Power and energy characteristics of concrete

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Abstract. A new installation for testing concrete samples has been developed. The methodology for testing concrete samples with a crack has been clarified. Tested. Strength and energy characteristics of crack resistance of concrete samples are obtained. The results are presented in the form of graphs and tables. The results of experimental studies are compared with the theoretical characteristics of concrete obtained by modeling the behavior of concrete samples by the finite element method. The research results showed the possibility of using the proposed installation and test methodology in further studies.

1 Introduction

A significant drawback of the calculation methods laid down in the current standards is the large number of different empirical coefficients and dependencies that do not affect the physicochemical nature of the processes that determine the property constants of multi component, multi modular conglomerate - concrete and reinforced concrete composite. The lack of uniformity in the calculations of the strength and deformability of structures, especially at the stage of their work with cracks, the use of empirical formulas devoid of physical meaning, the lack of scientifically based prediction of the state of structures when changing the properties of the starting materials, the impossibility of predicting the life of the structure in the presence of macro damage and defects become an obstacle to the creation of the theory of reinforced concrete resistance [1-14].

One of the important tasks that arise during the inspection and design of concrete and reinforced concrete structures is related to the effect of cracks on the structure. In this case, most often it is necessary either to determine the dimensions of the expected cracks, or to evaluate the bearing capacity of a structure with cracks. The presence of cracks (power and technological) is predetermined by both the nature of the formation of the concrete structure and the nature of the work of the composite material under load. To determine the maximum load-bearing capacity of the structure with the actual system of cracks formed in it, fracture mechanics are used by the calculation apparatus [15-21].

When considering concrete as a structural material in the general framework of common

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concepts of mechanics of a solid deformed body and fracture mechanics, the critical values of the parameters of the stress-strain state in the cross sections of structural elements, determined by the results of testing control samples, are used as new characteristics of its fracture toughness properties. The introduction of these characteristics into the calculation of concrete and reinforced concrete elements makes it possible to determine the parameters of the bearing capacity under the real stress-strain state in the structure at given load levels.

In experimental fracture mechanics, critical stress intensity factor K_{IC} (МПа·М$^{1/2}$) and the released elastic energy G_i are one of the main forces and energy characteristics of the structural material. These parameters characterize the resistance of concrete to external force effects, get usually under non-equilibrium tests [15-19].

Today, experimental data on the resistance of concrete to crack propagation are still relatively small, and therefore obtaining new experimental data with the determination of the strength and energy characteristics of concrete made from local materials is an urgent task.

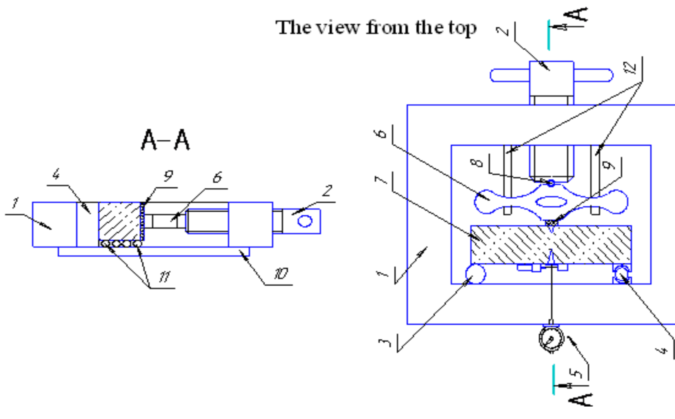
2 Materials and Methods

The methodology for testing concrete elements was developed with the aim of obtaining power and energy data characterizing the crack resistance of concrete. Obtaining the descending branch of the deformation diagram of a concrete specimen with a crack is possible only when it is tested with strain control. Such a test can be carried out either by a standard method, loading in parallel with the test specimen additional elastic elements to which the force from the specimen is gradually redistributed as it loses its rigidity during loading, or by rigid loading with a controlled deformation rate. In the studies used the second scheme, which greatly simplifies the testing process [9].

For this, a special installation was created that allows you to control the process of the test. This was achieved by the fact that the installation was located in a horizontal plane, and the sample was placed on a field of steel balls. The test sample, perceiving the load in the horizontal direction, deformed unhindered and did not experience the influence of its own weight. The schematic diagram of the installation is shown in Fig. one.

To determine the values of Kc, Gce, in accordance with the instructions of GOST 29167-91, during the test 5 ... 7 short-term unloading of the sample was carried out to determine the directions of the discharge lines in the falling section of the diagram branch.

