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RHEOLOGICAL PROPERTIES OF ELASTOMERS IN COMPRESSION

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Creep processes associated with the uniaxial compression of rubber samples are studied in relation to the applied load and preliminary stressing. It is found that the delay time is influenced by the degree of compression.

Problems facing research workers concerned with engineering practice usually include that of allowing for the actual stressed state of materials when using these as construction elements. For many materials, however, constructions are calculated without allowing for their deformational anisotropy and the time dependence of their elastic characteristics. Many investigations have been concerned with the deformation characteristics of elastomers under tensile conditions [1]; compression has been far less considered, although rubber parts are often used under compressive conditions in practice. We therefore set ourselves the problem of studying the rheological properties of rubbers subject to the uniaxial compression of the samples.

The investigations were carried out in an apparatus (Fig. 1) facilitating the uniaxial compression of a cylindrical sample in accordance with a stepped loading program. At the instant of applying the load the readings of the indicators were recorded on a motion-picture film, which enabled the transient processes preceding steady-state creep to be studied. The deformations were measured during the transient processes by means of a capacitive sensor, to which an alternating voltage of frequency 1 MHz was applied, and an electron-beam indicator; after 120 sec, i.e., after the creep process had settled down, an indicator of the dial type was employed. In the first case the accuracy was $1 \cdot 10^{-6}$ m and in the second, $5 \cdot 10^{-6}$ m. In order to eliminate friction between the sample surfaces and the support we used a finely divided boron nitride powder. The samples took the form of cylinders 10 mm high; we studied samples of SKS-type rubber with an elastic modulus of 3.5 MPa. For a stepped loading program the apparatus allowed the mechanical behavior of the samples to be studied in two modes: a) the reaction of the sample to shock loading, which involved the development of an oscillatory transient process (from the characteristics of which the elastic properties of the

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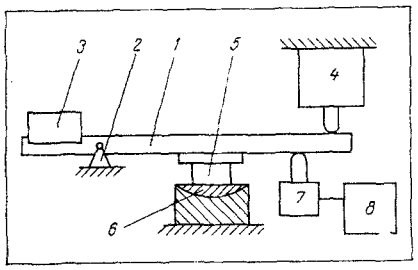

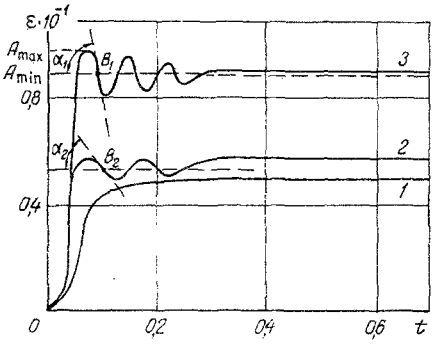

Fig. 1 Fig. 2

Fig. 1. Arrangement of the apparatus for the discrete loading of the sample: 1) lever; 2) lever rotation axis; 3) counterweight; 4) mechanical loading device; 5) sample; 6) floating support; 7) sensor; 8) indicator.

Fig. 2. Transient vibrational processes while loading; curves 1, 2, and 3 correspond to loads of 0.16, 0.28, and 0.5 MPa; t is in sec.

sample material could be judged; b) a monotonic time dependence of the deformation, i.e., creep per se; this section of the creep curve enabled us to calculate the relaxation characteristics and, in particular, to establish the delay time. The mass of the movable part of the apparatus was taken into account when analyzing the experimental results. The whole experiment lasted 8-12 h; then the load was removed and was applied again after the sample had rested for a day.

Figure 2 shows the $\varepsilon(t)$ relationship in the initial section. The oscillatory velocity was determined from the slope of the tangent at the point with the sharpest loading edge (in the figure point B); this was the maximum velocity. The greatest excursion of the horizontal part was taken as the peak value of A_{max}, and from these data we calculated the frequency of the vibrations, considering that for the maximum oscillatory velocity $\omega = v_{max}/A_{max}$. We see from Fig. 2 that as the load increases the frequency does likewise, the increment being some 45% for a threefold increase in load. Since the vibration frequency of the damped sample is proportional to $\sqrt{E}$ where E is Young's modulus, if we know the sample size and density we may calculate E. It follows from our measurements that for loads of 3.6, 5.5, and 8.4 MPa the value of E was, respectively, 0.1, 0.16, and 0.3 MPa.

