The study of the rheological properties of composite materials of power elements of building structures

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Abstract. The dependences of residual strains on the residence time of the polymer composite material in various media are presented. Samples were taken in the form of flat long elements reinforced with fibreglass. The studied samples were deformed in the form of a three-hinged fastening, by analogy with the longitudinal bending method, mechanical deformation was assumed to be 20, 30, and 60 \% of the destructive deformation. When conducting intermediate measurements, the equipment was disassembled and, after performing control measurements, reassembled. Test temperature accepted 18 ± 3 degrees. Samples were aged in selected media for 540 days with intermediate measurements. Relations are proposed for determining the residual strength, the parameters of which can be obtained on the basis of experimental data on three-point bending. A multifilament high-strength polyethylene fibre with the number of filaments in a multifilament bundle of 900 pieces and a filament diameter of 17 mkm was investigated. The tests were carried out under uniaxial tension with different temperatures and stresses. The method of minimizing the quadratic residual was used according to the results of a numerical analysis of three experiments with temperatures $T = 20^\circ\text{C}$, $40^\circ\text{C}$, $50^\circ\text{C}$ and $60^\circ\text{C}$. The optimal values of the temperature-time analogy coefficients were obtained to develop a methodology for assessing the service life of polymer building structures.

Keywords: composite materials, high-strength polyethylene fibre, temperature-time analogy, temperature-time reduction, time behaviour, prediction of deformation.

1 Introduction

Currently, the need for the use of load-bearing structural elements made of polymer composite materials has significantly increased. This necessitates studying the mechanisms of damage and its development that affect the load-bearing capacity and durability of elements and compounds.

The disadvantage of the methods for calculating such elements and compounds is the lack of accurate experimental data, as well as the variety of compositions of modified composites with different operational properties.

The calculation of polymer composite materials for resistance and durability, a description of their rheological properties, assessment of the characteristics of long-term creep-rupture is an undeniable task today.

The pultrusion process is the most versatile and technological in the production of various fibreglass elements of load-bearing structures. The manufactured products have fibreglass reinforcement in one direction in which the mass is pulled.

The full range of effects on the polymer composite material during operation is temperature, aqueous, alkaline or acidic environment, the influence of the atmosphere, various biodeteriorations leading to climatic and natural ageing [1-10].

The working capacity of the material is characterized by three qualitative characteristics - heat resistance, strength, and durability, each of which is determined by a set of physical constants, where a change in one working parameter can be achieved by changing the other two [11]. Thus, experimentally determining the values of physical constants, it is possible to predict the durability of the material.
The proposed study will allow us to develop a calculation method to predict the service life of polymer structures providing strength and reliability, a design method for polymer composite structures taking into account damage accumulation and aggressive factors affecting the decrease in the strength of the studied material.

2 Materials and methods

2.1 The study of flat elements reinforced with fibreglass

In this work, we investigate a polymer composite material in the form of flat extended elements reinforced with fibreglass. Research media were selected: air, distilled water, and aqueous alkali solutions. It is known that when moisture penetrates PCM, weakening of bonds at the fibre-binder boundary occurs, microcracks appear [12-15], which leads to a decrease in strength. The first aqueous solution of alkali, modelling the liquid phase of concrete, adopted of NaOH – 8 g. and KOH – 22.4 g. per 1 liter of distilled water (GOST 31938-2012), the pH of the alkaline solution was in the range from 12.6 to 13. To exclude the interaction of air with CO₂ and evaporation, the alkaline solution was in a closed container. The concentration of the second aqueous solution was doubled.

The studied samples were deformed in the form of a three-hinged fastening (Figure 1) similar to longitudinal bending [16-22]. Mechanical deformation was assumed to be 20, 30, and 60 % of the destructive deformation. When conducting intermediate measurements the equipment was disassembled. After control measurements, the equipment was reassembled. Test temperature accepted 18 ± 3 degrees. Samples were aged in selected media for 540 days with intermediate measurements. Measurements were carried out with KM-8 cathetometers with an accuracy of 0.001 mm.

The dependences of residual deformations on time are obtained (figures 2-5).

