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COMPARISON OF THE SHEAR STRENGTH IN HEAVY AND SELF-COMPACTING CONCRETE

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Abstract

Introduction. The shear strength of concrete, while not being an independently standardized indicator of concrete quality, plays an important role in the analysis of reinforced concrete structures. The concepts related to the dependence of the shear strength of concrete on the standardized compressive and axial tensile strength are quite ambiguous. Self-compacting concrete (SCC), which has been widely used recently, is somewhat different from ordinary concrete (OC) compacted by vibration in terms of structure and properties, and data on the shear strength of SCC are sparse. **Purpose of the study**: We aimed to clarify the dependence of the shear strength of concrete on the standardized compressive and axial tensile strength, and assess the shear strength of SCC in comparison with that of OC. **Methods**: We compared the shear strength of SCC with that of OC experimentally, by applying the common methodology with the use of a Mörsch specimen and performing modeling in MATLAB with the use of six strength theories. **Results**: No significant differences were found in the dependence of the shear strength of SCC in comparison with that of OC at the design age of 28 days. In terms of quantity, the excess of the shear strength of SCC relative to OC is less than 12%. The best agreement with the experimental data among those analyzed is provided by the Geniev theory. The shear strength of concretes is most likely described by the equation $R_{sh} = k\sqrt{R \cdot R_t}$ at k = 0.5–0.6.

Keywords: shear strength, self-compacting concrete, strength theories, fracture criteria.

Introduction

The shear strength of concrete is essential, for example, in the behavior of column consoles, including those made of widely used SCC (Dhanabal and Sreevidya, 2018; Prakash et al., 2021), the ultimate resistance calculation (Filatov et al., 2020), the assessment of the monolithic character of reinforced concrete structures erected with horizontal or vertical construction joints, and in other cases. A comprehensive review of the shear strength of concrete was given by Palieraki et al. (2021). It is known that the fracture of masonry materials, including concrete, can occur as a result of splitting and (or) shear (Timoshenko, 1950). When assessing the magnitude of the transverse force in reinforced concrete elements subject to bending, researchers usually take into account the limiting value of shear stresses as the main factor. This factor is considered as the resistance of concrete to shear. In the shear and ultimate resistance calculation of structures, the compressive or tensile strength of concrete are commonly used. The shear strength of concrete, in contrast to, for example, the tensile strength, is not standardized depending on the class of concrete. One of the earliest methods to calculate the ultimate resistance was to use the assessment of shear stresses and compare them to concrete properties (Talbot, 1913). The values of the shear strength of fine-grained concrete ranged from 3.7 to 6.5 MPa. The shear strength of concrete was considered (Borishansky, 1946; Gvozdev, 1949; Morsh, 1903; Stolyarov, 1941) as the ratio *Rsh*/*R* (shear/compression) in the following form: *Rsh* = k·*R* at, e.g., k = 0.2 (Stolyarov, 1941), k = 0.166…0.195 (Gvozdev, 1949), k = 0.15 (Borishansky, 1946). Some dependences of the shear strength of concrete on the compressive and tensile strength are given in Table 1.

Fig. 1. Dependence of the shear strength on the compressive strength according to Table 1.

The results presented (Fig. 1) show a significant divergence of views regarding the shear strength of concrete. The available experimental data are also quite ambiguous (Dovzhenko et al., 2016). In the construction of various reinforced concrete structures, SCCs are widely used, the macrostructure and deformation properties of which are somewhat different from those of ordinary concretes compacted by vibration (Dey et al., 2021; Liu et al., 2021; Mailyan et al., 2023; Stel'makh et al., 2022; Uğur and Ünal, 2022; Zeng et al., 2021). It seems relevant to compare the available (Table 1) suggestions for assessing the shear strength of concrete depending on the standardized values of the compressive and axial tensile strength and compare the shear strength of SCC relative to OC, especially in connection with the revealed (Nesvetaev et al., 2022b) tendency of increased brittleness in SCC in the early (up to 3 days) curing period. Some results of assessing the shear strength of SCC (De Gois Laufer and Savaris,

