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Relationship between mechanical properties of bilayer textile systems and their components

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Abstract. The goal of this research was to define the relationship between the mechanical properties of fused bilayer textile systems and their constituent layers, i.e. fabrics and fusible interlinings. The objects of investigation were four samples of broken twill outer fabric different in thickness (1.01–2.28 mm) and mass per square metre (222–398 g/m^2), and two types of fusible interlinings: nonwoven with longitudinal threads and warp knitted. Fused bilayer textile systems were created by changing the orientation of the fusible interlining by 0°, 45°, and 90° in respect to the outer fabric's warp direction. Mechanical properties (tensile, shear, bending, and surface properties) of fused textile systems and their components were determined using KES-F automated testing devices. The relationships $z = z(x, y)$ between fused textile systems' mechanical parameters (z) and parameters of the outer fabrics (x), as well as parameters of fusible interlinings (y) in 0°, 45°, and 90° orientations were defined. The obtained theoretical relationships were confirmed experimentally by finding proper mechanical properties of fusible interlinings (y) on the basis of which bilayer textile systems with mechanical properties (z) falling into the allowable value range of the KES-F quality chart could be composed. Selection of compatible components for fused textile systems with certain mechanical parameters allows avoiding problems in garment manufacturing processes and predicting the appearance and quality of the final textile product.

Key words: material science, mechanical properties, fused textile system, KES-F, layer orientation.

INTRODUCTION

The optimal combination of the components of multi-layer textile structures is important for the behaviour, appearance, and quality of final textile products. A fused textile panel as a joined bilayer textile system has specific properties in respect to the shell fabric and interlining. Thus for the selection of a proper interlining it is important to know not only the mechanical properties of the whole fused panel but also the mechanical properties of the built-in shell fabric and interlining [1]. However, the choice of the most suitable fusible interlining for a specific outer fabric or a specific range of outer fabrics is not an easy task [2].

It is known that the properties of the fused panel can be predicted on the basis of specified mechanical and physical properties of the shell fabric and fusible interlining [3]. The relationship between certain mechanical properties (tension stiffness, residual extension, bending stiffness, and shear stiffness) of fused composites and those of the outer fabric and fusible interlining were studied by Shishoo et al. [4], who found that the mechanical properties of a composite can be predicted on the basis of the corresponding properties of its constituent components. Linear regression analysis was applied and a good agreement between experimental and calculated properties was obtained.

Fan et al. [2,5,6] suggested a set of equations to predict the low stress mechanical behaviour of fused textile systems on the basis of the mechanical properties of the outer fabrics and fusible interlinings. It was found

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that in order to achieve a superior handle and drape for the fused areas of garments the mechanical properties of the fused composite must fall within a certain value range [5]. Besides, the type and quality of both – the shell fabric and the fusible interlining – must be harmonized [7]. Fan et al. [5,6] defined the desirable range of the mechanical properties of fused textile systems by integrating experimental and sensory investigations and developed a new method for proper selection of the fusible interlining for different outer fabrics based on FAST fabric objective measurement technology.

A different approach to this problem is the method of machine learning, which provides a successful technique to predict the properties of new fused panels on the basis of the existing ones [7]. Machine learning from a given set of examples with the tree structured regression method is used for building up the regression tree algorithm [1]. Examples are described by the set of attributes, where each attribute has its possible set of values. However, regression trees are limited for particular types of fabrics; therefore, this research still needs new data to be added to the existing database [7]. On the other hand, a machine learning method for the prediction of a fabric behaviour refers to a wide range of fabric behaviour studies. On the basis of the input data (parameters of mechanical properties) and input knowledge (fabric behaviour responses) it offers the prediction of fabric behaviour in garment manufacturing processes [8].

Recently research in this area was conducted by Kim et al. [9], who verified the method of fused panels bending rigidity prediction based on the laminate theory, but further development of this model is necessary for more accurate results. For investigating mechanical properties at low-stress level loads KES-F and FAST systems are used, but these apply different testing principles; therefore, to use the proposed equations results of different researchers should be recalculated. In our latest research [10] we investigated the relationship between KES-F and FAST bending rigidity parameters for heavy-weight fabrics and compared it with the results provided by different references. We observed that a more reliable relationship for the conversion of KES-F bending rigidity values into FAST bending rigidity values can be obtained if a group of fabrics with similar characteristics is purposively selected. The groups can be composed of fabrics of the same weave type or of the same fabric samples exposed to different final treatment conditions.

According to Jeong and Kim [11], the optimal interlinings for unknown fabrics can be properly selected through mapping and applying the method of local approximation. Their paper reports about the development of an integrated tool consisting of an artificial neural network and a subjoined local approximation technique for application in the sewing process, especially for selecting optimal interlinings for worsted fabrics. The artificial neural network model successfully established the prediction model for fused textile system quality grades, thus providing fashion designers with a tool to predict the final quality grade of a fused textile system even before face fabrics are fused with the interlinings [12].

