Creep and Creep Recovery Behaviour of Textile Fabrics and their Fused Systems

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Creep and creep recovery behaviour of two suit fabrics, and two fusible interlinings as well as their binary systems are investigated under the different constant loads. The total elongation is assumed to be comprised of elastic, viscoelastic, instantaneous irreversible and progressively developing irreversible ("plastic") components. Referring to this the mechanical model, which included generalized Voigt elements possessing regular discrete retardation time spectra was proposed for theoretical analysis of the processes. The model units representing irreversible components of elongation have fixers. Good correspondence between theoretical and experimental results proves that the proposed model is appropriate for the analysis of the time-dependent mechanical behaviour of the textile fabrics and their fused systems.
Keywords: model, creep, recovery, textile fabric, fusing.

INTRODUCTION

Seeking the best form stability of garments and other sewing goods the double-layer or multi-layer textile systems are worldwide used. In such systems the main fashionable component ("the face") often is a woven or knitted fabric. The long-term mechanical behaviour of textile fabrics as well as textile fabric systems can be notably revealed by the analysis of their creep and creep recovery data [1 – 4]. Mechanical models were successfully used by a number of authors [5 – 10] for the experimental data analysis and theoretical interpretation of the development of these processes.

It was indicated in the studies [11, 7] that the irreversible elongation of textile systems develops ambivalently: one part of it develops instantaneously at a rate of force application, while the other ("plastic") part develops progressively. In such a way the increase of fabric elongation during creep process can be interpreted as the resultant process of the development of both viscoelastic and "plastic" elongations.

Our task in this study was to propose a mechanical model that could represent the creep and creep recovery of a textile product including the separation of irreversible elongation into both above mentioned parts. Other aim of the study was to investigate theoretically and experimentally the features of mechanical time-dependency of textile fabrics as well as heterogeneous fused systems made up of them.

THEORETICAL

The mechanical model (Fig. 1) proposed for the theoretical analysis of creep and creep recovery consists of four parts all of them connected in series. Each part represents the individual component of the total deformation. The immediate reversible ("elastic") deformation is represented by Hookean spring, the elasticity constant of which is E_T. The delayed reversible (viscoelastic) deformation is represented by generalized Voigt model, and its elasticity and viscosity constants are respectively E_{E1}, E_{E2}, …, E_{En} and η_{E1}, η_{E2}, …, η_{En}. The assumption is made that the regularity of viscoelastic deformation development during creep process is identical to the regularity of its decrease during creep recovery. The instantaneous irreversible deformation is represented by the spring with fixer, the spring elasticity constant is E_{SL}. The deformation developing progressively ("plastic") is represented in the model by generalized Voigt element with spring fixers. The elasticity and viscosity constants of the element are respectively $E_{P1}, E_{P2}, …, E_{Pm}$ and η_{P1}, η_{P2}, …, η_{Pm}.

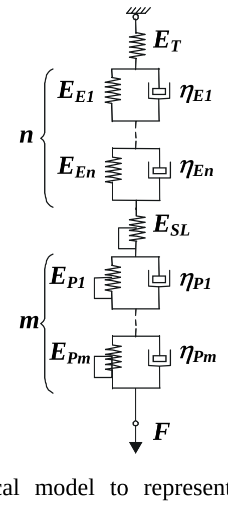

Fig. 1. The mechanical model to represent creep and creep recovery processes

The tensile creep and creep recovery test cycle applied in the study is presented in Fig. 2. The model as well as a real test specimen is loaded and creep process at constant load F is developed during the time period ($t_a – t_b$). Elongation, which upstarts during the time period ($0 – t_a$), till the beginning of creep process, i.e. while the load reaches its nominal value, is conventionally named "fast developing elongation" (ε_S). It consists of elastic

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elongation (ε_T) and of instantaneous irreversible elongation (ε_{SL}).

