On validity of the value of tensile strength of dry moulding and core mixtures

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The tensile strength in the cured state of molding and core sands is one of the important characteristics of molding materials. However, there is a significant spread of values at determining the tensile strength, which indicates the deficiencies of the existing methodology. The standard sample for tensile strength is a "figure-of-eight" shape. When it is tested for tension, the stresses in the holdsite points under central loading are 2–2.5 times greater than in the neck; therefore 8–12 % of the samples are destroyed in the holdsite points, and not along the neck. In this article, it is proposed to change the design of the standard "figure-of-eight" sample – to make a recess on one side of the neck, while creating an eccentric loading of the sample. The conducted studies and modeling show that using eccentric loading of the sample, due to the manufacture of a one-sided recess in the neck of the sample with a depth of 2–3 mm and a radius of at least 4 mm, the spread of strength indicators on the samples is 2–3 times less than on the standard one, and therefore the validity of the indicators is much higher.

Key words: moulding materials, tensile strength, validity of results, moulding sand, core sand.
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Introduction

Sand-clay molds are the most common in foundry, due to such advantages as the low cost of starting materials, the ease of production casting molds, the possibility of repeated use of the mixture, the ability to produce castings of almost any weight, configuration and from any metal and alloy.

The quality of castings directly depends on the properties of the mixture, so control over the technological and physical-mechanical properties of molding and core mixtures is mandatory. Many researchers strive to improve the properties of the mixture by changing the composition of molding sands, optimizing and modeling foundry processes, using neural networks [1–3] in order to obtain high-quality castings.

According to the number of tests carried out to determine the tensile strength in a dry (cured) state, by GOST 23409.7-78 (outside the Russian Federation – other DIN, ASF standards, Indian Standard [4–6], moulding and core sands occupy one of the first places in foundry. Grate industrial experience in carrying out of strength tests should contribute to the improvement of the existing methodology. However, the widespread using of this method makes it possible to state the presence of major deficiencies in testing, primarily in the large spread of values of the measured strength values of the samples. The dispersion in strength is caused, first of all, by the heterogeneity of the mixtures compositions after their preparation, the difference in the conditions of compaction and removal the sample from the core box, the difference in temperature and other hardening treatments, the rate of application of the load, and by other production reasons [7, 8].

In connection with the using in the production of new progressive technological processes of forming and manufacturing of cores, the requirements for the validity of the obtained strength indicators have increased.

The purpose of this work is to improve the methodology for determining the tensile strength of dry (cured) core mixture samples by changing the configuration of the standard figure-of-eight sample to obtain more reliable data.

Initial data for identification of disadvantages of existing technology

The 22 batches of mixtures of the following composition (wt. %) were made: water glass (modulus 2.2, density 1480 kg/m^3) – 6.0 %, refractory filler – quartz sand $2K_1O_302$, "figure-of-eight" samples were made from these mixtures, drying temperature – 200 °C, drying time – 20 minutes.

For appraisal the quality of the mixture, according to Standard, it is necessary to test three samples in parallel. Their arithmetic mean is taken as the result. If the tensile strength of one sample differs from the arithmetic mean by more than 10 %, the test is repeated [4]. In practice, the differences sometimes reach 100 % or more, that is described in the article [9]. Therefore, it is clear that it is necessary to look for the cause of this appearance.

Fig. 1. Standard samples after testing

Fig. 1 shows figure-of-eight samples after a tensile test. It can be seen that destruction occurs both along the neck and in the places where the sample is captured.

