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Mechanical Properties of Polyurethane Coated Knitted Fabrics

Abstract

The aim of this study was to analyse the elongation properties of polyurethane coated knitted fabrics in order to predict their behaviour using the regression models calculated. Seven samples of the knitted fabric, each coated with 3 different polyurethane coatings, were specifically selected. The elongation in the wale direction and breaking forces in the course and wale directions of the coated knitted fabric can be predicted and explained with the results of the elongation of knitted fabric. However, elongation in the course direction cannot be clearly explained. In addition to the elongation of the knitted fabric itself, the relationship between fabric thickness and coating thickness plays an important role. While elongation and breaking forces in the case of elongation in the wale and course directions of the coated fabric increase in comparison to the non-coated fabric, the elongation of the coated fabric decreases in the case of ball bursting.

Key words: *coated knitted fabrics, polyurethane, elongation properties, tensile strength.*

■ Introduction

Polyurethane-coated knitted fabrics are of interest because they exhibit several positive properties, and yet they are little studied, especially those used in the garment industry. The advantages of polyurethane coatings in comparison to other polymers are greater resistance to abrasion and splitting, increased strength and durability. The treatment of polyurethane-coated knitted fabrics can be antibacterial, antiallergic, they can be fungus and mildew treated as well as antistatically and flame-retardantly [1, 2].

Polyurethanes are formed by the poly-addition reaction of a polyisocyanate with a polyalcohol (polyol) in the presence of a catalyst and other additives. Polyisocyanate is a molecule with two or more isocyanate functional groups, $R\text{-}(N\text{=}C\text{=}O)_{n \geq 2}$ and a polyol is a molecule with two or more hydroxyl functional groups, $R'\text{-}(OH)_{n \geq 2}$. The reaction product is a polymer containing the urethane linkage, $-RNHCOOR'-$ [3].

Knitted fabric as the substrate of the composite can be designed in such a way that it meets different physical and mechanical requirements. Varying the structure of the fabric, density, mass and yarn used, it is possible to obtain a coated knitted fabric with different properties in conformity with customer requirements.

Coated knitted fabrics are generally more stretchable and elastic than woven fabrics. Elongation may be disadvantageous in certain fields of application, but advantageous in others. For example, there are specific indicators how future restrictions of the waste amount will reduce the production of disposable protective clothing made of nonwovens and increase the production of washable protective clothing made of coated textile materials [4]. There is a chance to develop coated knitted fabrics as protective clothing, work clothing, sportswear and casual wear more comfortable than clothes made out of coated woven fabric because movements are less restricted if clothing is made of elastic knitted material.

Tests of elongation properties of coated knitted fabrics are rare. Coated woven fabrics have been more frequently tested. The influence of polyurethane coatings and woven fabric structure on the properties of composites [5, 6], tensile strength [7], anisotropy [8] and the adhesion between layers [9] was tested. Multi-axial coated warp-knitted fabrics were mostly tested among the coated knitted fabrics because they find a wide technical application [10, 11]. Elongation properties of coated knitted fabrics suitable for making protective, work and sports clothing were tested in other papers [12, 13], but according to the authors' knowledge not in this volume, with carefully selected knitted fabrics of different properties.

Table 1. Properties of knitted fabric.

Sample of knitted fabric	KF1	KF2	KF3	KF4	KF5	KF6	KF7
Structure	Simplex	Locknit	Power-net	Voile	Power-net	Plain structure	Interlock
Photograph_ (200× magnification)							
Material composition	PA	PA	PES	PES	PA	PA	PES
Mass, g/m²	184	152	47	60	134	110	109
Thickness, mm	0.74	0.62	0.26	0.32	0.40	0.68	0.50
Density per cm wales/courses	18/17	14/24	10/60	12/54	12/68	11/64	15/15