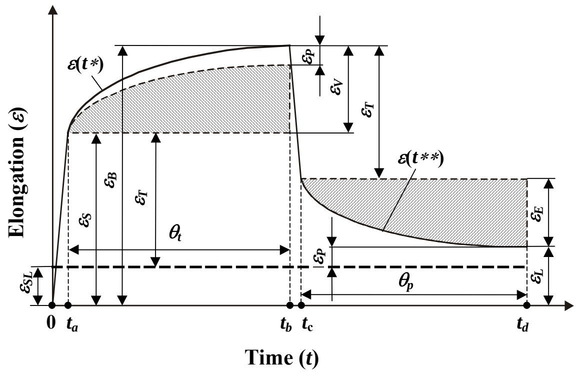

Fig. 2. Creep and creep recovery test cycle applied in the study

At the end of creep process (when $t_b - t_a = t^* = \theta_t$) the elongation of the model or a test specimen reaches the value ε_B, which is considered as a total elongation ($\varepsilon_B = \varepsilon_S + \varepsilon_V$), where ε_V is the creep amount during the loading period θ_t. As soon as the load is removed, elastic elongation ($\varepsilon_T = \varepsilon_B - \varepsilon_{t^{**}=0}$) immediately contracts as well, and this is followed by creep recovery – the decrease in elongation with time. Elongation at the end of observed creep recovery process (when $t_d - t_c = t^{**} = \theta_p$) is assumed to be irreversible elongation (ε_L), and elongation contracted during the time θ_P is assumed to be viscoelastic elongation (ε_E). So, the lined areas in Fig. 2 represent the development of viscoelastic elongation both in creep and creep recovery processes. The residual part of the total elongation developing in creep process represents the increasing plastic elongation, the value of which at the end of creep process is ε_P. The time periods, during which the real specimens are loaded and unloaded (correspondingly $(0 - t_a)$ and $(t_c - t_b)$), are very short, they don't exceed $2 \div 3$ s. They are assumed to be negligible and are not considered in the study.

Creep process of the model as elongation development with respect to time t^* at constant load F is expressed by the following equation:

$$\varepsilon(t^*) = \frac{F}{E_T} + \frac{F}{E_{SL}} + \sum_{i=1}^{n} \frac{F}{E_{Ei}} \left[1 - \exp\left(-\frac{t^*}{\tau_{Ei}}\right)\right] + \sum_{j=1}^{m} \frac{F}{E_{Pj}} \left[1 - \exp\left(-\frac{t^*}{\tau_{Pj}}\right)\right], \quad (1)$$

where $\tau_{Ei} = \eta_{Ei}/E_{Ei}$, and $\tau_{Pj} = \eta_{Pj}/E_{Pj}$ are retardation times of the Voigt elements. Creep recovery of the model as elongation decrease with respect to the time t^{**} after unloading is expressed by:

$$\varepsilon(t^{**}) = \frac{F}{E_{SL}} + \sum_{i=1}^{n} \frac{F}{E_{Ei}} \left[1 - \exp\left(-\frac{\theta_t}{\tau_{Ei}}\right)\right] \exp\left(-\frac{t^{**}}{\tau_{Ei}}\right) + \sum_{j=1}^{m} \frac{F}{E_{Pj}} \left[1 - \exp\left(-\frac{\theta_t}{\tau_{Pj}}\right)\right]. \quad (2)$$

Calculation of the model constants if referring to the experimental data, begins from creep recovery period. The constant of the elastic component is $E_T = F/\varepsilon_T = F/(\varepsilon_B - \varepsilon_{t^{**}=0})$. Assuming the residual specimen's elongation at the end of creep recovery period θ_P to be the irreversible elongation (ε_L), its instantaneous part $\varepsilon_{SL} = \varepsilon_S - \varepsilon_T$ is separated and the constant $E_{SL} = F/\varepsilon_{SL}$ is obtained. To calculate the constants of both the generalized Voigt elements the regular discrete retardation time spectra [9] were taken. First of all the longest retardation times are chosen which should be somewhere comparable with the durations of creep and creep recovery periods. Since in our experiments these periods were equal ($\theta_t = \theta_p = 1800$ s), the longest retardation times were chosen $\tau_{En} = \tau_{Pm} = 1000$ s. The other, shorter retardation times are obtained from the relations $\tau_{Ei} = \tau_{En}/10_{n-i}$, and $\tau_{Pj} = \tau_{Pm}/10_{m-j}$. Next, to obtain the constants $E_{E1}, E_{E2}, \ldots, E_{En}$, part of elongation decreasing in time t^{**} is separated from the equation (2):

$$\varepsilon_E(t^{**}) = \varepsilon(t^{**}) - \varepsilon_L = \sum_{i=1}^{n} \frac{F}{E_{Ei}} \left[1 - \exp\left(-\frac{\theta_t}{\tau_{Ei}}\right)\right] \exp\left(-\frac{t^{**}}{\tau_{Ei}}\right). \quad (3)$$

