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EFFECT OF LONG-TERM LOADING AND FIRE TEMPERATURES ON MECHANICAL PROPERTIES OF CONCRETE

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Abstract. During a fire, reinforced concrete structures are exposed to high temperatures and subjected to long-term action of variable and permanent loads. This paper deals with analysis of influence of fire temperatures and long-term action of loads on compression strength and deformability of normal weight concrete. Results of experimental investigations of compression strength and deformability of normal-weight concrete subjected to long-term load and exposed to high temperature are presented. Specimens in the shape of prisms of normal-weight concrete were subjected to long-term compression of intensity $\eta(t) = \sigma_c / f_c(\tau) = 0{,}3$. The long-term compression was sustained for 400 days. Some of the specimens were heated (at 250 °C and 450 °C) before application of long-term load; other specimens were heated after application of long-term load. The paper presents coefficient of service conditions for concrete subjected to long-term load and exposed to high temperature that gives opportunity to evaluate compression strength and deformation properties of concrete.

Keywords: concrete, long-term load/loading, fire temperatures, compression strength, deformations.

1. Introduction

Often it is essential to predict influence of long-term loads and fire temperatures on the strength of concrete. This evaluation is required for rehabilitation, strengthening or reconstruction of structures. When influence of loads on the physical and mechanical properties of concrete in structures is known in advance, it is possible to forecast the strength of concrete subjected to the action of long-term loads and exposed to high temperatures.

Concrete in structures and elements is subjected to long-term either compression or tension due to long-term loads, but its failure takes place due to compression or tension stress. Thus, concrete under long-term compression can break due to compression or tension with application of corresponding additional short-time action, and similarly, concrete under long-term tension can break due to additional short-time compression or tension. Further on, these possible cases of failure are referred to as „compression-compression“, compression-tension“, “tension-compression“, and „tension-tension“ [1–5]. In these tests only “compression-compression“ cases of failure are investigated. The long-term load acting on the specimen was removed and the specimen was subjected to short-time compression load up to destruction.

Actual performance of concrete in reinforced concrete structures is modelled by application of short-term loads without reloading. The value determining the character, time and intensity of the loading is intensity of the initial stress $\eta(\tau) = \sigma_c / f_c(\tau)$.

For investigation of state of structures exposed to fire temperatures or calculation of carrying capacity it is necessary to assess compression strength of concrete f_c as accurately as possible. In this case influence of high temperatures on concrete strength is very great. The influence of temperature on strength and deformations of concrete subjected to short-term loads is sufficiently investigated in many works [6–15].

The goal of this investigation is to study the influence of long-term loads and fire temperatures on mechanical properties of concrete.

2. Effect of long-term loading on concrete compressive strength

Opinions of investigators about the influence of „compression-compression” on physical-mechanical properties of concrete coincide [1–3]. Analysis of experimental data presented in publications, which are not numerous, indicate that in the case of “compression-compression” there is a positive effect of long-term loading on the concrete even when initial compression stress intensity $\eta(\tau)$ is low (Fig 1).

Positive effects of long-term compression can be described by several inter-related factors, effective in all loading, compression and failure stages.

The initial compression with the intensity of $\eta(\tau)$ = 0,3–0,6 positively effects the formation of concrete structure and strengthens the matrix of concrete under compression.

