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# Influence of the Straining Level on the Long-Lasting Relaxation Behaviour of Polyester Yarns

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**Abstract**

*The main problem in the investigation and prediction of stress relaxation is the long time periods (not in seconds or minutes but in days or even months) of measurements for each kind of textile, especially in cases where users need to know the behaviour of the textile in prolonged time usage. Previously it was found that the rate of relaxation on the log scale can be described by two straight lines and the values of relaxation can be predicted over a long time by the rate of relaxation of the second linear dependency. The present paper shows investigations of 29.4 tex polyester yarn's relaxation behaviour at different levels of elongation, i.e. at 3, 5, 7 and 10%. Investigations show that the place of the break-point of relaxation depends on the level of elongation – by increasing the level of elongation the time decreases till the break-point. This phenomenon is clearly visible at higher levels of elongation, while at low levels (3 and 5%) the difference is quite small. Using the data presented, it is possible to predict long-lasting relaxation without long-lasting experiments; only shorter than 1000 second tests are needed.*

**Key words:** *stress relaxation, strain, polyester yarns, textile.*

## Introduction

Stress relaxation and the possibilities of its prediction are very important properties for various types of textile. The relaxation of textiles depends on the raw material of yarns (on a polymer), the construction of yarns (spun or multifilament, twisted or twistless etc.), as well as on the structure of the woven fabric or knit. The relaxation phenomenon arises due to the viscoelastic properties of polymeric textile materials.

It is well known that Hooke's law is unsuitable for the prediction of textiles' stress relaxation because their viscoelasticity is usually non-linear. Structural changes in the materials in long-lasting deformations and relaxations after unloading are very sophisticated and depend primarily on the molecular structure of the polymers, and it is "… a serious challenge to fully understand these phenomena through experimental techniques" [1].

Some authors generate various theoretical models which can give information about the relaxation and relationship between the structure and properties of polymers. One of them has been presented in literature [2] and describes the phenomenon of deformation and relaxation after unloading (see ***Figure 1***).

Other authors analysed viscoelastic behaviour from the viewpoint of the theory of viscoelasticity originating from the material structure as well as from the material processing or its usage according to a specific purpose. To provide information about the viscoelastic behaviour of a polymeric material various experimental techniques have been used, among which the stress relaxation, creep,

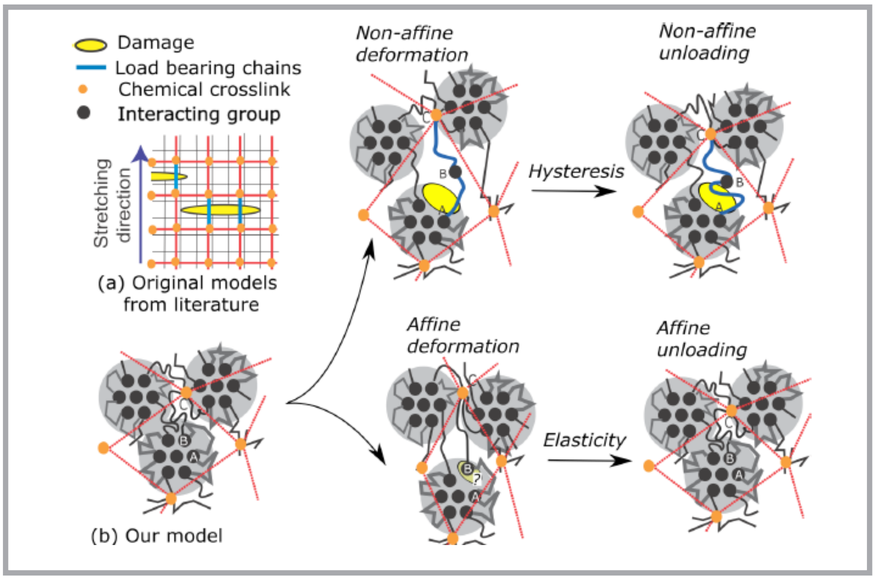

***Figure 1.*** *Molecular dynamic models: a - recent models of double-network gels presented in the literature, b - our models structure: ABC-load-bearing chains bridging the damaged zone;, two modes of structure evolution during the loading/unloading cycle and their assumed relation to the type of deformation [2].*

