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Experimental Study of the Sleeve Material Mechanical Properties During the Sample Tensile Test

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Abstract. Composite materials are widely used in various industries. Both ordinary household items and specialized equipment used, in particular, in emergency and rescue formations, are made from them. Each equipment has a different level of reliability. One of the types of such equipment with the lowest level of reliability is fire hoses. Fire hoses work under different internal working pressures, and depending on this indicator, during their manufacture, such materials are chosen that are able to withstand it. High-pressure fire hoses are a separate type of fire hoses. In order to ensure the necessary strength of the material, it includes an internal reinforcing layer, which is a weaving of textile threads or metal wire. The composite structure of the material greatly complicates the process of checking the technical condition of high-pressure fire hoses, which may have hidden defects. These defects can cause their destruction during operation and lead to non-fulfillment of the tasks assigned by units of emergency and rescue formations. Therefore, the study of changes in the properties of the composite material from which high-pressure fire hoses are made due to the influence of various factors on it is relevant.

1 Literature Analysis and Problem

The process of operating high-pressure fire hoses is related to the fact that the composite material from which they are made is exposed to various influences [1].

In [2], a change in the mechanical properties of rubber-like materials that occurs during their long-term storage, which subsequently affects the appearance of defects in them, is considered. Unfortunately, the material structure of the experimental samples used in this work does not correspond to the structure of the composite material from which high-pressure fire hoses are made. In [3], the change in the mechanical properties of rubber cord composites subjected to cyclic tensile loads was investigated, taking into account the characteristics of their self-heating. Based on the results of the tests, the curves of the stress-strain state of the samples, which form hysteresis loops under cyclic loading, were determined. Test samples of rubber cord composites were obtained from automobile tires with modes of operation that are significantly different from high-pressure fire hoses.

In [4], an analytical model of the unit cell was proposed for evaluating the mechanical characteristics of textile-reinforced flexible hoses. The model can be applied to textile yarn-reinforced hoses subjected to internal pressure and longitudinal forces to analyze load-induced deformation. The bending resistance of experimental samples of materials was not taken into account in the work.

In [5], an analytical solution for determining the external critical pressure for multilayer cylindrical shells that are under constant external pressure is proposed. The outer layers were made of cast iron, and the inner layer was made of rubber. The specified structure of the material of the investigated cylindrical shell does not correspond to the structure of the material from which high-pressure fire hoses are made.

In [6] it is proposed to use the methods of computer industrial tomography to study the condition of rubber hoses. This method cannot be applied to some composite materials [7], which is its limitation.

In [8], a criterion for predicting the onset of failure in rubber-like materials with already existing cracks is proposed, which is based on the internal bond energy, which includes crystallization effects. The named criterion can be applied to elastomers that have a simple structure, that is, in the case of composite materials, the application of this criterion will not be possible [9].

In [10], the mechanical and fatigue behavior of carbon-filled acrylonitrile-butadiene rubber during tensile tests under the influence of changing temperature was investigated. Fatigue behavior at different temperatures was evaluated using a crack growth approach. According to the results of these studies, lower resistance to crack growth at higher temperatures was found.

In [11], a model was analyzed that describes the transverse oscillations of an elastic hose caused by inharmonic pulsations of the fluid flow. The equation of motion of the liquid flow is given in the form of a nonlinear equation. The impact of transverse vibrations on the formation of damage to the material from which the elastic hose is made was not considered in this work.

