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CONTROL OF HEAVY CONCRETE CHARACTERISTICS AFFECTING STRUCTURAL STIFFNESS

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Abstract. New experimental data have been obtained on the strength and deformation characteristics of heavy concrete o strength classes B30-B100 (strength from 36.2 to 115.1 MPa), prepared from self-compacting mixtures using crushed stone from various dense rocks as a coarse aggregate - granite, basalt and gabbro-diabase, as well as crushed stone from gravel.

It has been established that the values of the compressive strength of concrete "R_{bn}" (prism strength) are 24% higher than the normalized indicators given in Table 6.7 of the current set of Building Code of the Russian Federation SP 63.13330.2018. For high-strength concrete on crushed granite of strength classes from B70 to B100, the values of the static modulus of elasticity E_b, which largely determines the stiffness of reinforced concrete structures, exceed by 5-14% the values given in Table 6.11 of SP 63.13330.2018. At the same time, the use of gabbro-diabase or basalt crushed stone as a coarse aggregate instead of granite does not affect the strength and Poison's ratio. However, this allows increasing the static modulus of elasticity of concrete by 9 and 19%, respectively. The values of the dynamic modulus of elasticity of heavy concrete are in the range from 41.1 to 60.4 GPa and exceed the static modulus of elasticity of concrete by 2.2-5.3 GPa depending on the classes of concrete.

The paper shows the possibility of using a less time-consuming method for monitoring the values of the static modulus of elasticity of concrete in structures by determining the dynamic modulus using the calibration dependence E_b - E_d.

The obtained results indicate that the real potential of high-strength concretes is not fully used in structures designed in accordance with normative characteristics R_{bn} and E_b provided for by SP 63.13330.2018. The actual values of these characteristics are higher and can be controlled by technological tricks.

Keywords: High-strength heavy concrete, deformation characteristics of concrete, structural stiffness, crushed stone from dense rocks, modulus of elasticity, Poisson's ratio, compressive strength, organomineral modifier, self-compacting concrete mix.

УПРАВЛЕНИЕ ХАРАКТЕРИСТИКАМИ ТЯЖЁЛОГО БЕТОНА, ВЛИЯЮЩИМИ НА ЖЁСТКОСТЬ КОНСТРУКЦИЙ

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Аннотация: Получены новые экспериментальные данные о прочностных и деформационных характеристиках тяжёлых бетонов классов по прочности на сжатие В30-В100 (прочностью от 36,2 до 115,1 МПа), приготовленных из самоуплотняющихся смесей с использованием в качестве крупного заполнителя щебня из разных плотных горных пород – гранитного, базальтового и габбро-диабазового, а также щебня из гравия.

Установлено, что значения нормативного сопротивления бетонов осевому сжатию R_{bn} (призменная прочность) на 24 % превосходят нормируемые показатели, приведенные в таблице 6.7 действующего свода правил РФ СП 63.13330.2018. Значения статического модуля упругости E_b, в значительной степени предопределяющего жесткость железобетонных конструкций, для высокопрочных бетонов на гранитном щебне, классов от В70 до В100 превышают на 5-14 % значения, приведенные в таблице 6.11 СП 63.13330.2018. При этом, использование в качестве крупного заполнителя габбро-диабазового или ба-

зальтового щебня взамен гранитного, не влияет на прочность и коэффициент поперечных деформаций, но позволяет повысить статический модуль упругости бетонов на 9 и 19 %, соответственно. Значения динамического модуля упругости тяжелых бетонов находятся в диапазоне от 41,1 до 60,4 ГПа и, в зависимости от классов бетона, превышают статический модуль упругости бетонов на 2,2-5,3 ГПа.
Показана возможность использования менее трудоемкого метода контроля значений статического модуля упругости бетона в конструкциях посредством определения динамического модуля с использованием градуировочной зависимости $E_b - E_d$.
Полученные результаты свидетельствуют о том, что реальный потенциал высокопрочных бетонов не полностью используется при проектировании конструкций с учётом предусмотренных СП 63.13330.2018 нормативных характеристик R_{bn} и E_b, фактические значения которых выше и могут управляться технологическими приёмами.

Ключевые слова: Высокопрочный тяжелый бетон, деформационные характеристики бетона, жёсткость конструкций, щебень из плотных пород, модуль упругости, коэффициент Пуассона, прочность на сжатие, органоминеральный модификатор, самоуплотняющаяся бетонная смесь.

INTRODUCTION

The construction of high-rise buildings and other unique structures predetermined the increasing importance of the deformation characteristics of concrete affecting the stiffness of structures.

Calculations performed for the limit states of both the first and second groups in most cases show that the limiting design factor is not the strength of concrete, but its deformation parameters characterizing the process of deformation and movement of structures under load.

Among several normalized deformation characteristics of concrete, the most significant for the stiffness of structures is the static modulus of elasticity (E_b), which, according to SP 63.13330.2018, is currently tied mainly to strength classes and types of concrete. Other deformation characteristics, according to SP 63.13330.2018, are either tied to the modulus of elasticity (shear modulus ($G = 0.4E_b$), or it is accepted as constant value (ratio of lateral strain to longitudinal one - Poisson's ratio $\nu_b = 0.2$; ultimate compression and tension strain short-term load $\varepsilon_{b0}=0.002$ and $\varepsilon_{bt0}=0.0001$), or not standardized (dynamic modulus of elasticity of concrete E_d).

