BUILDING MATERIALS AND PRODUCTS

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STRENGTH AND PERFORMANCE OF RUBBER CONCRETES

Problem statement. Rubber concrete, a modern construction material, is formed by synthetic binder and mineral filler and it possesses a number of valuable and unique properties.
Results and conclusions. Applicability of a dynamic loading method for rubber concrete durability calculation has been analyzed. The method of estimation of unknown parameters in expression of durability by results of measurements of prism has been proposed. Mathematical processing of results of measurements of rubber concrete prism strength at different temperatures with the use the method suggested has been presented. Calculated values are in good agreement with the experimental values.

Keywords: rubber concrete, rubber matrix, composite material, strength, performance, dynamic loading method.

Introduction

One of the basic mechanical property of construction materials is defined as resistance to plastic flow, failure and cracks development. Strength as a property of matter is determined by many factors such as a substance’s internal structure and external factors as well. Rubber concrete, a modern construction material, is formed by synthetic binder and mineral filler and it possesses a number of valuable and unique properties. Heterogeneous structure and presence of organic binder leads to significant dependence on material strength in extreme temperature conditions. Presently the problem of rubber concrete ultimate strength performance assessment at various temperature effects such as fires, heat, freezing, etc.

1. Analysis of applicability of a dynamic loading method for rubber concrete durability calculation

Rubber concrete temperature rise and fall immensely influence its mechanical properties. In negative temperature areas ultimate strength increases, plasticity therewith decreases. Temperature rise thus leads to opposite relationships [1].Construction material is typically placed under constant working pressure and exposed to temperature change. The joint influence of these factors result in a more drastic change in mechanical properties than temperature and time effects.

At constant pressure as well as at cyclic one there is damage accumulation in rubber concrete. The relation between time before the failure (static durability) τ and the level of long-time static loading with level σ_τ takes the form of power law:

$$\tau^{m_\tau}\sigma_\tau = C_\tau, \tag{1}$$

where m_τ, C_τ are material constants.

At equal levels of stress ($\sigma_\tau = \sigma_a$, where σ_a is stress cycle amplitude) static durability values are more than the cyclic ones, since during static stress the influence of relaxation processes which lower stress concentration at micro- and macro levels is more significant. Long-time static loading may be considered a special case of high-cycle $\sigma_m = \sigma_\tau$ with mean stress and amplitude $\sigma_a = 0$.

The analogy of pressure and temperature influence is traced in the fact that pressure increase brings about changes similar to those during cooling: an increase in density of the material and in limit stress, transition between liquid to solid state. The joint influence of temperature and pressure, as a rule, is stronger than this of separate effects, which also testifies about a complicated temperature-time relation of solid bodies strength [2, 3].

Durability as a stress function σ and absolute temperature (T) in kinetic thermofluctuation theory of solid bodies strength and failure is expressed through a formula justified and experimentally proved by academician S. N. Zhurkov which was later modified by S. B. Ratner by introduction of the fourth constant. This formula is in good agreement with experimental values for solid bodies. The generalized formula for brittle and plastic failure takes the following form:

$$\tau = \tau_m exp\left(\frac{U_m - \gamma\sigma}{RT}\left(1 - \frac{T}{T_m}\right)\right), \quad (2)$$

where U_m is failure activation energy ($U_m = E_a$ is thermochemical destruction activation energy); T_m is limiting temperature at higher values of which material does not perform, the value $1/T_m$ is called the pole shift (from *Y*-axis); τ_m is the minimal durability under any load or without any; multiplier $\left(1-T/T_m\right)$ sets up temperature limits for primary splitting of these or those bonds in the material [2, 3]. The equation (2) expresses force temperature time analogy rule. Basic parameters for durability of any material will be defined in case a few constants are known. $\left(\gamma, U_m, T_m, \tau_m\right)$. Since it is easier to preset stress and temperature, in actual practice durability of strength type (i.e. values of constants γ, U_m, T_m, τ_m) is suggested to be determined at a number of pre-assigned stresses and temperatures.

In [2, 3] experimental measurements were taken in order to determine rubber concrete constants γ, U_m, T_m, τ_m. The time before sample failure (durability of strength) was defined by lateral bending under constant stress. The tests were performed on a single-station bench under two equal forces at stress level at a beam mean point of 5.7, 6.1 and 6.5 MPa and at constant temperature ranging from 60 to 100 ºC. Durability values defined for various temperatures and stresses vary from 3 minutes at 105 ºC and stress of 5.7 MPa to 552 minutes at 65 ºC and stress of 6.07 MPa.

