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Nanostructured high-performance concretes based on low-strength aggregates

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Abstract. In the modern world, construction is often located in remote and hard-to-reach regions, where there are no acceptable quality aggregates for concrete. The transportation of high-quality aggregates leads to a significant increase in the cost of concrete. This paper considers the possibility of developing high-performance concretes using aggregates available in the construction region. This is possible with the use of modern achievements in the field of construction science and construction chemistry, as well as nanotechnology. The strength and mineralogical properties of gneissic granite from the Kem river bed, as well as gabbro-diabase, were investigated. During the experimental work, a high-performance nanostructured concrete based on low-strength gneissic granite was developed. The strength and operational properties of the concrete were determined. The dynamic of gain in strength of concrete at the ages of 7, 28, and 180 days was also studied. The developed binder combination can also be used to produce high-performance concretes with other low-strength aggregates.

1. *Introduction*

In the modern world, construction is often located in remote and hard-to-reach regions with adverse climatic conditions. However, there is also a need for high-quality building materials in such regions. This can be considered on the example of the northern regions of Russia. Moreover, this particular case can be scaled, since the proposed solutions are universal and applicable in other similar situations since other low-strength aggregates can be used in the developed binders for the manufacturing of high-performance concrete.

Regions of the North of Russia have huge economic and energy potentials [1]. But considering the absence of large settlements and the underpopulation far away from the coastal strip, the transport infrastructure is developed very limitedly [2], which always leads to additional huge logistic expenses for the construction of large construction projects. That concerns such objects as, for example, small hydropower plants. Their energy potential for the northern regions is proved and there are already constructions of several of them conducted [3]. Moreover, there is a long-term global movement to abandon nuclear power in its current form for the benefit of other methods of obtaining energy, especially after the Fukushima accident [4].

Small hydropower plants and other infrastructure facilities can be built on such northern rivers as Pechora, Northern Dvina, Kem, Mezen.

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In particular, this problem also occurred during the construction of small hydroelectric power plants in the Karelia on the Kem river.

The bed of the Kem river consists of gneissic granite. Moreover, it should be noted that it is one of the most widespread rocks of the Karelia region.

Due to the fact that gneissic granite has a layered structure and inclusions of low-strength minerals, it quite often has a low mechanical performance [5]. For that reason, it is not suitable for use in responsible construction, as like small hydropower plants in a traditional way, because a high-strength hydrotechnical concrete is necessary for this task. It is regulated by the Russian national standard GOST 26633-2015 “Heavy-weight and sand concrete. Specifications“ as well as DaCS (SP) 40.13330.2012 “Concrete and reinforced concrete dams. Updated version of Building code (SNiP) 2.06.06-85”.

The construction of such objects means remoteness from large settlements and, as a further consequence, developed transportation infrastructure is absent. Therefore, the transportation of high-quality fillers for concrete to the site often increases the cost of concrete significantly.

This problem also occurred during the construction of small hydroelectric power stations in Karelia on the Kem River. The nearest sandpits and stone pit with suitable loose materials for this construction were at a distance of about 200 km from the construction site.

In view of this, developers try to use those materials, which are in the location of the construction site, whenever it is possible. For the production of concrete of low classes, it is possible to use low-quality aggregates, such as broken brick, crushed concrete, crushed stone from stones mined on the location of the construction site, etc [6–8]. However, for the high-quality hydrotechnical concrete developing other technical solutions are necessary.

Hydrotechnical concretes are subject to special requirements because of their special operating conditions, especially if they are in northern regions. The most stringent requirements are imposed in the zone of variable water level since operating conditions imply unequal climatic effects, as well as unequal water saturation of concrete. For that reason, strict requirements for freeze-thaw resistance and waterproofing are imposed on the concrete of the variable water level. Moreover, due to the movement of water, concrete should have increased resistance to abrasion. Additionally, a characteristic feature of hydrotechnical concrete is the determination of grade strength at the age of 180 days. This is due to the operating conditions of hydrotechnical concrete in a water-saturated state, which contributes to the gain of strength after 28 days [9, 10].

Fortunately, the science in the 21st century (in particular the concrete science) has moved far ahead and rather large amounts of additives to concrete have appeared. For example, the water-cement ratio can be significantly reduced with plasticizing agents [11]. This allows to increase the strength of concrete or reduce the amount of cement in concrete. Silica fumes lead to more homogeneity of concrete mixture, as well as to mechanical characteristics enhancement [12]. Cement accelerators [13], cement hardening retarders [14] allow you to regulate the hardening time of concrete, then it is especially relevant if the concrete needs to be transported or concrete work is carried out in adverse weather conditions. The use of non-metallic fibers leads to a flexural strength enhancement of concrete, as well as an increase in its ductility [15]. When properly used, they allow obtaining high characteristics of concrete, even when using low-quality raw materials.