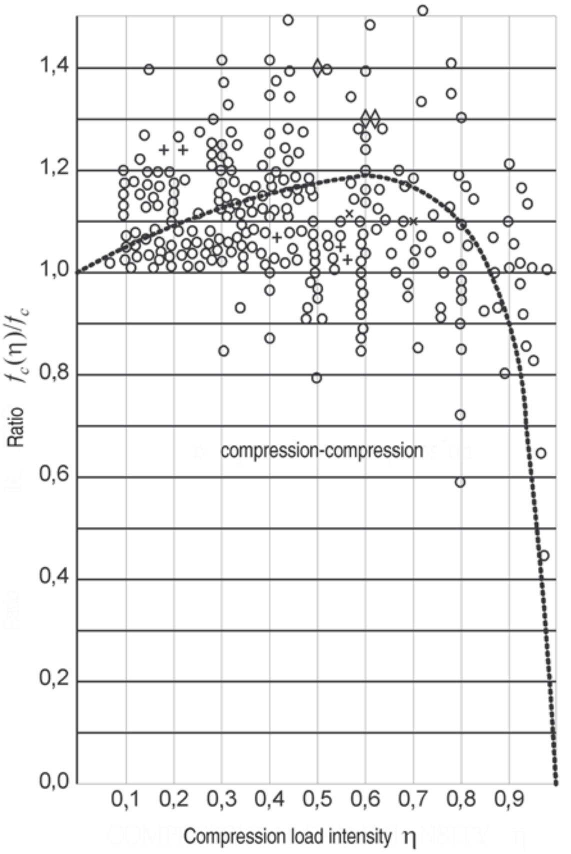

Fig 1. Influence of long-term compression of concrete on short-term compression strengths of concrete according to experimental data by Makarenko [1], Azirov [2], Kudzys – Papinigis [3], Karapetian [4]

The effect of stress intensity is associated with the lower limit of micro-cracking. When $\eta(\tau)>0,4$, a decrease in compression strength is observed and none of the theories on strength of concrete structure is able to explain why when compression stress intensity is reached at which new micro-cracks occur and the former ones continue to develop, the structure of concrete is able to stabilise deformations and retain strength. Increase in modulus of elasticity of concrete is 12–15 %. It is evident that the more defects are there in the concrete structure before loading, the larger concrete deformations are obtained in the initial loading stage. Such defects are insufficient contact between aggregates and cement stone due to evaporation of water, cracks of various origins. Under the action of long-term load transverse cracks close and the concrete structure thickens. According to [13], the surfaces of transverse cracks due to elastic deformations come closer by

$$\Delta l = \frac{\sigma_c}{(1-S)}\frac{1}{E_c}\chi, \qquad (1)$$

where σ_c – average stresses in the concrete; S – area of the cracked cross-section; E_c – elasticity modulus of the concrete; χ – distance between the cracks. Consideration of results obtained from expression (1) indicate that surfaces of the cracks come closer with increase in compression stresses σ_c by larger value of the distance Δl for lower values of E_c. Also it can be noted that opening of cracks and defects under the action of loading are effected by the distance between cracks χ characterising the amount of cracks in the unit volume of the concrete.

When the amount of defects (cracks and other damages) in the concrete structure is larger, local stresses will have a greater effect on the initial deformation of the concrete and especially in the initial loading stage when stresses σ_c are relatively low. Further closure of cracks proceeds with time due to creep deformations, which is followed by the thickening of structure of the concrete.

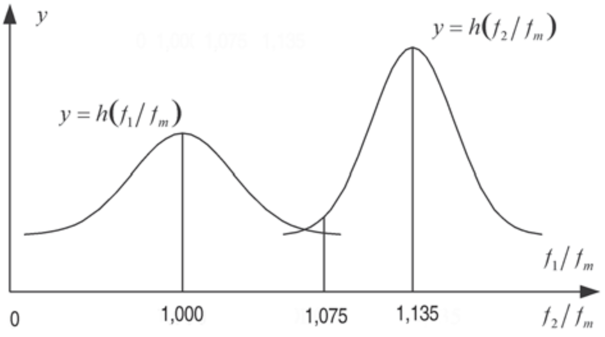

Fig 2. Density of reliability distribution for relative increase in concrete strength f_i/f_m without pre-compression $y=h(f_1/f_m)$ and for pre-compression with long-term load $y=h(f_2/f_m)$; $\gamma_{c,lt}$=1,075 – design value for the factor of service conditions for concrete under long term compression

It was established from available experimental data that coefficient of service conditions for concrete under long-term compression, which takes into account intensity of initial compression, concrete age and compression duration is $\gamma_{c,lt}$= 1,075. In this case intensity of initial compression stress is in such a range that an increase of concrete strength is guaranteed by reliability of 95 % (Fig 2). When quasi-short-time part of the load is applied without reloading, $\gamma_{c,lt}$= 1,14 [3].

3. Effect of fire temperatures on mechanical properties of concrete

It has been established by investigations that the compression strength of concrete begins to decrease at fire temperatures of 60–90 °C. This decrease may reach up 20–30 %. With a temperature rise up to 200–300 °C, the increase in concrete compression strength due to additional thickening of concrete structure is observed.

With a further temperature rise compression strength decreases. Often at temperatures over 500 °C dehydration of Ca(OH)2 starts resulting in strength reduction of hardened cement paste and of concrete as well.

