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Assessment of the Electrostatic Properties of Polyester Knitted Fabrics Containing Carbon Fibres after Enzymatic Modification for the Improving of Hygroscopic Properties

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Abstract
The paper presents findings concerning the assessment of the biochemical modification effect on the electrostatic and sorption properties of polyester knitted fabrics containing a yarn with carbon fibres in their structure. The modification of hygroscopic properties of polyester fibres was carried out during the laboratory finishing process of fabrics with the use of an enzyme from the group of hydrolases – esterase under trade name of Texazym PES. The effect of the enzyme on the structure of the fibre surface was shown by means of SEM images, while the efficiency of its hydrophilic action was assessed by testing the sorption parameters of the fabrics. To assess the effect of hygroscopic properties on the electrostatic parameters of the fabrics, tests were carried out under various conditions of air humidity. An analysis of changes in the hygroscopic and electrostatic properties of knitted fabrics after the biochemical modification was made in relation to fabrics after the conventional finishing process. The experiments were performed at the initial stage for selected stitch structures of polyester warp knitted fabrics with various contents of the yarn with conductive fibres and different procedures of its incorporation. The test results obtained showed the advantageous influence of finishing with hydrolytic enzyme on knitted fabric's electrostatic properties with respect to protective functions against static electricity. The method of biochemical modification of polyester fibres used on a laboratory scale in this study can find practical use in creating the physiological comfort function of fabrics from conventional synthetic fibres by providing special features resulting from the content of conductive fibres in their structure.

Key words: *biochemical modification, polyester fibres, electro-conductive fibres, warp kitted fabric structure, hygroscopic properties, electrostatic properties.*

Introduction

The incorporation of yarns containing conductive fibres into the structure of textile materials is a known and effective method being used to protect against or reduce the generation and accumulation of electric charges on textile materials made of them. The electrostatic charge is carried off the fabric surface by dissipation when the surface of fibres with low electric conductivity comes into contact with an antistatic or conductive fibre or yarn. The results of research also carried out at the Textile Research Institute within the scope of the antistatic properties of knitted fabrics containing conductive fibres have shown that these properties depend on the linear resistance of the electrostatic yarns modified, their contents, the method of incorporating into the knitted fabric structure as well as on the accompanying raw material and knitted fabric structural properties [1 – 6]. These factors also exert an influence on the dissipation intensity of electrostatic charges accumulated on the fibre surface. Textile materials contained in the structure of conductive fibres provide a high stability of electrostatic properties in finishing processes with the use of special chemical agents which create wide possibilities within the scope of the multidirectional creation of practical functions retaining protective action against static electricity [7, 8].

The comfort of wearing clothing of knitted textiles materials depends, first of all, on the type of raw material and stitches used in the given knitting process [9 - 11]. In modeling the physiological comfort features of clothing, one should take into account the hygienic functions of knitted fabrics that depend on hygroscopic properties and the related knitted fabric capability to carry out moisture from the underwear layers. The technology of textiles designed for protective clothing uses, first of all, yarns of synthetic fibres to obtain the strength, structural stability and functional durability of knitted fabrics. In designing knitted fabrics of conventional synthetic raw materials, especially polyester fibres, one should take into account technological measures towards imparting hygroscopic properties to knitted fabrics with respect to the physiological comfort of using clothes made of them. The known methods used to achieve that objective include the modification of the fibre surface with enzymatic agents in the process of textile finishing [12 - 14]. The modification of polyester fabrics with esterases causes the hydrolysis of ester bonds on the fibre surface and the creation of reactive hydroxyl and carboxyl groups [12, 14 - 16]. This method is an ecological alternative to the standard process of alkaline hydrolysis, which requires the use of high pH and temperature [13, 15, 17]. It should be emphasised that imparting hydrophilic features to synthetic fibres is