An overview of scientific publications also shows that using modern methods, it is possible to develop high-strength concretes using low-strength aggregates [16–18].

Moreover, the use of additional binders, such as silica fume and shale ash, reduces the environmental impact from the region, since they are industrial waste and need to be disposed of [19, 20].

Also, nanomodifiers are the most prospective ones [21]. For the moment, a large number of studies are already available, where the effectiveness of using catalytic amounts of various nanoparticles to significantly improve the characteristics of concrete has been proved [22–24]. Due to the rapid development of various methods of nanomaterials producing new types of nanoparticles are regularly synthesized in recent years. Based on a review of the literary data, as well as the authors' studies, it can be concluded that at the present point in time carbon nanomaterials show the highest efficiency. In particular, there are carbon nanotubes and carbon toroidal nanoparticles [25–27]. The authors of this paper had several studies on the influence of carbon toroidal nanoparticles on the properties of cement matrices, as well as polymer matrices [28]. In these papers, it was found that the introduction of catalytic amounts of carbon toroidal nanoparticles into concrete led to a significant increase in the strength of concrete since carbon toroidal nanoparticles became centres of crystallization of cement stone.

Furthermore, numerous almost significant results on their use have been obtained. High-disperse silica fumes and fine-ground cement can also be considered as inorganic nanomaterials [29, 30]. Fine crushing increases the specific surface area of the substance, which increases its chemical activity. Moreover, it is worth noting that with fine crushing/milling, even many materials that are not binders in the macrostate in any kind can have binding properties after fine crushing/milling [31, 32].

Also, there are a sufficient number of studies on the positive effect of carbon nanomodifiers on the frost resistance of concrete, as well as other fine-milled additives [33, 34].

Based on the above, the task of this research is to develop a high-strength nanostructured concrete with high mechanical and operational characteristics. The feature of this concrete is the use of local raw materials as aggregate. It allows to lower the logistic expenses and, as a result, the construction cost, and also to lower the environmental pressure on the region. This is especially relevant if the construction is conducted in highly protected regions, and additional actions (such as the investigation of deposits of high-quality rocks for the construction) negatively influence the ecological situation of the region. Moreover, the increased traffic flows would influence the quality of the roads of the region and the ecological situation of the region.

2. Methods

2.1. Concrete aggregates

Inert aggregate from the boulders of gneissic granite has been used for the development of empirical research. Boulders have been mined in the Kem river bed and have been crushed down in several steps.

Gneissic granite has a multilayer structure. The characteristics of each of the layers are quite different. The goal of crushing it in several stages was to consist in that on each of the stages to sift soft rocks that disintegrate the first.

At the first stage, the boulders were crushed into small fragments, into fractions of 150–200 mm, and further on, into fractions of crushed stone of 3–10, of 10–20 mm. Fractions were obtained by sieving on laboratory sieves. Gneissic granite sand of fraction of 0–2.5 mm was pulverized from the fraction of 0–3 mm.

The crushing of samples of a stone from local explosive rocks was made in a laboratory jar mill 80JM-1a.

For comparison, gabbro-diabase crushed stone of three different manufactures was also investigated: Berezovsk Ltd., Goloday-gora Ltd., Ramrucheyskoe Ltd. Two of the gabbro-diabase mines (Goloday-gora Ltd., Ramrucheyskoe Ltd.) were located in the same region where gneissic granite was mined. The mineralogical composition of gabbro-diabase from the Urals (Berezovsk Ltd.) was also investigated to expand the geography of the comparison.

2.2. Determination of gneissic granite crushed stone characteristics

The freeze-thaw resistance of gneissic granite crushed stone was determined according to Russian national standard GOST 8269.0-97. The freeze-thaw resistance of crushed stone was determined by loss of sample weight when immersed in saturated sodium sulphate solution and the following drying according to the method described in Russian national standard GOST 8269.0-97.

The sodium sulphate solution was prepared in the following way. 185 grams of anhydrous sodium sulphate according to Russian national standard GOST 4166 were weighed and dissolved in one litre of distilled water heated to 40 °C by gradually adding anhydrous sodium sulphate to it with careful stirring until the solution was saturated. After that, the solution was cooled to room temperature, was drained into a bottle and was stored for 2 days.

An analytical sample of gneissic granite crushed stone was poured into a vessel in one layer, poured with a solution of sodium sulphate so that the gneissic granite crushed stone was completely immersed in the solution. This was maintained therein for 20 hours at room temperature.

Next, the solution was drained (for reuse), and a vessel with gneissic granite crushed stone was placed for 4 hours in a drying cabinet “Snol”, in which the temperature was maintained (105 ± 5) °C. After that, the gneissic granite crushed stone was cooled to room temperature and again poured with the solution.

