Ingrida Padleckienė,
Donatas Petrulis

Monitoring Flexing Fatigue Damage in the Coating of a Breathable-Coated Textile

Kaunas University of Technology,
Faculty of Design and Technologies,
Department of Textile Technology,
Studentu str. 56, LT-51424, Kaunas, Lithuania,
e-mail: ingrida.padlackiene@stud.ktu.lt
donatas.petrulis@ktu.lt

Abstract
In this study, different samples of commercially available breathable polyurethane (PU)-coated fabrics were experimentally tested applying the crumple/flex method. The flexing fatigue resistance test involves the nucleation of damage that is responsible for coated fabric failure. Therefore, views of coating were made by means of scanning electron microscopy (SEM) to look for signs of coating cracking or other damage. In addition, we tested two of the most important end use characteristics, i.e. windproofness and waterproofness, of breathable-coated textile materials before and after the flexing fatigue resistance test. To study the trends in relationships between the number of flexing cycles and the resistance to water penetration of the materials tested, a regression analysis was made. The dependencies of all the fabrics tested in the warp and weft directions can be described by exponential equations with the coefficient of determination R^2 *within the range of 0.72 and 0.96. Residual values of the resistance to water penetration were also computed with respect to their initial values. On the grounds of the dependencies proposed, the suitability of the fabrics is discussed.*

Key words: *breathable-coated textile, flexing fatigue damage, air permeability, resistance to water penetration.*

Introduction

Breathable-coated textile materials for outerwear have to be waterproof as well as windproof. Nowadays, there are lots of technologies for producing breathable-coated fabrics with initially required properties. However, the challenge is to retain the properties for a particular time of wear. In other words, an important task is to monitor how long the garment will serve as acceptable waterproof and windproof outwear. The full potential of a material can only be realized if the loss of long-term material properties are properly understood and controlled [1].

The air permeability of windproof textile materials has to be zero [2, 3]. A textile material is termed waterproof if the resistance to water penetration is higher than 130 cm of water column [2, 4]. In practice, the higher the initial resistance to water penetration, the better the durability and service life of the garment [5].

In earlier our works [6 - 9], we analysed abrasion and tension damage in breathable-coated textile materials. However, in the current study, we monitored flexing fatigue damage in the coating of a breathable-coated textile.

There are many kinds of flexing fatigue resistance test methods, for example the De Mattia method, the Schildknecht method, the crumple/flex method, etc. [2, 10 - 13]. Since the methods differ from each other in principle, the results obtained from them cannot be compared. It is worth noting that the crumple/flex method has extra importance because the size of the specimen is enough and suitable for the determination of air permeability and resistance to water penetration after the flexing fatigue resistance test. In addition, during the crumple/flex fatigue resistance test, the breathable-coated textile material is exposed to various wear factors, i.e. flexing, tension and compression at the same time. Thus, the test conditions are very close to real wear conditions.

The flexing fatigue process occurs in different materials, i.e. in textile materials without coating, composite laminates, coated textile materials, etc. Several important investigations on this phenomenon are given in the references [2, 13-15]. The serviceability of coated textile materials is closely related to the mechanical destruction of the coating layer. However, no study is available on the monitoring of flexing damage in the coating of breathable-coated textiles. Thus, the purpose of this research was to fill this gap and show the main regularities of flexing fatigue damage in the coating.

Experimental

In this study, four different samples of commercially available breathable-covered fabrics, i.e. A, B, C, and D were tested. A typical cross-sectional view of sample A, in which the outer woven fabric has a coating on the reverse side, is shown in ***Figure 1***. All the samples comprised woven fabrics coated with breathable polyurethane (PU) coating. The main structural data and mechanical properties of the materials investigated are given in ***Table 1***. Plain weave samples A - C have a rather similar structure, i.e. masses per unit area and densities. Sample D differs in twill weave. Moreover, the density and mass per unit area values are greater if compared with those of samples A - C.

