UDC 614.843/083
DOI: 10.15587/1729-4061.2021.248972

ESTABLISHMENT OF THE DEPENDENCE OF THE STRENGTH INDICATOR OF THE COMPOSITE MATERIAL OF PRESSURE HOSES ON THE CHARACTER OF SINGLE DAMAGES

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Experimental studies are presented and the dependence of the change in the strength of the material of a pressure head fire hose of type T with an inner diameter of 77 mm in the longitudinal direction is established, taking into account single damages. The work describes the plan of the experiment and carried out a number of field experiments to determine the effect of the length ld and the depth K damage on the strength F of the hose material, that is, obtaining the dependence $F=f(l_d, K)$. A mathematical method of experiment planning was used and a plan was drawn up for a complete multivariate experiment of type 2^k with an acceptable model accuracy of 5 %. The limits of variation of the factors are set taking into account a priori information, experimental capabilities and on the basis of the results of preliminary search experiments. The dependence in the coded and natural values of the factors is obtained. The reliability of the relationship was checked using the Fisher test, the calculated value of which was 5.98, which confirms the adequacy of the described process with a probability of 95 %.

Analyzing experimental studies of the dependence of the change in the strength of the hose material on the length and depth of damage, it can be said that the change in the strength of the hose almost linearly depends on the specified damage parameters. It is found that with increasing damage, the strength of the hose material significantly decreases. When varying the length factor and the greatest depth of damage, K=0.4 mm, the strength of the hose material decreases from 11.67 kN to 8.77 kN, and in percentage terms by 25 %.

The results obtained can be used in practical units of emergency rescue teams, when diagnosing hidden damage in pressure head fire hoses in order to prevent their failure in case of fires

Keywords: pressure head fire hose, material strength, experimental studies, experimental design, damage variation limits

Received date 12.11.2021
Accepted date 13.12.2021
Published date 29.12.2021

***How to Cite:** Nazarenko, S., Kushnareva, G., Maslich, N., Knaub, L., Naumenko, N., Kovalenko, R., Konkin, V., Sukharkova, E., Kolienov, O. (2021). Establishment of the dependence of the strength indicator of the composite material of pressure hoses on the character of single damages. Eastern-European Journal of Enterprise Technologies, 6 (1 (114)), 21–27. doi: https://doi.org/10.15587/1729-4061.2021.248972*

1. Introduction

Ensuring the safety of the population is one of the main functions of any country in the world. This function is realized through the creation of various formations, in particular, civil protection units. Civil protection divisions are engaged in preventive work of the corresponding direction and carry out the elimination of dangerous events and emergencies that arise in a certain territory. Among hazardous events and emergencies, the highest frequency of fires. When extinguishing fires, such a factor is important as the time it takes to complete certain stages of operational work, which depends on the level of readiness of forces and means. The level of readiness of forces and means to carry out actions as intended is a complex criterion that takes into account various possible indicators. These indicators include: the probability of the readiness of a sufficient amount of equipment, the time required to complete certain types of operational work by the unit, as well as the likelihood of failure-free operation of fire-fighting equipment.

There are a lot of types of fire-fighting equipment on the equipment of subdivisions, and each of them has a different probability of failure-free operation, in particular, pressure fire hoses (PFH) have the lowest [1]. Failure of an oil pumping station on fires happens quite often. This, of course, creates a certain danger for the personnel of the unit, which is involved in firefighting and increases the duration of this process, which is associated with the expenditure of additional time to replace damaged PFH s. The reliability of the PFH operation depends on the observance of proper operating conditions and periodic inspections of their technical condition. It is preferable to check the technical condition of the PFH by means of their hydraulic tests, but this method in practice turns out to be rather unreliable. The use of other alternative methods, which had a higher reliability compared to hydraulic tests, is most often limited or completely impossible due to the complex structure of the material from which the PFH is made. Mostly this material is multicomponent; therefore, it is rather difficult to predict its behavior under the influence of various factors. At the same time, it is impossible to develop and implement modern effective methods for testing PFH without a preliminary study of the behavior of the material from which they are made, subject to the action of various influences.