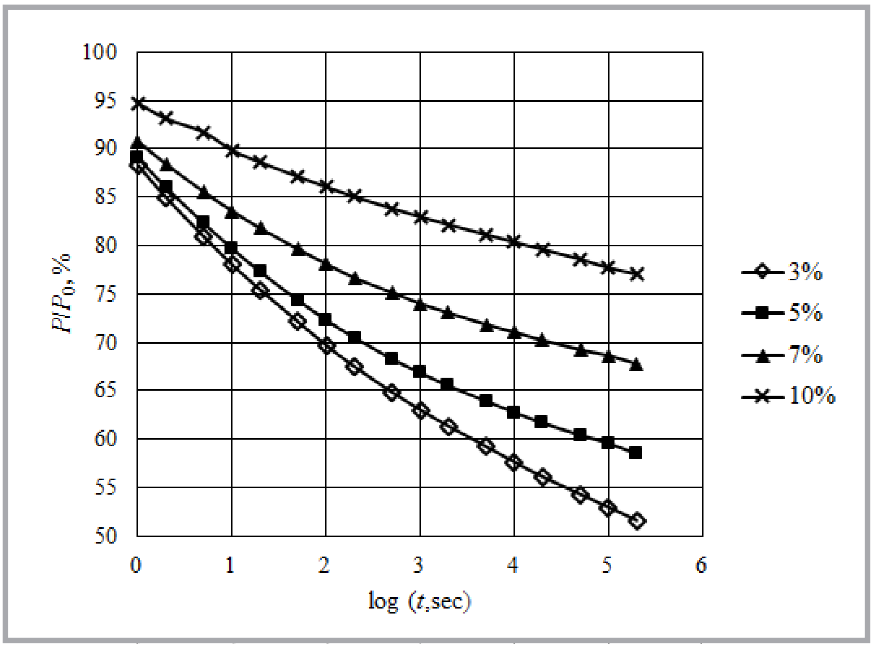

***Figure 2**. Relative stress relaxation curves of the multifilament polyester yarns at 3%, 5%, 7% and 10% elongation.*

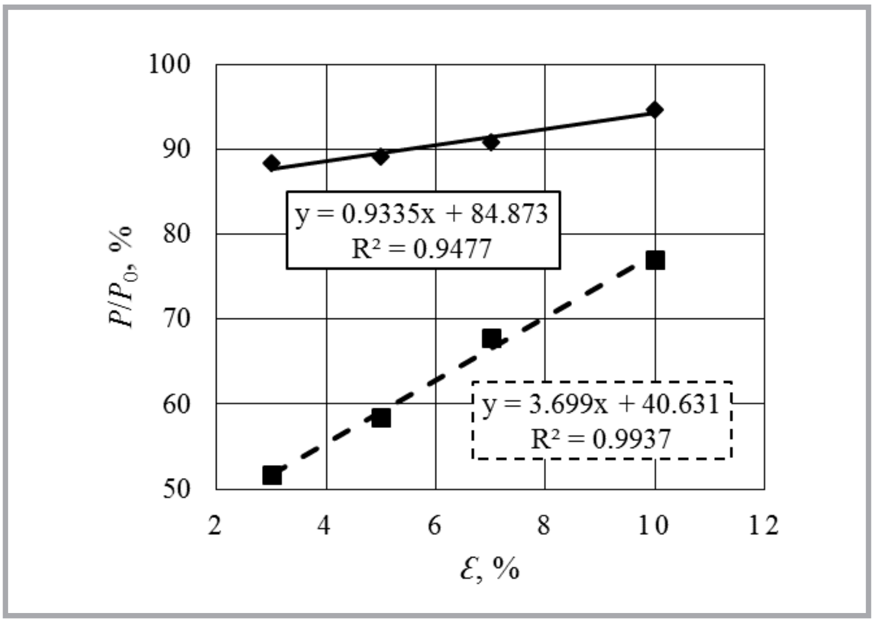

***Figure 3.** Dependences of relative stress relaxation on elongation at a time of 1 second and 200000 seconds; t; ◆ 1 s, ■ 200 000 s.*

and viscoelastic recovery after preceding sustaining at constant strain or at constant load are continually in common use [3].