When $t^{**} >> \tau_{E(n-1)}$, the recovery process is determined by the only Voigt element, retardation time of which is $\tau_{Ei} = \tau_{En}$. Taking two experimental values of the decreasing part of elongation at different time instants, e.g. at $t^{**}_1 = 1000$ s and $t^{**}_2 = 1800$ s, and putting them into equation (3), it yields:

$$E_{En} = F\left[1 - \exp\left(-\frac{\theta_t}{\tau_{En}}\right)\right] \frac{\exp\left(-\frac{t^{**}_1}{\tau_{En}}\right) - \exp\left(-\frac{t^{**}_2}{\tau_{En}}\right)}{\varepsilon_E(t^{**}_1) - \varepsilon_E(t^{**}_2)}. \quad (4)$$

The remaining constants E_{Ei} are obtained by the usual procedure of sequential subtraction [9].

After the separation of viscoelastic part of elongation from the experimental creep data, by analogy with the procedure stated above the constants $E_{P1}, E_{P2}, \ldots, E_{Pm}$ are obtained.

EXPERIMENTAL

Two suit textile fabrics were taken for the investigation as face components of fused systems: the woven fabric T (Table 1) and the knitted fabric K (Table 2). They were fused with the interlinings I1 and I2 on fusing device Stirovap, according to the recommended regimes of the interlinings' producers (Table 3).

Creep and creep recovery processes of the single face fabrics and interlinings as well as of fused systems T + I1, T + I2, K + I1, K + I2 were measured in uniaxial loading to the principal directions. The experiments were provided on the special relaxometer [4], developed in Kaunas University of Technology. Optical sensor was used to measure elongation of the specimen, and tensoresistor sensor to measure tensile force on it. During the entire test cycle digital values of specimen elongation or/and tension are obtained the step of 0.11 s. The relaxometer gauge length was 250 mm, the width of specimens – 50 mm.

Table 1. Structural characteristics of face woven fabric

Fabric code	Fibre constitution	Yarn linear density, tex		Number of threads per dm		Area density, g/m^2	Weave
		warp	weft	warp	weft		
T	PES	26	46	370	250	214	Derived twill

Table 2. Structural characteristics of face knitted fabric

Fabric code	Fibre constitution	Yarn linear density, tex		Stitch length, mm		Number of stitches per dm		Area density, g/m^2	Weave
		right stitches	left stitches	right	left	wales	courses		
K	Wool, PES	18	18	2.6	2.7	110×2	280+110	306	Rib jacquard

Table 3. Structural characteristics of warp-knitted fusible interlinings and fusing regimes

Fabric code	Fibre constitution	Weave	Inlay linear density, tex	Resin dots	Number of dots per cm^2	Area density*, g/m^2	Fusing regime		
							Temperature, ^{0}C	Pressure, kPa	Time, s
I1	Wool, PES	Combined with weft inlay	26	PA	52	50	135	25	20
I2	CV, PA		39	PA	49	71	145	25	30

Note: ∗ - including the resin dots

Three levels of the load (40 N, 45 N, and 50 N) were taken and they were somewhere between (36 – 45 %) of the breaking force of the weakest component. It was shown in [2], that namely within this region of loads all the deformation components appear.

The duration of creep period was 30 min, and it was equal to the duration of creep recovery period. From the creep and creep recovery curves the components (ε_T, ε_E, ε_{SL}, ε_P) of the total elongation (ε_B) were obtained. The development of tension on a single textile system component was also measured at constant total load on a system. In such cases the face fabric of the system was only assembled together with the interlining but not fused. It was obviously shown in our former investigation [4] that the omission of fusing in such cases has no appreciable influence on the system's behaviour. Other test conditions are indicated in [4].

RESULTS AND DISCUSSION

Creep and creep recovery curves of all investigated textile specimens are presented in Figure 3. It is apparently seen that for both the face fabrics and the interlinings a high mechanical anisotropy is characteristic. At the load 50 N the lengthwise/crosswise fast developing elongations (ε_S) of fabric T are 10.7 / 16.2 %; the alike elongations of knitted fabric K are 35.7 / 38.9 %, of interlining I1 are 11.1 / 19.7 %, and of interlining I2 are 15.1 / 7.8 %. Very important characteristic is fabric's creep elongation (ε_V) because when the system "face fabric+interlining" is under constant tensile load, the tension on less extensible system component comprises higher part of the total system load.