The end use of a fused panel drape is dependent on the orientation of the shell fabric and the fusible interlining, as well as on the constructional and mechanical properties of the shell fabric and the fusible interlining separately [3,12,13]. The effect of the layer orientation upon textile systems' tensile and shear behaviour was investigated in our earlier works [14–16]. Tensile and shear properties were defined with an KES-F system, and on their basis recommendations were given for achieving the desirable mechanical reaction of the fused system. The proper selection of the interlining is very important from the standpoint of the quality properties of the produced garments [3].

The goal of this research was to define theoretical relationships between the mechanical parameters of fused textile bilayer systems and of their constituent parts, i.e. of outer fabrics and fusible interlinings orientated in 0°, 45°, and 90° directions, and to confirm them experimentally by comparing the obtained results with the allowable value range of the KES-F quality chart.

MATERIALS AND METHODS

Fused bilayer textile systems composed of woven outer fabrics and interlinings were investigated. Tests were performed with four samples (ST8, ST10, SM, and R) of broken twill fabric reinforced in the weft direction (Table 1) and two interlinings: nonwoven with longitudinal threads P1 and warp knitted TR1 (Table 2). The selected outer fabrics are mainly used as winter/autumn suiting materials. The thickness of the outer fabrics varied in the range 1.01–2.28 mm and the mass per square metre varied in the range 222–398 g/m^2.

The investigated interlinings are not stretchable in the longitudinal direction but are stretchable in the transverse direction; therefore, the changes of their orientation provide fused textile systems with different mechanical properties. The fused bilayer textile systems were formed by changing the orientation of interlining: 0° (system PAR), 45° (BIAS), and 90° (PER) in respect to the outer fabric's warp direction (Fig. 1) and following the fusing conditions presented in Table 2.

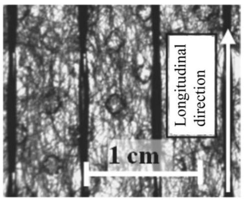
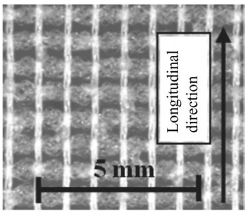
The mechanical properties (tensile, shear, and bending) of the bilayer textile systems and their components were determined using KES-F automated testing devices. Tests were carried out with 20 cm × 20 cm specimens. For tensile property determination the specimen was stretched at a constant displacement rate of

Table 1. Characteristics of the tested outer fabrics [14]

Code	Composition[a]	Mass per sq. m W, g/m^2	Thickness T_m, mm	Density[b], 1/cm		Linear density[c], tex	
				D_{warp}	D_{weft}	LD_{warp}	LD_{weft}
ST8	80% wool, 20% PA	246	1.16	9.5	8.7	120	117
ST10	80% wool, 20% PA	245	1.01	10.4	10.2	98	109
SM	50% wool, 50% AC	222	1.55	16.2	12.0	63	70
R	80% wool, 20% PES	398	2.28	16.5	12.9	110	114

[a] PA – polyamide, AC – acetate, PES – polyester.
[b] D_{warp} – density in warp direction, D_{weft} – density in weft direction.
[c] LD_{warp} – linear density in warp direction, LD_{weft} – linear density in weft direction.

Table 2. Characteristics of tested interlinings

Code	View	Composition[a]		Mass per sq. m W, g/m^2	Thickness T_m, mm	Density, 1/cm	Adhesive mesh, dots/cm^2	Regime of fusing[b]
		Base	Adhesive					
P1		100% PES	PA	38	0.56	No. of threads in 1 cm = 2.4	52	τ = 15 s; t = 150 °C
TR1		100% PES	PA	35	0.40	Coarse: 14; Wale: 13	118	τ = 15 s; t = 145 °C

[a] See Table 1 for abbreviations.
[b] τ – fusing duration, t – temperature.

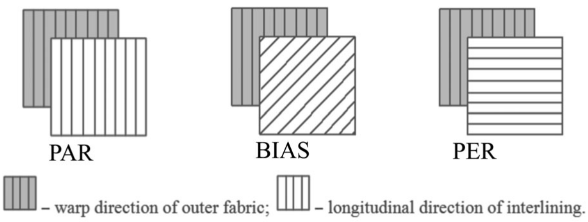


Fig. 1. Types of fused textile systems: PAR – the outer fabric warp direction and fusible interlining longitudinal direction are parallel; BIAS – fusible interlining forms bias 45° angle with the outer fabric warp direction; PER – the outer fabric warp direction and fusible interlining longitudinal direction are perpendicular [14].

