrate an average compressive strength of 25.99 MPa, which is 1.85 time higher than the reference samples (14 MPa),

Table 1. Characteristics of reinforced concrete samples
Таблица 1. Характеристики образцов железобетона

Test number	Length a, mm	Width b, mm	Height h, mm	Scale factor α	Load F, kN	Pressure σ, MPa
1	100	100	96	0.96	238.041	22.85
2	100	95	100	0.95	254.406	25.44
3	100	100	95	0.95	341.573	32.45
4	100	100	96	0.96	238.308	22.88
5	97	98	100	0.97	227.741	23.24
6	97	95	100	0.92	291.142	29.07

Table 2. Characteristics of reinforced concrete samples after electrolysis tests
Таблица 2. Характеристики образцов железобетона после проведения электролизных испытаний

Test number	Length a, mm	Width b, mm	Height h, mm	Scale factor α	Load F, kN	Pressure σ, MPa
2 hours						
1	96	99	95	0.99	179.294	18.67
2	99	104	100	0.99	192.683	18.71
3	102	98	100	0.98	204.509	20.46
4 hours						
4	101	100	99	0.99	183.413	17.98
5	97	105	103	0.94	188.220	17.37
6	100	100	97	0.97	183.795	17.39

Table 3. Characteristics of concrete samples with composite mesh
Таблица 3. Характеристики образцов бетона с композитной сеткой

Test number	Length a, mm	Width b, mm	Height h, mm	Scale factor α	Load F, kN	Pressure σ, MPa
1	100	102	100	0.98	157.411	15.12
2	100	100	98	0.98	151.552	14.85
3	100	101	100	0.99	157.353	15.42
4	95	103	100	0.97	174.101	17.25
5	100	103	97	0.94	154.784	14.12
6	100	100	100	1.00	152.146	15.21

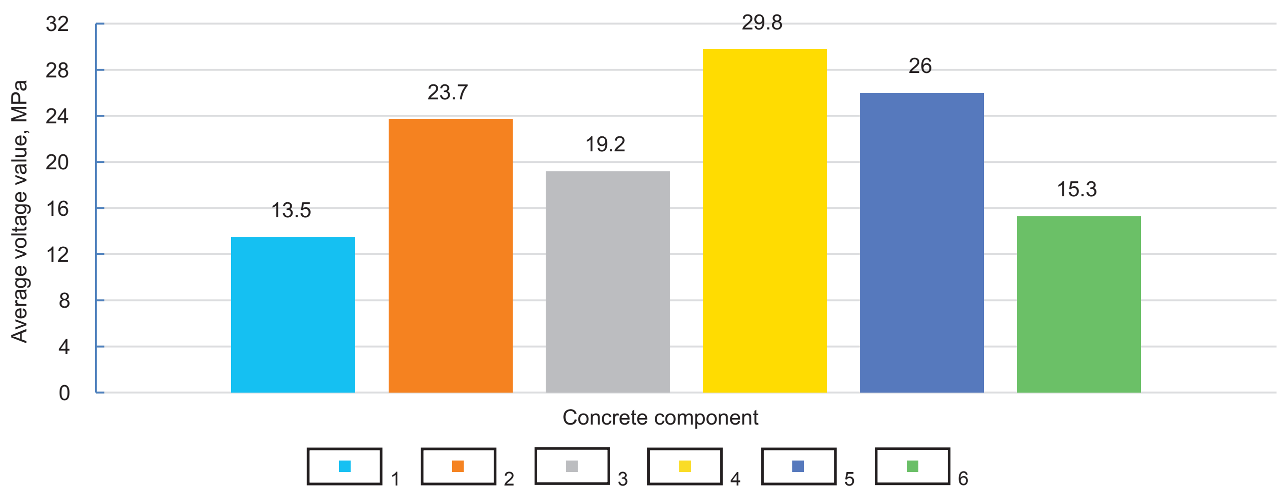


Fig. 6. Mechanical stress vs components added to the concrete:
1 – M400; 2 – polypropylene fiber and M400; 3 – steel reinforcement and M400; 4 – M600; 5 – basalt fiber and M400; 6 – composite reinforcement and M400
Рис. 6. График зависимости напряжения от компонентов, добавляемых в состав бетона:
1 – М400; 2 – полипропиленовая фибра и М400; 3 – стальная арматура и М400; 4 – М600; 5 – базальтовая фибра и М400; 6 – композитная арматура и М400

