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Relationship Between the Inverse Stress Relaxation and the Viscoelastic Recovery of Filament Yarns

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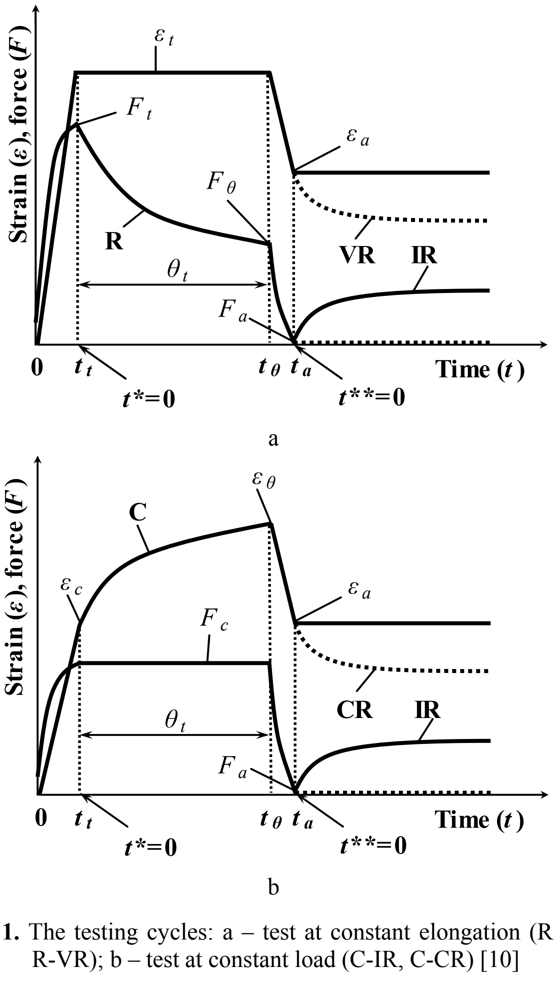
The relationship between two mechanical time-effects, inverse stress relaxation (IR) and viscoelastic recovery (VR, CR) in filament yarns is studied by modelling and experimentally in order to reveal possibilities to predict the amount of inverse stress relaxation by the viscoelastic recovery tests. The effects are studied on 16.6 tex acetate and 15.6 tex polyester multifilament yarns in two different testing cycles: the relaxation (R-) cycle and the creep (C-) cycle. It is shown that the statistical dependency of the amount of stress increase $(F - F_a)$ in the inverse relaxation test on the amount of strain decrease $(\varepsilon_a - \varepsilon)$ in the viscoelastic recovery test is suitably well defined by the power equation that can be useful to predict stress development in IR process by the data obtained in viscoelastic (creep) recovery test.

Keywords: relaxation, creep, inverse stress relaxation, recovery, textile yarn.

INTRODUCTION

The study of the time-dependent mechanical behaviour of textile yarns is of great importance from both the theoretical and practical viewpoint. Different time-effects can manifest in the tensioned yarn during textile multi-stage processing depending on the level and the duration of imposed strains as well on the strains to which the yarn was undergone in the past [1 – 3]. In a number of cases they can result in the formation of faults in the fabrics and sometimes seriously degrade their quality. One of such time-effects, the inverse stress relaxation (IR), is in the focus of attention for researchers during last decades [3 – 9]. Comprehensive studies of the mechanical time-effects are time-consuming ones and often require special equipment. It may be predicated that namely lack of adequate experimental equipment determined the fact that inverse stress relaxation was noticed and began been studied later than creep (C), stress relaxation (R) and viscoelastic recovery (VR). As a result up to now the features of inverse relaxation have not been revealed adequately yet. In [10] the four above-mentioned time-effects have been experimentally investigated in two different tensile testing cycles: the relaxation cycle at constant elongation (R-) and the creep cycle at constant load (C-) (Fig. 1). It is necessary to note that viscoelastic recovery manifesting in the latter testing cycle after unloading the specimen is customary termed as creep recovery (CR).

