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Inverse Stress Relaxation and Viscoelastic Recovery of Multifilament Textile Yarns in Different Test Cycles

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The article presents the results of the experimental research of inverse stress relaxation (IR) and viscoelastic recovery (VR) that take place in acetate and polyester multifilament yarns in dependance on the mechanical pre-history. The above-mentioned time-effects are investigated in two different – stress relaxation (R-) and creep (C-) testing cycles.

The fact that inverse stress relaxation process takes place in C- test cycle, i.e. after previous sustaining the specimen at constant load is experimentally confirmed. It is shown that viscoelastic recovery is the slower process than the inverse stress relaxation. At identical elongations of the yarns at the end of loading period the inverse relaxation and viscoelastic recovery processes go on similarly regardless of the character of testing cycle.

Keywords: relaxation, inverse relaxation, creep, recovery, yarn, viscoelasticity.

INTRODUCTION

Strength and deformability of textile yarns are important only mechanical properties determining the behaviour of yarns in woven or knitted fabrics making-up as well as the behaviour of a fabric in end-use. The behaviour of textile materials as of any polymeric bodies is mostly viscoelastic. The response of a material to the specific mechanical action depends not only on the action itself but also on the former actions undergone, i. e., it depends on mechanical pre-history of material [1, 2]. This implies that time-dependence of the response of any textile material opposing the applied forces, should be taken into account [1 – 6]. Viscoelastic properties can serve as an index of greatly various purposes, e. g. for comparative evaluation of materials or as a criterion at the control of the specific process.

Experimental investigation of viscoelastic properties in textile fibres and yarns is commonly based on the results of tensile tests that can be related to two main groups of testing cycles, taking into consideration the conditions of mechanical action on the material and the parameters measured.

The tests at constant elongation ε_t (Fig. 1, *a*) are related to the first group. In these tests stress relaxation (R) as well as inverse stress relaxation (IR) (smooth lines) or viscoelastic recovery (VR) in length of a specimen (dotted lines) can be observed.

The tests at constant force or load F_c (Fig. 1, *b*) are related to the second group. In this case a creep (C) as well as viscoelastic creep recovery (CR) (dotted lines) or inverse stress relaxation (IR) (smooth lines) can be observed in the tests.

Numerous works are done revealing the features of creep, recovery and stress relaxation in textiles: the publications [3, 7 – 13] can serve as the proper examples. The phenomenon of inverse stress relaxation was first mentioned in 1946 by Stein, Halsey and Eyring [14], i. e. substantially later than the above mentioned phenomena. Inverse relaxation is often met with under practical conditions [15 – 17], so its study is a matter of great interest. Despite of the fact that the studies of the inverse relaxation became more intensive during last decades [16 - 22], knowledge on the regularities of the phenomenon are obviously insufficient. Except for theoretical model proposed in [21], up to now there are no experimental data on the inverse relaxation manifesting in the testing cycle of the second group (Fig. 1, *b*).

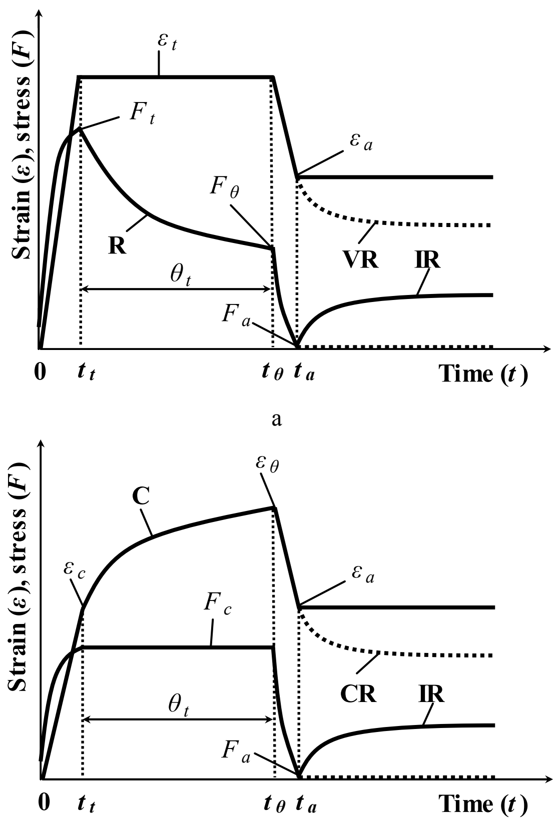

Fig. 1. The testing cycles: a – test at constant elongation; b – test at constant force

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In some publications the attempts have been made to predict the development of one viscoelastic aftereffect by the data on the another one [1, 7, 23 – 25]. Presumptively positive results could be obtained predicting the inverse relaxation by viscoelastic recovery, for the both phenomena start to develop at the absolutely identical mechanical pre-history (points F_a in Fig. 1, *a* and *b*). Such prediction would be especially useful because the inverse relaxation test implicates much more problems than the comparatively simple recovery test [17].