In a general approximation, the modulus of elasticity of heavy concrete, considering the characteristics of its composition, can be determined by the expression:

$$E_b= E_{cp} \cdot V_{cp} + E_{fa} \cdot V_{fa} + E_{ca} \cdot V_{ca} , \qquad (1)$$

where:

E_{cp}, E_{fa} and E_{ca} are modulus of elasticity of cement stone, fine and coarse aggregates respectively;

V_{cp}, V_{fa} *and* V_{ca} are the specific volumes of cement stone, fine and coarse aggregates in concrete respectively.

A more accurate determination of the modulus of elasticity allows more complex calculation models, which additionally considers other factors that can affect the parameters of the concrete structure - the porosity of the cement stone, the degree of cement hydration, the properties of the contact zone, the properties of coarse aggregate, etc. Examples of such calculation models are given by P.-C. Aitcin [1]. Aitcin notes its' differences associated with the use in the calculations of certain factors depending on the technology of preparation and the material composition of concrete. This indicates the importance of technological factors (the quality of the concrete components and their volume ratio, the method of preparation and the consistency of concrete mixtures) in regulating the most important deformation characteristic - the static modulus of elasticity.

A number of studies, devoted to this issue, show the role of the characteristics of the filler, the mortar part of concrete, the structure of the cement stone and the contact zone in changing the elastic modulus [2-6].

Particularly noteworthy is the study of the deformation characteristics of high-strength concretes of strength classes B60-B100, which are the main structural material of unique structures [7-14].

Studies [15-18] of concretes with high-strength fractionated aggregates and with highly active cement at a reduced water-cement ratio confirmed the pattern represented by expression (1). Increased values of the strength and elasticity modulus of concrete are provided by the high density and strength of the cement stone, high-quality aggregate and its increased concentration, i.e., dense packing in the volume of concrete.

Studies of modified concretes with organo-mineral modifiers of the MB type revealed an important role in changing the elasticity modulus of such cement stone parameters as phase composition (balance of hydrate neoplasms) and porosity, which are regulated by the dosages of additives [10-14]. This allows not only to control the strength and deformation characteristics of high-strength concretes under short-term and long-term loading of structures, but also to derive a corrective function for S.V. Aleksandrovsky and I.E. Prokopovich used to describe the creep measure [13].

The dependences between the deformation characteristics of high-strength concretes and the parameters of the cement stone structure established in [10-12, 19] allow significantly expand the ideas of A.E. Sheikin [20] on the influence of technological factors and the structure of cement stone on the deformation characteristics of concrete. In particular, it has been shown that the values of the static modulus of elasticity for fine-grained concretes of the same class in terms of compressive strength can vary depending on the phase composition and differential porosity of the cement stone [10–13].

If accept that the static modulus of elasticity is a complex and variable parameter, the value of which depends on a number of factors, including the modulus of elasticity and the specific content of concrete components, it seems relevant to assess the influence of the type and quality of large aggregates, the most common in Russia, on deformation characteristics and strength both conventional and modified high-strength heavy concretes. Despite the availability of information on this issue [5-9], the assessment of the significance of the factor of the nature of the aggregate on the deformation characteristics of concrete should probably be decided considering the specific properties of materials and compositions of concrete mixtures.

The purpose of the research was to determine the effect of coarse aggregate made of different rocks on the strength and deformation characteristics of concretes of classes from B30 to B100, prepared from self-compacting mixtures, with the justification of the method for controlling the initial modulus of elasticity of concrete in erected structures.

To achieve the purpose, the following tasks have been solved:

- Determination of strength and deformation characteristics of 7 series of self-compacting concretes of classes B30-B100 at the age of 28 and 90 days. Each of which had the same composition, but was prepared with 4 types of coarse aggregate;
- Establishing the dependences of the deformation characteristics of concretes with various types of coarse aggregates on the class of concrete in terms of compressive strength;
- Evaluation of the obtained results by its comparing with the standard values given in the Building code of the Russian Federation SP 63.13330.2018 “Concrete and reinforced concrete structures. General provisions”, recommended by FIB international standard Model Code MC 2010 and European standard EN 1992-1-1:2004 Eurocode 2;
- substantiation of the method for control of the static modulus of elasticity of concrete in erected structures by establishing a calibration dependence between the values of the static (E_b) and dynamic (E_d) modulus of elasticity of concrete.

1. MATERIALS AND TEST METHODS

1.1. Applied materials

The materials (cement, modifier, microfiller, sand and crushed stone), which satisfy the standards of the Russian Federation and applied in the production of self-compacting concrete mixes for construction projects at the Moscow-City MIBC, were