Some attempts have been made to find the relationship between different time-effects [11 – 15]. Such relationship can lead to the simplifying and even time-saving in the time-effect studies. As it has been proposed by Matukonis and Vitkauskas [11], the relationship between the inverse stress relaxation and the viscoelastic behaviour could be presumable because at the very beginning of the both processes the material had the identical mechanical pre-history. Unfortunately, except the brief study on viscose yarn [15] no more data on the matter have been found in the literature. The aim of the present study is to look at both these processes (IR and VR) through the modelling and experimental treatment in different testing cycles with wide mechanical pre-history in order to reveal possibilities to predict the amount of inverse relaxation by the viscoelastic recovery tests.



a

b

Fig. 1. The testing cycles: a – test at constant elongation (R-IR, R-VR); b – test at constant load (C-IR, C-CR) [10]

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MODELLING

Theoretical investigation of the relationship between the inverse stress relaxation and the viscoelastic recovery has been made analysing the behaviour of the mechanical model [16] comprised of 5 Maxwell units possessing relaxation times differing exactly by one time order and of a single spring, all of them connected in parallel. The model possesses regular discrete spectrum of relaxation times. Set of the model‘s constants corresponding two different relaxation time spectra – “peak” and “box” – are shown in [15]. The inverse relaxation‘s and viscoelastic recovery‘s equations of the model have been presented in [7].

The model was tested in both R- and C- cycles (see Fig. 1)at constant strain (ε_t) or at constant force (F_c). The sustaining time (θ_t) was varied. The extension rate was $v_t = \mathrm{d}\varepsilon / \mathrm{d}t = 100$ and it was equal to the rate of retraction that always ended at $F_a = 0$. All the data are shown as being the dimensionless conventional values expressed in coherent measuring units.

The typical inverse relaxation and viscoelastic recovery curves of the model obtained in R- cycle for “peak” and “box” relaxation time spectra are shown in Fig. 2. It is evidently seen that despite of identical mechanical pre-history the both processes run differently. While VR/CR processes are determined by the entire relaxation time spectrum of the model, the IR process is determined only by a part of the spectrum, i.e. by set of the short relaxation times of the model. The remaining part of the spectrum represents stress relaxation process that overruns further increase of stress. With increase of the sustaining time θ_t, the IR process becomes slower and less affected by the superposing stress relaxation process. Therefore, the maximum in the IR curves moves towards longer time of observation (t^{**}).

The dotted curves in Fig. 2 show that VR process is evidently slower than the IR process of the model. It’s main character is also determined by the sustaining time θ_t and the relaxation time spectrum of the model. The type of testing cycle (R- or C-) has been found as having no appreciable effect on IR and VR/CR processes of the model provided the strain levels just before retraction were identical ($\varepsilon_t = \varepsilon_\theta$, see Fig. 1).

From the character of curves in Fig. 2 it is evidently seen that the interrelation can be found between the amount of decrease in strain $(\varepsilon_a - \varepsilon)$ and the amount of increase in stress $(F - F_a)$ provided that the latter is not influenced by the superposing process of ordinary stress relaxation. Analysing IR curves of the model obtained for various relaxation time spectra and different sustaining times θ_t it has been found that the influence of ordinary relaxation became significant approximately at one order of time to the point corresponding to maximum stress in an IR curve.

EXPERIMENTAL

To check the reliability of theoretical results and to discover the interrelation between IR and VR processes the behaviour of two types of multifilament textile yarns, the acetate (CA) 16.6 tex and the polyester (PES) 15.6 tex, substantially differing in the polymer origin and in physical properties, was experimentally studied. The yarns were tested in both tensile testing cycles shown in Fig. 1. The characteristics of the testing cycles have been presented in our previous work [10].

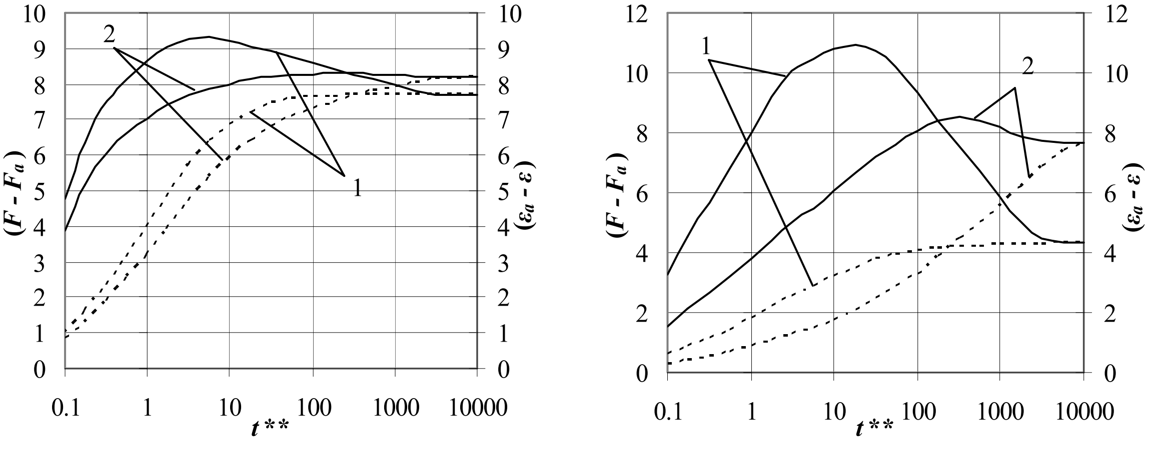
The experiments were provided on Zwick/Z005 universal testing machine. All specimens were preconditioned, then conditioned and tested according to the deformation in the atmospheres according to ISO 139.