The corresponding changes in lengthwise/crosswise elongation of the fabrics during creep process are: T – 2.1 / 5.0 %, K – 12.8 / 20.4 %, I1 – 3.9 / 4.8 %, I2 – 4.5 / 3.0 %. Since the extensibility of the interlinings I1 and I2 are different and the different part of total constant system's load falls on each of them, the system of the face fabric fused with different linings possesses different extensibility (Fig. 4).

For the knitted fabric K which stretched highly during the load application time (0 – t_a), some difficulties arose in indicating the beginning time of creep process (instant t_a,

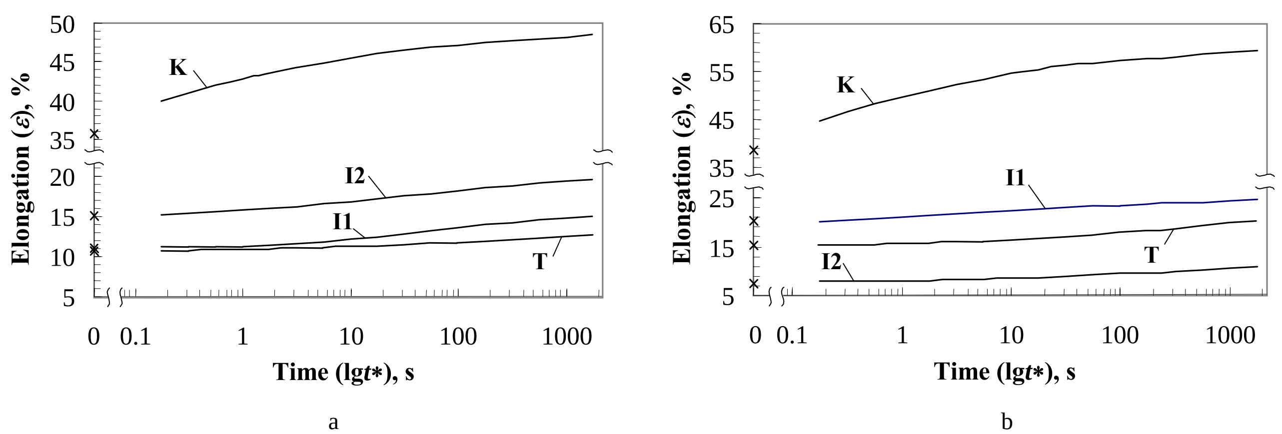

Fig. 3. Creep curves of the face fabrics and the interlinings used for the fusing at constant load F = 50 N applied lengthwise (a) and crosswise (b)

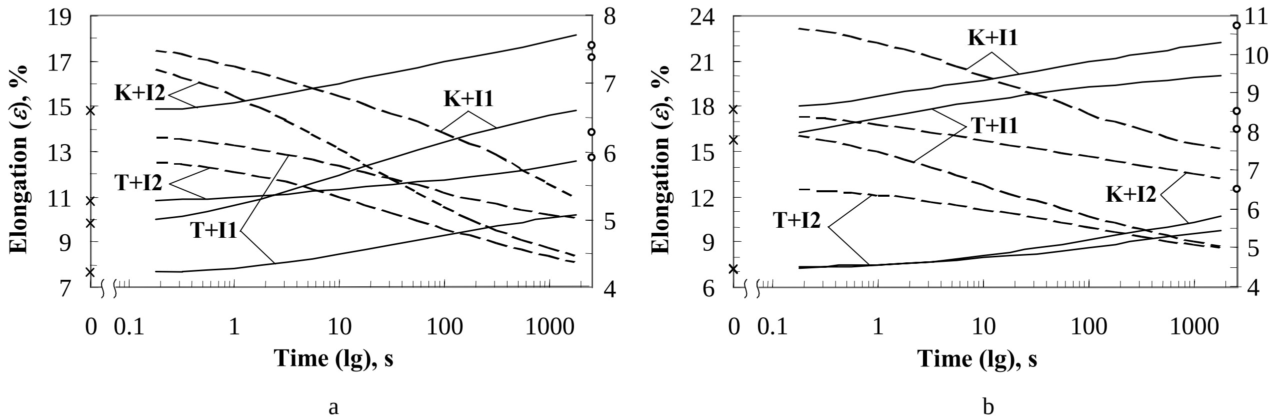

Fig. 4. Creep (——) and creep recovery (– – ·) curves of fused systems loaded lengthwise (a) and crosswise (b) (constant load F = 50 N); left scale for creep (× – at $t*$ = 0), right scale for recovery (o – at $t**$ = 0)