Thus, there is a problem in the low reliability of pressure head fire hoses and their sudden destruction when extinguishing fires, which is accompanied by an increase in losses. In addition, this also creates an additional danger for the personnel of civil protection units who are involved in extinguishing fires.

2. Literature review and problem statement

Structurally, PFHs mainly consist of composite materials, which may include: metal, fabric, rubber, polymers, and others. Considering that each of these materials has its own individual mechanical and physicochemical properties, the study of changes in the characteristics of a material that affect its integrity is an extremely complex process.

In [2], a study was carried out of the damage that occurs in rubber-cord materials as a result of tedious processes. On the basis of the results obtained, a mathematical model is proposed that describes this process, but its disadvantage can be considered the fact that it does not allow determining the possible place of damage.

During storage, the PFH is preferably rolled up or wound on tubular reels. In the process of operational deployments, they are unwound, and upon completion, they are unwound, that is, they are subjected to cyclic loads. According to [3], cyclic loads affect the change in the dissipative properties of gum-cord composites that are part of the PFH and cause their self-heating. In work [3], studies related to stretching of prototypes of the material were carried out to determine changes in their characteristics and to construct deformation curves based on the data obtained. Unfortunately, studies of the characteristics of samples of materials that would have a certain nature of damage were not carried out in this work.

In [4], the phenomenon of cyclic deformation of a hydraulic hose used in the brake system of a car was investigated. In order to predict its behavior, methods of numerical analysis were used. Due to the complex structure of the weaving of the metal reinforcing layer of the hose, some simplifications were adopted, which further negatively affected the final results obtained using the mathematical model proposed in this work.

In work [5], the characteristics of the deformation of the hose, in which the reinforcing layer was made of woven fabric, were investigated. Typically, the flexibility of such hoses is greater than those with a metal reinforcement layer. The mathematical model proposed in this work makes it possible to estimate the value of the deformation of the hose depending on the weaving structure of its reinforcing layer. The specified model makes it possible to establish the value of the fluid pressure inside the hose at which it will be destroyed. But this work did not take into account the influence of such factors as aging of the material and the presence of external mechanical damage on the surface of the hose. Taking these factors into account is an important condition when checking the technical condition of the oil pumping station.

The work [6] investigated the dependence of the characteristics of a rubber pipeline depending on the structure of the inner fabric reinforcing layer. Based on the research results, mathematical models have been obtained that make it possible to evaluate the characteristic of deformation, namely, the value of the twist angle and the length of extension, and, in addition, bursting pressure is possible. The disadvantage of these mathematical models is that they do not take into account the characteristics of the rubber material that is part of the pipeline.

According to [7], it is possible to establish existing defects in flexible pipelines using the method of computerized industrial tomography. Considering that the material from which the PFH is made is composite, the application of this method can be limited and requires preliminary analysis of its internal structure.

In [8], the influence of various factors affecting the integrity of a flexible pipeline laid under water was investigated. In this case, the external pressure acting on the flexible pipeline was considered as the main influencing factor. In the case of possible conditions for the PFH use, such effects on it are not rendered.

The work [9] investigated the elasticity and strength of a plastic material printed on a 3D printer. For this purpose, the samples under study were fixed and stretched using the FP 100/1 testing machine until the moment of their complete destruction. Of course, it can be assumed that the characteristics of elasticity and strength of a plastic material in the presence of damage of various natures will differ from the characteristics of samples without damage. In this work, this assumption was not tested.

In [10], a mathematical model was proposed that allows one to quantitatively assess the behavior of a rubber-like material during uniaxial and biaxial loading, as well as the effect of crystallization on the occurrence of cracks. According to [11], cracks in rubber that do not crystallize as a result of material fatigue do not significantly affect the change in its mechanical properties. Accordingly, doubts arise about the adequacy of the mathematical model proposed in [10]. In addition, it is necessary to take into account the peculiarity that the material from which the NPR is made is predominantly composite and consists not only of rubber, which is not taken into account by the mathematical model [10].