Subsequent test cycles consisted of maintaining the gneissic granite crushed stone for 4 hours in a sodium sulphate solution, drying for 4 hours, and cooling to room temperature.

After 3, 5, 10, and 15 cycles, the crushed stone sample was washed with hot water to remove sodium sulphate, dried in a laboratory oven «Snol» to a constant mass, and sieved through with a sieve mesh of 5 mm.

The residue on the sieve was weighed on laboratory weights VTB-12, and weight loss of gneissic granite crushed stone (Δm, %) was determined by the formula:

$$\Delta m = \frac{m - m_1}{m} 100, \tag{1}$$

where m is the mass of the crushed stone sample before testing, g; m_1 is the mass of residue on the control sieve of 5 mm, g.

The crushability (ΔC) of gneissic granite crushed stone was determined by the grain destructiveness during compression (crushing) in the cylinder. For this purpose, a steel cylinder with a diameter and height of 150 mm according to GOST 8269.0-97 was used. Crushed stone samples are filled into the cylinder and a load of 200 kN was made using the hydraulic laboratory testing machine WK-18 ZARZAD SPRZETU (Poland). The loading speed was 1 kN/s. Laboratory scales "VTB-12" were used to determine the mass.

$$\Delta C = \frac{m - m_1}{m} 100, \tag{2}$$

where m is the mass of crushed stone test sample, g; m_1 is the mass of residue on the control sieve after sieving of crushed stone sample crushed in the cylinder, g.

Radiographic studies were conducted for the determination of the mineral composition of the crushed stone. Radiographic studies were conducted by using the automatic powder diffractometer D2Phaser (Bruker) (radiation of an x-ray tube is CoKα 1 + 2, wavelengths CoKα 1 = 1.78900 Å и CoKα 2 = 1.79283 Å, tube operating mode 30 kW/10 mA, position-sensitive detector, geometry on reflection, scheme of focusing Bregg-Brentano, speed of rotation of a sample of 20 revolutions per minute, the interval of angles of diffraction 2theta = 5-80 °, scanning step 0.02o, exposition in a point is 1.0 seconds, T = 25 °C, the atmosphere is air).

The sample was made by dry pressing of the studied substance in low-background to a ditch of single-crystal silicon (depth is 0.5 mm, the diameter of the studied area is 20 mm). The identification of the phases was contacted by using the base of powder diffraction data of the Powder Diffraction File. The results of the quantitative X-ray phase analysis are given in Table 7.

Flakiness index, water absorption, specific gravity, packed density were determined according to the method described in Russian national standard GOST 8269.0-97.

2.3. Preparation of concrete samples and determination of their characteristics

Laboratory mixing of concrete according to Russian national standard GOST 10180-2012 was carried out according to the following recipes:

Table 1. Concrete recipes.

Components	% of masses		
	Recipe №1	Recipe №2	Recipe№3
Portland Cement CEM I 42.5 N manufactured by JSC Mordovcement	18.14	18.14	18.14
Gneissic granite crushed stone (fraction of 10–20)	52.44	56.51	–
Gneissic granite sand (fraction of 0–2.5)	18.14	14.07	–
Gabbro-diabase crushed stone (fraction of 10–20)	–	–	52.44
Gabbro-diabase sand (fraction of 0–2.5)	–	–	18.14
Dry mix of: 1. Silica fume manufactured by pilot production of INRTU 2. Shale ash Zolest-bet manufactured by PCV LLC 3. Modified basalt microfiber manufactured by NTC of Applied Nanotechnologies 4. Plasticizing agent REOMAX PC 3901P manufactured by KUBAN-POLYMER LLC 5. Carbon nanoparticles Astralene manufactured by NTC of Applied Nanotechnologies	4.03	4.03	4.03
Water of mixing according to Russian national standard GOST 23732-2011	7.25	7.25	7.25

The concrete was mixed as follows. Initially, water, binding materials and plasticizing agent were first mixed in the concrete gravity batch mixer Eco CM-71 for one minute. After that, fine aggregate and crushed stone were introduced and mixing lasted another minute. Fiber and Astralene were introduced last into the concrete mixture. The final mixing also lasted for one minute.

Nanomodifiers (Astralene) were introduced into concrete by the serial dilution method [35]. Astralene were deposited on the surface of the basalt microfiber (TC 5761-014-13800624-2004), and microfiber was introduced directly into the concrete. This resulted in a more uniform distribution of nanomaterials throughout the concrete volume.

The volume of concrete mixing was 40 litres.

Concrete density was determined according to Russian national standard GOST 10181-2014.