Therefore a textile material behaves as a viscoelastic solid – its response to external effects is delayed, and its properties at various time points are different. After external impacts textile materials relax – in the beginning they react quickly, then the reaction rate decreases until a certain balance occurs. Such a steady-state process is called relaxation phenomena. The four load modes are used for the description of deformation behaviour – permanent deformation or permanent speed of deformation when changes in stresses are observed (1st and 2nd modes), observation of deformation at constant stress (3rd mode) and periodical changes in deformation according to the programme (4th mode). At the time of the 3rd mode, when tests are carried out during which the sample is kept at a constant elongation, stress relaxation occurs due to the macromolecular arrangement of polymers. In this case, relative stress relaxation ($P/P_0$) is usually used for the relaxation evaluation [4 - 9]. A lot of researchers have published works of such investigations, starting with Meredith [10], Guthrie and Wibberley [11] and others [12 - 24]. Some authors analysed the behaviour of polyester (PET) and stated that the properties of PET generally depend on the degree of crystallinity and the crystal morphology, such as the spherulite size, fibril width, molecular tying between fibrils, and the degree of orientation [25]. Previous works of the authors show that relative stress relaxation ($P/P_0$), which characterises the rate of relaxation, as a logarithm of the time (log($t$, s)) is not linear and can be described by two linear dependences with the break-point (the moment of time when the rate of relaxation decreases) after approximately 100 seconds [26]. This paper continues previous investigations and shows that the place of the break-point of polyester yarns is not steady and depends on the level of elongation.

## Materials and methods

Stress relaxation tests were carried out using a universal tensile testing machine - Zwick/Roell at the standard atmosphere of 20 ± 2 °C temperature and 65 ± 4% relative humidity. Specimens were stretched at a speed of 500 mm/min up to the strain level (from 3% till 10%) and held in this position. The stress was recorded as a function of time (from 1 second up to 200 000 seconds). Complete equipment for such research and an extending machine were operated by the *testXpert*® software at a gauge length of 500 mm. Polyester (PET) multifilament (48 filaments, twisted 100 $m^{-1}$) yarns with a linear density of 29.4 tex (OAO Mogilevkhimvolokno, Belarus) were tested in the loading cycle. The tensile properties of the yarns investigated were as follows: tensile at break 18.10 N and elongation at break 13.31%. The coefficient of variation is lower than 2% for strength values, and lower than 7% for elongation values. The accuracy of all the measurement was 0.01 N for stresses and 0.01 % for elongation.

The relaxation process of materials was investigated by the fixed elongation method, i.e. the test specimens were stretched at 3, 5, 7 and 10%. When it is stretched to a given strain and held thereat, the stress decreases as time passes. The stress relaxation was calculated as ($P/P_0$), where $P_0$ is the initial stress at zero time ($t$ = 0) and $P$ is the stress at subsequent times. The stress relaxation curve for mathematical description was calculated from a series of experimental points, i.e. the stress relaxation value was measured after 1, 2, 5, 10, 20, 50, 100, 200, 500, 1000, 2000, 5000, 10000, 20000, 50000, 100000, 200000 seconds for each curve.

The related error between experimental values and those ($\delta$) calculated by straight line equation 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, $(P/P_0)_c$ – values of stress relaxation calculated by straight line equations.

The maximum related error between the experimental values and those calculated by the straight line equation ($\delta_{max}$) for investigations was used.

## Experimental results and discussions

Curves of relative stress relaxation of the multifilament polyester yarn at 3, 5, 7 and 10% elongation are presented in ***Figure 2***.

