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RELATIONSHIP BETWEEN STRENGTH AND DEFORMATION CHARACTERISTICS OF HIGH-STRENGTH SELF-COMPACTING CONCRETE

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Abstract. The paper provides data on the strength and deformation characteristics of heavy self-compacting concrete of classes B30-B100 with a cubic compressive strength of 36.5-114.8 MPa. It has been established that the values of the concrete prism compressive strength (36.2-104.2 MPa) are 42-64% higher than the normalized values given in the building code of the Russian Federation SP 63.13330.2018. The values of the static modulus of elasticity for high-strength concretes of classes B80-B100 are 44.1-48.1 GPa and exceed by 5-12% the values given in SP 63.13330.2018. The ultimate compressive strains of concrete of classes B30-B100 are in the range from 261×10^{-5} to 326×10^{-5} and exceed the value of 200×10^{-5} given in SP 63.13330.2018. Complete deformation diagrams of self-compacting concretes of classes B30-B100 have been constructed. The nonlinearity of these ones decreases with increasing concrete strength. The descending branch of the σ-ε diagram is observed only for concrete of a class below B55 with a total relative compressive strain of 403.3×10^{-5} under a loading level of $0.85R_b$. Concrete of classes B55-B100 has no descending branch. Previously established dependencies are refined for the analytical description of strains and stresses at any stages of loading structures.

Keyword. High-strength self-compacting concrete, complete strain diagrame, deformation characteristics, Poisson's ratio, ultimate compressive strains, compressive strength, static modulus of elasticity.

ВЗАИМОСВЯЗЬ ПРОЧНОСТНЫХ И ДЕФОРМАЦИОННЫХ ХАРАКТЕРИСТИК ВЫСОКОПРОЧНЫХ САМОУПЛОТНЯЮЩИХСЯ БЕТОНОВ

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Аннотация. Получены данные о прочностных и деформационных характеристиках тяжёлых самоуплотняющихся бетонов классов В30-В100 с кубиковой прочностью на сжатие 36,5-114,8 МПа. Установлено, что значения призменной прочности бетонов на сжатие (36,2-104,2 МПа) на 42-64 % превосходят нормируемые показатели, приведенные в своде правил РФ СП 63.13330.2018. Значения статического модуля упругости, для высокопрочных бетонов классов В80-В100 составляют 44,1-48,1 ГПа и превышают на 5-12 % значения, приведенные в СП 63.13330.2018. Предельные относительные деформации сжатия бетонов классов В30-В100 находятся в диапазоне от 261×10^{-5} до 326×10^{-5} и превышают значение 200×10^{-5}, приведенное в СП 63.13330.2018. остроены полные диаграммы деформирования самоуплотняющихся бетонов классов В30-В100, нелинейность которых уменьшается по мере роста прочности бетона. Нисходящая ветвь диаграммы σ-ε наблюдается только у бетона класса ниже В55 с суммарной относительной деформацией сжатия $403,3\times10^{-5}$ при уровне нагружения $0,85R_b$. У бетонов классов В55-В100 нисходящая ветвь отсутствует. Уточнены ранее установленные зависимости для аналитического описания относительных деформаций и напряжений на любых этапах нагружения конструкций.

Ключевые слова: Высокопрочный самоуплотняющийся бетон, полная диаграмма деформирования, деформационные характеристики, коэффициент Пуассона, предельные относительные деформации сжатия, прочность на сжатие, статический модуль упругости.

INTRODUCTION

All regulatory documents for the calculation of reinforced concrete structures both in Russia (set of rules SP 63.13330.2018) and abroad (international standard Model Code MC 2010, European standard EN 1992-1-1: 2004 Eurocode 2) are based on the relationship between the strength and deformation characteristics of concrete.

In Russia, the generalized strength parameter is the compressive strength class of concrete determined by the values of cubic (R) and prism (R_b) compressive strength. Among several normalized deformation characteristics of concrete, the most significant is the static modulus of elasticity (E_b), which according to SP 63.13330.2018 "Concrete and reinforced concrete structures. General Provisions", depends mainly on the classes and types of concrete. The remaining deformation characteristics are either depends on the elastic modulus (shear modulus ($G=0,4\cdot E_b$), or are taken constant (transverse strain coefficient - Poisson's ratio $\nu_b=0.2$; ultimate strain for axial compression under short-term load $\varepsilon_{b0}=0.002$).