Figure 3 illustrates the second part of the $\varepsilon(t)$ curves, i.e., the creep curves from which the deformation relaxation time (delay time) was also determined. For calculating the deformation relaxation time and other rheological characteristics we used the concepts of the theory of viscoelasticity, namely, the model of a standard linear body. We used the method of calculation proposed in [2], which facilitates calculations over a wide time interval. Tests at various load levels served as a basis for the use of this model. We created a stress σ_1 in the sample and plotted the creep curve $\varepsilon_1(t)$, noting the isochrones ε_1', ε_1'', etc. Then the same operation was carried out for loads σ_2 and $\sigma_3 = \sigma_1 + \sigma_2$. On the $\varepsilon_3(t)$ curve we noted the values $\varepsilon_1' + \varepsilon_2'$, $\varepsilon_1'' + \varepsilon_2''$, etc. The points lay on the curve $\varepsilon_3(t)$, so indicating the linearity of the deformation.

From the equation of a standard linear body

$$H\tau \frac{d\varepsilon}{dt} + E\varepsilon = \sigma + \tau \frac{d\sigma}{dt}. \tag{1}$$

Let us obtain the solution for a constant stress:

$$\varepsilon(t) = \varepsilon_0 + (\varepsilon_\infty - \varepsilon_0)\left[1 - \exp\left(-\frac{t}{\tau}\right)\right], \tag{2}$$

whence

$$\tau = -\frac{t}{\ln\left(1 - \dfrac{\varepsilon_t - \varepsilon_0}{\varepsilon_\infty - \varepsilon_0}\right)}, \tag{3}$$

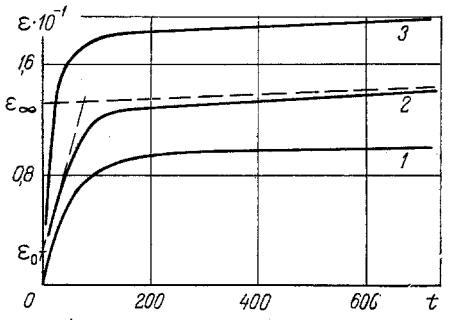

Fig. 3

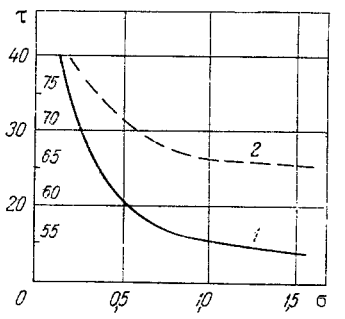

Fig. 4

Fig. 3. Steady creep processes. Curves 1, 2, and 3 are as in Fig. 2; $H = \sigma/\varepsilon_0$; $E = \sigma/\varepsilon_\infty$; t, sec.

Fig. 4. Deformation relaxation time as a function of pressure; the numbers to the right of the ordinate axis refer to a previously stressed sample: 1) sample loaded for the first time; 2) sample previously loaded to 2 MPa τ, sec; σ, MPa.

where τ is the deformation relaxation time; H is the instantaneous elastic modulus; E is the relaxation modulus; ε_t, ε_∞, ε_0 are the deformations at the current instant of time and the extrapolated values for $t \to \infty$, respectively. These values are shown in Fig. 3.

Experiments showed that the instantaneous and relaxation moduli of the materials under testing increased with rising load; however, this increment was not very great, since the ratio H/E was either constant or increased by 4-6%. The latter applied to samples which had not been loaded before the experiment. For samples previously compressed to a 10% deformation and then loaded in stages, the ratio H/E = const.

