KAUNAS UNIVERSITY OF TECHNOLOGY

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METHOD OF YARNS LONG-LASTING STRESS RELAXATION PREDICTION

Summary of Doctoral Dissertation
Technological Sciences, Materials Engineering (08T)

2018, Kaunas

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INTRODUCTION

<u>Research Problem Justification and Relevance of the Work.</u> Recently there has been an increasing focus on the production and use of technical textiles. Products for technical use normally consist of yarns of chemical fibres, however, depending on the intended purpose of the product, natural fibres can be used as well. As fibres are of a diverse origin and differ in their mechanical features, it is therefore important to investigate the behaviour of these yarns under mechanical strain. Consequently, there is a need to further investigate the mechanical and particularly the important relaxation characteristics of yarns. Technical textile products, depending on their purpose, need to meet certain requirements: they have to be sufficiently strong during deformation, have to withstand appropriate temperatures, have to be resistant to chemical and biological factors, have to be highly or minimally absorbent, and so on. It is also important to create fibres and yarns for products that are used in extreme conditions. When analysing the suitability of fibres for technical textile, usually it is the mechanical characteristics that are assessed, i.e. the stretching characteristics are determined: the strength while stretching and the elongation. When conducting more thorough technological investigations, the influence of deformation (resilient, elastic, plastic), humidity and temperature of the strength and deformation is assessed.

The relaxation processes of the textile fibres are studied during the manufacturing process. Technologically processed yarns are always more or less stretched and applied with force, where the value, duration of exposure, nature of loading and unloading determines the behaviour of the yarns in technological operations. Like any other polymer fibres, the reaction of the yarns to the acting forces is strongly dependent on time. Due to the relaxation phenomena, eventually there is a change in the deformations or the stress of the yarns, which makes the yarns resist shape changes. The reaction of the yarns to any mechanical disruption is considered to be their relaxation characteristics.

The relaxation characteristics are important, not only for the characteristics of the intended use of the product that is made of yarns, but also for assessing the behaviour of the yarns during a certain mechanical process. In various technological processes, the stresses of the yarns change constantly and change depending on what the yarns had experienced before, i.e. their mechanical history. After the application of force, it is very important how the yarns are able to restore to their original parameters. This restoration, also called the elongation relaxation, is also a process related to time. If the yarns are affected by a new strain before fully restoring, their reaction additionally depends on their mechanical history. After processing yarns with features of diverse relaxation or yarns of the same raw materials and composition, but with a different mechanical history, into a certain product, irremovable defects (e.g. undulation, blistering) may form or other technological issues may appear in the product.

Relaxation processes of fibres have been examined in sufficient detail in both textile and other polymeric fibres. Various scientists have observed that the speed of stress relaxation during relaxation is changing, however, there is no further analysis about predicting long-lasting relaxation. Despite a large amount of investigations, no method has been created to predict long-lasting relaxation behaviour, lasting a few days or even weeks, by using short-lasting empirical investigations.

Diverse textile fibres have a very different and multilevel structure. The more complex the structure of the fibre, the more complex the systems of forces affecting the fibre can be. Thus, the characteristics of the analogue nature of diverse fibres often present themselves in different features and are expressed in different quantitative parameters.

A lot of time is spent on detailed investigations of relaxation processes - from one second to a few days or weeks, and in some cases even more. When carrying out long-lasting stress relaxation or creep, the problem of long-term stability of the electronic machinery appears. Therefore, a method is required that would allow users to predict long-lasting relaxations under empirical investigations lasting only up to several thousands of seconds. In such a way, the time wasted on investigations would shorten and the user could easily predict the behaviour of the product during long-lasting stresses.

The aim of the dissertation - to create a new method for predicting long-lasting stress relaxation of yarns under short-lasting empirical investigations of stress relaxation.

The objectives of the research:

- to investigate the behaviour of yarns of various constructions and origins during long-lasting stress relaxation, and to set the regularities of long-lasting yarn stress relaxation processes,
- to investigate the influence of deformation to the development of long-lasting relaxation of yarns and to assess its regularities,
- to assess the time of existence of the break point of the stress relaxation process and its dependence to the structure, origin and value of deformation of the yarns,
- to create a method of predicting long-lasting relaxation of yarns, which is based on investigations of short-lasting stress relaxation and the time of appearance of the break point of the relaxation process, and to check the suitability for its use,
- to check the suitability of applying the created method for predicting stress relaxation for the creep of yarns.

Scientific novelty and practical importance. In this work major attention is given to such textile products that are constantly stretched for a long time and whose quality and durability may affect human health or even life. For example, conveyor belts, drive belts, tents, cables, attachment straps, ropes an etc., which are constantly deforming under various force application during work, and that the deformation can be long-lasting. Different relaxation processes inside the yarns are investigated extensively, however, within a short period of time in comparison, therefore, the behaviour of the product during long-lasting workloads cannot be predicted with reference to them.

While carrying out the investigation, a new method of predicting stress was created according to the break point observed during relaxation. It was found that this break point is common to all the investigated yarns of different constructions and origins, and while having different deformation values. Therefore, such a method can also be applied to other yarns that were not examined in this work. As the experimental investigations of stress relaxation can only be carried out up to a maximum of 1 000 seconds using the created method, the output data can be used to predict the relaxation process for a period of several days. The suggested method allows users to significantly decrease empirical investigations and can assess the relaxation process of the product quite fast, within an hour, in addition to calculating its behaviour for a long period of several days and additionally assist in making a decision about the suitability of the product and/or the values of the load with which the product can be operated.

Using the suggested method, a significantly larger amount of yarns can be investigated during the same time period and yarns whose characteristics and relaxation process are more suitable to the use of the product can be selected. In this way, the structure of the product can be optimized and a suggestion of how to produce a product with the yarns most suitable for its use can be made.

The suggested method also makes assumptions of how to choose such deformation regimes, according to which the product deformations could be predicted and controlled, which is particularly important when using large moveable tents.

Approbation of the research results. The results of this research were presented in 4 scientific publications, including three articles published in Clarivate Analytics Web of Science listed journals with a citation index (IF/AIF>0.2) and at 8 international conferences.

Structure of the dissertation. The dissertation consists of an introduction, 3 chapters, conclusions, a list of references (165 positions) and a list of scientific publications.

CONTENT OF THE DISSERTATION

The "Introduction" presents the relevance of the topic, the formulated aim of the work, the set objectives, along with the scientific novelty and where the practical value of the work is discussed.

The first chapter, "Literature review", introduces general information about relaxation processes of various textile fibres, stress relaxation, the peculiarities of the process of creep and stress relaxation, and the theoretical prediction of the relaxation processes are reviewed.

The second chapter, "Research methodology", describes the object of research and the methodology of experimental investigations.

Experimental materials.

Three different types of fibres and yarns were selected for the experimental investigations: the multifilament (48 filament) polyester (PET) yarn with a linear density of 29.9 tex, the cotton yarn with a linear density of 25 tex ×2 and the woollen yarn with a linear density of 25 tex. These types of yarns were chosen with the intention to test very different structures of the yarns – multifilament (polyester), spun single yarn (wool) and spun double yarn (cotton). Although the method of prediction for long-lasting relaxation has only been assessed for the experimentally selected three kinds of yarns, it is possible to state that this method can also be acceptable for other types of yarns.

Experimental methodology.

In this work, two main regimes were selected to investigate long-lasting relaxations and to predict the further processes - stress relaxation and creep.

The samples before the experiments were kept for 24 hours and the experiments themselves were done under standard environment conditions in accordance with the LST EN ISO 139:2006, the standard "Textiles. Standard conditioning and testing environment", i.e. set temperature (20 ±2) ^{o} C and a relative humidity (65 ± 5) %.

1. **Mechanical properties testing.** The Zwick/Roell universal materials testing machine was used for investigation of the yarns tensile properties; a gauge length of 500 mm was set in the test; the extension speed was 500 mm/min. All testing parameters were chosen according to LST EN ISO standard 2062:2010. The tensile properties of the investigated yarns were repeated 10 times and the average values were then calculated.

2. **Stress relaxation testing.** The same testing machine, Zwick/Roell, was used for the stress relaxation tests. Specimens were stretched at a speed of 500 mm/min up to the strain level (3 %, 5 %, 7 % and 10 %) and held in this position for a set time. The stress was recorded as a function of time (from 1 second up to 200 000 seconds). All the equipment for this research and the stretching machine were operated by *testXpert*® software at the gauge length of 500 mm, and load cell 50 N.

Since the elongation of cotton yarns does not reach 10 %, the stress relaxation was done only at 3%, 5% and 7%.

The relaxation processes were investigated by the fixed elongation method, i.e. the test specimens were stretched at 3 %, 5 %, 7 % and 10 %. If a yarn is stretched up to the given strain and held at the same strain for a particular time, the stress decreases during that time. The stress relaxation was calculated as the ratio (P/P_0), where P_0 is the initial stress at zero time (t=0 sec) and P is the stress at subsequent times. Stress relaxation curves were mathematically described by calculations from a series of experimental points, i.e. stress relaxation values were measured after 1, 2, 5, 10, 20, 50, 100, 200, 500, 1000, 2000, 5000, 10000, 20000, 50000, 100000, 200000 seconds for each curve. All data is the average of five elementary test measurements. The coefficient of variation of stress measurements did not exceed 5 %.

To locate the break point, the suggested method by R. Milašius (2003) was used, according to which the break point is found after analysing all the possible variants and is selected in the place where the relative error δ, calculated by both linear equations and having the empirical value, is the lowest.

