Strength of heavy concrete during static-dynamic deformation

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Abstract. Method and results of determination of strength and deformation characteristics of heavy concrete at static loading to the specified stress level, followed by high-speed loading with dynamic load, are presented. The process of testing a series of concrete samples of one strength class is described to obtain the performance characteristics of concrete at static, dynamic and static-dynamic loading. Comparative analysis of the obtained experimental data was carried out under different loading modes of prototypes. It was established that during dynamic and static-dynamic loading there is an increase in the level of relative stresses corresponding to the beginning of concrete dilatation by 20-30% relative to the results of static tests. The obtained experimental results are of interest for solving problems related to the problem of survivability of buildings and structures and their protection against progressive collapse, in particular in determining criteria of strength and deformability of concrete at a special limit state.

1. Introduction

A number of studies [1-6] are known on the determination of concrete deformation parameters under short-term, long-term and dynamic loads. Materials of similar studies describe criteria of limit states for concrete and reinforced concrete structures. Currently, in the territory of the Russian Federation and other countries there are regulatory documents containing requirements for the protection of buildings and structures from special emergency impacts [7,8]. There is a need to solve problems related to modeling and analysis of stress-strain state of concrete and reinforced concrete structures under emergency impacts. One likely scenario of a particular impact on a structural system is when high-speed dynamic loading is added to a structure already loaded with operational load, caused by hypothetical removal of one of the load-bearing structures.

At the same time, analysis of said and other scenarios of possible local destruction of structural systems [9-17] shows that dynamics of structural modification of the system and stress state of concrete and reinforcement depends on a number of factors (topology of the structural system, structural material, type of stress - deformed state, time and mode of action, etc.). At the same time, the evaluation of the modes of static-dynamic deformation of concrete, including on the basis of the new hypothesis put forward by the authors in the development of the theory of G.A. Geniev that the ultimate deformation of concrete depends not only on the type of stress state, but also on the initial level of the stress state from which dynamic loading is carried out [1], requires experimental verification. The expansion of the field of physical experiment, as a continuation of the previous experimental studies [18-24] on the assessment of the effect of dynamic effects on a two-component
material of the reinforced concrete type, in terms of experimental determination of experimental characteristics of strength and deformation of concrete at a mode high-speed single loading of concrete with dynamic load after application of static loading, seems to be an urgent task.

This article presents the author's methodology and results of experimental studies for determining parameters of static - dynamic deformation of concrete, in particular, the dynamic module of concrete deformations, dynamic strength and ultimate deformation of concrete under various modes of its loading.

2. Research methods

The purpose of the studies was to obtain new experimental data on determining the dynamic module of concrete deformations depending on the limit time of dynamic loading and the level of stress from which dynamic loading is carried out, as well as obtaining the dynamic strength of concrete and the maximum deformation of concrete under various loading modes. To implement the study, a series of samples of concrete prisms and cubes of various strength classes were made. Samples are made in accordance with the requirements of GOST 10180-2012 and GOST 24452-80.

For the production of samples, Portland cement of grade М500, washed sand of fraction 2-2.5 mm, and granite crushed stone of fraction 5-10 mm were used.

The strength of the samples took place in a normal hardening chamber at a temperature of 20 ± 2 °C, a relative humidity of 95 ± 5% for 28 days, after which the conditioning of the samples lasted at least 30 days.

For experimental studies, a combination of standard equipment in the form of a MEGA 6-3000-100 hydraulic press, a universal dynamic test machine LabTest 6.500H.5.01.1 and a specially designed mechanical device for fixing static load was used. This test equipment is equipped with an automatic control and reading recording system. The maximum test load of the press is 3000 kN, the universal test machine is 500 kN, and the maximum data recording frequency is 5 kHz. Values of longitudinal and transverse deformations of concrete prisms were fixed using strain gauges on polyester substrate PLF-30. Measuring base of sensors is 30 mm. Tensoresistor readings were recorded using NI PXIe-1082 equipment. This equipment allows recording readings with a sampling frequency of up to 10 kHz. Besides the sensor of force which is built in the test LabTest car the duplicating sensor of force DYLF-102 synchronized by means of the NI PXIe-1082 complex with tensoresists was used.

The actual strength class of concrete for samples of a particular series is determined by six control samples according to the GOST 10180-2012 method. The sample was loaded to fracture at a constant stress build-up rate (0.6 ± 0.2) MPa/s. Then concrete strength was determined as arithmetic average for four of the six samples tested, which showed the highest strength value.

After determining the actual strength class, static tests of concrete prisms were carried out to determine the prism strength, modulus of elasticity and Poisson coefficient of concrete.

Tensoresistors were placed on each side face of the sample with a cyanocrylate adhesive. To determine transverse deformations, strain gauges are located in the middle of the height of the prototype normally to sensors measuring longitudinal deformations. A spherical hinge was installed in the working space of the test equipment. The samples are then centered in the test machine. The initial squeezing force of the sample, which was subsequently taken as a conditional zero, was assigned no more than 2% of the expected destructive load. Then, the sample was loaded to a load level equal to (40 ± 5)% prism strength Rb in steps of 10% of the expected destructive load, while maintaining a loading rate of (0.6 ± 0.2) MPa/s within each step. After reaching the indicated stress level, the sample was continuously loaded until the level of constant stress growth rate (0.6 ± 0.2) MPa/s was destroyed. The use of strain gauges made it possible to obtain a complete diagram of concrete deformation with the application of short-term static load.