Samples and working method

Samples

Seven knitted fabrics with different structures (designations KF1 - KF7) were chosen to cover a wide interval of values of the characteristics of elongation and breaking forces tested (*Tables 1 & 2*). They were coated under the same conditions, on the same coating line, with three different polyurethane coatings (designated PU1 - PU3). The first type of polyurethane coating (PU1) was prepared on the basis of hydrophilic polyester, which is used to obtain polyurethane coatings which let water vapour pass through. The second type (PU2) on the polyester basis was used to obtain a coating that let a moderate amount of water vapour pass through, and the third type of coating (PU3) was obtained from the copolymer of polyester and polyether, providing an impermeable compact polyurethane coating. The polyurethane coatings have nearly equal average thicknesses and weights, but different mechanical properties (*Table 3*).

Polyurethane was applied to the knitted fabric using the transfer procedure. Polyurethane paste was applied to the backing paper using a pump. The coatings were adjusted in the distance between the knife on which the polyurethane paste was applied and the roller under the knife. The polyurethane paste applied with the paper passed through the dryer, where the temperature was adjusted to 80 °C. The other coating of the same polyurethane paste was applied in the same way. The final coating was a polyurethane binding agent on which the knitted fabric was laminated. In the dryer at 160 °C the binder was cross linked [14, 15].

As described above, the total number of coated knitted fabrics was 21 (7 knitted fabrics × 3 polyurethane coatings).

Working method

Knitted fabrics of different construction were selected because of their expected differences in behaviour. The construction of knitted fabric itself cannot be characterised by any value. Moreover the aim of this paper was not to link the construction of fabric and mechanical properties because in that case the research would have been differently designed. This time we observed mechanical properties before and after coating, and formed conclusions on the prediction of their behaviour.

Table 2. Elongation properties of knitted fabric.

Sample of knitted fabric	Elongation in the:		Breaking force in the:		Ball bursting	
	wale direction - ε_{kw}. %	course direction - ε_{kc}. %	wale direction - F_{kw}. N	course direction - F_{kc}. N	elongation - ε_{kb}. mm	breaking force - F_{kb}. N
KF1	116.35	126.49	907.52	501.82	33.67	1058.30
KF2	107.20	102.88	347.64	429.30	33.67	651.70
KF3	46.41	34.96	117.99	66.27	26.17	102.50
KF4	124.97	49.11	104.61	71.71	31.00	73.33
KF5	309.93	145.22	237.48	185.68	54.33	113.33
KF6	101.15	157.93	264.29	212.09	39.83	351.67
KF7	65.91	151.21	384.03	212.12	29.83	581.70

Table 3. Properties of polyurethane coating.

Coating sample	Raw material composition	Mass, g/m²	Thickness, mm	Elongation, %	Ball bursting:	
					elongation, mm	breaking force, N
PU1	PU on the basis of hydrophilic polyester	81	0.16	456.00	72.00	72.00
PU2	PU on the basis of polyester	80	0.15	562.67	65.50	63.25
PU3	PU on the basis of copolymer of polyether/ polyester	77	0.16	680.67	62.67	45.00

Table 4. Elongation properties of coated knitted fabric.

Sample of coated knitted fabric	Average (PU1-PU3) elongation in the:		Average (PU1-PU3) breaking force in the:		Average (PU1-PU3) ball bursting	
	wale direction- ε_{cw} %	course direction - ε_{cc} %	wale direction - F_{cw}, N	course direction - F_{cc}, N	elongation - ε_{cb}, mm	breaking force - F_{cb}, N
KF1c	127.61	206.44	1030.99	556.96	31.50	1227.73
KF2c	117.47	140.32	387.76	639.72	32.89	697.20
KF3c	47.73	112.62	149.98	117.36	25.13	124.28
KF4c	163.71	196.92	147.90	120.53	31.50	91.39
KF5c	372.63	353.94	291.19	250.04	47.72	147.50
KF6c	105.62	279.84	411.67	201.77	32.33	408.06
KF7c	79.46	262.60	516.92	251.54	27.61	621.10

Determination of the tensile strength and elongation at break were performed in conformity with ISO 1421: 1998 [16]. The behaviour of knitted and coated knitted fabrics in the linear application of force was compared with that of the same specimens in the case of spherical force application. This test was done in conformity with EN 12332-1:1998 [17].

