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Materials Science

Experimental and Theoretical Investigation of Slow Reversible Deformation of Concrete in Surface-Active Media and Physical Model of Processes

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ABSTRACT. Many-year investigations of the nature of damping creep of rigid bodies and materials led to the discovery of the fundamental character of this phenomenon. It occurs only when a rigid body comes in contact with a surface-active medium (liquid or gaseous), which brings about a decrease of free surface energy of a rigid body as a result of adsorption, chemosorption or wetting. The reversibility of the process consists in a gradual disappearance of creep deformation when the action of the surface-active medium stops. To clarify the essence of processes, physical model is constructed by using Griffith's scheme and the well-known representation formulas of deformation origination and failure processes. The total creep deformation is caused by the formation and opening of microcracks throughout the material volume under the action of load. This supposedly happens in macroscopically homogeneous silicate and organic glasses, while in polycrystals (tuff, gypsum, steel) contacting with a surface-active medium the microcracks are formed mainly on the grain boundaries. *© 2019 Bull. Georg. Natl. Acad. Sci.*

Key words: surface-active medium, Rebinder's effect, microcrack, creep

Many-year investigations of the nature of damping creep of rigid bodies and materials [1-4] enabled us to discover the fundamental properties of this phenomenon, namely: 1) the origination and development of this phenomenon only in the conditions of contact of a rigid body with a surface-active medium (liquid or gaseous) when the free surface energy of a rigid body decreases as a result of adsorption, chemosorption or wetting; 2) the reversibility of the process consists in gradual disappearance of creep deformation with the removal of the surface-active medium. We suggest that the found phenomenon of damping reversible creep is a new form of the manifestation of Rebinder's effect which was meticulously studied on rigid bodies of various nature and structure [5-8]. Specific behavior of the curve of the development and subsequent disappearance of deformation (reversible creep) with the removal of the surface-active medium is shown in Fig. 1.

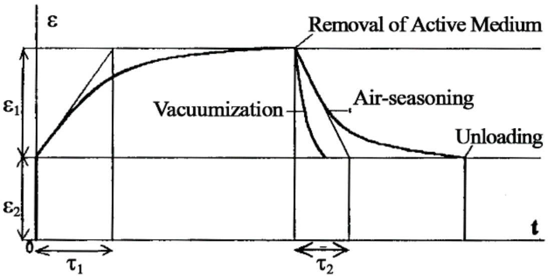

Fig. 1. Specific behavior of reversible creep deformation curves of rigid bodies:
ε_2 – elastic deformation in the absence of the surface-active medium that does not change in time; ε_1 – maximal creep deformation in the surface-active medium; τ_1 – period of creep relaxation in the surface –active medium; τ_2 – period of deformation recovery relaxation after the removal of the active-surface medium; t – time.

Materials and Methods

Specimens of 50×50×250 mm heavy-weight concrete were tested. The concrete filling consisted of crushed granite stone of 5-15 mm fraction and washed river sand. The binding material was Portland cement of strength 400 produced at Rustavi Cement Plant. The composition of concrete (kg/1 m^3) was as follows: cement – 300, crushed stone – 1300; sand – 700, water – 160, water/cement ratio – 0.5. The concrete curing time was 2 months. The ultimate strength of dry concrete under tension was 1.5 MPa, while that of the water-saturated concrete was 1.2 MPa. The load was 0.65 of the ultimate strength. Deformation was measured by 150 mm indicators of clock type with the accuracy of 0.2 μm.

For water-saturated concrete specimens, the creep test results processed by computer software are presented in Fig. 2.

Here the following notations are used:
ρ is the correlation coefficient;
$\varepsilon = \varepsilon_{max} [(1-P_1.\exp(-t/\tau_1)-(1-P_1)\exp(-t/\tau_2)]$

1. Water-saturated concrete. Tension test: load 2440 N = 0.65 $P_{break.}$;
$\varepsilon_{max} = 9.6 \cdot 10^5$; $\tau = 20.1$ days; $\rho = 0.9981$.

2. Concrete in the standard thermo-moisturized atmosphere. Tension test: 1. load 1500 N = 0.5 P_{break}; $\varepsilon_{max} = 9.2 \cdot 10^5$; $\tau = 100$ days; $\rho = 0.999$; 2. $\varepsilon_{max} = 11.1$ μm; $\tau = 3.53$ days; $\rho = 0.986$.

3. Water-saturated concrete. Compression tests: 40×40×160 mm specimens; load 400 N =0.5 P_{break}; $\varepsilon_{max} = 230 \cdot 10^5$; $\tau = 100$ days; $\rho = 0.999$.