As is seen from ***Figure 2***, the related stress depends on the level of elongation - in the case of higher elongation, related stresses are higher for all the time of relaxation and the dynamic of relative stresses change is also not the same. At a time of 1 second during stretching till 10%, the relative stress is only 6.77% higher than the analogous value of relaxation at stretching till 3%, while after 200000 seconds this difference reaches 33%. All values of relaxation are presented in ***Table 1*** (see page 72). The dependence of relative stress relaxation at the level of elongation is presented in ***Figure 3***.

**Table 1.** *Results of relative stress relaxation of the multifilament polyester yarns at different elongation.*

| Time | | $P/P_0$, % | | | | |
|---|---|---|---|---|---|---|
| **t,s** | **log(t, s)** | **1** | **3** | **5** | **7** | **10** |
| 1 | 0.0 | 96.25 | 88.30 | 89.05 | 90.77 | 94.71 |
| 2 | 0.3 | 95.21 | 84.96 | 85.99 | 88.41 | 93.11 |
| 5 | 0.7 | 93.68 | 80.93 | 82.30 | 85.55 | 91.71 |
| 10 | 1.0 | 92.44 | 78.03 | 79.70 | 83.59 | 89.84 |
| 20 | 1.3 | 91.14 | 75.45 | 77.29 | 81.79 | 88.61 |
| 50 | 1.7 | 89.25 | 72.14 | 74.37 | 79.64 | 87.13 |
| 100 | 2.0 | 87.70 | 69.72 | 72.32 | 78.12 | 86.07 |
| 200 | 2.3 | 86.10 | 67.52 | 70.51 | 76.67 | 85.06 |
| 500 | 2.7 | 83.69 | 64.88 | 68.31 | 75.17 | 83.84 |
| 1000 | 3.0 | 82.08 | 63.04 | 66.87 | 74.02 | 82.98 |
| 2000 | 3.3 | 80.37 | 61.37 | 65.54 | 73.07 | 82.17 |
| 5000 | 3.7 | 77.82 | 59.26 | 63.94 | 71.87 | 81.14 |
| 10000 | 4.0 | 75.98 | 57.65 | 62.79 | 71.07 | 80.36 |
| 20000 | 4.3 | 73.90 | 56.15 | 61.70 | 70.24 | 79.60 |
| 50000 | 4.7 | 70.90 | 54.33 | 60.44 | 69.26 | 78.59 |
| 100000 | 5.0 | 68.34 | 52.99 | 59.58 | 68.67 | 77.70 |
| 200000 | 5.3 | 66.76 | 51.64 | 58.49 | 67.79 | 77.08 |

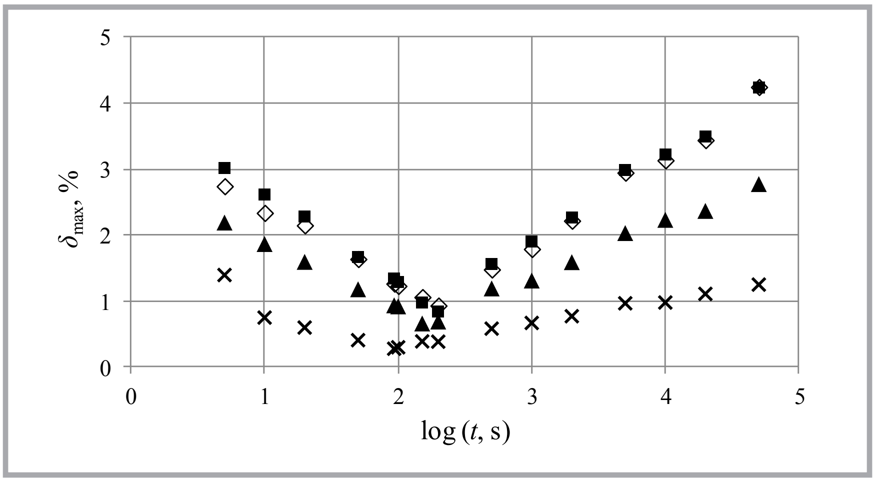

***Figure 4.*** *Dependences of the maximum relative error on the log (t, s) at different places of the break-point in the cases of 3, 5, 7 and 10% elongation.*