used for the preparation of concrete in laboratory conditions. In addition, other types of coarse aggregate were used: crushed gravel, gabbro-diabase and basalt crushed stone. The reason for choosing 4 different types of crushed stone was the difference in true density and in parameters characterizing strength, in particular: “mass loss during compression in the cylinder” and “grain content of weak rocks”, which allow more accurate than the classification parameter dependent on its "crushability", to evaluate the strength of coarse aggregate.
The characteristics of the materials were as follows:
- Portland cement PC 500-D0-N with a normal density of 24.6% and a C_3A content of 4.9%, which meets the requirements of the RF standard GOST 10178;
- organo-mineral concrete modifier MB10-50S A-II-2, including microsilica (45%), fly ash (45%) and superplasticizer (10%) [21], which meets the requirements of the RF standard GOST R 56178 and TU 5743- 083-46854090-98 amend. No. 1-3;
- microfiller - non-activated mineral powder grade MP-1 (ground limestone) with a particle size of less than 1.25 mm, corresponding to the requirements of the RF standards GOST R 52129 and GOST R 56592;
- SikaPlast E4 superplasticizer based on a mixture of modified lignosulfonates and polycarboxylate esters, which meets the requirements of the RF GOST 24211 standard;
- Class I quartz sand with fineness modulus Mcr = 2.55, with a content of dust and clay particles of 0.95%, corresponding to the requirements of the RF GOST 8736 standard;
- crushed stone from gravel with a fraction of 3-10 mm, corresponding to the requirements of the RF standard GOST 8267;
- crushed stone of granite fraction 5-10 mm, corresponding to the requirements of the RF standard GOST 8267;
- crushed stone gabbro-diabase fraction 5-10 mm, corresponding to the requirements of the RF standard GOST 8267;
- crushed stone basalt fraction 5-10 mm, corresponding to the requirements of the RF standard GOST 8267;
- water for mixing concrete mixtures that meets the requirements of the RF GOST 23732 standard.
Table 1 provides physical and technical characteristics and mineralogical composition of coarse aggregate varieties.

Table 1. Physical and technical characteristics and mineralogical composition of coarse aggregate

Characteristic	*Type of coarse aggregate (crushed stone)*			
	gravel	*granite*	*gabbro-diabase*	*basalt*
1	2	3	4	5
True density, kg/m^3	2650	2670	3070	3000
Mass loss during compression in the cylinder,%	6.02	6.55	3.17	1.03
Breakability grade	1200	1400	1400	1400
The content of lamellar and angular grains, %	7.98	22.0	8.2	28.0
Grain content of weak rocks, %	4.15	1.50	0	0
The content of dust particles, %	0.99	0.96	0.70	0.8
Mineralogical composition, %:				
- organogenic limestone	40.0	-	-	-
- quartz	8.8	-	-	-
- flint	7.7	-	-	-
- dolomite	7.6	-	-	-
- quartzite	4.9	-	-	-
- limestone organogenic silicified	2.8	-	-	-

- tuff sandstone	2.5	-	-	-
- sandstone	1.6	-	-	-
1	2	3	4	5
- iron oxides and hydroxides	0.5	-	-	-
- granite	23.6	54.8		
- granodiorite	-	40.9	-	-
- diorite	-	3.8	-	-
- intensely altered rock (dolerite)	-	0.5	-	-
- intensively altered basalt	-	-	60.5	-
- intensively modified gabbro	-	-	39.5	-
- intensively altered picrobasalt	-	-	-	97.8
- effusive rock intensively altered	-	-	-	2.2

1.2. Compositions and Properties of Concrete Mixes

In laboratory of Research Institute of Reinforced Concrete, 7 series (28 compositions) of concrete from self-compacting mixtures with a cement consumption of 290 to 480 kg/m^3 with the addition of MB modifier and microfiller at a water-binding ratio W / (C + MB) from 0.25 to 0.69 have been prepared. Each series was prepared with 4 types of coarse aggregate - crushed stone from gravel, granite, gabbro-diabase and basalt crushed stone. The compositions of concrete mixtures were selected with the expectation of the same volumetric dosage of each of these materials. Respectively, the actual volume of coarse aggregate in different concrete series was in a narrow range - from 0.310 to 0.335 m^3/m^3. Table 2 presents the compositions and properties of self-compacting concrete mixtures are presented.

Concrete mixtures were prepared in a 60-liter forced-action mixer with mixing of each batch for 5 minutes. The test results of concrete mixtures showed (table 2) that their average density ("γ") depends on the true density of coarse aggregate and varies in a wide range - from 2386 to 2541 kg/m^3. The mobility of mixtures, determined by the spread of a normal cone [22], is in the range from 55 to 70 cm. Considering also the absence of signs of water separation and stratification of mixtures, according to [23], this allows to classify them as self-compacting.

Table 2. Compositions and Properties of Self-Sealing Concrete Mixes

Series number	*Compositions of concrete mixes, kg/m^3*							*Properties of concrete mixtures*			
	C	*MB*	*MP-1*	*P*	*G*	*SP*	*W*	*γ, kg/m^3*	*V_G, m^3/m^3*	*SC, cm*	*W/(C+MB)*
1	290	-	150	820	855^1/870^2/ 995^3/970^4	3,52	198	2316-2456	0,322-0,326	55-58	0.69
2	300	30	170	835	830^1/835^2/960^3/940^4	-	176	2341-2471	0,308-0,313	55-59	0.53
3	300	50	180	845	835^1/850^2/970^3/950^4	-	158	2368-2503	0,314-0,318	60-63	0.45
4	350	65	150	815	820^1/840^2/955^3/930^4	-	160	2360-2495	0,309-0,311	60-70	0.39
5	420	70	100	825	830^1/845^2/955^3/930^4	-	161	2406-2531	0,310-0,317	60-68	0.33
6	450	100	50	790	870^1/875^2/1005^3/1000^4	-	154	2414-2549	0,327-0,333	62-70	0.28
7	480	130	50	725	880^1/905^2/1015^3/985^4	-	152	2417-2552	0,328-0,339	62-70	0.25

Notes: C is Portland cement; MB is organomineral concrete modifier; MP-1 is microfiller; P is quartz sand; G is crushed stone: 1) gravel, density 2650 kg/m^3, 2) granite, density 2670 kg/m^3, 3) gabbro-diabase, density 3070 kg/m^3, 4) basalt, density 3000 kg/m^3; SP is superplasticizer; W is water, γ is average density of the mixture; V_G is the volume of coarse aggregate in the volume of the concrete mix; SC is the mobility along the spread of a normal cone.

