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Engineering

Relationship between Concrete Stresses and Deformations, Taking into Account Strength, Age, Hardening Conditions and Loading Speed

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The paper, based on experimental-theoretical research, evaluates the stressed-deformed state of heavy concrete used in monolithic construction; the dependence between concrete stresses and deformations, taking into account its strength, age, hardening conditions and loading speed, is studied. Qualitatively new analytical attitudes are proposed taking into account the main factors acting under operating conditions. Important result of the presented study is that during the maintenance of concrete and reinforced concrete constructions, it is possible to assess the quality of the stressed-deformed state and to determine the stress corresponding to the preliminarily given deformation. The mentioned attitude was brought to the stage that it is possible to realize specific engineering tasks. Based on the obtained approach, it is possible to solve the inverse problem - to determine the deformation corresponding to the preliminarily given voltage. In order to demonstrate the practical significance of the obtained approach, a numerical example is discussed. *© 2023 Bull. Georg. Natl. Acad. Sci.*

strength of concrete, stresses and deformations, speed of loading, age of concrete, hardening conditions

Despite the development of new efficient materials and constructions, concrete and reinforced concrete have been established as the main structural building materials in civil engineering practice. The properties of concrete and reinforced concrete must be in full compliance with the conditions of construction and operation in order to ensure the reliability and durability of the structure so that their potential is fully utilized.

Concrete and reinforced concrete structures often work under limited deformation conditions during operation. At the same time, the humidity of the environment, the age of the structure and the speed of loading are different.

The law of work of concrete and reinforced concrete structures under load is determined by many factors. The most important among them are: loading speed, concrete age, humidity conditions and temperature. Therefore, in order to evaluate pressed-deformed state of concrete under operating conditions, it is necessary to know σ(ε) dependence from ε=0 (corresponding to σ=0) to ε_{lim} (corresponding to σ=R) over the entire load range. Such dependence in relative values is expressed in the following form [1-5]:

$$\frac{\sigma}{R_0} = \left(\frac{\varepsilon}{\varepsilon_{lim}}\right)^c \tag{1}$$

Graphically, the aforementioned relations (dependences) are expressed with the curves of the deformation diagram, and analytically by parabolic functions of the second or third degree.

The dependence of the concrete strength of the given composition on the mentioned factors at positive air temperature conditions can be expressed in a general way by the formula [6-8]:

$$R_0 = R \cdot F(v,t,w) = R \cdot f_1(v) \cdot f_2(t) \cdot f_3(w) \tag{2}$$

where R_0 is the strength of the concrete of the given composition when being hardened and tested under standard conditions $\upsilon=\upsilon_0$=0,25 Mpa/sec $t=t_0$=28 days; W=1,0.

R is the strength of concrete determined at any, non-standard values of the mentioned factors.

$f_1(v)$ dependence describes R_V strength of the concrete under different *V* loading speed. $f_2(t)$ expresses dependence of the concrete strength on its age, while $f_3(w)$ the increase of the concrete strength based on the humidity conditions in the environment. The influence sizes of samples (scale factor) is not considered by the research.

In order to determine $f_1(v)$ dependence, on the basis of experimental data, R(lgυ), dependence in which concrete strength and loading speed varied in a quite wide range existing in practice, has been studied. These dependences are linear, but not parallel. As the class of concrete increases, the angel of inclination increases.

The dependence of concrete strength $f_2(t)$ on its age is approximately described by the following classical formula:

$$R_t = R_{28}\frac{\lg t}{\lg 28}$$

The mentioned formula gives relatively satisfactory results for heavy concretes at *W* relative humidity which is close to 1.

There are no measurable dependences of the kinetics of concrete strength growth on environmental humidity. But it is known that the lower *W* is, the slower the growth of concrete strength in air-dry environment is, when *W*<0.5, the strength of concrete after 28 days almost does not increase due to the slowing down or complete cessation of the cement hydration process, and in some cases it decreases due to the development of internal shrinkage stresses [1-3].

(4) the $f_2(t)$ და $f_3(w)$ functions left in the formula are interconnected: it is known that the kinetics of concrete strength increase in time significantly depends on *W*- the humidity of the environment. The complex dependence of the kinetics of concrete strength growth in time, taking into account the numerical characteristic of the w-humidity of the environment, was selected as a test function based on the analysis of experimental data [9-14].