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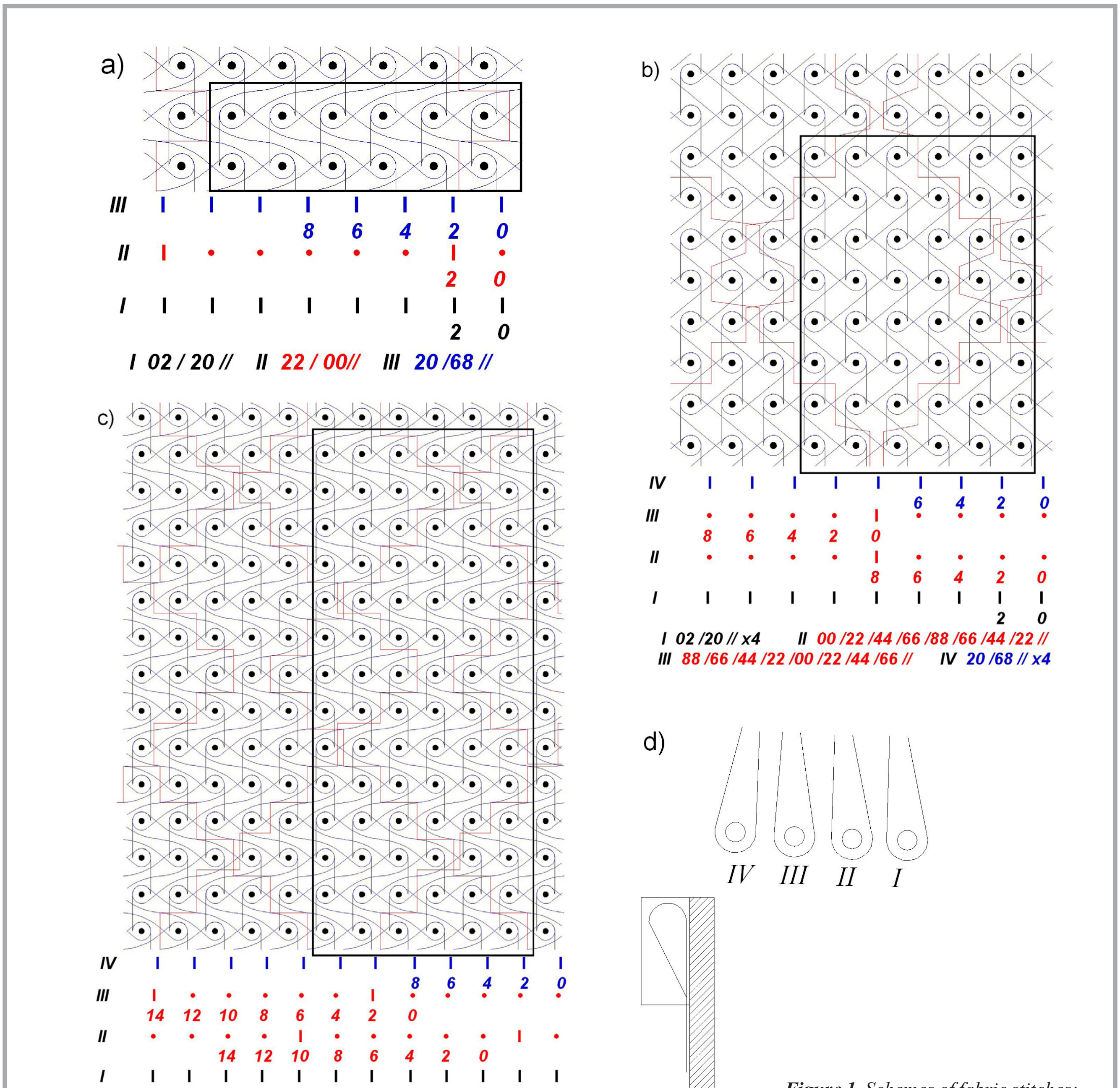

***Figure 1.** Schemes of fabric stitches: a – variant 1), b – variant 2), c – variant 3) and the specification of needle combs in relation to the machine needle comb – d.*

also advantageous in view of the possibility of forming other special functions of the enzyme-modified knitted fabrics in the finishing process. An example of this is the use of biochemical hydrophilisation to provide stable polyester fibre bonds with bacteriostatic or bactericidal agents [16, 18]. To impart resorption capabilities to knitted fabrics, one can also modify the fibre surface with pigments, sols- gels or by such plasma treatment as in the technology of hygienic and medical products of regenerated cellulose fibres [19, 20]. Such treatments are also aimed at improving the thermal and electric conductivities of fibres [20, 21].

This paper presents experimental results whose purpose was the assessment of the impact of the biochemical modification of polyester materials containing conductive fibres on sorption properties. This research work constitutes the new area of effects due to the kind of materials and the assessment of the impact of the biochemical modification chosen on electrostatic indicators in the aspect of the forming of physiological comfort features of protective clothing made from synthetic fibres.