The aim of this study is to investigate experimentally the character of both inverse relaxation and viscoelastic recovery in different textile yarns at identical mechanical pre-history. A special consideration is paid to the inverse relaxation development following the creep in the yarns because there are no any experimental data on the effect in the yarn being undergone by constant force.

EXPERIMENTAL

Two different types of multifilament yarns were taken for the experimental investigation: acetate (CA) 16.6 tex and polyester (PES) 15.6 tex. All specimens were pre-conditioned, then conditioned and tested in the atmospheres according to ISO 139. The experiments were provided on Zwick/Z005 universal testing machine. To ensure the setting of testing cycle parameters with as possible higher accuracy the gauge length was taken 700 mm, i. e., larger than it is customary used in yarn testing. Each specimen was pretensioned to 2.4 mN/tex before the testing.

The testing cycle at constant elongation R- (for symbols used below in Fig. 1, *a*) consisting of four phases was provided in two different regimes (R-IR and R-VR). The first three phases were identical for both regimes:

1) constant rate (v_t) extension up to the strain ε_t,
2) sustaining at ε_t up to the time $t^* = (t - t_t) = \theta_t$, while stress relaxation (R) was going on and measured,
3) constant rate (v_a) retraction down to pretension (F_a).

The fourth phase was different for the particular regime. For the regime R-IR the specimen was sustained at strain ε_a corresponding to F_a, and the inverse relaxation (IR) was going on and measured in time $t^{**} = (t - t_a)$. For the regime R-VR, in the last fourth phase viscoelastic recovery VR, i.e the decrease in specimen strain ε was going on and measured in time $t^{**} = (t - t_a)$ at constant pretension F_a.

The testing cycle at constant force (for symbols used below look at Fig. 1, *b*) was also provided in two regimes (C-IR and C-CR). The first three phases were identical for both regimes:

a) constant rate (v_t) extension up to the force F_c corresponding to the strain ε_c,
b) sustaining at force F_c up to the time $t^* = (t - t_t) = \theta_t$, while creep (C) was going on and measured,
c) constant rate (v_a) retraction down to pretension (F_a).

For the regime C-IR the fourth phase was identical to that of the regime R-IR, while for the regime C-CR the fourth phase was identical to that of the regime R-VR.

In all tests the rate of extension (v_t) was 525 mm/min (1.25 %/s) and it was equal to the rate of retraction (v_a). The limits of extension (ε_t, F_c) during the first phases of the regimes, and the sustaining times (θ_t) during the second phases were varied. The inverse relaxation (IR) and the viscoelastic recovery (VR, CR) were mainly measured during the time $t^{**} = 1000$ s. In some cases the measuring time was prolonged up to $t^{**} = 10000$ s.

To examine the characters of both IR and CR processes running in the C- testing cycle as distinct from the corresponding IR and VR processes running in the R- testing cycle the tests were provided in two different modes:

Mode I: The level of force F_c in C- testing cycle is equal to the corresponding level of force F_θ in R- testing cycle.

Mode II: The level of strain ε_t in R- testing cycle is equal to the corresponding level of strain ε_θ in C- testing cycle.

RESULTS AND DISCUSSIONS

Stress relaxation curves of CA and PES yarns are shown in Fig. 2. Stress relaxation process is very distinctive in CA yarn, where the obvious yield point is observed in its stress-strain curve. With increase of the set extension level (ε_t) the values of stress increase as well. However, when the extension level of CA yarn is in the yield zone ($\varepsilon_t = 5 \div 9.1$ %), from time $t^* \approx 300$ s the values of stress are lower than at elongation $\varepsilon_t = 1$ %. This anomalous behaviour of acetate yarn was formerly noticed by Meredith [10], who explained it as a kind of adiabatic sudden stretch. In our case, the extension rate is not so high to rise the temperature of the specimen. It is possible that the above-mentioned anomaly of the behaviour is related to complex entropy changes in stretched yarn. Extending the CA yarn over the yield point, the relaxation curves become almost parallel. The yield zone is not characteristic for PES yarn so as extension level increases, relaxation is going on at higher stresses throughout the whole observation time θ_t.