RELATIONSHIP OF THE TIME-EFFECTS

Preliminary study has shown that the statistical dependency of the amount of stress increase $(F - F_a)$ in the inverse relaxation test on the amount of strain decrease $(\varepsilon_a - \varepsilon)$ in the viscoelastic recovery test can be expressed by a power function:

$$(F - F_a) = r(\varepsilon_a - \varepsilon)^p, \qquad (1)$$

where r is the coefficient associated with yarn stiffness; p is the power coefficient.



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b

Fig. 2. Inverse stress relaxation (IR) (———) and viscoelastic recovery (VR) (- - - - -) curves of the model in R- cycle at $\varepsilon_t = 10$: 1 – $\theta_t = 10$; 2 – $\theta_t = 1000$. Relaxation time spectra: a – peak; b – box

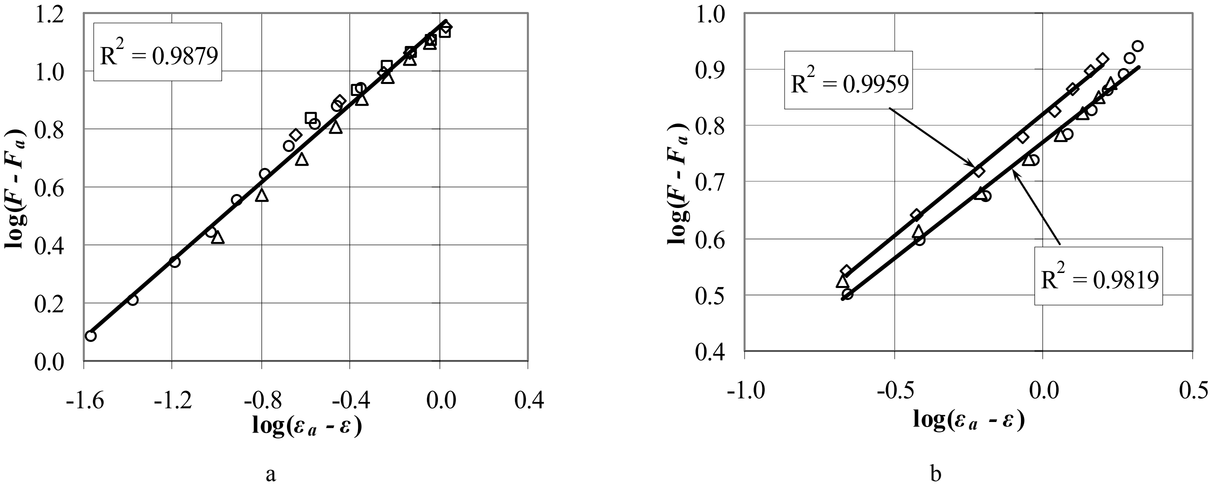

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Fig. 3. The dependence between $(\varepsilon_a - \varepsilon)$ and $(F - F_a)$ when tested in R- cycle: a – CA yarn at ε_t = 9.1 %; b – PES yarn at ε_t = 14.4 %; θ_t: □ – 1 s, ◇ – 10 s, △ – 100 s, ○ – 1000 s