By means of the earlier method presented, it was proposed to describe these experimental points with two straight lines. The average curve of the relaxation calculated from five relaxation curves was used for the investigations. The relative error between experimental values and those calculated by the straight line equation (δ) for all experimental points of the stress relaxation curve is calculated as:

$$\delta_i = \frac{(P/P_0)_e - (P/P_0)_c}{(P/P_0)_e} \times 100\% \qquad (1)$$

where: $(P / P_0)_e$ – experimental values of stress relaxation,

$(P/P_0)_c$ – stress relaxation values calculated by straight line equations.

The maximum relative error between experimental and calculated by the straight-line equation values (δ_{max}) were used for investigations.

To specify the location of the break point, new relative values of stress relaxation were entered and new curves were calculated, and therefore a new break point was located using the same methodology. This is repeated until the most optimal value of the break point place is found.

3. **Creep testing.** To carry out the experiments, the universal stretching machine Zwick/Roell was used. Chosen settings: gauge length of 500 mm, extension speed was 500 mm/min and load cell 50 N. During this investigation, elongation components are determined. To carry out the creep tests, multifilament polyester yarns were chosen, because out of the three chosen test subjects of different origin and structure they are the most commonly used in textile products that have new structural and specific features, along with the manufacturing technological processes of those products as well.

For the creep tests, the values of the used force are selected from the tensile diagram of the investigated yarns. To carry out the investigation, the following regime of deformation was selected: multifilament polyester yarns are loaded with different forces 4 N, 7 N and 12 N using a constant speed, the duration of the load is 200 000 seconds.

The third chapter, „Results of investigations“, presents the results of the experimental investigations and their analysis.

Determination of mechanical properties of investigated yarns. The tensile properties of the investigated yarns are presented in Figure 1 and Table 1.

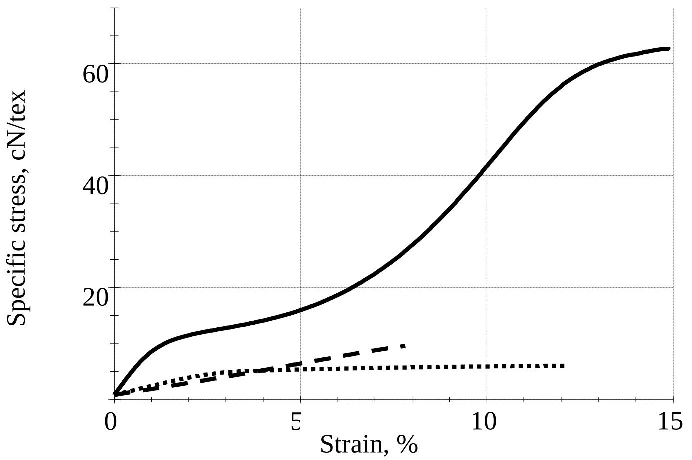


Figure 1. Yarn stretch diagrams: continuous curve - multifilament polyester yarn; dashed line - cotton yarn; dotted curve - woollen yarn

Table 1. Mechanical properties of investigated yarns

Yarn	Linear density, tex	Specific stress, cN/tex	Strain, %	Coefficient of variation	
				Specific stress, %	Strain, %
Multifilament polyester	29.4	61.53	13.34	1.92	6.98
Cotton	25×2	9.46	7.41	3.20	4.19
Woollen	25	5.59	12.30	5.91	11.63

The obtained results show that for further investigation of relaxation features, the same treatments cannot be applied to all the yarns - cotton yarns break at 7.41%, while multifilament polyester yarns and woollen yarn stretch up to more than 12%. As a consequence of this, it was chosen to apply 3%, 5%, 7% and 10% elongations for the investigation, except for cotton yarn, whose maximum elongation was 7%. Out of the three yarns that were chosen to be analysed, the maximum and the steadiest characteristics are those of the multifilament polyester yarns. When comparing the properties of cotton and woollen yarns, it is seen that the cotton yarns are stronger, however, the woollen yarns possess higher elongation, which is close to the multifilament polyester yarns.

Long-lasting relaxation of yarns different origins. Long-lasting stress relaxation of yarns of different thread structure and origin was analysed under various deformation (3%, 5%, 7% and 10%) in 200 000 seconds.

While analysing the polyester yarn stress relaxation under different stresses, it was noticed that, despite the value of stress, the type of relaxation curves are the same in all cases. When stretching the yarn up to the chosen elongation, the time *t*=0, when the relaxation process begins is recorded (Figure 2). The greater the stress applied, the more time is needed to reach that stress: 3% – 2.12sec, 5% – 3.32sec, 7% – 4.57sec and 10% – 6.3sec.

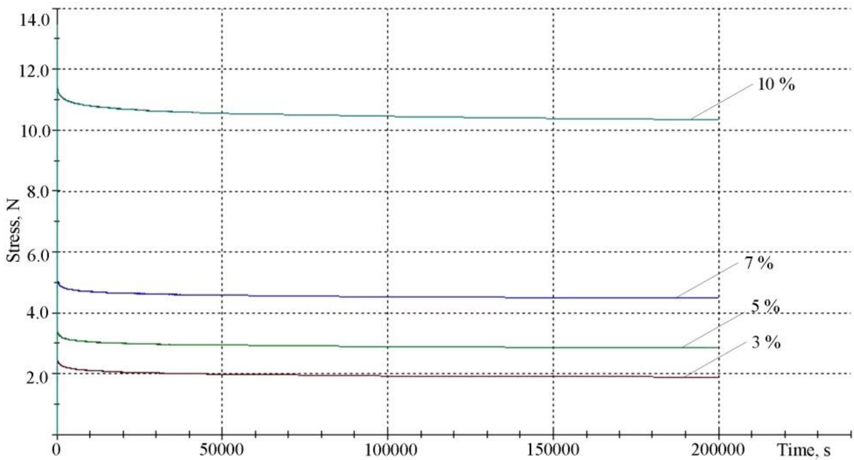


Figure 2. Development of multifilament polyester yarn stress relaxation during different stages of relaxation process after 200 000 seconds

The beginning of the cotton yarn relaxation is shown in Figure 3. Stretching the cotton yarns up to a 3% elongation, t_0 is reached after 2.18 seconds, stretching up to 5% – 3.34 seconds, stretching up to 7% – 4.52 seconds. When analysing the development of cotton yarn relaxation, it is seen that under different stresses (3%, 5% and 7%) the relaxation process is gradually equal. It can be stated that the change of the relaxation process of these yarns is not dependent on the extent of the stresses.

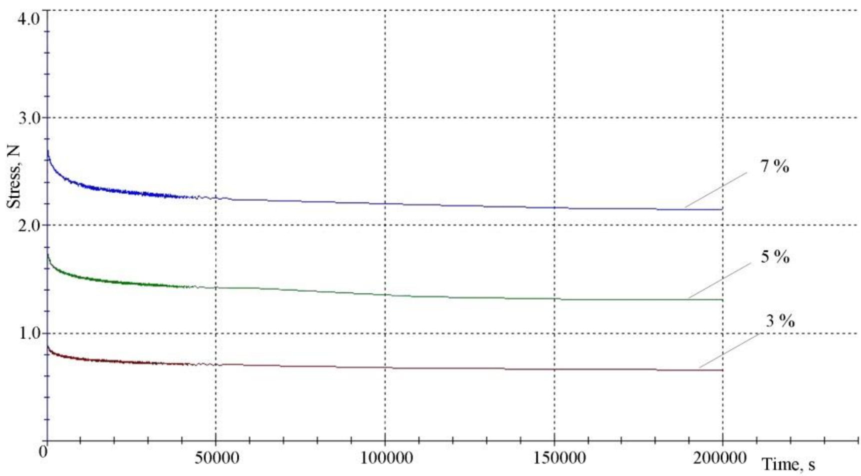


Figure 3. Development of cotton yarn stress relaxation during different stages of relaxation process after 200 000 seconds

According to the relaxation process, it was found that during the process of stress relaxation between 10 000 – 50 000 seconds, waves of periodical differences become apparent. This can be explained by the specific structure of cotton fibre and the regrouping of internal connections. However, to obtain statistical performances, these differences are eliminated because all the results are processed by software, which is directly connected to the stretching machine. During long-lasting relaxation, the values of stress relaxation decreased gradually. This can be seen in the chart and the results in Table 3.2. After 200,000 seconds the stress relaxation of cotton yarns decreased: under 3% – 48%, under 5% – 47.81%, under 7% – 45.13%. Thus, the process of cotton yarn stress relaxation decreased gradually, and this allows the research to predict further processes.

Figure 4 shows the development of woollen yarn stress relaxation under different stresses. The process of the beginning of the woollen yarn stress relaxation under different deformations is: 3% – 2.25sec, 5% – 3.30sec, 7% – 4.5sec and 10% – 6.3sec. As seen in the chart, the stress relaxation of woollen yarns under different stress was different than multifilament polyester yarns and cotton yarns. Greater stress values were obtained by stretching up to 10% and 5% elongation. The investigation results show that the process of relaxation of the woollen yarns under different stresses is similar.