In work [12], the elastic and dissipative properties of PFH with a diameter of 66 mm under static load conditions were investigated. The prototype was subjected to periodic loading-unloading cycles, which made it possible to determine the modulus of elasticity when stretching the material of the hose in the longitudinal direction. In work [13], the mechanical properties of PFH with a diameter of 77 mm were investigated under a static load by stretching prototypes in the transverse direction. In contrast to [12, 13], [14] investigated the change in the mechanical properties of PFH with a diameter of 77 mm by rotating the prototypes at a certain angle. When conducting research on rotation [14], certain normalized values of hydraulic pressure were maintained in the inner cavity of the PFH prototypes. Unfortunately, the works [12–14] did not study the effect of damage on the possible change in the mechanical properties of the material from which PFH s are made.

Thus, the material from which the PFH is made is composite, which significantly complicates the study of the influence of the nature of damage on the change in its mechanical properties. The overwhelming majority of the analyzed works [2–7, 9–11] are devoted precisely to the study of the mechanical properties of various materials from which the PFH is structurally made. The assessment of the change in the mechanical properties of the PFH prototypes as a result of exposure to external influences was carried out only in [12–14]. In works [12–14], the influence of damage on a possible change in the mechanical properties of the material from which PFH s are made remained unexplored, which could later be used to check their technical condition.

3. The aim and objectives of research

The aim of research is to establish the dependence of the change in the strength index of the material of the pressure head fire hose on tension in the longitudinal direction, depending on the nature of single damage by conducting field experiments. This will allow in the future to diagnose hidden damages in pressure head fire hoses in order to prevent them from failing in fires.

To achieve the aim, the following objectives were set:

– to develop a methodology and plan for conducting an experiment to determine the strength of the material of a pressure head fire hose, depending on the nature of single damage;

– to conduct experimental studies and establish the dependences of changes in the strength of the material of the pressure head fire hose, depending on the nature of single damage.

4. Materials and methods of research

In order to establish the dependence of the change in the strength of the “T” type PFH material with an inner diameter of 77 mm, a number of full-scale experiments were carried out on rupture in the longitudinal (along the base) direction, taking into account single damages.

Testing machine FP 100/1 was used for testing, in which the sample of the hose was fixed with the help of special clamps to prevent slipping of the hose material. The speed of the movable clamp was 30–40 mm/min. A standard mechanical dynamometer was used to measure the loading. The test was carried out at a temperature of 20–22 °C.

The prototypes (fragments) of the material were separated from different sections in the longitudinal (along the base) direction of the fire hose and had the following dimensions (Fig. 1):

– test length l=100 mm;

– width (working area) b=50 mm;

– thickness of the outer fabric (power) frame δ_f=1.2 mm;

– thickness of the inner rubber layer δ_r=1.5 mm.

For the research, samples of geometry were used that meet the requirements of the standard for testing fabric frames for fire hoses (GOST 30135-94).

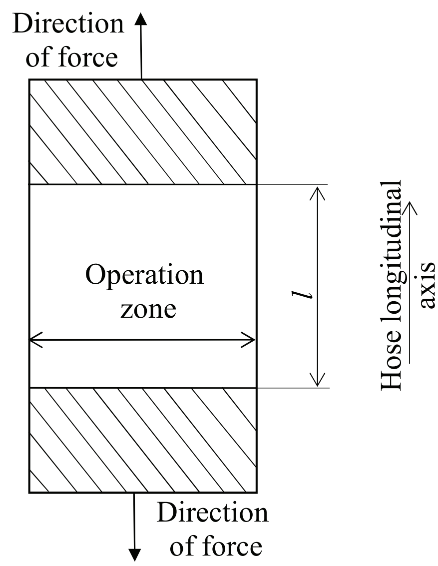

Fig. 1. Prototype fire hose

Taking into account the design of the pressure head fire hose [12], it was decided to inflict damage on the power frame, which receives the forces from hydraulic pressure.