Creep curves of the yarns at constant forces in the C- test cycle are presented in Fig. 3. With increase of the force (F_c), elongations of the yarns during creep process increase as well. Creep of CA yarns is especially intense at yield zone and over it, while in PES yarn – at the zone where the slope of its stress-strain curve markedly grows up through the most structure change, i.e. when $\varepsilon_c > 5$ %.

Due to characteristic yield zone in stress-strain curve of CA yarn the data obtained in R- and C- cycles when testing in mode I are unlikely comparable. It is seen in Fig. 2, *a* that in R- test cycle at $t^* \approx (300 \div 1000)$ s stresses of CA yarn during relaxation process narrowly differ between themselves while the relaxation is going on at completely different elongations ε_t.

Stress development (IR) curves of the yarns in both test cycles of mode I (the values of F_c, mN/tex for CA/PES yarn are: 59.7/284.9 at $\theta_t = 1$ s, 46.4/257.4 at $\theta_t = 10$ s, 36.5/220.8 at $\theta_t = 100$ s, 28.3/199.7 at $\theta_t = 1000$ s) are shown in Figure 4, *a* and 5, *a*. In R- test cycle of CA yarn the amount of stress increase is slightly dependent on the sustaining time before the retraction. Due to superposition of inverse relaxation and ordinary stress relaxation processes, the distinct maximum in the curves is observed. With increase of the sustaining time θ_t, the inverse

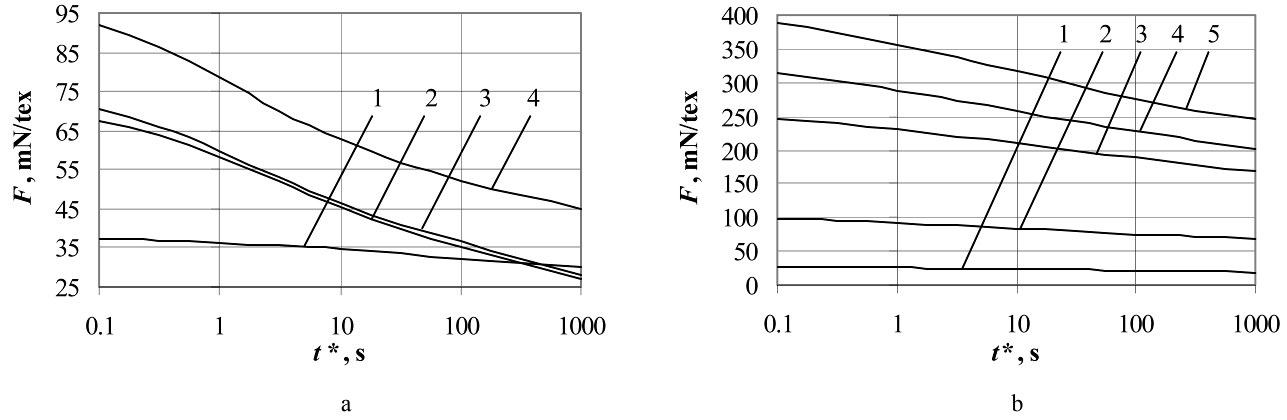

Fig. 2. Stress relaxation curves of the yarns. a – CA yarn; ε_t: 1 – 1 %, 2 – 5 %, 3 – 9.1 %, 4 – 22.1 % (mode II); b – PES yarn; ε_t: 1 – 1 %, 2 – 5 %, 3 – 10 %, 4 – 14.4 %, 5 – 32.1 % (mode II)