1.3. Object of research and test methods

Six samples-cubes of 100×100×100 mm size have been prepared from concrete mixtures without vibration compaction to determine the cubic compressive strength of concrete (R) at the age of 28 and 90 days according to the standards of the Russian Federation GOST 10180 and GOST 31914. And 6 prism samples of 100 × 100 × 400 mm have been prepared to determine the prism compressive strength of concrete (R_b), static and dynamic modulus of elasticity, Poisson's ratio at the age of 28 and 90 days according to the standards of the Russian Federation GOST 24452, GOST 31914 and [24, 25].

Control samples were stored before testing under normal temperature and humidity conditions (temperature plus 20 ± 2 °C, humidity 95 ± 5%).

The determination of the static modulus of elasticity and Poisson's ratio was carried out on a hydraulic press (see Figure 1) using 3 prism samples. The loading of the prism specimens was carried out in steps equal to $0.1R_b$ with holding at each step for 4-5 minutes to a level of 40% of the prism strength.

<u>Figure 1.</u> Tests of prism specimens with determination of the static elasticity modulus and Poisson's ratio of concrete on a hydraulic press

Determination of the dynamic modulus of elasticity (E_d) was carried out on the device Erudite MKIV CNS Farnell Limited (PC 1004) (see Figure 2) using 3 prism specimens. The determination of the dynamic modulus of elasticity of concrete with a length of prism specimens of 400 mm was carried out at a longitudinal resonant oscillation frequency in the range of 4–6 kHz according to the formula of the technical manual [24]:

$$E_d=4\cdot n^2\cdot l^2\cdot \gamma\cdot 10^{-12}, \qquad (2)$$

where: n – is resonant frequency of longitudinal vibrations, Hz; l – is specimen length, mm; γ – is average density of concrete in a sample, kg/m^3.

<u>Figure 2</u>. Tests of prism specimens with determination of the dynamic elasticity modulus of concrete using the Erudite MKIV (PC 1004) device

The value of the static and dynamic modulus of elasticity, as well as the Poisson's ratio at each age, was taken as the average value of the test results of all 3 prism specimens.

The actual class of concrete in terms of compressive strength (B_f) and the compressive strength of prisms (R_{bn}) were determined in accordance with the RF standard GOST 18105, considering the requirements of GOST 31914 for the minimum value of the required strength coefficient K_T = 1.14 (with a coefficient of variation V = 10%) according to the formulas:

$$B_f=\frac{R}{K_T}=\frac{R}{1,14}, \qquad (3)$$

$$R_{bn}=R_b\cdot\left(1\text{-}1,64\cdot\frac{V}{100}\right)=0,836\,R_b, \qquad (4)$$

2. TEST RESULTS AND DISCUSSION

Table 3 presents test results for concretes with various types of coarse aggregates in terms of: average density, cubic (R) and design compressive strength of prisms (R_b), actual class (B_f), compressive strength of prisms (R_{bn}) static E_b) and dynamic (E_d) elastic modulus, and also Poisson's ratio (ν) at the age of 28 and 90 days.

Table 3. Strength and short-term deformation characteristics of concrete

Series and composition number	*Age of concrete. days*	*Average density of concrete. kg/m³*	*Indicators of concrete compressive strength. MPa*				*Deformation characteristics of concrete*		
			R	*$B_ф$*	*R_b*	*R_{bn}*	*E_b. GPa*	*E_d. GPa*	*ν*
1	2	3	4	5	6	7	8	9	10
1-1	28	2326	36.2	32	35.0	29.3	32.2	37.1	0.207
	90	2332	38.3	33	37.8	31.6	33.6	37.4	0.206
1-2	28	2330	36.5	33	36.2	30.3	32.5	38.1	0.206
	90	2327	40.1	35	38.6	32.3	34.5	39.5	0.207
1-3	28	2448	37.6	33	36.3	30.3	36.0	41.1	0.207
	90	2451	38.1	33	37.6	31.4	37.8	41.5	0.205
1-4	28	2452	38.4	34	36.3	30.3	38.8	42.8	0.204
	90	2448	39.6	35	38.0	31.8	39.3	43.7	0.205
2-1	28	2358	61.0	53	57.2	47.8	38.3	41.8	0.212
	90	2352	65.3	57	60.0	50.2	39.1	42.2	0.208
2-2	28	2378	61.8	54	56.0	46.8	39.2	42.8	0.214
	90	2384	65.4	57	63.4	53.0	40.1	43.7	0.206
2-3	28	2476	62.2	55	58.1	48.6	40.5	44.2	0.223
	90	2481	66.1	58	62.4	52.2	41.4	45.9	0.211
2-4	28	2480	62.8	55	57.8	48.3	44.1	47.3	0.214
	90	2479	67.4	59	61.5	51.4	46.4	48.6	0.206
3-1	28	2363	68.2	60	58.4	48.8	38.8	42.1	0.205
3-2	28	2387	68.0	60	63.7	53.3	39.5	43.5	0.206
3-3	28	2451	70.0	61	61.8	51.7	42.8	48.0	0.209
3-4	28	2502	66.8	59	60.5	50.6	44.8	49.2	0.198
4-1	28	2372	65.6	58	60.4	50.5	38.8	42.3	
	90	2358	76.5	67	71.3	59.6	38.9	42.5	0.207
1	2	3	4	5	6	7	8	9	10
4-2	28	2414	73.8	65	68.6	57.3	40.2	45.3	
	90	2407	80.2	70	74.5	62.3	40.5	45.7	0.198
4-3	28	2483	76.0	67	70.1	58.6	43.0	47.4	
	90	2482	81.8	72	74.9	62.6	43.2	48.0	0.214
4-4	28	2473	73.6	65	68.0	56.8	46.2	51.1	
	90	2496	82.3	72	75.8	63.4	46.5	51.3	0.213
5-1	28	2410	78.2	69	71.8	60.0	42.4	47.7	
	90	2418	82.8	73	76.8	64.2	43.5	48.2	0.220
5-2	28	2432	82.6	72	79.8	66.7	43.2	48.9	
	90	2426	92.5	81	85.3	71.3	44.1	49.4	0.205