Damage was applied artificially on the load-bearing frame of the fire hose material by means of a single cut of a specified depth and length. Such damage can occur during the operation of fire hoses, further affecting their reliability when used for their intended purpose in the bodies and divisions of civil protection.

The hose was damaged with a 0.1 mm wide razor blade. The blade was installed in a special tool, which made it possible to inflict damage of different depths on the power frame of the hose and vary their depth in the range from 0.2 to 1 mm. The length and depth of damage were determined visually using an MBS-9 microscope; this device allows using a built-in scale to determine the numerical value of these parameters.

Damage to the material of the fire hose was applied perpendicular to the weaving of the threads of the base of the power frame, that is, along the width of the prototype fire hose (Fig. 2).

If the damage deviated from the specified parameters for planning the experiment, the sample was not accepted for consideration.

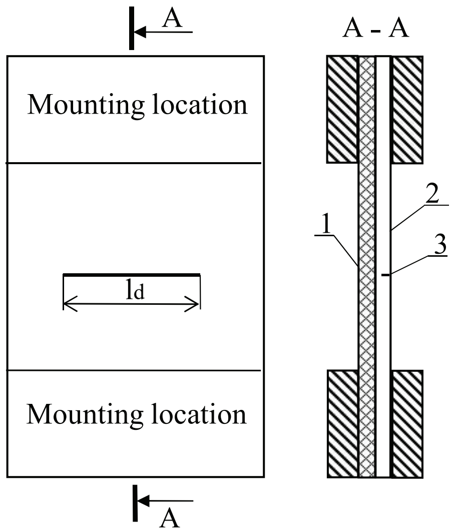

Fig. 2. Placement of damage on the hose: 1 – waterproofing layer; 2 – power frame; 3 – place of damage

5. The results of experimental studies and the establishment of the dependence of the change in the strength of the hose material

5. 1. Technique and plan of the experiment to determine the strength of the hose material

The research was carried out as follows. First, the pressure hoses were tested for overpressure. For the appropriate tests, a pump is used that fills the cavity of the hose with water until the air is completely released, for which an overlapping fire nozzle is attached at the other end of the hose. After removing the air, the pressure in the hose increases to the test pressure (2.4 MPa according to DSTU 9069:2021). The hose is kept under the test pressure for 180±5 s. At the end of the test, the tube is dried and cut into appropriate specimens, the dimensions of which are given above (section 4). After that, the test sample is clamped in special clamps and installed in the testing machine and tests are carried out under a gradual static load of the samples until rupture. The results are recorded on graph paper. A series of tests was carried out both on an undamaged hose and with damage of various depths and lengths.

When planning the experiment, orthogonal planning of the second order was used [15] with the number of factors k=2.

To conduct research and achieve the goal, a full-factor experiment (FFE) of type 2^k was planned, allowing a random error of the model at a level of no more than 5 %. The length l_d (x_1) and the depth of damage K(x_2) were chosen as factors, and the strength of the hose F(y) was taken as a response, that is, obtaining the dependence $F=f$ (l_d, K).

Based on the a priori analysis of the information, the choice of the experimental area of the factor space was made. The center of the interval in which the study is planned to be carried out was chosen as the zero level of the factor. The variation interval, the value of the upper and lower levels of factors in natural and coded terms are also selected. The values of the factor levels and the intervals of variation are presented in Table 1.

The value of the damage length on the hose varied from 20 to 40 mm, where 20 mm is the smallest damage length, 40 mm is the largest, that is, the upper level of the damage length. The length of the damage was limited not only by taking into account a priori information, but also by the size of the test sample of the fire hose.

