Determination of the Viscosity Modulus of Concrete Under Static-Dynamic Loading Regimes

Nataliya V. Fedorova[1](✉), Ngoc T. Vu[1], Mikhail D. Medyankin[1], and Dinh Q. Phan[2]

[1] Moscow State University of Civil Engineering (National Research University), Yaroslavl Highway, 26, 129337 Moscow, Russian Federation
[2] Vinh University, Le Duan Street, 182, Vinh City, Vietnam

Abstract. The results of experimental and theoretical studies to determine the viscosity modulus of concrete under static-dynamic loading are presented. The considered model of concrete deformation is based on the plasticity theory of concrete and reinforced concrete of G.A. Geniev, whose deformation dependences are constructed taking into account the adopted static-dynamic loading regime. According to a specially developed and patented technique, the results of uniaxial tests of concrete prisms were obtained in a two-stage regime of their static-dynamic loading and the parameters of concrete deformation in time were experimentally determined, which allow experimentally to obtain the viscosity modulus of concrete of different classes. It is shown that the viscosity modulus of concrete and its dynamic strength depends not only on the class of concrete but also on the level of its static loading at the first stage. The results obtained are of interest for solving problems, the strength, and deformability of sections of reinforced concrete structures at a special limiting state, to ensure the protection of buildings and structures from progressive collapse.

Keywords: Static-dynamic loading · Kelvin-Voigt model · Viscosity modulus · Dynamic strength · High-strength concrete · Special limiting state

1 Introduction

A significant number of domestic and foreign studies [1–4] and others are devoted to the determination of the parameters of static deformation of concrete under various types of the stress state. Experimental studies of recent years have noticed that the process of formation, development of cracks, and, accordingly, damage in concrete specimens begins even when a relatively small static load is applied in relation to the ultimate strength of concrete. Based on these studies, a number of important parameters of the strength of concrete have been obtained, which are reflected in Russian and foreign standards, calculation models, and design.

With the development of design methods, on the one hand, and the variety of actions on concrete and reinforced concrete structures, on the other, the need for a more rigorous description of the physical and mechanical parameters of concrete under such

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actions, including dynamic ones, has increased. Studies of the behavior of concrete under dynamic loading were considered in the works of Yu.M. Bazhenov, G.A. Geniev, V.S. Plevkov, O.G. Kumpyak, A.G. Tamrazyan, O.V. Kabantsev [5–8]. These studies revealed the influence of various factors on the dynamic strength, impact and explosion resistance, and endurance of concrete.

In the last decade, more and more attention has been paid to studies aimed at solving problems associated with a two-stage regime of static-dynamic deformation of brittle materials (for example, rocks), see, for example, [9–11]. Such problems arise in the design of underground structures (metro, underground tunnel, oil platform…) when there is a need for a more rigorous assessment of the characteristics of deformation and failure of rocks by an explosion under high geological pressure. Experimental studies of the parameters of deformation of rocks carried out in these works made it possible to clarify a number of fundamental features of the deformation and failure of such brittle materials under the considered modes of action.

Until now, the problems related to the deformation and failure of heavy concrete under the conjugate regime of static-dynamic loading have not been considered in domestic and also in foreign studies. At the same time, the relevance of such studies in recent years has increased in connection with the need to solve the problem associated with the protection of buildings and structures from progressive collapse [12–15] and new tasks have appeared necessary to solve this problem. In particular, this refers to the problems of the survivability of structures associated with special actions and, accordingly, the static-dynamic regime of loading of structures and structural systems under such actions.

Under static-dynamic action, the mechanical behavior of heavy concrete differs significantly from the behavior exclusively under static or dynamic loading, which leads to the fact that the traditional theory and parameters of reinforced concrete mechanics are not correct enough for calculating reinforced concrete structures under such loading regimes. Consequently, new experimental data on the characteristics of deformation and failure of concrete under such conditions is important for assessing the stability and preventing the progressive collapse of the structure of buildings.

In [16, 17], the authors constructed a version of the model of the plasticity theory of concrete and reinforced concrete by G.A. Geniev to determine the parameters of static-dynamic deformation of concrete. In the development of these works, the purpose of this study was the experimental-theoretical determination of the viscosity modulus of concrete of different classes and the parameter of the dynamic strength of concrete and the maximum permissible time of dynamic action before the failure of concrete under the considered loading regime, depending on this modulus. The tasks of the study included the development of a new test procedure for specimens of prisms made of concrete of different strengths, testing, and determination of experimental parameters of static-dynamic deformation of concrete, as well as the construction of analytical dependencies for calculating the modulus of concrete viscosity, and approbation of these dependencies with the obtained experimental values of the parameters of concrete deformation diagrams.