0.2 mm/s until the force of $F = 490$ N/m was reached. From the tensile load–tensile strain curve (Fig. 2) tensile strain EMT (%), tensile resilience RT (%), tensile curve linearity LT (–), and tensile energy WT (Nm/m^2) were determined [17].

In the KES-F system, the principle of pure bending is applied whereby specimens are bent in an arc of constant curvature, which is changed continuously. From the experimental curve (Fig. 3) the bending rigidity B (10^{-4} Nm^2/m) and bending hysteresis $2HB$ (10^{-2} Nm/m) were defined [17].

The shear behaviour of fused bilayer textile systems and their constituent components could be characterized by shear stiffness (G, N/m × degrees), shear hysteresis at the shear angle of 0.5° ($2HG$, N/m) and hysteresis at the shear angle of 5° ($2HG5$, N/m) determined from the shear force–shear angle curve (Fig. 4). This curve is obtained by applying the shear force for a sample at a constant velocity of 0.2 mm/s, in the range of 8° to –8° [17].

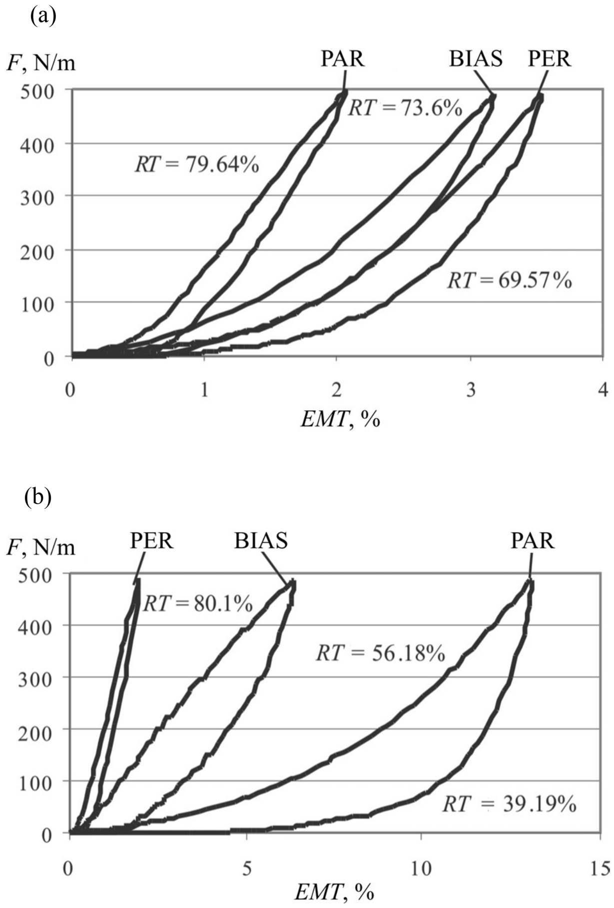


Fig. 2. Tensile hysteresis of fused textile system ST10 + P1, deformed in longitudinal (a) and transverse (b) directions. *F* – force, *RT* – tensile resilience, *EMT* – tensile strain.

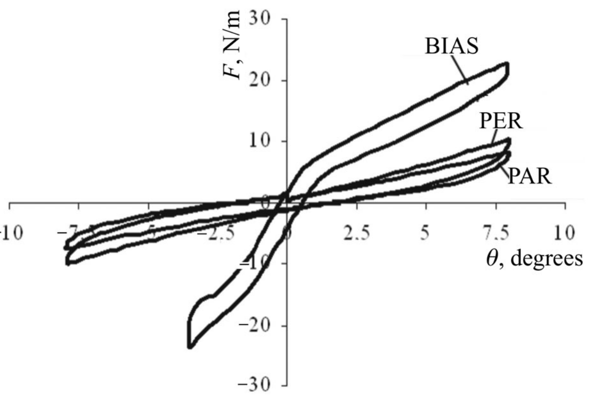


Fig. 3. Shear hysteresis of fused textile system ST8 + TR1 deformed in transverse direction. *F* – force, θ – shear angle.

For the investigations nine mechanical parameters of fused textile systems (Table 3) were analysed for four outer fabrics and two fusible interlinings oriented in three different directions (0°, 45°, and 90°). At the same

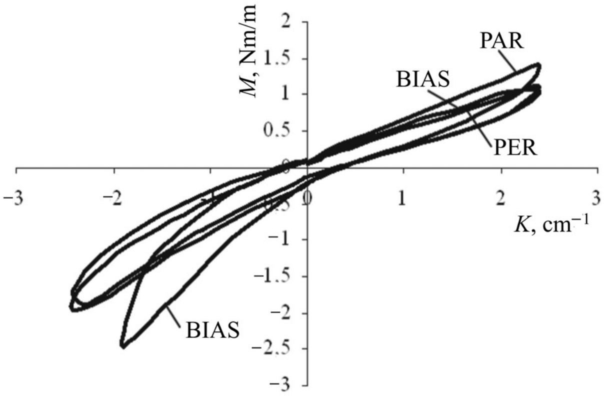


Fig. 4. Bending hysteresis of fused textile system ST8 + TR1 deformed in transverse direction. *M* – bending momentum per unit width, *K* – curvature.