in turn, samples with composite mesh are only 0.24 times stronger. The strength of reinforced concrete samples is 81% higher than composite ones.

There is a graph of the stress dependence on the components added to the concrete (Fig. 6).

Based on the graph, it can be concluded that concrete has the highest performance, which contains:

– basalt fiber in combination with M400 cement;

– steel reinforcement combined with M400 cement;

– M600 cement.

Concrete, which contained only M400 cement, had the lowest value.

Conclusion

Experimentally, it was possible to identify a number of specific features related to concrete:

1. A constant temperature drop, in other words, the “thawing of the rock mass” negatively affects the strength properties of the concrete support, over time the concrete becomes more brittle, and also begins to lose its strength, while the concrete structure remains visually unchanged, as a result, the support becomes unusable quickly, this creates a risk of collapse of the ribs and roof of the workings. To prevent destruction and loss of strength, a more constant temperature with the least fluctuations is required. This problem is especially relevant for mines and

mining operations that are being developed in permafrost conditions.

2. M600 grade concrete turned out to be more resistant to temperature fluctuations compared to M400 grade concrete, while the sample lost a certain part of its strength properties as a result, which also indicates its insufficient freeze-thaw resistance, and M600 grade concrete samples have the highest strength compared to M400 grade concrete, but its cost is many times higher, that is why M600 grade concrete is not used for supporting mine workings.

3. The use of additives such as polypropylene and basalt fiber directly helps to increase the strength characteristics of concrete, while basalt fiber in the composition of M400 concrete has shown itself to be the best, demonstrating the highest strength indicators compared to all other methods. At the same time, construction fiber increases the freeze-thaw resistance of concrete several times, and no loss of strength was detected during the test. According to the manufacturer of basalt fiber, in addition to freeze-thaw resistance, the fire resistance of concrete is significantly increased, which is typical for mines and mining operations that operate at high temperatures. Also, in addition, construction fiber has a low cost and minimal consumption in the production of concrete mix.

4. One of the most negative factors affecting the strength of the mine support is water, which contains aggressive elements. During the test, it was revealed how such factors affect the strength of reinforced concrete. The reinforcement in the concrete was completely destroyed in 4 hours, only some of its parts remained in the sample, while the strength decreased significantly. Such conditions may lead to early wear of the mine support and its subsequent destruction, which may entail additional costs. Waters containing salts are particularly aggressive. In just a few weeks, they can destroy a metal structure, thereby disrupting the maintenance of a rock mass.

5. Composite material is currently not used in the construction of mine support, since the behavior of composite materials under conditions of high loads and prolonged exposure to rock pressure has not been sufficiently studied, but at the same time such a material is actively used in the construction of buildings and structures on the surface. The composite has the lowest strength compared to steel reinforcement, but at the same time it is more resistant to aggressive elements of the underground environment, the NaCl solution in no way affected the change in the strength of concrete samples, since polymer materials, compared with steel, are not susceptible to corrosion. At the same time, the polymer material also has the lowest cost.

Thus, the behavior of concrete structures is constantly changing with changes in various environmental conditions, as well as with the addition of various components to increase strength. Any component added to the concrete has various advantages, therefore, the most in-depth research is required to study the negative impact on the strength of concrete structures in an aggressive environment. A more detailed study will help us choose the necessary material that will be able to show itself in certain conditions in the best way. The obtained results can contribute to the most correct study of the strength properties of concrete.

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