INFLUENCE OF ANTISTATIC POLYESTER FIBERS ON THE PROPERTIES OF COTTON AND POLYESTER SINGLE JERSEY KNITTED FABRICS

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***Abstract**: In this research, the influence of the antistatic polyester fibers containing carbon black on the comfort properties of 100% and blended cotton as well as on 100% and blended polyester single jersey knitted fabrics was evaluated. The research results revealed that the behavior of the investigated knitted fabrics was dependent on their structure and mechanical characteristics. The electrical resistance of knitted fabrics decreased significantly due to the use of 4% antistatic polyester fibers. The electrical resistance of the pure and blended cotton knitted fabric was lower than that of the pure and blended polyester knitted fabrics. Antistatic polyester fibers positively influenced the air permeability of the polyester knitted fabric. The air permeability of 100% and blended cotton fabrics was approximately 3.5 times compared to both 100% and blended polyester fabrics, respectively. The carbon black polyester fibers influenced the decrease in thermal resistance, the increase in vapor permeability, and the minor increase in vapor resistance of both cotton and polyester knitted fabrics. Thermal resistance was lower, water vapor resistance was significantly higher, and relative water vapor permeability was slightly lower for the cotton and cotton/antistatic polyester knitted fabrics than for the polyester and polyester / antistatic polyester knitted fabrics, respectively. Therefore, the research results revealed that the presence of 4% antistatic polyester fibers in cotton and polyester knitted fabrics positively influenced their antistatic behavior and improved or almost did not alter their comfort properties.*

***Keywords:** knitted fabric, polyester, cotton, black carbon, antistatic properties, comfort properties.*

1 INTRODUCTION

Textiles are most commonly used to cover the human body. However, the responsible and motivated choice of textile fabric for a particular garment aiming to fulfil its required functions taking into account also both environment conditions and wearing intensity is a very complicated process. Therefore, textiles suitable for fulfilling specific functions of active leisure or sportswear are only those manufactured from innovative microfibers with complicated knitted structures such as double or three layers [1] and with finishes such as those that provide antistatic properties, etc. Donciu [2] investigated polyester and cotton fabrics knitted from yarns with copper and stainless steel core conductive fibers to approve their suitability for protective garments. Hebeish et al. [3] developed the new antistatic non-woven and weft knitted materials with conductive fibers. They concluded that the achieved specific properties of the weft knitted fabrics confirm their suitability for the manufacture of protective garments, i.e., for clean-room clothing, which should create a barrier for the generation of static charges.

Donciu [4, 5] investigated integral bilayer knit fabrics with carbon-based fibers and determined that the outer layer that was open to the working environment was mainly dissipative and capable of ensuring protection against electrostatic energy transfer to the working environment. However, the inner layer that contacted the human body became mainly conductive and ensured the controlled conductivity of the accumulated electrostatic charge. The antistatic properties of knit fabrics made from two types of modacrylic knitted fabrics containing antistatic PET fibers were investigated by Kim and Kim [6]. The results obtained were compared with those of the antistatic properties of cotton fabric by rubbing with wool and cotton fabrics attached to the measuring apparatus. Excel® knit fabric with modacrylic was observed to show better antistatic properties [6]. Kwon, et al. [7] showed that poly (ethylene terephthalate) (PET)/lyocell blended textiles had better antistatic property than the 100% polyester and lyocell fabrics. Seshadri and Bhat [8] determined that polypyrrole incorporated into cotton fabrics improved their antistatic and antimicrobial properties.

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Abdel Halim et al. [9] proposed permanent fixation of chitosan or monochlorotriazinyl-β-cyclodextrin for the finishing of cotton/polyester and polyester fabrics. In this way, they determined that the suggested finish improved the fabric's ability to better absorb moisture from air and water. Furthermore, it was determined that increased humidity of the fabric improved its electrical conductivity and antistatic properties. Pasta, et al. [10] determined that dislocated carbon nanotubes on the surface of cotton fibers created an electrically conductive network. Previous researches [11] also determined that electrical resistivity decreased and thermal conductivity increased due to the coating of cotton fabrics with carbon black particles. Hu, et al. [12] determined that the mixture of carbon black, dispersing agent, and PBT leads to the desirable conductivity of the fibers. Moreover, they also stated that fabrics manufactured from fibers with the core/sheath configuration could be successfully used for different applications within the textile industry. Thus, an overview of the published research showed that the antistatic properties of textiles can be improved most commonly by applying different finishes for their treatment. However, the antistatic properties created in this way showed a tendency to deteriorate due to textile laundering.