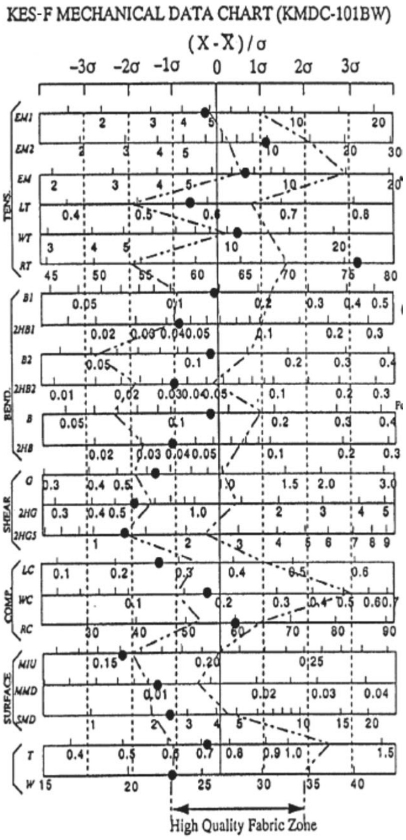
time the fused bilayer textile systems were tested in two directions: longitudinal and transverse. So, altogether 54 cases were analysed.

At the first stage of the investigations the relationships $Z = f(x, y)$ between the experimentally found mechanical parameters of fused textile systems (Z) and the parameters of the outer fabric (x) and fusible interlining (y) in different orientations (0°, 45°, and 90°) were determined. For this *Table Curve 3D* software was used and equations with the highest coefficients of determination were analysed. The coefficient of determination R^2 shows which part of the investigated parameters' dispersion is covered using the applied mathematical model. The mathematical model is more acceptable if it better overlays the scatter of the investigated parameter.

Several linear, power, and logarithmic functions (having up to six coefficients *a*, *b*, *c*, *d*, *e*, *f*) with the highest determination coefficients R^2 were chosen from many proposed equations. Later, on the basis of experimental equations, theoretical values z were calculated for all tested bilayer textile systems composed of each outer fabric in combination with three different interlining orientations. Here mechanical parameters of the investigated outer fabrics (x) and mechanical parameters of the investigated interlining in three different directions (y) were known. The results of the calculations of theoretical z values were compared with experimental Z values, i.e. with mechanical properties of the corresponding bilayer textile system defined by KES-F testing devices. Errors $\Delta = Z - z$ between experimentally defined (Z) and theoretically calculated (z) values were computed and relative errors δ were calculated:

$$\delta = \frac{\Delta}{z}. \qquad (1)$$

Table 3. KES-F mechanical data chart for the ideal suiting (winter/autumn) [18] and the limits of high quality zone for the investigated mechanical parameters

<table>
<tr><td rowspan="16">
</td><td colspan="2" rowspan="2">Mechanical parameter</td><td colspan="2">High quality zone</td></tr>
<tr><td>min</td><td>max</td></tr>
<tr><td>EMT, %</td><td>Tensile deformation at 490 N/m tensile load</td><td>7.60</td><td>16.0</td></tr>
<tr><td>LT, –</td><td>Linearity of tensile curve</td><td>0.50</td><td>0.65</td></tr>
<tr><td>WT, Nm/m^2</td><td>Tensile energy</td><td>9.00</td><td>13.0</td></tr>
<tr><td>RT[a], %</td><td>Tensile resilience</td><td>54.0</td><td>70.0</td></tr>
<tr><td colspan="4">[a] $RT < 54$: difficulties in steam-press operations [19]; difficult control in sewing processes; poor appearance [20]. $RT < 70$: difficulties in cutting process [19]; difficulties in overfeed operations [20].</td></tr>
<tr><td>B[b], 10^{-4} Nm^2/m</td><td>Bending rigidity</td><td>0.07</td><td>0.19</td></tr>
<tr><td colspan="4">[b] $B < 0.04$: seam puckering; produced seams are not smooth [21]. $B > 0.19$: stitching holes and stitches of uneven length; problems in sticking sewing parts together, creasing of one or both components at the seam; poor ability to stick to the contour in guiding curved lines; poor shaping ability, e.g. inability to be shaped by ironing [21].</td></tr>
<tr><td>2HB, 10^{-2} Nm/m</td><td>Bending hysteresis</td><td>0.03</td><td>0.08</td></tr>
<tr><td>G[c], N/m°</td><td>Shear stiffness</td><td>0.55</td><td>1.00</td></tr>
<tr><td colspan="4">[c] $G < 0.55$: distortions in laying: creasing, straight and oblique distortions; considerable fabric instability in cutting; considerable seam puckering; poor appearance of the inset sleeve [21]; difficulties in overfeed operations [20]; poor appearance [20]. $G > 1$: poor sticking together of the sewn parts, creasing of one or both parts at the seam; poor shaping ability, e.g. inability to be shaped by ironing [21]; difficulties in overfeed operations [19,20].</td></tr>
<tr><td>2HG, N/m</td><td>Shear hysteresis at a shear angle of 0.5°</td><td>0.60</td><td>1.40</td></tr>
<tr><td>2HG5, N/m</td><td>Shear hysteresis at a shear angle of 5°</td><td>1.30</td><td>2.40</td></tr>
</table>