Table 1. **Some equations to determine the shear strength of concrete**

No.	Equation	Reference	Possible representation of the equation as suggested by the authors*
1	$R_{sh} = 2 \cdot R_t$	Stolyarov, 1941	$R_{sh} = 0.58 \cdot R^{0.6*}$
2	$R_{sh} = 0.2 \cdot R$	Stolyarov, 1941	
3	$R_{sh} = 0.7\sqrt{R \cdot R_t}$	Mikhailov, 1977	$R_{sh} = 0.377 \cdot R^{0.8*}$
4	$R_{sh} = k \cdot \sqrt{R \cdot R_t},\ k = 0.5 \ldots 1$	Golyshev et al., 1990	$R_{sh} = (0.27 \ldots 0.539) \cdot R^{0.8*}$
5	$R_{sh} = 0.5\sqrt{R \cdot R_t}$	Nesvetaev and Belyaev, 2016	$R_{sh} = 0.27 \cdot R^{0.8*}$
6	$R_{sh} = (0.15 \ldots 0.3) \cdot R$	Krasnoschekov and Galuzina, 2016	
7	$R_{sh} = \left(0.093 \cdot (10R)^{\frac{2}{3}}\right)$	Ctcmetar.ru, 2023	$R_{sh} = 0.43 \cdot R^{2/3}$
8	$R_{sh} = 0.5 \cdot R_t$	Maximum-shear theory (Tresca–Saint-Venant)	$R_{sh} = 0.145 \cdot R^{0.6*}$
9	$Q_{b1} = 0.5 \cdot R_{bt} \cdot b \cdot h_0$	Regulations SP 63.13330.2018, Eq. 8.61	$R_{sh} = 0.5 \cdot R_{bt} = 0.22 \cdot R^{0.6*}$
10	$R_{sh} = k \cdot \sqrt{R}$, $k = f(R) = 0.41 \ldots 0.58$	De Gois Laufer and Savaris, 2021	
11	$R_{sh} = 0.75 \cdot \sqrt{R \cdot R_t}$	Zhang et al., 2020	$R_{sh} = 0.4 \cdot R^{0.8}$

Note: 1 — R_{bt} — the class of concrete by axial tensile strength, R_{btn} — the axial tensile strength of concrete, $R_{btn} = 1.5 \cdot Rbt$; R, R_t — the experimental values of the compressive and axial tensile strength in the studies; * — with account for $R_t = 0.29 \cdot R^{0.6}$ (Nesvetaev et al., 2022a)

2021) show relatively low values (Fig. 1, 10, max). This study compares the shear strength of SCC with that of OC, by applying the common methodology as a function of the values of the compressive and axial tensile strength standardized for concretes. In addition to the experimental studies, the shear strength of SCC and OC was assessed with the use of six widely known strength theories.

Subject, tasks, and methods

Methodology of experimental studies

Since the methodology of determining the shear strength of concrete is not regulated by regulatory documents, various specimens are used in experimental studies. According to (Dovzhenko et al., 2016), the most common way to determine the shear strength of concrete is to use the Gvozdev specimen