A numerical method for predicting the deformed state and fatigue damage of a rubber hose made of composite material is proposed in [12, 13]. This method is based on the use of nonlinear finite element analysis of large deformations. The method was developed to estimate the residual life of rubber hoses that are subjected to constant cyclic deformations, namely hoses that are part of the car's brake system. High-pressure fire hoses, unlike hoses used in the car brake system, have a different mode of operation, and therefore the adequacy of the use of the specified method in relation to the former needs to be checked. In [14], the compression resistance of a hose used for transporting substances under water was investigated by using the finite element method. This type of hose is made of a composite material that has a reinforcing layer in the form of a spiral or rings in its structure to ensure stability as a result of compression. In [15], a study of the effect on the axial, torsional and bending stiffness and mass of a floating marine hose of changes in the placement, structure and material of its reinforcing layer was carried out. Changing the material of the reinforcing layer and its location in the general structure of the material from which floating sea hoses are made allowed to reduce their mass and improve the stiffness characteristics. These hoses work under conditions of influence on the material from which they are made of both external and internal hydraulic pressure, which distinguishes their operating conditions from high-pressure fire hoses.

In [16], a method of increasing the fire protection of a material made of fabric fibers due to its preliminary impregnation with an organosilicon composition is considered, and in [17] a composition based on organic-inorganic ash SiO_2. A reinforcing layer of composite material is built from fabric fibers, from which one of the types of high-pressure fire hoses is made. The behavior of composite materials, which include a layer of fabric fibers that were previously treated with the specified compositions under the influence of temperature or flame, was not investigated in this work.

In [18], the mechanical properties of the material from which fire hoses with an internal diameter of 66 mm are made, and in [19] of hoses with an internal diameter of 77 mm under static load conditions, were investigated. The test samples were fixed in a tensile machine and subjected to cyclic loading and unloading. This made it possible to determine the modulus of elasticity when stretching the material of the sleeve in the longitudinal direction. The fire hose from which the test samples of the material were separated is designed for a working hydraulic pressure of up to 1 MPa, and high-pressure fire hoses work under a much higher working pressure.

In [20], a study of the mechanical properties of the material from which a fire hose with an internal diameter of 77 mm was made, which had no mechanical damage during its torsion tests, was conducted. The tests were carried out by creating a hydraulic pressure sleeve in the inner cavity of the test sample. According to the research results, the deformation curves of the samples were constructed, which formed hysteresis loops under conditions of cyclic loading and unloading.

In [21], an experimental plan was developed, which is similar to that in [20], but the main difference between these studies was the use of test samples with mechanically applied defects. According to this plan, an experiment was conducted, and its results are presented in [22]. An almost linear dependence of the values of the twisting angle of the test sample of the fire hose on the internal water pressure and the length of the defect was established. The largest discrepancy in the maximum twisting angle of the test sample of the fire hose - 21% was observed at the values of the internal hydraulic pressure of 0.4 MPa. In the studies [20, 21, 22], the test samples of fire hoses designed for working hydraulic pressure up to 1 MPa, which had a different material structure, unlike high-pressure fire hoses, were used.

Thus, in the majority of works, materials with an internal structure that is significantly different from the structure of the composite material from which high-pressure fire hoses are made were used as test samples. Some samples had a rather specific material structure, which was related to the conditions of their operation. In addition, the experiments mainly used test samples that did not have any damage. Accordingly, the mechanical properties of the material from which high-pressure fire hoses are made remain insufficiently studied, which complicates the process of checking their technical condition.

In this work, it is proposed to carry out full-scale experimental studies on the determination of some mechanical properties of the material of a high-pressure fire hose when testing samples for rupture in the longitudinal direction.

The purpose of the work is to determine the ultimate loads, stiffness and normal elasticity (Young's modulus) of a high-pressure fire hose type 1 ST with a diameter of 19 mm when testing specimens for rupture in the longitudinal direction.

2 Presentation of Basic Material

In order to determine the stiffness and normal elasticity, a number of full-scale experiments were conducted on the rupture in the longitudinal direction of the high-pressure fire hose material.

The FP 100/1 testing machine was used for the experiments, in which the sleeve sample was fixed with the help of special cylindrical clamps that prevent the sleeve material from slipping. The speed of the moving clamp was 30–40 mm/min. A standard mechanical dynamometer was used to measure the load, and the results were recorded on chart paper. The tests were carried out at a temperature of 20–22 ºC.