In addition, for error evaluation the sum of squares $\Sigma\Delta^2$ was calculated, the smaller value of which shows the more proper equation. Thus, the selected functions were evaluated by the determination coefficient and by the value of errors.

At the second stage of investigations the opposite relationship was analysed, i.e. what should the mechanical properties of the fusible interlining (y) be to achieve that the mechanical properties of the fused bilayer textile system (z) fell into the allowable value range of the KES-F quality chart when the outer fabric's (x) properties are known. For this reason the variable y was expressed from the equation $z = f(x, y)$ taking into account that z values could not exceed the limits of high quality zones (Table 3). Critical limits of this zone are based on the KES-F quality chart, created in collaboration of researchers and industry experts with the purpose of producing high quality textile materials [18].

The presented limits of quality zones for certain mechanical parameters are stated for winter/autumn suiting materials. In this research these limits were used for the selection of the fusible interlining to compose a high quality fused bilayer textile system with a known outer fabric on the basis of nine mechanical parameters.

RESULTS AND DISCUSSION

In this research theoretical relationships between mechanical parameters of a fused textile system (z) and its constituent parts, i.e. outer fabric (x) and fusible interlining (y), were defined. For this purpose 54 equations with the highest determination coefficients R^2, the smallest relative errors δ, and the smallest sum of squares $\Sigma\Delta^2$ were selected from 211 equations tested. In our investigations several linear, power, and logarithmic functions were used instead of one common function because the main task was to find out the best equation for each relationship with the smallest error that would ensure accurate calculation of mechanical parameters in order to get fused textile systems of the highest quality. For this reason the selected equations that had the highest coefficient of determination R^2 were additionally checked by the sum of squares $\Sigma\Delta^2$ and by relative error δ. The most suitable equation for the calculation of the mechanical parameters of a bilayer system was considered to be the one that had the smallest sum of squares $\Sigma\Delta^2$.

Equations (2)–(4) are presented as an example of the best function selection for the calculation of tensile resilience *RT* parameter. All three equations have high coefficients of determination R^2 (>0.94) and small values of relative errors δ (0.00–0.07). Nevertheless, a significant difference exists between the sums of squares $\Sigma\Delta^2$, especially in Eq. (3), which has R^2 higher than Eq. (4).

Thus, the selection of the most suitable equation only by the highest R^2 when relative errors are small does not guarantee the best results. The smallest sum of squares $\Sigma\Delta^2$ ensures the smallest errors and is the most suitable function for the prediction of the mechanical parameters of bilayer systems. Considering all this, Eq. (2) from the presented example was selected as the most suitable for further calculations of tensile resilience *RT* parameter.

$$z = 87.83 - \frac{43877}{x} + \frac{1318662}{x^2} + 4.09y, \qquad (2)$$

$$R^2 = 0.959;\ \Sigma\Delta^2 = 10.97;\ \delta = 0.00{-}0.03;$$

$$z = 308.66 - 15.38x + 1.45y + 0.077x^2 - 0.011y^2 + 0.072xy, \qquad (3)$$

$$R^2 = 0.947;\ \Sigma\Delta^2 = 87.50;\ \delta = 0.01{-}0.07;$$

$$z = 7.11 - 9.35x + 0.077x^2 - 4.09y, \qquad (4)$$

$$R^2 = 0.940;\ \Sigma\Delta^2 = 16.27;\ \delta = 0.00{-}0.04.$$

The described method was applied to find the most accurate and suitable equations also for the rest of the investigated mechanical parameters. In this research theoretical relationships between the mechanical parameters of fused textile systems and the mechanical parameters of their constituent parts are presented for three mechanical characteristics: tensile resilience *RT*, shear resistance *G*, and bending rigidity *B*.