A flexing fatigue resistance test of the samples was carried out on a crumple/flex tester M262 (SDL International Ltd.,

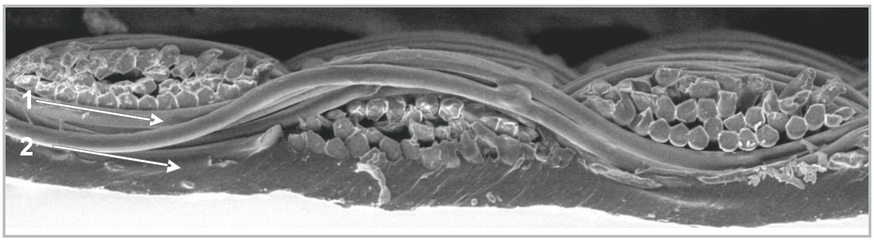

Figure 1. *Cross-sectional structure of breathable-coated sample A: 1 - outer woven fabric, 2 – reverse side coating.*

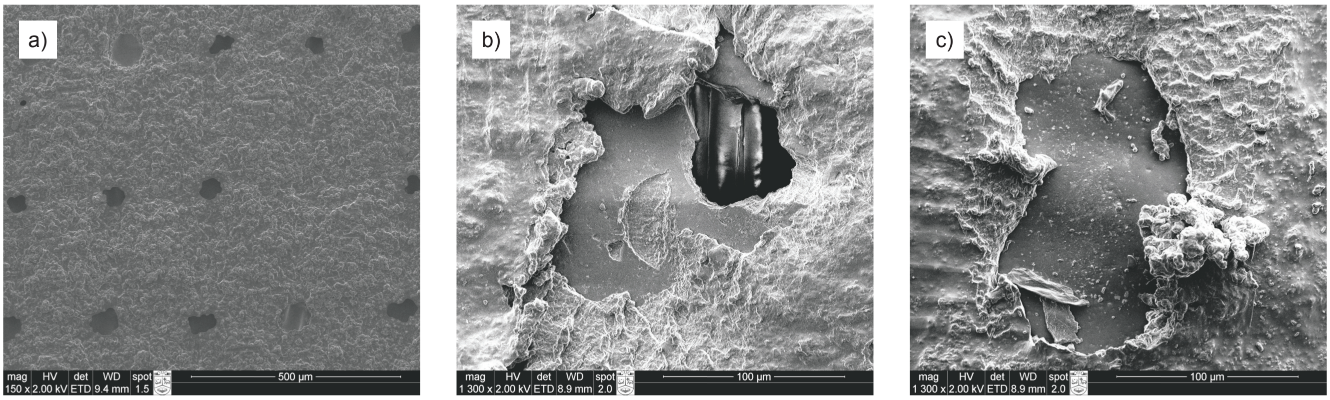

Figure 2. *SEM views of the reverse side of sample A; a) initial, b) after 9000 flexing cycles in the warp direction, c) after 9000 flexing cycles in the weft direction.*

England), according to method C of the standard [10]. Using this equipment, a tube of fabric was tested by twisting it through approximately 90° and alternately stretching and compressing the tube at the same time. To show the flexing damage at various stages, the samples were tested for rather a wide range of numbers of cycles *n*: 30000, 60000, 90000, and 120000. Additional monitoring was also applied after 9000 flexing cycles.

At the beginning of the next stage, scanning electron microscopy (SEM) analysis was performed for evaluation of the damage after the flexing fatigue resistance test of the breathable-coated textile materials. Photographs of the reverse side of the samples after the above-mentioned number of flexing cycles were compared with the initial appearance of the specimens. Later on, the air permeability was measured using an air permeability tester - L14DR (Karl Schröder KG, Germany), as specified in the standard [16], at a pressure drop of 200 Pa. In this test, the specimens were clamped, with the coating towards the lower air pressure side. Eventually, the hydrostatic head test was used for examination of the cover damage. A method according to the standard [17] was applied to determine the resistance of the fabrics to water penetration at a constant rate of increasing water pressure. The test was performed on a Shirley Hydrostatic Head Tester M018 (SDL International Ltd., England). The outer side of the breathable-coated fabric was placed in contact with water during the test. The rate of water column rise was 60 cm/min. The hydrostatic pressure (H) at which water penetrates the fabric in the third place was observed. The lowest values in cm of the penetration of the first, second, and third water drops were noted. The accuracy of the measurement was ± 2 cm. To determine changes in the properties, the samples were tested at the beginning and after a certain number of flexing cycles. After that, the values of residual resistance (H_r) were computed. This index is actual resistance to water penetration divided by initial resistance to water penetration. H is absolute value in cm and H_r is residual value in %.