The specificity of this method is that a steel ball stretches the textile material spherically, and the angle of force application and the material surface to which the force acts continuously change during the material test [18]. The technical coated knitted fabrics tested can find wide application and during use be exposed to force application from different directions. Therefore, it was interesting to observe their behaviour during both methods of sample tests. It should be borne in mind that these two ways of testing are not directly comparable.

The mass (g/m²) of the knitted fabric, the polyurethane coating and polyurethane coated knitted fabric was determined according to Standard EN ISO 2286-2:1998 [19].

The thickness was measured according Standard EN ISO 5084:1996 [20].
The samples were statistically analysed (descriptive statistics, hypothesis testing - t-test, regression analysis).

Results and discussion

Elongation properties of the coated knitted fabrics (designations KF1c - KF7c) are presented in *Table 4*.

Elongation of coated knitted fabrics in relation to the knitted fabric

Elongation in the wale direction
Individual elongations in the wale direction of all samples of knitted fabrics tested, as well as of the coated knitted
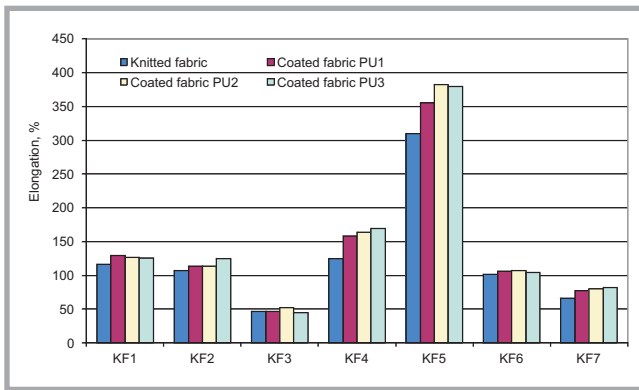
Figure 1. Elongation in the wale direction of the knitted fabric.
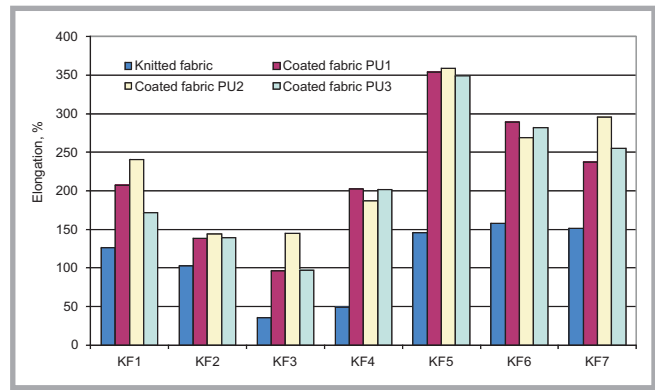

Figure 3. Elongation of the test samples in the course direction of the knitted fabric.

fabrics, are shown in **Figure 1**. The knitted fabrics elongated from 46.41% to 309.93%, which is a consequence of their different structures. The coated knitted fabrics elongated in the wale direction from 44.41% to 382.44%.

The coated knitted fabric has a considerably higher average elongation in the wale direction in relation to the knitted fabric - on average about 16%, apart from the least stretchable knitted fabric (KF3), which was not affected by the coating. Namely the KF3 sample was knitted in a power-net structure (**Table 1**), where elongation in the wale direction depends directly on elongation properties of the vertically laid yarn (and not formed into loops).