One of the most important tensile parameters is the tensile resilience *RT*, which is the ratio of the energy retained in the textile material in the loading/unloading cycle. The higher the resilience *RT*, the higher is the stability of the fused system and the better it keeps its own original shape. A smaller area of hysteresis shows a higher resilience *RT* (Fig. 2).

It can be also seen that the interlining direction in fused textile systems (PAR – 0°, BIAS – 45°, or PER – 90°) affects the shape of tensile hysteresis more significantly when the systems are stretched in transverse direction (Fig. 2b) than in the case they are stretched in the longitudinal direction (Fig. 2a). This proves that for different stretch directions separate equations are required. More detailed research concerning the influence of layer orientation upon textile systems' resilience properties is presented in our earlier paper [14]. Resilience *RT* of fused textile systems (z) with different orientation of the interlining (y) can be calculated using the equations presented in Table 4. Determination coefficients of these functions are high $(R^2 = 0.69{-}0.99)$, relative errors are small $(\delta = 0.00{-}0.05)$, but the sums of squares $\Sigma\Delta^2$ are comparatively high (2.86–11.2) due to high values of the resilience parameter.

Table 4. Theoretical equations for the calculation of fused textile systems' tensile resilience *RT* (*z*) from its components: the tensile resilience of the outer fabric (*x*) and of the fusible interlining of different orientations (*y*)

System	Equation	R^2	$\Sigma\Delta^2$	δ
	RT in the longitudinal direction:			
PAR (0°)	$z = 87.8 - \frac{43900}{x} + \frac{1320000}{x^2} + 4.09y$	0.959	11.2	0.00–0.03
BIAS (45°)	$z = 24.5 - 2.38x + 0.025x^2 + 2.27y$	0.965	8.75	0.00–0.03
PER (90°)	$z = -771 + 0.879x + 230\ln y$	0.958	10.8	0.00–0.05
	RT in the transverse direction:			
PAR (0°)	$z = -122 + 0.813x + 4.43y$	0.689	8.32	0.02–0.03
BIAS (45°)	$z = 406 - 15.7x + 0.168x^2 + 0.336y$	0.769	3.43	0.00–0.02
PER (90°)	$z = -765 + 18.7x - 0.213x^2 + 5.11y$	0.992	2.86	0.00–0.02

Shear properties are important in many practical applications. Shear mechanism is one of the essential properties influencing the draping, pliability, and handling of textile materials. In our research shear parameters were investigated on the basis of shear hysteresis curves (Fig. 3), which show significant differences in the case various orientations of interlining are used, especially 45° orientation (system BIAS). So, the necessity to use separate equations for different interlining directions is validated. More detailed research concerning the influence of layer orientation upon textile systems' shear properties is presented in our earlier paper [16].

The equations for the calculation of fused textile systems' shear rigidity G (z) from shear rigidities (x) and (y) of their constituent components are presented in Table 5 separately for the longitudinal and transverse directions. Determination coefficients of these functions are very high ($R^2 = 0.83–0.99$), relative errors are comparatively high ($\delta = 0.00–0.23$), but the sums of squares are comparatively small ($\Sigma\Delta^2 = 0.13–1.99$).

The character of bending hysteresis curves and shear hysteresis curves is similar (Figs 3 and 4), but the effect of interlining orientation upon fused textile systems' bending parameters is different. If the shear rigidity G is the highest with bias orientation of interlining, the bending rigidity B is the highest with the longitudinal orientation of interlining (Fig. 4, system PAR). The bias orientation of interlining stiffens the fused system but less than the longitudinal orientation and more than the transverse orientation.

The theoretical equations for the calculation of the bending rigidity B of fused textile systems with different interlining orientations are presented in Table 6. The determination coefficients of these functions are the highest ($R^2 = 0.99–1.00$), relative errors are medium ($\delta = 0.00–0.16$), and the sums of squares are very small ($\Sigma\Delta^2 = 0.001–0.06$).