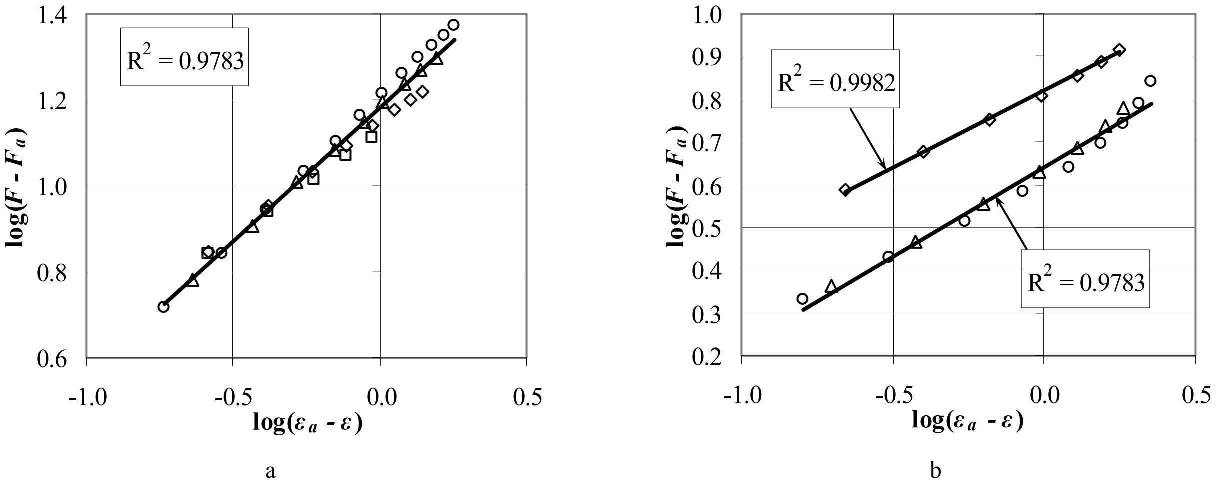

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Fig. 4. The dependence between $(\varepsilon_a - \varepsilon)$ and $(F - F_a)$ when tested in C- cycle: a – CA yarn at F_c = 71.5 mN/tex; b – PES yarn at F_c = 319.6 mN/tex; θ_t: □ – 1 s, ◇ – 10 s, △ – 100 s, ○ – 1000 s

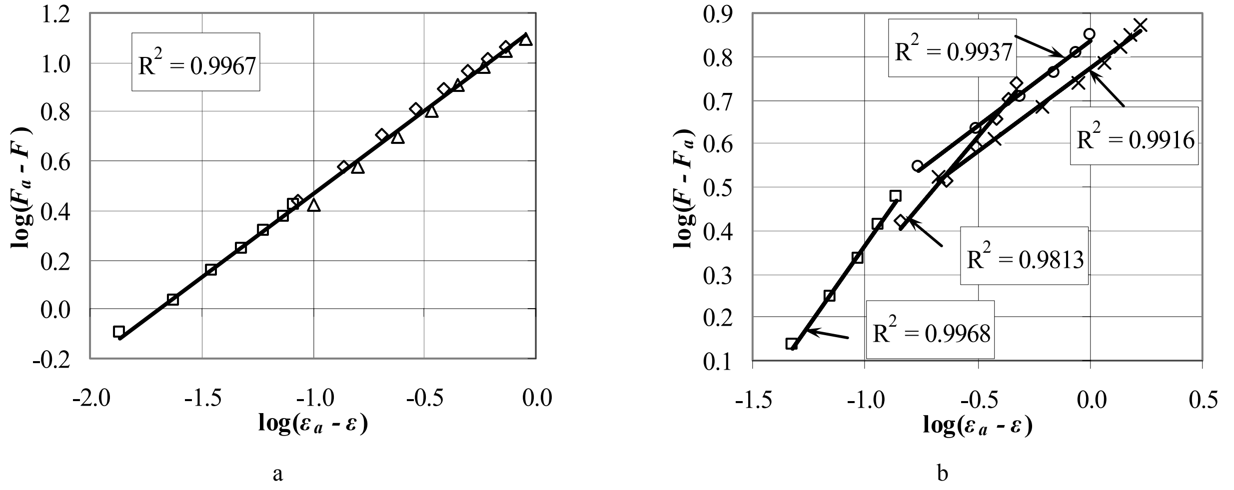

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Fig. 5. The dependence between $(\varepsilon_a - \varepsilon)$ and $(F - F_a)$ when tested in R- cycle at θ_t = 100 s: a – CA yarn; b – PES yarn; ε_t: □ – 1 %, ◇ – 5 %, △ – 9.1 %, ○ – 10 %, × – 14.4 %