It is interesting to investigate whether there is a difference between the knitted fabrics coated with three different types of PU coating. However, the t-test shows that there is no statistically considerable difference between the mean values of elongation of the groups of samples tested (p = 0.92) or they can be observed

as the same type of polyester coating for elongation in the wale direction. Regression analysis indicates the relationship between the elongation of the knitted fabric and that of the polyurethane-coated knitted fabric. Linear regression model $\varepsilon_{cw} = 1.2312 \, \varepsilon_{kw} - 8.4717$ explains the relationship of the occurrences observed, giving the possibility to predict the values of elongation of the polyurethane-coated knitted fabric (ε_{cw}) for known values of elongation of the knitted fabric (ε_{kw}) (**Figure 2**). The coefficient of determination $R^2 = 0.9915$ confirms that 99.15% of the elongation variance in the wale direction in the samples of coated knitted fabrics studied is explained with the elongation of the samples of the same knitted fabrics studied. With such a high coefficient of determination R^2, it can be concluded that it is possible to use the regression model obtained for easy prediction of the behaviour of the coated knitted fabric and the choice of an appropriate knitted fabric substrate, which accelerates and simplifies the manufacturing process of

the corresponding polyurethane coated knitted fabric.

Elongation in the course direction
Figure 3 shows individual elongations in the course direction of all samples of the knitted fabrics tested as well as that of the coated knitted fabrics. The knitted fabrics elongated from 34.96% to 157.93%, which is a consequence of the different structures of knitted fabrics and yarns used. The coated knitted fabrics elongated in the course direction from 96.15% to 358.75%. The coated knitted fabric has a considerably higher average elongation in the course direction in relation to the knitted fabric - on average about 102%.

The t-test shows that there is no statistically considerable difference between the mean values of elongation of the knitted fabrics coated with three different types of PU coating (p = 0.72) for the elongation in the course direction.

Regression analysis showed that the relationship between the elongation of the knitted fabric and the coated knitted fabric in the course direction have only a medium correlation (r = 0.79).
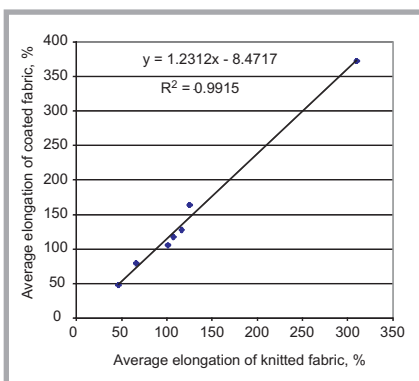

Figure 2. Elongation: Scatter diagram and linear regression model in the wale direction of the knitted fabric.
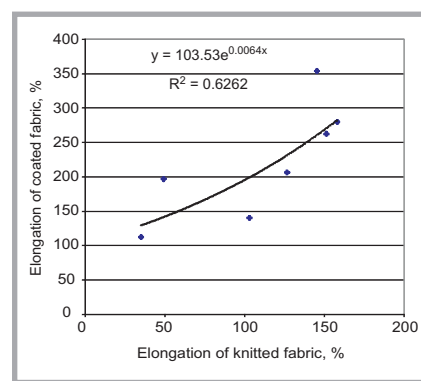

Figure 4. Elongation: Scatter diagram and model of exponential regression in course direction of the knitted fabric.
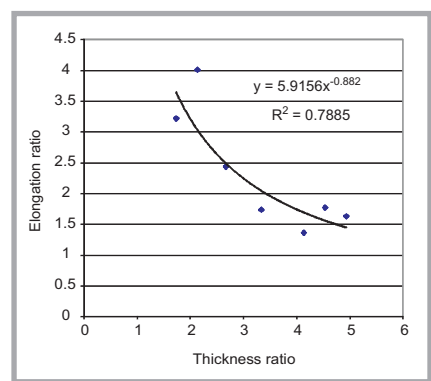

Figure 5. Relationship between the ratio of knitted fabric thickness and coating thickness and that of the elongation of the coated fabric and fabric.
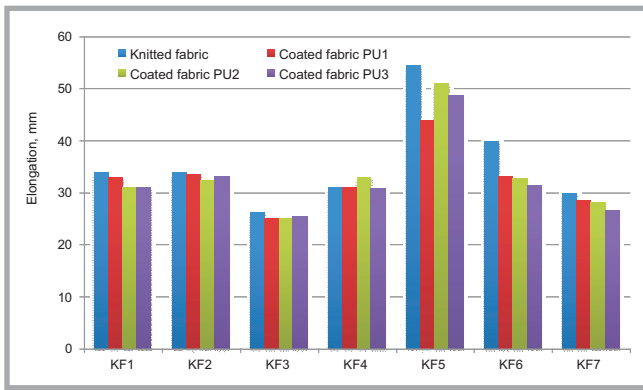
Figure 6. Elongation of the test samples of knitted fabric and coated knitted fabric during ball bursting.