Concrete cubes with dimensions of 100×100×100 mm in the quantity of 30 pieces were made according to Russian national standard GOST 10180-2012.

The concrete samples were prepared in moulds and removed from the moulds after 1-day curing at room temperature. All the samples (and also the control samples) have been hardened in thermo-humidity conditions for 28 days according to Russian national standard GOST 10180-2012.

The compressive strength test of concrete cubes with dimensions of 100×100×100 mm was carried out on the hydraulic laboratory testing machine MP-1000 «Nutcracker» according to Russian national standard GOST 10180-2012.

The freeze-thaw resistance was determined on the climatic chamber SM 55/50-120 SB according to Russian national standard GOST 10060-2012. The freeze-thaw resistance was determined in a water-saturated state (F1). The dispersion of the density values of individual samples in the series before their saturation did not exceed 30 kg/m^3.

Waterproofing of concrete control samples by air permeability was determined by the device AGAMA-2 according to Russian national standard GOST 12730.5-2018.

3. Results and Discussion

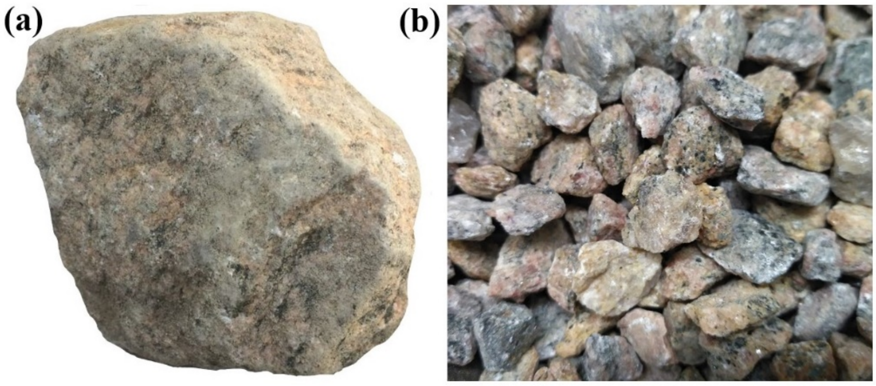

Figure 1. Large fragments of gneissic granite – (a), gneissic granite crushed stone of fraction of 10–20 mm – (b).

Table 2. Determination of crushability of gneissic granite crushed stone.

Test number	The mass before crushing, g.	Mass passed through sieve 5 mm, g.	Crushability, %	Medium value of crushability
1	3259	984	30.2	
2	3237	959	29.6	30.3
3	3281	1018	31.1	

The value of crushability corresponds to the grade of 200 according to Russian national standard GOST 8267-93, which is the lowest grade declared in Russian national standard GOST. This means that the average person will be able to easily break crushed stone with fingers of an oblong (flatness) shape or spread about a hard surface.

Table 3. Main properties of gneissic granite crushed stone.

Parameter	Unit of measure	Fraction of crushed stone	Obtained value	Regulation value	According to GOST
Flakiness index	%	10–20	34	35	Yes
		3–10	25		Yes
Freeze – thaw resistance	cycle	10–20	200	200–600	Yes
		3–10	200		Yes
Crushability	%	10–20	30.3	28–35%	Yes
		3–10			Yes
Water absorption	%	10–20	2,1	not applicable	not applicable
		3–10	2,3		
Specific gravity	–	10–20	2785	not applicable	not applicable
		3–10			
Packed density	kg/m³	10–20	1492	not applicable	not applicable
		3–10	1559		

Table 4. Main properties of gabbro-diabase crushed stone declared by manufacturer.

Parameter	Freeze – thaw resistance	Flakiness index	Crushability	Specific gravity	Packed density	Water absorption
Value	300 cycles	14 %	3.6 %	2986	1.53 kg/m³	0.1 %

The value of crushability corresponds to the grade of 1400 according to Russian national standard GOST 8267-93, which is the lowest grade declared in Russian national standard GOST.

By comparison of the properties of the gneissic granite and gabbro-diabase, a significant qualitative superiority in favour of the latter is obvious. The most significant difference is crushability (strength). The crushability of gabbro-diabase is almost 10 times the crushability of gneissic granite. The significant difference in the flakiness index is not critical, since the flakiness index can be controlled when appropriate in the industrial production of gneissic granite crushed stone. This can be done by optimizing the crushers to suit the characteristics of the gneissic granite, as well as by sieving out an excessive amount of flatness grains. [36].

Table 5. Quantitative phase analysis of gneissic granite sample (weight. %) according to the full-height analysis by Rietveld method.