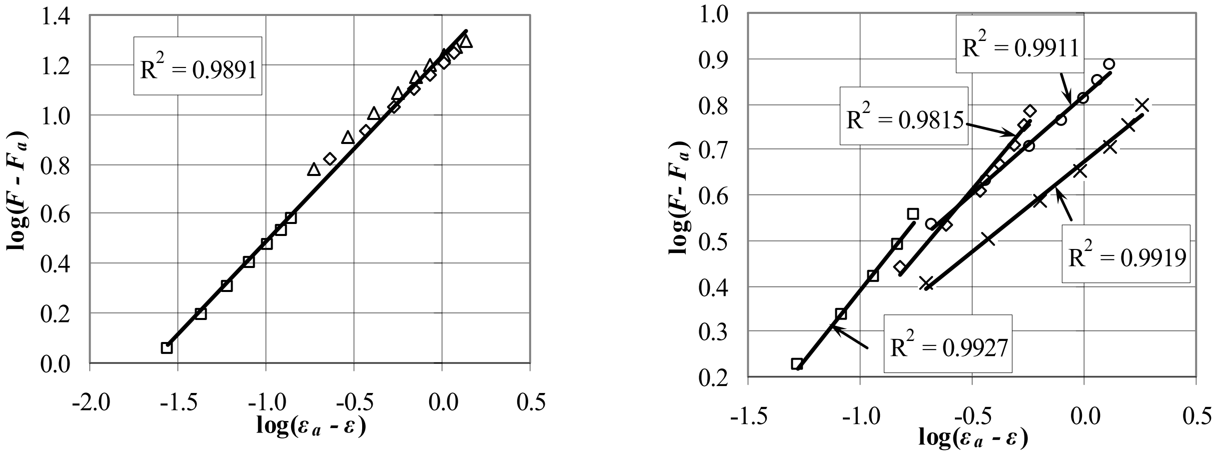

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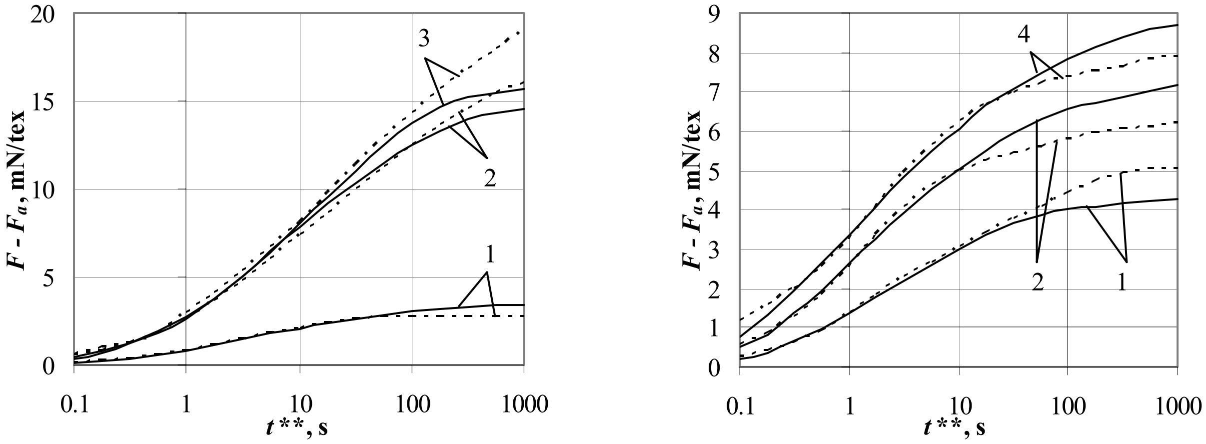
Fig. 6. The dependence between $(\varepsilon_a - \varepsilon)$ and $(F - F_a)$ when tested in C- cycle at θ_t = 100 s: a – CA yarn, when F_c, mN/tex: □ – 28.3; ◇ – 68.3; △ – 71.5; b – PES yarn, when F_c, mN/tex: □ – 27.0; ◇ – 99.6; ○ – 242.5, × – 319.6



a

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Fig. 7. The experimental curves of IR (———) when tested in R- cycle at θ_t = 100 s and those predicted by eq. (1) (- - - - -): a – CA yarn; b – PES yarn; ε_t: 1 – 1 %, 2 – 5 %, 3 – 9.1 %, 4 – 14.4 %