The relationship between variables is not linear. Exponential regression model $\varepsilon_{cc} = 103.53 \times 1.0064\varepsilon_{kc}$, with a coefficient of determination $R^2 = 0.6262$, is the best explanation of elongation variance in the course direction of the samples of coated knitted fabrics (ε_{cc}) studied with regard to the elongation of the samples of the same knitted fabrics (ε_{kc}) examined. It is interesting to investigate which elements together with the elongation of the knitted fabric affect the elongation of the coated knitted fabric in the course direction.

The samples of coated fabric KF3, KF4 and KF5 show a greater difference in the elongation of the coated fabric and uncoated fabric (*Figure 4, Table 5*) and more significantly deviate from the adapted theoretical curve of the exponential model. By further research it could be concluded that these coated knitted fabrics have a common property - that they were produced from a low thickness knitted fabric (*Table 1*). The ratio between knitted fabric thickness and coating thickness in comparison with other knitted fabrics is lower (*Table 5*), i.e. there is relatively more coating, making a greater contribution to elongation in such coated fabrics.

The relationship between the ratio of thicknesses (T_r) and that of elongation (ε_r) clearly shows ($r = 0.89$) that the relationship between the elongation of the coated and non-coated knitted fabric decreases with increasing the ratio between knitted fabric thickness and coating thickness according to model $\varepsilon_r = 5.9156 \ T_r^{-0.8882}$ (*Figure 5*). Or more simply: the elongation decreases if there is relatively less coating on the coated fabric.

By using multiple linear regression, a much better relationship between the

elongation of the coated fabric in the course direction and both variables (elongation of the knitted fabric and ratio of knitted fabric thickness and coating), which significantly affect the elongation of the coated fabric in the course direction, was determined. Now with greater certainty and using equation: $\varepsilon_{cc} = 149.3042 + 2.032309 \ \varepsilon_{kc} - 44.866 \ T_r$ (ε_{cc} = elongation of coated fabric (%); ε_{kc} = elongation of knitted fabric (%); T_r = thickness ratio of knitted fabric and coating), the elongation of the coated fabric can be predicted. The coefficient of multiple correlation ($R = 0.91$) indicates a strong relationship between the elongation of the coated knitted fabric in the course direction and the two variables observed. The so-called aggregate test of the significance of the regression model confirms that the model is statistically significant. The P-value of the empirical F-ratio (Significance F) = 0,0304 ($p < 0.05$). Technologically these findings show how extremely sensitive it is to predict the behaviour of coated knitted fabrics with a very thin substrate (thickness > 0.4 mm). In addition to the elongation of the knitted fabric, the ratio of the knitted fabric thickness and coating should be considered.

Comparison of the elongation of the knitted fabric and coated knitted fabric during spherical elongation

Individual breaking elongations of all the types of knitted fabrics tested as well

as the mean values of elongations of the coated knitted fabrics (PU1-PU3) are shown in *Figure 6*. The knitted fabrics elongated from 26 to 68 mm until ball bursting. The coated knitted fabrics elongated from 25 to 66 mm. The t-test shows again that there is no statistically significant difference between the arithmetic means of the three types (PU1 - PU3) of samples tested ($p = 0.8372$), and they can be observed as one group of samples.