Research was conducted as follows. First, the high-pressure fire hose was tested under excess pressure. For the corresponding tests, a pump is used, which fills the cavity of the sleeve with water until the air is completely released, for which an overlapping fire barrel is attached to the other end of the sleeve. At the end of the test, the sleeve is dried and cut into appropriate samples (Fig. 1).

The design of the high-pressure fire hose consisted of: an internal waterproofing layer, a layer of textile threads on top of which a protective layer of polymer was applied.

Test samples (fragments) of the material were separated from different sections in the longitudinal direction of the high-pressure fire hose and had the following dimensions: working area l = 0,1 m, inner diameter d_0 = 0,019 m, outer diameter d_1 = 0,027 m.

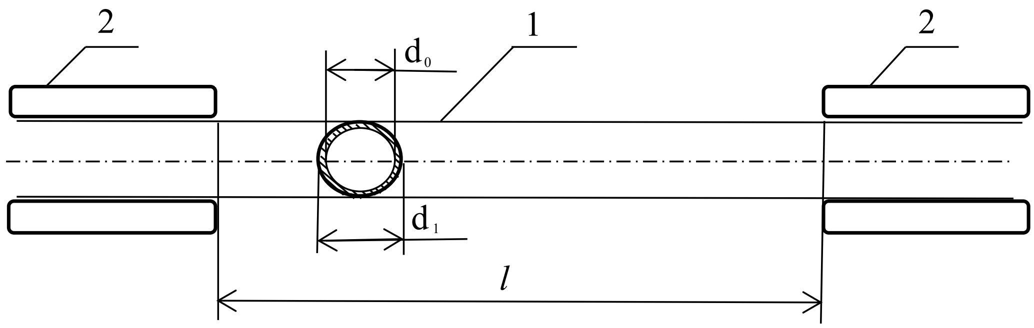

Fig. 1. A test sample of the material of a high-pressure fire hose: 1 – a high-pressure fire hose, 2 – a special clamp of a cylindrical shape.

Fig. 2-5 show the results of experimental studies of the high-pressure fire hose material.