Minerals	Chemical formula	% of masses
Quartz	SiO_2	41.2
Microcline	$K(AlSi_3O_8)$	17.6
Albite	$Na (AlSi_3O_8)$	24.3
Biotite	$K (Mg, Fe)_3[AlSi_3O_{10}] (OH, F)$	5.3
Amphibole	$(Na, Ca)_2 (Mg, Fe^{3+}, Fe^{2+}, Al, Ti)_5 Si_8O_{22}(OH, F)_2$	4.1
Magnetite	$Fe^{2+}Fe^{3+}{}_2O_4$	2.0
Chlorite	$(Mg, Fe)_6Si_4O_{10}(OH)_8$	3.9
Talc	$Mg_3Si_4O_{10}(OH)_2$	1.2
Calcite	$CaCO_3$	trace levels
Zirconium silicate	$ZrSiO_4$	trace levels

From these experiments it was concluded that the majority of the minerals, which are a part of crushed stone, received from sedimentary rocks of a bed of the Kem river (88.8 % of masses) is not specified on the "blacklist" of harmful components and impurity under the table A of the Russian national state standard GOST 8267-93 „Crushed stone and gravel of solid rocks for construction works. Specifications". Chlorite (3.9 % of masses), magnetite (2 % of masses) and biotite (rock-forming mica) make the exception. The amount of these rocks doesn't exceed 5.3 % of the mass according to the results of the mineralogical research.

However, for the specified harmful components of crushed stone, red lines are proceeding from the same table A of the Russian national state standard GOST 8267-93, including for magnetite, hematite, apatite, nepheline and phosphorite. Their content up to 10 % on crushed stone volume is allowed, or the sum of the quantity of all specified minerals together should not exceed 15 % of the mass. The amount of these minerals is allowed to be up to 10 % on crushed stone volume, or the sum of the quantity of all of the specified minerals should not exceed 15 % of the mass.

At gneissic granite crushed stone from the Kem river bed, there is the only magnetite from the listed minerals. Its quantity is bearable at the rate of 10 % of the mass. The results of the mineralogical analysis of gneissic granite crushed stone from the Kem river bed showed the availability of magnetite only in the amount of 2 % of the mass. That is admissible.

The same situation occurred also for chlorite as a part of crushed stone (3.9 % of the mass) and biotite (rock-forming mica, 5.3 % of masses). According to Table A of the Russian national standard GOST 8267-93 is allowed when the total amount of layered silicates (micas, hydromicas, chlorites) will not exceed 15 % of the mass. The sum for gneissic granite crushed stone from the bed of the Kem river is not more than 9.2 % of the mass as both biotite and chlorite are minerals, which density is much more than 1 g/cm³. Consequently, the detailed analysis of the components of the structure of gneissic granite crushed stone from the Kem river bed led to a conclusion about a possibility to use the crushed stone as an aggregate for hydrotechnical concrete, because in this case, the quantities of harmful components are admissible for the recipes of hydrotechnical concrete.

Based on this, it can be concluded that there are no mineralogical and physicochemical restrictions for the use of gneissic granite crushed stone in concrete. This allows to study the mechanical characteristics of gneissic granite crushed stone, as well as the characteristics of concrete based on gneissic granite crushed stone and their compliance with actual Russian national construction standards GOST 8267-93 and GOST 26633-2015.

Table 6. Quantitative phase analysis of gabbro-diabase samples (weight. %) according to the full-height analysis by Rietveld method.

Minerals	Permissible amount, %	Amount received, %		
		Berezovsk	Goloday-gora	Ramrucheyskoe
Actinolite (Amphibole)	100	31	4	45
Feldspar (Anorthite, Albite, Microcline)	100	29	48	18
Chlorite	10	11	7	18
Biotite (mica)	10	–	–	13
Diopside - hedenbergite	100	4	17	4
Crystalline silica	100	–	10	2
Mica (Phlogopite-annite)	10	–	6	–
Dolomite	100	–	1	–
Clinozoisite	100	25	–	–

It follows from the table that even high-strength material does not always satisfy the requirements of regulatory documents. Only one of the three crushed stone satisfies the requirements for hydrotechnical concrete for the content of chlorides. Based on this analysis, crushed stone manufactured by Goloday-gora Ltd. was selected for comparative testing in concrete.

Table 7. Main properties of concretes.