Table 1

Factor variation levels

Variation interval and factor level	Damage length	Damage depth
	L_d, мmm	K, mm
Zero level x_i=0	30	0.2
Variation interval	10	0.2
Lower level x_i=–1	20	0
Upper level x_i=+1	40	0.4
Code designation	x_1	x_2

The lower level of the damage depth was 0 mm, which is due to the need to trace the change in the strength of the material on the damaged hose. The maximum damage depth is 0.4 mm. The factorial limitation of the depth of damage was chosen due to the thickness of the outer tissue (power) frame.

Based on the FFE plan, a working matrix was drawn up and a full-scale experiment was carried out to determine the strength of the fire hose material. First, a first-order orthogonal plan was developed and the results were obtained using it. These results could not be linearly approximated; therefore, it was decided to choose a second-order FFE. The working matrix of planning and the results of the experiment were performed in threefold A repeatability. The need to perform a threefold repeatability of each of the experiments is a prerequisite for obtaining results with an acceptable level of reliability in accordance with the established experiment planning methodology [16]. The total number of experiments was also determined taking into account the previously mentioned experimental planning technique for the second-order orthogonal plan and is 9. The FFE plan and the results obtained are presented in Table 2.

Table 2

Planning work matrix and research results

Experiment	L_d, mm	K, mm	Result			
	x_1	x_2	$\mathring{y}_1$	$\mathring{y}_2$	$\mathring{y}_3$	$\bar{y}$
1	40	0.4	8.2376	8.6495	8.2376	8.37
2	40	0	12.2583	12.376	13.1899	12.608
3	20	0.4	10.7873	11.0815	11.0717	10.98
4	20	0	12.2583	12.376	13.1899	12.608
5	30	0.2	11.5718	11.768	11.9641	11.768
6	40	0.2	10.297	10.6696	10.7873	10.584
7	20	0.2	11.562	12.2093	12.0131	11.928
8	30	0.4	10.0028	10.0028	9.4144	9.81
9	30	0	12.2583	12.376	13.1899	12.608

As a model of the object of research, a polynomial of the 2nd degree was used [16]:

$$y = b_0 + b_1x_1 + b_2x_2 + b_1^2x_1^2 + b_2^2x_2^2 + b_{12}x_1x_2, \quad (1)$$

where b_1, b_2 – regression coefficients.

The following formula is used to determine the regression coefficients for orthogonal planning:

$$b_i = \frac{\sum_{u=1}^{n} x_{iu}y_u}{\sum_{u=1}^{n} x_{iu}^2}, \quad (2)$$

where u=9 – the number of studies in the experiment; i – the number of the column in the layout matrix; y_u – the average value of the criterion in each study, obtained during the experiment (Table 2); x_{iu} – encoded values of factors.

Values $\sum_{u=1}^{n} x_{iu}^2$ for kernel type 2^2: x_0=9, x_i=6, x_{ij}=4, $x_i^{2\Phi}=2$.

After substitution of the values of the coefficients and the data of the planning matrix of expression (2), the regression coefficients will be:

b_0=11.686; b_1=–0.659; b_2=–1.44;

$b_1^2=-0.285$; $b_2^2=-0.318$; b_{12}=–0.653.

After substituting the numerical values of the coefficients into expression (1), it was obtained:

$$y=11.686-0.659x_1-1.44x_2-$$
$$-0.285x_1^2-0.318x_2^2-0.653x_1x_2. \quad (3)$$

Let's check the hypothesis about the adequacy of the regression equation using the Fisher criterion [17]:

$$F_{calc}=\frac{S_{ad}^2}{S_{\{y\}}^2}, \quad (4)$$

where

$$S_{ad}^2=\frac{\sum_{u=1}^{N}\left(\overline{y}_u-y_u\right)^2}{n\frac{(k+2)(k+1)}{2}}$$

– the adequacy variance;

$$S_{\{y\}}^2=\frac{\sum_1^N\sum_1^n\left(y_{uj}-\overline{y}_u\right)^2}{N(n-1)}$$

– reproducibility variance.