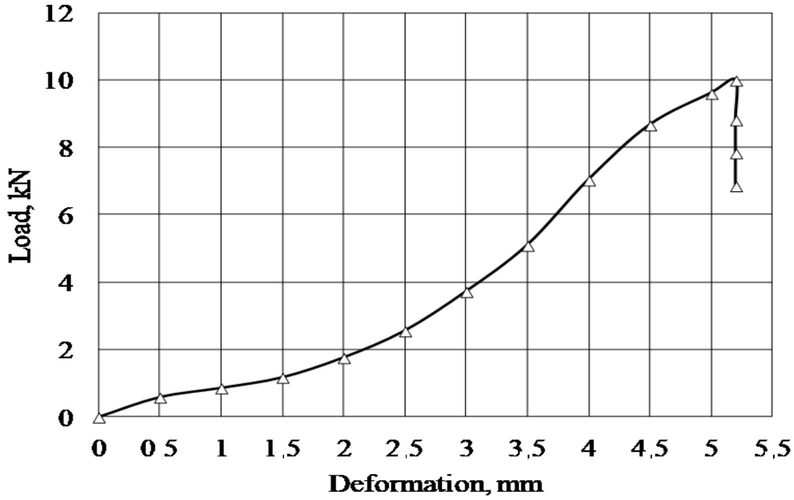

Fig. 2. Results of experimental studies of test sample No. 1

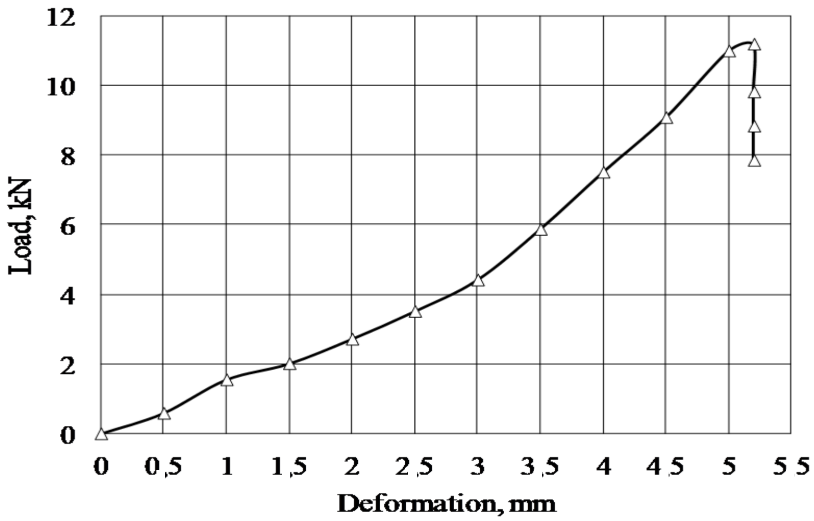

Fig. 3. Results of experimental studies of test sample No. 2

Fig. 2 and 3 show the deformation curve of test samples 1 and 2.