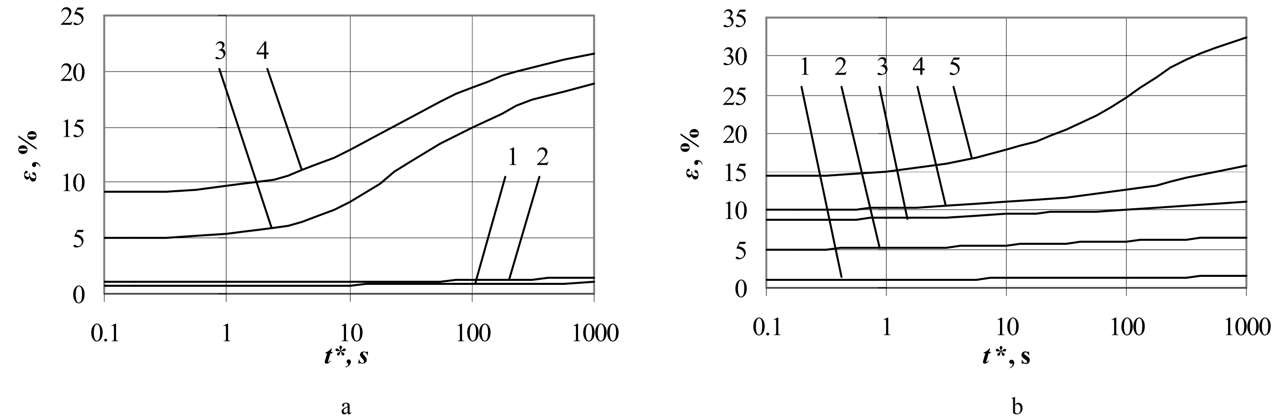

Fig. 3. Creep curves of the yarns. a – CA yarn; F_c, mN/tex : 1 – 28.3, 2 – 37.4, 3 – 68.3, 4 – 71.5; b – PES yarn ; F_c, mN/tex : 1 – 27.0, 2 – 99.6, 3 – 199.7, 4 – 242.5, 5 – 319.6

relaxation process becomes slower and less affected by the stress relaxation process. Therefore, the maximum in the curves moves towards longer time of observation (t^{**}). After $\theta_t = 1000$ s the maximum is moved so considerably that it could not be reached even till observation time $t^{**} = 10000$ s. The IR process is more slow as the sustaining time is increased. In C- test cycle the maximum in IR curves moves towards time t^{**} axis in dependence on the sustaining time θ_t in the similar way as in the R-cycle. Nevertheless, the increase in stress (IR) is approximately four times lower than in R- test cycle. In the tests by mode I the values of strain ε_t in R- cycle is 9.1 %, i.e. above the yield point, while all values of strain ε_θ in C-cycle at constant force are below the yield point ($\varepsilon_\theta = 2.0$ % at $\theta_t = 1$ s, $\varepsilon_\theta = 1.5$ % at $\theta_t = 10$ s, $\varepsilon_\theta = 1.2$ % at $\theta_t = 100$ s, $\varepsilon_\theta = 1.0$ % at $\theta_t = 1000$ s). So, the increase in stress depends more on the sustaining time than on the yarn elongation: the increase in stress at time $\theta_t = 1000$ s is the highest despite the amount of strain (ε_θ) before the retraction is the lowest ($\varepsilon_\theta = 1.0$ %). It is supposed that this fact is associated with more pronounced orientation of polymer chains during creep if compared to that during relaxation at constant elongation.

For the PES yarn the maximum in the stress development (IR) curves is beyond the observation time, but the tendency of its movement towards longer time of observation (t^{**}) can be distinguished. The character of stress increase dependence on test regime is analogous to that of CA yarn. However, for PES yarn the difference in the values of strains when testing in the different cycles is not so distinct as for CA yarn: in R- cycle $\varepsilon_t = 14.4$ %, while in C- cycle at $\theta_t = 1$ s $\varepsilon_\theta = 12.2$ %, at $\theta_t = 10$ s $\varepsilon_\theta = 11.8$ %, at $\theta_t = 100$ s $\varepsilon_\theta = 11.4$ %, and at $\theta_t = 1000$ s $\varepsilon_\theta = 11.3$ %. Therefore, inverse relaxation is quite comparable in its amount when testing in the different cycles.

The results obviously showed that the presupposition of the inverse stress relaxation process as taking place in C- test cycle, i.e. after previous sustaining the specimen at constant load is proven out. The effect must be also credibly characteristic for any for any viscoelastic polymeric material.

The viscoelastic recovery (VR, CR) of the yarns in mode I depends on the test regime similarly to the IR process (Fig. 4, *b* and Fig. 5, *a*). Due to the reasons discussed above creep recovery values of the yarns in the C- testing cycle are lower than in R- testing cycle: approximately ten times lower for CA yarn and approximately 1.5 times lower for PES yarn.