The specimens were allowed to recover for 24 hours before being used for evaluation of the damage and for measurements of the air permeability and resistance to water penetration. All the specimens were conditioned, and tests were carried out in a standard atmosphere of 65 ± 2% RH and temperature of 20 ± 2 °C.

To study trends in the relationships between the number of flexing cycles and the properties of textile materials, regression analysis was made using a Microsoft Excel Analysis Tool Pak.

Results and discussion

Typical surfaces of the PU coating of sample A are shown in ***Figure 2***, where the initial view (a) and views after 9000 flexing cycles in the warp and weft directions, i.e. (b) and (c), are presented.

In ***Figure 2.a*** it can be seen that the coating surface has regularly positioned pits, but no microcracks were found. The pits formed during the material coating process. The PU melt has typical pits in the cavities between neighbouring yarns of the woven fabric. However, the wholeness of the coating is not broken in these places. The formation of pits is conditioned by various coating formation parameters, i.e. viscosity of the coating, force of press roll, angle of coating knife, speed of coating, fabric tension, etc. Samples B and D also have a similar view of the coating. Meanwhile, sample C has a plain surface without regular pits. The flexing fatigue resistance test involves the nucleation of damage that is responsible for coated fabric failure. Void formation, cavitations, or initial nano-sized cracks occur in the coating during the early stages of fatigue. The nucleated voids then continue to grow and coalesce while the fatigue process continues. The danger zones in the samples tested, where damage can first occur and small cracks initiate, are bending lines, which occur during the first cycles of the flexing fatigue resistance test. In subsequent cycles the material buckles in the same places, and small defects start to develop. In ***Figures 2.b*** and ***2.c***, the damage is easily found and can be clearly seen after 9000 flexing cycles. ***Figure 2.b*** also shows that yarns of woven fabric can be seen on the reverse side of sample A. Thus, signs of coating delamination are visible on the sample tested in the warp direction. It is necessary to note that after the flexing fatigue test in the weft direction, coating delamination appeared later. ***Figure 2.c*** shows that after a fixed number of

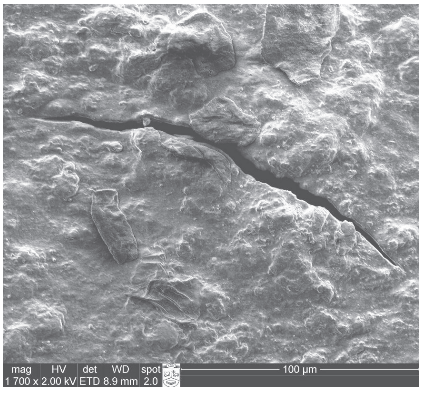

Figure 3. *SEM views of the reverse side of sample C with signs of cracks after 9000 flexing cycles in the warp direction.*

flexing cycles (9000), the damage to the coating is not so deep if compared with that shown in ***Figure 2.b***.

Figure 3 shows the signs of cracks in the coating of breathable-coated materials after 9000 flexing cycles in the warp direction. We observed cracks in the coating of all samples. The lengths of the greatest cracks after 9000 flexing cycles are 160 - 640 μm. With an increase in the number of flexing cycles, the cracks grow and new damage appears in the lines of sample bending.

In the next stage of the research, we studied two of the most important characteristics for breathable-coated textile materials, i.e. windproofness and waterproofness.

The initial air permeability of all the samples was zero. This value did not change for the samples after all the stages of the flexing fatigue resistance test previously mentioned. In other words, the local cracks were too small to increase the air permeability of the samples.

Other trends were observed with respect to waterproofness. The resistance to water penetration (H) before mechanical treatment was 1500 cm of water column for samples A-D, which is very high resistance; usually it is enough if a new material withstands about 700 cm of water column [5]. ***Figures 4.a*** and ***4.b*** show that with an increase in the number of flexing cycles n, the value of H declines with each stage of the flexing fatigue resistance test. In addition, the values of water column are obtained when the first, second and third drops appear on the test area of the specimen (see ***Figure 4***). It is important to note that the first drop shows the most damaged place of the coating. In the first stages of the test, the differences between the H values of the three drops are significant, but later they are marginal, i.e. all three drops appear almost at the same time. As can be seen from ***Figure 4***, the test gives remarkably less values of H after initial flexing (9000 cycles) in the warp direction compared with those after flexing in the weft direction. These differences may be conditioned by the delamination mentioned above (see ***Figure 2.b***). As was mentioned above, the specimens were tested up to a fixed deformation of flexing. In our opinion, the different damage occurring after the same number of flexing cycles in the warp and weft directions could be a re-