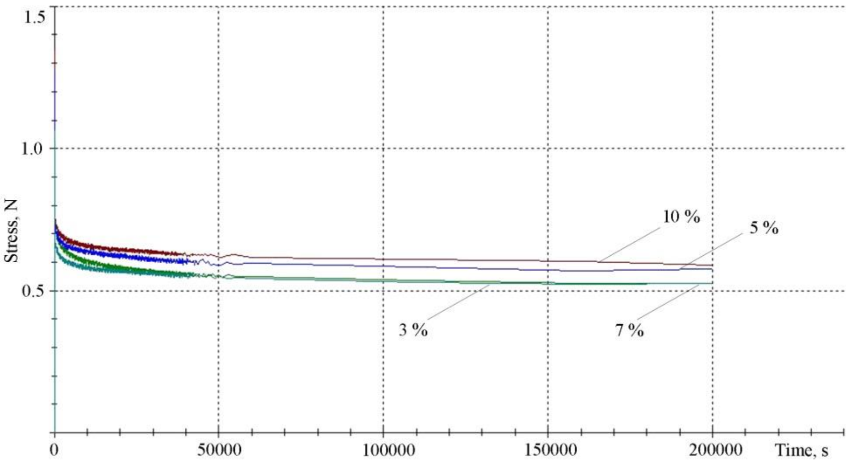


Figure 4. Development of woollen yarn stress relaxation during different stages of relaxation process after 200 000 seconds

Figure 4 shows the relaxation stages of woollen yarns. The graph chart shows that in the relaxation process of up to 50 000 seconds, there are noticeable waves of periodical differences, which are eliminated by using software. After 200 000 seconds the stress relaxation under 3% and 7% stresses became almost equal (difference is only 0.02 N). The values of woollen yarn stress relaxation under 3% stress decreased by 50%, under 5% – 54.33%, under 7% – 58.20% and under 10% – 55.97%.

Thus, as can be seen from figures 3.2 – 3.4, the start time of the relaxation process *t*=0 under different stresses (3%, 5%, 7%, 10%) does not depend on the origin and structure of the yarn. During long-lasting relaxation, the values of stress relaxation in all investigations decreased depending on time. A greatest change of stress relaxation is noticed at the beginning of the process, when the relaxation speed is the highest, however later, with speed decreasing, the values of stress decreased more slowly.

<u>The influence of the fibre structure of yarns to relative stress relaxation.</u> Analysis of relative stress relaxation was carried out, which shows only the process of relaxation, i.e. in what regularities did the stress relaxation change, not what value it had. To simplify the analysis of the process of relaxation, the analysis of the relaxation process on a logarithmic scale was chosen, and to simplify the mathematical statistical analysis of the process, the type of analysis chosen was the dependency of relative stress to the time logarithm.

Figure 5 shows the relative stress relaxation of multifilament polyester yarns under different stresses.

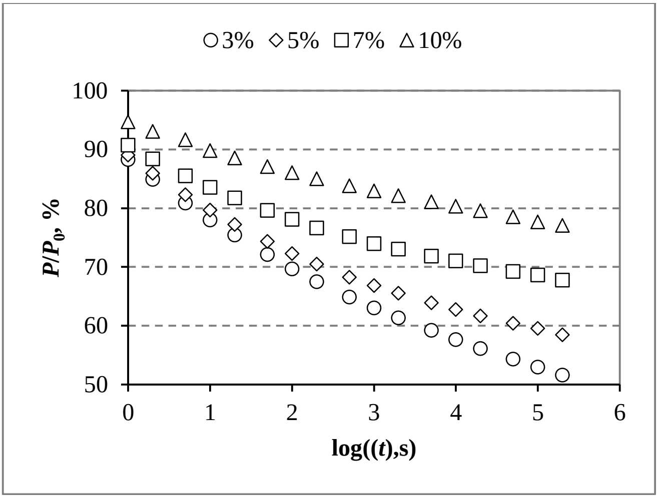


Figure 5. The relative stress relaxation curves of the multifilament polyester yarns at different strain elongation

Curve equations are appropriate to describe this dependence, as the values of the coefficients of determination are: 3% – 0.9792, 5% – 0.9633, 7% – 0.9615 and 10% – 0.9842. During constant elongation of 10%, after 1 second of relaxation, the relative stress relaxation is almost 6.77 % higher than under 3% of stress. After investigating long-lasting relaxation, it was found that after 200 000 seconds the stress relaxation between these stresses already differs by 33%. It can be stated that the higher the constant stress of the yarns, the higher the values of stress relaxation are and change gradually over time. The given results show that with the change of elongation stress from 3% to 5%, the stress relaxation curves of the yarns are close to one another. Thus, it can be stated that stress relaxation of multifilament polyester yarns depends on the size of the elongation, though the dynamic changes of relaxation are not equal.

As mentioned before, the elongation of cotton yarn break is only 7.41%, therefore, the stress relaxation was investigated with a deformation of 3%, 5% and 7% (Figure 6). In this case, the relative relaxation under different stresses is almost equal, and the coefficients of determination R^2 are close to 1, i. e. 3% – R^2 = 0.9987, 5% – R^2 = 0.9959 and 7% – R^2 = 0.9933. After one second of stretching, the relative stress relaxation of 3% is only 2.9% higher than when stretching under 7% stress. After 5000 seconds, the relative stress relaxation becomes equal under all stresses (P/P_0 = 62%). After 200 000 seconds, the relative stress relaxation under 7% is only 5.5% higher than under the lower 3% and 5% stresses. Therefore, it can be stated that the process of cotton yarn relaxation was gradual. Although there are some differences between the curves, it is not as great as in the case of the polyester yarns.

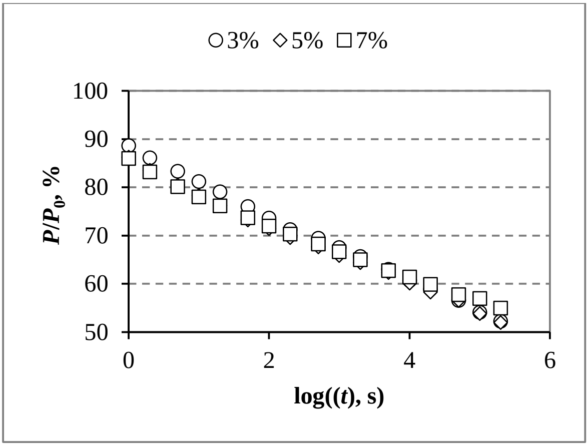


Figure 6. The relative stress relaxation curves of the cotton yarns at different strain elongation

The relative stress relaxation curves of woollen yarns are shown in Figure 7. As the results have shown, the type of stress relaxation process of woollen yarns under different stress is identical. When describing the curves in a linear equation, such values of the coefficient of determination R^2 are obtained: 3% – $R^2 = 0.9540$, 5% – $R^2 = 0.9337$, 7% – $R^2 = 0.9337$ and 10% – $R^2 = 0.9111$.

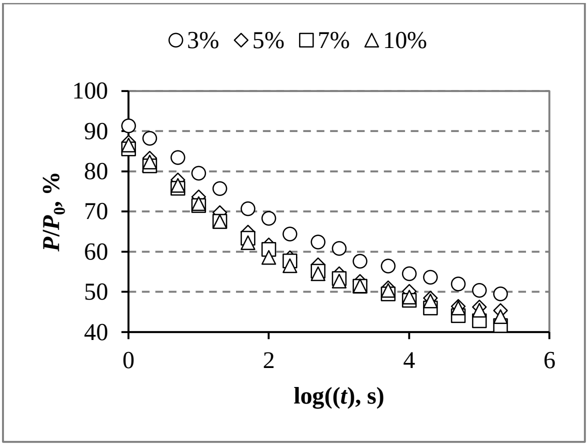


Figure 7. The relative stress relaxation curves of the woollen yarns at different strain elongation

The greatest values of relative stress relaxation were obtained by stretching the yarns up to 3%. After one second, the 3% relative stress is greater by 6.3% and after 200 000 seconds - greater by 16% in comparison to other stresses. Under 5%, 7% and 10% stresses the relative stress relaxation is very similar: after one second the relative stress relaxation P/P_0 is 85 – 87 %, however under 7% stress after 10 000 seconds the relative stress relaxation falls by 4%, and after 200 000 seconds falls by 8%. It can be stated that under low stresses the woollen yarns have a faster relaxation process. This can be explained by the fact that under such stresses the woollen yarns do not reach the yield strength, and here it appears the larger influence of the stretching properties to the relaxation process.

To further analyse the behaviour of yarns of different origins during long-lasting relaxation, four charts were created (3%, 5%, 7% and 10%) in which the relaxation curves of the investigated yarns under different stretching are shown; Figure 8-11.

Figure 8 shows the relaxation curves of yarns of different origins and structure while stretching to a 3% elongation. Under low force, the nature of change of different yarns in time is similar. At the beginning of the process, from 1 second to 10 seconds, the nature of the change of the woollen yarns is more intense by 3.2%. Under greater duty cycles, the relaxation process is more intense in the woollen yarns. The largest difference in the relaxation intensity between yarns of different origins appears after 2 000 seconds: in the multifilament polyester yarns it is higher by 6.5% than in the woollen yarns and lower by 12.7% in the cotton yarns.

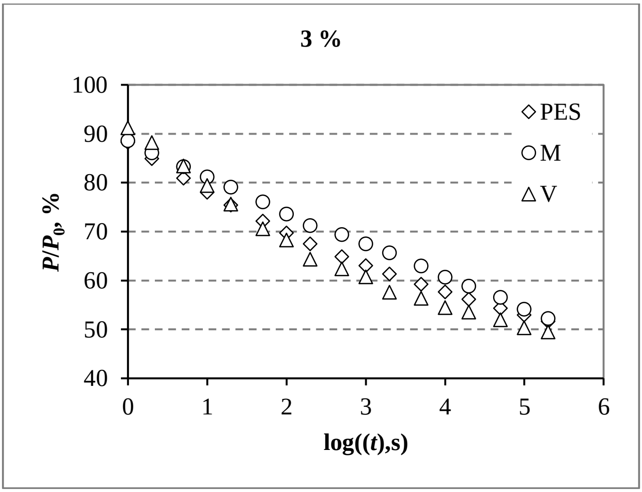


Figure 8. Relative stress relaxation curves of the multifilament polyester, cotton and woollen yarns at 3% of elongation

At the greatest duty cycle of 200 000 seconds, the change of the processes of the cotton yarns and the multifilament PES yarns evens by P/P_0 = 51.64% – 52.25%, but for the woollen yarns it remains lower by 5.28%.