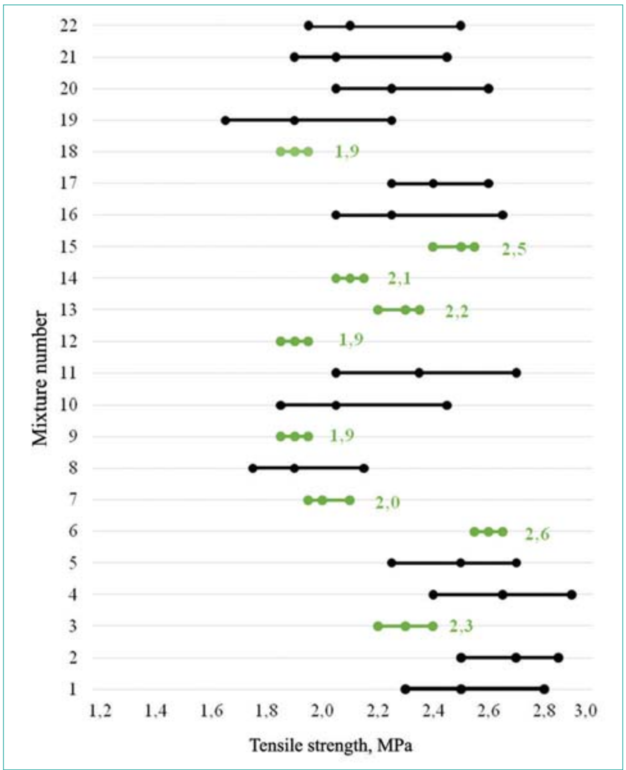


Fig. 2. Statistical data on the dispersion in the strength indicators of the mixture in the cured state

Fig. 2 shows the results of strength tests of these mixtures. As can be seen, out of 22 batches, only batches 3, 6, 7, 9, 12, 13, 14, 15, 18 correspond to the Standard requirements for a ten percent discrepancy, and the average strength of this samples, respectively, is 2.3, 2.6, 2.0, 1.9, 1.9, 2.5, 2.1, 2.2, 1.9 MPa. In addition, the performance indicators of 13 batches out of 22 cannot be used, due to the non-fulfillment of GOST according to the difference in the strength of the samples by more than 10 %.

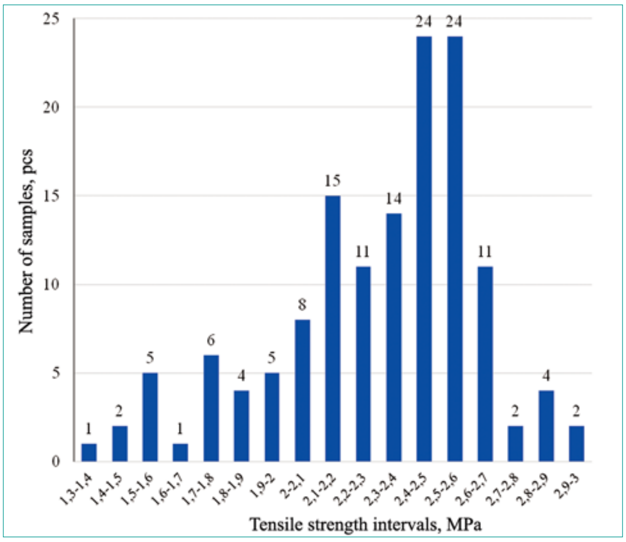


Fig. 3. Distribution of the number of samples by tensile strength intervals

According to the above method, 139 samples were made and tested. The strength indicators of these samples were divided into groups with a discreteness of 0.1 MPa. On the diagram in **Fig. 3** the number of samples per group was shown. It can be seen from the diagram that the tensile strength of the samples varies in a wide range from 1.3 to 2.9 MPa, in the intervals of 2.4—2.5 MPa and 2.5—2.6 MPa there are the largest number of samples – 24 each. With such a large scatter of indicators, it is impossible to reliably determine the tensile strength.

At the same time, a significant number of samples (about 40 %) during testing are destroyed not in the neck, but in the places of holdsite when a load is applied to them. Apparently, in places of holdsite, stresses are formed higher than in the neck of the sample.

Modeling the stress state of a sample

To study the changes of the strain-stress state in a standard sample (**Fig. 4**) in the process of strength testing, finite-element modeling was carried out in the SIMULIA/Abaqus licensed software package using the Abaqus/Explicit module, which uses an explicit integration scheme for highly nonlinear transient fast-flowing dynamic processes. The calculation was carried out using the Mises model. To generate a finite-element mesh, 8-node linear hexagonal elements with reduced integration (C3D8R) were used. In the zones of the neck and contact of the grippers with the sample, the grid cell size did not exceed 0.5 mm.