see Fig. 2), and in separating the immediate irreversible elongation (ε_{SL}) from the fast developing elongation (ε_S). For this fabric to obtain the value of immediate irreversible elongation the additional specimens were used. They were during the time interval ($0 - t_a$) loaded and straight away unloaded. After the short rest (3 ÷ 5 s) the measured residual elongation was considered as elongation ε_{SL}. So, the beginning of creep process of the fabric K was considered taking the value of the fast developing elongation from the relationship $(\varepsilon_S = \varepsilon_{SL} + \varepsilon_T)$.

With the increase of the total load (40 N, 45 N, and 50 N), the systems' total elongation (ε_B), fast developing elongation (ε_S) as well as creep amount (ε_V) increase, too. Nevertheless amount of this increase isn't equal or even proportional to the corresponding values of single components of the systems. The reason is that the tension, which falls on each system's component, differently increases with the increase of the total load (Table 4, Fig. 6). Higher tension was found fallen on the interlinings except the systems T+I2 lengthwise and T+I1 crosswise directions. Moreover, under constant load on a system the tensions on its components don't remain constant, but change in time $t*$ (Fig. 5, Table 4). In most cases it is found, that if the tension fallen on the particular component of the system is higher than the tension on the other component, it decreases in time. Nevertheless, the opposite direction is found with the system T+I2 loaded lengthwise and the system K+I1 loaded crosswise, where

Table 4. The elongation indices of textile fabrics systems and the tensions on the systems' individual components

Fabric system code	Total load, N	Tension*) on the system components, N		ε_B, %		D_T, %		D_E, %		D_{SL}, %		D_P, %	
		∧	>	∧	>	∧	>	∧	>	∧	>	∧	>
T+I1	40	9.3+30.7 11.7+28.3	38.4+1.6 37.4+2.6	7.5	17.6	49.3	58.0	9.4	15.3	32.0	20.5	9.3	6.2
	45	12.5+32.5 15.3+29.7	42.3+2.7 41.5+3.5	8.3	19.1	47.0	59.7	9.6	14.7	32.5	19.9	10.9	5.7
	50	13.7+36.3 18.7+31.3	44.3+5.7 43.2+6.8	10.2	20.0	38.2	59.5	12.8	15.0	36.3	20.0	12.7	5.5
T+I2	40	21.3+18.7 28.5+11.5	4.1+35.9 5.2+34.8	11.2	8.3	51.8	30.1	8.0	15.7	36.6	47.0	3.6	7.2
	45	26.7+18.3 32.1+12.9	4.8+40.2 6.5+38.5	11.9	8.9	49.6	34.8	10.1	15.7	37.0	40.4	3.3	9.1
	50	31.1+18.9 36.3+13.7	5.2+44.8 7.8+42.2	12.5	9.7	52.8	32.0	12.0	16.5	33.6	44.3	1.6	7.2
K+I1	40	2.0+38.0 3.2+36.8	11.9+28.1 11.2+28.8	10.0	19.9	51.0	50.8	18.0	15.1	24.0	30.2	7.0	3.9
	45	2.4+42.6 3.8+41.2	12.0+33.0 11.5+33.5	12.5	21.5	46.4	51.6	18.4	14.4	20.0	28.8	15.2	5.2
	50	3.0+47.0 5.1+44.9	13.2+36.8 12.4+37.6	14.8	22.2	48.6	51.3	20.3	14.9	17.6	28.8	13.5	5.0
K+I2	40	4.0+36.0 5.7+34.3	2.1+37.9 3.4+36.6	15.8	8.4	59.5	19.0	16.5	15.5	22.2	48.8	1.8	16.7
	45	5.1+39.9 6.3+38.7	2.6+42.4 3.9+41.1	17.2	10.2	58.1	20.6	16.3	14.7	22.1	47.1	3.5	17.6
	50	6.1+43.9 7.3+42.7	3.0+47.0 5.5+44.5	18.2	10.8	58.8	21.3	16.5	15.7	22.5	46.3	2.2	16.7

Notes: *) at $t*$ = 0 / at $t*$=1800 s. ∧ – loaded lengthwise; > – loaded crosswise.