From the experimental data considered in the second stage of the main (1) dependence investigation, the σ(ε) dependences at different loading rates were studied for several concrete compositions. The characteristics and test conditions of these concretes are given in Table 1.

Table 1. Concrete characteristics and test conditions

Composition №	Experiment №	R_0 Mpa	υ MPa/sec	R MPa	w	$\varepsilon_{\lim}$ 10^{-5}
1	1-1	58.8	1.55	62.0	0.85	280
	1-2	58.8	136.0	73.5	0.85	275
	1-3	58.8	980.0	78.0	0.85	275
2	2-1	44.3	0.29	44.0	0.85	240
	2-2	44.3	65.0	54.5	0.85	250
3	3-1	29.6	0.425	28.0	0.85	200
	3-2	29.6	128.0	36.0	0.85	190
4	4-1	20.5	0.00087	14.2	0.5	120
	4-2	20.5	0.036	15.0	0.5	115

Concrete deformation curves significantly depend on the speed of load modes, however threshold deformation $\varepsilon_{\lim}$ is practically the same for all values of R, i.e. does nor depend on the load speed υ. As the speed increases, the given constant value $\varepsilon_{\lim}$ is reached at high load (stress σ=R) and vice versa, when the speed of load decreases, the breaking load decreases, as it seems, it comes close to the long-term strength value of concrete [10-13]. In addition, the greater the strength of the concrete hardened in the same humidity conditions (estimated by its value R_0), the greater is the threshold $\varepsilon_{\lim}$ deformation. By decreasing the humidity of the environment, in which the concrete hardens, $\varepsilon_{\lim}$ value decreases. Relevantly, the dependence of $\varepsilon_{\lim}$ on the concrete strenght is looked for through $\varepsilon_{\lim}(R_0, w)$ function for the three meanings – *w=0,5; w=0,85; w=1*-of w.

As a result of experimental data processing, the $\varepsilon_{\lim}(R_0, w)$ dependency testing function was selected [6-8].

(1) at the next stage of the function investigation, we determined the structure and numerical values of the quality indicator C for which, based on the experimental data of the four considered compositions, the dependences of $\sigma/R_0 = f(\varepsilon/\varepsilon_{\lim})$ were studied.

Based on the processing of experimental data, the testing function of the quality index C was selected in the form of $C = f\left(R_0, \frac{\varepsilon}{\varepsilon_{\lim}}\right)$ [6-8].

Thus, for the members of the main dependences, the test functions in the following form have been obtained:

$$R_0 = R\left[1 - \left(0,098 - 0,0053\lg\frac{V}{V_0}\right)\lg\frac{V}{V_0}\right]\frac{\lg 28}{(\lg t)^w} \tag{3}$$

$$\varepsilon_{\lim} = (191,174 + 3,513R_0)\left[1 - (0,759 - 0,0023R_0)(1-W)^{0,392}\right]\cdot 10^{-5} \tag{4}$$

$$C = (0,563 + 0,006R_0) + (0,494 - 0,0024R_0)\frac{\varepsilon}{\varepsilon_{\lim}} \tag{5}$$

In order to illustrate the practical importance of the obtained dependences, a numerical example was considered with the following initial conditions: for a reinforced concrete multi-layer construction with B30 concrete class, the relative compression in the lower pillar caused by the construction's own weight in the end of the construction should not exceed the value of $\varepsilon = 60\cdot 10^{-5}$. Construction duration T=30 days.

Relative air humidity W=0,70. Air temperature positive. It is needed to determine the threshold value of the compressive stress σ_1 in the concrete pillar, that at the end of the construction, corresponds to the mentioned allowable deformation.

For the purpose of practical implementation of the mentioned task, it is necessary that the class of the concrete is determined under standard conditions: t=28 days, V=0,25 MPa/sec, then the concrete resistance for calculation (prismatic strength) for the threshold state of the second group (calculations on deformations) in accordance with Building Regulation 2.03.01-84 (СНиП 2.03.01-84) for the B30 class concrete equals to 22 MPa. According to the data obtained in the present work this corresponds to R_0 =22 MPa. The calculation algorithm is as follows: we define the threshold deformation $\varepsilon_{\lim}$ by the formula (4); then we find out the ration $\frac{\varepsilon}{\varepsilon_{lim}}$, c indicator of quality based on formulas (5); the value $\left(\frac{\varepsilon}{\varepsilon_{lim}}\right)^c$ and the concrete age (from production) are defined, σ stress in the case of standard conditions is defined, T load duration, load speed $V=\frac{\sigma}{T}$ are defined, the values $\lg\frac{V}{V_0}$ და $(\lg t)^w$ are defined from the formula (3), R value is defined and in the end the threshold stress in the concrete σ_1 is defined. The results of the calculation are presented in Table 2.