At the same time, foreign standards give strength and deformation characteristics (except for Poisson's ratio) for each class of concrete.

An analysis of the existing concrete strain diagrams under compression in Russian and foreign regulatory documents has shown that the ultimate compressive strain of concrete in many countries is taken as a variable. And non-linear dependences of strain diagrams are proposed, considering the ascending and descending branches [1]. In addition, the values on the ascending branch of the corresponding cylindrical strength and the total strain, taking into account the descending branch, are determined for each class.

However, the application of the dependencies given in foreign standards and literature is difficult in Russia, since the methods for determining the main characteristics of concrete have significant differences regarding the shape and size of the samples, the conditions for their maintenance, the speed and discreteness of loading, etc.

A number of studies [2-9] showed that the experimentally obtained dependences between the strength and deformation characteristics of ordinary concrete with a compressive strength not exceeding 40 MPa cannot always be used for high-strength concrete with a strength of 60-120 MPa.

Therefore, the study of the relationship between the strength and the complex of deformation characteristics of both ordinary and high-strength concretes with the construction of complete strain diagrams (including the descending branch) and the refinement of the previously obtained dependencies is an urgent task. This is of particular interest for concretes made of self-compacting mixtures, the volume of which is growing.

The purpose of the research was to determine the relationship between the strength and deformation characteristics of concrete classes from B30 to B100, prepared from self-compacting mixtures, with the refinement of previously obtained dependencies

To achieve the purpose, the following tasks were solved:

- determination of strength (cubic and prismatic compressive strength) and deformation (static modulus of elasticity, Poisson's ratio, ultimate compressive strains) characteristics of five compositions of self-compacting concrete of classes B30-B100;
- construction of complete concrete deformation diagrams, including the descending branch;

- refining of the previously established in [8, 9] dependences of the deformation characteristics of concretes on their prism compression strength;
- comparing of the obtained results with the standard values given in the building code of the Russian Federation SP 63.13330.2018.

MATERIALS AND TEST METHODS

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.

The characteristics of the materials were as follows:

- Portland cement CEM I 52.5 N, corresponding to GOST 31108;
- organomineral concrete modifier MB10-50C A-II-2, including microsilica (45%), fly ash (45%) and superplasticizer (10%) [10], corresponding to GOST R 56178;
- micro-filler - non-activated mineral powder MP-1 (ground limestone) with a particle size of less than 1.25 mm, corresponding to GOST R 52129 and GOST R 56592;
- superplasticizer SikaPlast E4 based on a mixture of modified lignosulfonates and polycarboxylate esters, corresponding to GOST 24211;
- class I quartz sand with fineness modulus M_{cr}=2.55, corresponding to GOST 8736;
- crushed granite fraction 5-10 mm, corresponding to GOST 8267;
- water for mixing concrete mixtures, corresponding to GOST 23732.

Compositions and Properties of Concrete Mixes

In laboratory conditions, 5 concrete compositions were prepared using self-compacting mixtures with a cement consumption of 287 to 482 kg/m^3 with the addition of MB modifier and micro-filler at a water-binding ratio W / (C + MB) from 0.25 to 0.69.

The compositions of self-compacting concrete mixtures are presented in table 1.

Table 1. Composition of self-compacting concrete mixtures

No composition	Composition of self-compacting concrete mixes, kg/m^3						
	C	**MB**	**MP-1**	**FA**	**CA**	**SP**	**W**
1	287	-	148	822	871	3,53	198
2	305	29	167	836	836	-	177
3	349	65	150	818	838	-	161
4	423	70	101	826	846	-	161
5	482	131	50	733	904	-	151

Note: C - Portland cement; MB - modifier; MP-1 - microfiller; FA - sand; CA - crushed stone; SP - superplasticizer; W - water.