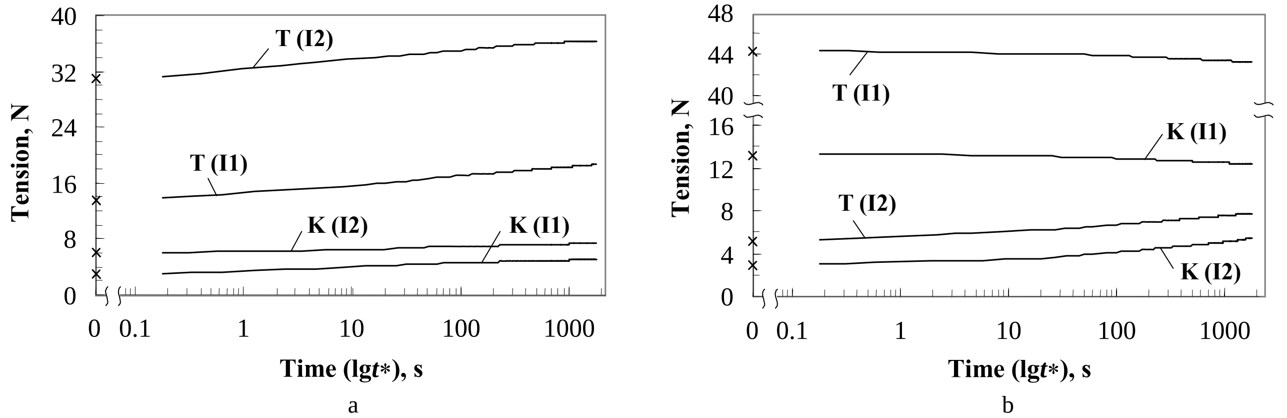

Fig. 5. The development of tension on the components T and K of the textile systems, loaded by force F = 50 N (the second component of the system is shown in the brackets): a – loaded lengthwise, b – loaded crosswise

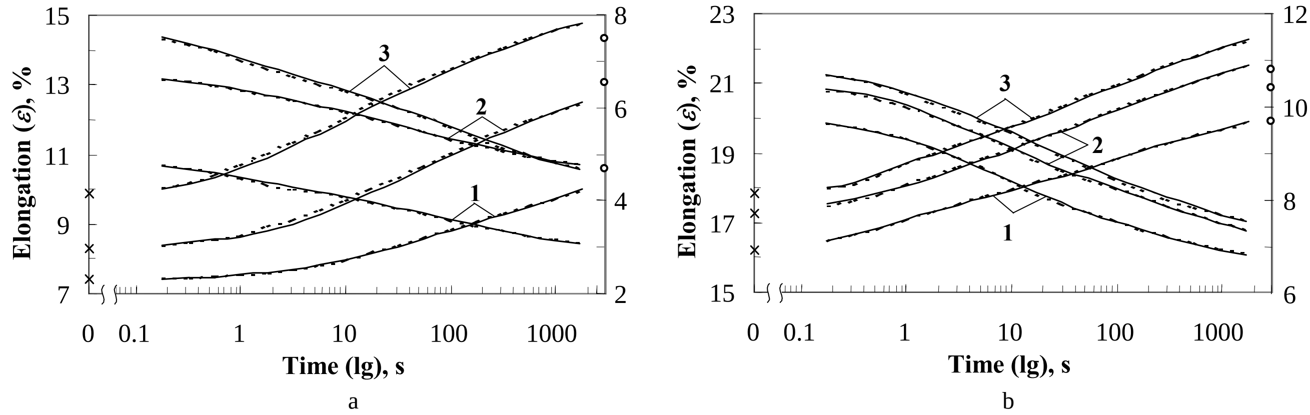

Fig. 6. Experimental (——) and theoretical (- - ·) creep and creep recovery curves of the system K+I1 loaded lengthwise (a) and crosswise (b); load: 1 – 40 N, 2 – 45 N, 3 – 50 N. Left scale for creep (× – at $t*$ = 0), right scale for recovery (o – at $t**$ = 0)

the component's tension increased in time. This feature needs more special investigations, nevertheless the matter exceeds the border of our present study.

