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PREDICTING LONG-TERM STRENGTH OF COMPRESSED CONCRETE

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ABSTRACT

The article characterises the features of compressed concrete deformation under the action of long-term loads. The aim of the research presented in the article was to establish the analytical dependence of determining the long-term strength of compressed concrete. It hypothesises that the specific potential energy of its ultimate deformation (destruction) is invariant and independent of the concrete loading mode. Other researchers' critical analyses have confirmed the functional dependence of the level of long-term strength of compressed concrete not only from its standardised elastic-plastic characteristics but also from the concrete strain rate. The proposed methodology evaluation for determining the long-term strength of compressed concrete is reduced to a comparison of the relevant theoretical calculated results with the various researchers' published experimental data.

Keywords: concrete, energy model, specific potential energy, strain rate, level of long-term strength

INTRODUCTION

Studies of compressed concrete's long-term strength have become one of the determining factors in reinforced concrete theory since it came to be used in the practical design of reinforced concrete elements and structures. Therefore, it is not surprising that the most active research in this direction began in the 1930s–1960s. The first serious studies of compressed concrete's long-term strength were carried out by Graf and Brenner (1937). However, the most thorough among them was the research of Rüsch (1956, 1960), which mainly concerned concretes of low and medium strength classes. They, like other studies of this period (Shank, 1949; Sell, 1959), showed that even after a long period, the long-term strength of low-class concretes did not exceed $0.75f_c$, and that of medium-class concretes was lower than $0.8f_c$. It was also established that under such constant loads, even the further long-term hydration of cement stone in early-aged concrete is not able to stop the process of its eventual destruction. At the same time, it was noticed that at relatively moderate stress levels in compressed concrete ($\eta_c = \sigma_c/f_c = 0.4$–$0.6$), a slight positive effect of long-term loading on its strength is observed.

Subsequently, most of the high-profile studies (Yashin, 1969; Zaitsev, 1972; Prokopovich, 1978; Ngab, Slate & Nilson, 1981; Smadi, Slate & Nilson, 1985; Han, 1996; Iravani & MacGregor, 1998; Tasevski, Fernández & Muttoni, 2018; Empelmann & Javidmehr, 2020; Holovata, Neutov & Surianinov, 2021; Raupov & Malikov, 2023) were already directly or indirectly aimed at attempting to standardise the long-term compressive strength of concrete. However, modern design standards still lack clear and sufficiently substantiated recommendations for considering the influence of long-term loads in the calculations of reinforced concrete elements for limit states,

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referring here not only to the maximum safe levels of this long-term loading, but also to the modes of applying (creating) these loads. After all, it is apparent that a change in the rate of applying a load or the concrete strain rate will lead not only to a change in the safe level of long-term load, but also to a change in the deformation capabilities of the compressed concrete. In other words, the long-term strength of compressed concrete and its critical (limiting) deformations will depend not only on the class of the concrete itself but also on its strain rate.

The real modes of applying operating loads are actually quite long, therefore establishing similar dependencies between the parameters of compressed concrete will be important for building a universal model of concrete and reinforced concrete element and structure deformation.

This article is aimed at developing the key provisions of the general model of compressed concrete deformation under the action of long-term loads. The main task posed in this case is to establish the analytical dependence of the level of compressed concrete's long-term strength. It should provide a simple approach to considering the influence of long-term loading on the behaviour of compressed concrete both from the standpoint of its strength and its ability to maximally deform during the design of reinforced concrete elements and structures. The previously developed energy model (Romashko & Romashko, 2019a; Romashko & Romashko-Maistruk, 2022) can serve as the basis for such an approach, which is based on the general laws of preservation of the material's deformation potential energy under different modes of its loading.

MATERIAL AND METHODS

These studies are based on the most important laws of physical and mathematical modelling of the deformation processes of concrete and reinforced concrete elements and structures (Romashko & Romashko, 2019b; Romashko & Romashko, 2019c; Romashko, 2021) and the well-known law of the conservation of the specific potential energy of material deformation regardless of its loading mode.

Although Rüsch (1960) developed the first concept of concrete's long-term strength, he did not propose an analytical dependence on determining this strength. Later, Yashin (1969) attempted to solve this task, and later still, other researchers (Prokopovich, 1978; Bezgodov, 1996; Holovata et al., 2021; Raupov & Malikov, 2023) used a simple logarithmic dependence:

$$\eta_l = a - b \cdot \lg(t - t_0), \tag{1}$$

where:
a, b – empirical coefficients,
$(t - t_0)$ – load duration [days].

However, Function (1) is too primitive, as it does not consider the influence of a number of important technological and age factors, or the main concrete components, on its long-term strength.