As is seen from ***Figure 3***, the coefficients of determination of both equations are high - 0.9477 and 0.9937, meaning that by means of the dependences presented, it is possible to predict the level of relaxation at different levels of elongations. Similar results were also found for polyester yarns by other researchers, such as Nachane and Sundaram [27], and Yamaguchi with co-authors [28]. Thus the behaviour of relaxation depends on the level of elongation, and for prediction of long-lasting relaxations it is impossible to use the same empirical data, which were achieved earlier [26], where the behaviour of polyester yarns at 10% elongation was analysed and the break-point of relative stress relaxation was determined. It means that the place of the break-point of relative stress relaxation at different levels of elongation cannot be the same. Due to that, in the next step of investigations the place of the break-point of relative stress relaxations at various levels of elongations was found.

In earlier investigations it was found that at a level of elongation of 10% the break-point occurs at approximately 100 seconds, i.e. the rate of relaxation changes after 100 seconds [26]. After additional analysis, using the method presented in our previous paper [26], it was found that the break-point occurs after 94 seconds (log($t$, s)=1.97). The same analysis was also made for others curves at lower levels of elongation. It was estimated that the place of the break-point at a different level of elongation is not the same – at a lower level of elongation (7%) the time till the break-point increases until 150 seconds, but at a level of 3% and 5% elongation the time is the same (200 seconds) or differs within the limits of error (see ***Figure 4***). Hence it is possible to state that in the case of straining at higher levels of deformation the rate of relative stress relaxation changes faster than in the cases of lower deformation. This phenomenon can be explained by faster arrangement of macromolecules in polyester fibres after unloading, and