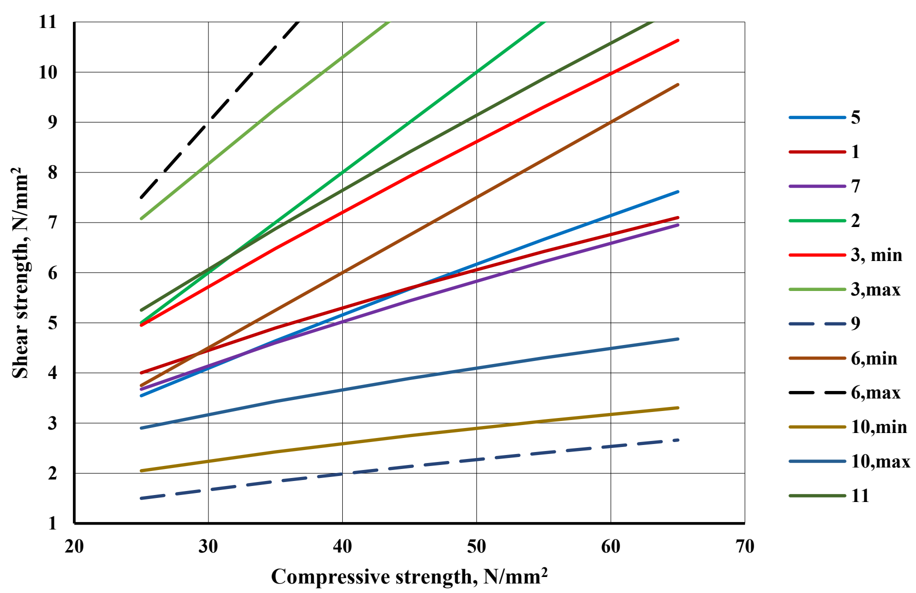


Fig. 1 graphically shows the dependences according to Table 1 or the Mörsch specimen. Both specimens provide almost identical statistical values (Dovzhenko et al., 2016). According to Dovzhenko et al. (2016), the Gvozdev specimen shows a better agreement between the theoretical and experimental values. According to Petrov (1967) and Verigin (1960), it is impossible to provide test conditions corresponding to pure shear for brittle materials, therefore, the shear strength should be excluded from the theory of brittle materials strength. However, in engineering practice, methods providing some conditional values for practical purposes are widely used in production control or comparative tests. Therefore, since the Mörsch specimen is easier to manufacture and tests involving it are quite simple and easily reproducible, we used it in our experimental studies (Fig. 2).

The experimental studies were performed with the use of four OC series made with four different W/C ratios without chemical additives and three SCC series made with three different W/C ratios using polycarboxylate-ether superplasticizers (Plank et al., 2009). In the experimental studies, ordinary concrete mixtures with consistency grade P2 according to GOST 7473-2010 for OC were used. Concrete mixtures for SCC corresponded to grade RK1 according to GOST R 59714-2021 (SF1 according to EN) with a W/C ratio from 0.4 to 0.55. The compressive strength at the design age varied for OC from 35.5 to 52.4 MPa, and for SCC — from 50.1 to 61.6 MPa. Concrete specimens 100x100x310 mm were used as Mörsch specimens (Fig. 2). To determine the compressive and tensile strength (in splitting), specimens 100x100x100 mm according to GOST 10180-2012 were used. The number of specimens in a series was taken according to GOST 10180-2012. Portland cement CEM I 42.5, crushed granite with a particle size of 5–20 mm, and quartz river sand with a particle size of 0.14–2.5 mm were used. The specimens were tested at the design age after 28 days of curing under normal conditions.

Methodology for numerical analysis

Numerical modeling was performed in two-dimensional formulation by the finite element method based on six strength criteria:

1. Maximum-shear theory (Tresca–Saint-Venant). According to this theory, the strength condition has the following form:

$$\sigma_1 - \sigma_3 \le R_t. \tag{1}$$

2. Mohr's strength theory (Andreev et al., 2014):

$$\sigma_1 - \chi\sigma_3 \le R_t, \quad \chi = \frac{R_t}{R}. \tag{2}$$

3. Pisarenko–Lebedev theory (Bazhenov et al., 2022):

$$(1-\chi)\cdot\sigma_0 + \frac{\sigma_i}{3}\left(3\chi + (1-\chi)\left(\sqrt{3}\cdot\cos\psi - \sin\psi\right)\right) \le R_t;$$

$$\sigma_0 = \frac{\sigma_1 + \sigma_2 + \sigma_3}{3};$$

$$\sigma_i = \frac{1}{\sqrt{2}}\sqrt{(\sigma_1-\sigma_2)^2 + (\sigma_2-\sigma_3)^2 + (\sigma_1-\sigma_3)^2};$$

$$\psi = \frac{1}{3}\operatorname{asin}\left(\frac{27 I_3}{2\sigma_i^3}\right);$$

$$I_3 = (\sigma_1-\sigma_0)(\sigma_2-\sigma_0)(\sigma_3-\sigma_0). \tag{3}$$

4. Balandin's strength criterion (Andreev and Potekhin, 2019):

$$\begin{aligned} F(\sigma_1,\sigma_2,\sigma_3) &= \sigma_1^2 + \sigma_2^2 + \sigma_3^2 - \\ &-(\sigma_1\sigma_2 + \sigma_2\sigma_3 + \sigma_1\sigma_3) + \\ &+(R - R_t)\cdot 3\sigma_0 - R\cdot R_t \le 0. \end{aligned} \tag{4}$$

