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MODELING AND INVESTIGATION OF THE INFLUENCE OF THE LOADING MODE ON CREEP AND DAMAGE OF RHEONOMIC MATERIALS

ABSTRACT

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Relevance of the research. The use of rheonomic materials in engineering structures is one of the most important issues in determining strength and durability.

When analyzing the mechanical properties of a material under the action of external forces, its deformation is taken into account. The main task of solid mechanics is modeling of deformation processes of viscoelastic materials. In this case, the model is conditionally divided in to two classes: scleronomous and rheonomic. The defining relations of scleronomic models with respect to time transformations are invariant. Rheonomic models are described by operator relations that explicitly depend on time.

Currently, there are sufficiently developed viscoelastic theory and methods which allow the determination and description of viscoelastic properties of the materials. They distinguish between linear and nonlinear viscoelasticity. In the linear and nonlinear theory of viscoelasticity, such a problem is reduced to finding creep and relaxation kernels. The creep and relaxation kernels are linked by a known integral relation, which establishes a relationship between stress, strain and time.

The defining relation characterizing the nonlinear creep deformation of viscoelastic materials was first proposed by Yu.N. Rabotnov and is still the subject of mathematical problems. This defining relation is widely used in describing the mechanical properties of rheonomic materials.

The problem under study is known, many publications are devoted to it. However, in these publications, it is based on increase in the number of basic parameters in order to match the experimental values of the material strain creep. Therefore, for problems of creep mechanics, the use of a fractional-exponential Rabotnov kernel or Abel kernel, which must be determined from the basic experiment. These kernels allow us to accurately describe the creep curves of real materials at constant stresses and are successfully used to solve boundary value problems of rheonomic creep theory. Thus, this work requires the search for a new effective method for determining the parameters of the nonlinear hereditary equation of Yu.N. Rabotnov in the study of physical linear (nonlinear) rheonomic processes.

If you want to calculate the behavior of a structure over a long service life, you must take into account the impact of the loading history. The parametric equation of nonlinear creep deformation of rheonomic materials can be used to describe constant stress, stepwise and cyclic loading, as well as loading at a constant rate. The

application of such an equation is effective in engineering experimental calculations of material structures.

In this work, we study one of the rheonomic materials – asphalt concrete. Fine-grained hot dense asphalt concrete is used in many countries, including Kazakhstan, to cover the road surface. Asphalt concrete layers of highways during operation are subjected to complex combinations of mechanical impacts of vehicles' wheels and ambient temperature. As it is known, mechanical properties of asphalt concrete depend greatly on temperature and load characteristics, such as value, duration and rate of loading. Thus, it is practically very important to study the deformability, strength and durability of asphalt concrete at different loading speeds (at different values and durations of loads) and different temperatures.

In this regard, at the Kazakhstan highway research Institute, asphalt concrete samples are tested in different loading modes under direct tension. The influence of the loading mode on the creep of asphalt concrete samples is investigated. In addition, when determining the strength of asphalt concrete material, the influence of the loading mode on the process of failure of asphalt concrete samples is analyzed.

Microstresses are present in all solids and especially in polycrystals. Their primary cause is microinhomogeneity and microanisotropy structure of solids. A great influence on the field of microstresses has any deformation and especially a plastic one. The latter develops, as is known mainly in the deformation bands occupying a relatively small part of the body's volume, the greater part of the body continues to work elastically beyond the yield point. The process of plastic deformation is nonuniform, and therefore a random microdeformation field, arises in the body.

Where microstresses reach the highest values, micropores and microcracks appear in the body. When the plastic deformation continues, their number gradually increases and the dimensions grow. This process, referred to as damage accumulation is the first stage of destruction. Due to the accumulation of such damages, the process of destruction of rheonomic materials is faster. In this paper, the influence of the loading mode on the strength of rheonomic materials is investigated.

The aim of the study is to modeling and investigation of the influence of the loading mode on creep and damage of rheonomic materials. Evaluation of the strength and durability of materials.

The objective of the study:

- to investigate the equations for determining the creep properties of rheonomic materials;
- to develop a new effective method for determining the parameters of the nonlinear-hereditary equation Yu.N. Rabotnov;
- to investigate rheonomic nonlinear physical processes using the developed method;
- research and analysis of the creep loading history of physically linear and nonlinear rheonomic materials;
- study of the history of loading on the damage of physically linear and nonlinear rheonomic materials.

The object of the study is the values of creep deformation based on the results of experimental tests of nylon 6, glass-reinforced plastic TC 8/3-250 (θ=0°, 45°, 90°), aramid fiber SVM, EDT-10 resin, polycrystalline graphite, epoxy-phenolic fiberglass, polyester polymer concrete and asphalt concrete materials.