The principal difference of the proposed test procedure consists in the fact that the tests were carried out according to a “rigid” scheme by defining the deflection of the test sample. The loading step was 0.05 mm with a shutter speed at each step. The criterion for a further increase in deformations was the constancy of the readings of indicators measuring the deflection and magnitude of the load for 15 seconds. The choice of such a loading scheme was caused by the need to obtain a behavior diagram of concrete with a falling branch. All strains were measured by indicators with a division value of 0.001 mm.



1-power frame;
2-screw;
3 - jointed movable support;
4 - hinged-fixed support;
5- the displacement sensor;
6 - dynamometer;
7 - sample;
8 - hinge;
9 - distribution plate;
10 - tray;
11 - balls;
12 - support for the dynamometer.

Fig. 1. Diagram of the experimental setup:

Another distinctive feature of the tests was the simultaneous and permanent recording of all indicators using a digital video camera, which allowed us to accurately construct load-deflection, load-crack diagrams when processing the received data.

3 Results

For research, eleven series of samples were made: concrete prisms 100 × 100–400 mm in size (six samples in each series) and 150 × 150 × 600 mm (three samples in each series). The starting materials for the preparation of the samples were: Portland cement, grade M400, quartz sand, fraction 0-5 mm (Mk = 2.9), porphyrite crushed stone, fraction 5-10, Magnitogorsk granite quarry. The compositions of concrete are given in table 1.

Table 1. The formulations of concrete

Series	Brand of cement	Material consumption kg/m^3 of concrete				The density of concrete, N/m^3	The conditions of hardening
		Cement	Sand	Crushed stone	Water		
1	400	400	540	101	176	26210	ET
2	400	518	540	101	176	25720	ET
3	400	400	450	101	176	26531	ET
4	400	518	450	101	176	26608	ET
5	400	451	540	101	176	26509	ET
6	400	451	450	101	176	26210	ET
7	400	400	495	101	176	26875	ET
8	400	518	495	101	176	26608	ET
9	400	451	495	101	176	26458	ET
10	400	451	495	101	176	26571	ET
11	400	451	495	101	176	26210	ET

A total of 77 prismatic samples and 33 control cubes of the base size (150x150x150 mm) were made. All samples of the series were made simultaneously. During the manufacturing process, samples of 100x100x400 mm in size were provided for the creation of initiating cracks by laying metal plates 1 mm thick, 30 mm high (2 pcs. From each series), and 40 mm (2 pcs. From each series).

The production of samples with different crack lengths in one series was due to the fact that in addition to the force approach for determining Kc, the energy approach was also used. The main characteristics of concrete, determined by the results of testing cubes and prisms for compression are given in table. 2.

Table 2. The main characteristics of the tested samples

Series	The volumetric weight of the mixture, N/m^3	The initial modulus of elasticity, MPa	Cube strength, MPa	Prism strength, MPa
1	26210	16681	31,15	24
2	25721	22909	30,50	25,5
3	26531	36660	29,95	21,3
4	26608	33020	33,50	25
5	26210	28738	30,05	30
6	26875	24809	26,81	19,6
7	26608	19523	21,63	25,5
8	26458	17057	26,88	20

9	2671	23382	19,89	17,5
10	26210	17912	20,70	16

Typical behavior diagrams of a bent concrete specimen with a crack obtained as a result of equilibrium tests in an experimental setup are shown in Figure 2.

The obtained equilibrium test results of the samples were processed according to the method described in GOST 29167-91 [9]. The characteristics obtained as a result of testing are given in table. 3. The table shows the notation adopted in GOST 29167-91 [9].