In order to determine material physical constants, the experimental data were processed in the coordinates $"lg\left(\tau\right) - 1/T_m"$. The experimental data were plotted on the plane, the values at equal parameters were approximated with a graphically straight line. The lines at different stress levels were prolonged into the limiting areas till intersection. The coordinate of the intersection point specified the parameters T_m, τ_m. The parameters γ, U_m were determined by effective energy activation and stress relation:

$$U(\sigma) = \frac{2.3R\Delta\lg\tau(\sigma)}{\Delta 1/T}. \qquad (3)$$

The value U is calculated and the plot $U(\sigma)$ is drawn for each single load. The value γ is determined by the tangent of the intersection line angle $"U - \sigma"$, and U_m is the line ordinate, $"U - \sigma"$ is the ordinate at its extrapolation to no-load. The values of strength constants calculated for asbestos fibre rubber and epoxy are given in Table 1 [3].

Table 1

Polymer composites strength constants

Polymer	Filler	Filler content, %	Stressed state type	U_m, kJ/mol	$\lg(\tau_m)$, c	γ, $\frac{\text{kJ×mm}}{\text{mol×H}}$	T_m, $10^{-3} K^{-1}$
Rubber	Sand, crushed rock	90	Bending	293.9	-1.6	25.7	2.15
Rubber and epoxy	Asbestos fibre	60	Bending	198	-0.8	2.9	2.2

The method considered requires a long-time sample observation and repetition for each external parameters relation as well in order to provide the prescribed statistical accuracy. The time of observation restricts the temperature range where the measurements may be practically realized. In the area of low and negative temperatures the restriction is related to the problem of cryogenic system building and a significant increase in the amount of time of observation as well. Carrying out these experiments is labour- and money-consuming.

2. Mathematical processing of results of measurements of rubber concrete prism strength

In the process of investigation of building materials and concrete in particular measurements of prism strength, modulus of elasticity and Poisson's ratio are carried out (according to GOST (State Standard) 24452-80). Such measurements of rubber concrete parameters were performed at different temperatures in 2007 [1]. They involved loading rubber concrete samples in a stepwise manner by 10% from the assumed material failure limit $\sigma_{ПЧ}$ and holding it for 15 minutes on each stage. Within each stage the value of loading speed is (0.6 +/- 0.2) MPa/sec (Table 2).

Table 2

Rubber concrete characteristics

Characteristics	Temperature t, °C / measurement number									
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
	-75	-60	-40	-20	-10	0	20	40	60	80
$\overline{R}_{npt}$, MPa	123.5	121.4	116.2	111.0	106.5	104.4	103.8	91.7	82.5	64.1
$m_{\sigma t}$	1.19	1.17	1.12	1.07	1.03	1.01	1.00	0.88	0.80	0.62
$\overline{E}_t$, MPa	30100	29250	25650	24350	23550	22600	22300	21900	19600	11650
β	1.35	1.31	1.15	1.09	1.06	1.01	1.00	0.98	0.88	0.50
$\overline{\varepsilon}_{npt}$, %	0.0074	0.0076	0.0077	0.0079	0.0081	0.0085	0.0086	0.0093	0.0114	0.0212
a	0.86	0.88	0.90	0.92	0.94	0.99	1.00	1.09	1.33	2.47

Basing on prism strength measurement similarity $\overline{R}_{npt}$, MPa and sample loading limit value σ_p, MPa, let us assume that $\overline{R}_{npt} = \sigma_p$, MPa. The above described sample loading is complex dynamic.

The theory of thermofluctuational nature of strength may be as well applied to the cases of complex loading mode, since failure is an irreversible process taking place in time as accumulation of certain bonds splits; these splits do not vanish after a solid body unloading [3]. For any case of external factor failure is considered a process of damage accumulation in time. Then, if $\tau_i[\sigma_i; T_i]$ is solid body durability at constant pressure σ_i and external temperature T_i, within the time $t_i < \tau_i$ when placed in these temperature and force conditions, the material will run out of some of its resource of durability equal to $t_i / \tau_i[\sigma_i; T_i]$.The remaining resource is a part equal to $1 - t_i/\tau_i\left[\sigma_i; T_i\right]$. With the same damage mechanism if loading mode may be assumed step-by-step (i = 1, 2, 3,…, n), the ultimate failure taking the form of material splitting into parts will occur when the resource of durability is fully exhausted:

$$\sum_{i=1}^{n} \frac{t_i}{\tau_i\left[\sigma_i, T_i\right]} = 1. \quad (4)$$

If stress $\sigma(t)$ and temperature $T(t)$ are not constant but slowly changing in time, the failure condition may be presented in the integral form:

$$\int_0^{\tau_p} \frac{dt}{\tau\left[\sigma(t), T(t)\right]} = 1, \tag{5}$$

where τ_p is the time since the moment of loading beginning to the complete failure; $\tau[\sigma(t). T(t)]$ is a mathematical model of strength temperature-time plot. The conditions (4) and (5) are called the time summation principle. The failure criterion in the form of this principle was suggested by J. Bailey in 1939.