5. Luksha's strength criterion (Luksha, 1977):

$$\begin{aligned} F(\sigma_1,\sigma_2,\sigma_3) &= \sigma_1^2 + \sigma_2^2 + \sigma_3^2 - \\ &-2\cdot(\sigma_1\sigma_2 + \sigma_2\sigma_3 + \sigma_1\sigma_3) + \\ &+(R - R_t)\cdot 3\sigma_0 - R\cdot R_t \le 0. \end{aligned} \tag{5}$$

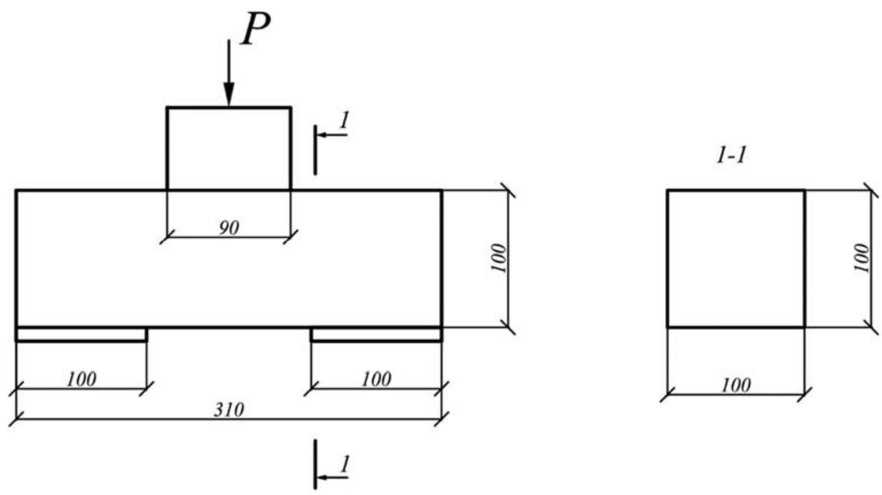


Fig. 2. Test scheme

6. Geniev strength theory (Chepurnenko et al., 2021):

$$F(\sigma_1,\sigma_2,\sigma_3)=\tau_i^2-T_c(T_c+\lambda\tau_i)(1+\delta)\le 0;$$

$$\tau_i=\frac{1}{\sqrt{6}}\sqrt{(\sigma_1-\sigma_2)^2+(\sigma_2-\sigma_3)^2+(\sigma_1-\sigma_3)^2};$$

$$\lambda=\frac{f\sigma_0}{\tau_i},\ f=\frac{3\tau_i(R-R_t)}{R\cdot R_t};$$

$$\delta=e\left(\frac{S}{\tau_i}\right)^3,\ S=\sqrt{3}\left[\frac{1}{2}\cdot I_3\right]^{\frac{1}{3}}, \qquad (6)$$

where T_c — ultimate shear stress intensity at pure shear.

To determine the breaking load according to the above strength criteria, a program was developed in the MATLAB environment. Because of symmetry, half of the specimen was considered. The calculation model is shown in Fig. 3.

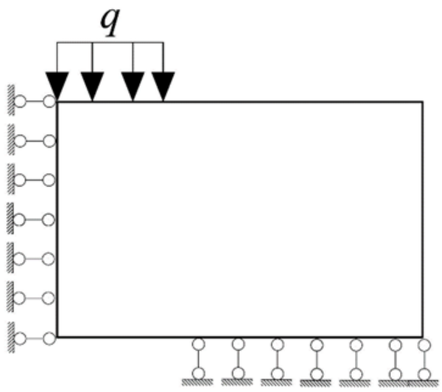


Fig. 3. Calculation model

Results and discussion

During the experimental studies with the use of the Mörsch specimen, various cases of fracture were observed (Fig. 4), which is consistent with the statement (Petrov, 1967) that the Mörsch specimen experiences shear, bending and local buckling under loading.

According to Stolyarov (1941), during tests involving the Mörsch specimen, at first, the initial crack under scheme C appears (Fig. 4). Further, fracture under scheme A (“pure” shear according to Stolyarov (1941)) or scheme B (i.e., bending and “pure shear”) is possible. However, in our studies, all the above cases were observed as the final scheme, with only Scheme C fracture being a one-off case. This is probably due to the higher deformability of SCC.