Table 5. Theoretical equations for the calculation of a fused textile system's shear rigidity G (z) from its components: the shear rigidity of the outer fabric (x) and of the fusible interlining of different orientation (y)

System	Equation	R^2	$\Sigma\Delta^2$	δ
	G in the longitudinal direction:			
PAR (0°)	$z = -0.292 + \frac{2.13}{x} - \frac{0.915}{x^2} + 1.71y$	0.979	0.29	0.00–0.12
BIAS (45°)	$z = -87.3 + 338x - 465x^2 + 209x^3 + 5.12y$	0.963	0.77	0.01–0.11
PER (90°)	$z = -22.3 + 90.5x - 115x^2 + 48.1x^3 + 1.52y$	0.994	0.13	0.01–0.22
	G in the transverse direction:			
PAR (0°)	$z = -2.56 + 9.21x - 5.92x^2 + 1.13y$	0.974	0.32	0.02–0.23
BIAS (45°)	$z = 4.99 - 18.3x + 16x^2 + 1.93y$	0.828	1.99	0.03–0.13
PER (90°)	$z = -1.03 + 4.45x - 2.64x^2 + 1.94y$	0.987	0.22	0.01–0.14

Table 6. Theoretical equations for the calculation of a fused textile system's bending rigidity B (z) from its components: the bending rigidity of the outer fabric (x) and of the fusible interlining of different orientation (y)

System	Equation	R^2	$\Sigma\Delta^2$	δ
	B in the longitudinal direction:			
PAR (0°)	$z = 0.022 + 4.74x - 1.82x^2 + 0.336y$	0.987	0.06	0.01–0.12
BIAS (45°)	$z = (0.099 + 1.3x + 20.8y)/(1 - 0.447x - 8.67y)$	0.999	0.01	0.00–0.07
PER (90°)	$z = (0.24 + 1.94x + 13.4y)/(1 - 0.52x + 30.4y)$	1.000	0.001	0.00–0.04
	B in the transverse direction:			
PAR (0°)	$z = (0.199 + 1.1x + 6.52y)/(1 - 1.58x + 9.99y)$	1.000	0.001	0.00–0.04
BIAS (45°)	$z = (0.113 + 0.578x + 17y)/(1 - 1.72x + 0.115y)$	0.999	0.003	0.00–0.07
PER (90°)	$z = (0.236 + 1.47x + 4.49y)/(1 - 1.5x + 2.19y)$	0.993	0.03	0.00–0.16

In the second part of investigations preferable mechanical parameters for fusible interlinings were calculated. On the basis of these parameters most suitable interlining can be selected to create a fused textile bilayer system of good quality. To set the limits of recommended parameters of fusible interlining ($y_{\min}$) and ($y_{\max}$) the spreadsheet of the 54 selected functions was used. Here (x) designated certain mechanical parameters of the investigated outer fabrics, ($z_{\min}$) and ($z_{\max}$) were the preferred limits of certain mechanical parameters of a fused bilayer textile system according to the KES-F quality chart (Table 3). When the outer fabric's mechanical parameters are input into this spreadsheet, preferable intervals of mechanical parameters of fusible interlinings are calculated. If a selected fusible interlining does not fit into the calculated intervals, information about the expected problems in the tailorability and garment appearance is presented next to the parameter. This information warns the manufacturer about the potential troubles.

Further the process of preferable interlining selection as a separate case study will be demonstrated for fused bilayer textile systems created with the outer fabric SM and interlinings P1 and TR1 in respect to three mechanical properties, i.e. the tensile resilience RT, %; bending rigidity B, 10^{-4} Nm^2/m; and shear stiffness G, N/m°.

Mechanical parameters (x) tensile resilience RT, bending rigidity B, and shear stiffness G of the outer fabric SM in warp and weft directions defined with KES-F testing devices are presented in Table 7. The same mechanical parameters in three different directions (longitudinal, transverse, and bias) were defined for P1 and TR1 interlinings (Table 8). The outer fabric SM does not fit well into the quality zones of the indicated mechanical parameters (Table 3) because the mean values of tensile resilience RT and shear stiffness G do not reach their minimal preferable limits ($RT < 54\%$ and $G < 0.55$ N/m°). Only bending stiffness B is in the high quality zone (0.07–0.19 10^{-4} Nm^2/m).

Table 8 presents the values of fusible interlinings' mechanical parameters ($y_{\min}$) and ($y_{\max}$) calculated according to the functions defined earlier (Tables 4–6) with showing the limits of the quality zones for interlining selection. It can be seen that the warp knitted interlining TR1 is more suitable than the nonwoven interlining P1 with longitudinal threads for the system stretched in the longitudinal direction, because its tensile resilience RT in PAR (0°), BIAS (45°), and PER (90°) directions falls into the required limits (in bold). This can also be seen for the same system stretched in the transverse direction when the TR1 interlining is orientated in PER (0°) direction (in bold). This means that a suitable interlining can perfect the tensile behaviour of the outer fabric SM because without an interlining its tensile resilience RT did not reach the minimal preferable value of 54% (Table 6). The same phenomenon can be observed for the shear stiffness G, but only for the system PAR with parallel orientation.