The changes in components' tension throughout creep period comprise 6 – 20 % of the initial tension. The changes in the tension fallen on the system components can have influence on creep recovery of the systems and also on the values of partial elongation (ε_T, ε_E, ε_{SL}, ε_P) as well as of the relative values D_T, D_E, D_{SL}, D_P, calculated as a percentages of the total elongation ε_B (Table 4). The tendencies in their dependency on the total load rather differ from those of the single face fabrics and interlinings (Table 5). For example, with the increase of total load, relative part of elastic elongation (D_T) of single components decreases and the instantaneous part of irreversible elongation (D_{SL}) increases. Due to different levels of tension on single fabrics in the fused systems and, consequently, the different response to the tension, fused

Table 5. The elongation indices of face fabrics and interlinings

Fabric code	Load, N	ε_B, %		D_T, %		D_E, %		D_{SL}, %		D_P, %	
	∧ / >	∧	>	∧	>	∧	>	∧	>	∧	>
T	40	11.6	17.2	60.3	36.0	9.5	18.0	28.4	43.0	1.7	3.0
	45	12.3	20.2	52.8	32.2	12.2	19.3	32.5	46.5	2.5	2.0
	50	12.8	21.2	53.1	31.1	14.8	21.2	30.5	45.3	1.6	2.4
K	40	44.6	51.3	61.9	58.3	19.1	18.3	12.1	13.1	6.9	10.3
	45	47.3	56.0	61.7	53.6	18.6	19.6	13.1	13.6	6.6	13.2
	50	48.5	59.3	59.8	51.1	20.0	21.1	13.8	14.5	6.4	13.3
I1	40	9.9	23.3	49.5	63.5	14.1	12.0	29.3	17.2	7.1	7.3
	45	13.8	23.7	38.4	48.1	20.3	14.8	34.0	32.5	7.3	4.6
	50	15.0	24.5	30.0	44.9	24.0	15.1	44.0	35.5	2.0	4.5
I2	40	16.8	7.8	60.7	17.9	13.1	14.1	22.6	62.8	3.6	5.1
	45	17.4	9.6	56.3	17.7	14.4	17.7	27.0	55.2	2.3	9.4
	50	19.6	10.8	49.5	17.6	17.3	18.5	27.6	54.6	5.6	9.3

Note: ∧ – loaded lengthwise; > – loaded crosswise.

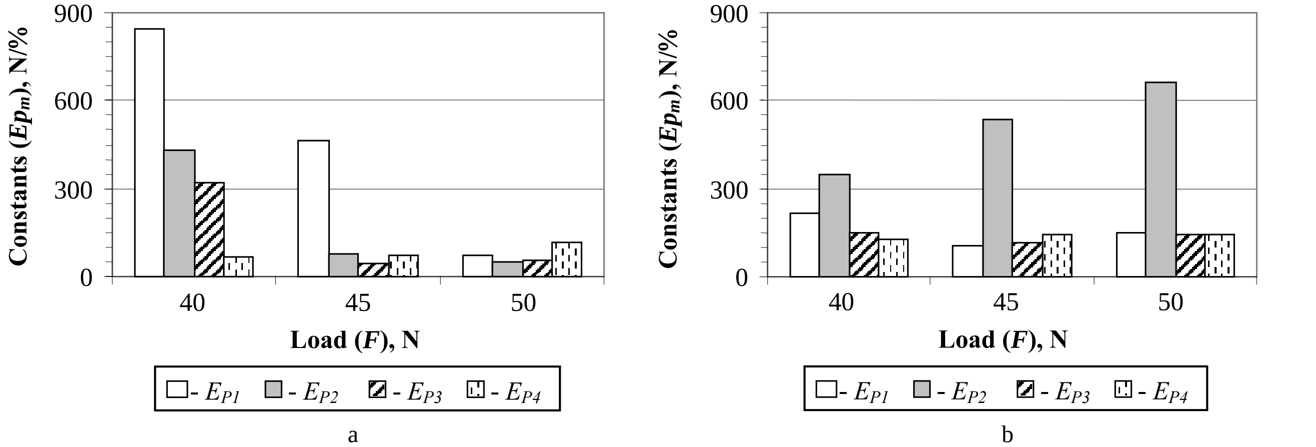

Fig. 7. Elasticity constants of the Voigt elements of the model representing progressively developing irreversible elongation of the system K+I1: a – loaded lengthwise, b – loaded crosswise