Table 2. Calculation results

$\varepsilon_{\lim}$, 10^{-5}	$\frac{\varepsilon}{\varepsilon_{\lim}}$	C	$\left(\frac{\varepsilon}{\varepsilon_{\lim}}\right)^c$	t, days	σ, MPa	T, sec, 10^6
1	2	3	4	5	6	7
149.9	0.4	0.871	0.45	58	9.9	2.592

$V, MPa/\sec$, 10^{-6}	$\lg\frac{V}{V_0}$	$(\lg t)^w$	R, MPa	σ_1, MPa
8	9	10	11	12
3.819	-4.816	1.49	19.46	8.75

In order to evaluate the accuracy of the obtained dependences, we compared σ/R experimental values (1) with the values calculated by the formula for ten heavy concrete compositions. The difference between σ/R experimental and theoretical values in most cases of individual experiments does not exceed 10%, while it is close to zero depending on the whole concrete composition.

Based on the proposed dependences, it is determined that the deformation capacity limits of heavy concrete during hardening at the same temperature and humidity conditions increases with the increase of the concrete class. By reducing the humidity of the environment in which the concrete hardens, the index of its deformation capacity limits decreases.

Based on the proposed relationships, it is determined that the deformation capacity limits of heavy concrete during hardening at the same temperature and humidity conditions increases with the increase of the concrete class. By reducing the humidity of the environment in which the concrete hardens, the size of its deformation capacity limits is reduced.

An important consequence of the above-mentioned relationships is that during the operation of concrete and reinforced concrete, it is possible to determine the stress corresponding to the preliminarily given deformation. The mentioned approaches have been brought to the stage that it is possible to realize specific engineering tasks. Based on the obtained approach, it is possible to solve the inverse problem - to determine the deformation corresponding to the preliminarily given tension.

ინჟინერია

ბეტონის ძაბვებსა და დეფორმაციებს შორის დამოკიდებულება მისი სიმტკიცის, ასაკის, გამყარების პირობებისა და დატვირთვის სიჩქარის გათვალისწინებით

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ნაშრომში ექსპერიმენტულ-თეორიული კვლევის საფუძველზე შეფასებულია მონოლითურ მშენებლობაში გამოყენებული მძიმე ბეტონის დაძაბულ-დეფორმირებული მდგომარეობა, შესწავლილია ბეტონის ძაბვებსა და დეფორმაციებს შორის დამოკიდებულება მისი სიმტკიცის, ასაკის, გამყარების პირობებსა და დატვირთვის სიჩქარის გათვალისწინებით. შემოთავაზებულია თვისობრივად ახალი ანალიზური დამოკიდებულებები საექსპლუატაციო პირობებში მოქმედი ძირითადი ფაქტორების გათვალისწინებით. აღნიშნული გამოკვლევების მნიშვნელოვანი შედეგი არის ის, რომ ბეტონისა და რკინაბეტონის კონსტრუქციების ექსპლუატაციის დროს შეგვიძლია შევაფასოთ დაძაბულ-დეფორმირებული მდგომარეობის ხარისხი და განვსაზღვროთ წინასწარ მოცემული დეფორმაციის შესაბამისი ძაბვა. აღნიშნული დამოკიდებულება მიყვანილია იმ სტადიამდე, რომ შესაძლებელია განხორციელდეს კონკრეტული საინჟინრო ამოცანების რეალიზაცია. მიღებული დამოკიდებულების საფუძველზე შესაძლებელია გადაწყდეს შებრუნებული ამოცანაც – განვსაზღვროთ წინასწარ მოცემული ძაბვის შესაბამისი დეფორმაცია. მიღებული დამოკიდებულებების პრაქტიკული მნიშვნელობის თვალსაჩინოების მიზნით განხილულია რიცხობრივი მაგალითი.

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