Methods

Research work was carried out for selected structures of polyester knitted fabrics containing yarn with carbon fibre. The fabrics were made during previous work of the Textile Research Institute[1] according to structural solutions of stitches that were developed for use in the technology of warp knitted fabrics with protective properties against static

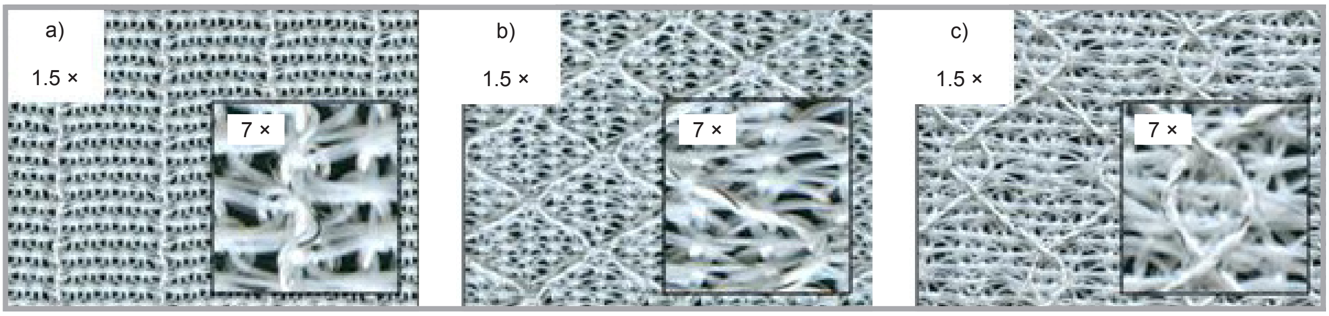

***Figure 2.** Photos of the knitted fabric's reverse side: a – variant 1), b – variant 2), c – variant 3).*

electricity [22]. The fabrics were made with the use of a Raschel knitting machine from Mayer (Germany), type RM6, with a needle gauge of 32/2 S. The fabric background was made of conventional polyester yarn with a linear density of 110 dtex, f24, with the use of a full threading of needle combs I and III or I and IV. The knitted fabrics used in experimental works were made incorporating a yarn with carbon fibre into the structure with incomplete threading of needle combs in the system 1 × 5. The variants of warp knitted fabrics included in the experimental works contained a bicomponent rotor yarn (VSc Lenzing 75/25% PES) with a linear density of 40 tex. The yarn sheath was composed of polyester multifilament yarn 100 dtex f33 twisted with carbon fibre Resistat F9605 (Spolsin, spol. s r.o, Czech Republic). Schemes of the fabric stitches with the specification of the stitch repeat together with the notation of chain links of component stitches for the stitch repeat and the sequence of needle combs in relation to the machine's needle comb are presented in ***Figures 1.a – 1.d*** (see page 85)**.**

For specified stitch solutions, the yarn with conductive fibres is incorporated into the fabric back in the form of a vertical weft (fabric variant "1") and a network in a diagonal system (variants "2" and 3"). The real appearance of the fabric back is illustrated in ***Figures 2.a – 2.c.***

Biochemical modification of knitted fabrics containing conductive fibres was carried out with the use of esterase, an enzyme from the group of hydrolases, and Texazym PES from Inotex (Czech Republic), designed for textiles of polyester fibres [23]. The finishing process was carried out under laboratory conditions according to verified methods developed within the previous research works of the Textile Research Institute [16]. The knitted fabrics were treated with a bath containing 2% of the enzymatic agent. The modification process was performed at a temperature of 30 °C for 30 min in an acidic medium, pH = 4. Before the finishing process, the knitted fabrics were subjected to purification using a nonionic bath at a temperature of 40 °C.

Assessment of the effect of the biochemical modification on hygroscopic and antistatic properties of the knitted fabrics was carried out within the range of specified stitch structures for knitted fabrics that were finished under laboratory conditions using conventional procedures for knitted fabric of synthetic raw materials. Analysis of tests results was carried out under various conditions of relative air humidity: 25 and 65%. The tests were conducted after 48 h of acclimatisation at a temperature of 20 ± 2ºC and relative air humidity of 65 ± 2%. Hygroscopic properties of the knitted fabrics were expressed with the hygroscopicity index, which determines the knitted fabric's capability to absorb moisture from the environment. The tests were carried out by the gravimetric method according to the standard for textile materials [24]. This method consists in determining the sample weight at a relative air humidity of 0% after 4 h of sample acclimatisation at RH = 100%. The hygroscopicity parameter was determined in relation to the dry sample weight, constituting a constant weight of the sample obtained by drying. Sorption properties of the knitted fabrics were determined on the basis of the capillarity index, which determines the directional fabric ability to transport water and the time of water drop absorption by the fabric surface. The capillarity parameter was determined for both the lengthwise (along wales) and crosswise directions (along course) of the knitted fabrics after immersing the edge of the sample in a 0.5% solution of potassium dichromate for 15 minutes at intervals of 2 min. [25]. These samples were tested under a load of 2 × 5 g. The time of water drop absorption was determined according to the Tegewa drop Test [26]. While testing, a water drop with a volume of 0.05 cm^3 was dropped on the sample tested from a height of 40 mm.