The results of our measurements of the deformation relaxation time as a function of stress are presented in Fig. 4. The dashed line relates to the sample "conditioned" by preliminary compression. We see from the figure that preliminary compression leads to creep retardation, which from the basic principles of viscoelastic theory indicates a relative weakening of the elastic properties of the material. For a sample not previously loaded $\tau(\sigma)$ is rectified in semilogarithmic coordinates, which corresponds to an exponential character of the relationship, since it may be represented by an equation similar to that obtained in [3] for the tensile strain of rubber vulcanizates at low temperatures, namely,

$$\tau = \tau_0 \exp\left(\frac{u_0 - \gamma\sigma}{kT}\right). \qquad (4)$$

The deformation relaxation time of the previously loaded sample cannot be approximated by Eq. (4); for such samples creep takes place more rapidly and varies less sharply with the load. We see from Fig. 4 that a slight preliminary compression produces strengthening of the material; this effect evidently bears an orientational character and expresses itself chiefly as an increment in elastic modulus and an acceleration of creep. At the same time, for uniaxial compression of the sample the latter may develop local bond ruptures in places at which, by virtue of structural inhomogeneities, the bonds were initially extended; this leads to an intensification of the yield processes. Depending on the stress level, the deformation process may be initiated either by the deviator part of the stress tensor alone or else governed by the necessity of allowing for the spherical part of the stress tensor as well.

It is well known that the model of a standard linear body assumes the existence of a directly proportional relationship between the relaxation and delay times, subject to the condition that the ratio of the instantaneous and relaxation moduli is constant. We may therefore assume that the stress relaxation time for the uniaxial compression of a sample loaded for the first time depends on the stress in exactly the same way as the delay time, i.e., obeys Eq. (4).

In samples not subjected to preliminary loading, the fall-off in deformation relaxation time for low levels of external load as the latter increases may be explained as being due to the distortion of the potential barrier overcome by the kinetic units, the distortion amounting to γσ.

If the material is preliminarily loaded, then by virtue of the orientation of the structural elements (presumably sooty structures) strengthening of the material takes place. This in turn leads to an increase in the height of the potential barrier and a deviation from Eq. (4).

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FRACTURE OF MATERIAL THROUGH THE ACTION OF AN INTERNAL HEAT SOURCE

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An analytic study was made of the displacement of the vaporization front and of the resultant thermoelastic stresses in a semiinfinite solid through the action of an internal spherical heat source.

A heat source with a maximum at a certain depth is formed through the action of an electron beam, as noted in [1-3]. In principle, much of the same mechanism of energy deposition is possible for a pulsed laser focused at some depth in the material, for a pulsed discharge with the Lenz–Joule effect predominant, etc. With sufficiently sharp focusing and significant intensity of the heat source, volume vaporization is possible at artificial centers (fluctuation and gas bubbles, inclusions, etc.) which can lead to additional removal of mass as noted in [4].

We consider the following as a model problem for the analysis of the physical processes occurring through the action of such heat sources. Through the action of an enclosed volume heat source, vaporization of material takes place immediately and a high-temperature vapor region is created which occupies a sphere of radius R_0 at the initial time. Heat transfer from this region gives rise to heating of the solid with subsequent phase transition (vaporization). With this kind of physics for the process, volume vapor formation occurs in the medium at high pressure. The kinetics of such a process was not developed. Therefore, Frenkel' kinetics [5] was chosen at the zeroth approximation for this work. Displacement of the phase-transition boundary is determined from a solution of the Stefan problem (the effect of a free surface is not considered):

$$\frac{\partial T}{\partial t} = \frac{a}{r^2} \cdot \frac{\partial}{\partial r}\left(r^2 \frac{\partial T}{\partial r}\right), \qquad R_0 + \int_0^t v(\tau)\,d\tau \leqslant r < \infty, \tag{1}$$

$$M(t)\,c_v \frac{dT_v}{dt} = H(t)\,(T_{r=R_0+\int_0^t v(\tau)d\tau} - T_v), \quad r < R_0 + \int_0^t v(\tau)\,d\tau, \tag{2}$$

$$-\lambda\left(\frac{dT}{dr}\right)_{r=R_0+\int_0^t v(\tau)d\tau} = \frac{H(t)}{4\pi\left(R_0 + \int_0^t v(\tau)\,d\tau\right)^2}\,(T_v - T_{r=R_0+\int_0^t v(\tau)d\tau}) - \rho L v(t), \tag{3}$$

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