Today, sportswear development is directed towards enhancing their functional properties and suggesting optimal decisions about how to integrate electronic devices within a garment structure to monitor or increase its comfort properties. However, due to the static electricity of synthetic knitted fabrics, a negative impact on the functionality and stability of smart clothing during its wear process may occur. Thus, it is necessary to improve their antistatic properties. Furthermore, the literature review showed that the analyzed antistatic fibers were more suitable for protective clothing, etc., but not for leisure or sportswear. Thus, the objective of the current research was to investigate the influence of carbon black-containing antistatic polyester fibers on the structure, antistatic and comfort properties of cotton and polyester single jersey knitted fabrics. In this investigation, the differences between the properties of newly developed cotton and polyester knitted fabrics were also highlighted.

2 EXPERIMENTAL WORK

Antistatic polyester fibers were produced from the mixture of 0.5% carbon black and melted polyethylene terephthalate applying the fiber extrusion technique (Table 1). Polyester fiber, specifically poly(ethylene terephthalate) (PET) fiber, is the largest volume of synthetic fiber produced worldwide. Later, from the filaments produced, the staple fibers were cut. Commercially available cotton and polyester fibers produced by Masood Textile Mills Ltd. (Pakistan) were chosen to also manufacture knitted fabrics. The characteristics of the fibers involved in this research are summarized in Table 1.

Table 1 Characteristics of the fibers

Code	Fiber	Density [g/cm^3]	Linear density [dtex]	Length [mm]
CO	cotton	1.54	1.77-1.84	28
PES	polyester	1.39	1.3	38
PET^C	antistatic polyester	1.40	1.3	38

From the prepared fibers, CO, CO/PET^c, PES and PES/PET^c yarns of the same count 24.6 tex (24 Ne) were twisted. Their characteristics are presented in Table 2.

Before testing, the fibers′ samples were conditioned and all tests were performed under standard atmospheric conditions: 20±2°C temperature and 65±2% relative humidity for 24 hours as required according to the standard ISO 139 [13].

Tensile strength and elongation of the manufactured yarns were determined using the Uster® Tensorapid measurement system according to the standard ASTM D 2256 [14]. The relative measurement errors of the mean tensile strength values, calculated from the five tested samples, in each sample group varied from 1.87% up to 5.09%, and for the yarn elongation from 2.46% up to 7.69%. The twist per inch of the yarns was determined according to the ISO 17202 standard [15].

A simple and widely used single jersey pattern was chosen to manufacture the knitted fabrics. In this research, the circular weft knitting machine of diameter 30 and the machine gauge 20 (Fukuhara, Japan), with the needles 1860 and the feeders 90, was used. The stitch length of 3.2 mm was chosen to knit all investigated fabrics.

Table 2 Yarns characteristics

Yarn code	Composition	Diameter [mm]	Twist [inch^{-1}]	Tensile strength [N]	Elongation [%]
CO	100% cotton	0.255	20.8	3.39	4.29
CO/PET^C	96% cotton 4% antistatic polyester	0.254	21.6	3.73	5.92
PES	100% polyester	0.313	13.8	7.16	10.97
PES/PET^C	96% polyester 4% antistatic polyester	0.268	13.2	7.50	11.11

Table 3 Characteristics of the knitted fabrics

Fabric code	Yarn code	Thickness [mm]	Area density [g/m²]	Density [cm⁻¹]		Loop length [mm]	Tightness factor	Porosity
				Wale count	Course count			
M1	CO	0.80	186	13	18	4.2483	1.17	0.90
M2	CO/PET^C	0.84	193	13	19	4.2316	1.17	0.89
M3	PES	0.60	152	10	16	5.2146	0.95	0.93
M4	PES/PET^C	0.59	153	10	16	4.4649	1.11	0.94

The samples of the knitted fabrics′ were washed according to the standard test method AATCC 135 [16] in aqueous detergent at 40°C temperature. After the washing, the knitted fabrics′ samples were tumbler dried and placed on the racks for 48 h of relaxation. The characteristics of the knitted fabrics manufactured are given in Table 3.

Fabric thickness was measured with the UNI-THICKNESS LAB 1880 meter (MESDAN, Italy) according to the ASTM D 1777 standard [17] applying a pressure of 1 kPa in a 20 cm^2 area. The thickness of each sample was measured at five different places and the mean value of the thickness for each knitted fabric was calculated. The relative errors of the measured thicknesses varied from 1.19% up to 1.69%.

The area density of the investigated knitted fabrics was determined according to the standard ASTM D 3776 [18], and the course and wale counts per cm according to the standard ASTM D 8007 [19]. The coefficient of variation did not exceed 5%.