Taking into account the previously obtained values of the variance of adequacy and reproducibility, the value of the Fisher criterion is F_{calc}=5.98.

Depending on the calculated degrees of freedom of greater and lesser variance, the tabular value of the Fisher criterion $F_{(0.05;f_{ad};f_y)}<F_{rab}$ is determined at f_{ad}=7, and f_y=4, F_{tab}=6.09.

Since F_{calc}<F_{tab}, the regression equation (3) can be considered adequate to the process under study with 95 % probability.

5. 2. The results of experimental studies and the establishment of the dependence of the change in the strength of the hose material

In practice, it is not convenient to use the mathematical dependence in the encoded values. To obtain an adequate regression equation, it is transformed by replacing the coded values with the named (actual) ones. For this, let's use (5) and (6), which characterize the relationship between the quantities under consideration.

$$x_1=\frac{l_d-x_1}{\Delta x_1}; \quad (5)$$

$$x_2=\frac{K-x_2}{\Delta x_2}, \quad (6)$$

where x_1 and x_2 – the values of the corresponding factor at the zero level (Table 1), and Δx_1 and Δx_2 are their variation intervals according to the same table.

Transforming the regression equation (3) to the nominal form and after the reduction, the expression is obtained:

$$F=10.254+0.17l_d+5.885K-$$
$$-0.0028l_d^2-8.295K^2-0.326l_dK. \quad (7)$$

The proposed dependence (7) makes it possible to determine the value of the strength of the composite material, from which the PFH with a diameter of 77 mm is made with the specified parameters of the depth and length of damage.

Fig. 3 shows the corresponding response surface of the dependence of the change in the strength of the hose F of the material of the pressure head fire hose with a diameter of 77 mm on the damage length l_d and the damage depth K.

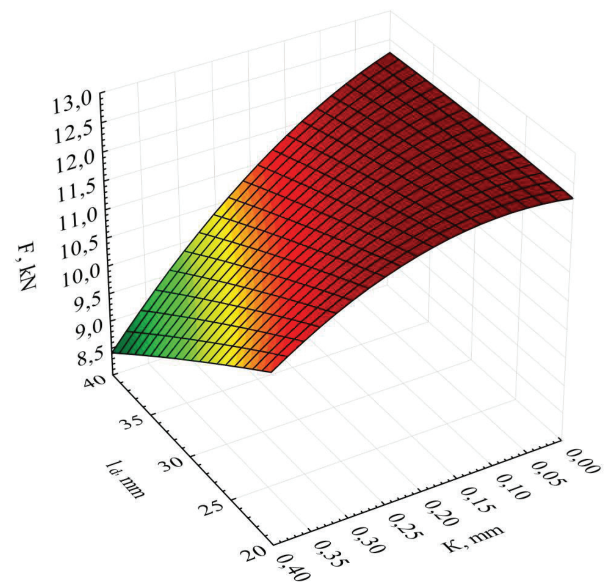

Fig. 3. Dependence of the change in the strength of the hose material on the damage length l_d and the damage depth K

Using the STATISTICA 10.0 software package, a response surface for changes in the strength F of the hose material on the damage length l_d and damage depth K was constructed.

Analyzing the response surface in Fig. 3, it is clear that with an increase in the damage length l_d and its depth, the strength of the hose material F significantly decreases. The smallest strength of the hose F=8.37 is observed with the damage length l_d=40 mm and the damage depth K=0.4 mm. It was found that the change in the strength of the hose material F is almost linearly dependent on the length and depth of damage. It can be seen that the influence of the damage length on the strength of the hose in the proposed range does not exceed 4 kN.

Taking this into account, equation (7) can be simplified by recalculating at a steady upper value of the damage depth factor K=0.4 mm. After that, the equation will look like this:

$$F=11.666+0.0396l_d-0.0028l_d^2. \quad (8)$$

Fig. 4 shows the dependence of the strength of the hose material F on the damage length l_d at the largest damage depth K=0.4 mm.