As we see, the creep of water-saturated concrete is described by relaxation period.

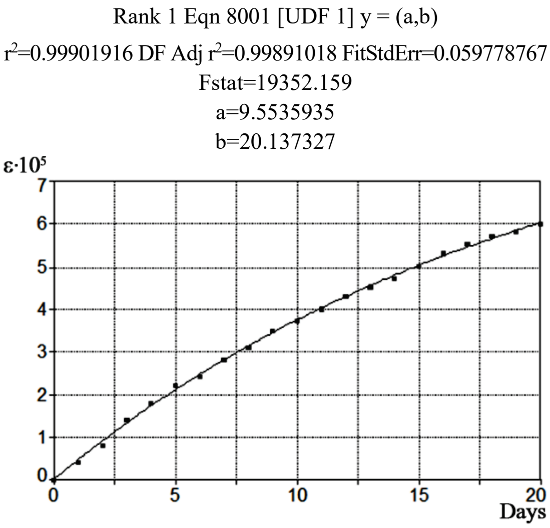

Fig. 2. The curve of water-saturated concrete creep at stretching.

Let us construct physical model to clarify the essence of the processes and their nature. For this we use Griffith's scheme and the well-known representation formulas of development of deformation and failure processes.

Griffith's criterion is based on the purely thermodynamic reasoning: the equilibrium of changes of the free energy of the tensioned plate of unit thickness when a through crack of dimension *r* is formed in it. An increase of the free energy at the expense of formation of new surfaces (crack banks) is 2γr (per unit thickness). During the formation of the crack, in the surrounding material there occurs a relief of stresses on the area of approximately r^2, which is equal to the product of this area by the density $\sigma^2/2E$ of elastic energy in the stressed body, where E is the elasticity modulus. Then the equilibrium looks like $\Delta F = 2\gamma r - \sigma^2 r^2/2E$.

Differentiating with respect to r, we obtain the Griffith equation $\sigma_c = \alpha(E\gamma/r_c)^{1/2}$.

It is important for us to know the behavior of the material under loads smaller than the critical one which leads to failure. For small cracks the change of free energy is proportional to the crack size. The left branch of the curve is the region of instability when the formed (as a rule, as a result of thermo+fluctuation processes, including those connected to dislocations) crack must get closed. Thus, in the absence of a surface-active medium the microcracks get formed and disappear, while the entire deformation of the specimen depends on the elasticity of the material, i.e. on the change of valence bonds and angles.

Deformation in the presence of a surface-active substance is a different matter. A surface-active substance, adsorbed or chemoadsorbed on the surfaces (banks) of cracks (even of those formed by thermo+fluctuation processes) essentially increases the energy of activation of the crack reverse closure and the crack gradually grows. The growth rate of such a pre-critical crack can be determined either by the velocity of movement of the surface-active substance to the crack vertex (by a viscous flow, diffusion on the crack walls or the Knudsen mode of gas distribution along the crack) or by the kinetics of thermo+fluctuation rupture of bonds in the crack vertex as it happens, for instance, in glass in the case of hydrolytic rupture of siloxane bonds under the joint action of water and the applied stress.

Hence it is natural to suppose that the total creep deformation is a result of the formation and the opening of microcracks throughout the material volume mass which is under load. One can assume in first approximation that cracks are distributed uniformly throughout the entire volume. This probably occurs in macroscopically homogeneous silicate and organic (acrylic-plastic) glasses. In polycrystals (tuff, gypsum, steel) microcracks are most probably formed at the boundary of grains; this is testified by the fact that polycrystals in surface-active media get damaged mainly along the grain boundaries. The creep of rubber is due to its swelling activated by the applied stress.

The comparison of experimental data on the reversible creep of various materials in different media led to a conjecture that there are possible mechanisms of formation and growth of microcracks which cause reversible creep deformation.

Results and Conclusions

1. Under the action of load, embryo cracks exist (or are formed) in a rigid body. Rebinder called them microslots.
2. The presence of water leads to a slow development of cracks by thermo-fluctuation rupture of bonds at the crack apex as a result of stress-activated hydrolytic split of siloxane bonds with the formation of silanol bonds. According to experimental data, there occurs the linear growth of the crack growth velocity logarithm due to applied various stresses.
3. Cracks are formed and grow throughout the entire volume of the tensioned material and their growth takes place when there is a supply of a sufficient amount of water. Thus it can be conjectured that a certain percolation system is formed, in which cracks are connected with one another by some kind of channels, for example, by dislocation tubes.
4. Despite the fact that the size of cracks is smaller than the critical value and they are in the region of thermodynamic instability and are subjected to restraint, they preserve stability at the expense of water adsorption on their walls. When the stress reaches some critical value σ_c the breakdown occurs. Using the thermodynamic approach, Griffith calculated the oncoming of such a critical state. We use it for evaluation of the critical and the current dimensions of microcracks.