Table 7. Mechanical parameters (x) of the outer fabric SM defined with KES-F testing devices

Mechanical parameter	Outer fabric SM		
	Warp	Weft	Mean
RT, %	54.81	46.54	50.68
B, 10^{-4} Nm^2/m	0.13	0.08	0.11
G, N/m°	0.51	0.48	0.50

Table 8. Example of TR1 interlining selection for the fused system with the outer fabric SM. Boldface highlights parameters that are within the required limits

Mechanical parameter	System	Recommended interval for interlining in systems longitudinal direction		Interlining			Recommended interval for interlining in systems transverse direction		Interlining		
		$y_{\min}$	$y_{\max}$	Direction	P1	TR1	$y_{\max}$	$y_{\max}$	Direction	P1	TR1
RT, %	PAR	80.14	84.05	long.	85.20	**82.90**	31.19	34.80	trans.	–	29.70
	BIAS	37.38	44.43	bias	**40.98**	**38.78**	44.03	91.65	bias	40.98	38.78
	PER	29.30	31.41	trans.	–	**29.70**	80.25	83.38	long.	85.20	**82.90**
B, 10^{-4} Nm^2/m	PAR	0.00	0.00	long.	0.06	0.011	0.00	0.00	trans.	0.006	0.014
	BIAS	0.00	0.00	bias	0.032	0.013	0.00	0.00	bias	0.032	0.013
	PER	0.00	0.00	trans.	0.006	0.014	0.00	0.00	long.	0.06	0.011
G, N/m°	PAR	0.11	0.37	long.	1.80	**0.31**	0.002	0.40	trans.	2.44	**0.29**
	BIAS	1.70	1.79	bias	2.58	2.32	2.71	2.72	bias	2.58	2.32
	PER	2.02	2.62	trans.	**2.44**	0.29	0.03	0.26	long.	1.80	0.31

Thus, considering the mechanical properties of the outer fabric and the required property limits of the KES-F quality chart, a proper interlining can be chosen for the fused textile system. Consequently, bilayer textile systems of high quality can be developed on the basis of mechanical properties of the outer fabric and the fusible interlining.

CONCLUSIONS

1. Separate equations for the calculation of mechanical parameters of a fused textile system from its components should be used for interlinings of different orientation because of the high divergence in their mechanical behaviour.
2. Small relative errors δ (0.00–0.23) were obtained for experimental and theoretically calculated mechanical parameters; the equations with the smallest sum of squares $\Sigma\Delta^2$ were selected in order to ensure the best prediction of fused textile systems' mechanical parameters from the relevant mechanical parameters of their components.
3. The developed spreadsheet of equations can help to select the components of known properties in order to obtain a fused bilayer textile system of the desired properties.
4. Suitable interlinings can improve the mechanical behaviour of fused textile systems. The orientation of the same interlining can essentially change the mechanical properties of the whole textile system.
5. The obtained theoretical relationships were confirmed experimentally by finding proper mechanical properties of fusible interlinings (y) on the basis of which bilayer textile systems with mechanical properties (z) falling into the allowable value range of the KES-F quality chart could be composed.
6. The selection of compatible components for the textile bilayer systems with certain mechanical parameters allows avoiding problems in the garment manufacturing process and predicting the appearance and quality of the final textile product.

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Kahekihiliste liimitud tekstiilipakettide ja nende koostisosade mehaaniliste omaduste seos

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Uurimuse eesmärk on kindlaks teha kahekihiliste liimitud tekstiilipakettide ja nende kihtide (kanga ning liimvaheriide) mehaaniliste omaduste omavaheline seos. Uuriti nelja erineva paksuse (1,01–2,28 mm) ja pindtihedusega (222–398 g/m^2) murdtoimset pealiskangast ning kaht tüüpi liimvaheriiet: pikiniitidega mittekootud materjalist ja lõimkootud materjalist. Kahekihilised liimitud paketid saadi liimvaheriide paigutamisel 0°, 45° ja 90° nurga all pealiskanga lõime suuna suhtes. Automaatse katseseade KES-F abil tehti kindlaks liimitud tekstiilipakettide ja nende üksikute koostisosade mehaanilised omadused (tõmbe-, nihke-, painde- ning pinnaomadused). Määrati kindlaks teoreetilised seosed liimitud tekstiilipakettide ja pealiskangaste ning liimvaheriiete mehaaniliste omaduste vahel vaheriiete erinevate orientatsioonide (0°, 45° ja 90°) korral ning kontrolliti neid katseliselt. Selgitati välja liimvaheriiete mehaaniliste omaduste vahemik, mille alusel saab moodustada etteantud (KES-F-i kvaliteedikaardil lubatud) mehaaniliste omadustega kahekihilisi pakette. Teatud kindlate mehaaniliste omadustega liimitud tekstiilipakettide koostamiseks kokkusobivate komponentide valimine hõlbustab rõivatootmise protsessi ja võimaldab ennustada valmistekstiiltoote välimust ning kvaliteeti.