5-3	28	2518	87.8	77	82.3	68.8	47.6	50.4	
	90	2523	97.5	85	89.2	74.6	48.0	50.7	0.196
5-4	28	2523	91.4	80	83.7	70.0	51.2	56.5	
	90	2536	101.5	89	93.4	78.1	51.6	56.6	0.210
6-1	28	2412	97.5	86	91.1	76.2	44.8	48.4	
	90	2418	100.4	88	94.5	79.0	45.6	48.8	0.222
6-2	28	2423	100.3	88	92.6	77.4	46.1	50.2	
	90	2426	109.2	96	100.0	83.6	48.0	52.8	0.220
6-3	28	2515	107.0	94	98.2	82.1	51.0	55.0	
	90	2519	111.3	98	104.4	87.3	52.0	55.9	0.228
6-4	28	2532	102.9	90	94.6	79.1	54.1	58.8	
	90	2540	113.1	99	100.5	84.0	56.2	59.9	0.235
7-1	28	2425	100.2	88	95.4	79.8	46.8	50.6	
	90	2430	103.8	91	97.2	81.3	47.0	51.2	0.226
7-2	28	2443	102.8	90	97.2	81.3	47.5	52.9	
	90	2438	114.8	101	104.2	87.1	48.1	53.1	0.230
7-3	28	2520	112.8	99	102.1	85.4	51.6	56.4	
	90	2511	115.1	101	105.0	87.8	52.0	56.6	0.237
7-4	28	2553	108.5	95	104.5	87.4	55.4	60.2	
	90	2544	114.6	101	107.0	89.5	56.4	60.4	0.242

2.1. Average density

The average density of heavy concretes with various types of coarse aggregates varies in a wide range from 2326 to 2553 kg / m^3 and generally corresponds to the trend of changes in the average density of concrete mixes (see Table 2) and in some cases slightly exceeds the standard value up to 1.8%. according to RF Standards GOST 25192 and SP 63.13330.2018 (2000-2500 kg/m^3), however complies with the requirements of EN 206:2013 (2000-2600 kg/m^3).

2.2. Compressive strength of cubes

The cubic compressive strength (R) of all concretes with various types of coarse aggregates at the age of 28 days is in the range from 36.2 to 112.8 MPa and corresponds to the actual compressive strength classes of concrete from B_f32 to B_f99. And in age 90 days, it is in the range from 38.1 to 115.1 MPa and corresponds to the actual classes of concrete in terms of compressive strength from B_f33 to B_f101.

The use of various types of coarse aggregate (crushed stone of gravel, granite, gabbro-diabase and basalt crushed stone) slightly changes the cubic compressive strength of concrete (see Figure 3), which for all concrete compositions ranges from 89 to 111% of the strength of concrete on crushed granite. At the same time, concretes with granite, gabbro-diabase and basalt crushed stone aggregate with a crushability grade of 1400 have approximately the same cubic compressive strength. And on crushed stone of gravel with a crushability grade of 1200, the strength of concrete takes minimum values.

2.3. Compressive strength of prisms

The design prism compressive strength (R_b) of concrete of classes B30 to B100 at the age of 28 days is in the range from 35.0 to 104.5 MPa. And at the age of 90 days it was from 37.6 up to 107.0 MPa, does not depend on the type of coarse aggregate and is a linear function of the concrete class in terms of compressive strength (see Figure 4).

The experimentally obtained actual values of the concrete prism compressive strength (R_{bn}) are 24% higher than those normalized according to the building code SP 63.13330.2018 (see Figure 4). The calculation of reinforced concrete structures for strength, performed on the basis of the normalized and design characteristics of concrete according to table 6.7 of the building code SP 63.13330.2018, in essence, leads to significant reserves of their bearing capacity.

If we evaluate the above results according to the criterion of the prismatic strength ratio, determined as the ratio of the prismatic compressive strength of concrete to cubic strength ($K_{pp} = R_b / R$), then its actual values are in the range from 0.86 to 0.99 and significantly exceed the values of this coefficient calculated according to the parameters given in SP 63.13330.2018 (from 0.71 to 0.73).