Much more comparable results are obtained in R- and C- test cycles, when testing in mode II, i.e. when identical elongations values at time instant t_θ are maintained in both test cycles (Fig. 5, *b* and Fig. 6). The values of strain $\varepsilon_t = \varepsilon_\theta$, % for CA/PES yarn are the following: 9.4/15.1 at

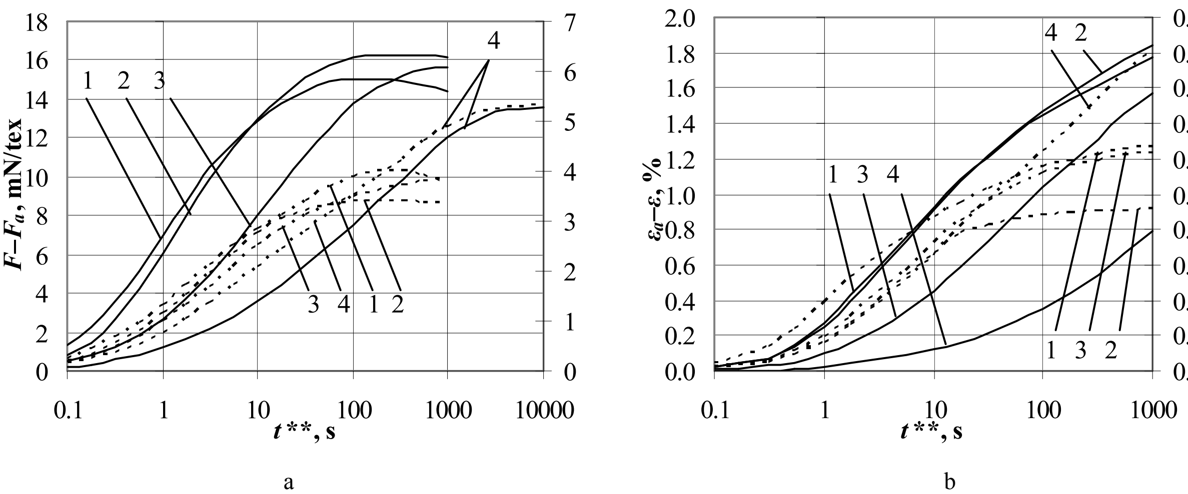

Fig. 4. Inverse stress relaxation (*a*) and viscoelastic recovery (*b*) curves of CA yarn in R- (——, left scale) and C- (- - - - -, right scale) test cycles, mode I (ε_t = 9.1 %); θ_t : 1 – 1 s, 2 – 10 s, 3 – 100 s, 4 – 1000 s