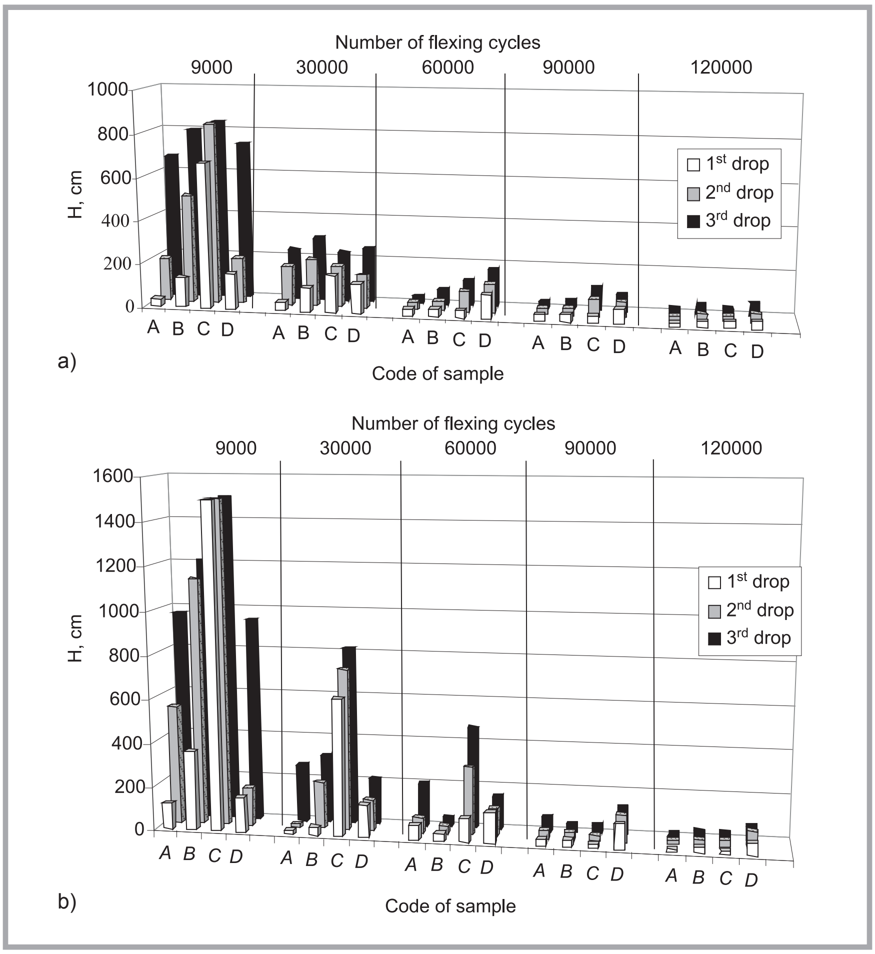

Figure 4. *Resistance to water penetration (H) for the first, second, and third drops after flexing in the warp (a) and weft (b) directions.*

Table 1. *Characteristics of breathable-coated fabrics;. PA - polyamide, PU – polyurethane.*

Characteristic	**Fabric code**			
	A	**B**	**C**	**D**
Composition of woven fabric, %	PA, 100	PA, 100	PA, 100	PA, 100
Material for coating	PU	PU	PU	PU
Weave	Plain	Plain	Plain	Twill 1/2
Mass per unit area, g/m^2	105	86	113	142
Density of woven fabric, cm^{-1} warp weft	 38.3 33.3	 40.8 32.5	 42.0 35.0	 59.2 37.1
Ratio of bending rigidities in the warp to weft directions	4.65	3.33	2.22	1.54

Table 2. *Exponential regression equations and correlation between the number of flexing cycles and resistance to water penetration (H) in cm and residual resistance to water penetration (H_r) in %; n – number of flexing cycles.*

