Determination of elasticity modulus of flexible reinforced PVC hoses material at temperature change based on experimental studies and finite element modeling

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Abstract. A description of laboratory unit and a finite-element mathematical model is given, the joint use of which makes it possible to carry out studies of the stress-strain state of flexible hoses based on plasticized PVC with spiral reinforcement made from rigid PVC. The results of laboratory tests and numerical modeling of PVC hoses during freezing and heating to various temperatures are presented. The result of the study is the determination of the modulus of elasticity of the PVC hose base material depending on temperature.

1. Introduction

Today flexible polymer hoses are indispensable in everyday life, in agriculture, in construction, in many areas of industry [1-3]. One of the most promising hose materials is polyvinyl chloride (PVC). This material is insoluble in water, resistant to weak acids, alkalis, alcohols, mineral oils. Among the advantages of PVC - hoses should be highlighted the relatively high mechanical strength, flexibility, low weight and low cost [4]. At the same time, hoses with a homogeneous structure do not have the required consumer properties. Only reinforced products have good mechanical characteristics. The composite structure of the hoses is always improving and it is a high technology product. The problem of choosing the structure and type of material for reinforcing flexible hoses has two aspects: the optimal mechanical strength of the reinforcement and the physicochemical compatibility of the reinforcement and the material of the hose base during manufacture and using. The spiral made of rigid PVC as a reinforcing material is the most convenient choice of manufacturing and not causing any questions during operation.

To ensure the effective using of PVC - hoses, it is necessary to solve such important problems as ensuring their reliability, performance and durability. Therefore, experimental and theoretical studies have a great importance, which make it possible to correctly assess the strength and deformation characteristics of finished products and the materials used in their manufacture and find optimal design solutions in relation to various operating conditions.

To solve applied problems, along with natural tests, it is allowed to use numerical experiments. Currently, computer-modeling methods are widely used in almost all scientific fields. One of the most widespread and effective methods used in numerical experiments is the finite element method [5-7]. The wide area and relative simplicity of its application due to the flexibility and universality of the approach explain the leading position of this method. Many scientific works are devoted to research in this direction [8-13]. The use of finite element models can significantly reduce the volume of field experiments and simplify the laboratory research.
2. Formulation of the problem

Since the operating conditions of flexible PVC hoses can vary from winter frosts to summer heat, it is important to determine the deformation and strength characteristics of hoses depending on temperature.

One of the key deformation characteristics of a flexible hose is the value of the elastic modulus (Young's modulus) for the material of the reinforcing spiral and the material of the base of the hose. Since the reinforcing spiral is made of rigid PVC, it is possible to make samples, carry out tests and determine the elastic modulus of this material depending on the temperature. Such tests are carried out at enterprises manufacturing transparent structures made of PVC profiles [14]. The results is shown in table 1.

| Temperature (°C) | Modulus of elasticity $E_W$ (MPa) |
|------------------|----------------------------------|
| −30              | 3000                             |
| −20              | 3000                             |
| −10              | 2950                             |
| 0                | 2900                             |
| 20               | 2750                             |
| 50               | 2250                             |

For the material of the base of the hose, there is no data on the dependence of the elastic modulus on temperature, since specialized equipment is required to test samples from soft modified PVC. One way to solve the problem is to carry out bending tests on finished products aged at different temperatures. However, there is no direct relationship between the test results of the reinforced hose and the value of the elastic modulus of the hose base material. Therefore, when determining the mechanical characteristics of the hose base material, a combined research scheme with natural experiments and numerical solution of the problem by the finite element method is used.

This work is devoted to computer modeling of reinforced PVC hoses with different geometric characteristics and different base materials. A comparative analysis of the results of the numerical and laboratory experiment on measuring the parameters of the flexibility of hoses during freezing and heating to different temperatures makes it possible to determine the dependence of the elastic modulus of the base material on temperature.

3. Description of the laboratory unit

In order to determine the deformation characteristics of flexible hoses, a laboratory device was made at the Irkutsk National Research Technical University for conducting PVC hose bending tests. A general view of the laboratory unit is shown in figure 1.

The test unit is a frame on which two rigid detachable clamps installed, the diameter of which is adjustable according to the size of the hose. The test hose is installed in the clamps so that it cantilever protrude beyond the clamps. Console length $l \approx 6 \cdot D$. At the end of the cantilever, a fixed load applied to the hose.

The object of the research was selected flexible hoses made of modified PVC with reinforcement of rigid PVC in winter and summer versions. A cross-sectional diagram of the hoses is shown in figure 2. The characteristics of the tested hoses given in table 2.