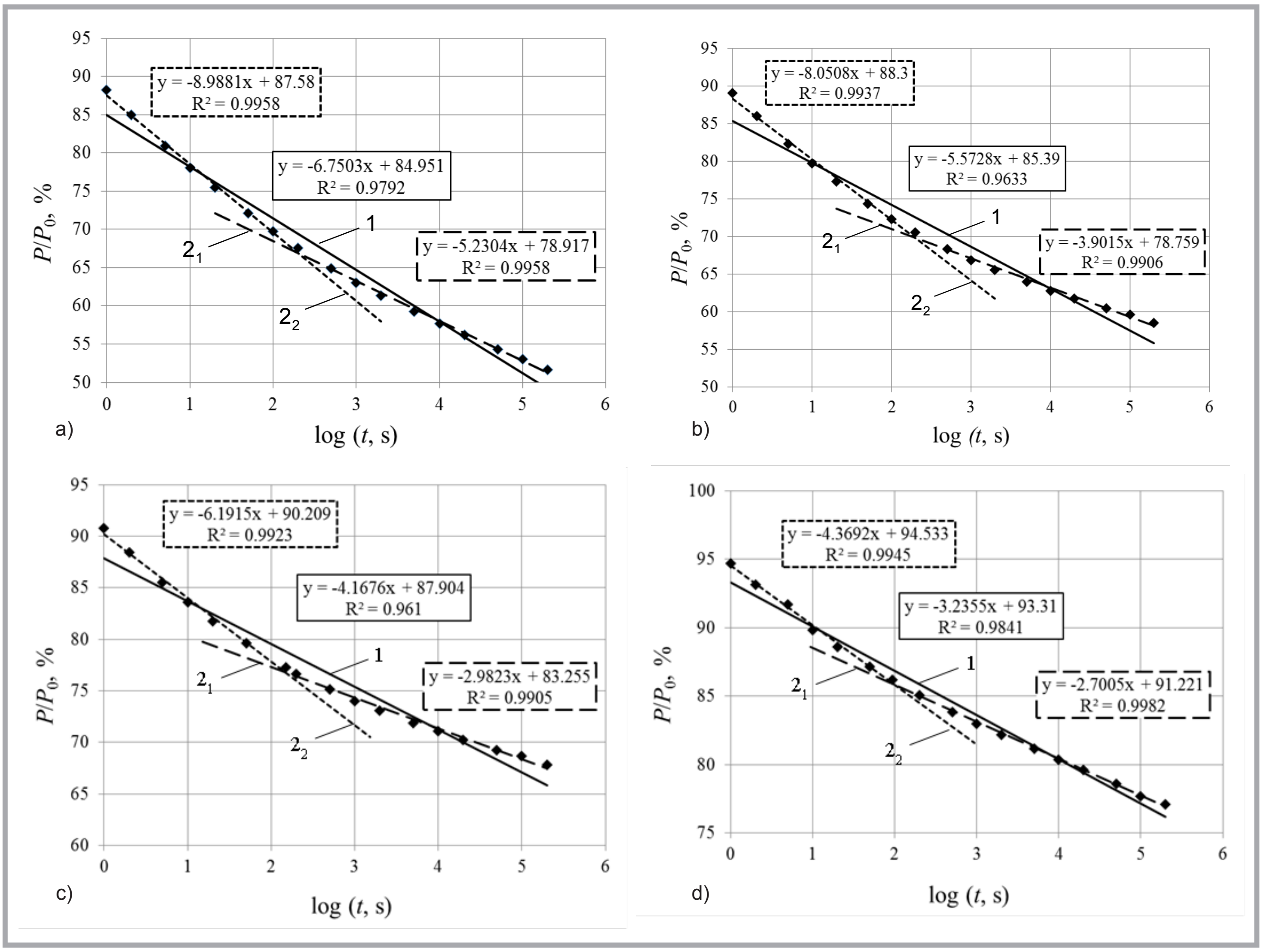

***Figure 5.** Relaxation process of polyester yarn: 1 – described by one straight line, 2 – described by two straight lines ($2_1$ – line of the first part, $2_2$ – line of the second part), a) 3% elongation (break point at t = 200 s, b) 5% elongation (break point at t = 200 s), c) 7% elongation (break point at t = 150 s), d) 10% elongation (break point at t = 94 s).*

these results coincide with the well-known theory of polymers relaxation behaviour, i.e., higher straining – higher rate of relaxation, consequently, higher rate – faster relaxation and lower time till the break-point.

A description of the relaxation process by two straight lines regarding the place of the break-point was established and is presented in ***Figure 4***, and its comparison with the process described by the one linear equation is presented in ***Figure 5***.

The higher coefficients of determination mean better reflection of experimental results using the description of relative stress relaxation behaviour by two straight lines than by one. From the equations the place of the break point can be calculated:

$t_{\text{break point}}$ (10%) = 99.15 s,
$t_{\text{break point}}$ (7%) = 146.85 s,
$t_{\text{break point}}$ (5%) = 199.25 s and
$t_{\text{break point}}$ (3%) = 202.02 s.

Results calculated at a high level match empirical ones, which are presented in ***Figure 5***. The dependence of the place of the break point on the level of elongation is presented in ***Figure 6***.