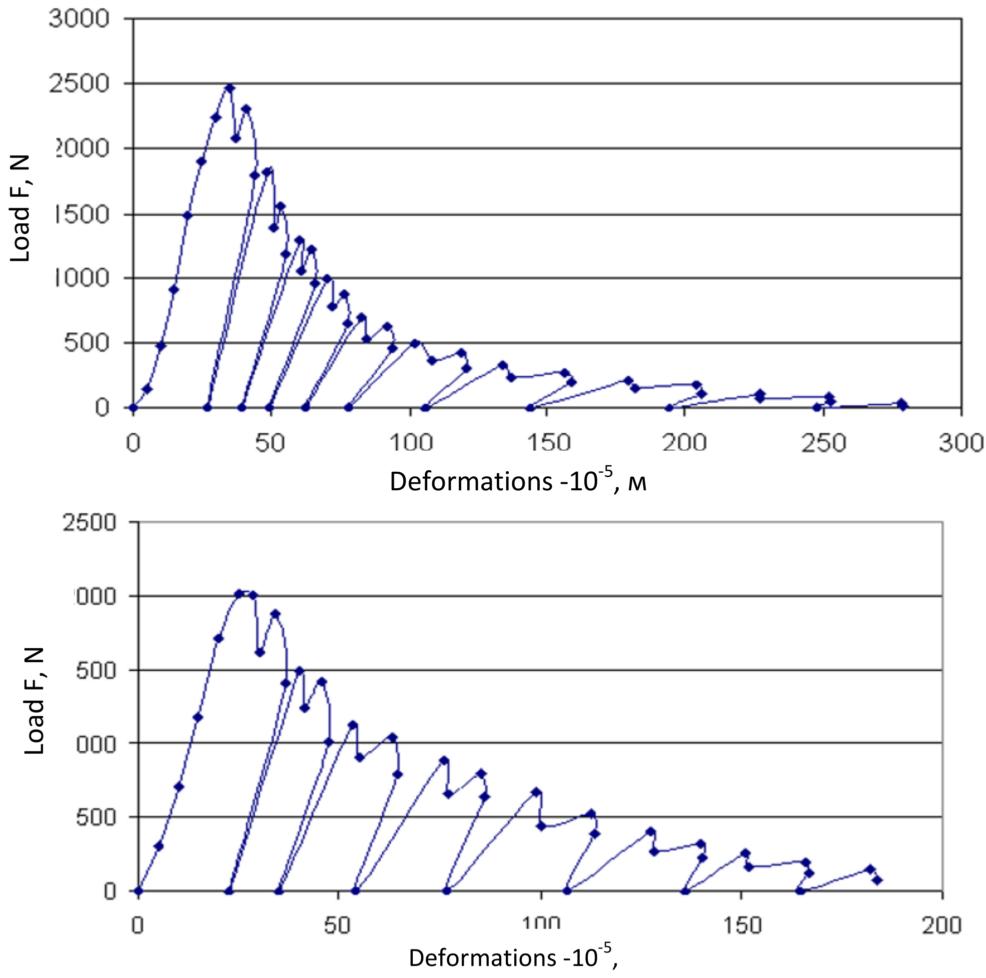


Fig. 2. Fully equilibrium behavior charts for concrete samples of one series with the initiating crack 30mm(top) and 40 mm (bottom graph)), respectively.

To analyze the obtained experimental data, a theoretical determination of the critical coefficient of stress intensity was carried out using the finite element method. In the calculation scheme (Fig. 3, 4), two types of finite elements were used - a triangular and a quadrangular shell element. Near the crack tip, quadrangular finite elements with a side size of 0.2 mm were used. The dimensions of the largest finite elements were 10 mm. The load was applied evenly distributed over a site having the dimensions of a metal plate used in field tests.