Two assumptions were used in the simulation:

1). Due to significant differences in the strength characteristics of the steel of the grips and the core mixture, the grips were modeled as non-deformable bodies (discrete rigid);

2) Taking into account the low plasticity of the core mixture, modeling was carried out only in the elastic domain until the value of the applied load at which the most durable samples (1875 N) were destroyed was reached.

Such an approach is admissible if not specific values of reaching the damage threshold are required, but the nature

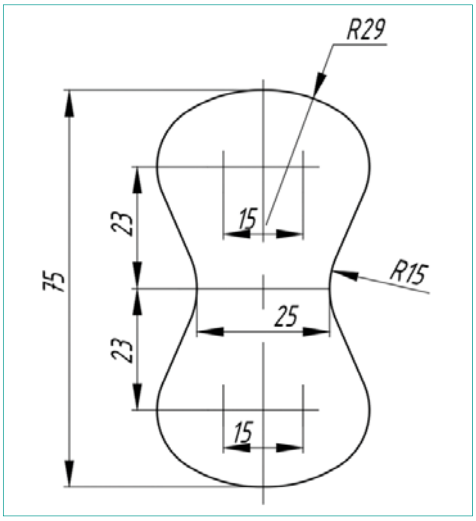


Fig. 4. Standard sample dimensions in accordance with GOST 23409.7-78

of the stress distribution over the sample volume is revealed. Tension was carried out by lowering the lower grip at a speed of 0.01 mm/s until a force of 1875 N was reached.

The resulting visualization of the Mises equivalent stress distribution on the outer surface of the sample and inside its volume is shown in **Fig. 5**. The maximum equivalent stresses (about 6 MPa) are localized in relatively small areas near the contacts with the wedge grip surfaces and on the lateral surfaces of the sample neck. A significant part of the neck volume is practically unloaded, and damage along it can occur only as a result of the development of a crack that originated on the lateral surface. An analysis of the horizontal and vertical components of the formed stresses (Fig. 5, *b* and *c*) shows that in the zone of contact with the surface of the grips, the horizontal components of the compressive stresses range from 8 to 9 MPa, and the vertical components are up to 14 MPa. On the lateral surface of the neck, the horizontal component of tensile stresses is not more than 1 MPa, and the vertical component is up to 7 MPa.

It is possible to change the nonuniform distribution of stresses over the sample section by changing the design of the sample as follows:

– increase the sizes of the sample in the places of its holdsite, but this will require a change in the core box and gripping devices;

– reduce the cross section of the sample and load it in the center, in which case the dispersion of strength indicators in accordance with the “scale factor” should increase with a general decrease of the sample cross section;

– reduce the section of the sample neck on one side and load it eccentrically.

The cross section of the standard sample (Fig. 4) for determining the tensile strength of the mixture in the cured state is a square with a side of 25 mm with the load applied centrally. In order to redistribute the stresses arising during testing, it was decided to make a one-sided recess in the sample neck (**Fig. 6**), the recess was made with a depth of 4 mm and a radius of 4 mm.

A variant of the sample shown in Fig. 6, with a section size of 25 × 21 mm and a load applied with an offset from the center of gravity of the sample section by 2 mm towards the recess (**Fig. 7**) was accepted.