Electrostatic properties of the knitted fabrics were determined on the basis of the surface resistance, time of half-decay of the electrostatic charge and the screening factor. The tests were conducted according to the standard for protective clothing [27]. The surface resistance parameter was determined as a ratio of the constant voltage supplied to the sample to the current intensity on the fabric surface. Tests were carried out for the reverse side of the knitted fabrics using a voltage of 100 ± 5 V. Parameters of the charge decay half-life and screening coefficient were determined by the induction method, which consists in the stepwise supplying of a high voltage of 1200 V for 30 μs to a field electrode located directly under the fabric tested. A measurement probe located over the fabric tested recorded field intensity changes appearing in the presence of the sample tested. For a fabric that is characterised by conductive properties, the field intensity measured will be lower than that in the absence of fabric. This parameter is defined as the time after which the field intensity with the sample tested achieves a half of that without the sample. The screening coefficient parameter allows one to assess to what extent the field intensity for the sample tested is reduced in relations to the field intensity value without the sample. Thus the lower the field intensity with the sample tested, the higher the screening coefficient. If the fabric tested is a dielectric, the absolute values of the field intensity with and without the sample are the same.

The morphology of the polyester fiber surface was assessed on the basis of SEM images using a JEOL JSM-35C microscope (Japan) with a definition of 6 nm as

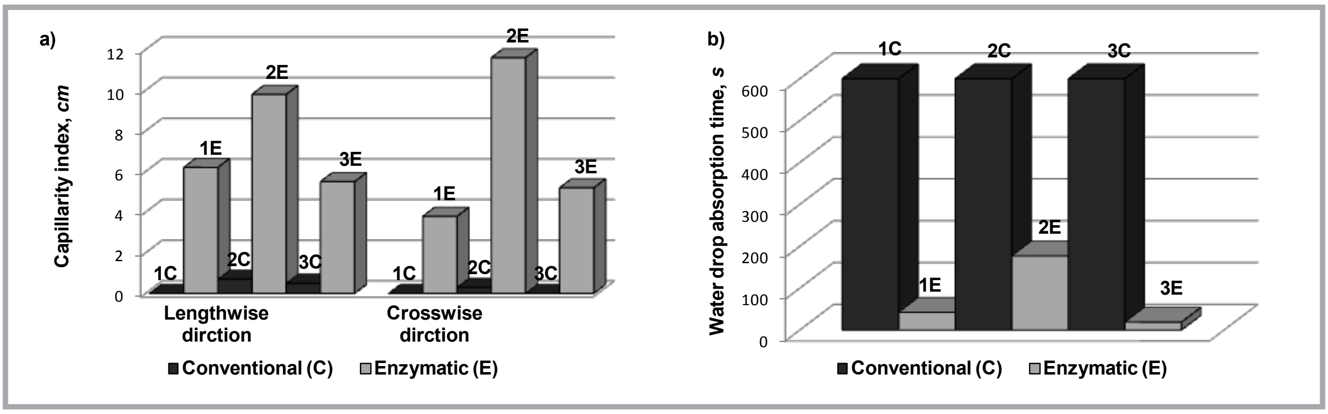

Figure 3. *Characteristics of the sorption properties of knitted fabrics after the conventional finishing process (1C – 3C) and after the enzymatic finishing process (1E – 3E): a –capillarity index, b – water drop absorption time.*

well as the ORION 6 program to archive and analyse SEM images. To fully assess hygroscopic, sorption and electrostatic properties of the knitted fabrics, their basic structural parameters were also tested including the course density, wale density, knitted fabric thickness and surface weight [28]. The tests were carried out at accredited laboratories of the Textile Research Institute.

Results

The tests performed showed no weight loss of the knitted fabrics after their biochemical modification with Texazym PES. Neither did they show any significant effect of the finishing methods on the knitted fabric's structural parameters, such as the stitch density and thickness, which results from the similar thermal conditions of knitted fabric finishing and similar conditions of wet fabric relaxation. Characteristics of these parameters in the form of average measurement values with the errors of average values, determined independently by the knitted fabric finishing method, are listed in ***Table 1*** (see page 88). The effect of the enzymatic modification of the knitted fabrics on their sorption properties, such as the capillarity index [25] and water drop absorption time, determined by the Tegewa Drop Test [26], is shown in ***Figures 3.a*** and ***3.b***, respectively. The morphology of the fibre surface after conventional finishing and biochemical modification is illustrated in ***Figures 4.a*** and ***4.b***, respectively. The SEM photos were taken with a magnification of × 2000. Results for knitted fabric hygroscopicity and electrostatic properties determined at an air related humidity of 25 and 65% are listed in ***Table 2*** and ***Tables 4 - 6*** (see page 88).