The preparation of samples for dynamic tests was similar to that described earlier. An additional strain gauge sensor of the strain gauge type was introduced into the test installation circuit, which is synchronized in time with the readings of strain gauges.
The initial squeezing force of the sample, which was subsequently taken as a conditional zero, was not more than 2% of the expected destructive load. High-speed (impact) load application was carried out, which allows to implement a voltage increment rate of 500-800 MPa/s in the sample. The starting criterion for comparing the test results of samples of different strength classes was to ensure the minimum possible spread in the time of destruction of samples of the same series. At these loading rates, it was possible to ensure the destruction time of samples in the range of 0.075 ± 0.015 s. Data were recorded at a frequency of 5 kHz.

The method of static-dynamic tests for uniaxial compression is a symbiosis of the two methods described above. The essence of the experience is to load the sample with a static load to a given voltage level, and then implement a high-speed load application. Three levels of initial static load of the corresponding one were adopted: 0.2 Rb, 0.4 Rb, 0.6 Rb. The samples are loaded to the specified initial stress level in steps of 0.1 prism strength Rb.

Such a series of tests allows to obtain physical and mechanical parameters of heavy concrete operation under various loading modes.

3. The results of the study and their analysis

As a result of the experiment, experimental data were obtained for a series of samples of concrete prisms of strength class В35.

Based on the results of tests during static, dynamic and static-dynamic loading of concrete prism samples, strength and deformation characteristics of concrete were obtained under the considered loading modes (Tables 1-3) and "stress-strain," "stress-volumetric deformation" diagrams of concrete were drawn under the test parameters described by your (Figures 1-4).

Table 1. Static test results.

|   | Rb, MPa | E0, MPa | εub, % | εub,c, % |
|---|---------|---------|--------|----------|
| 1S | 36.04   | 30240   | 0.172  | 0.070    |
| 2S | 37.05   | 31560   | 0.184  | 0.063    |

Table 2. Dynamic test results.

|   | Rb, MPa | E0,din, MPa | t, c | Rb,din/Rb | εub, % | εub,c, % |
|---|---------|-------------|------|-----------|--------|----------|
| 1D | 41.10   | 31090       | 0.067| 1.12      | 0.224  | 0.153    |
| 2D | 40.90   | 38050       | 0.064| 1.12      | 0.209  | 0.149    |
Based on the analysis of the given data, the influence of the considered loading modes on the strength and deformation characteristics of concretes during uniaxial compression can be estimated.

**Figure 1.** Stress-longitudinal strain diagram for static and dynamic loads

**Table 3.** Results of static-dynamic tests.

|     | $R_b$, MPa | $E_0$, MPa | $E_{0,\text{din}}$, MPa | $t$, c | $R_{b,\text{din}}/R_b$ | $E_{0,\text{din}}/E_0$ | $\varepsilon_{ub}$, % | $\varepsilon_{ub,c}$, % |
|-----|-----------|-----------|----------------|-------|----------------|----------------|---------------|---------------|
| 1D20| 44.91     | 36030     | 34980          | 0.060 | 1.23          | 0.97           | 0.180         | 0.078         |
| 2D20| 42.86     | 34070     | 33700          | 0.057 | 1.17          | 0.99           | 0.190         | 0.059         |
| 1D40| 43.03     | 32400     | 33220          | 0.056 | 1.18          | 1.03           | 0.208         | 0.120         |
| 2D40| 43.76     | 31990     | 31550          | 0.063 | 1.20          | 0.99           | 0.206         | 0.078         |
| 1D60| 42.65     | 34220     | 35760          | 0.043 | 1.17          | 1.05           | 0.200         | 0.124         |
| 2D60| 44.23     | 35600     | 37770          | 0.045 | 1.21          | 1.06           | 0.199         | 0.110         |

Based on the analysis of the given data, the influence of the considered loading modes on the strength and deformation characteristics of concretes during uniaxial compression can be estimated.
**Figure 2.** "Stress - longitudinal strain" diagram at static-dynamic loading from 0.6 Rb level

**Table 4.** The level of relative stresses at the start of section dilatation.

|        | 1S | 2S | 1D | 2D | 1D20 | 2D20 | 1D40 | 2D40 | 1D60 | 2D60 |
|--------|----|----|----|----|------|------|------|------|------|------|
| $\sigma/R_b$ | 0.52 | 0.57 | 0.68 | 0.74 | 0.64 | 0.68 | 0.68 | 0.70 | 0.68 | 0.66 |

**Figure 3.** Stress - Volumetric Strain Diagram for Static

**Figure 4.** "Stress - volumetric deformation" diagram at static-dynamic loading from 0.6 Rb level
4. Conclusions
Experimental confirmation of hypothesis proposed in [1] on presence of one-parameter dependence of limit deformations on level of static load from which dynamic loading is performed is obtained. The dynamic hardening factor of concrete during static-dynamic loading turned out to be 7% more than during dynamic loading, however, the greatest ultimate deformation of concrete was realized during dynamic loading. Analyzing the data of Table 3, the dependencies of the deformation characteristics of concrete during dynamic loading on the initial level of static loading are traced. With dynamic and static-dynamic loading, there is an increase in the level of relative stresses corresponding to the beginning of concrete dilatation by 20-30% relative to the results of static tests. Further work on deeper data analysis is required to establish the parametric dependencies required in emergency impact calculations.

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