Zaitsev (1972) proposed another dependence:

$$\eta(t,\ t_0) = \frac{m(t,\ t_0) \cdot R_c(t)}{R_c(t_0)} \cdot \sqrt{\frac{E(t_0)}{E(t)} \cdot \frac{1}{1 + E(t_0) \cdot C(t,\ t_0)}}, \tag{2}$$

where:
$\eta(t, t_0)$ – level of concrete's long-term strength,
$m(t, t_0)$ – function of the relative intensity of the surface energy of the fracture crack,
$R_c(t)$ – concrete's predicted strength at the time of its destruction $t \to \infty$ [MPa],
$R_c(t_0)$ – concrete's strength at the time of its loading [MPa],

$E(t_0)$, $E(t)$ – modulus of concrete's elasticity at the time of its loading and at the failure time, respectively [MPa],
$C(t, t_0)$ – measure of concrete creep.

The main disadvantage of Function (2) and its modifications (Ashrabov & Zaytsev, 1982; Krishan, Rimshin, Erofeev, Kurbatov & Markov, 2015; Raupov, Karimova, Zokirov & Khakimova, 2021) is that using it requires knowledge of the concrete's basic physical and mechanical characteristics at the age of 28 days, and at the times of its loading τ and probable destruction $t \to \infty$.

Further studies of compressed concrete's long-term strength (Awad & Hilsdorf, 1971; Stöckl, 1972; Ngab et al., 1981; Smadi et al., 1985; Han, 1996; Iravani & MacGregor, 1998) have been concerned not only with low- and medium-strength classes of concrete but also with high-strength concrete. The results of these studies have subsequently been reflected both in earlier and in current normative documents (Comité Euro-International du Béton [CEB], 1993; Fédération Internationale du Béton [FIB], 2013) with a more complex logarithmic-exponential dependence:

$$\eta_l = (0.96 - 0.12) \cdot \left(\ln\left(72\left(t - t_0\right)\right)\right)^{\frac{1}{4}} \cdot \exp\left(s\left(1 - \sqrt{\frac{28}{t_0}}\right)\right), \tag{3}$$

where:
η_l – level of concrete's long-term strength,
t_0 – concrete's age at the time of its loading [days],
s – coefficient depending on the cement class (R, N, S).

This dependence, although free of some of the above-mentioned disadvantages, is quite limited in use (Tasevski et al., 2018; Empelmann & Javidmehr, 2020).

Thus, considering all the above, it can be stated that research related to the resistance of compressed concrete to long-term loads will continue to be one of the most relevant topics in the general theory of reinforced concrete.

It is well known that such physical and mechanical characteristics of concrete as the compressive f_c and tensile f_{ct} strength and the corresponding critical strain ε_{c1} and ε_{ct1} largely depend on its strain rate. It is quite obvious that the lower the concrete's strain rate, the lower its strength will be and the greater will be the limiting (critical) concrete deformations at the moment of its destruction. At the same time, it is known that the product of the two above-mentioned parameters characterises the specific potential energy of the concrete's deformation. And, according to the law of conservation of potential energy, it should remain unchanged and independent of the loading mode of the material itself. In other words, the area of the compressed concrete strain diagram will remain constant or unchanged under any load type (Fig. 1).

In the case of instantaneous loading, the concrete will deform elastically, since plastic deformations or creep deformations will not have time to manifest themselves. Under such circumstances, the specific potential energy of the compressed concrete's deformation at the moment of its destruction can be calculated using a very simple expression (Romashko-Maistruk & Romashko, 2024):

$$u_d = \frac{f_{c,du}^2}{2E_{c0}}, \tag{4}$$

where:
E_{c0} – initial modulus of concrete elasticity under stress $\sigma_c = 0$ [MPa],
$f_{c,du}$ – strength of compressed concrete under instantaneous dynamic loading [MPa],
$\varepsilon_{c,du}$ – corresponding critical (limit) concrete strain under instantaneous dynamic loading.