2 Methods

During the tests, two twin specimens were used to study the features of deformation under different loading regimes. The loading of the first twin specimen was carried out in two stages. At the first stage, low-speed static loading was carried out under a press at a speed of 0.6 ± 0.2 MPa/s to a given stress level $\eta = \sigma_b^{st}/R_b^{st}$, $(0 \leq \eta < 1)$ not exceeding the static compressive strength of concrete, and after reaching this level, the stress in the concrete specimen was fixed using a special device. The specimen is kept for up to 5 min at this stress level and moved from under the press to the dynamo machine with the measurement of deformations before and after holding. At the second stage, the first specimen was loaded with a high-speed (impact) load with a given loading rate until its failure. The second twin specimen was loaded with a static load in the same way as in the first stage of testing, but until the specimen failed [18].

In the course of loading, the increments of longitudinal and transverse deformations, the ultimate load, and ultimate deformations before the failure of the specimen were recorded. Then, according to these data, the diagrams of the "stress-strain" of concrete were plotted under static-dynamic loading for the first specimen and static loading for the second specimen. These diagrams were used to calculate the dynamic modulus of deformation E_b^{st-d} depending on the limiting time of dynamic reloading t_d and the level of stress state at the first stage of loading $\eta = \sigma_b^{st}/R_b^{st}$, $(0 \leq \eta < 1)$, from which the dynamic reloading was performed, as well as the dynamic strength of concrete R_b^{st-d} and the coefficient of increasing the dynamic strength of concrete $(\varphi_b = R_b^{st-d}/R_b^{st})$.

Experimental studies were carried out on a series of specimens of prisms with dimensions of 100 × 100 × 400 mm made of concrete of classes B25, B35, B50, and B70. The first stage of testing included loading the prism with a static load to the level of $\eta = 0$; 0.2; 0.4; 0.6. For specimens of concrete prisms of the same series (the second twin specimen), static tests were carried out, which served as a reference. The obtained physical and mechanical characteristics of the concrete prisms of the second twin specimen under static testing are shown in Table 1.

Table 1. Experimental values of physical and mechanical static parameters of deformation of heavy concrete of different classes.

		B25	B35	B50	B70
R_b^{st}, MPa		25.2	37.61	49.2	67.53
$\varepsilon_{b,ult}^{st}$	longitudinal	0.0019	0.00188	0.00203	0.00185
	transverse	0.00075	0.000704	0.00095	0.00065
E_b^{st}, MPa		24079	29915	38260	45260

To calculate the experimental values of the viscosity modulus of concrete $K(\eta)$ under the considered static-dynamic loading regime, depending on the level of static loading $\eta = \sigma_b^{st}/R_b^{st}$, $(0 \leq \eta < 1)$, the simplest rheological model of deformation of Kelvin-Voigt-Geniev concrete was used (Fig. 1). The model includes parallel-connected elements A and B, the first of which is described by G.A. Geniev, the constant in which the experimental value of the ultimate strength of concrete under static loading R_b^{st} is accepted. A purely viscous (Newtonian) element B is characterized by the viscosity modulus of concrete $K(\eta)$, depending on the level of static loading η, corresponding to the accepted hypothesis. When the structural element of concrete is exposed to stress intensity equal to the experimental values of the ultimate strength of concrete under static-dynamic loading R_b^{st-d}, the effective work of element B ends at very small values of the time t, counted from the moment of application of dynamic stresses to the failure of the specimen. However, during this short period of time, viscous element B helps to inhibit the development of deformations initiated in element A.

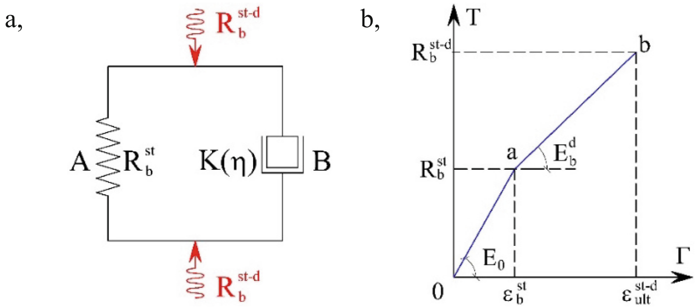

Fig. 1. Mechanical model (a) and diagrams "$\sigma - \varepsilon$" (b) of visco-elastic-plastic deformation of concrete.