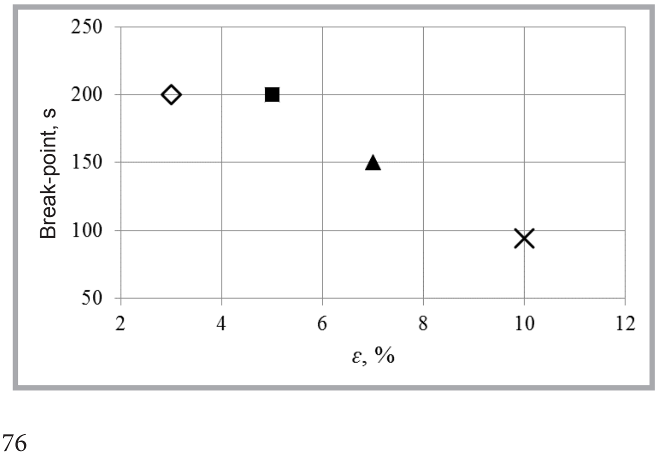

***Figure 6.** Dependence of time till the break-point on the level of elongation: ◊ - 3%, ■ - 5%,▲ - 7%, × - 10%.*

As is seen from ***Figure 6***, the dependence of the break-point on the level of elongation is not linear, this dipendenc e is similar to liner only from 10% till 5% of elongation, while at low values of elongation (from 5% till 3%) the time until the break-point can be identified becomes constant. Consequently the maximum time till the break-point was established is 200 seconds, i.e. log(*t*, s*)* = 2.3. This means that according to the method presented in [21, 26], the empirical data of relaxation till 500 seconds is not enought for prediction of long-lasting (till 500,000 seconds) relaxation. In investigations presented in sources [21, 26] the levels of straining were approximately 10%, and hence the presented conclution about 500 seconds were made in these sources. Current investigations show that this conclusion is not acceptable for lower straining. In the cases of lower deformation an additional empirical point is needed. By the method presented in source [21] the next empirical point is at 1000 seconds. Hence the empirical data till 1000 seconds is needed. In summary it is possible to state that for prediction of long-lasting relaxation at any deformation of polyester yarns, empirical investigations till 1000 seconds is needed, and with these results it is possible to predict relaxation behaviour and residual stresses till 500000 seconds.

The results obtained at very low straining (1%) differ from all others – the break-point was not found and the character of rate changes varied, without the rate decreasing from a certain value of the relaxation time (see ***Table 1***). This phenomenon needs deeper analysis as it does not match the well-known theory of polymer relaxation, and hence it will be the object of our further investigations.

## Conclusions

The behaviour of multifilament polyester yarn relaxation at different levels of elongation is not the same and the rate of relative stress relaxation is higher in the case of a lower value of elongation. The rate of relative stress relaxation at the time of relaxation is not the same and after some time changes. The time when the break-point is reached depends on the level of deformation, and this time decreases at higher values of elongation, while at lower values of elongation it become constant. In all cases, the description of the relative stress relaxation process by using the method of two straight lines with the break-point gives a higher correlation with the empirical data than the linear dependence. Determination of the place of the break-point allows prediction of the long-lasting relaxation behaviour of the polyester (PET) yarns investigated without long time experimental investigations - for relaxation prediction till 500000 seconds, only tests till 1000 seconds are needful.