Properties	Recipe № 1	Recipe № 2	Recipe № 3
Compressive strength (7 days), MPa	64.6	56.4	71.2
Compressive strength (28 days), MPa	98.2	77.5	116.6
Compressive strength (180 days), MPa	115.4	90.1	133.1
Fresch concrete density, kg/m³	2481	2487	2496
Concrete density (28 days), kg/m³	2405	2398	2416
Concrete density (180 days), kg/m³	2392	2387	2396
Freeze-thaw resistance, cycles	400	400	400
Water absorption, %	3.5	3.7	3.4
Waterproofing, Class	W20	W20	W20
Flowability, Class	F4	F4	F5
Fresh concrete density, kg/m³	2481	2487	2496

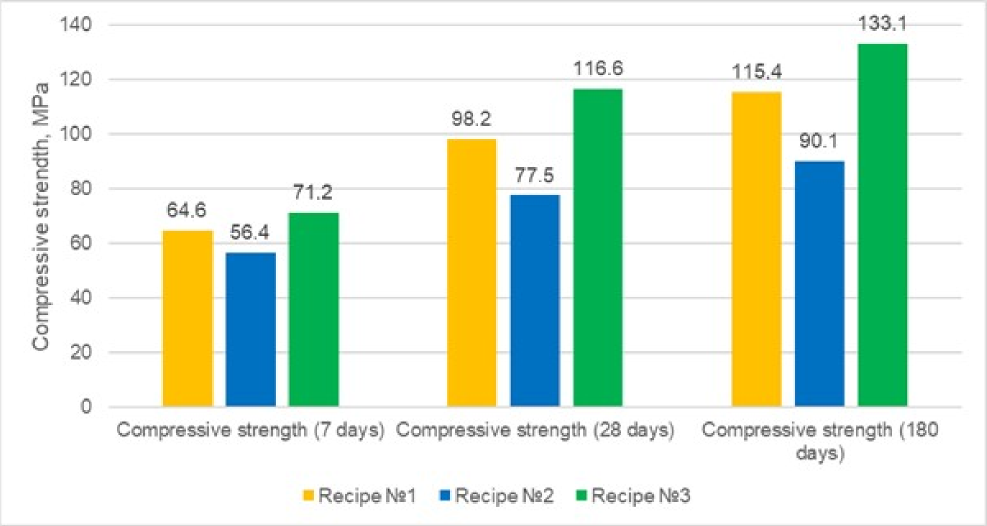

Figure 2. Compressive strength of concrete, MPa.

Table 7 and Fig. 2 show that the compressive strength of concrete with gneissic granite crushed stone of fraction of 10–20 mm differs from the compressive strength with gabbro-diabase crushed stone of fraction of 10–20 mm only by 18.7 % at the age of 28 days and 15.3 % at the age of 180 days. This is a rather nonsignificant difference considering the strength (crushability) of the crushed stone. The grade of gneissic granite in strength (crushability) was only 200 according to Russian national standard GOST 8269.0-97, while the grade of gabbro-diabase was 1400, which is the maximum strength (crushability) grade of crushed stone according to Russian national standard GOST 8269.0-97. By comparison of absolute values, the compressive strength of concrete with gneissic granite crushed stone of fraction of 10–20 mm differs from the strength of concrete with gabbro-diabase crushed stone of fraction 10–20 mm by 18.4 MPa at the age of 28 days and 17.7 at the age of 180 days.

Compressive strength values at the age of 7 days were determined as additional to characterize the concrete hardening process. At the age of 7 days, concrete with gneissic granite crushed stone of fraction of 10–20 mm had 66 % of compressive strength compared to concrete compressive strength at the age of 28 days, on the concrete with gneissic granite crushed stone of fraction of 3–10 mm had 73 % of compressive strength compared to concrete compressive strength at the age of 28 days, on the concrete of gabbro-diabase crushed stone of fraction of 10–20 mm had 61 % of compressive strength compared to concrete compressive strength at the age of 28 days.

However, following the regulatory documents for hydrotechnical concrete, it is possible to determine the grade strength at the age of 180 days. Due to the operation of hydrotechnical concrete in a water-saturated state, the strength gain does not stop at the age of 28 days but continues to gain strength further.

The difference in compressive strength in 28 and 180 days corresponds to regulatory documents, which provide for the introduction of increasing factors for analysing the strength gain of concrete after 28 days of maturing. This is also supported by numerous experimental data from other researchers, [9, 37, 38].