Usually investigation of influence of fire temperatures on physical-mechanical properties of concrete is limited by standard tests on heated concrete with short-term static load. The same may be said about investigations of influence of long-term load on concrete properties as well, ie often such investigations are performed dissociated from environment and consequently from the effect of temperature.

During a fire reinforced concrete structures are exposed to high temperatures and subjected to variable and permanent loads that have been acting for a long time. Structures can be exposed to fire temperatures when they are not loaded yet or still partially loaded, thus structures exposed to fire temperatures later can be subjected to full service loads.

In the analysis of performance of structures exposed to fire temperatures it is very important to evaluate the effect of long-term loads as well.

Variations with temperature of compression strength f_c of light-weight and normal-weight concrete with Portland cement exposed to fire temperatures are similar. Compression strength f_c of haydite (keramzit)-concrete heated up to 200–400 °C and then cooled down increased by 10–20 %, and that of one heated up to 500–600 °C decreased by 30–40 % in comparison with the initial strength. Compression strength f_c of non pre-compressed haydite-concrete and of normal-weight concrete reduced by 20–30 % more than that of pre-compressed up to 0,2–0,3 f_c ones before heating [10].

Effect of temperature and long-term loading on properties of the concrete is governed by changes in the structure of the concrete. These changes in its own way affect failure mode of the concrete under compression. The best indication of such a failure is micro-cracking.

The micro-cracking can be assessed by variation of transverse deformations n and relative volumetric deformation Θ with an increase in compression stress [13].

Characteristic parametric point is defined by the stress $\sigma_{cr,1}$, under the action of which the volume of the concrete attains its minimum value.

Relative change of the concrete volume in comparison with the initial state is determined by:

$$\varepsilon_1 = -2(\varepsilon_2)\,, \tag{2}$$

where ε_1 – longitudinal, ε_2 – transversal deformations.

The minimum value of the concrete volume is determined by the condition

$$\left.\begin{aligned}\Delta\varepsilon_1 + 2\Delta\varepsilon_2 = 0 \text{ or}\\ \Delta\varepsilon_2/\Delta\varepsilon_1 = -0{,}5\end{aligned}\right\}. \tag{3}$$

This condition is applied for determining the stress $f_{cr,1}$.

The decrease in volume of the concrete corresponds to the minimum value of the volumetric strain, which is determined by expression

$$\Theta = \varepsilon_1(1 - 2\nu)\,. \tag{4}$$

4. Materials, specimens and method of tests

In this investigation the influence of long-term loads and fire temperatures on concrete compression strength f_c and deformations was studied by testing 100×100×400 mm concrete prisms and 100×100×100 mm cubes. All specimens were made of normal-weight concrete mixture of the same composition. Crushed stone of local gravel, quartz sand and CEM 40 cement were used for concrete mixtures. The specimens were subjected to a long-term load with intensity of $\eta(\tau) = 0{,}3$. A part of the prisms was heated before subjecting them to a long-term loading, the other part was heated after long-term loading. The age of concrete at the moment of loading was 72 days. The specimens were kept under long-term load conditions for 400 days.

The samples were heated at 250 and 450 °C temperatures. The rate of increase in temperature was 150 °C/h. At the constant temperature the specimens were heated for 4 hours, then immediately taken out of the oven, cooled in the air and after 7 days tested under short-term compression static load up to destruction, with the other part of specimens subjected to a long-term compression load. When the specified time period expired, the long-term load was removed and the specimens were tested for short-time compression load up to destruction in the same way as other specimens.

Long-term tests were carried out in a special chamber at constant ambient temperature and humidity; ambient temperature was +18 °C and relative air humidity 75–80 %. The specimens were subjected to long-term compression loading in special presses via springs. Part of the specimens was tested under short-term load for determining the concrete compression strength at the moment of application of long-term loading. Together with pre-compressed specimens under the same conditions non-loaded specimens were kept for shrinkage tests and determination of influence of long-term loading on mechanical properties of concrete. Strength and deformation properties of specimens are presented in Table.

5. Results of experimental investigations

The temperature influence on concrete strength is evaluated by coefficient $k_c(\theta)=f_{c,\theta}/f_c$, which indicates a decrease in concrete compression strength due to exposure to fire temperatures. Usually this coefficient is determined by tests of short-term loading of concrete specimens exposed to high temperatures.