Concrete mixtures were prepared in a 25-liter forced-action mixer with mixing of each batch for 5 minutes. The results of tests of concrete mixtures showed that their mobility, determined by the spread of a normal cone [11], is in the range from 55 to 65 cm.

Object of Research and Test Methods

Samples were formed from the prepared concrete mixtures: 3 cubes with a size of 100 × 100 × 100 mm to determine the cubic compressive strength of concrete (R) according to Russian standards GOST 10180 and GOST 31914; 6 prisms with a size of 100 × 100 × 400 mm to

determine the prism compressive strength of concrete, the static modulus of elasticity, Poisson's ratio according to the standards of the Russian Federation GOST 24452 and GOST 31914; 3 prisms with size of 70.7 × 70.7 × 280 mm to establish complete strain diagrams of concrete according to the method [13, 14].
Control specimens were stored for 28 days under normal conditions (temperature plus 20 ± 2 °C, humidity 95 ± 5%) before testing. The loading of the prisms was carried out in steps equal to $0{,}1R_b$ with holding at each step for 5 minutes until the destruction of the specimens. The static modulus of elasticity and Poisson's ratio were determined at a loading level of 30-40% of the prism strength.

TEST RESULTS AND DISCUSSION

Table 2 presents concrete test results in terms of: concrete class (B), cubic (R) and prism (R_b) compressive strength, static modulus of elasticity (E_b), Poisson's ratio (ν_b), ultimate compressive strain (ε_{b0}). And figure 1 shows complete strain diagrams of concrete.

Table 2. Strength and short-term deformation characteristics of concrete

No	Strength and deformation characteristics of concrete						
	B, MPa	R, MPa	R_b, MPa	E_b, MPa	ν_b	$\varepsilon_{b0} \times 10^5$	$\varepsilon_{b0}^{-0,85} \times 10^5$
1	B30	36.5	36.2	32.5	0.206	261	403
2	B55	61.8	56.0	39.2	0.214	276	-
3	B70	80.2	74.5	40.5	0.198	299	-
4	B80	92.5	85.3	44.1	0.205	294	-
5	B100	114.8	104.2	48.1	0.230	326	-

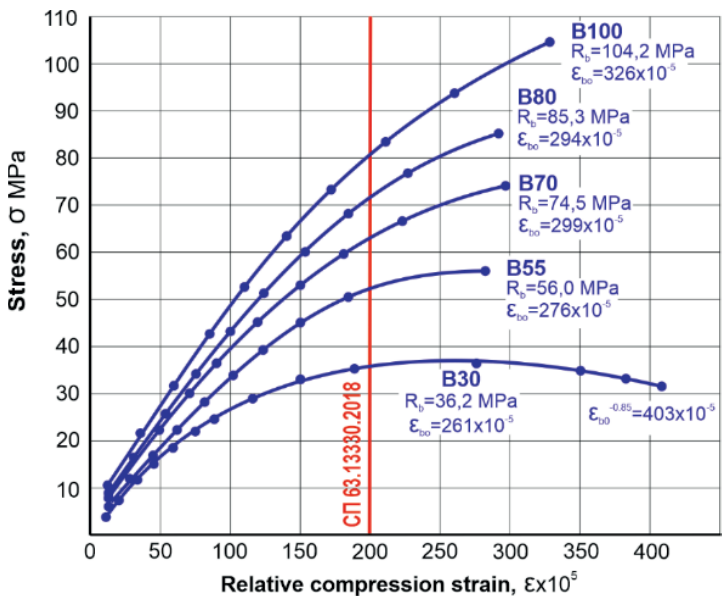

Figure 1. Complete concrete compressive strain diagrams σ–ε

Compressive Strength

The cubic compressive strength (R) for all concretes at the age of 28 days is in the range from 36.5 to 114.8 MPa and corresponds to concrete compressive strength classes from B30 to B100. The prismatic compressive strength of concrete (R_b) at the age of 28 days is in the range from 36.2 to 104.2 MPa. Evaluation of the above results according to the criterion of the prism strength coefficient, determined by the ratio of the prismatic compressive strength of concrete to cubic strength ($K_{pp} = R_b / R$) shows that its actual values are in the range from 0.91 to 0.99 and significantly exceed the values of this coefficient calculated according to the parameters given in the building code of Russian Federation SP 63.13330.2018 (from 0.71 to 0.73).