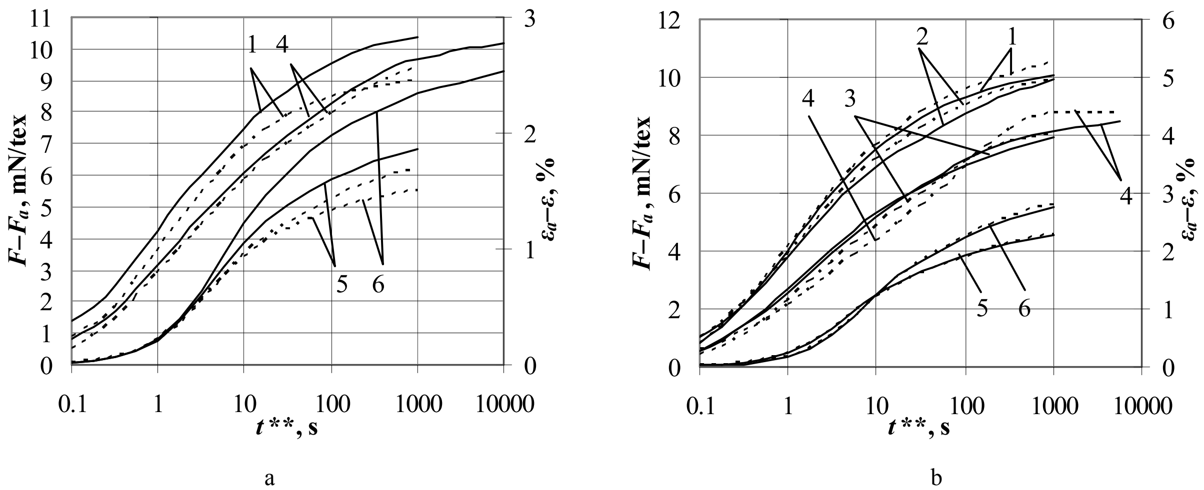

Fig. 5. Inverse stress relaxation (IR, left scale) and viscoelastic recovery (VR (CR), right scale) curves of PES yarn in R- (——) and C- (- - - - -) test cycles. *a* – mode I, (ε_t = 14.4 %); *b* – mode II, (F_c = 319.6 mN/tex); IR curves as θ_t: 1 – 1 s, 2 – 10 s, 3 – 100 s, 4 – 1000 s; VR and CR curves as θ_t : 5 – 1 s, 6 – 1000 s

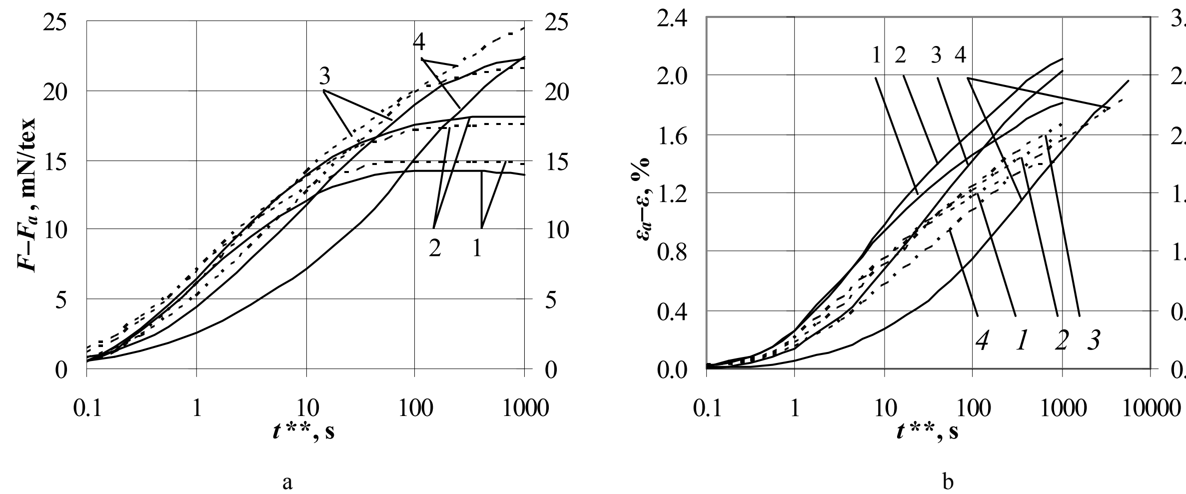

Fig. 6. Inverse stress relaxation (*a*) and viscoelastic recovery (*b*) curves of CA yarn in R- (——, left scale) and C- (- - - - -, right scale) test cycles, mode II (F_c = 71.5 mN/tex); θ_t : 1 – 1 s, 2 – 10 s, 3 – 100 s, 4 – 1000 s

θ_t = 1 s, 13.1/17.6 at θ_t = 10 s, 19.7/25.7 at θ_t = 100 s, and 22.1/32.6 at θ_t = 1000 s. It is seen that when the same strain value is held on before the retraction the amount of stress increase and of viscoelastic contraction in R- and C-cycles are similar and that with increase of sustaining time before the retraction the processes go on slower similarly to mode I.

As a result, it is obviously seen that at identical elongations of the yarns at the end of loading period the inverse relaxation and viscoelastic recovery processes go on similarly regardless of the character of testing cycle.

CONCLUSIONS

The inverse stress relaxation process is proven out as taking place in the yarns in C- test cycle, i.e. after previous sustaining the specimen at constant load. The effect must be also credibly characteristic for textile fabrics and for any polymeric material.

Viscoelastic recovery is the slower process than the inverse stress relaxation.

The time during which the yarns are undergone by specified constant elongation or constant load is the most effective factor influencing the amount and character of both inverse relaxation and viscoelastic recovery in the yarns.

At identical elongations of the yarns at the end of loading period the inverse relaxation and viscoelastic recovery processes go on similarly regardless of the character of testing cycle.

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