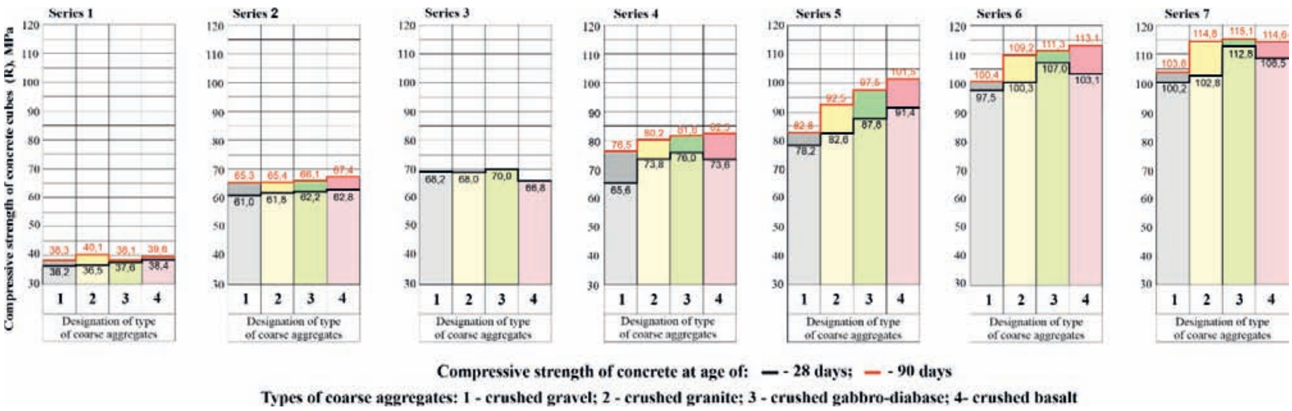


Figure 3. Compressive strength of concrete cubes with various types of coarse aggregates

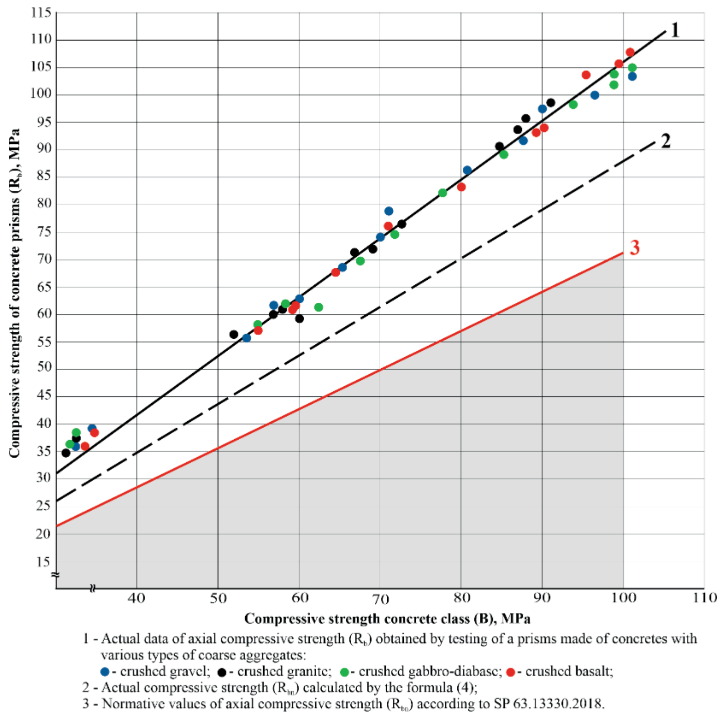


Figure 4. Axial compressive strength of heavy-weight concrete with various types of coarse aggregates

2.4. Elastic modulus

Table 3 and Figure 5 provide the results of determination of static (E_b) and dynamic (E_d) modulus of elasticity and dependencies on the actual classes of concrete (B_f32-B_f101) with compressive strength 36.2 -115.1 MPa with various types of coarse aggregates.

The obtained results (see Figure 5) show that the static and dynamic modulus of elasticity of concrete are directly proportional to the compressive class of concrete and largely depend on the type of coarse aggregate, in particular:

- static modulus of elasticity of heavy concrete with aggregate on crushed stone from gravel of actual classes B_f32-B_f91 (strength 36.2-103.8 MPa) is in the range from 32.2 to 47.0 GPa; the dynamic modulus of elasticity exceeds the static modulus by 3.1-4.9 GPa and is in the range from 37.1 to 51.2 GPa;

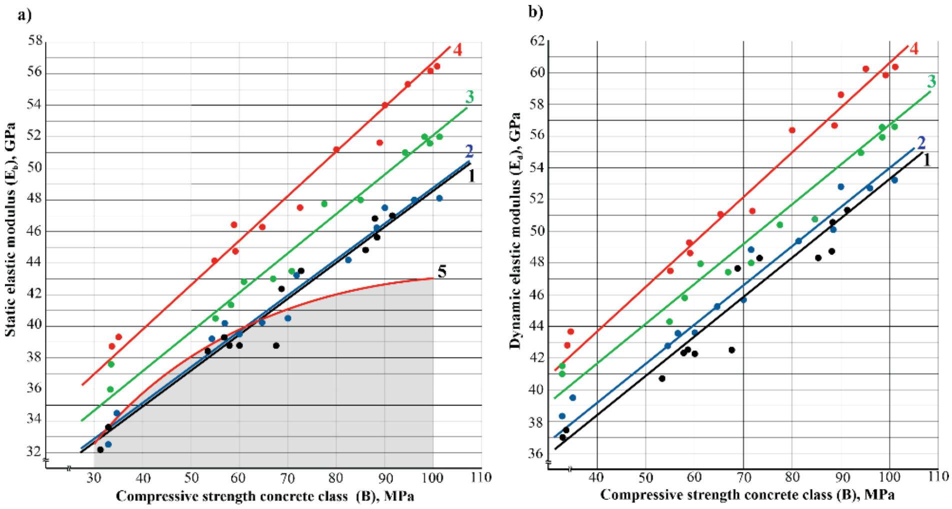


Figure 5. Static (a) and dynamic (b) elastic modules vs compressive strength of concretes of B30-B100 classes