Then, according to the accepted model, we can write:

$$R_b^{st} + K(\eta) \cdot \dot{\varepsilon}_b = R_b^{st-d}. \tag{1}$$

From this formula, the experimental viscosity modulus of concrete $K(\eta)$ is determined by the expression:

$$K(\eta) = \frac{R_b^{st-d} - R_b^{st}}{\dot{\varepsilon}_b}, \tag{2}$$

where $\dot{\varepsilon}_b$ is the average strain rate of the specimen in the time interval $0..t_d$ and is defined by the formula:

$$\dot{\varepsilon}_b \approx \frac{\varepsilon_{b,ult}^{st-d} - \varepsilon_b^{st}}{t_d}, \tag{3}$$

where $\varepsilon_{b,ult}^{st-d}$; ε_b^{st}- accordingly, the ultimate deformation of concrete and the deformation of concrete at a given level of static loading.

Substituting the expression (3) in (2), we obtain an equation for determining the experimental values of the viscosity modulus of concrete $K(\eta)$.

3 Results and Discussion

3.1 Dynamic Tests ($\eta = 0$)

At the second stage of testing the deformation of the experimental prisms when they are loaded from a zero level of static loading ($\eta = 0$) to failure by a high-speed (impact) load, the nature of the stress-strain state of the experimental prisms has changed significantly. Experimental parameters of dynamic deformation of concrete of different classes, such as dynamic reloading time, ultimate deformation, average strain rate, are given in Table 2.

From the consideration of Table 2, it can be seen that with a high-speed impact load, the time of dynamic reloading is of the order of tenths of a second ($\mathrm{t_d} = 0.067\ldots\ 0.13$ s).

Table 2. Dynamic parameters of deformation of heavy concrete of different classes at $\eta = 0$.

	B25	B35	B50	B70
t_d, s	0.078	0.067	0.097	0.13
$\varepsilon_{b,ult}$	0.0024	0.0022	0.0023	0.0025
$\dot{\varepsilon}_b, s^{-1}$	0.031	0.033	0.024	0.019
$\varphi_E = E_b^d / E_b^{st}$	1.12	1.04	1.16	1.11
$\varphi_b = R_b^d / R_b^{st}$	1.19	1.38	1.35	1.25
$K(\eta), MPa \cdot s$	151	403	722	866
$\omega = G_0 / K(\eta),\ s^{-1}$	67	31	22	22

Comparison of the experimental values of the ultimate deformations of concrete under static and dynamic loading showed that their value is insignificant, about 10%, differs from each other. Hence, an important conclusion can be drawn that the ultimate deformation of concrete practically insignificantly depends on the loading rate. This is due to the fact that the failure of such a brittle material as concrete is due to the development of a sufficient number of microcracks. As a rule, this occurs when the ultimate deformation of concrete is reached, regardless of how this is achieved and at what speed the deformation process proceeds. The value of the ultimate deformation largely depends on the structure of the concrete and can be constant for heavy concrete. Proceeding from this, in practical estimations for the progressive collapse of a building and structure with a sudden removal of individual elements, the developers of the normative document SP 385.1325800.2018 took the value of ultimate deformations for concrete equal to their values under static loading $\varepsilon_{b2} = 0.0035$.

Figure 2 shows typical patterns of dynamic failure recorded by a camera for concrete specimens of different strength classes. The higher the class of concrete, the more fragile the specimen is destroyed.

Fig. 2. General view of the failure of test specimens of concrete of different classes.

3.2 Static-Dynamic Tests

Analysis of the experimental data obtained from the results of static-dynamic tests of concrete prisms at $\eta = 0.2;\ 0.4;\ 0.6$ showed that deformation, cracking and failure of the test specimens have a number of features.

At the first stage of static loading, the influence of the level of static loading on structural changes in the specimens was analyzed. Using the PULSAR 2.1 device with through sounding sensors, a decrease in the speed of ultrasound passage through the specimen was established with an increase in the value of static loading (Fig. 3a). This confirms that the process of formation and development of microcracks, and, accordingly, damage in concrete specimens occurred even at a low level of static loading. With an increase in the value of static loading, the density and length of microcracks steadily increased and opened throughout the body of the prototype, and a "lattice" was formed in the concrete body, preventing the passage of ultrasound. Thus, the specimens change their strength and deformation characteristics at each level of static loading.

