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 $K_c$, $G_{ce}$, 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.

![Diagram]

The view from the top

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  | 450           | 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 $K_c$, 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                  |
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].

| Load F, N | 2671 | 23382 | 19.89 | 17.5 |
|-----------|------|-------|-------|------|
| Load F, N | 26210| 17912 | 20.70 | 16   |

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.
Obtaining a design scheme that adequately describes the experimental data was
necessary for further use in assessing the correctness criterion for determining $K_c$ 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:

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

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  | $K_{IC}$ 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%                      | -0.91%                        | 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%                      | -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%                      | ---                           | 0.57                        | 6.14%                       |
| 2 - 40-2 | 0.441                                | -9.62%                      | -11.27%                       | 0.48                        | -1.78%                      |
| 3 - 30-1 | 0.41                                 | -2.19%                      | ---                           | 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%                      | ---                           | 0.53                        | 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%                      | ---                           | 0.29                        | -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%                      | -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%                       | 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%                     | 12.09%                        | 0.32                        | 15.25%                      |
| 9 - 40-2 | 0.299                                | 9.81%                       | -6.35%                        | 0.34                        | 0.83%                       |
| 10 - 30-1| 0.32                                 | -5.37%                      | ---                           | 0.32                        | ---                         |
| 10 - 30-2| --                                   | ---                         | --                            | --                          | --                          |
| 10 - 40-1| 0.28                                 | -4.68%                      | 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.

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