Results of experimental investigations in compression strength and deformability of concrete exposed to fire temperature and subjected to long-term loads are presented in Table and Figs 3, 4.

Results of experimental investigations presented in Table and in Figs 3 and 4 indicate that the compression strength and elasticity modulus of concrete depend not only on the exposure to fire temperatures but on the action of long-term loading and succession of exposure to

Results of experiments on concrete exposed to fire temperatures and subjected to long-term compression

Description of treatment of specimens	Specimen No	Temperature °C	Compression strength of prism f_c, MPa	Elasticity modulus $E_c \times 10^{-4}$, MPa	$\frac{f_{c,\theta}}{f_c}$	$\frac{E_{c,\theta}}{E_c}$	Poisson's ratio
Control specimens, tested before application of long-term load	1,1	20	35,87	2,77	1	1	0,21
	1,2	250	28,5	2,13	0,79	0,77	0,19
	1,3	450	21,4	0,66	0,6	0,24	0,12
Heated and then subjected to long-term load	2,1	250	28,73	1,64	0,71	0,55	0,18
	2,2	450	19,64	0,73	0,43	0,25	0,18
Heated after long-time action of load	3,1	250	27,71	1,35	0,68	0,45	0,11
	3,2	450	17,51	0,51	0,43	0,17	0,12
Control specimens, subjected to the action of long-term load	4,1	20	40,6	2,97	1	1	0,17
Control specimens, tested after 400 days	5,1	20	39,9	2,95	1	1	
	5,2	250	29,7	1,98	0,74	1,67	0,5
	5,3	450	24	1,08	0,60	0,37	0,35
Control specimens, not subjected to long-time load action, tested after 400 days	6,2	250	30,97	2,09	0,78	0,71	0,6
	6,3	450	22,9	1,05	0,57	0,36	0,23

high temperature and action of long-term loading as well. Prism compression strengths of concrete not subjected to the action of long-term loading and heated at 250 °C and 450 °C temperatures decreased by 20 % and 40 % respectively.

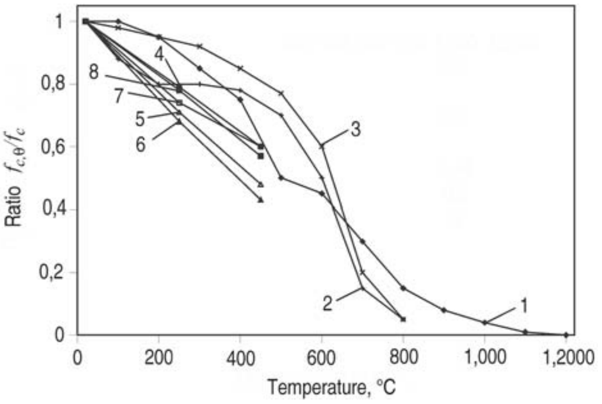

Fig 3. Influence of fire temperature and long-term loading on concrete compression strength

The age of concrete has almost no effect on the compression strength decrease due to the exposure to fire temperature. Influence of fire temperature on prism compression strengths of concrete was similar for concrete irrespective of whether it was heated after 72 days of its hardening (control specimens) and then tested after 400 days by short-time load or it was stored for 400 days at normal temperature and heated before the test (Table).

Results presented in Fig 3: 1 – in accordance with EC2 [16]; 2 – in accordance with [11]; 3 – in accordance with [11] at $\eta(\tau)$= 0,3; 4 – control tests of authors on specimens before long-term loading; 5 – tests of authors on specimens initially heated and then subjected to long-term loading; 6 – tests of authors on specimens subjected to long-term loading and then heated; 7 – tests of authors on control specimens heated and tested after 400 days; 8 – tests of authors on control specimens not subjected to long-term loading and tested after 400 days.

The decrease in compression strength for the concrete that was heated and then subjected to long-term loading was less than that for the concrete initially subjected to a long-term load and then heated. This difference was just about 4 % and 11 % for the concrete heated at 250 °C and 450 °C temperatures respectively.