The results of ultrasound studies also showed that to increase the stability of the results obtained, the level of static stresses at the first stage of loading should not exceed 60% of the concrete strength for uniaxial compression due to the tendency to the development of dilatation deformation in the sample before impact loading.

At the second dynamic stage of loading the specimen to fracture by a high-speed (impact) load with a given loading rate, the dynamic compressive strength for a B70 concrete specimen without static preloading was 84.19 MPa, while its strength under static-dynamic loading from various levels of static loading ($\mu = 0.2;\ 0.4;\ 0.6$) respectively amounted to 81.06 MPa; 79.42 MPa; 78.83 MPa (Fig. 3b). The same tendency towards a decrease in strength with increasing levels of initial static loading was also observed for concrete specimens of other classes.

At the same time, from the analysis of experimental data, it was noted that with an increase in the level of static loading of concrete at the first stage, the dynamic

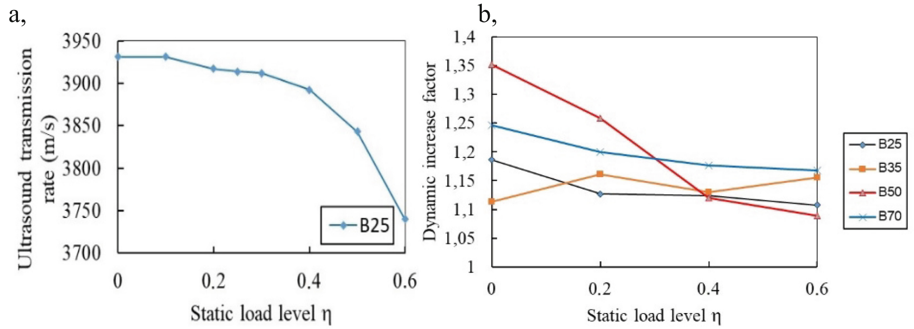

Fig. 3. Dependence of the speed of ultrasound transmission on the level of static loading (a) and dependence of the coefficient of static-dynamic strength on the level of static loading (b).

modulus of deformation of the specimen decreases. Thus, the modulus of deformation of a specimen from B70 concrete at $\eta = 0$ was 50.1 GPa, which is 1.1 times more than that of a specimen from the same concrete with $\eta = 0.6$.

The analysis of experimental data also showed that the ultimate deformability of concrete is insensitive to changes in the level of static loading. Thus, the average value of the static-dynamic deformation limit of concrete of different classes was about 0.002, which is close to the value obtained during static testing of specimens. This makes it possible to substantiate the accepted numerical value of the ultimate deformations adopted for concrete in SP 385.1325800.2018.

The experimental values of the concrete viscosity modulus $K(\eta)$, determined by the formula (2), are shown in Fig. 4. From which it can be seen that the higher the level of static loading at the first stage, the lower the value of $K(\eta)$.

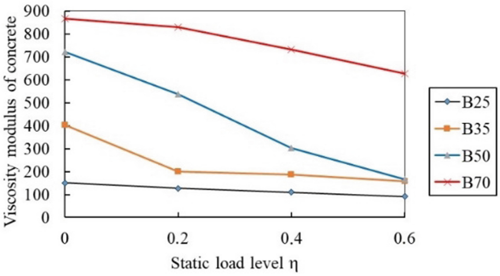

Fig. 4. Experimental dependence of the viscosity modulus of concrete on the level of static loading.

This can apparently be explained by the fact that the viscosity modulus of concrete describes the macroscopic response of the internal microstructure to dynamic action. With an increase in the level of static loading, the formed microcracks inside the specimens develop and combine, reducing the strength of the concrete. In this case, the viscosity modulus of the concrete specimen also decreases. When η is close to unity, there is a complete merging of microcracks and the failure of the concrete specimen occurs.

4 Conclusions

Experimental and theoretical studies have established that the stress-strain state of concrete under static-dynamic loading depends not only on dynamic reloading, but also on the level of static loading and, accordingly, the level of microcracking in concrete.

The values of the viscosity modulus of concrete at different levels of static loading for concretes of different classes have been determined experimentally and theoretically. It is shown that the results of calculations based on the proposed version of the deformation model are in good agreement with the experimental data.

The results of the study made it possible to establish a number of important parameters of static-dynamic deformation of concrete, which can be used to solve various problems of deformation and strength of reinforced concrete under its regime loading.

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