The knitted fabric variants used in the research work are characterised by different structures of plain wale stitches (***Figure 1.a - 1.c***). Knitted fabric variants "2" and "3", containing two component stitches in the background and two component stitches incorporating the carbon fibre-containing yarn into the network system, are characterized by similar values of thickness and surface weight. However, variant "2" shows a higher loop density by about 15%. Knitted fabric variant "1", whose two component stitches form the knitted fabric background and one stitch consist of carbon fibre-containing yarn in the system of vertical wefts, is characterised by lower values of surface weight (by about 20%) and thickness (by about 30%) and surface density (by 15 – 30%) compared to those of knitted fabric variants "2" and "3". The content of yarn with carbon fibre in the structures of the variants analysed ranges from to 5.1 to 13.8% depending on the method of its incorporation and the background stitch structure.

The test results of knitted fabric capillarity and surface water absorption (Tegewa Drop Test) shown in ***Figures 3.a*** and ***3.b*** indicate the effectiveness of knitted fabric biochemical modification with the enzymatic agent Texazym PES in improving sorption properties of the knitted fabrics investigated. The capillarity index increased about 10 to 30 times for the lengthwise direction and about 40 to 50 times for the crosswise direction, depending on the knitted fabric structure parameters. From the measurements of the water drop absorption time it follows that the biochemical modification of knitted fabrics improves their hydrophilic properties.

The changes in the knitted fibre surface and knitted fabric sorption properties (***Figure 4.b***) with specified changes in the sorption properties of the fabrics (***Figures 3.a*** and ***3.b***) can be explained by the mechanism of action of the specified enzyme type on the polyester fibre surface, consisting in hydrolysis ester bonds (–COO–) and forming reactive hydroxyl groups (-OH) as well as carboxyl groups (-COOH) according to the following general scheme [15, 29, 30]:

$$\text{R-COOR'} \xrightarrow{enzyme} \text{R-COOH + HO-R'}$$

where: R-COO-R' - general formula of aliphatic esters, R, R' - alkyl groups.

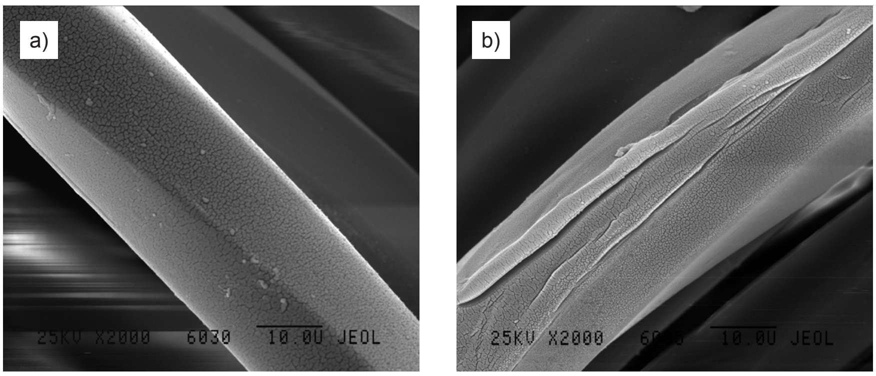

Figure 4. *SEM images of polyester fibres; a) after the conventional finishing of fabric, b) after the biochemical modification of fabric.*

Table 1. Characteristics of basic structural parameters and surface weight of knitted fabrics.

Knitted fabric variant	1	2	3
Knitted fabric course density, number of courses/dm	109.0 ± 1.04	151.0 ± 2.48	130.0 ± 1.96
Knitted fabric wale density, number of wales/dm	64.6 ± 0.68	66.8 ± 1.04	67.0 ± 0.88
Knitted fabric surface density, number of loops/dm^2	7050 ± 82	10090 ± 290	8710 ± 225
Knitted fabric thickness, mm	0.54 ± 0.01	0.75 ± 0.01	0.73 ± 0.01
Knitted fabric surface weight, g/m^2	104.3 ± 2.3	128.5 ± 2.9	134.3 ± 1.6
Content of yarn with carbon fibre in knitted fabric, %	5.1 ± 0.4	13.8 ± 0.2	9.8 ± 0.6

Table 2. Hygroscopicity index of knitted fabrics.