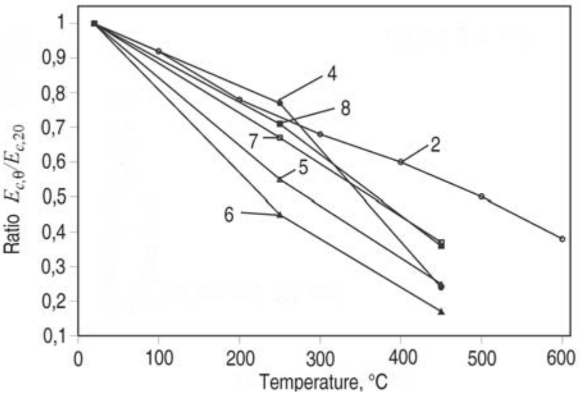

Fig 4. Influence of fire temperature and long-term loading on elasticity modulus of concrete in compression (notations as in Fig 3)

It is obvious from comparison of the coefficient of service conditions for compression strength of concrete exposed to fire temperatures determined on the basis of experimental data with these determined by other authors and recommended by EC2 (at fire temperatures of 250 °C and 450 °C the value of coefficient $k_c(\theta)$ is equal to 0,9 and 0,72 respectively) that coefficient of service conditions for concrete subjected to the action of long-term loads and exposed to high temperatures is less than that recommended by other authors and by EC2. Seeking to evaluate as accurately as possible the effect of fire temperature on compression strength of concrete, it has to be performed in association with the effect of long-term load on compression strength of concrete.

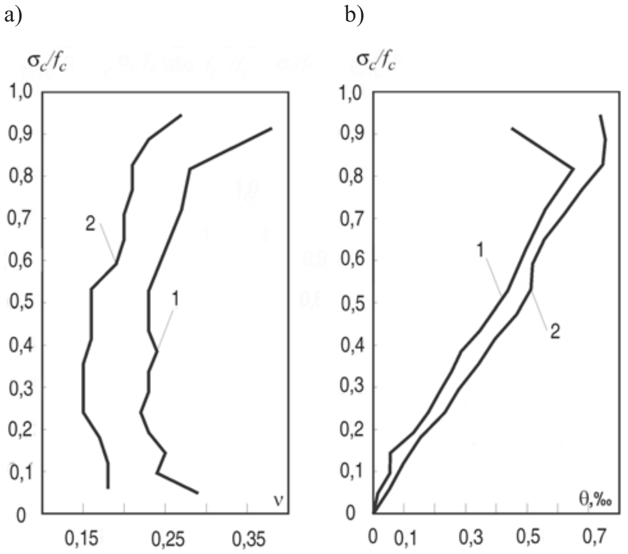

Fig 5. Variation of coefficient of transverse deformations ν (a) and relative volumetric deformation Θ (b): 1 – control specimens tested before subjection to long-term load (t = 20 °C); 2 – tests of specimens subjected to long-term load (t = 20 °C)

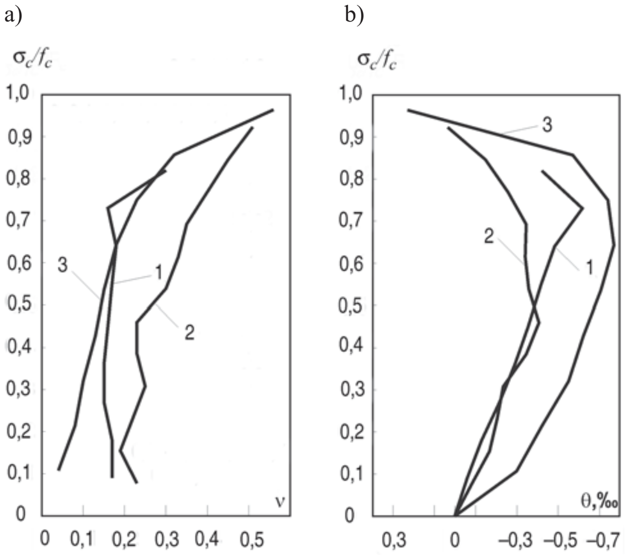

Fig 6. Variation of the coefficient ν (a) and relative volumetric deformation Θ (b) for the concrete heated at temperature of 250 °C: 1 – control specimens tested before subjection to long-term load; 2 – specimens heated, then subjected to loading; 3 – specimens subjected to long-term load, then heated

After analyses of relative volumetric deformations of the concrete for specimens exposed to the fire temperatures and subjected to long-term loading, the following tendencies can be observed. From graphs in Figs 5–7 one can notice that effect of long-term loading for concrete exposed to the fire temperature is less than that in the case when it is exposed to the fire temperature after long-term loading. Relative volumetric deformation for the concrete heated at temperatures of +250 °C and +450 °C before long-term loading is achieved at the relative stress σ_c/f_c values of 0,26 and 0,46 respectively. It indicates that the failure of the structure (opening of micro-cracks) for the concrete heated at the temperature of 450 °C begins much earlier. It influences compression strength of the concrete (Table).