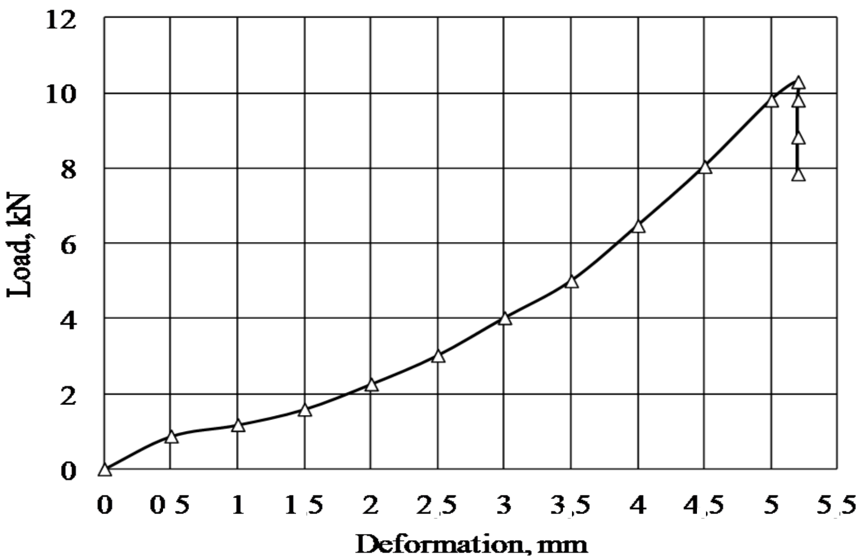

Fig. 4. Results of experimental studies of test sample No. 3

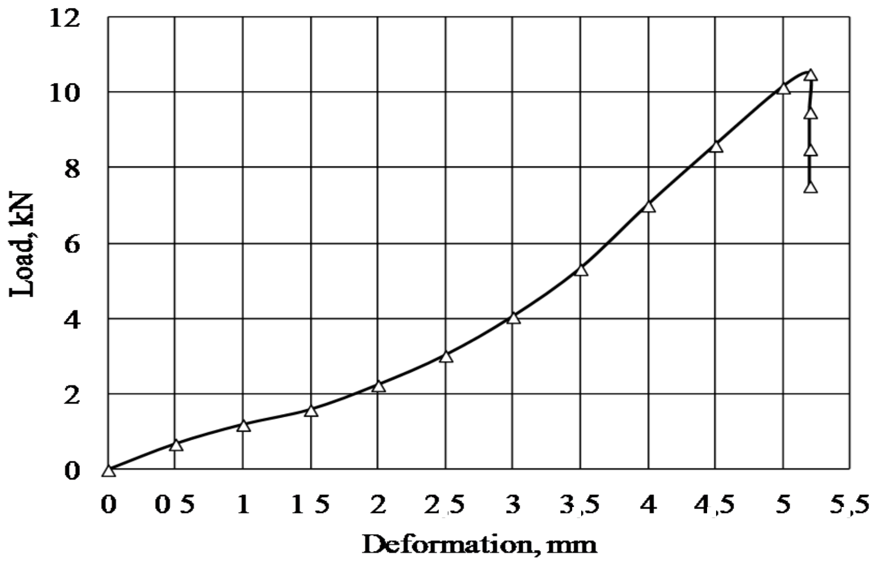

Fig. 5. Results of experimental studies of test sample No. 4

Based on the results of experimental studies, we will calculate some mechanical properties of the high-pressure fire hose material, namely:

- average breaking load:

$$\bar{F} = \frac{\sum F_i}{n}, \qquad (1)$$

where $\sum F_i$ – the sum of the breaking force values, N; n – the number of tested samples;

- relative elongation at samples break, %

$$\varepsilon_i = \frac{100 \cdot \Delta L}{L}, \qquad (2)$$

where ΔL – maximum elongation at break, m; L – working area, m;

- the average relative elongation at break of the samples, %

$$\bar{\varepsilon} = \frac{\sum \varepsilon_i}{n}, \qquad (3)$$

Table 1. Data on determination of average elongation and breaking load

Sample No.	Load, [N]	Average breaking load, [N]	Relative elongation, [%]	Average relative elongation at break, [%]
1	10002.8	10493.1	5.3	5.22
2	11179.6		5.2	
3	10296.9		5.2	
4	10493.1		5.2	

When calculating stiffness and modulus of elasticity. To determine stiffness and modulus of elasticity

$$C_i = \frac{F_i^{max}}{\Delta L}, \quad (4)$$

where C_i – stiffness of the fragment, kN/m

$$E_i = \frac{F_i^{max} \cdot L}{\pi \cdot (\Delta L)(d_0 + \delta) \cdot \delta}, \quad (5)$$

where E_i – modulus of elasticity of the sleeve material in the longitudinal direction, MPa; d_0 – inner diameter of the high-pressure fire hose, m; δ – sleeve wall thickness, m;

Table 2. Data on stiffness and modulus of elasticity of test samples

Sample No.	Fragment stiffness	Average fragment stiffness, [kN/m]	Modulus of elasticity	Average modulus of elasticity, [MPa]
	C_i, [kN/m]		E_i, [MPa]	
1	1923.62	2017.91	653.3	695.4
2	2149.92		744.2	
3	1980.17		685.5	
4	2017.91		698.5	

Table 2 shows the results of experimental studies, the stiffness of the sleeve material fragments and the modulus of elasticity (Young's modulus) were calculated.

3 Discussions of Results

The results of the study to determine the stiffness and modulus of elasticity of the material of the high-pressure fire hose type 1 ST with a diameter of 19 mm after calculations are given in table. 2. The limit loads that act on the material of the high-pressure fire hose during the tear test are set in table. 1. Fig. 2–5 graphically show the deformation curves of the samples when testing the material for breaking.

The conducted tests were limited to the study of only one type of sleeve, while its wear and tear or working time were not taken into account.

These shortcomings can be eliminated by researching different types of sleeves with an arbitrary period of use and statistical processing of the results.

The further development of relevant research is the experimental analysis of the effect of cyclic deformation, as well as the effect of high temperatures on the physical and mechanical properties of the high-pressure fire hose material.

These studies require the development of both a new method of conducting experiments and the manufacture of appropriate equipment.

4 Summary

The conducted experimental studies made it possible to determine the physical and mechanical properties of the high-pressure fire hose material, namely the stiffness and modulus of elasticity during tear tests of the material. The limit loads that act on the material of a high-pressure fire hose during a tear test have been established. The almost linear relationship between the load and deformation characteristics brings the behavior of the sleeve material in the longitudinal direction closer to the elastic one. The relative elongations of the high-pressure fire hose material during tear tests were established.

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