Flexing direction	**Code of sample**	**Resistance to water penetration (H) in cm**		**Residual resistance to water penetration (H_r) in %**	
		$H = 1500 \times \exp(-k_1 \times n)$		**$H_r = 100 \times \exp(-k_2 \times n)$**	
		$k_1 \times 10^5$	**R^2**	**$k_2 \times 10^5$**	**R^2**
Warp	A	4.191	0.79	4.192	0.79
	B	3.614	0.79	3.615	0.79
	C	3.385	0.85	3.388	0.85
	D	3.102	0.83	3.102	0.83
Weft	A	3.754	0.96	3.756	0.96
	B	3.888	0.80	3.887	0.80
	C	3.258	0.90	3.257	0.90
	D	2.940	0.72	2.940	0.72

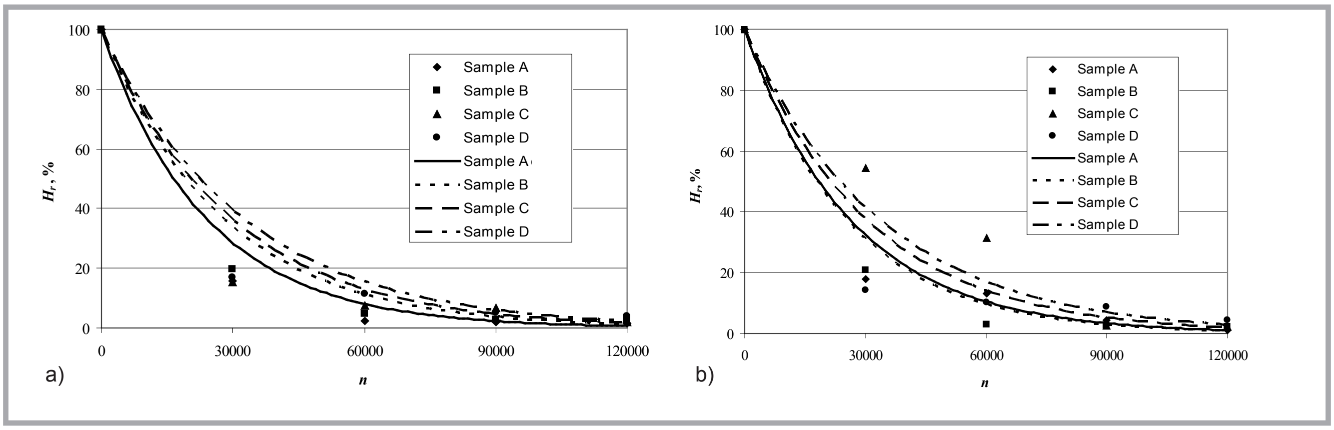

Figure 5. *Dependencies of residual resistance to water penetration (H_r) on the number of flexing cycles (n) when flexing in the warp (a) and weft (b) directions.*

sult of greater stress in the warp direction compared with that in the weft. Probably, the differences in stress appear because of the various bending rigidities in these directions. As shown in ***Table 1***, the values of the ratio of bending rigidities in the warp and weft directions are above one, i.e. for samples A - D these values fluctuated between 1.54 and 4.65.

Thus, after this stage of the current study, westated the resistance to water penetration can be applied as a suitable index for evaluating damage to breathable-coated textiles, in which air permeability does not show the level of coating failure. This is due to local cracks found only in some places, being too small to change the air permeability. However, in our previous studies [8], the air permeability index was successfully used for evaluation of changes in rather equally arranged damage caused by abrasion.

In the next stage of the research, the non-linear behaviour of the resistance to water penetration of the test fabrics during the flexing fatigue resistance test was analysed. Two types of regression, i.e. polynomial and exponential, were applied for the study of results, but the exponential type of regression seemed to best fit. As shown in ***Table 2***, the dependencies for all the test fabrics in the warp and weft directions can be described by exponential equations, with the coefficient of determination R^2 within the range of 0.72 and 0.96. The equations can help to predict the change in resistance to water penetration *H* when the number of flexing cycles *n* is known and the initial resistance to water penetration is 1500 cm. As seen from the dependencies, the higher *n* is, the lower the *H* of the materials investigated will be. At a range of variable *n* between zero and 30000, index *H* decreases with greater intensity if compared with subsequent ranges of *n*.

Residual values of resistance to water penetration H_r, computed with respect to their initial values, were also applied. Graphic views of the dependencies of H_r on *n* when flexing in the warp and weft directions are presented in ***Figures 5.a*** and ***5.b***, respectively. In both directions, the change in H_r has a specific character, i.e. - at the initial stage of the fatigue test, this index decreases very intensively. For instance, the values of H_r at the end of a range of numbers of flexing cycles of 0 - 30000 equalled 15.3 - 19.7%. However, after over 30000 flexing cycles, a not so intensive decrease in H_r was observed.