.**Table 3.** The summarized results of tests of samples in bending

Sample	Wm	We	Wl	Wui	Wce	Gi	Gf	Gce	Ji	Ki	K_{Ic}
1 -30-1	0,10	0,32	0,89	0,22	0,07	69,58	201,44	11,14	32,82	1,48	0,59
1 -30-2	0,04	0,12	0,76	0,09	0,06	16,68	91,67	6,10	6,87	0,73	0,44
1 -40-1	0,08	0,35	0,81	0,21	0,03	70,98	193,58	5,59	36,73	1,50	0,42
1 -40-2	0,21	0,17	0,47	0,09	0,03	62,07	105,62	5,01	46,28	1,40	0,40
2 -30-1	0,12	1,14	0,05	0,66	0,05	180,50	171,12	7,47	86,30	2,83	0,58
2 -30-2	0,08	0,29	0,87	0,17	0,05	53,79	166,04	7,42	29,56	1,54	0,57
2 -40-1	0,09	0,37	0,80	0,32	0,04	76,32	195,44	6,52	22,57	1,84	0,54
2 -40-2	0,44	0,62	0,21	0,38	0,04	176,57	138,81	6,91	113,25	2,80	0,55
3 -30-1	0,12	0,43	0,74	0,28	0,03	77,75	166,72	3,96	37,33	1,86	0,42
3 -30-2	0,23	0,53	0,45	0,61	0,03	108,13	139,12	4,66	21,29	2,11	0,44
4 -30-1	0,16	0,20	0,80	0,20	0,04	50,50	142,02	5,67	21,50	1,29	0,43
4 -30-2	0,50	0,54	0,84	0,40	0,05	149,24	197,30	7,69	92,04	2,22	0,50
4 -40-1	0,06	0,21	0,65	0,13	0,03	44,49	142,98	4,93	23,26	1,21	0,40
4 -40-2	0,08	0,18	0,62	0,16	0,04	43,19	134,51	6,20	16,98	1,19	0,45
6 -30-1	0,06	0,14	0,86	0,10	0,06	28,95	142,54	8,72	13,96	1,11	0,61
6 -30-2	0,08	0,17	0,85	0,12	0,07	35,90	145,57	10,05	18,72	1,24	0,66
6 -40-1	0,06	0,22	0,22	0,12	0,04	46,32	74,00	6,62	25,53	1,41	0,53
6 -40-2	0,10	0,24	0,64	0,18	0,09	55,11	145,50	14,20	25,29	1,54	0,78
7 -30-1	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
7 -30-2	0,16	0,22	0,64	0,26	0,06	54,19	121,86	8,97	16,57	1,24	0,50
7 -40-1	0,10	0,16	0,37	0,13	0,04	43,97	87,86	6,40	22,83	1,11	0,42
7 -40-2	0,07	0,15	0,28	0,16	0,04	36,34	71,20	6,14	10,27	1,01	0,42
8 -30-1	0,09	0,55	0,62	0,35	0,04	92,15	167,69	5,89	41,77	1,98	0,50
8 -30-2	0,04	0,09	0,25	0,06	0,05	18,59	48,54	6,57	10,55	0,89	0,53
8 -40-1	0,03	0,08	0,30	0,05	0,02	17,19	63,19	4,13	9,47	0,86	0,42
8 -40-2	0,05	0,10	0,38	0,07	0,04	25,89	80,22	7,50	14,46	1,05	0,57
9 -30-1	0,07	0,18	0,65	0,13	0,10	35,12	118,82	14,09	16,32	0,77	0,49
9 -30-2	0,05	0,11	0,37	0,07	0,02	22,96	69,54	2,18	13,41	0,63	0,19
9 -40-1	0,08	0,15	0,73	0,10	0,05	36,75	145,64	9,02	20,83	0,79	0,39
9 -40-2	0,09	0,12	0,85	0,10	0,02	35,64	161,25	3,33	18,74	0,78	0,24
10 -30-1	0,08	0,12	0,87	0,11	0,02	28,94	141,97	3,12	13,38	1,03	0,34
10 -30-2	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
10 -40-1	0,16	0,14	0,54	0,11	0,02	49,23	112,99	3,74	30,87	1,34	0,37
11 -30-1	0,10	0,32	0,95	0,22	0,05	59,66	181,18	7,24	28,87	1,03	0,36
11 -30-2	0,07	0,12	0,33	0,07	0,02	26,48	63,50	2,67	16,23	0,69	0,22
11 -40-1	0,13	0,18	0,85	0,12	0,03	50,78	171,06	4,33	30,19	0,95	0,28
11 -40-2	0,08	0,18	1,12	0,13	0,02	42,10	215,88	3,38	20,17	0,87	0,25

Obtaining a design scheme that adequately describes the experimental data was necessary for further use in assessing the correctness criterion for determining Kc in field structures.