The lower elongation of the coated knitted fabric during spherical elongation, on average 8%, is especially interesting. As the spherical elongation of polyurethane coatings is higher than the elongation of the knitted fabric (*Tables 2* and *3*), the elongation of the polyurethane coating does not reduce that of the coated knitted fabric. It is possible to conclude that coating fixes the yarn and the knitted fabric structure, i.e. the polyurethane adhesive glues the yarn which forms loops, hence it cannot move freely and deform the fabric structure nor adapt to spheri-
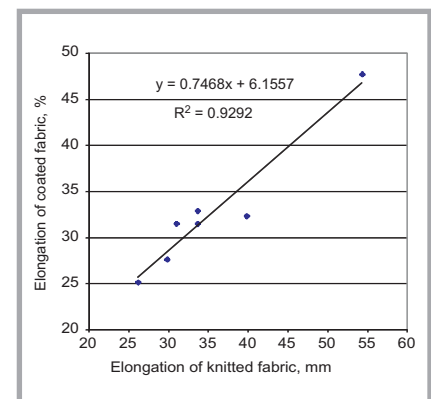

Figure 7. Elongation: Scatter diagram and model of linear regression during ball bursting.

cal elongation, causing an early burst of the coated knitted fabric. Accordingly the same coated knitted fabric, which will show better characteristics than the knitted fabric itself during elongation in the course or wale direction, exposed to
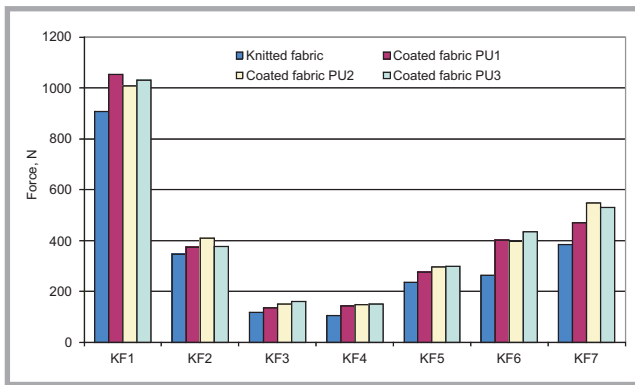
Table 5. Thickness and elongation ratio.

Sample	Elongation of knitted fabric (course), %	Elongation of coated fabric (course), %	Elongation ratio - ε_r	Thickness ratio - T_r
KF3	34.96	112.62	3.22	1.73
KF4	49.11	196.92	4.01	2.13
KF5	145.22	353.94	2.44	2.67
KF7	151.21	262.6	1.74	3.33
KF2	102.88	140.32	1.36	4.13
KF6	157.93	279.84	1.77	4.53
KF1	126.49	206.44	1.63	4.93

Figure 8. *Breaking forces measured in the test samples in the wale direction of the knitted fabric.*
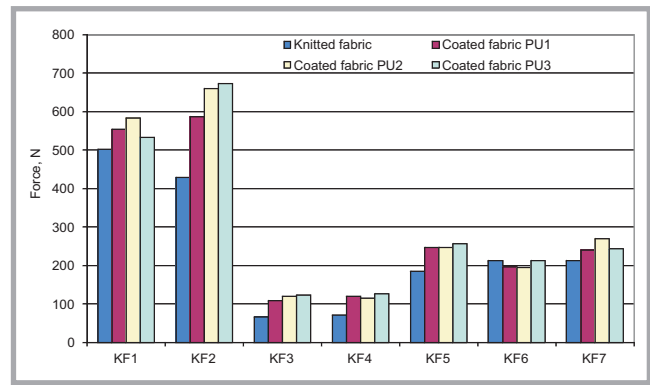

Figure 10. *Breaking forces measured in the test samples in the course direction of the knitted fabric.*

spherical elongation will show poorer characteristics.

The model of linear regression $\varepsilon_{cb} = 0.7468\ \varepsilon_{kb} + 6.1557$, with coefficient of determination $R^2 = 0.9292$, explains the relationship between the occurrences observed, giving the possibility to predict the values of elongation of the polyurethane-coated knitted fabric (ε_{cb}) for known values of elongation of the knitted fabric (ε_{kb}) (**Figure 7**).