The exponential regression equations and the results of correlation between *n* and H_r are presented in ***Table 2***. Using these equations, it is possible to evaluate the behaviour of breathable-coated materials with different initial values of *H*. Since all the samples have a constant initial value of *H*, the equations for index H_r and coefficients of determination R^2 shown in ***Table 2*** are very similar to those presented in ***Table 2*** (on the left).

Samples A - D differ not only in the weave but also in other parameters, i.e. the density of the woven fabrics and linear density of yarns. Therefore it is not possible to make a decision as to whether the fabric weave has an effect on the results. As can be seen from the results mentioned above, there is no significant difference between the change in resistance to water penetration during the flexing fatigue resistance test of plain weave (A - C) and that of the twill 1/2 weave (D) samples. Hence, such breathable-coated material of twill 1/2 weave can be used in cases where the high strength of the product manufactured is important. However, when the strength is not a primary factor, it is recommended to choose samples A - C.

It is important to note that stress amplification not only occurs at a microscopic level but can also occur at a macroscopic level with respect to the material structure. For instance, the micropores of breathable coating are very small [3, 5] when compared with the pits mentioned earlier, shown in ***Figure 2.a***. Since all the samples with regularly situated pits (A, B, and D) and without pits (C) exhibited rather similar flexing fatigue behaviour, we can conclude that the impact of pits on damage developing in the breathable coating was not so important. Thus, such small stress raisers as micropores and small cracks showed a prevailing effect on coating damage.

The possibility of predicting the resistance to water penetration value was checked for sample A after 9000 flexing cycles. The calculations showed that the values of experimental and predictive residual resistance to water penetration are in good agreement. The difference between these values is 4.4%.

As noted earlier, a height of 130 cm of water column is generally regarded as the minimum for a fabric to be termed waterproof or resistant to water penetration. In our case, the initial value of *H* was about 1500 cm for all fabrics tested. Hence, the materials would still be acceptable even with a reduction in *H* of 91.3%. In other words, the materials tested can be used up to 58500 - 75000 flexing cycles.

Conclusions

In this paper, SEM photographs were used as an informative source for monitoring PU coating damage after the flexing fatigue test of a breathable-coated textile. Danger zones in the samples tested, where the damage can first occur and small cracks initiate, are the bending lines, which occur during the first cycles of the flexing fatigue resistance test.

Cracks can be clearly seen in SEM photographs after 9000 flexing cycles. The lengths of the greatest cracks are 160-640 μm at this stage. Moreover, signs of delamination were observed in the coating after 9000 flexing cycles in the warp direction. Probably, because of the large values of the ratio of bending rigidities in the warp to the weft direction, the delamination of the coating after the same test of flexing appeared later in the weft direction when compared with that in the warp direction.

The resistance to water penetration H as well as its residual value H_r are suitable indices for evaluating damage to the coating of breathable-coated textiles after the flexing test: air permeability does not show the level of material failure.

The exponential dependencies suggested show that the higher the number of flexing cycles, the lower the resistance to water penetration of the materials investigated will be. In the warp and weft directions, indices H and H_r decrease very intensively at the initial stage of the fatigue test, i.e. until 30000 flexing cycles. The intensity of the decrease in H and H_r values fell within a range of high numbers of flexing cycles.

As regards minimal waterproofness requirements, the fabrics tested are still acceptable even with a reduction in H_r of 91.3%. Therefore, it is possible to state that flexing up to 58500 - 75000 cycles shows the safety limit of the materials investigated.

The results of the resistance to water penetration of the test samples presented do not allow to state whether the fabric weave has an effect on the life of PU-coating in all cases; however, the results of the materials tested show that there is no significant difference between the changes in the resistance to water penetration during the flexing fatigue resistance test of all the samples tested. Thus, when the high strength of the sample manufactured is important, it is recommended to use sample D. Moreover, it is good to choose samples A - C if the strength is not a primary factor.