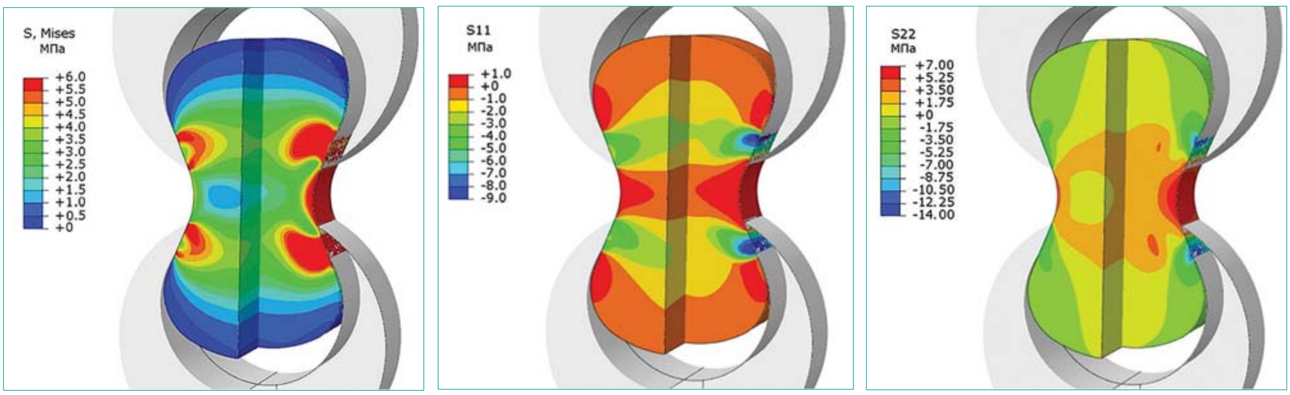
An analytical calculation of the stresses arising in the neck of a sample with a one-sided recess has been carried out. With such a calculation scheme (Fig. 7), the sample works for off-center tension – in its cross section, not only an internal axial (tensile) force arises, but also an internal bending moment relative to the central axis, which does not intersect with the tensile force F (*y* axis).

For a standard sample with cross-sectional dimensions of 25 × 25 mm (sectional area 625 mm²), the calculation the stresses according to the formula (1) described in the [10]:

$$s_{22} = \frac{F}{A_0}, \qquad (1)$$

where s_{22} – normal tensile stresses (along thevertical axis); F – the magnitude of the tensile force; A_0 – the cross-sectional area of the standard sample (without recess).

In this case, when a load of 1875 N is applied to the sample, the stress value at any point of its cross section will be 3 MPa.



a *b* *c*

Fig. 5. Visualization of the formed stresses in the sample from the core mixture along the end surface and section views along the planes of symmetry: *a* – equivalent by Mises; *b* – horizontal component; *c* – vertical component

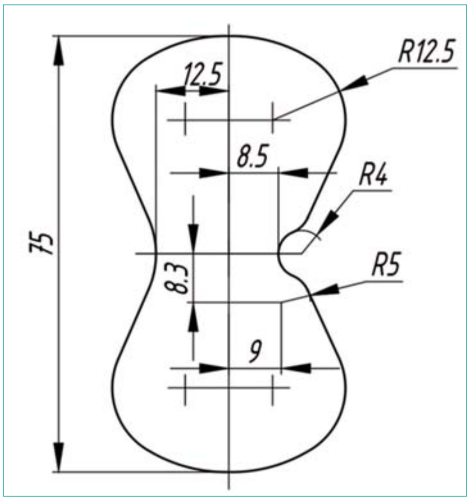


Fig. 6. Dimensions of sample with eccentric loading

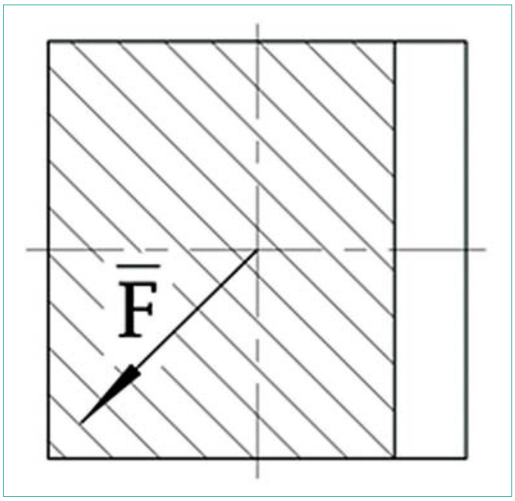


Fig. 7. Cross section of the test sample under eccentric loading

For a sample with a recess, the stress value s_{22} at an arbitrary point of the section was determined by the formula (2) corresponding to the eccentric tension by the force *F*:

$$s_{22} = \frac{F}{A}\left[1 + \frac{x_p}{\left(J_y / A\right)} x\right], \qquad (2)$$

where F – the cross-sectional area of a non-standard sample (with a recess); J_y – the moment of inertia about the central axis y of the sample with a recess; x_p – the coordinate of the load application point about to the main central axis x; x – the coordinate of the point at which the value of normal stresses is determined; A – the cross-sectional area of the sample with a recess.