The relative stress relaxation curves of multifilament polyester, cotton and woollen yarns at 5% elongation are shown in Figure 9. The stress relaxation process of the multifilament polyester yarn was more intense during the whole experiment. During a low duty cycle (from 1 to 2 second), the change of the process of the cotton and woollen yarns is 3.10%, which is lower by 2.09% than that of the polyester yarns. During a higher duty cycle (from 5 to 5 000 seconds) the type of alteration of relaxation of multifilament polyester yarns and cotton yarns is similar: PES yarns P/P_0 = 82.30% – 63.94%, cotton yarns P/P_0 = 80.46% – 62.35%. However, the stress relaxation of the woollen yarns falls distinctly P/P_0 = 77.82% – 50.94%. The relaxation process of the yarns is completely different after 10 000 seconds (log (t, s) = 4): the process change of the cotton yarns, compared to the multifilament polyester yarns, falls rapidly by 4.19%, and the relaxation of the woollen yarns falls by 20.24%. Throughout the whole project, the speed of stress relaxation of the multifilament polyester yarns falls gradually, however a more significant change of the relaxation speed of the cotton yarns appears after 20 000 seconds and of the woollen yarns - after 50 000 seconds.

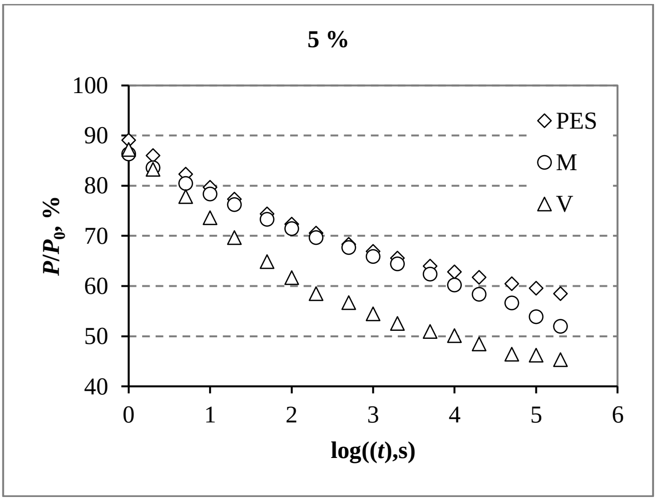


Figure 9. Relative stress relaxation curves of the multifilament polyester, cotton and woollen yarns at 5% of elongation

The curves in Figure 10 show the relative stress relaxation in the yarns of different origin and structure at up to 7% elongation. The investigation results showed that the relaxation process of the multifilament polyester yarns, the cotton and woollen yarns is similar. The intensity of the relaxation speed of all the yarns shifted gradually. During the first second, the relative stress is larger in the multifilament PES yarns (P/P_0 = 90.77%), while in the cotton and woollen yarns the stress is almost the same (respectively P/P_0 = 85.99% and P/P_0 = 85.54%). With a higher duty cycle, the woollen yarn relaxation speed was more intense and the stress fell gradually. The graphic chart shows that the stress of the woollen yarns during relaxation fell to 51.40%.

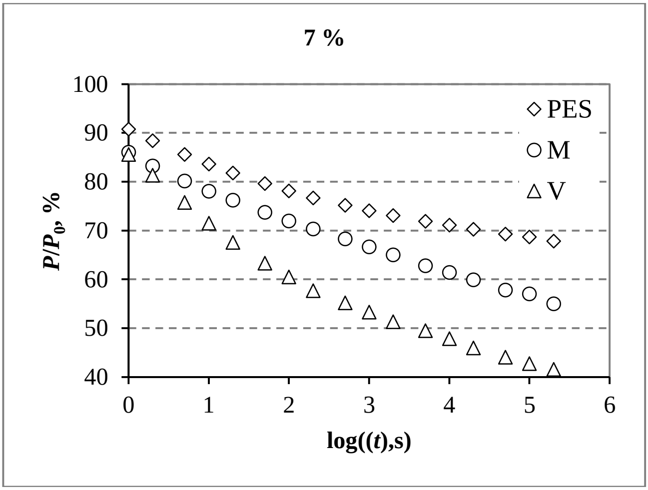


Figure 10. Relative stress relaxation curves of the multifilament polyester, cotton and woollen yarns at 7% of elongation

The relative stress relaxation curves, when stretching the yarns of different origins up to 10% elongation, are shown in Figure 11. As mentioned before, because of a low elongation of the cotton yarns (Table 1), only the multifilament polyester yarns and the woollen yarns were tested. During a low duty cycle (from 1 s to 5 s), the stress of the multifilament PES yarns is 8.68% greater than of the woollen yarn. The relaxation process of the multifilament polyester yarns was gradual, and after 200 000 seconds fell by only 18.62%. It can be seen from the curves that the relaxation speed of the woollen yarns was greater, and the stress values throughout the whole time period fell rapidly, i.e. fell by 49.34%.

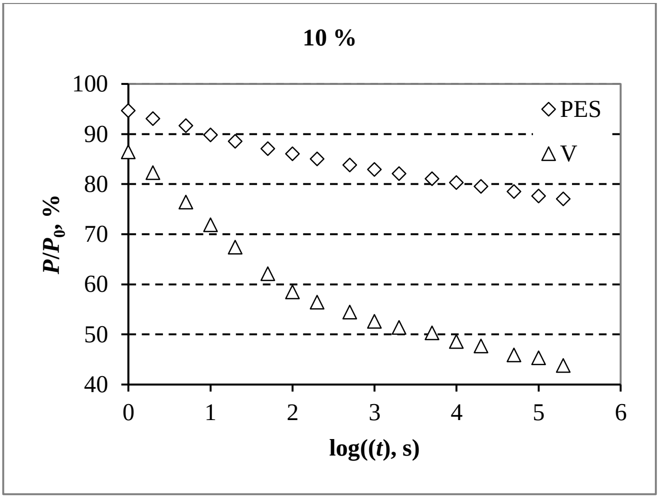
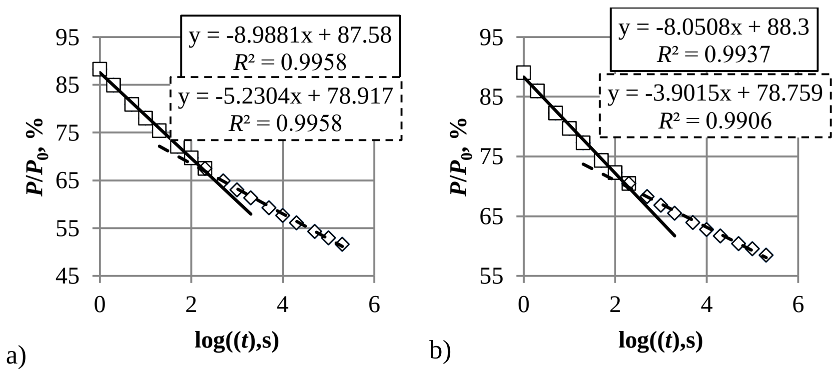
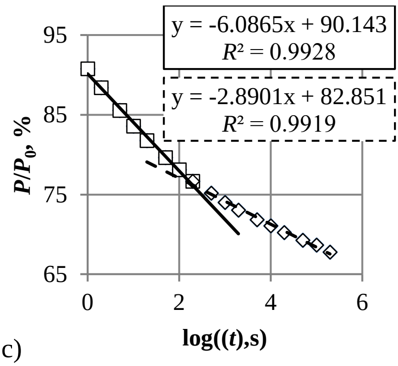


Figure 11. Relative stress relaxation curves of the multifilament polyester, cotton and woollen yarns at different levels of elongation: a) – 3%, b) – 5%, c) – 7%, d) – 10%

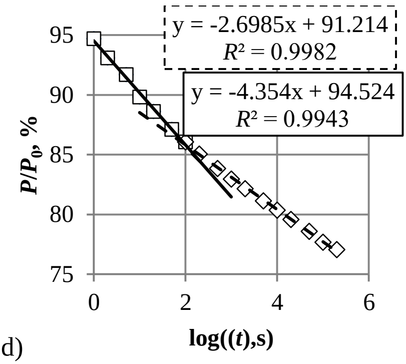
Stress relaxation break point analysis. The process of stress relaxation was analysed by searching for the break point of the relaxation process. All further calculations and analysis of the break point are carried out according to the methodology described in Chapter 2, using both types of search for the break point - both the coefficient of determination R^2, and the maximum relative error δ_{max}.

Figures 12–14 show the assessment of the break point with the maximum relative error δ_{max} for the multifilament polyester yarns, cotton and woollen yarns under different deformations.