- static modulus of elasticity of heavy concrete with aggregate on crushed granite actual classes B_f33-B_f101 (strength 36.6-114.8 MPa) is in the range from 43.2 to 48.1 GPa; the dynamic modulus of elasticity exceeds the static modulus by 3.2-5.7 GPa and is in the range from 38.1 to 53.1 GPa;
- static modulus of elasticity of heavy concretes with filler on gabbro-diabase crushed stone of actual classes B_f33-B_f101 (strength 37.6-115.1 MPa) is in the range from 36.0 to 52.0 GPa; the dynamic modulus of elasticity exceeds the static modulus by 2.7-5.2 GPa and is in the range from 41.1 to 56.4 GPa;
- static modulus of elasticity of heavy concrete with aggregate on basalt crushed stone of actual classes B_f34-B_f101 (strength 38.4-114.6 MPa) is in the range from 38.8 to 56.4 GPa; the dynamic modulus of elasticity exceeds the static modulus by 2.2-5.3 GPa and is in the range from 42.8 to 60.4 GPa.

Comparison of the experimentally obtained values of the static elastic modulus, and, consequently, the stiffness of reinforced concrete structures made of heavy concrete of compressive strength classes B30-B100, prepared with various types of coarse aggregate, with standardized values showed that:

- the static modulus of elasticity of concretes of classes B30-B70 on ordinary large aggregates (granite crushed stone and gravel crushed stone) corresponds to the values given in SP 63.13330.2018, Model Code MC 2010 and EN 1992-1-1: 2004 Eurocode 2;
- the static modulus of elasticity of high-strength concretes of classes B71-B100 on the same

conventional large aggregates (granite crushed stone and gravel crushed stone) exceeds by 5 ... 14% the values given in SP 63.13330.2018, corresponds to Model Code MC 2010 and is consistent with previously obtained results [10-14, 17, 18];

- the use of gabbro-diabase and basalt crushed stone as a coarse filler allows increasing the static modulus of elasticity of heavy concretes of compressive strength classes B30-B100 by 9 and 19%, respectively, which is consistent with the information given by the FIB in Table 5.1-6 of Model Code 2010, and paragraph 3.1.3 of EN 1992-1-1:2004 Eurocode 2.

The increase in the static modulus of elasticity of concretes on gabbro-diabase and basalt crushed stone in comparison with concretes on granite crushed stone is obviously associated with higher characteristics of the elastic properties of the rocks from which it is obtained. As is known, the elastic modulus of granite is 30-68 GPa, while in denser rocks it is higher: gabbro 60-125 GPa, diabase 80-110 GPa, basalt 20-100 GPa [15, 20, 26].

The same nature of the curves presented in Figures 5a and 5b indicates the presence of a linear dependence of the static modulus of elasticity of concrete not only on the compressive strength, but also on the dynamic modulus of elasticity, which corresponds to the information given in [27]. Based on the data in Table 3, the relationship between the static modulus of elasticity and the dynamic modulus of elasticity of heavy concretes of classes B30-B100 with various types of coarse aggregates was established (Figure 6), which can be expressed by the equation:

$$E_b = 0.982E_d - 3.437, \qquad (5)$$

The indicators of the dependence presented in Figure 6 are as follows: the number of test results (n) - 52; the average value of the static modulus of elasticity (E_{bm}) is 44.1 GPa; calculated standard deviation of the established dependence (S_2) is 1.203 GPa; standard deviation of the static modulus of elasticity actually obtained from the results of concrete testing (S_3) is 0.819 GPa; the root-mean-square deviation of the method used in constructing the dependence was assumed to be $0.02E_{bm}$ (S_4=0.881 GPa); correlation coefficient of the established dependence (r) is 0.99; the error in determining the static modulus of elasticity $[(S_2/E_{bm})\cdot 100]$=1.9%.