Breaking force of the coated and uncoated knitted fabrics

Breaking force in the wale direction
The individual breaking force measured in the wale of all the samples of the knitted fabrics tested as well as that of the coated knitted fabrics are shown in **Figure 8**. Breaking forces from 104.6 N to 907.5 N were measured in the knitted fabric of different structures. Breaking forces from 136.7 N to 1053 N were measured in the coated knitted fabrics. The coating caused slightly higher breaking forces – on average 24%.

The t-test shows again that there is no statistically significant difference be-

tween the breaking forces of the three polyurethane-coated groups of samples tested (p = 0.93).

Linear regression model $F_{cw} = 1.098\,F_{kw} + 48.736$, with the coefficient of determination $R^2 = 0.9802$, explains the relationship between the occurrences observed, giving the possibility to predict the values of breaking forces in the wale direction of the polyurethane-coated knitted fabric (F_{cw}) for known values of breaking forces of the knitted fabric (F_{kw}) (**Figure 9**).

Breaking force in the course direction of the knitted fabric
The individual breaking forces measured in the course direction of the samples of knitted fabrics tested as well as those of the coated knitted fabrics are shown in **Figure 10**.

Breaking forces from 66.27 N to 501.8 N were measured in the knitted fabric. The bursting of the coated knitted fabrics in the course direction occurred at breaking forces from 108.1 N to 672.2 N. The coating caused an increase in breaking

forces in the course direction of the knitted fabric - on average about 27%.

The t-test shows again that there is no statistically significant difference between the breaking forces of the three polyurethane-coated groups of samples tested (p = 0.88).

Regression model

$$F_{cc} = 99.51 \times 1,0039^{Fkc},$$

with the coefficient of determination $R^2 = 0.9367$, explains the relationship between the occurrences observed, giving the possibility to predict the values of breaking forces in the course direction of the polyurethane-coated knitted fabric (F_{cc}) for known values of breaking forces of the knitted fabric (F_{kc}) (**Figure 11**).

Breaking force of the spherical burst of the knitted fabric and coated knitted fabric
The mean breaking force measured in all samples of the knitted fabric tested as well as that of the coated knitted fabrics are shown in **Figure 12**. Breaking forces from 73 N to 1058 N were measured in the knitted fabrics and from 91 N to 1228 N in the coated knitted fabrics.

However, the t-test shows again that there is no statistically significant difference between the breaking forces of the three polyurethane-coated groups of samples tested (p = 0.989). Coating caused an increase in the resistance to spherical bursting - on average about 13%.

Linear regression model

$$F_{cb} = 1,1214\,F_{kb} + 4,0992$$

explains the relationship between the occurrences observed (**Figure 13**). The coefficient of determination $R^2 = 0.9956$ confirms that 99.56% of the variance of
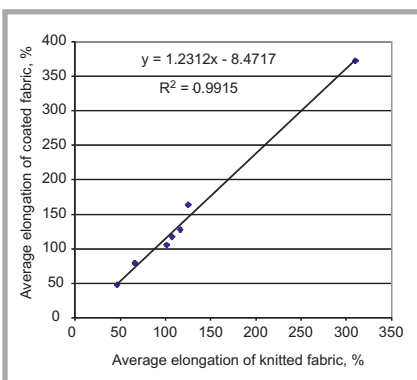

Figure 9. *Breaking forces: Scatter diagram and model of linear regression in the wale direction of the knitted fabric.*
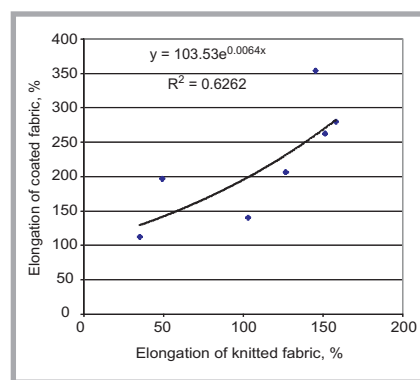