In concrete, having both macro- and micro porosity, the initial saturation with water prior to load application leads to a partial filling of pores with water. It is sufficiently obvious that despite the

10-day immersion in water, only the surface layer gets saturated. Further saturation is prevented by the restrained air. That is why no advantages in the growth velocity of surface cracking (for example, in glass) are observed; this explains the absence of the second relaxation period. Micro+cracks formed in the cement component of concrete under the action of load are further filled with water via micro+pores. The results of the investigation of open micro porosity of cement stone by Brunauer *et al*. testify to the fact that the dimensions of micro+pores range within 10-30 nμ, which is close to the dimensions of water conducting channels. Then it can be conjectured that the time of creep process termination for concrete depends on the thickness of its specimens. Therefore it is natural to assume that the total time of creep in compression tests, when a greater part of pores closes or tapers, is essentially large.

One can consider an alternative mechanism of reversible creep for porous bodies, which is the restraint of air in blind pores (cracks). Since aluminosilicates are hydrophilic materials whose wetting angle is not large and does not exceed 30-40°, when water gets into a pore which can be treated as a plane capillary with an aperture height h, a liquid meniscus is formed, which compresses the restrained air up to pressure $P=2\gamma/h$, where γ is the surface tension of water approximately equal to 6×10^{-2} N/m. If we take $h=10^{-7}$m (0.1 μm), then $P=10^5$ or 0.1 MPa. Let us recall that the concrete specimens were tested under tension 0.6 MPa, i.e. the pressure value that may initiate the crack growth is commensurable in order with the applied stress value. It is impossible to determine exactly the value of this capillary pressure without measuring the width of the crack opening. We can only notice the fact that in concrete compression tests such a counterpressure of the restrained air manifests itself in the first 24 hours when despite the compression pressure, the specimen first expands and then compresses according to the law of reversible creep deformation. When water evaporates and both mechanisms – capillary compression of the restrained air and Rebinder's effect – stop working, the specimen practically returns to its original state.

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მასალათმცოდნეობა

ზედაპირულად აქტიურ გარემოში ბეტონის შენელებული შექცევადი დეფორმაციის ექსპერიმენტულ-თეორიული კვლევა და მოქმედი პროცესების ფიზიკური მოდელი

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(წარმოდგენილია აკადემიის წევრის გ. გაბრიჩიძის მიერ)

მრავალწლიანი კვლევები მყარი ტანის მილევადი ცოცვადობის ბუნების შესახებ გვიჩვენებს ამ მოვლენის ფუნდამენტურ ხასიათს. იგი ვლინდება, როდესაც მყარ ტანს აქვს კონტაქტი ზედაპირულად აქტიურ გარემოსთან (თხევად ან აირად მდგომარეობაში), რაც იწვევს მყარი ტანის თავისუფალი ენერგიის შემცირებას ადსორბციის, ან ქემოადსორბციის, ან დასველების შედეგად. პროცესების შექცევადობა და ცოცვადობის დეფორმაციის თანდათანობითი გაქრობა დამოკიდებულია ზედაპირულად აქტიური ნივთიერებების მოქმედების ცვლილებასთან. პროცესის განმარტების მიზნით აგებულია ფიზიკური მოდელი გრიფიტსის მოდელის გამოყენებით, სადაც ცნობილი წარმოდგენებით მასალაში ბზარების წარმოშობის და რღვევის საერთო დეფორმაცია გამოწვეულია მასალის მთელ მოცულობაში დატვირთვის მოქმედებით, მიკრობზარების წარმოშობითა და განვითარებით. ეს შესაძლებელია მოხდეს მაკროსკოპულად ერთგვაროვან სილიკატურ და ორგანულ მინებში. პოლიმერკრისტალებში (ტუფი, თაბაშირი, ფოლადი), რომლებიც კონტაქტირებენ ზედაპირულად აქტიურ გარემოსთან, წარმოიქმნება მიკრობზარები, ძირითადად, მარცვლების საზღვრების გარშემო. რეზინის ცოცვადობის მიზეზი ბენზინში აქტივირებული ძაბვით მისი გაჯირჯვაა.

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