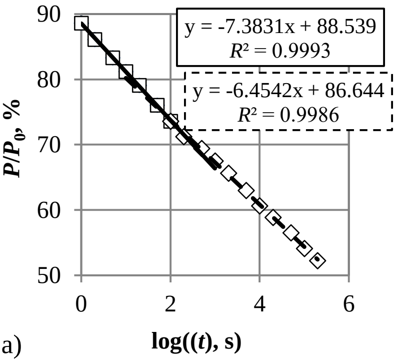


c)

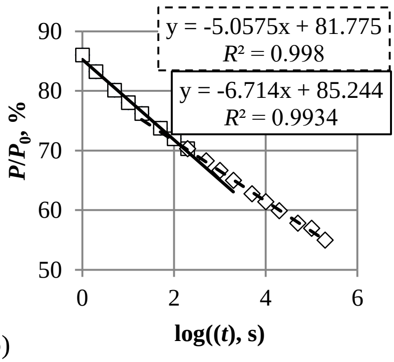


d)

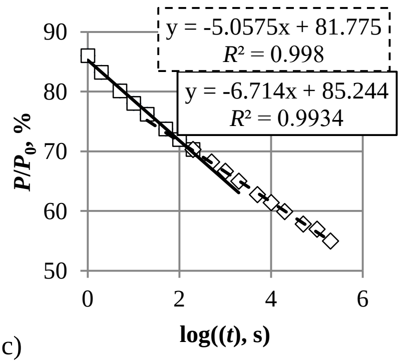
Figure 12. The break point of stress relaxation of the multifilament polyester yarns under different deformations: a) – 3%; b) – 5%; c) – 7%; d) – 10%



a)



b)



c)

Figure 13. The break point of stress relaxation of the cotton yarns under different deformations: a) – 3%; b) – 5%; c) – 7%

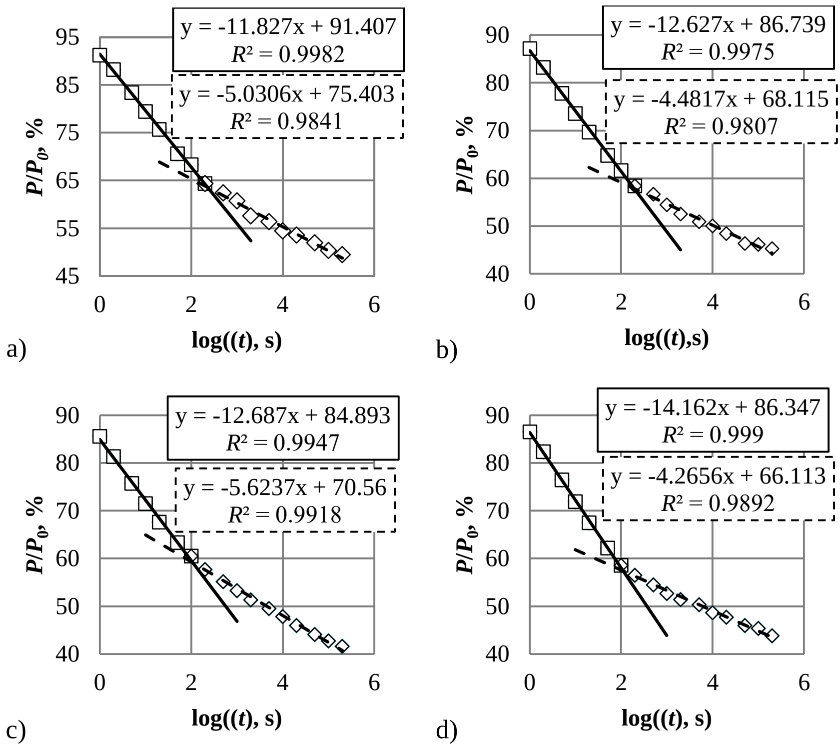


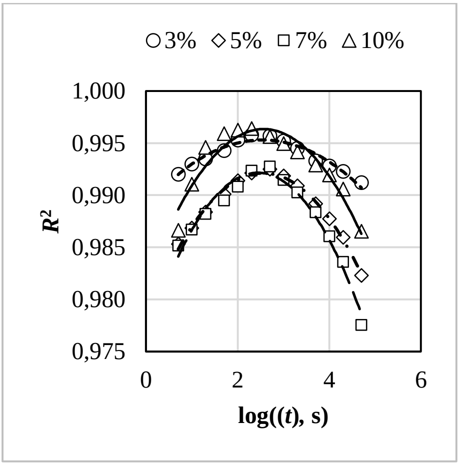
Figure 14. The break point of stress relaxation of the woollen yarns under different deformations: a) – 3%; b) – 5%; c) – 7%; d) – 10%

It can be stated that under lower stress (3% and 5%) the break point in the relaxation process shows up earlier, i.e. the relaxation speed decreases earlier. However, when investigating the woollen yarn, the results are completely opposite – the relaxation speed changes when the stresses are higher (7% and 10%).

When comparing the results of the assessed break point of the three yarns of different origin, it is seen that in the multifilament polyester yarns and in the woollen yarns the relaxation process settles earlier (100 seconds) while on higher loads (10% and 7%).

The dependencies on the time logarithm of the averages of the coefficient of determination R^2 of the break point of stress relaxation are shown in Figure 15. In the listed graphs and results it is seen that when describing the R^2 dependency to the time logarithm log((*t*), s), in most cases there is a 2nd degree polynomial dependency with the peak at log((*t*), s) = 2.0 – 2.5. Only the curve of the cotton yarns is not compliant with this consistent pattern under a 7% load.

Such a discrepancy can be explained by the value of the fracture strain of the cotton yarn – the stress while investigating the relaxation behaviour was close to the break point. Under lower stress the cotton yarns behave similarly to the woollen yarns and the polyester yarns. Therefore, the behaviour of all the yarns under stresses, which vary when the elongation fractures, is quite similar – the break point is found in approximately the same place after 100 – 300 seconds.



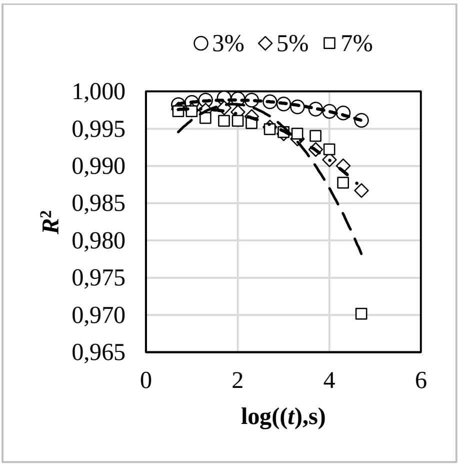
Stress 3%
$y = -0.001x^2 + 0.005x + 0.989$
$R^2 = 0.9373$

Stress 5 %
$y = -0.0021x^2 + 0.0108x + 0.9783$
$R^2 = 0.9919$

Stress 7 %
$y = -0.0027x^2 + 0.013x + 0.9764$
$R^2 = 0.9718$

Stress 10 %
$y = -0.0022x^2 + 0.0114x + 0.9818$
$R^2 = 0.9071$

a)

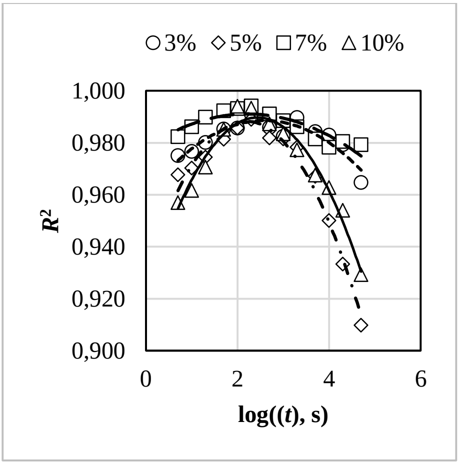


Stress 3 %
$y = -0.0003x^2 + 0.0013x + 0.9976$
$R^2 = 0.9679$

Stress 5 %
$y = -0.0008x^2 + 0.0017x + 0.9968$
$R^2 = 0.9918$

Stress 7 %
$y = -0.0026x^2 + 0.0098x + 0.9889$
$R^2 = 0.7560$

b)



Stress 3 %
y = -0.0043x^2 + 0.0223x + 0.9597
R^2 = 0.8149

Stress 5 %
y = -0.0119x^2 + 0.0524x + 0.9307
R^2 = 0.9744

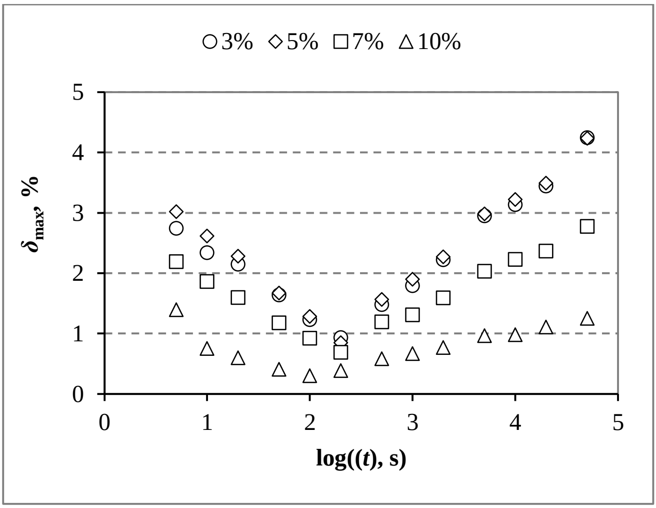
Stress 7 %
y = -0.0026x^2 + 0.0117x + 0.9782
R^2 = 0.7681

Stress 10 %
y = -0.0116x^2 + 0.0566x + 0.9207
R^2 = 0.9610

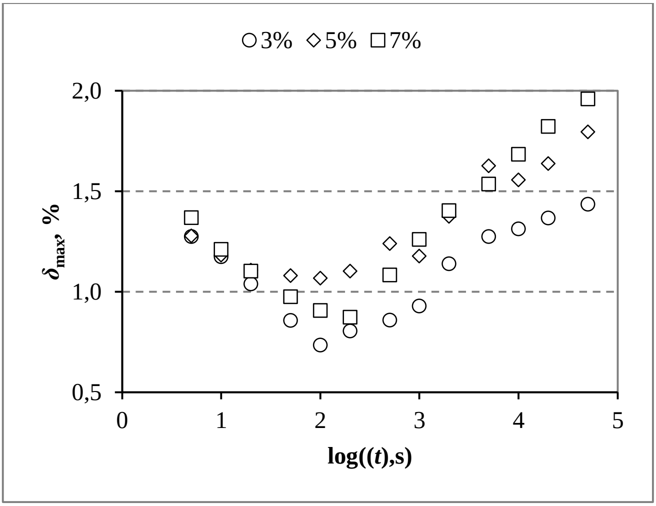
c)