Figure 11. *Breaking forces: Scatter diagram and model of exponential regression in the course direction of the knitted fabric.*
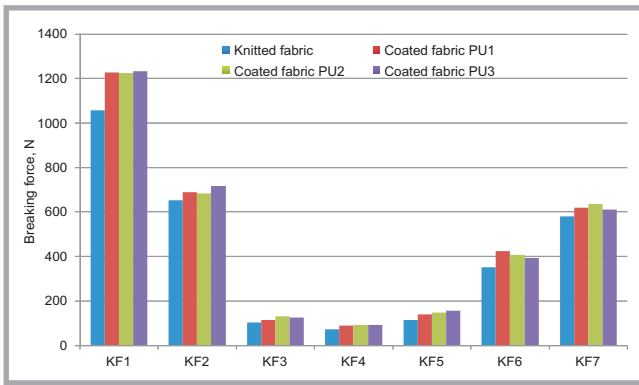
breaking forces in the samples of coated knitted fabrics (F_{cb}) studied is explained with the breaking forces of the samples

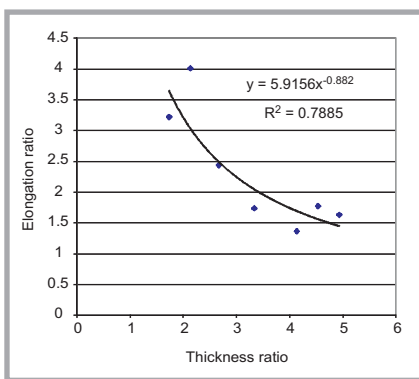*Figure 13. Breaking forces: Scatter diagram and model of linear regression in ball bursting.*

of the same knitted fabrics investigated (F_{kb}).

Conclusions

Although coating significantly changes the mechanical properties of knitted fabrics, the properties of coated knitted fabrics are primarily determined by the properties of the knitted substrate.

Elongation in the course direction of the knitted fabric significantly increases after coating - on average by about 102%, while the increase in elongation by coating in the wale direction is lower, amounting to about 16%.

Elongation in the wale direction of coated knitted fabrics can be predicted with great certainty knowing that of the knitted fabric. A linear regression model explains 99.15% of the relationship between the elongation of the knitted fabric and coated knitted fabric.

Elongation in the course direction of coated knitted fabrics can be predicted

with great certainty knowing that of the knitted fabric and the ratio of knitted fabric thickness and coating. A multiple linear regression model, with a coefficient of multiple correlation R = 0.91, explains the relationship between the elongation of the knitted fabric and coated knitted fabric.

Elongation of coated knitted fabrics in ball bursting decreases in comparison to the same non-coated knitted fabrics by about 8%. It is possible to conclude that polyurethane coating prevents fabric stitches from taking a favorable position for the spherical application of force, thereby providing greater resistance. A model of linear regression explains 92.92% of the relationship between the elongation of the knitted fabric in ball bursting and that of the coated fabric.

Coating caused an increase in the breaking force during the bursting of the samples of coated knitted fabrics in the course direction by about 27% and in the wale direction by about 24%.

Breaking forces in the wale direction of the coated knitted fabrics may be predicted with great certainty. A linear regression model explains 98.02% of the variance of breaking forces in the wale direction of the samples of coated knitted fabrics studied.

Breaking forces in the course direction of the coated knitted fabrics can also be predicted. An exponential regression model explains 93.67% of the variance of the breaking forces in the course direction in the of coated knitted fabrics samples studied.

Coating caused greater resistance to spherical bursting - on average 13%. A linear regression model explains 99.56% of the relationship between breaking forces measured in the knitted fabric and those in the polyurethane-coated knitted fabric.

It is possible to use the regression model obtained for simple prediction of the behaviour of coated knitted fabric and choice of an appropriate knitted fabric substrate to accelerate and simplify the manufacturing process.

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