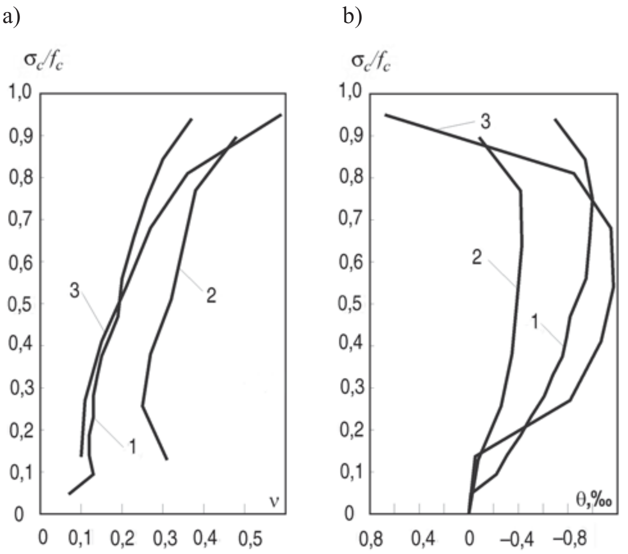

Fig 7. Variation of the coefficient of transverse deformations ν (a) and relative volumetric deformation Θ (b) for the concrete heated at temperature of 450 °C: 1 – control specimens tested before subjection to long-term load; 2 – specimens heated, then subjected to loading; 3 – specimens subjected to long-term loading, then heated

Numerical values of relative volumetric deformations for the concretes heated at fire temperatures of +250 °C and +450 °C after long-term loading are much greater (Figs 6 b, 7 b). It indicates that the failure of structure in such concretes begins much earlier – at the values of relative stresses σ_c/f_c equal to about 0,21–0,3. It is recommended to take this into account in state assessment and design of rehabilitation for structures exposed to fire temperatures.

6. Conclusions

Compression strength and elasticity modulus of concrete depend not only on exposure to high temperatures, but also on the action of long-term loading and on the sequence of long-time action of loads and exposure to high temperatures.

Decreases in compression strength of concrete are less when the concrete is initially heated and then subjected to the action of long-term loads in comparison with the concrete that is initially subjected to the action of long-term loads and then heated. The value of the coefficient of service conditions for the concrete subjected to the action of long-term loads and exposed to high temperature $k_c(\theta)$ is less than that recommended in EC2.

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ILGALAIKĖS APKROVOS IR GAISRO TEMPERATŪRŲ ĮTAKA BETONO MECHANINĖMS SAVYBĖMS

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Santrauka

Nagrinėjamas gaisro temperatūrų ir ilgalaikės apkrovos poveikis sunkiojo betono gniuždomajam stipriui ir deformacinėms savybėms. Pateikiami ilgalaike apkrova ir aukšta temperatūra paveikto sunkiojo betono stiprumo ir deformacijų tyrimo rezultatai. Sunkiojo betono bandiniai – prizmės, apkrautos ilgalaike gniuždančia apkrova, kurios intensyvumas $\eta = \sigma_c / f_c = 0{,}3$. Ilgalaikių bandymų trukmė – 400 parų. Dalis bandinių kaitinti (temperatūra 250 °C ir 450 °C), prieš juos apkraunant ilgalaike apkrova, kiti bandiniai kaitinti po to, kai buvo apkrauti šia apkrova. Pateikiami ilgalaike apkrova ir aukšta temperatūra paveikto betono patikimumo koeficientai, leidžiantys įvertinti betono gniuždomąjį stiprį ir deformacines savybes.

Raktažodžiai: betonas, ilgalaikė apkrova, gaisro temperatūros, gniuždomasis stipris, deformacijos.

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