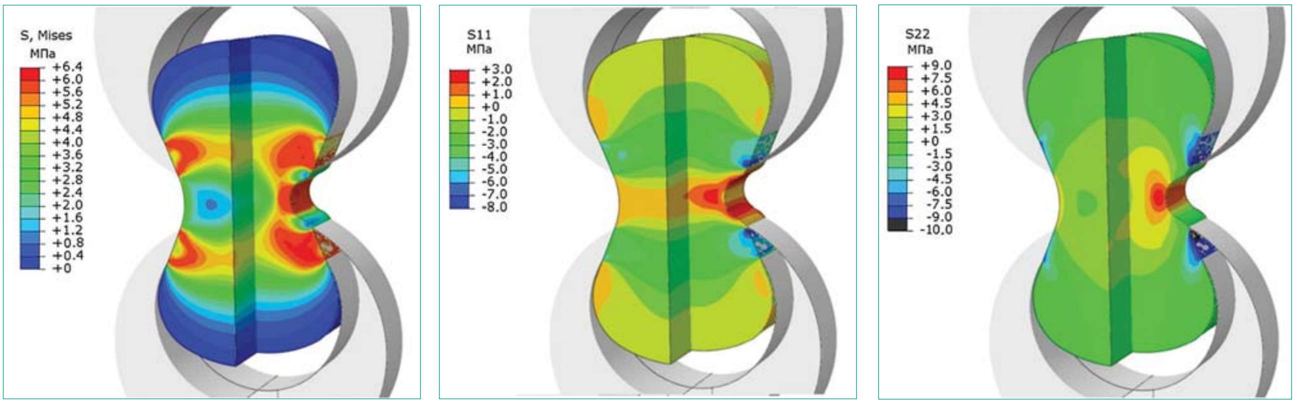
The axial moment of inertia J_y of a rectangular section (Fig. 7) was determined by the formula (3):

$$J_y = \frac{hb^3}{12}, \qquad (3)$$

where b – the width of the section of the sample with a recess ($b = 21$ mm, Fig. 6, 7); h – the height of the section ($h = 25$ mm, Fig. 7).

According to the analytical calculation, when a non-standard sample is stretched with a load of 1875 N, tensile normal stresses s_{22} with a maximum value of 5.61 MPa appear on the side of the recess, and tensile stresses also act on the opposite side of the section, reaching a value of 1.53 MPa. The stress difference at opposite sides of the section arises due to the action of an internal bending moment with an eccentric application of the load. At the same time, the results of the analytical calculation are in good agreement with the data obtained in the numerical simulation of tensile tests of a sample with a recess (**Fig. 8**).

The simulation of tensile tests of a modified sample using a technique similar to modeling the behavior of a standard sample showed a significant redistribution of stress fields at the same tensile force (Fig. 8): the thickness of the zone with high Mises equivalent stresses increased (up to 6.4 MPa) in the neck along the boundaries of the recess. The maximum values of the horizontal component of tensile stresses in the neck are 2.8 MPa, and the vertical component – 9 MPa. Such a redistribution of stresses makes it possible to reliably transfer the center of destruction of the sample from the core mixture to the neck.



a *b* *c*

Fig. 8. Visualization of the formed stresses in the modified sample from the core mixture along the end surface and section views along the planes of symmetry: *a* – equivalent by Mises; *b* – horizontal component; *c* – vertical component

Table 1. Composition of the samples mixture and properties of samples with different radius of the recess