Taking into account the strength time dependence equation (2) formulated with the use of the Bailey criterion (5), we get the following for step-by-step loading:

$$\sum_{i=1}^{n} \frac{t_i}{\tau_m \exp\left(\frac{U_m - \gamma \cdot \sigma_i}{RT_i}\left(1 - \frac{T_i}{T_m}\right)\right)} = 1. \tag{6}$$

The equation for continuous loading takes the following form:

$$\int_0^{\tau_p} \frac{dt}{\tau_m \exp\left(\frac{U_m - \gamma\sigma(t)}{RT(t)}\left(1 - \frac{T(t)}{T_m}\right)\right)} = 1, \tag{7}$$

it also allows to predict the time of failure beginning t_p and the limit stress value $\sigma(t_p) = \sigma_p$ for different loading modes $\sigma(t)$.

The application of the summation principle was put forward by S. V. Zhurkov in 1959 as a means of durability assessment at single-stage static loading with constantly growing force and at loading with П-shaped cycles.

In order to test the application of the dynamic method of loading while taking measurements of prism strength to material durability calculation mathematical processing of the experimental data presented in Table 2 was performed. In view of the identity $\bar{R}_{npt} \equiv \sigma_p$ in the calculations by stress limit value σ_p we will basically mean an experimentally measured prism strength (see Table 2).

Let us find out the expression for equivalent continuous changes $\sigma(t)$ at step-by-step loading in the method of rubber concrete strength measurement: $\sigma_э(t) = t/900$, N/mm^2. Basing on the stress limit value for rubber concrete at 20 ºC equal to 103 MPa, a step of pressure change is 10 MPa and exposure time is 900 c. As seen from Table 2, not all values of prism strength are equal to 10 MPa. Whole numbers of continuous loading stages a sample underwent without a failure at a corresponding temperature was defined as a value equal to a whole number from division of limit prism strength by a loading step. The fractional part was used for the evaluation of generalized time for limit stress achievement needed to reach the limit stress calculated by the function inverse to $\sigma_э(t)$. Let us rewrite (6) in view of the below said information:

$$\sum_{i=1}^{N_j} \frac{t_s/\tau_m}{\exp\left(\frac{U_m - \gamma \cdot 10 \cdot i}{RT_j}\left(1 - \frac{T_j}{T_m}\right)\right)} + \frac{\tau_p - t_s/\tau_m}{\exp\left(\frac{U_m - \gamma \cdot \sigma_{p\,j}}{RT_j}\left(1 - \frac{T_j}{T_m}\right)\right)} = 1, \tag{8}$$

where t_s is the time of a stage of loading; T_j is the temperature j of the experiment; $\sigma_{p\,j}$ is limit stress of a failure at the temperature T_j. The unknown values γ, U_m, T_m, τ_m are to be calculated. With this aim in view, let us formulate a set of equations and write the expression (8) for at fewest four different values of the temperature T_j:

$$\begin{cases} \sum_{i=1}^{N_1} \frac{t_s/\tau_m}{\exp\left(\frac{U_m - \gamma \cdot i}{RT_1}\left(1 - \frac{T_1}{T_m}\right)\right)} + \frac{\tau_1 - t_s/\tau_m}{\exp\left(\frac{U_m - \gamma \cdot \sigma_{p1}}{RT_1}\left(1 - \frac{T_1}{T_m}\right)\right)} = 1; \\ \sum_{i=1}^{N_2} \frac{t_s/\tau_m}{\exp\left(\frac{U_m - \gamma \cdot i}{RT_2}\left(1 - \frac{T_2}{T_m}\right)\right)} + \frac{\tau_2 - t_s/\tau_m}{\exp\left(\frac{U_m - \gamma \cdot \sigma_{p2}}{RT_2}\left(1 - \frac{T_2}{T_m}\right)\right)} = 1; \\ \sum_{i=1}^{N_3} \frac{t_s/\tau_m}{\exp\left(\frac{U_m - \gamma \cdot i}{RT_3}\left(1 - \frac{T_3}{T_m}\right)\right)} + \frac{\tau_3 - t_s/\tau_m}{\exp\left(\frac{U_m - \gamma \cdot \sigma_{p1}}{RT_3}\left(1 - \frac{T_3}{T_m}\right)\right)} = 1; \\ \sum_{i=1}^{N_4} \frac{t_s/\tau_m}{\exp\left(\frac{U_m - \gamma \cdot i}{RT_4}\left(1 - \frac{T_4}{T_m}\right)\right)} + \frac{\tau_4 - t_s/\tau_m}{\exp\left(\frac{U_m - \gamma \cdot \sigma_{p1}}{RT_4}\left(1 - \frac{T_4}{T_m}\right)\right)} = 1. \end{cases} \tag{9}$$