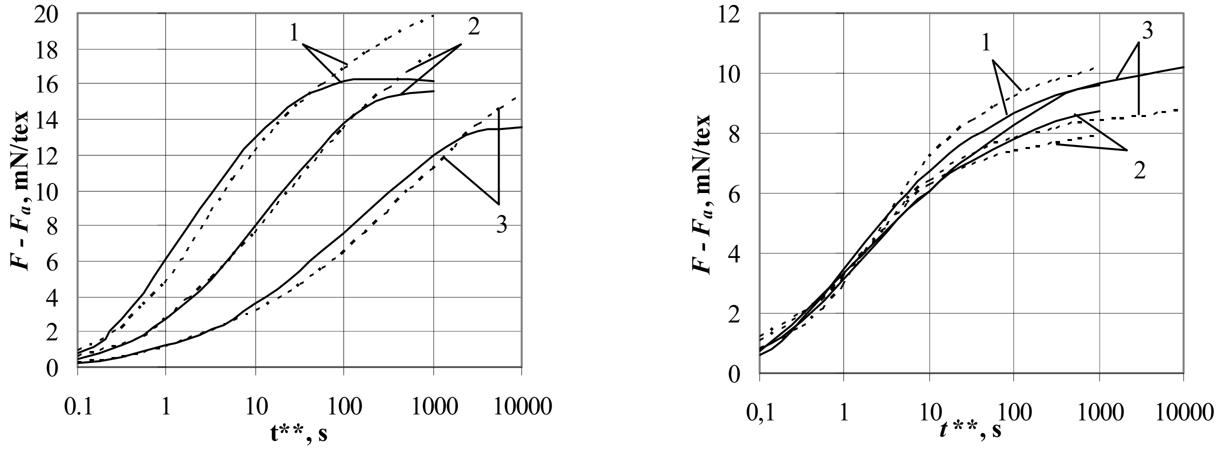

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Fig. 8. The experimental curves of IR (———) when tested in R- cycle and those predicted by eq. (1) (- - - - -): a – CA yarn at ε_t = 9.1 %; b – PES yarn at ε_t = 14.4 %; θ_t: 1 – 10 s, 2 – 100 s, 3 – 1000 s

Defining in equation (1) $\log(\varepsilon_a - \varepsilon) = x$, $\log r = n$ and $\log(F - F_a) = y$ we get a linear equation:

$$y = px + n. \qquad (2)$$

The dependence between the amount of the strain decrease $(\varepsilon_a - \varepsilon)$ in VR process and the corresponding amount of the stress increase $(F - F_a)$ in IR process straightens in the logarithmic coordinates for both CA and PES yarns tested in different testing cycles under different elongations (ε_t) or forces (F_c) as well as at different sustaining times (θ_t) (Figures 3 and 4). For CA yarn one regression line has been drawn through all experiment points. Experiment values for PES yarn clearly divide into two groups in dependence of sustaining time and this tendency is especially pronounced when tested in C- cycle. Therefore, one regression line has been drawn through the points at $\theta_t = 10$ s, and the second one – at $\theta_t = 100$ s and $\theta_t = 1000$ s. A good coincidence of experimental data to the straight line is obtained: the coefficient of determination for CA yarn changed from 0.9783 to 0.9879 and that for PES yarn changed in the range of 0.9783–0.9998.

The results obtained under different levels of loading (ε_t, F_c) at $\theta_t = 100$ s are given in Figures 5 and 6. As it can be seen, the dependencies for CA and PES yarns are different. For CA yarn values of the the coefficients p and n are nearly independent of the loading level. For PES yarn the value of coefficient p increases and of n – decreases with increase of the loading level. The same tendency is valid for both R- and C- testing cycles.

The values of the coefficient of determination being close to unity (Figures 3 – 6) show that the power function is suitably able to define the relationship between inverse stress relaxation and visoelastic (creep) recovery in the yarns. It can be used to predict the level of inverse relaxation from yarn recovery tests.

In Figures 7 and 8 the experimental curves of inverse relaxation in the yarns are shown alongside the curves predicted from the results of viscoelastic recovery test by using equation (1). The curves show that the amount of inverse relaxation in the yarns can be suitably predicted with accuracy of (5 – 10) % up to the time t^{**} approximately one time order shorter than that at which the stress reaches its maximum value during the IR process.

CONCLUSIONS

It has been found by modelling that despite of the character of relaxation time spectrum and the deformation regime the inverse stress relaxation (IR) becomes significally influenced by ordinary relaxation approximately at one order of time to the point corresponding to maximum stress in an IR curve.

The relationship between the viscoelastic (creep) recovery and the inverse stress relaxation in filament yarns is suitably well defined by the power equation that can be useful to predict stress development in IR process by the data obtained in viscoelastic (creep) recovery test.

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