№	Composition of the mixture, wt. %	Number of samples failing at holdsite points	Standard		2 mm recess		4 mm recess		8 mm recess		10 mm recess	
			Average tensile strength, MPa	Mean square deviation	Average tensile strength, MPa	Mean square deviation	Average tensile strength, MPa	Mean square deviation	Average tensile strength, MPa	Mean square deviation	Average tensile strength, MPa	Mean square deviation
1.1	Water glass – 6.0 Sand $2K_1O_302$ – 94.0	3	2.11	0.2416	1.95	0.2090	1.58	0.1372	1.38	0.092	0.76	0.2342
1.2		4	2.05		1.59		1.52		1.25		0.4	
1.3		2	2.57		2.05		1.84		1.41		0.91	
1.4		5	2.1		2.0		1.75		1.40		0.88	
2.1	Water glass – 6.0 Refractory clay $C1T_2$ – 2.0 Sand $2K_1O_302$ – 92.0	2	1.61	0.2844	1.21	0.2562	1.08	0.1941	0.87	0.133	0.78	0.2485
2.2		1	1.54		1.33		1.12		0.85		0.65	
2.3		4	1.08		0.85		0.77		0.67		0.31	
2.4		3	1.09		0.82		0.76		0.60		0.28	
3.1	Urea-formaldehyde resin –1–3.0 Lignosulphonate – 4.5 Refractory clay $C1T_2$ – 3.5 Sand $2K_1O_302$ – 89.0	6	1.6	0.265	1.48	0.2505	1.21	0.1875	0.96	0.112	0.74	0.2159
3.2		4	1.1		0.96		0.81		0.68		0.28	
3.3		6	1.2		1.1		0.83		0.72		0.61	
3.4		2	0.98		0.88		0.76		0.64		0.3	
3.5		3	0.93		0.86		0.78		0.62		0.29	
4.1	Carbamide-formaldehyde resin – 2.2 Lignosulphonate – 0.3 Sand $2K_1O_302$ – 97.5	2	1.16	0.1934	0.91	0.1479	0.75	0.1179	0.56	0.118	0.42	0.1514
4.2		4	0.84		0.64		0.52		0.41		0.14	
4.3		3	1.19		0.83		0.68		0.44		0.18	

Samples with a one-sided recess were destroyed strictly in the neck.

Research results and their discussion

In order to objectively compare the accuracy of strength tests of a standard "figure-of-eight" sample and the proposed sample with a one-sided recess along one of the concave surfaces, standard samples and samples with a recess of 2, 4 and 11 mm were made from mixtures with binders of various classes and their compositions. The samples were compacted with three impacts of a load of a laboratory impact tester mod. 5033A. The number of trials in all experiments was 30 pcs. The number of samples destroyed in the places of holdsite was determined. The magnitude of the dispersion of strength indicators was estimated from the value of the standard deviation of the average values of several parallel tests. The tests were carried out on a tensile testing machine RM-500.

The experimental data are presented in **Table 1**. It can be seen from the table that for 30 tested standard samples, there are from 1 to 6 samples which torn at the holdsite points, which is 3.3–20 %. This is due to the nonuniform distribution of stresses in the places of holdsite and in the neck of the sample. With an increase in the size of the recess to 8 mm, the standard deviation decreases, this confirms by the reduction in the dispersion of experimental data. With an increase in the size of recess to 10 mm, the value of the standard deviation sharply increases, i.e. the dispersion of indicators has increased. This is because the neck cross-section with such a recess is significantly reduced, during its manufacture is more difficult to remove the sample from the core box, while a larger number of critical structural defects are formed in the neck of the sample, which lead to an increase in the dispersion of strength indicators.

The influence of the radius of the recess on the dispersion of strength indicators was studied. The studies were carried out at various recess sizes from 2 to 10 mm. Experimental data are shown in **Table 2**. Composition 2 from Table 1 was chosen for the study. For each value of the recess radius, 30 samples were made and tested.

From the presented data, it can be seen that with a decrease in the radius of the recess from 6 to 4 mm, the standard deviation increases from 0.1166 to 0.1734, which indicates an increase in the dispersion of indicators.

When the radius decreases from 4 to 3 mm, the standard deviation increases sharply from 0.1734 to 0.2564. With a further decrease in the radius to 1 mm, the standard deviation continues to grow to 0.2847. 4 mm can be taken as the optimal radius, because with its decrease, the dispersion of strength indicators sharply increases; increasing the radius without changing the design of the core box is not structurally possible.