Peirce [20] stated that for a normal structure, the length of the loop *L* depends only on the thickness of the yarn *d*. Thus, the loop length of the investigated knitted fabric was calculated according to equation (1):

$$L = 16.66\mathrm{d} \tag{1}$$

The tightness factor (*TF*) of the knit fabrics was calculated according to equation (2):

$$TF = \frac{\sqrt{T}}{L} \tag{2}$$

where: *T* is the count of yarns [tex]; *L* is the loop length of the knit fabric [mm].

The porosity *P* of the knitted fabrics was calculated according to equation (3):

$$P = 1 - \frac{(\rho_b)}{(\rho_s)} \tag{3}$$

where: ρ_b is the density [g/cm^3] of the knitted fabric (fabric weight in g/cm^2 and fabric thickness in cm); ρ_s is the fiber density [g/cm^3].

The influence of the antistatic polyester fibers produced (PET^C) on the antistatic properties of the cotton and polyester knitted fabrics involved in this research was evaluated on their electrical resistance R_m. This parameter was measured using the 4339B high resistance meter (Ohmmeter) manufactured by Hewlett Packard. Electrical resistance measurements were carried out at the test voltage setting V_s of 100 V and the electrical current I_M of 10 mA. Readings were recorded after 60 s of electrodes′ placement on a knitted fabric sample. The mean values of the measured resistance R_m were calculated from five samples in each sample group. The coefficient of variation ranged from 0.25% up to 0.53%.

To evaluate the comfort properties of the knitted fabrics produced, we analyzed the thermal resistance R_t, the relative water vapor permeability p_{wv}, *the* water vapor resistance *Ret,* and the air permeability *R* were analyzed.

The relative permeability of the water vapor p_{wv} in percent and the water vapor resistance R_{et} in m^2·Pa/W were determined applying the non-destructive method realized with PERMETEST (Sensora Instrument, Czech Republic) [21] according to the ISO 11092 standard [22]. Five samples were tested in each fabric sample group. The coefficient of variation ranged from 1.0% up to 2.0%.

The relative water vapor permeability p_{wv} [%] of the knitted fabrics tested was calculated according to equation (4) [21]:

$$p_{wv} = (u_s/u_o).100 \tag{4}$$

where: u_s is the heat loss of the free wet surface without a fabric sample; u_o is the heat loss of the wet measuring head (skin model) with a tested fabric sample.

The water vapor resistance R_{et} [m^{2}Pa/W] was calculated according to equation (5) [21]:

$$R_{et} = (p_{wsat} - p_{wo}).\left(\frac{1}{u_s} - \frac{1}{u_o}\right) = -C.(100 - \varphi).\left(\frac{1}{u_s} - \frac{1}{u_o}\right) \tag{5}$$

where: p_{wsat} is the partial saturation pressure of vapor valid for the temperature of the air in the measuring laboratory (T_o=20°C) [Pa]; p_{wo} is the partial water vapor in the laboratory air [Pa]; φ is the relative humidity [%] (φ=6%). The constant *C* was determined by applying the calibration procedure. A special hydrophobic polypropylene (PP) reference fabric was used for this purpose.

Five samples were tested in each fabric sample group to determine thermal resistance. The coefficient of variation ranged from 1.05% up to 3.19%.

The thermal resistance R_t [m^2K/W] was calculated from the equation (6) [21]:

$$R_t = K.(t_H - t_o).\left(\frac{1}{U_1} - \frac{1}{U_o}\right) \quad (6)$$

where: t_H is the measurement head temperature of the measuring head equal to 32-35°C; U_s and U_o represent the steady state electrical voltages shown on the digital display, for the case of measurement with and without the sample [21]. The sensitivity constant K was determined by applying the calibration procedure [21].

The air permeability test was carried out using the M021A air permeability tester with a test head of 100201 of 20 cm^2 manufactured by SDL ATLAS according to the ISO 9237 standard [23]. The test was repeated in ten places for each fabric sample. The coefficient of variation ranged from 0.19% up to 0.45%. Later, the mean air rate q_v in l/min was calculated for each fabric sample. The air permeability R was calculated according to equation (7):

$$R = \frac{q_v}{A}.167 \quad (7)$$

where: q_v is the air rate [l/min]; and A is the work area of the fabric specimen [cm^2].

3 RESULTS AND DISCUSSION

The determined characteristics of the yarns used for the manufacture of cotton, cotton/antistatic polyester, polyester, and polyester/antistatic polyester plain jersey knitted fabrics are presented in Table 2. By analyzing them, it can be seen that the tensile strength of cotton and polyester yarns increased after insertion of antistatic polyester fibers into their structure. Yang et al. [24] also stated that the use of carbon nanotubes increased the breaking strength of cotton yarns. The use of antistatic polyester fibers also increased the elongation of both cotton/antistatic polyester and polyester/antistatic polyester yarns compared to 100% cotton and 100% polyester yarns, respectively. It is worth mentioning that these mechanical parameters of the polyester and polyester/antistatic polyester yarns were almost two times higher than those of the cotton and cotton/antistatic polyester fibers, respectively. 100% and blended cotton yarns had the highest twist factor and smaller diameters compared with ones of 100% and blended polyester yarns, respectively (Table 2).