Before the test, the test hose is keeping at the specified temperature in a thermal chamber for three hours, and then installed on the test bench. Its stepwise loading performing, while at each step the value of the console deflection $\Delta$ is determined. The test results at various temperatures presented in table 3.
Table 2. Characteristics of investigated hoses.

|                         | Winter modification | Summer modification |
|-------------------------|---------------------|---------------------|
| Outer diameter $D$ (MM) | 114,4               | 114,4               |
| Inside diameter $d$ (MM)| 101,3               | 102,3               |
| Hose basis thickness $t$ (MM) | 4,7               | 4,9                 |
| Reinforcing wire diameter $d_{W}$ (MM) | 6,4               | 7,14                |
| Pitch of reinforcing wire spiral $s_{W}$ (MM) | 12               | 11,4                |
| Hose length $L$ (MM)    | 1040               | 1075               |
| Console length $l$ (MM) | 590                | 600                 |
| Number of spiral turns  | 87                 | 94                  |

4. Description of the finite element model

After experimental determination of the deflections, can proceed to the determination of the deformation characteristics of the material by establishing the relationship between the size of displacement and the flexural stiffness of the hose. However, use of analytical methods for determining the displacements...
considered in the course of structural mechanics [15] limited by the complex geometry of the PVC hose as a structural element. The difficulties associated with analytical calculation can be avoided by using numerical calculation methods. For this, finite element models of the studied products were created using the Femap pre- and post-processor engineering analysis using the NX Nastran solver.

The PVC hose model consists of two interconnected parts: a rigid PVC wire spiral model and a flexible PVC hose base model (figure 3).

![Finite element model of the hose with material characteristics.](image)

**Figure 3.** Finite element model of the hose with material characteristics.

The wire model has a circular cross-section with a diameter \(d\). There are twelve plate finite elements in the cross section of the wire model. The model of a reinforcing wire spiral is obtained by rotation the plate - elements relative to the horizontal axis of the model with the formation of solid finite elements from them. There are thirty solid elements along the length of each turn of the spiral. The pitch of the turns of the spiral \(s_W\) corresponds to the data from Table 2. The number of turns of the spiral is selected according to the total length \(L\) of the analysed hose. The geometric dimensions of the obtained wire spiral also correspond to the dimensions of the studied hoses, given in Table 2.

The wire material (rigid PVC) was assumed homogeneous, isotropic and absolutely elastic with the modulus of elasticity \(E_W\), determined for the design temperature in accordance with the data in table 1.

Model of PVC - hose base consists of plate finite elements obtained by rotating beam finite elements relative to the horizontal axis of the model. There are four plate finite elements along the width of the distance between the turns of the reinforcing wire, and thirty elements along the length of each turn of the spiral. Thus, the nodes of the plate elements of the hose base model coincide with the nodes of the solid elements reinforcing spiral model. The thickness of the plate elements corresponds to the thickness of the hose base \(t\) given in table 2.

The base material (soft modified PVC) was assumed homogeneous, isotropic and absolutely elastic. The modulus of elasticity of the base material \(E_B\) is selected so that the value of the cantilever deflection, determined by the numerical method, coincides with the displacement value obtained in a laboratory test at the same force and temperature.

To fix the resulting hose model, nodal rigid connections (fixed) of those nodes installed that corresponded to the locations of the clamps in the laboratory unit. In this case, only the upper and lower nodes fixed.

Two types of external load applied to the model: a volumetric distributed load from the weight of the hose and a nodal vertical force applied at the bottom node of the extreme turn of the wire spiral model.

To set the volumetric load, the tabular value of the PVC density is used \(\rho = 1.43 \, \text{g} \cdot \text{cm}^{-3} = 1.43 \cdot 10^{-6} \, \text{kg} \cdot \text{mm}^{-3}\) [14] and gravitational acceleration \(g = 9.81 \, \text{m} \cdot \text{c}^{-2}\). The value of the nodal load is set in accordance with the laboratory test log.
5. Experimental results
A comparison of the results of a numerical experiment and laboratory tests given in table 3. The values of the elastic modulus of modified PVC for the base of the studied hoses, obtained based on the data in table 3, are given in table 4.

6. Conclusion
During the research was carried out, a finite element model of a flexible hose was developed, which made it possible, based on information obtained during simple laboratory tests, to calculate the values of the elastic modulus of the PVC hoses base material at various temperatures. Knowing the value of the elastic modulus of a material allows get more adequate results during solving various research problems using mathematical modeling.

| Load $F$ (N) | Winter modification | Summer modification |
|--------------|---------------------|---------------------|
|              | Deflection $\Delta$ (mm) | Deflection $\Delta$ (mm) |
|              | experimental | computed | experimental | computed |
| 2.825        | 11          | 24.1    | 7            | 2.1       |
| 7.73         | 24          | 37.83   | 7.5          | 3.43      |
| 12.64        | 41          | 51.57   | 8            | 4.76      |
| Temperature (°C) | Winter modification | Summer modification |
|------------------|---------------------|---------------------|
| −30              | 7                   | 36                  |
| −10              | 5                   | 5                   |
| 0                | 3                   | 3                   |
| 20               | 2,7                 | 2,2                 |
| 50               | 1,1                 | 0,8                 |

### Table 4. Modulus of elasticity of the base material of investigated hoses, MPa.

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