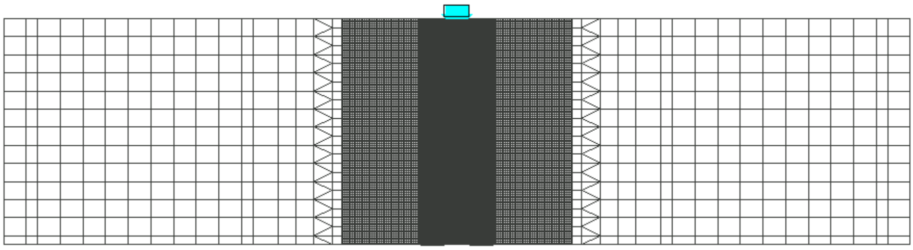


Fig. 3. General view of the finite element mesh of the simulated sample

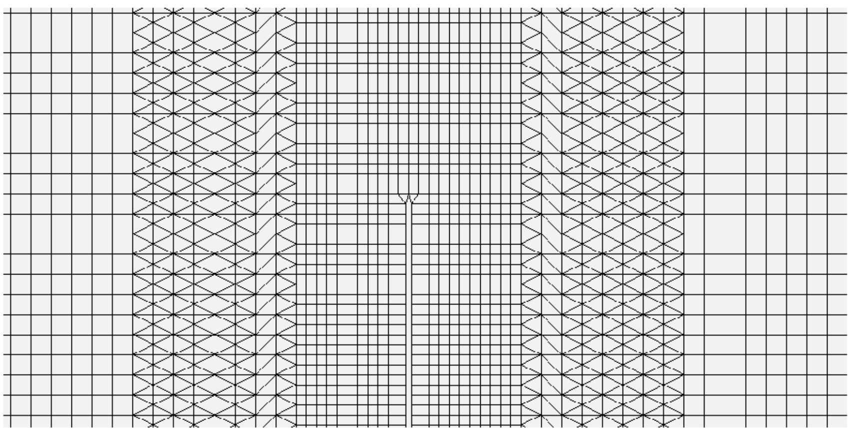


Fig. 4. The arrangement of finite elements at the crack tip

Definition K_{IC} produced using the ***J*** - integral, which was calculated from the diagram "load-displacement" Fig.4 [5]. Area between two curves connecting the load with displacement for cracks having the sizes *a* and *a+da* is equal to *(dV/da)da*, or that the area is equal to ***J***. In our case, a crack size of 30 mm and the other 40 mm.

Also, the K_{IC} is determined from the scheme of three-point bending by a polynomial [5], taking into account the finite dimensions of the sample:

$$K = \frac{P \cdot S}{B \cdot W^{3/2}} \cdot \left[2{,}9 \cdot \left(\frac{a}{W}\right)^{1/2} - 4{,}6 \cdot \left(\frac{a}{W}\right)^{3/2} + 21{,}8 \cdot \left(\frac{a}{W}\right)^{5/2} - 37{,}6 \cdot \left(\frac{a}{W}\right)^{7/2} + 38{,}7 \cdot \left(\frac{a}{W}\right)^{9/2} \right],$$

where *P* is the concentrated load; *S* - the distance between supports; *W* is the height of the cross section; *B* - width of the cross section; *a* - the length of the crack.

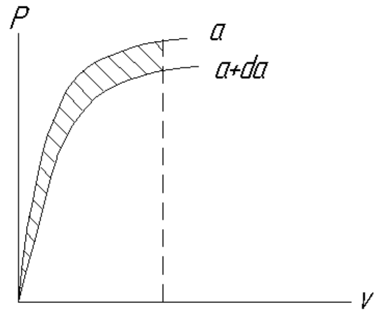


Fig. 5. Explanation of the experimental determination of ***J*** – integral.

The results obtained using the finite element method(FEM), J - integral and the polynomial is given in Table 4.

Table 4. The results of the determination of K_{IC}

Sample	The K_{IC} on the finite element method	The percentage differences	K_{IC} using the J integral	The percentage differences	K_{IC} using polynomial	The percentage differences
1 - 30-1	0,5	2,61%		-12,08%	0,54	9,32%
1 - 30-2	0,42	-4,39%	0,43	-0,91%	0,46	4,48%
1 - 40-1	0,47	7,46%		-0,11%	0,51	15,05%
1 - 40-2	0,34	-8,50%		15,09%	0,37	-0,24%
2 - 30-1	0,47	-7,83%	0,48	-15,65%	0,51	0,43%
2 - 30-2	0,477	1,25%		-8,42%	0,51	7,64%
2 - 40-1	0,52	-3,42%	0,42	---	0,57	6,14%
2 - 40-2	0,441	-9,62%		-11,27%	0,48	-1,78%
3 - 30-1	0,41	-2,19%	0,41	--	0,45	6,27%
3 - 30-2	0,39	-12,17%		--	0,43	-2,94%
4 - 30-1	0,4	-8,15%		-7,55%	0,43	-0,84%
4 - 30-2	0,49	-2,82%	0,40	---	0,53	5,48%
4 - 40-1	0,37	-9,01%		-0,28%	0,40	0,09%
4 - 40-2	0,44	-2,79%		-12,45%	0,48	5,97%
6 - 30-1	0,36	-12,92%		--	0,38	-5,86%
6 - 30-2	0,272	-9,98%	0,55	---	0,29	-2,80%
6 - 40-1	0,29	-6,89%		-3,32%	0,31	0,96%
6 - 40-2	0,527	-7,35%		-3,31%	0,57	0,22%
7 - 30-2	0,47	-6,96%	0,48	-3,70%	0,50	0,26%
7 - 40-1	0,38	-11,75%		12,40%	0,41	-3,57%
7 - 40-2	0,374	-11,28%		14,15%	0,40	-3,01%
8 - 30-1	0,531	5,63%	0,52	2,98%	0,57	11,62%
8 - 40-1	0,202	-13,55%	--	--	0,22	-5,22%
8 - 40-2	0,292	-9,45%		---	0,31	-1,78%
9 - 30-1	0,38	-15,30%		--	0,41	-9,12%
9 - 40-1	0,338	-15,04%	0,31	--	0,36	-7,75%
9 - 40-2	0,299	9,81%		12,09%	0,32	15,25%
10 - 30-1	0,32	-5,37%	0,32	-6,35%	0,34	0,83%
10 - 30-2	--	--		--	--	--
10 - 40-1	0,28	-4,68%	0,30	7,56%	0,31	4,22%
11 - 30-1	0,422	0,00%	---	0,00%	0,45	0,00%
11 - 30-2	--	--		--	--	--
11 - 40-1	0,286	2,60%	---	5,75%	0,31	9,26%
11 - 40-2	0,443	0,00%		-0,34%	0,48	0,00%