Knitted fabric variant	Hygroscopicity, %			
	RH = 25 ± 2%		RH = 65 ± 2%	
	Conventional (C)	Enzymatic (E)	Conventional (C)	Enzymatic (E)
1	1.72 ± 0.24	1.76 ± 0.20	2.12 ± 0.44	2.57 ± 0.46
2	1.89 ± 0.04	2.29 ± 0.32	2.52 ± 0.14	2.74 ± 0.30
3	1.94 ± 0.16	2.07 ± 0.26	2.08 ± 0.08	2.13 ± 0.14

Table 3. Results of significance statistic analysis of the effect of the finishing procedure and RH mesurement conditions on the fabric hygroscopicity index.

Knitted fabric variant / Factors tested	1	2	3
Air humididity in condition tested	0.00395	0.000301	0.2558
Kind of finishing process	0.1854	0.0181	0.3244
Air humididity in condition tested and kind of finishing process (interaction)	0.2680 $F(1.16) = 1.32$	0.4303 $F(1.16) = 0.65$	0.6502 $F(1.16) = 0.21$

Table 4. Test results of knitted fabrics surface resistance.

Knitted fabric variant	Surface resistance, 10^5 Ω			
	RH = 25 ± 2%		RH = 65 ± 2%	
	Conventional (C)	Enzymatic (E)	Conventional (C)	Enzymatic (E)
1	4.91 ± 0.19	5.93 ± 0.18	4.22 ± 0.13	4.70 ± 0.44
2	20.7 ± 2.2	5.42 ± 0.38	14.9 ± 2.4	4.62 ± 0.24
3	3.97 ± 0.18	3.80 ± 0.40	3.18 ± 0.27	3.12 ± 0.38

Table 5. Test results of half-decay time knitted fabric's charge.

<table>
<tr><th rowspan="3">Knitted fabric variant</th><th colspan="4">Time of charge half-decay, s</th></tr>
<tr><th colspan="2">RH = 25 ± 2%</th><th colspan="2">RH = 65 ± 2%</th></tr>
<tr><th>Conventional (C)</th><th>Enzymatic (E)</th><th>Conventional (C)</th><th>Enzymatic (E)</th></tr>
<tr><td>1</td><td>1.21 ± 0.27</td><td>0.11 ± 0.04</td><td rowspan="3">< 0.01</td><td rowspan="3">< 0.01</td></tr>
<tr><td>2</td><td rowspan="2">< 0.01</td><td rowspan="2">< 0.01</td></tr>
<tr><td>3</td></tr>
</table>

Table 6. Test results of knitted fabric's screening factor.

Knitted fabric variant	Screening factor, -			
	RH = 25 ± 2%		RH = 65 ± 2%	
	Conventional (C)	Enzymatic (E)	Conventional (C)	Enzymatic (E)
1	0.42 ± 0.01	0.47 ± 0.01	0.50 ± 0.01	0.51 ± 0.04
2	0.79 ± 0.01	0.82 ± 0.01	0.80 ± 0.01	0.82 ± 0.01
3	0.72 ± 0.01	0.72 ± 0.01	0.76 ± 0.02	0.75 ± 0.02

In the hygroscopicity index tests (***Table 2***) of the knitted fabric after conventional finishing at RH 25 and 65%, average values ranged from 1.72 to 1.94 and from 2.08 to 2.52, respectively, while corresponding values of the fabrics after modification with enzyme Texazym PES ranged from 1.76 to 2.29 and from 2.13 to 2.74, respectively. On account of considerable errors of the average hygroscopicity index value obtained on the basis of the measurements made, assessment of the effect of the fabric finishing procedure and measurement RH conditions on the hygroscopicity index was carried out in a statistical way on the basis of two-factor variance analysis with the use of the *STATISTICA* program. Analysis of the effect of the factors tested on the hygroscopicity index was carried out for the boundary value at a significance level of 0.05. The results of significance tests for the fabric variants used are listed in ***Table 3***.

Based on the statistical analysis performed, it was shown that the finishing procedure exerts a significant effect on the hygroscopicity index under specified conditions of relative air humidity of 25% and 65% only in the case of fabric variant "2", while in the case of variant "1", the feature tested was affected only by humidity conditions. In the case of fabric variant "3", the test results showed no significant effect of the parameters tested on the hygroscopicity index. The results of these tests show that the structural parameters of fabrics should be the fundamental criteria in the creation of hygroscopic properties by the biochemical modification used in this study.