The solution of this system of equations is analytically laborious, for it is formed by quickly oscillating functions with experimental values with errors. The solutions of the equations were performed by using a numerically iterative method with the help of the MathCAD package software. The solutions calculated by iterative approximation are heavily dependent on the choice of initial parameters of the estimated parameters. Preliminary estimation was carried out according to the results presented in Table 1. In view to the averaging, the following parameters were obtained (Table 3).

Table 3

Rubber concrete strength constants at dynamic loading

Polymer	Fillers	Filer content, %	Stressed state type	U_m, kJ/mol	τ_m, sec	γ, $\frac{kJ \times mm}{mol \times H}$	T_m, K
PBN	Sand, crushed rock	90	Bending	293	$6{\cdot}10^{-7}$	21	458

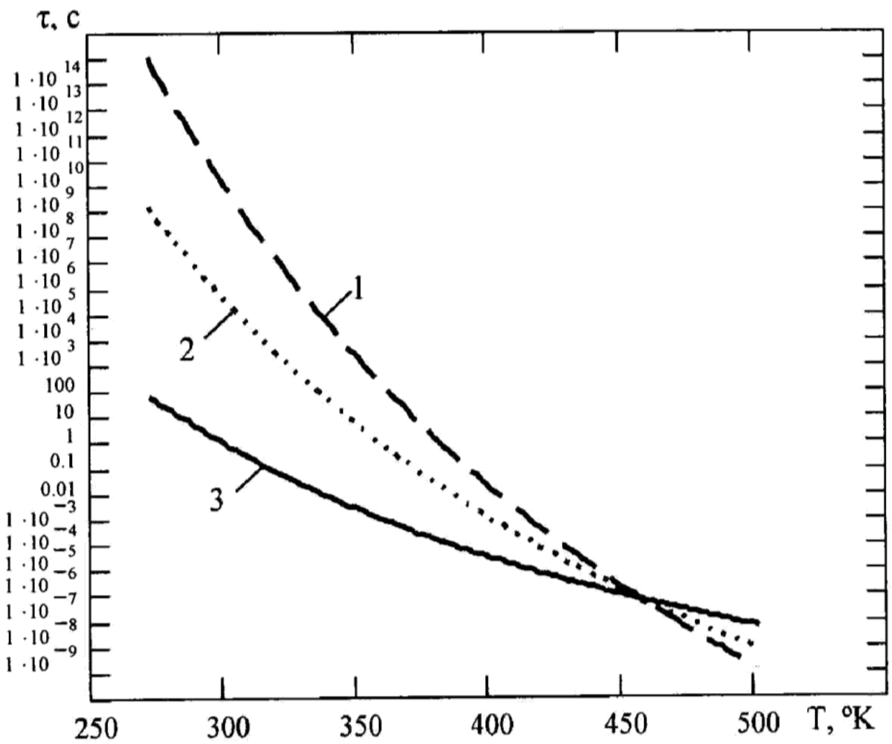

Fig. Rubber concrete durability

Let us find the time of failure (2) in view to the parameters from Table 3 for the temperature 20 ºC and pressure 103 MPa, the calculated value is τ = 2.8 sec.

In the Figure a set of curves calculated by experimentally obtained coefficients where curve 1 is 10 MPa, curve 2 is 50 MPa and curve 3 is 100 MPa. The relation shown above provides support for the above examined rubber concrete strength principles. Besides, the possibility of applying of the results of rubber concrete strength measurements for unknown parameters estimation in durability expression has been verified.

Conclusions

The experiments conducted display the possibility of the extension of information value of the method of rubber concrete strength experimental measurement when applied at various temperatures at the expense of the introduction of additional data mathematical processing.

The method suggested allows to reduce the labor content of rubber concrete durability measurements and financial expenses involved. The operability of the research can also be greatly enhanced.

The results of the presented mathematical calculations are physically justified and in good agreement with the experimental values.

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