4 Conclusions

In general, a comparison of the results shows that the new setup and test procedure developed allow us to obtain results that differ from the data obtained by FEM up to 15.3%, in compliance and up to 15.2%, in polynomial and can be used for further research

References

1. V.M. Bondarenko, A.M. Kurzanov, V.I. Rimshin, Bulletin of the Russian Academy of Sciences , **70**(11), 1005-1009 (2000)
2. N.I. Karpenko, V.A. Eryshev, V.I. Rimshin, *IOP Conference Series: Materials Science and Engineering*, **463**(**3**),032024 (2018)
3. A.A. Varlamov, *Concrete and reinforced concrete*, **3**, 27-30 (2012)
4. E. A. Guzeev, S. N. Leonovich, A. F. Milovanov, K. A. Piradov, L. A. Salanov, *Destruction of concrete and its durability* (1997)
5. Broek D. *Fundamentals of fracture mechanics* (1980)
6. A.A. Varlamov, Izvestiya KGASU,**29,**19-26 (2014)
7. A.A. Varlamov, V.I. Rimshin, S.Y. Tverskoi, IFAC-PapersOnLine, **51**(30), 808-811 (2018)
8. A.A.Varlamov, V.I.Rimshin, S.Y.Tverskoi, *IOP Conference Series: Materials Science and Engineering*, **463**(2), 022029 (2018)
9. GOST 29167-91. (1992)
10. G.J. Pochtovik, A.B. Zlochevsky, A.I. Yakovlev, *Methods and means of testing building constructions*. (1973)
11. A.B. Zlochevsky, *Experimental methods in structural mechanics* (1983)
12. A.A. Varlamov, V.B. Gavrilov, A.I. Sagadatov, *BST*, **11,** 29-31 (2017)
13. A.A. Varlamov, KGASU, **29,**19-26 (2014)
14. E.Kuzina, V.Rimshin, V. Kurbatov, *IOP Conference Series: Materials Science and Engineering*, **463**(**4**),042009 (2018)
15. A.A.Varlamov, V.I.Rimshin, S.Y.Tverskoi, *IOP Conference Series: Materials Science and Engineering*, **463**(**2**),022028 (2018)
16. A.A.Varlamov, V.I. Rimshin, S.Y. Tverskoi, Materials Science Forum, **931**, 340-345 (2018)
17. Y.M. Bazhenov, V.T. Erofeev, V.I. Rimshin, S.V. Markov, V.L. Kurbatov, Engineering Solid Mechanics, **4**(4), 219-225 (2016)
18. V.I. Rimshin, A.A. Varlamov, Textile technology series, **3**, 63-68 (2018)
19. Y.M. Bazhenov, V.T. Erofeev, V.I. Rimshin, S.V. Markov, V.L. Kurbatov, Engineering Solid Mechanics, **4**(4), 219-225 (2016)
20. E. Kuzina, A. Cherkas, V. Rimshin, *Structural mechanics of engineering structures and structures*, **365**(3),032053 (2018)
21. V.I. Rimshin, E.A. Larionov, Structural mechanics of engineering structures and structures, **2**, 77-81 (2012)