Table 2 presents the results of modeling the Mörsch specimen fracture schemes using various strength theories in the form of mosaics of equivalent stresses.

Table 3 shows a comparison of the experimental and theoretical values of the shear strength of concrete for OC and SCC specimens. The shear strength was calculated by different strength theories (Table 2).

a) b) c)

Fig. 4. Cases of specimen fracture when determining the shear strength of concrete: (a) by shear stresses (“pure shear” according to Stolyarov (1941)); (b) by shear and normal stresses (“shear” and “bending”); (c) by normal stresses (“bending”)

Table 2. **Numerical modeling results**

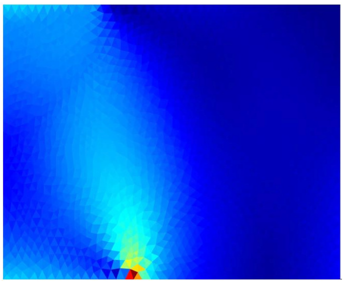
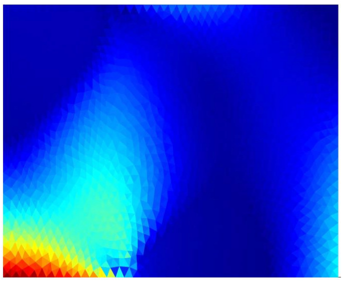
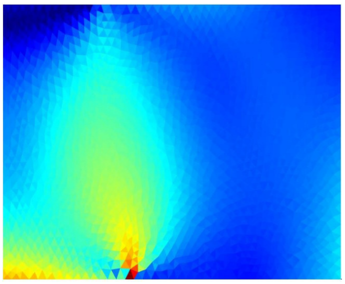
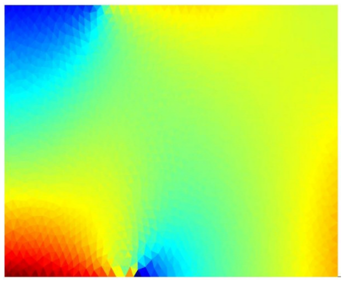
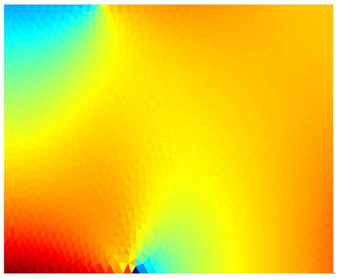
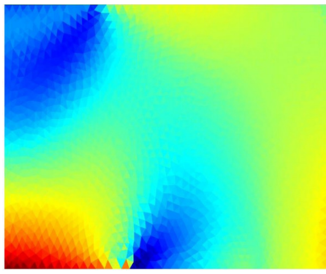
No.	Theory	Result
1	Tresca–Saint-Venant Possible fracture scheme (a), Fig. 4 Conditional shear strength[1]: $R_{sh} = 0.1 \cdot \sqrt{R \cdot R_t}$	
2	Mohr Possible fracture scheme (c), Fig. 4 Conditional shear strength[1]: $R_{sh} = 0.34 \cdot \sqrt{R \cdot R_t}$	
3	Pisarenko–Lebedev Possible fracture scheme (b), Fig. 4 Conditional shear strength[1]: $R_{sh} = 0.61 \cdot \sqrt{R \cdot R_t}$	

Table 2 (continued)

No.	Theory	Result
4	Balandin Possible fracture scheme (c), Fig. 4 Conditional shear strength[1]: $R_{sh} = 0.23 \cdot \sqrt{R \cdot R_t}$	
5	Luksha Possible fracture scheme (c), Fig. 4 Conditional shear strength[1]: $R_{sh} = 0.62 \cdot \sqrt{R \cdot R_t}$	
6	Geniev Possible fracture scheme (c), Fig. 4 Conditional shear strength[1]: $R_{sh} = 0.58 \cdot \sqrt{R \cdot R_t}$	

Note: 1 — based on the authors' modeling results

In the determination of the shear strength of concrete, the modeling results (Table 2) confirmed the possibility of the Mörsch specimen fracture according to the scheme presented in Fig. 4 by all options (a)–(c). Therefore, during the results processing, the shear strength of concrete in our studies in all cases was determined as the value of the breaking force based on the cross-section area, regardless of the fracture scheme.