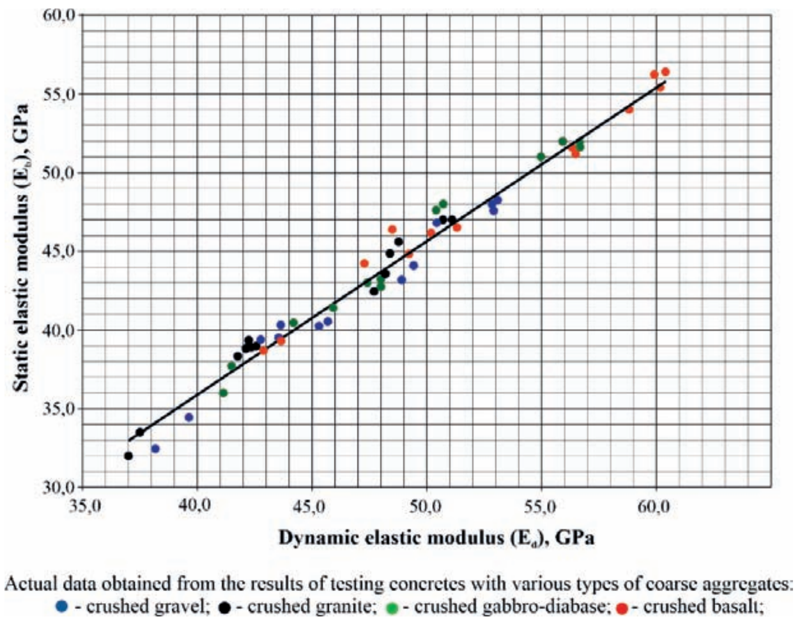
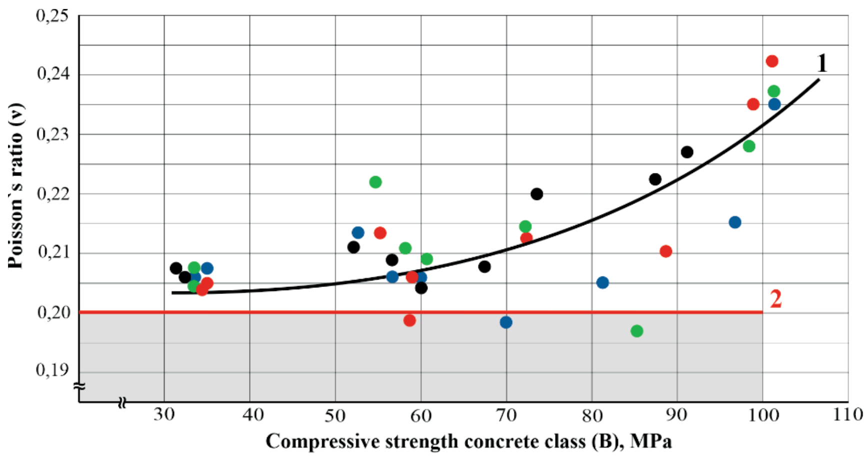


Figure 6. Dependence between values of static (E_b) and dynamic (E_d) elastic modulus of heavy-weight concretes of B30-B100 classes

The obtained indicators allow using the dependence established in this way to determine the static modulus of elasticity of concrete from core specimens taken from structures, based on the results of a less laborious determination of the dynamic modulus of elasticity, since the value of the correlation coefficient of the dependence is more than 0.7, and the value of the error in determining the initial static modulus of elasticity is less than 15%.

2.5. Poison's ratio

Poisson's ratio of heavy concretes of classes B30-B100 is in the range from 0.196 to 0.242, basically corresponds to the normalized value of the Poisson's ratio $\nu_{b,P}$=0.2) according to clause 6.1.17 of the building code of the Russian Federation SP 63.13330.2018. With an increase in the concrete compressive strength class from B30 to B100, the average Poisson's ratio increases from 0.20 to 0.23 and practically does not depend on the type of coarse aggregate (see Figure 7).



1 - Actual data obtained from the results of testing concretes with various types of coarse aggregates:
● - crushed gravel; ● - crushed granite; ● - crushed gabbro-diabase; ● - crushed basalt;
2 - Normative value of concretes Poisson`s ratio (ν_n) according to SP 63.13330.2018.

Figure 7. Poisson's ratio of concretes of B30-B100 classes

CONCLUSION

1. It is shown the possibility of controlling the strength and deformation characteristics of heavy concretes of classes B30-B100 (strength from 36.2 to 115.1 MPa) prepared from self-compacting mixtures due to technological factors - the use of various types of coarse aggregates and modifiers.
2. Use the crushed stone from more dense and durable rocks - gabbro-diabase or basalt (true density 3000- 3070 kg/m3, modulus of elasticity up to 125 GPa) as a coarse filler instead of crushed stone from gravel or crushed granite (true density 2650-2670 kg / m^3, modulus of elasticity up to 68 GPa), does not lead to significant changes in the cubic and prism compressive strengths of concrete and Poisson's ratio, but allows increasing the static modulus of elasticity of concrete by 9-19%.
3. The values of the dynamic modulus of elasticity of heavy concrete were obtained. This is in the range from 41.1 to 60.4 GPa and, depending on the classes of concrete, exceed the static modulus of elasticity of concrete by 2.2-5.3 GPa. The possibility of using a less time-consuming method for monitoring the values of the static modulus of elasticity of concrete in structures by determining the dynamic modulus

using the calibration dependence $E_b - E_d$ is shown.
4. The obtained results show that the values of the strength and deformation characteristics of modern concretes of classes B30-B100 exceed the standard values given in the code of rules of the Russian Federation SP 63.13330.2018, in particular:
- the actual prism compressive strength is 24% higher than the standard values according to table 6.7 of the building code;
- the static modulus of elasticity of high-strength concretes of classes B80-B100 is 5-14% higher than the standard values according to table 6.11 of the building code.
5. The above is the basis for making appropriate changes to the building code of the Russian Federation SP 63.13330.2018 in terms of increasing the standard values of prism strength and the modulus of elasticity of heavy concrete.
6. The ability to control the values of the modulus of elasticity of heavy concrete by selecting a large aggregate of the appropriate origin and quality should considered when calculating and designing reinforced concrete structures and, as an appropriate addition, is included in the building code of the Russian Federation SP 63.13330.2018. This is in line with the recommendations of CEB-FIP Model Code 2010 and EN 1992-1-1:2004 Eurocode 2.

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