## *References*

1. Wortmann FJ, Schulz KV. Non-linear viscoelastic performance of Nomex, Kevlar and polypropylene fibres in a single step stress relaxation test: 2. Moduli, viscosities and isochronal stress/strain curves. *Polymer* 1995; 36, 12: 2363 – 2369.
2. Zidek J, Jancar J, Milchev A, Vilgis T. Mechanical Response of Hybrid Cross-Linked Networks to Uniaxial Deformation: A Molecular Dynamics Model. *Macromolecules* 2014; 47, 24: 8795−8807.
3. Pocienė R, Vitkauskas A. Inverse Stress Relaxation in Textile Yarns After the Blockage of Viscoelastic Recovery. *Materials science (Medžiagotyra)* 2007; 13, 3: 240 – 244.
4. Kothari VK, Rajkhowa R, Cupta VB. Stress Relaxation and Inverse Relaxation in Silk Fibers. *Journal of Applied Polymer Science* 2001; 82: 1147-1154.
5. Vitkauskas A. Viscoelastic Properties of Textile Yarns. Research Problems. *Fibres & Textiles in Easter Europe* 1998; 6, 1: 36-38.
6. Bickerton S, Buntain MJ, Somashekar AA. The Viscoelastic Compression Behavior of Liquid Composite Molding Preforms. *Composites* 2003; A 34: 431-444.
7. Van Langenhove L, Kiekens P. Resilience Properties of Polypropylene Carpets. *Journal of the Textile Institute* 1997; 67, 9: 671-676.
8. Bednarski G, Kowalski K. Assessment of Rheological Properties of Distance Weft-Knitted Fabrics, Based on Dynamic Compression and Relaxation of Forces. *Fibres & Textiles in Easter Europe* 2002; 10, 2: 42-45.
9. Miltenburg JGM. Stress Relaxation and Tensile Modulus of Polymeric Fibers. *Textile Research Journal* 1991; 61, 6: 363-369.
10. Meredith R. Relaxation of Stress in Stretched Cellulose Fibres. *The Journal of the Textile institute* 1954; 45, 6: T438 - T461.
11. Guthrie JC, Wibberley J. The Effect of Time on the Recovery of Fibres. *The Journal of the Textile institute* 1965; 56, 3: 97-103.
12. Manich AM, Ussman MH, Barella A. Viscoelastic Behavior of Polypropylene. *Textile Research Journal* 1999; 69, 5: 325-330.
13. Inoue M, Niwa M. Tensile and Tensile Stress Relaxation Properties of Wool/Cotton Plied Yarns. *Textile Research Journal* 1997; 67, 5: 379-385.
14. Pocienė R, Vitkauskas A. Inverse Stress Relaxation and Viscoelastic Recovery of Multifilament Textile Yarns in Different Test Cycles. *Materials science (Medžiagotyra)* 2005; 11, 1: 68-72.
15. Geršak J, Šajn D, Bukošek V. A study of the relaxation phenomena in the fabrics containing elastane yarns. *International Journal of Clothing Science and Technology* 2005; 17, 3/4: 188-199.
16. Urbelis V, Petrauskas A. Influence of Hygrothermal Treatment on the Stress Relaxation of Clothing Fabrics' Systems. *Materials science (Medžiagotyra)* 2008; 14, 1: 69-74.
17. Hazavehi E, Azadiyan M, Zolghanein P. Investigation and Modelling of Stress Relaxation on Cylindrical Shell Woven Fabrics: Effect of Experimental Speed. *Fibres & Textiles in Eastern Europe* 2013; 21, 6: 64-73.
18. Matsuo M, Yamada T. Stress Relaxation Behavior of Knitted Fabrics under Uniaxial and Strip Biaxial Excitation as Estimated by Corresponding Principle between Elastic and Visco-Elastic Bodies. *Textile Research Journal* 2006; 76, 6: 465-477.
19. Pothan LA, Neelakantan NR, Rao B, Thomas S. Stress Relaxation Behavior of Banana Fiber-reinforced Polyester Composites. *Journal of Reinforced Plastics and Composites* 2004; 23, 2: 153-165.
20. Pocienė R, Žemaitaitienė R, Vitkauskas A. Mechanical Properties and a Physical-Chemical Analysis of Acetate Yarns. *Materials science (Medžiagotyra)* 2004; 10, 1: 75-79.
21. Milašius R, Milašienė D, Jankauskaitė V. Investigation of Stress Relaxation of Breathable-Coated Fabric for Clothing and Footwear. *Fibres & Textiles in Eastern Europe* 2003; 11, 2: 53-55.
22. Dubinskaitė K, Van Langenhove L, Milašius R. Influence of Pile Height and Density on the End-Use Properties of Carpets. *Fibres & Textiles in Eastern Europe* 2008; 16, 3: 47-50.
23. Shi F. Modelling Stretching-Relaxation Properties of Yarns. *Fibres & Textiles in Eastern Europe* 2013; 21, 2: 51-55.
24. Pan N, Brookstein D. Physical Properties of Twisted Structures. II. Industrial Yarns, Cords and Ropes. *Journal of Applied Polymer Science* 2002; 83, 3: 610 –630.
25. Chidambaram D, Venkatraj R, Manisankar P. Solvent-Induced Modifications in Polyester Yarns. I. Mechanical Properties. *Journal of Applied Polymer Science* 2003; 87, 9: 1500–1510.
26. Milašius R, Laureckienė G. Prediction of Long-lasting Relaxation Properties of Polyester Yarns and Fabrics. *Fibres & Textiles in Eastern Europe* 2014; 22, 6: 53-55.
27. Nachane RP, Sundaram V. Analysis of Relaxation Phenomena in Textile Fibres Part I: Stress Relaxation. *The Journal of the Textile institute* 1995; 86, 1: 10-19.
28. Yamaguchi T, Kitagawa T, Yanagava T, Kimura H. Relationship between Stress Relaxation and Tensile Recovery of Filament Yarns. *Journal of the Textile Machinery Society of Japan* 1981; 27, 2: 43-49.

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