References

1. *Harik V. M., Klinger J. R., Bogetti T. A.; Low-Cycle Fatigue of Unidirectional Composites: Bi-linear S-N Curves. International Journal of Fatigue, 2002, 24, pp. 455 - 462.*
2. *Weder M.; Performance of Breathable Rainwear Materials with Respect to Protection, Physiology, Durability, and Ecology. Journal of Industrial Textiles, 1997, 27, pp. 146-168.*
3. *Holmes D. A.; Waterproof Breathable Fabrics. In “Handbook of Technical Textiles”. Ed. A. R. Horrocks, S. C. Anand, Woodhead Publishing Ltd, Cambridge, 2000.*
4. *Mukhopadhyay A., Midha V. K.; A Review on Designing the Waterproof Breathable Fabrics: Part II: Construction and Suitability of Breathable Fabrics for Different Uses. Journal of Industrial Textiles, 2008, 38, pp. 17 – 41.*
5. *Fung W.; Coated and Laminated Textiles, Woodhead Publishing Ltd, Cambridge, 2002.*
6. *Padleckiene I., Petrulis D.; The Change of Air Permeability and Structure of Breathable-Coated Textile Materials after Cyclic Stretching. Materials Science-Medziagotyra, 2008 14, 2, pp. 162-165.*
7. *Padleckiene I., Petrulis D., Rubeziene V., Valiene V., Abraitiene A.; Breathability and Resistance to Water Penetration of Breathable-Coated Textiles after Cyclic Mechanical Treatments. Materials Science-Medziagotyra, 2009, 15, 1, pp. 69-74.*
8. *Padleckiene I., Petrulis D.; Effect of Abrasion on the Air Permeability & Mass Loss of Breathable-Coated Fabrics. Fibres & Textiles in Eastern Europe, 2009, 17, 2, pp. 50-54.*
9. *Padleckiene I., Petrulis D.; Investigation about Properties of Breathable-Coated Fabrics after Abrasion. Proceedings of Conference, Autex-2008, 2008, CD edition [1 - 5].*
10. *International Standard LST EN ISO 7854: 2000.*
11. *Palaty S., Joseph R.; Low Temperature Curing of NBR for Property Improvement. Journal of Elastomers and Plastics, 2006, 38, pp. 199-209.*
12. *Schwerin M. R., Walsh D. L., Richardson D. C., Kisielewski R. W., Kots R. M., Routson L. B., Lytle C. D.; Biaxial Flex-Fatigue and Viral Penetration of Natural Rubber Latex Gloves before and after Artificial Aging. Journal of Biomedical Materials Research, 2002, 63, pp. 739-745.*
13. *Milasienė D., Bubnyte K.; The Influence of Fatigue Conditions on the Mechanical Properties of Laminated Leather and its Separate Layers. Materials Science-Medziagotyra, 2007, 13, pp. 210-213.*
14. *Nielsen L. E., Landel, R. F.; Mechanical Properties of Polymers and Composites. 2nd ed., Marcel Dekkerr, Inc., 1994.*
15. *Chen Y., Lloyd D. W., Harlock S. C.; Mechanical Characteristics of Coated Fabrics. Journal of the Textile Institute, 1995, 86, pp. 690-699.*
16. *International Standard LST EN ISO 9237:1997.*
17. *International Standard LST EN ISO 20811:1997.*

Received 17.07.2009 Reviewed 22.01.2010

CORRECTION:

We apologise for the incorrect affiliation of Prof. Rabiej, Prof. Fraczek-Szczypta and Prof. Błażewicz due to an first in the article “*Strength Properties of Polyacrylonitrile (PAN) Fibres Modified with Carbon Nanotubes with Respect to their Porous and Supramolecular Structure”* published in issue No. 6 (77) 2009 of our journal. The correct details are shown below:

Mikołajczyk T(1), Rabiej S.(2), Szparaga G.(1), Boguń M.(1), Fraczek-Szczypta A.(3), Błażewicz S.(3)

1. Department of Man-Made Fibres, Faculty of Material Science and Textile Design, Technical University of Lodz, Zeromskiego 116, 90-924 Lodz
2. Institute of Textile Engineering and Polymer Materials, Faculty of Materials and Environmental Sciences, University of Bielsko-Biala, Willowa 2, 43-309 Bielsko-Biala
3. Department of Biomaterials, Faculty of Materials Science and Ceramics, AGH – University of Science and Technology, Al. Mickiewicza 30, 30-059 Krakow

The editors