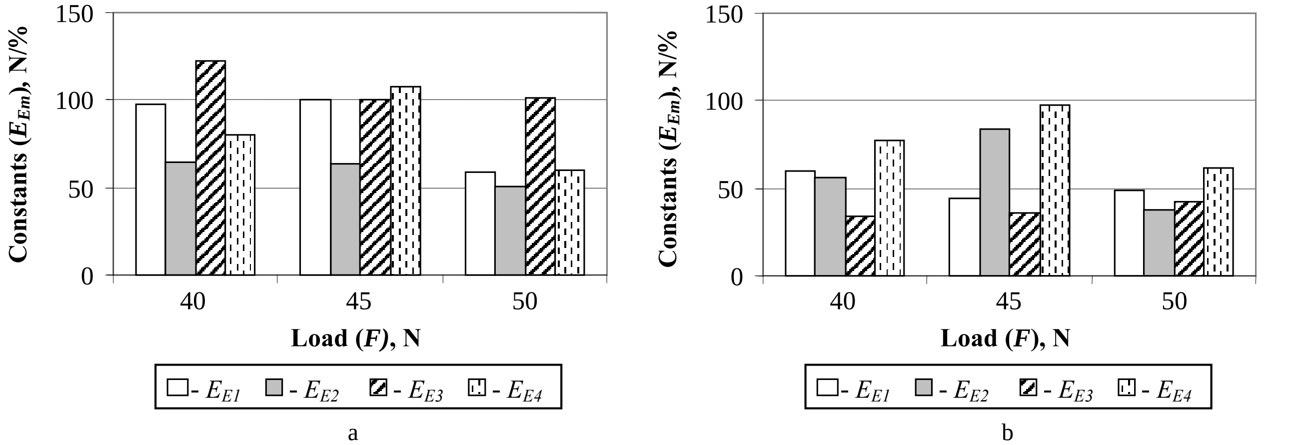

Fig. 8. Elasticity constants of the Voigt elements of the model representing viscoelastic elongation of the system K+I1: a – loaded lengthwise, b – loaded crosswise

systems show no such obvious elongation dependency of the relative components' on the level of total load. It is possible to see the less or more expressed increase in the relative component D_E of viscoelastic elongation with the increase of total load on the system.

The constants of the proposed model calculated from the experimental creep and creep recovery curves of the fused fabric system K+I1 (Fig. 6) and their dependency on the total load level are shown in Fig. 7, Fig. 8, and Table 6.

Table 6. The elasticity constants of the model's single springs

System code	Load, N	E_T, N/%		E_{SL}, N/%	
		∧	>	∧	>
K+I1	40	7.8	3.9	17.5	6.7
	45	7.8	4.1	18.0	7.3
	50	7.0	4.4	19.1	7.8

Note: ∧ – loading lengthwise; > – loading crosswise.

As it is seen, both the generalized Voigt elements representing viscoelastic progressively developing irreversible ("plastic") behaviour of the systems possess four retardation times, i.e. $n = m = 4$. With the increase of the total load on the system, in lengthwise direction the role of shorter retardation times to the plastic behaviour obviously decreases while in crosswise direction it increases (Fig. 7).

The role of different retardation times to the viscoelastic behaviour is not so evidently seen (Fig. 8). Referring to the Fig. 6, the calculated creep and creep recovery curves are very close to those experimental curves – the highest differences taking place at the very beginning of the processes don't exceed 1.5 % of the respective values of the experimental elongation values. Therefore it is possible to state that creep and creep recovery processes of the fused textile systems are in good way and in high scale represented by the proposed model.

CONCLUSIONS

The mechanical model is proposed to represent creep and creep recovery of textile fabrics and/or their systems. The model possesses regular discrete spectra of retardation times to describe both the reversible and the gradually developing irreversible ("plastic") deformation. The good correspondence of calculated and experimental data on creep and creep recovery enables the authors to maintain that the proposed model is appropriate for the analysis of the time-dependent mechanical behaviour of the textile fabrics and the fused systems made up of them.

With the increase the total load on the fused fabric systems the values of total, fast developing and creep elongations of the textile fabrics and the systems made up of them increase as well.

The high mechanical anisotropy of the face fabrics and the interlinings used for fusing as well as different values of the elongation components at constant load on the fused system are very important while estimating the system's behaviour: less extensible component of the system takes the higher part of total load and so influences the extensibility and recovery of the system.

The level of tension on the individual components of the fused system, and the direction of tension development in time has significant influence on the values of the total elongation's components.

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