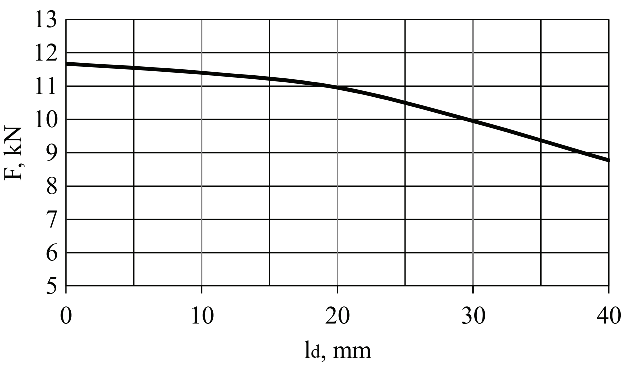

Fig. 4. Dependence (equation 8) of the change in the strength of the hose material on the damage length l_d

From the graph shown in Fig. 4, it is possible to see that with an increased damage length l_d from 0 to 40 at the largest damage depth K=0.4 mm, a decrease in the strength of the hose material is observed. It is found that at the indicated damage values, the strength of the hose material varied from 11.67 kN to 8.77 kN, that is, by 1.33 times, and in percentage terms by 25 %.

6. Discussion of the results of studies of the strength of the hose material

A full-scale experiment was carried out to determine the strength of the PFH material of the T type with an inner diameter of 77 mm from the nature of single damage. It was found that with an increase in the length and depth of damage, the strength of the hose material decreases significantly (Fig. 3).

With an increase in the damage length from 0 to 40 mm and a steady damage depth of 0.4 mm, a decrease in the strength of the hose material from 11.67 kN to 8.77 kN is observed (Fig. 4). This is due to a decrease in the cross-section of the threads of the power frame (base threads).

The obtained results of studies on determining the strength of the hose material with varying damages are of interest to conduct additional research and establish the corresponding dependencies, taking into account both several damages and their direction.

The tests carried out were limited to the study of only two factors, namely the depth and length of the damage, while the degree of wear of the hose material, the number and direction of damage on the test length was not taken into account.

These limitations can be eliminated by investigating changes in the properties of the material of a hose with an arbitrary period of use and conducting additional research, taking into account several damages and their direction.

For the purpose of reliable and safe use of the PFH in the practical divisions of the emergency rescue teams, hydraulic tests are carried out for tightness behind excess pressure. But this type of test defines a simplified assessment of the hose reliability.

A further development of the relevant studies is an experimental analysis of the effect of different sizes and directions of damage on the hose, as well as the effect of several damages on the test length of the PFH.

These studies require the development of both a new plan for conducting an experiment and a technique for conducting experiments, as well as the manufacture of appropriate equipment.

7. Conclusions

1. A technique and an experimental plan for determining the tensile strength of the material of a pressure head fire hose in the longitudinal direction, taking into account single damages, have been developed. Using the method of planning a multivariate experiment, a quadratic regression equation is obtained. The levels of variation of the factors and the working matrix of planning and the results of research were established, where the length and depth of damage were selected as factors, and the strength of the hose was selected as a response. A regression equation with coded values of factors is obtained, to adequately describe the dependence of such an objective function as the strength of the hose material on the influence of the length and depth of damage. The reliability of the regression equation was checked using the Fisher test, the calculated value of which was 5.98, which is less than the table value and confirms with a 95 % probability the adequacy of the described process.

2. Experimental studies have shown that with an increase in the length l_d and depth K of damage, the strength of the hose material F decreases significantly. The smallest strength of the hose material F=8.37 is observed with the damage length l_d=40 mm and the damage depth K=0.4 mm. With the indicated numerical values of the length and depth of damage, the strength of the hose material in comparison with the undamaged one decreases by 34 %. Based on the research results, equation (7) was obtained, which can be used in further research for subsequent calculations of fire hoses.

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