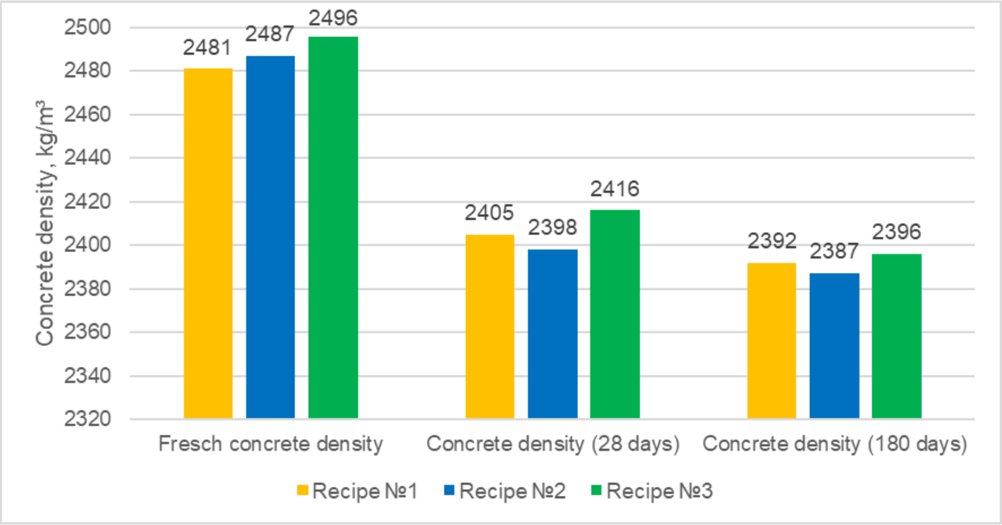

Figure 3. Fresh concrete density, kg/m³.

Table 7 and Fig. 3 show that the concrete density of all recipes is practically equal at the same age. The concrete density value is quite typical for concrete with coarse aggregate. This demonstrates that the structure of concrete is not disturbed when replacing one crushed stone with another. The lowering of concrete density does not occur even when the crushed stone of the fraction of 3–10 mm was used, although this effect is quite often observed when the aggregate size is lowered.

The difference in the flowability of concrete with aggregate from gabbro-diabase (recipe 3) in comparison with concrete based on aggregate from gneissic granite (recipes 1 and 2) is primarily associated with different water absorption of aggregates since the value of water absorption of gneissic granite (~2.2 % of masses) is significantly higher than that value of water absorption of gabbro-diabase (0.1 % of masses). Gneissic granite is saturated with water from the composition, which leads to a decrease in water amount in the matrix. The introduction of toroidal nanoparticles (Astralene) leads to a better penetration of suspension from water and binding materials deep into the crushed stone, as well as directed crystallization of cement stone [40].

This moment also has a huge positive effect. Gneissic granite crushed stone has rather large pores, which leads to saturation with a suspension of water and the binder materials. This leads to the strengthening of the crushed stone itself, as well as stronger adhesion between the crushed stone and the matrix.

Table 8. Determination of freeze-thaw resistance of concrete with gneissic granite crushed stone of fraction of 10–20 mm.

Reference sample					Control sample (12 freezing/thawing cycles)							
No	Sample dimension, cm		Ultimate load, kN	Comp. strength, MPa	No	Sample dimension, cm		Ultimate load, kN	Comp. strength, MPa	Weight, g		Weight loss, %
	length a	length b				length a	length b			before testing	after testing	
1	10	10	941.4	94.1	1	10.1	10.0	900.9	89.2	2475	2475	
2	10.1	10	960.5	95.1	2	10	10.1	910	90.1	2479	2479	
3	10	10	956.7	95.7	3	10	10	892.44	92.4	2464	2465	
4	10	10	1061.2	96.1	4	10	10	935.8	93.6	2484	2484	
5	10	10	9971.9	97.2	5	10	10	947.6	94.8	2466	2467	
6	10.1	10	1008	99.8	6	10	10	957.3	95.7	2477	2477	
Strength average value				96.3	Strength average value				92.6	Total:	Total:	
Mean root square deviation				1.8	Mean root square deviation				2.36	14845	14847	-0.02
Coefficient of variation				1.88	Coefficient of variation				2.54			
Lower range value of confidence interval, Xк min				91.1	Lower range value of confidence interval, Xo min				86.1	No weigth loss		
The freeze-thaw resistance condition Xo>0.9 Xк min is positive (86.1>0.9*91.1 or 86.1>82)												
These concrete samples correspond to the frost resistance grade F1400 according to Russian national standard GOST 10060-2012												

The freeze-thaw resistance of concretes with gabbro-diabase of the fraction of 10–20 mm and gneissic granite of fraction of 3–10 mm was also F1400. Calculation tables are not specified, since they do not carry a semantic charge. Tests were carried out according to the same standard method as the freeze-thaw resistance test of concrete with gneissic granite of the fraction of 10–20 mm (Table 8).

The freeze-thaw resistance value F400 is a very high class of freeze-thaw resistance even for concrete with high-quality aggregates. The freeze-thaw resistance class of concrete the most frequently used in civil engineering is class F50-150. It is safe to notice in this case that the combination of basalt microfiber (which is distributed evenly throughout the entire volume of concrete) and carbon toroidal nanoparticles (Astralene) contributes to achieving such a high freeze-thaw frost resistance class. The effect of fibers on the freeze-thaw resistance of concrete has been studied in [41, 42], and the effect of nanoparticles has been studied here [34, 43].