Figure 15. The dependences on the time logarithm of the averages of the coefficients of determination R^2 of the break point of the stress relaxation: a) – multifilament PES yarn; b) – cotton yarn; c) – woollen yarn

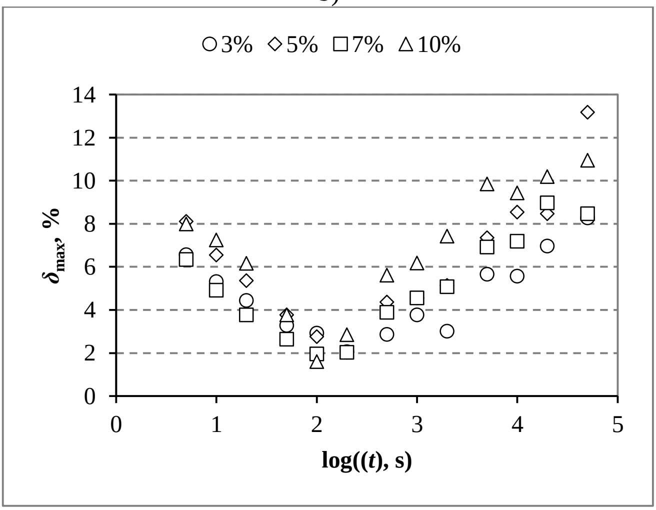
Analogical investigations were undertaken using the method which calculates the greatest relative error. Using formula 1, the relative error δ_{max}, was calculated, with the results shown in Figure 16.



a)



b)



c)

Figure 16. Dependences of maximum relative error on the time log (*t*, s) of different yarns and different levels of straining: (a) – multifilament polyester yarn, (b) – cotton yarn, (c) – woollen yarn

In the case of all yarns, the peak is noticed at 100 – 200 seconds. During the next stage, a more accurate location of the break point was analysed, while doing additional measurements and calculations in every peak environment.

When the multifilament polyester yarns were under 10% stress and while using the method of the intersection of two lines, the break point shifted and was identified after 94 seconds (log((t), s) = 1.97). During the experiment, it was found that under lower deformations the break point occurs later. Under 3% and 5% stress the break point is noticed after 178 seconds (log((t), s) = 2.25) and under 7% – after 151 s (log((t), s) = 2.18).

After doing additional calculations of the break points δ_{max} of stress relaxation of the cotton yarns, it was found that the speed of the stress relaxation under the lowest 3% stress changes later, and under 5% and 7% the process occurs earlier: 3% - after 158 seconds (log((t), s) = 2.20), 5% - after 89 seconds (log((t), s) = 1.95) and 7% - after 178 seconds (log((t), s) = 2.25). In this case there is an apparent irregularity of cotton yarn behaviour under greater stress to other cases. As mentioned before, this can be explained by the deformation of the investigation being too great - the yarns are close to the breaking elongation and destructive processes may begin appearing in them.

To calculate the woollen yarn break points $\delta_{max,}$ additional measurements were made between 100 – 320 seconds, and the obtained results showed that the break point under all types of deformation appears later. It was found that under 3% stress the break point δ_{max} appears after 240 seconds (log((t), s) = 2.38), under 5% stress – after 263 seconds (log((t), s) = 2.42), under 7% stress – after 162 seconds (log((t), s) = 2.21) and under 10% stress – after 112 seconds (log((t), s) = 2.05). Therefore, as in all cases of the polyester yarns and the two cases of the cotton yarns, the greater the elongation, the earlier the break point appears. This confirms the assumption that the process is faster due to the faster regrouping of macromolecules.

This method was additionally tested by analysing the relaxation characteristics of the polyester yarns and predicting their residual stress after 200000 seconds. The analysis was done to 4 different variants, using the investigation results of the polyester yarns, because the uniformity of these yarns and also the reliability of the calculations were the greatest. The analysis is shown in Figure 17, where the prediction of the residual stress after 200 000 can be seen. Figure 17 part a; shows the prediction using the break point, but investigating up to 200 000 seconds, part b; - using the suggested method (using the break point, but investigating only up to 1000 seconds), part c; - not determining the break point and investigating up to 200 000 seconds, part d; - also not determining the break point, but investigating only up to 1000 seconds. The relative errors of the residual stress after 200 000 seconds between the experimental value and the one calculated using the equations for the 4 variants are shown in Table 2.

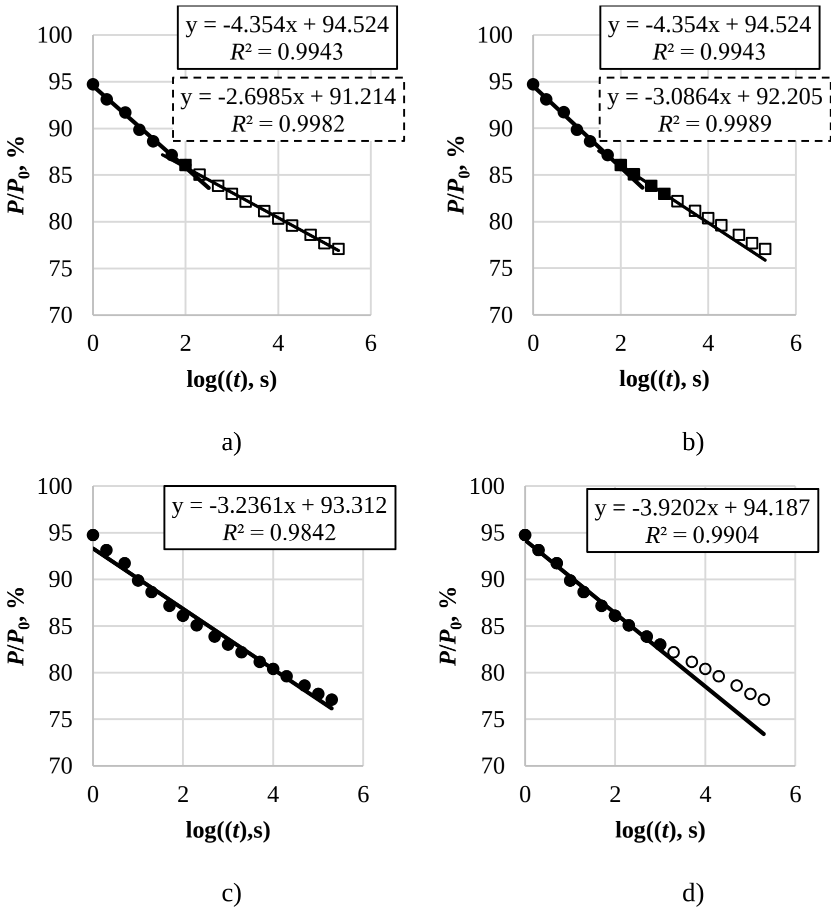


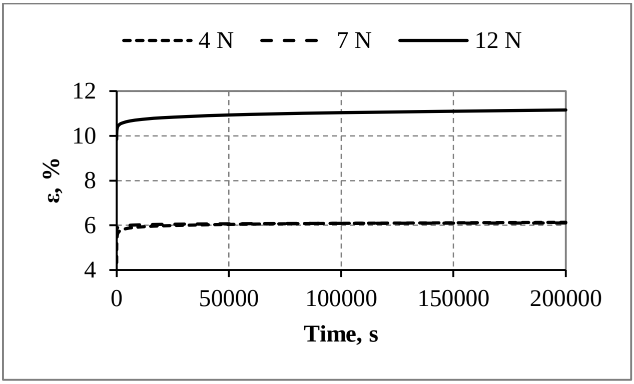
Figure 17. Predicting the break point after 200 000 seconds (the white dots mark the results that were not used for the calculation of the equation)

Table 2. Relative error δ_{2000} value

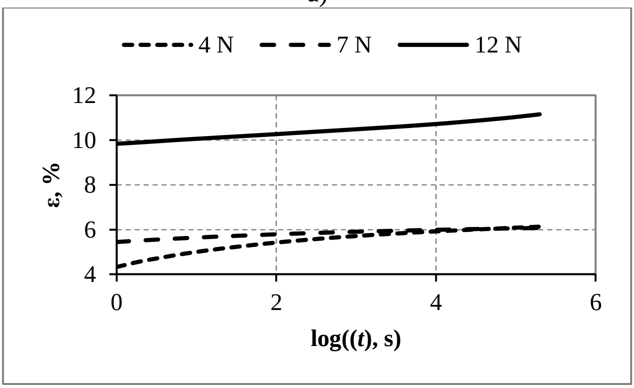
Relative error	**Relative error value, %**			
	a)	**b)**	**c)**	**d)**
δ_{2000}	0.3007	1.5972	1.4785	4.7592

The best results (lowest relative error) are achieved with variant a). Therefore, the longer the investigation takes place, the more accurate the results can be predicted, and consequently the shorter it is (variant d): the worse the results are. The advantage of the suggested method can be clearly seen when comparing variant b) with c) and d). As seen in Table 2, the relative error for variants b) and c) is very close (only 7.4% difference), which means that long-lasting stress relaxations can be predicted using very similar reliability, but according to the suggested method, only 1000 seconds were spent for the investigations, while according to variant c) it was actually 200 000 seconds. Therefore, the value of the practical use of the method is evident. When comparing variant b) with variant c), when in both cases the investigation was carried out in only 1000 seconds, it is seen that using the suggested method the reliability is 3 times greater. Therefore, the suggested method allows to greatly shorten the investigation time without fundamentally lowering the reliability of predicting long-lasting relaxation properties.