In order to identify the reasons affecting the spread of strength indicators (reduction of the cross-sectional area under central and eccentric loading), the following studies were carried out. "Figure-of-eight" samples with two- and one-sided recesses were made; the dispersion of strength indicators for the same cross-sectional areas of the sample neck was estimated. **Table 3** shows the ratio of one- and two-sided recesses in the sample neck with the same cross-sectional area. The composition of the studied mixture, the time and temperature of drying are taken from Table 1. In all series of experiments, 30 samples were made and tested.

Table 2. The influence of the radius of the recess on the dispersion of strength indicators

№	6 mm recess radius		5 mm recess radius		4 mm recess radius		3 mm recess radius		2 mm recess radius		1 mm recess radius	
	Average tensile strength, MPa	Mean square deviation	Average tensile strength, MPa	Mean square deviation	Average tensile strength, MPa	Mean square deviation	Average tensile strength, MPa	Mean square deviation	Average tensile strength, MPa	Mean square deviation	Average tensile strength, MPa	Mean square deviation
1	1.00	0.1166	1.08	0.17315	1.10	0.1734	1.26	0.2564	1.12	0.2779	1.18	0.02847
2	1.04		1.12		1.16		1.20		1.20		1.08	
3	0.80		0.77		0.78		0.72		0.58		0.62	
4	0.78		0.76		0.82		0.78		0.64		0.56	
5	0.88		0.84		0.86		0.80		0.84		0.68	

Table 3. The ratio of one- and two-sided recesses in the sample neck with the same cross-sectional area

Sectional area of the sample neck, 10^{-4} mm^2	6.25	5.75	5.25	4.25	3.75
One-sided recess, mm	0	2.0	4.0	78.0	11.0
Double-sided recess, mm	0	1.0	2.0	4.0	–

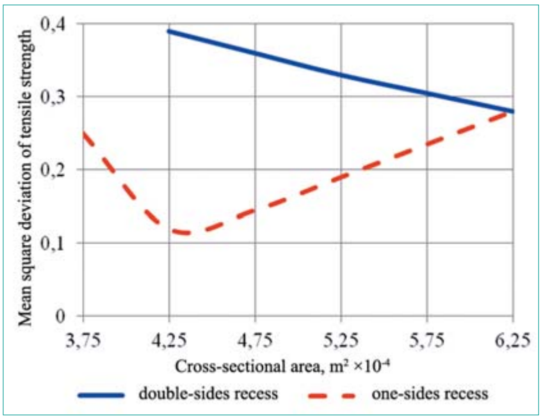


Fig. 9. Dependence of the standard deviation of the tensile strength of dry samples of the core mixture

Fig. 9 shows the dependences of the mean square deviation on the cross-sectional area of the sample neck for one- and two-sided recess.

From the presented data, it can be seen that with a one-sided recess of the cross-sectional area is 4.25×10^{-4} m^2, which corresponds to a recess of 8 mm, the dispersion of strength indicators decreases due to a more rational redistribution of stresses over the sample section. With a further increase in the recess to 11 mm, the cross section area of the sample is reduced to 3.75×10^{-4} m^2, while the dispersion of strength indicators has sharply increased due to the appearance of critical structural defects. With a two-sided recess, with a decrease in the cross-sectional area from 6.25 to $4.25–3.75 \times 10^{-4}$ m^2, the dispersion of strength indicators increases, which does not contradict the scale factor [11, 12].

Conclusions

Based on the results of the research, the following conclusions can be drawn:

– stresses at the holdsite points under central loading of the sample for determine the tensile strength of dry moulding or core sands are 2–2.5 times greater than at the sample neck, therefore 8–12 % of the samples are destroyed at the holdsite points;

– it is possible to redistribute stresses by applying eccentric loading of the sample by making a one-sided recess in the neck of the sample with a depth of 2–3 mm and a radius of at least 4 mm, while the dispersion of strength indicators of samples with a recess is 2–3 times less than standard, and therefore the reliability of the indicators is much higher.

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