According to Table 3, the shear strength of concrete can be represented by the following relationship:

$$R_{sh} = k \cdot \sqrt{R \cdot R_t}\,. \tag{7}$$

Table 4 shows dependences for the shear strength of OC and SCC according to the authors' experimental data.

Fig. 5 shows a comparison of the experimental results for the shear strength of concrete with values from Table 2 and some dependences from Table 1.

The results of the studies show the following:

- since the difference in the values of the coefficients in the equations of Table 4 (0.59/0.53 = 1.113) for the shear strength of SCC at the design age of 28 days in comparison with OC does not exceed 12%, we can argue that, at the design age, the shear strength of SCC is insignificantly higher than that of OC; the issue of whether or not it is reasonable to consider this fact for practical purposes can be further discussed;
- the best agreement with our experimental data is provided by the Geniev strength theory, the ratio of the calculated values and average experimental values is as follows: $R_{sh,calc}/R_{sh,test}$ = 0.98 for SCC and $R_{sh,calc}/R_{sh,test}$ = 1.09 for OC;
- the Balandin criterion also provides close values: $R_{sh,calc}/R_{sh,test}$ = 1.03 for SCC and $R_{sh,calc}/R_{sh,test}$ = 1.15 for OC;
- the Luksha theory provides a good result: $R_{sh,calc}/R_{sh,test}$ = 1.05 for SCC and $R_{sh,calc}/Rsh,test$ = 1.17 for OC;
- the best agreement with our experimental data is provided by Eq. (4) in Table 1 at k = 0.5–0.6.

Conclusions

As a result of the studies, no significant difference between the shear strength of SCC and that of OC, depending on the $\sqrt{R \cdot R_t}$ value, was revealed; the difference does not exceed 12 %. The best agreement with the experimental data among those

Table 3. **Experimental and theoretical values of the shear strength of concrete with the use of the Mörsch specimen**

No.	Strength values, MPa R	R_t	$\sqrt{R \cdot R_t}$	R_{sh}, MPa Experiment	R_{sh}, MPa Theory according to Table 2: 1	2	3	4	5	6
SCC										
1	50.1	2.76	11.8	7.12	1.15	3.95	2.75	7.35	7.5	6.85
2	57.9	2.84	12.8	7.87	1.2	4.2	2.85	7.8	7.85	7.4
3	61.6	3.11	13.8	7.86	1.3	4.5	3.1	8.35	8.4	7.85
OC										
4	35.5	1.65	7.65	4.67	0.725	2.48	1.67	4.58	4.63	4.35
5	41.8	2.63	10.5	6.06	1.09	3.71	2.59	6.53	6.68	6.19
6	47.9	2.81	11.6	5.6	1.16	4.01	2.78	7.2	7.31	6.68
7	52.4	3.12	12.8	6.6	1.3	4.45	3.1	8	8.2	7.5
8**	21.3*	1.79*	6.2*	3.6*	0.75	2.38	1.73	4.1	4.15	3.78

Notes: 1–7 — according to the authors' data; 8 — Petrov (1967); * — according to the authors' assessment; ** — fine-grained concrete

Table 4. **Suggested equations for determining the shear strength of OC and SCC**

No.	Concrete	Equation	R^2
1	OC	$R_{sh} = 0.53\sqrt{R \cdot R_t}$	0.993
2	SCC	$R_{sh} = 0.59\sqrt{R \cdot R_t}$	0.999

analyzed is provided by the Geniev strength theory. The Tresca–Saint-Venant, Pisarenko–Lebedev and Mohr strength theories are not applicable in describing the shear behavior of concrete. The shear strength of concrete is most likely described by the equation $R_{sh} = k\sqrt{R \cdot R_t}$ at k = 0.5–0.6.