Creep of polyester yarns. Multifilament polyester yarns were chosen for the investigation, the curves of their creep process are shown in Figure 18.



a)



b)

Figure 18. Curves of creep process under diverse loads: a) - time scale in seconds; b) - time logarithm scale

After deforming the yarns with 4 N force, the start of the creep process t_0 is achieved after 2.5 seconds and elongation ε_0 = 3.7580% is obtained, with 7 N force – t_0 = 4.65 s, ε_0 = 5.2428% and with 12 N force – t_0 = 5.91s, ε_0 = 9.4876%.

At the beginning of the investigation, it was expected that the break point could additionally be determined during the creep process, although the results are best described as a linear dependency and high coefficients of determination are found: 4 N – R^2 = 0.9364; 7 N – R^2 = 0.9631; 12 N – R^2 = 0.9925. Therefore, the method of finding the break point of two intersecting straight lines is not applicable to predict the process, because the creep process lasts an unlimited time. Such conclusions were made by Steinberger (1936), while studying the creep process for 29 days, and by Abbott (1951), while investigating yarns for more than a year.

CONCLUSIONS

1. After investigating the long-lasting (up to 200 000 seconds) stress relaxation of the yarns of diverse origins and characteristics (multifilament polyester and cotton and woollen yarns), it was found that the speed of the stress relaxation of all the examined yarns is inconstant (the dependence of the relative stress relaxation to the time logarithm is not fully linear), however, the relaxation process itself is different - the values of the relative stress relaxation show great differences, even up to 2 times of the relaxation properties of the yarns.
2. It was found that the size of the elongation of the yarns and the origins of the yarns, while investigating the process of the stress relaxation, has a huge impact on both the residual value of the stress relaxation and the whole process. Under higher stress (with 7% or 10% deformation), the multifilament polyester yarns are distinguished by the slowest speed of relaxation, their residual stress stays up to 77% within the range, whereas in the woollen yarns it decreases to 44% and in the cotton to 55%. It was also found that the speed of the relaxation depends on the level of the stresses - with higher stresses, the speed increases and the residual stress decreases; which is common for all the yarns that were investigated.
3. In all cases of the investigation, a breaking point of the relaxation process was discovered, when at a certain time of the relaxation the speed of the relaxation decreases and, according to the initial data, there cannot be any prediction of long-lasting relaxation stress. The time during which a major change of the relaxation speed occurs depends both on the origins of the yarns and the level of deformation - with the higher deformation the breaking point can be seen sooner than with the slower, which is explained by the faster reorganisation of the polymer macromolecules. In all cases, the breaking point is found between 94 and 268 seconds from the beginning of the relaxation process. After the breaking point, the relaxation process

progresses evenly, therefore, the second part of the relaxation process can be described in a linear relative stress dependency on the time logarithm.

4. A method was suggested during the investigation, according to which the experimental investigations are done only up to 1000 seconds. The breaking point was discovered and the dependency of the linear relative stress on the time logarithm assessed by the second part of the relaxation process, which was confirmed for all the examined yarns.
5. It was found that when using the suggested method, the residual stress relaxation can be predicted with the same accuracy while doing experimental investigations only up to 1000 seconds, not 200 000 seconds - the difference for polyester yarns is only 7.4%.
6. It was found that without using the suggested method and trying to predict long-lasting relaxations after 200 000 seconds, according to experimental investigations up to 1000 seconds, the inaccuracy is 3 times higher than when using the method. The suggested method of predicting the characteristics of long-lasting relaxation allows to shorten the time of investigations up to 200 times and obtain sufficiently accurate predictions of the behaviour of the textile materials.
7. Investigations of long-lasting creep (200 000 seconds) of the multifilament polyester yarns confirmed the results of other authors, i.e. that creep has a changing speed throughout the whole investigation under higher values of load, the value and the intensity of the creep increase, but the type of process is not entirely equal while on different loads. It was found that the process of creep cannot be described while applying the same method, as in the stress relaxation (with the break point), because a concrete break point cannot be distinguished after 100 or 300 seconds - the whole process is quite gradual, i.e. the speed decreases gradually.

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Articles in journals in the Clarivate Analytics Web of Science list

1. Laureckienė, Ginta; Milašius, Rimvydas. Behaviour of long-lasting stress relaxation of various types of yarns // AUTEX Research Journal. Warsaw: De Gruyter Open. ISSN 1470-9589. eISSN 2300-0929. 2017, Vol. 17, iss. 4, p. 379-385. DOI: 10.1515/aut-2017-0017.
2. Laureckienė, Ginta; Milašius, Rimvydas. Influence of the straining level on the long-lasting relaxation behaviour of polyester yarns // Fibres and textiles in Eastern Europe. Lodz: Institute of Biopolymers and Chemical Fibres. ISSN 1230-3666. 2016, vol. 24, iss. 1(115), p. 73-77. DOI: 10.5604/12303666.1183199.
3. Milašius, Rimvydas; Laureckienė, Ginta. Prediction of long-lasting relaxation properties of polyester yarns and fabrics // Fibres and textiles in Eastern Europe. Lodz: Institute of Chemical Fibres. ISSN 1230-3666. 2014, vol. 22, no. 6 (108), p. 97-100.

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1. Laureckienė, Ginta; Milašius, Rimvydas. Prediction of stress relaxation in textiles // Magic world of textiles: 7th International Textile Clothing & Design Conference, October 5-8, 2014, Dubrovnik, Croatia: book of proceedings / University of Zagreb. Faculty of Textile technology. Zagreb: University of Zagreb, 2014. ISSN 1847-7275. p. 396-399.

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1. Laureckienė, Ginta; Milašius, Rimvydas. Comparative analysis of yarns long-lasting stress relaxation // Advanced materials and technologies: book of abstracts of the 19th International Conference-school, 27-31 August 2017, Palanga, Lithuania. Kaunas: Kaunas University of Technology. ISSN 1822-7759. 2017, P73, p. 100.
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REZIUMĖ

Tiriamosios problemos pagrindimas ir darbo aktualumas. Pastaruoju laikotarpiu vis daugiau dėmesio skiriama techninės tekstilės gamybai ir panaudojimui. Techninės paskirties gaminiams dažniausiai naudojami cheminės kilmės pluoštų siūlai, tačiau, priklausomai nuo gaminio paskirties, gali būti naudojami ir natūralūs pluoštai. Kadangi pluoštai yra įvairios kilmės ir skiriasi savo mechaninėmis savybėmis, todėl svarbu ištirti skirtingos kilmės siūlų elgseną esant mechaniniams poveikiams. Dėl to atsiranda poreikis plačiau tirti mechanines ir ypatingai svarbias relaksacines siūlų savybes. Techninės tekstilės gaminiai pagal savo paskirtį turi atitikti tam tikrus reikalavimus: turi būti pakankamai stiprūs deformacijos metu, turi atlaikyti atitinkamas temperatūras, turi būti atsparūs cheminiams bei biologiniams veiksniams, turi pasižymėti dideliu arba mažu higroskopiškumu ir t. t. Svarbu sukurti pluoštus ir siūlus gaminiams, kurie naudojami ekstremaliomis sąlygomis. Analizuojant pluoštų tinkamumą techninei tekstilei, dažniausiai vertinamos mechaninės charakteristikos, t. y. nustatomos tempimo charakteristikos: tempiamasis stipris ir ištįsa. Atliekant išsamesnius mokslinius technologinius tyrimus, nustatomos deformacijos (tamprioji, elastingoji, plastiškoji), drėgmės ir temperatūros įtaka stiprumui ir deformacijai.

Gamybos metu tekstilės medžiagose stebimi relaksaciniai procesai. Technologiškai perdirbami siūlai visada yra mažiau ar daugiau įtempti ir apkrauti jėgomis, kurių dydis, poveikio trukmė, apkrovimo ir nukrovimo pobūdis lemia siūlų elgseną vykstant technologinėms operacijoms. Kaip ir bet kokių polimerinių medžiagų, siūlų reakcija į veikiančias jėgas labai priklauso nuo laiko. Dėl relaksacijos reiškinių ilgainiui kinta siūlų deformacijos arba įražos, kurios verčia siūlus priešintis formos pokyčiams. Siūlų reakcija į bet kokį mechaninį sutrikdymą laikoma jų relaksacinėmis savybėmis.

Relaksacinės savybės svarbios ne tik iš siūlų sudaryto gaminio vartojimo pagal paskirtį savybėms, bet ir vertinant siūlų elgseną vykstant tam tikriems technologiniams procesams. Įvairių technologinių procesų metu siūlų įražos pastoviai kinta ir kinta priklausomai nuo to, ką siūlai yra patyrę praeityje, t. y. kokia buvo jų mechaninė istorija. Jėgoms nustojus veikti, labai svarbus siūlų gebėjimas atstatyti pirmykščius parametrus. Šis atsistatymas, dar vadinamas ištįsos relaksacija, taip pat su laiku susijęs procesas. Jei siūlai, dar nespėję visiškai atsistatyti, patiria naują poveikį, jų reakcija irgi priklauso nuo mechaninės istorijos. Perdirbus į tam tikrą produktą skirtingų relaksacinių savybių siūlus ar tokios pačios žaliavos bei sandaros siūlus, tačiau turinčius skirtingą mechaninę istoriją, produkte gali susidaryti nepašalinamų ydų (pavyzdžiui, banguotumas, pūslėtumas) ar kilti kitokių technologinių nesklandumų.