The subject of the study is the modeling of the creep process of rheonomic materials, their loading modes, and the study of the influence of the loading mode on the creep and damage of asphalt concrete. The research is carried out using approaches based on the observed facts in solid and continuum mechanics.

Methods of the research. Nonlinear hereditary equations of Yu.N. Rabotnov, the Yu.N. Rabotnov and Abel functions creep kernel for materials, isochronous creep curves of Yu.N. Rabotnov, to find the parameters α by bisection method, in the investigation of asphalt concrete materials, methods are used according to the direct tension scheme and the methods of the theory of viscoelasticity and elasticity.

Provisions for defense. According to the results of the study, the following problems were solved:

- when evaluating the strength and durability of rheonomic materials, an effective algorithm for describing the nonlinear deformation of rheonomic materials is proposed based on the method of isochronous creep curves by Yu.N.Rabotnov. The improved methods have been given for determination of creep parameters α, $\varepsilon 0$, δ, β and λ. In particular, new efficient methods has been proposed for determining of parameters (α, δ) for Abel's kernel. The bisection method is used to find the parameter α.
- algorithms and a corresponding computer program for calculating the parameters α and δ have been developed. Stress relaxation curves are based on the creep curve of rheonomic materials.
- experimental studies have been conducted on uniaxial under direct stretching of asphalt concrete samples. The results of testing of asphalt concrete samples according to the scheme of direct tension at constant stress, stepwise and cyclic loading, as well as under loading at a constant rate are presented.

The reliability and validity of scientific statements, conclusions and results of the dissertation. To determine the accuracy of the proposed algorithms, we used the results of experiments with nylon 6, glass-reinforced plastic TC 8/3-250 (Θ = 0°, 45 °, 90 °), aramid fiber SVM, EDT-10 resin, polycrystalline graphite at temperatures T=2000, 2200, 2400, 2600, 2800 ° C and epoxyphenolic fiberglass at temperatures T= 20, 30, 40, 50, 60° C and polyester polymer concrete materials. The high accuracy of the proposed method is shown. Qualitative and quantitative correspondence of the mathematical apparatus, theoretical research and experimental data, application of research results in practice.

Theoretical and practical significance of the research. Investigation of the defining equations describing the creep properties of rheonomic materials.The search for new effective method of determining the parameters of nonlinear equations Yu.N.Rabotnov It is necessary to study the physical nonlinear (linear) rheonomic processes according to the developed method. Asphalt concrete material was studied experimentally. The creep of asphalt concrete material under the influence of the

loading mode is modeled and the influence of the loading mode on the damage is studied. This will be of practical importance in assessing the strength of materials and the long-term strength of asphalt concrete.

Methods and algorithms for calculating nonlinear creep deformation of rheonomic materials and a properly designed computer program can be a good algorithm describing the deformation of all other rheonomic materials.

Approbation of the work. The main provisions and results of the dissertation were reported and discussed at the following scientific events:

- 12th All-Russian Congress on Fundamental Problems of Theoretical and Applied Mechanics: "Analysis of the processes of creep and relaxation of materials based on Rabotnov's nonlinear hereditary theory". (Ufa, Russia, August 19-24, 2019);
- International Scientific-Practical Conference "Science and education in the modern world: Challenges of the XXI century". (Nur-Sultan, Kazakhstan, October 29-31, 2019);
- Workshop on "Smart Nanostructured Materials: from Molecular Self-assembly to Advanced Applications": «Analysis of the influence of loading mode on creep of rheonomic materials». (Rome, October 2-4, 2019);
- International scientific conference "Theoretical and applied questions of mathematics, mechanics and computer science", dedicated to the 70th anniversary of the doctor of physical and mathematical sciences, professor M.I. Ramazanov. "Study of stress relaxation by the Rabotnov method". (Karaganda, Kazakhstan, June 12-13, 2019);
- V International Scientific Conference of Students and Young Scientists "Farabi Alemi". (Almaty, Kazakhstan, April 10-12, 2018);
- scientific seminars of the Department of Mechanics of al-Farabi KazNU (Almaty, Kazakhstan, 2017-2020).

Publications. The author published 10 works on the topic of the thesis, including 5 publications in scientific journals indexed by the Scopus and Web of Science databases; of which 3 publications in scientific journals recommended by the Committee for Control in Education and Science of the Ministry of Education and Science of the Republic of Kazakhstan for publishing the main results of scientific activity; 5 publication in the proceedings of international conferences.

Personal contribution of the author:

- related to all stages of the development process of calculation methods for modeling the creep curve of rheonomic materials;
- the researcher is directly involved in the development of a program for determining numerical values;
- participation in testing the results of the study of creep of rheonomic materials;
- preparation of publications on the results obtained;
- participated in experimental studies of asphalt concrete in the "Kazakhstan highway research Institute".