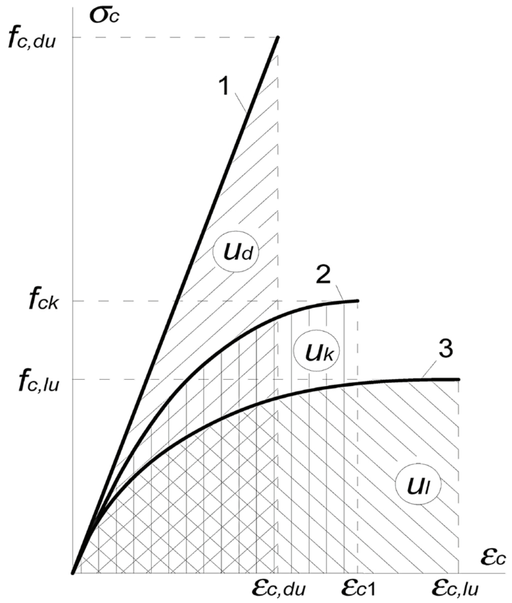

Fig. 1. Plots of specific potential energy of concrete destruction under loading: 1 – instantaneous dynamic; 2 – standardised short-term; 3 – long-term

Source: Romashko-Maistruk and Romashko (2024).

In the case of a short-term quasi-static mode of loading or deformation described by an incorrect fractional-rational function σ_c–ε_c (Romashko & Romashko, 2019b; Romashko, 2021), this energy should be calculated according to Romashko-Maistruk & Romashko (2024) by the expression:

$$u_k = \frac{dU}{dV} = \int_0^{\varepsilon_{c1}} \sigma_c d\varepsilon_c = \frac{f_{ck} \cdot \varepsilon_{c1}}{(k-2)} \left[-\frac{1}{2} + \frac{(k-1)^2}{(k-2)} - \left(\frac{k-1}{k-2} \right)^2 \cdot \ln(k-1) \right], \tag{5}$$

where:

k – characteristics of the compressed concrete's deformability ($k = E_{c0} \cdot \varepsilon_{c1} / f_{ck}$),
ε_c – compressed concrete's current strain,
f_{ck} – strength of the compressed concrete under the action of standardised static loads [MPa],
ε_{c1} – critical strain of the compressed concrete under the action of standardised static loads.

By a similar expression, it would be possible to determine the specific potential energy of compressed concrete's destruction under the long-term load action:

$$u_l = \int_0^{\varepsilon_{c,lu}} \sigma_c d\varepsilon_c = \frac{f_{c,lu} \cdot \varepsilon_{c,lu}}{(k_l-2)} \left[-\frac{1}{2} + \frac{(k_l-1)^2}{(k_l-2)} - \left(\frac{k_l-1}{k_l-2} \right)^2 \cdot \ln(k_l-1) \right], \tag{6}$$

where:

$f_{c,lu}$ – limit values of the long-term strength of the compressed concrete [MPa],
$\varepsilon_{c,lu}$ – corresponding critical strain of the compressed concrete,
k_l – characteristic of the compressed concrete's ultimate deformability under the action of long-term loads ($k_l = E_{c0} \cdot \varepsilon_{c,lu} / f_{c,lu}$).

However, the main parameters of this dependence, $f_{c,lu}$ and $\varepsilon_{c,lu}$ (as well as k_l), are unknown, and it is therefore practically impossible to determine the level of the concrete's long-term strength from the joint solution of Equations (5) and (6). However, from the joint solution of Equations (4) and (5), the dependence of the limit values of the compressed concrete's dynamic increase factor (DIF_u) was obtained (Romashko--Maistruk & Romashko, 2024):

$$DIF_u = \frac{f_{c,du}}{f_{ck}} = \sqrt{\frac{2k}{(k-2)}\left[-\frac{1}{2}+\frac{(k-1)^2}{(k-2)}-\left(\frac{k-1}{k-2}\right)^2 \ln(k-1)\right]}. \tag{7}$$

Function (7) characterises the ultimate strength of compressed concrete during its instantaneous deformation. With a decrease in the strain rate $\acute{\varepsilon}$, the dynamic increase factor will also decrease and will reach its minimum value at $\acute{\varepsilon} = 10^{-6}$ s^{-1} and equal the maximum possible level of compressed concrete's long-term strength, $DIF = \eta_l = 1$. This provides a single methodological approach to determining the compressive strength of concrete under any loading mode.

It is quite obvious that a further decrease in the level of compressed concrete's long-term strength will occur with a further decrease in its strain rate. With the help of numerical analysis methods, it was possible to link this process with the following dependence:

$$\eta_l = \frac{f_{c,lu}}{f_{ck}} = DIF_u^{\left(\frac{\left(\log\left(\frac{\acute{\varepsilon}}{\acute{\varepsilon}_s}\right)+1\right)}{9}\right)} \text{ for, } \acute{\varepsilon} \le 10^{-6} \text{ s}^{-1}, \tag{8}$$

where:
$\acute{\varepsilon}_s$ – maximum strain rate of compressed concrete under quasi-static loads ($\acute{\varepsilon}_s = 10^{-5}$ s^{-1}).