Relaksaciniai medžiagų procesai yra pakankamai išsamiai tirti tiek tekstilės, tiek kitose polimerinėse medžiagose. Įvairūs mokslininkai pastebėjo,

jog įražos relaksacijos greitis relaksacijos metu yra nepastovus, tačiau išsamesnės analizės apie ilgalaikės relaksacijos prognozavimą nėra. Nepaisant labai didelio kiekio tyrimų, iki šiol nėra sukurta metodo kaip pagal trumpalaikius empirinius tyrimus prognozuoti ilgalaikes, kelias dienas ar net savaites trunkančią, relaksacinę elgseną.

Įvairios tekstilės medžiagos turi labai skirtingą ir keliapakopę sandarą. Kuo medžiagos sandara sudėtingesnė, tuo sudėtingesnės gali būti medžiagą veikiančių jėgų sistemos. Todėl skirtingų medžiagų analogiško pobūdžio savybės dažnai pasireiškia skirtingais požymiais ir išreiškiamos skirtingais kiekybiniais parametrais.

Detaliems relaksacijos procesų tyrimams tenka sugaišti daug laiko – nuo sekundės iki kelių dienų ar savaičių, o gal ir dar ilgiau. Atliekant ilgalaikę įražos relaksaciją ar valkšnumą, iškyla elektroninės aparatūros ilgalaikio stabilumo problema. Todėl reikalingas metodas, kuris leistų prognozuoti ilgalaikes relaksacijas pagal empirinius iki kelių tūkstančių sekundžių trunkančius tyrimus. Taigi sutrumpėtų eksperimentams gaištamas laikas ir vartotojas galėtų gana lengvai prognozuoti gaminio elgseną ilgalaikių įtempių metu.

Darbo tikslas – sukurti naują siūlų įražos ilgalaikės relaksacijos prognozavimo metodą pagal trumpalaikius įražos relaksacijos empirinius tyrimus.

Darbo uždaviniai:

- ištirti įvairios konstrukcijos ir prigimties siūlų elgseną ilgalaikės įražos relaksacijos metu bei nustatyti ilgalaikės siūlų įražos relaksacijos eigos dėsningumus;
- ištirti deformacijos įtaką siūlų ilgalaikės relaksacijos raidai ir nustatyti jos dėsningumus;
- nustatyti įražos relaksacijos eigos lūžio taško egzistavimo laiką ir jo priklausomybę nuo siūlų sandaros, prigimties bei deformacijos vertės;
- sukurti siūlų ilgalaikės relaksacijos prognozavimo metodą, paremtą trumpalaikiais įražos relaksacijos tyrimais ir relaksacijos eigos lūžio taško atsiradimo laiku bei patikrinti jo taikymo tinkamumą;
- patikrinti sukurto įražos relaksacijos prognozavimo metodo taikymo tinkamumą siūlų valkšnumui.

<u>Darbo mokslinis naujumas ir praktinis vertingumas.</u> Šiame darbe didžiausias dėmesys skiriamas tokiems tekstilės gaminiams, kurie ilgą laiką naudojami nuolat įtempti ir nuo jų kokybės bei ilgaamžiškumo gali priklausyti žmogaus sveikata ar net gyvybė. Pavyzdžiui, konvejerių juostos, diržinės pavaros, tentai, lynai, tvirtinimo juostos, virvės ir kt., kurie darbo metu nuolat deformuojami įvairiomis apkrovomis, ir ta deformacija gali būti ilgalaikė. Siūluose vykstantys skirtingi relaksaciniai procesai yra tiriami gana nuodugniai, tačiau palyginti trumpą laikotarpį, todėl pagal juos negalima prognozuoti gaminio elgsenos ilgalaikių apkrovų metu.

Darbo metu sukurtas naujas įražos prognozavimo metodas pagal relaksacijos proceso metu stebimą lūžio tašką. Nustatyta, kad šis lūžio taškas būdingas visiems tirtiems skirtingų konstrukcijų ir prigimties siūlams, bei esant skirtingoms deformacijos vertėms. Todėl toks metodas gali būti taikomas ir kitiems, šiame darbe netirtiems, siūlams. Kadangi pagal sukurtą metodą eksperimentiniai įražos relaksacijos tyrimai gali būti atliekami tik iki 1 000 sekundžių, o relaksacinė eiga pagal jį gali būti prognozuojama kelių dienų laikotarpiui. Pasiūlytas metodas leidžia reikšmingai sumažinti empirinius tyrimus ir gana greitai, per valandą, nustatyti gaminio relaksacinę eigą, apskaičiuoti jo elgseną ilgam, kelių dienų, laikotarpiui ir priimti sprendimą dėl gaminio tinkamumo ir / arba vartojamųjų apkrovų verčių, kuriomis gaminys gali būti eksploatuojamas.

Panaudojant siūlomą metodą taip pat galima per tą patį laikotarpį ištirti ženkliai didesnę siūlų įvairovę ir parinkti siūlus, kurių savybės ir relaksacijos eiga labiau atitinka vartojamuosius gaminio reikalavimus. Taip galima optimizuoti gaminio sandarą ir pasiūlyti jį gaminti iš tinkamiausios vartojimui prigimties siūlų.

Pasiūlytas metodas taip pat sudaro prielaidas parinkti tokius deformavimo režimus, pagal kuriuos būtų galima prognozuoti ir kontroliuoti gaminio deformacijas, kurios ypač svarbios naudojant kilnojamus didelius tentus.

IŠVADOS

1. Atlikus skirtingos kilmės ir sandaros siūlų (daugiagijų poliesterinių ir medvilninių bei vilnonių verpalų) ilgalaikius (iki 200 000 sekundžių) įražos relaksacijos tyrimus nustatyta, kad visų tirtų siūlų įražos relaksacijos greitis nėra pastovus (santykinės įražos relaksacijos priklausomybė nuo laiko logaritmo nėra visiškai tiesinė), tačiau pats relaksacijos procesas vyksta skirtingai – santykinės įražos relaksacinės vertės rodo didelius, net iki 2 kartų, siūlų relaksacinių savybių skirtumus.
2. Nustatyta, kad siūlų ištįsos dydis bei siūlų kilmė, tiriant įražos relaksacinį procesą, turi didelę įtaką tiek įražos relaksacijos likutinei vertei, tiek ir pačio proceso eigai. Esant didesniems įtempiams (esant 7 % ar 10 % deformacijai) lėčiausiu relaksaciniu greičiu išsiskiria daugiagijai poliesteriniai siūlai, kurių likutinė įraža išlieka iki 77 % ribose, kai vilnos verpalų sumažėja iki 44 %, o medvilnės – iki 55 %. Taip pat nustatyta, kad relaksacinis greitis priklauso nuo įtempių lygio – didėjant įtempiams, greitis didėja ir likutinė įraža mažėja. Tai būdinga visiems tirtiems siūlams.
3. Visais tyrimų atvejais pastebėtas relaksacijos eigos lūžio taškas, kuomet tam tikru relaksacijos metu relaksacijos greitis sulėtėja ir pagal pirminius duomenis negalima prognozuoti ilgalaikes relaksacines įražas. Laikas, kurio metu atsiranda relaksacijos greičio esminis pokytis, priklauso tiek nuo siūlų kilmės, tiek nuo deformacijos lygio – esant didesnei deformacijai lūžio taškas

matomas anksčiau, nei esant lėtesnei, tai paaiškinama greitesniu polimero makromolekulių persitvarkymu. Visais atvejais lūžio taškas randamas tarp 94 ir 268 sekundžių nuo relaksacinio proceso pradžios. Nustatyta, kad po lūžio taško relaksacijos procesas vyksta tolygiai ir antrąją relaksacinio proceso dalį galima aprašyti tiesine santykinės įrąžos priklausomybe nuo laiko logaritmo.

4. Darbo metu pasiūlytas metodas, pagal kurį eksperimentiniai tyrimai atliekami tik iki 1 000 sekundžių, randamas lūžio taškas ir pagal antrąją relaksacinio proceso dalį nustatoma tiesinė santykinės įrąžos priklausomybė nuo laiko logaritmo pasitvirtino visiems tirtiems siūlams.
5. Nustatyta, kad, naudojant siūlomą metodą, galima tokiu pačiu tikslumu prognozuoti likutinę įrąžos relaksaciją, atlikus eksperimentinius tyrimus tik iki 1 000 sekundžių, nes atlikus tyrimus iki 200 000 sekundžių – poliesteriniams siūlams šis skirtumas yra vos 7,4 %.
6. Nustatyta, kad nenaudojant siūlomo metodo ir bandant pagal eksperimentinius tyrimus iki 1 000 sekundžių prognozuoti ilgalaikes relaksacijas po 200 000 sekundžių, gaunamos net 3 kartus didesnės santykinės paklaidos, nei naudojant siūlomą metodą. Pasiūlytas ilgalaikių relaksacinių savybių prognozavimo metodas leidžia iki 200 kartų sutrumpinti tyrimų trukmę ir gauti pakankamai tikslias tekstilės medžiagų elgsenos prognozes.
7. Atlikti ilgalaikiai (200 000 sekundžių) daugiagijų poliesterinių siūlų valkšnumo tyrimai patvirtino kitų autorių rezultatus, kad valkšnumas vyksta kintamu greičiu visą tyrimų laikotarpį. Esant didesnėms apkrovos vertėms, valkšnumo intensyvumas ir vertės didėja, tačiau proceso pobūdis nėra visiškai vienodas, esant skirtingoms apkrovoms. Nustatyta, kad aprašyti valkšnumo procesą, pritaikant tą pačią metodiką kaip įrąžos relaksacijai (su lūžio tašku), nėra galima, kadangi konkretaus lūžio taško po 100 ar 300 sekundžių išskirti negalima – visas procesas vyksta gana tolygiai kintamai, t. y. greitis tolygiai mažėja.

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