Concrete with freeze-thaw resistance class F400 belongs to the group of high freeze-thaw resistance. Concretes with this frost resistance class belong to the group of special concretes. They are intended for use in special cases. For example, such concretes are used when there is a variable level of water contacting the concrete structure in addition to low temperatures.

The high waterproofing class (maximum according to Russian national standard GOST 12730.5-2018) indicates that this concrete does not need additional water isolation. And even more, the concrete itself becomes a water isolation material. This is a very significant factor, as it seriously simplifies the tasks of water isolation during construction when temporary and financial resources are spent on additional water isolation.

A high class of freeze-thaw resistance in sum with a high class of waterproofing makes this one also more durable since when concrete is used in the north of Russia, the durability of concrete directly depends on its freeze-thaw resistance and waterproofing.

It should be noted that this study was originally aimed at demonstrating the fundamental possibility of developing high-strength concretes using low-quality (low-strength) aggregate. The matrix used provides extensive further opportunities for concrete development already directly for practical applications using solid industrial and construction waste, which meets the global challenges facing construction in the 21st century [39, 44]. Moreover, for the production of civil and even special-purpose concretes of low classes, it is possible to achieve a significant decrease in the amount of cement (up to 150–200 kg/m^3) using analogues of the developed matrix. Modern high performances concretes are not associated with an increased cement amount, but, above all, the use of current achievements in construction chemistry and pozzolan additives and fibers [45]. For example, when using pozzolan admixes and nanomodification, concrete strength values of more than 80 MPa were obtained in the paper [46]. Strength values of more than 100 MPa at the age of 90 days using nanomaterials were obtained in the paper [47].

It also stands to mention that this paper was not aimed at studying the effect of nanomodifiers on the properties of concrete. The influence of nanomodifiers has already been studied in previous works by the authors of this paper, as well as other researchers. Nanomodifiers were used as additives to concrete, such as silica fume, shale ash, etc., the effectiveness of which has already been proven in concrete.

4. Conclusions

1. Mineralogical, strength and climatic properties of gneissic granite crushed stone produced from gneissic granite rock by crushing were investigated. During the study, it was found that gneissic granite crushed stone has a rather high freeze-thaw resistance, but low strength and high value of water absorption. However, gneissic granite crushed stone does not have any restrictions for use in concrete in its mineralogical composition.

2. High-strength concretes with a strength of 98.2 MPa (fraction of 10 – 20 mm) and 77.5 MPa (fraction of 3 – 10 mm) at the age of 28 days based on two fractions of gneissic granite crushed stone was developed. Concrete strength increased up to 115.4 MPa (fraction of 10 – 20 mm) and up to 90.1 (fraction of 3 – 10 mm) after 180 days of maturation.

3. Obtained values of compressive strength of concrete based on low-quality gneissic granite crushed stone differed not too significantly from compressive strength of concrete made according to the same recipe using high-strength gabbro-diabase crushed stone. Compressive strength values were 98.2 MPa and 116.6 MPa (28 days) and 115.4 MPa and 131.1 MPa (180 days) for gneissic granite and gabbro-diabase crushed stone, respectively.

4. This nonsignificant difference in compressive strength of concrete compared to the huge difference in strength (crushability) of the crushed stone is due to the fact that in the case of using a low-strength aggregate, the main load was taken by the concrete matrix, not the aggregate. Due to the high value of water absorption of the crushed stone, crushed stone was saturated with a suspension of water and binder materials, which led to the strengthening of the crushed stone, as well as stronger adhesion to the concrete matrix, which made it possible to distribute the load more evenly.

5. The developed matrix makes it possible to produce high-strength concrete in hard-to-reach and remote regions with difficult access to high-strength concrete aggregates. It also makes it possible to obtain high-strength concretes when using aggregates from industrial and construction waste, which meets the global challenges facing construction in the 21st century.

6. The freeze-thaw resistance value F400 is a very high class of freeze-thaw resistance even for concrete with high-quality aggregates. The freeze-thaw resistance class of concrete the most frequently used in civil engineering is class F50-150. Concrete with freeze-thaw resistance class F400 belongs to the group of high freeze-thaw resistance. Concretes with this class of frost resistance belong to the group of special concretes. They are intended for use in special cases. For example, such concretes are used when there is a variable level of water contacting the concrete structure in addition to low temperatures.

7. It is safe to notice in this case that the combination of basalt microfiber (which is distributed evenly throughout the entire volume of concrete) and carbon toroidal nanoparticles (Astralene) makes contributes to achieving such a high freeze-thaw frost resistance class.

8. The combination of high compressive strength, the low value of water absorption, high water waterproofing class, and high freeze-thaw resistance makes the developed concrete unique since a low-strength aggregate was used.

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