If the strain rate of compressed concrete is taken to be $\acute{\varepsilon} = 10^{-10}$ s^{-1}, according to Table 1, then its safe level of long-term strength can be calculated using the expression:

$$\eta_{lu} = DIF_u^{-\frac{4}{9}}. \tag{9}$$

Table 1. Compressed concrete strain rate depending on the load mode

Load mode	Strain rate ($\acute{\varepsilon}$) [s^{-1}]
Long (‘creeping’)	10^{-10}–10^{-6}
Static, quasi-static	10^{-6}–10^{-5}

Source: Romashko-Maistruk and Romashko (2024).

RESULTS

Formula (8) shows that compressed concrete's long-term strength depends not only on its physical and mechanical characteristics, reflected in DIF_u and the coefficient of elastic-plastic concrete's properties $k = E_{c0} \cdot \varepsilon_{c1}/f_{ck}$, but also on its strain rate, $\acute{\varepsilon}$. The first of these parameters is directly affected by the plastic properties (creep) of the concrete. The larger they are, the greater the elastic-plastic coefficient of the concrete will be and the lower its long-term strength will be. In turn, the plastic properties of compressed concrete directly depend on its strain rate. Therefore, the lower the strain rate of the concrete, the lower its long-term strength will be. The calculations carried out fully confirmed the above. The values of the levels of compressed concrete's long-term strength, calculated according to Formula (8) for its different classes at different strain rates, are given in the Table 2.

Table 2. Levels of long-term compressive strength of concrete at different strain rates

Concrete class	Level of concrete long-term strength	
	η_l ($\acute{\varepsilon} = 10^{-8}$ s^{-1})	η_{lu} ($\acute{\varepsilon} = 10^{-10}$ s^{-1})
C8/10	0.794	0.630
C12/15	0.808	0.654
C16/20	0.823	0.678
C20/25	0.835	0.697
C25/30	0.845	0.714
C30/35	0.854	0.730
C32/40	0.863	0.744
C35/45	0.869	0.756
C40/50	0.878	0.77
C45/55	0.884	0.782
C50/60	0.890	0.793
C53/65	0.896	0.803
C56/70	0.901	0.813
C60/75	0.907	0.823
C65/80	0.912	0.831
C70/85	0.916	0.839
C75/90	0.921	0.848
C80/95	0.924	0.854
C85/100	0.928	0.862
C90/105	0.932	0.868
C95/110	0.935	0.874
C100/115	0.939	0.881
C105/120	0.941	0.886

Source: authors' compilation.

DISCUSSION

It is apparent that the dependence of the main physical and mechanical characteristics of concrete on its strain rate can be applied to a general model of concrete deformation. One of the first to draw attention to this was Rüsch (1956, 1960). However, most of the functions of compressed concrete's long-term strength known today, which are obtained mainly empirically, do not reflect any analytical connection with its strain rate. In addition, these functions were determined to be completely independent of the class of the concrete itself. This is true even though it is very apparent that the level of plastic deformation, and therefore the level of long--term strength of a compressed concrete, directly depends on both its class and strain rate.

The peculiarity of Function (8) is that it is free of the above-mentioned disadvantages, since it was obtained analytically within the framework of a single methodological approach to predicting the strength of any class compressed concrete at any strain rate (Fig. 2).

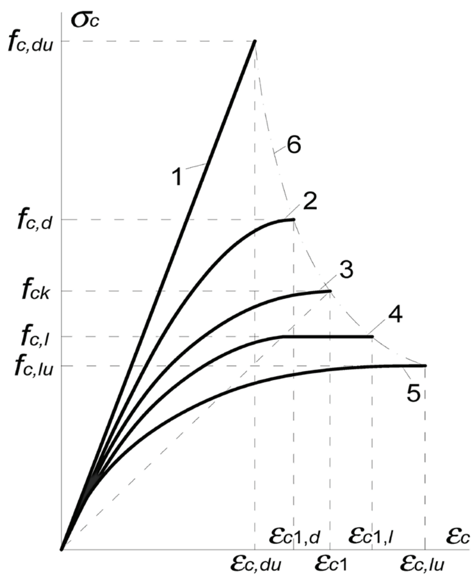

Fig. 2. Diagrams of compressed concrete deformation under different types and modes of loading: 1 – instantaneous; 2 – dynamic; 3 – short-term; 4 – long-term; 5 – extremely long-term; 6 – curve of limit deformations

Source: authors' compilation.

In order to evaluate the effectiveness of the developed method for determining the level of compressed concrete's long-term strength, the results of theoretical calculations according to expression (8) were compared with individual researchers' experimental data. All of them are displayed in Figure 3 and confirm that the lower limit of a compressed concrete's long-term strength should be predicted according to dependence (9).