Based on the results of testing the surface resistance index under RH conditions consistent with the requirements for protective clothing [27], the knitted fabrics selected for experiments show average values within the range of $3.97×10^5$ - $2.07×10^6$ Ω.

After finishing with the enzymatic agent Texazym PES, average values of this index amount to 3.80 - $5.93×10^5$ Ω, with a significant decrease in this parameter after modification (of about 70%) for knitted fabric variant „2". At RH 65% the knitted fabrics show lower surface resistance by about 15 - 30% compared to those obtained at RH 25%. Results of testing this parameter versus the knitted fabric hygroscopicity, determined at RH 25 and 65%, are illustrated in ***Figures 5.a*** and ***5.b***, respectively. For the knitted fabric stitch structures after the conventional finishing and enzymatic modification, the analysis of test results does not show any significant effect of the hygroscopicity index on the surface resistance parameter, except for knitted fabric variant "2".

For specified structures of knitted fabrics, their electrostatic properties are created by incorporating a yarn with conductive fibre and the way of doing it as well as by selecting an appropriate background structure into which the given yarn is incorporated [1 – 6]. ***Figures 6.a*** and ***6.b***

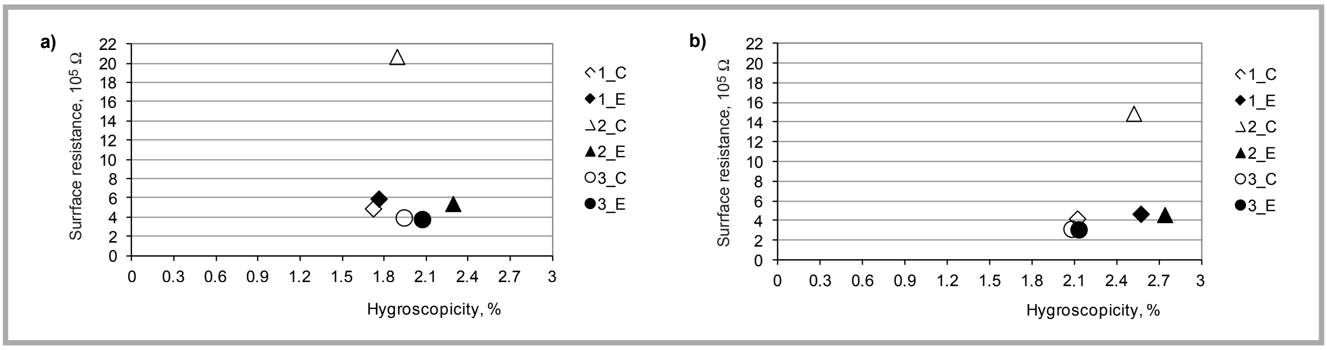

Figure 5. *Characteristics of the surface resistance parameter of knitted fabrics versus their hygroscopicity determined at RH 25% (a) and 65% (b).*

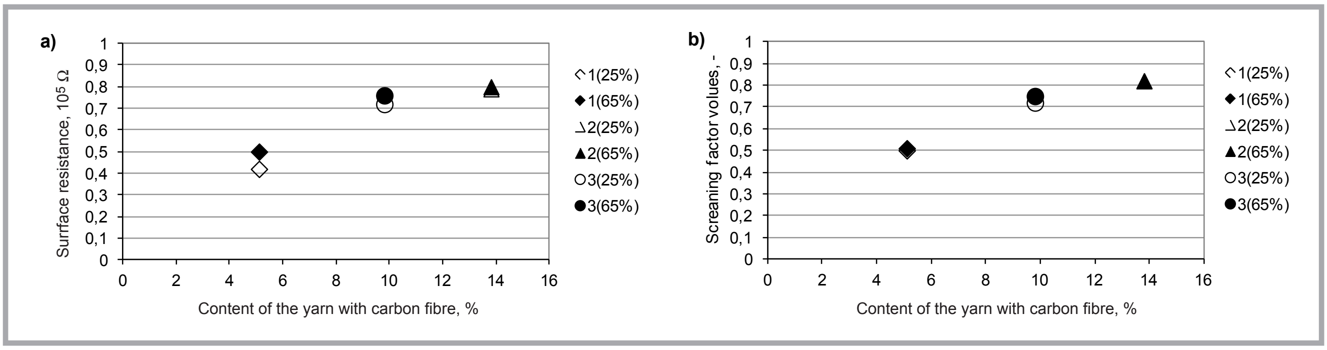

Figure 6. *Surface resistance (a) and fabric screening factor (b) versus the content of yarn with carbon fibre after conventional finishing (C) and enzymatic modification (E).*