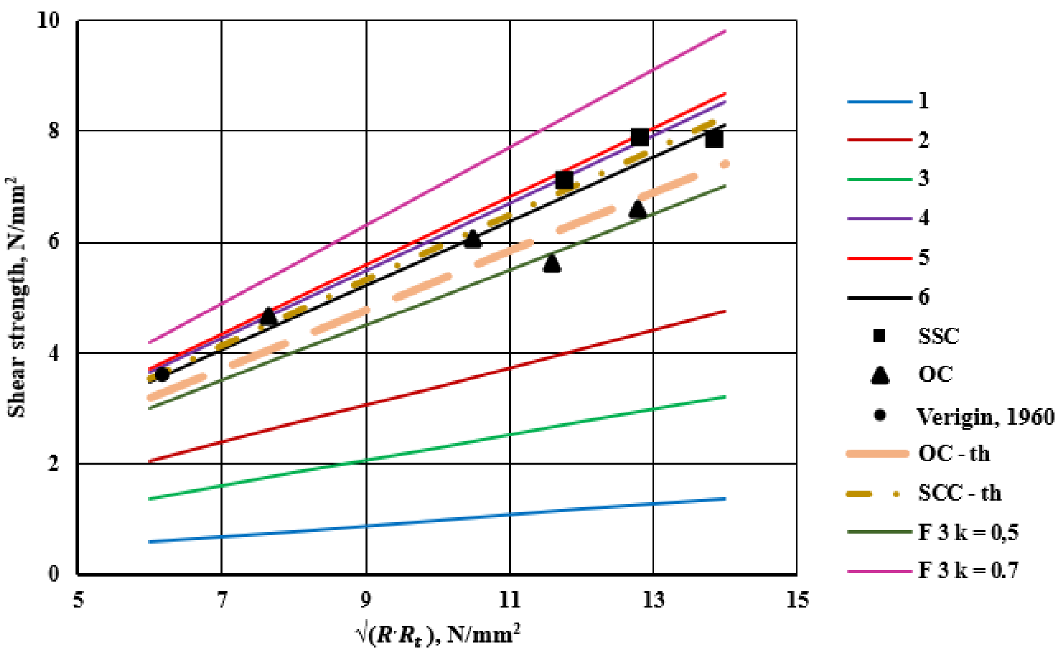


Fig. 5. Dependence of the shear strength of concrete on the compressive and tensile strength:
1–6 — the strength theories according to Table 2, respectively;
OC — experimental data for OC (Table 3);
SCC — experimental data for SCC (Table 3);
OC-th, SCC-th — by Eqs. 1, 2, Table 4;
F3 k=0.5 and 0.7 — by equations similar in structure to Eq. (4) in Table 1 at k = 0.5 and 0.7

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СРАВНЕНИЕ ПРОЧНОСТИ НА СРЕЗ ТЯЖЕЛОГО И САМОУПЛОТНЯЮЩЕГОСЯ БЕТОНОВ

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Аннотация
Введение. Предел прочности бетона на срез, не являясь самостоятельно нормируемым показателем качества бетона, играет важную роль при расчетах железобетонных конструкций. Представления о зависимости предела прочности бетона на срез от нормируемых показателей прочности на сжатие и осевое растяжение достаточно неоднозначны. Широко применяющийся в последнее время самоуплотняющийся бетон (СУБ) имеет некоторые отличия от традиционного бетона вибрационного уплотнения (ТБ) по структуре и свойствам, а данные о прочности на срез СУБ немногочисленны. **Цель исследования**: уточнение зависимости прочности бетона на срез от нормируемых показателей прочности на сжатие и осевое растяжение, оценка прочности на срез СУБ в сравнении с ТБ. **Методы**: Сравнение прочности на срез СУБ и ТБ выполнено экспериментально по единой методике с использованием образца Мерша и моделированием в среде MATLAB с использованием 6 теорий прочности. **Результаты**: Не выявлено существенного отличия зависимости предела прочности на срез в проектном возрасте 28 сут СУБ в сравнении с ТБ. Количественно превышение предела прочности на срез для СУБ относительно ТБ менее 12%. Лучшее соответствие с экспериментальными данными из проанализированных обеспечивает теория Гениева. Предел прочности бетонов на срез, наиболее вероятно, описывается уравнением $R_{sh} = k\sqrt{R \cdot R_t}$ при k = 0.5-0.6.

Ключевые слова: прочность на срез, самоуплотняющийся бетон, теории прочности, критерии разрушения.