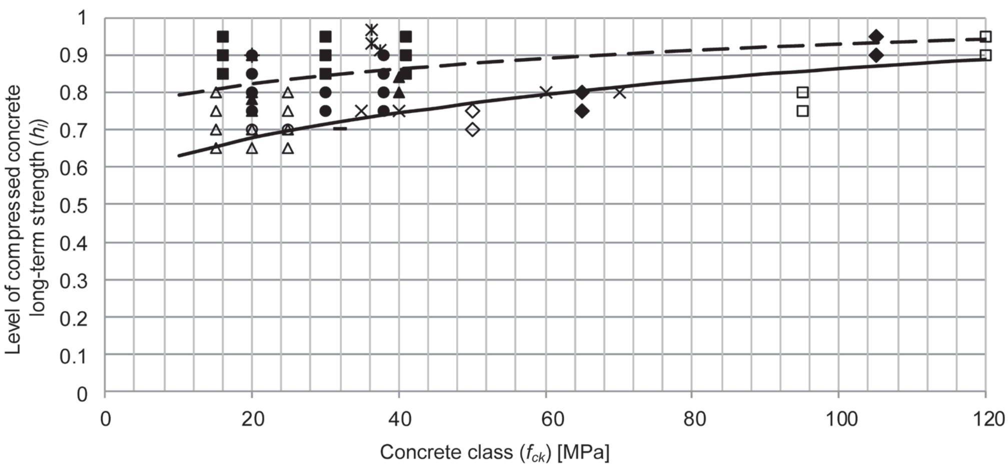

Fig. 3. Long-term strength of compressed concrete according to the results: of experiments with destroyed samples (▲ – Graf & Brenner, 1937; + – Shank, 1949; ● – Rüsch, 1956; ■ – Awad & Hilsdorf, 1971; × – Smadi et al., 1985; ◆ – Iravani & MacGregor, 1998; ⁎ – Tasevski et al., 2018) and with unbroken samples (– – Sell, 1959; △ – Yashin, 1969; ◇ – Stöckl, 1972; ○ – Smadi et al., 1985; □ – Iravani & MacGregor, 1998); calculations according to Formula (8) at strain rates ——— – $\acute{\varepsilon} = 10^{-10}\ s^{-1}$ and — — — – $\acute{\varepsilon} = 10^{-8}\ s^{-1}$

Source: authors' compilation.

CONCLUSIONS

The previously developed provisions and hypotheses of the energy model of concrete and reinforced concrete deformation confirm that:

- the foundations of the general model of concrete deformation under the action of long-term loads have been formed,
- for the first time, an analytical relationship has been proposed that links the level of compressed concrete's long-term strength not only with its defining elastic-plastic standardised characteristics under the action of short-term loads $k = E_{c0} \cdot \varepsilon_{c1} / f_{ck}$, but also with the concrete's strain rate $\acute{\varepsilon}$,
- the resulting dependence makes it possible to control the entire process of compressed concrete deformation in concrete and reinforced concrete elements and structures under the action of long-term loads and predict the level of its long-term strength.

In general, the above research results open up wide opportunities in the development of a universal calculating method of reinforced concrete elements and structures under any duration of the action of loads.

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PROGNOZOWANIE DŁUGOTRWAŁEJ WYTRZYMAŁOŚCI BETONU ŚCISKANEGO

STRESZCZENIE

Tematem artykułu jest charakterystyka cech odkształceń betonu ściskanego pod wpływem obciążeń długotrwałych. Celem badań, zaprezentowanych w artykule, było ustalenie zależności analitycznej na określenie poziomu wytrzymałości długotrwałej betonu ściskanego. Zastosowano hipotezę niezmienności i niezależności od sposobu obciążenia betonu konkretnej energii potencjalnej jego ostatecznego odkształcenia (zniszczenia). Dzięki krytycznej analizie prac innych badaczy uzyskano zależność funkcyjną poziomu wytrzymałości długotrwałej betonu ściskanego nie tylko od jego znormalizowanych charakterystyk sprężysto-plastycznych, lecz także od szybkości odkształcenia betonu. Ocenę proponowanej metodyki określania poziomu wytrzymałości długotrwałej betonu ściskanego sprowadza się do porównania odpowiednich wyników obliczeń teoretycznych z opublikowanymi danymi eksperymentalnymi różnych badaczy.

Słowa kluczowe: beton, model energetyczny, właściwa energia potencjalna, szybkość odkształcenia, poziom wytrzymałości długotrwałej