Figure 1. General view of the studied samples, the magnitude of the deflection of 30 mm, 25 mm and 15 mm.

Figure 2. Air environment, deformation height 30 mm, 25 mm and 15 mm, 538 days.
2.2 The investigation of the deformation of high-strength fibres at different temperatures and long operating times

This section presents the results of studies of high-strength polyethylene multifilament fibre, with the number of threads in a multifilament bundle of 900 pieces, filament diameter of 17 microns. The tests were carried out under uniaxial tension with different temperatures and stresses. To predict long-term creep, the method of analogies (superpositions) was chosen based on the use of factors accelerating relaxation processes. According to the principle of the temperature-time analogy, the temperature and the time of deformation are interconnected and mutually equivalent [24].

Using the method of analogies, the task of predicting creep for given values of temperature and stresses is reduced to finding the reduction coefficients, based on the experiments that establish the corresponding time scales of deformation. To describe the polymer behaviour, a model of a hereditarily elastic material with Abel’s kernel was adopted:

\[
\varepsilon = \frac{\sigma}{E} + \int_0^t \frac{C \cdot \sigma(\tau)}{(t-\tau)^\alpha} d\tau
\]

where \(C > 0\), \(0 < \alpha < 1\).
Here it was assumed that $C = \text{const}$, $\alpha = \text{const}$. After processing the obtained experimental data, regression functions are constructed to describe the behaviour of the polymer material in Eq. (1). Graphs of regression functions are presented in Figure 6. To find $C$ and $\alpha$, we used the method of minimizing the quadratic discrepancy between the experimental and numerical values of the strains at different instants of time.

To predict strains at different temperatures, the assumption that the material is “simple” was used. This means that creep strain can be determined by the following Eq. (2):

$$
\varepsilon^{cr} = \int_{0}^{t^*} \frac{C(T_0) \cdot \sigma(t^*)}{(t^* - \tau^*)^2} d\tau^*, \quad \tau^* = \frac{t}{a_T}
$$

where $a_T$ – coefficient of the temperature-time analogy, $T_0$ – reduction temperature, $T$ – the current temperature.
Using the reduction coefficient the problem of predicting the behaviour of the material under conditions that are closest to the operational conditions is solved, for example, for large values of the time interval or values of higher temperatures. To approximate the coefficient of temperature-time reduction, dependence is selected in the form Eq. (3):

\[
\ln(a_T) = \frac{a_1(T - T_0)}{a_2 + (T - T_0)}
\]

where \(a_1\), \(a_2\) – empirical coefficients.

3 Results

Using the method of minimizing the quadratic discrepancy according to the results of numerical analysis of three experiments with temperatures \(T = 20 ^\circ C, 40 ^\circ C, 50 ^\circ C\) and \(60 ^\circ C\), the optimal values of the coefficients \(a_1 = -9.98492\) and \(a_2 = 250\) are obtained. The value \(T_0 = 20 ^\circ C\) is taken as the reduction temperature.

Figure 7 shows the predicted dependences of elongation at \(T = 50 ^\circ C\), \(T = 60 ^\circ C\), obtained using Eq. (2). The obtained values of the forecast and experiments show that the order of the quadratic residual between the experimental and calculated values of the strains is the same for all cases. Thus, according to the results of the experiments and numerical analysis, we can assume that the material under consideration belongs to the class of “simple”. That allows, knowing the coefficient of the temperature-time analogy of \(a_1\), to predict the material behaviour in time at different temperatures and a long operating time.

4 Discussions

The study of a polymer composite material in the form of flat elements in various environments and multifilament high-strength polyethylene fibre at different temperatures. Relations are proposed for determining the residual strength, the parameters of which can be obtained on the basis of experimental data on three-point bending. They allow you to predict the level of permissible long-term load at a given design life. The advantage of this approach is that the number of test types is significantly reduced, as a result, the number of samples is reduced, less time and equipment are required to obtain the necessary data on the material. To predict deformations at various temperatures, a temperature-time analogy was used. This will allow further development of methods for assessing the service life of polymer building structures.

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