Structure and scope of the dissertation. The dissertation work includes an introduction, three chapters, a conclusion and a list of references.

The main content of the dissertation. To introduction includes the substantiation of the relevance of the dissertation research topic, the purpose of the

work, the object, the subject, the research objectives, the description of the applied methods, scientific novelty, theoretical and practical significance, the main provisions to be defended, information on published works on the topic of the dissertation and the degree of its development.

In the first chapter of the dissertation, the nonlinear integral equation of Yu.N.Rabotnov is considered when describing the creep process of rheonomic materials. Using the schematic form of the creep curves and isochronous creep curves of the material, the method of Yu.N. Rabotnov's isochronous creep curves is clearly explained.

This work proposes an effective algorithm for description of nonlinear deformation of hereditary materials based on Rabotnov's method of isochronous creep curves. Relevant equations have been determined from the nonlinear integral equation of Yu. N. Rabotnov for the application cases of Rabotnov's fractional exponential kernel or Abel's kernel for nonlinear deformation of hereditary materials at creep. The improved methods have been given determinftion of creep parameters α, $\varepsilon 0$, δ, β and λ. In particular, new efficient method has been proposed for determining of parameters (α, δ) for Abel's kernel. Bisection method is used for obtaining of parameter α. Algorithm and relevant software have been developed for calculating of parameters α и δ.

The detailed method has been developed for description of the nonlinear deformation process for rheonomic materials. The notions have been introduced for experimental and model rheological parameters and similarity coefficients of isochronous curves. It has been shown how using them, one can find instantaneous strains at various stress levels for description of nonlinear deformation of hereditary materials at creep.

By processing and using the test results for materials nylon 6, glass-reinforced plastic TC 8/3-250 (Θ=0°, 45°, 90°), aramid fiber SVM, EDT-10 resin, polycrystalline graphite at temperatures T=2000, 2200, 2400, 2600, 2800° C, epoxyphenolic glass-reinforced plastic at temperatures T = 20, 30, 40, 50, 60° C and polyester polymer concrete, the process has been shown for sequential implementation of the developed methods for description of linear and nonlinear deformation of these materials at creep and the corresponding software. The high accuracy of the proposed method is shown.

Mathematical modeling of the value of the creep deformation of polyester polymer concrete tested at stepwise and cyclic loading "loading-unloading" has been carried out. The deformation values of polyester polymer concrete at different stress levels are calculated by means of mathematical modeling. The mathematical modeling of the experimental values of the creep strain of epoxyphenolic glass-reinforced plastic, which was tested at a constant loading rate, is described. The problem of stress relaxation of viscous elastic materials is solved.

In the second chapter of the thesis, the results of experimental investigation an asphalt concrete of deformation at constant stress, stepwise and constant loading rate according on the scheme of direct tension are presented at the "Kazakhstan highway research Institute". Test temperature was 22-24° C. Nonlinear deformation of asphalt concrete at creep is adequately described by the proposed methods.

In the third chapter of the thesis the results of testing of asphalt concrete samples according to the direct tension scheme at constant stress, cyclic and constant loading rate loading are presented. The mechanical characteristics of the test results were obtained before the destruction of 148 asphalt concrete samples under a load from 0.036 MPa to 0.763 MPa at constant stress. Based on these data, the long-term strength of asphalt concrete at a temperature of 22-24° C was constructed, which was approximated by a power function. The dependences of the characteristics of failure the asphalt concrete (time of failure, deformation of failure, specific work of failure and strength) on the loading rate are described with high accuracy by a power function. The loading rate impacts greatly on the characteristics of deformation and failure of the asphalt concrete: failure time, specific work of deformation and failure strain are decreased in 242, 160 and 3 times respectively at the loading rate increase in 1158 (nearly 1200) times from 0.000563 MPa/s to 0.652 MPa/s, and the strength is increased in 5 times.

As a result of an experimental investigation of asphalt concretes deformation under cyclic loading, it was concluded that:

- in each cycle maximum creep strain of an asphalt concrete occurs in the end of loading period and maximum recovered strain occurs in the end of relax period. Both these strains increase with the growth of cycle number, but the increase rate of the first one is higher than of the second one.
- in the considered test conditions (durations of loading and relax periods equal to 600 seconds, values of applied stresses from 0.041 MPa till 3.0 MPa, temperature T = 22-24°C) an asphalt concrete is a very plastic body: the total amount of plastic strain is equal to 80-87% from the strain achieved in the end of loading period in each cycle.

In the conclusion, the main results and conclusions of the dissertation research, an assessment of the completeness solution of the tasks, recommendations for the actual use of the results are presented.