Static Modulus of Elasticity

The static modulus of elasticity of concretes of classes B30-B100 with prismatic strength from 36.2 to 104.2 MPa is in the range from 32.5 to 48.1 GPa (see Table 2). Figure 2 shows the dependence between the static modulus of elasticity and the prismatic compressive strength of concrete.

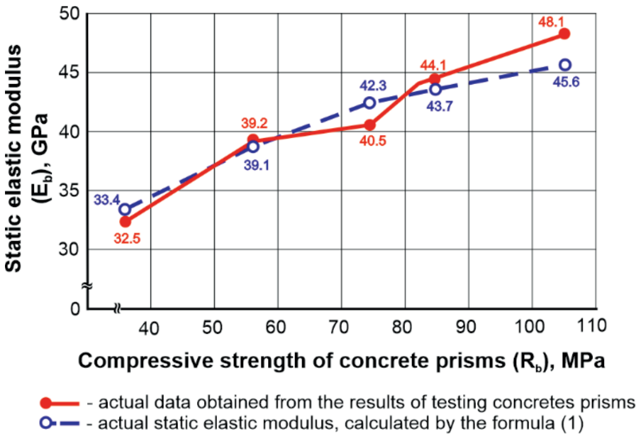

Figure 2. Static elastic modules vs compressive strength of concretes prisms

The obtained results (see Fig. 2) show that the static modulus of elasticity of concrete is proportional to the prismatic strength and can be determined by the corrected formula [8] in the form:

$$E_b = \frac{52000 \cdot R_b}{23 + 0.92 R_b} \qquad (1)$$

Comparison of the calculated results and those obtained experimentally shows (see Figure 2) that this formula can be used to determine the static modulus of elasticity of concrete, since the calculation error does not exceed 5%.

Comparison of the experimentally obtained values of E_b with normalized values showed that the static modulus of elasticity of high-strength concretes of classes B80-B100 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 [4-6, 15, 16].

Poisson's ratio

Poisson's ratio of heavy concretes of classes B30-B100 is in the range from 0.198 to 0.230 (see Table 2) and, in general, corresponds to the normalized value of the coefficient of transverse deformations $\nu_{b,P}$= 0.2 according to the building code of the Russian Federation SP 63.13330.2018.

Ultimate compressive strain

Ultimate compressive strains of concrete of classes B30-B100 with prismatic strength from 36.2 to 104.2 MPa are in the range from 261×10^{-5} to 326×10^{-5} (see Table 2) and exceed the value of 200×10^{-5} given in SP 63.13330.2018. The complete strain diagrams of concrete under compressive show (see Fig. 1) that the descending branch is observed only in class B30 concrete with a prism strength of 36.2 MPa, where the total relative compressive strain was 403.3×10^{-5} at the level of $0.85R_b$ of the descending branch. For concretes with higher strength, there is no descending branch, which corresponds to the results obtained in [9].

Figure 3 shows the dependence between the ultimate strain and the prismatic compression strength of concrete.

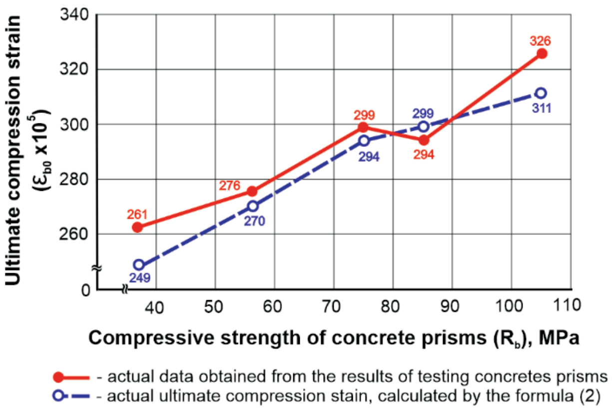

Figure 3. Ultimate compressive strain vs compressive strength of concretes prisms

The obtained results (see Fig. 3) show that the ultimate strain of concrete increase with an increase in prismatic strength and can be determined by the corrected formula [8, 9] in the form:

$$\varepsilon_{b0} = 0.024\sqrt[3]{\frac{R_b}{E_b}} \quad (2)$$

Comparison of the calculated results and those obtained experimentally shows (see Fig. 3) that this formula can be used to determine the limiting relative deformations of concrete, since the calculation error does not exceed 5%.