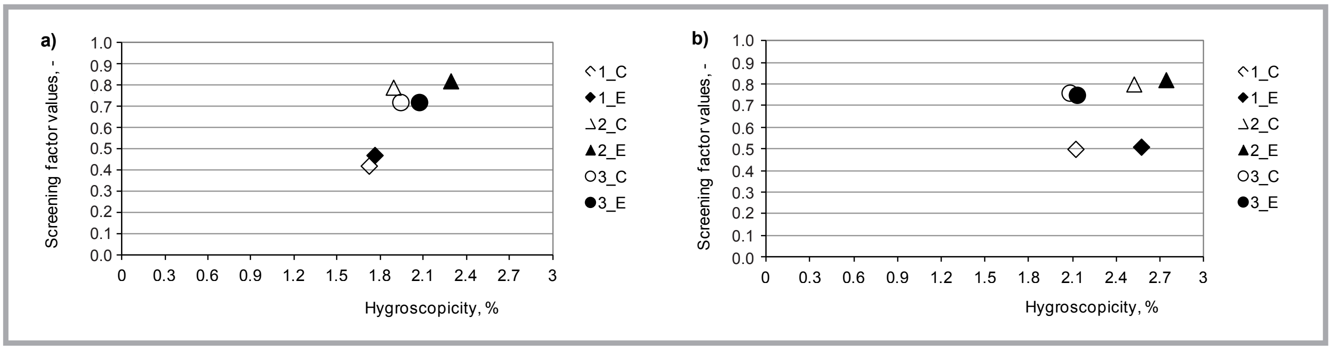

Figure 7. *Screening factor of knitted fabrics versus their hygroscopicity, determined at RH 25% (a) and 65% (b).*

present test results of the surface resistance and screening coefficient parameters obtained at a relative humidity of 25% in relation to the content of yarn with carbon fibre in the fabric structure for various fabric stitches used.

Charge half-decay time values of the knitted fabric structures used are generally lower than 0.01 s. Under the conditions of measuring this parameter according to the requirements for protective clothing [29], a higher value (1.21 s) is only shown by knitted fabric variant "1", which results from a lower content of yarn with carbon fibre in the structure of this variant compared to that of knitted fabric variants "2" and "3". From the example of structural variant "1" it follows that enzymatic modification with Texazym PES significantly decreases the half-decay time of the knitted fabric charge. For knitted fabric structural variants 1 and 2, the effect of the biochemical modification on the screening factor value is only observed under measurement conditions at RH 25%. The analysis of test results does not show any significant effect of hygroscopicity on the screening factor (***Table 3***), as is illustrated in ***Figures 7.a*** and ***7.b.***

Summary

The aim of the study was to assess the effect of the biochemical modification of polyester knitted fabrics containing carbon fibres on their electrostatic properties. The knitted fabrics used in this study included three variants of wale knitted fabrics with various stitch systems and structural properties. The biochemical modification of the knitted fabrics was carried out under laboratory conditions with the use of an enzymatic agent - Texazym PES. Investigations were performed in two stages: (a) the assessment of the hydrophilic effect of the enzymatic modification used, and (b) the assessment of its influence on the knitted fabric's electrostatic properties determined under conditions of 25% and 65%. relative air humidity A comparative analysis of the knitted fabrics selected was carried out for the fabric stitch structures used after their conventional finishing and enzymatic modification, respectively.

Conclusions

- Based on the test results for hygroscopicity, capillarity and water drop absorption parameters, it was shown that the enzymatic modification carried out with the use of esterase, under the trade name Texazym PES, imparts hydrophilic properties to knitted fabrics containing carbon fibres.
- Based on the test results of surface resistance, the charge decay half-life and screening coefficient, it was demonstrated that the biochemical modification of polyester knitted fabrics containing carbon fibre can beneficially influence the protective functions of the fabrics against static electricity; at the same time these functions primarily depend on the fabric's structural solutions and the content of yarn with carbon fibres as well as on the method of its incorporation into the fabric structure.
- In order to obtain a more reliable and unambiguous relationship concerning the electric and shielding properties of the knitted fabrics tested, a greater number of structures with varied amounts of carbon fibre content should be considered for a test programme.

Acknowledgement

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- *Algorithms of knitting for knitting materials constituting the material of examinations and analysis of the paper were drawn up using the AutoCAD 2007 program at The Department of Knitting Technology of the Faculty of Textile Engineering at The Technical University of Lodz.*

Editorial Notes:

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