Relationship between Strains and Stresses

It is necessary to determine the values of strains or stresses at any stage of loading or deformation of structures when calculating or testing. For an analytical description of relative strains and stresses at any stages of loading, it is proposed to use the refined equations [8, 9] in the form:

$$\varepsilon_\eta = \varepsilon_{b0} \cdot \left(1 \pm \sqrt[n]{1 - \frac{\sigma}{R_b}}\right) \quad (3)$$

$$\sigma_\eta = R_b - \left|1 - \frac{\varepsilon_\eta}{\varepsilon_{b0}}\right|^n \cdot R_b \quad (4)$$

where:

ε_η is strain at a given stress level;

σ_η is the stress at given strain, MPa;

η is the loading level equal to the ratio of stresses to prismatic strength (σ/R_b);

ε_{b0} is ultimate compressive strain;

R_b is the prismatic compressive strength of concrete, MPa;

n is the degree of non-linearity of the concrete strain diagram, which depends on its strength and can be determined by the formula:

$$n = 3.5 - \frac{R_b \cdot 10^3}{E_b} \quad (5)$$

The dependence between the degree of nonlinearity of deformation diagrams and the prism compressive strength of concrete is shown in Figure 4, from which it can be seen that with increasing strength, the degree of nonlinearity decreases and tends to unity. This confirms the results of previous studies [8, 17].

It should be noted that when determining the strain in the descending branch of the diagram σ–ε, the sign in front of the root of the second polynomial in formula (3) should be replaced from minus to plus.

Comparison of the strainf of self-compacting concretes of classes B30-B100, obtained experimentally, with the results calculated from the analytical dependence (3) showed satisfactory convergence, which makes it possible to use equations (3) and (4) to assess strains and stresses at all stages of loading structures.

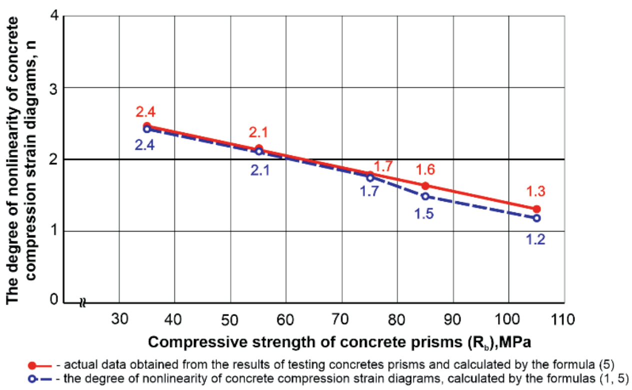

Figure 4. The degree of nonlinearity of concrete compressive strain diagrams vs compressive strength of concretes prisms

CONCLUSIONS

1. Strength (cubic and prismatic compressive strength) and deformation (static modulus of elasticity, Poisson's ratio, ultimate compressive strains) characteristics of five compositions of self-compacting concretes of classes B30-B100 were determined using standard and special methods.
2. The obtained results show that the values of the strength and deformation characteristics of high-strength self-compacting concrete of classes B80-B100 exceed the standard values given in the building code of the Russian Federation SP 63.13330.2018.
3. Complete strain diagrams of self-compacting concretes of classes B30-B100 are constructed. The nonlinearity of these diagrams decreases as the strength of concrete increases. The descending branch of the σ-ε diagram is observed only for concrete of classes below B55 with a prism strength of 36.2 MPa, while it is absent for concrete of classes B55-B100 with a prism strength of 56.0-104.2 MPa.
4. Previously established dependences for determining the static modulus of elasticity, ultimate compressive strains and analytical expressions for strains and stresses at any stages of loading the structures made of self-compacting concrete of classes B30-B100 have been refined.

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