Analysis of the characteristics of the manufactured knitted fabrics (Table 3) has shown that the higher fiber density values (Table 1), as well as the width and course counts of 100% and blended cotton knitted fabrics, influenced their higher area densities compared to those of 100% and blended polyester knitted fabrics, respectively. The higher densities of the wale and the course of cotton and cotton/antistatic polyester knit fabrics could be influenced by the ability of cotton fibers to readily absorb moisture and susceptibility to shrinkage. The area density of the knitted fabrics involved in this research was linearly related to their thicknesses. That is, the thinner fabrics demonstrated their lower area densities. This observation is relevant as the thickness of the fabric has a significant influence on its insulation properties, air permeability, etc. The small decrease in area density and the increase in porosity P of cotton/antistatic polyester knitted fabric were determined compared to those of 100% cotton fabric (Table 3).

In this research, the impact of antistatic polyester yarns containing carbon black on the electrical resistance R_m and comfort properties of single-jersey cotton and polyester knitted fabrics was studied. Furthermore, the comfort properties were evaluated by analyzing their four relevant characteristics: thermal resistance R_t, relative water vapor permeability p_{wv}, water vapor resistance R_{et} and air permeability R. The summary of these properties of the single jersey knitted fabrics investigated is given in Table 4.

Air permeability R is considered as the ability of textiles to pass air through their structure at a pressure difference depending on the type of knit fabric. It is also known from the literature that porosity is the dominant factor influencing the air permeability of knitted fabrics. Therefore, as expected, the linear relationship between air permeability and porosity P of the investigated knitted fabrics was determined (Figure 1). Thus, the increase in porosity P of the knitted fabrics also influenced the increase in air permeability R. Carbon black used to enhance the antistatic properties of the knitted fabrics tested in this investigation positively influenced the air permeability R of the polyester/antistatic polyester knitted fabric, despite the fact that its tightness factor TF was higher compared to that of 100% polyester fabric (Table 3).

Table 4 Properties of the fabrics: R_m – electrical resistance; R – air permeability; R_t – thermal resistance; p_{wv} – relative water vapour permeability; R_{et} – water vapour resistance

Fabric code	R_m [Ω]	R [mm/s]	R_t [m^2K/W]	p_{wv} [%]	R_{et} [m^2Pa/W]
M1(CO)	3.44×10^{12}	450	0.019	60	2.65
M2(CO/PET^C)	2.76×10^{12}	495	0.017	62	2.70
M3(PES)	3.72×10^{13}	1655	0.028	66	1.70
M4(PES/PET^C)	3.41×10^{12}	1660	0.027	68	1.88

Analysis of the air permeability of the tested knitted fabrics (Table 4) has shown that the air permeability of 100% cotton and blended cotton fabrics was found different. Cotton blended with antistatic polyester fabric showed high air permeability than 100% cotton. It was supposed to be due to presence of antistatic polyester fiber in the blend that caused high porosity. Similar trend of an increase in air permeability observed in 100% polyester and blended polyester fabric.

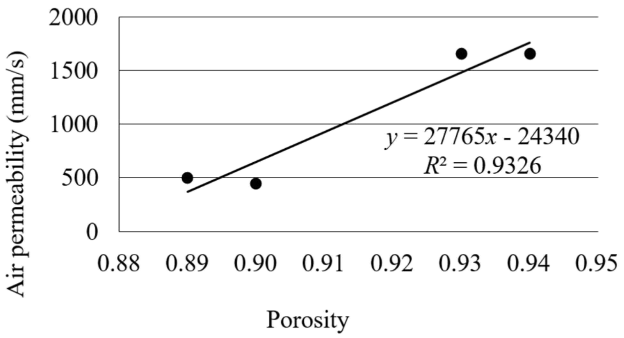

Figure 1 Dependence between air permeability *R* and porosity *P* of knitted fabrics

According to the resistance to standard [22], the resistance to water vapor R_{et} is defined as the difference in water vapor pressure between the two faces of a knit fabric divided by the resulting evaporative heat flux per unit area in the direction of the gradient. From the results presented in Table 4, it can be seen that the water vapor resistance R_{et} of cotton and cotton/antistatic polyester knitted fabrics was significantly higher than one of the polyester and polyester/antistatic polyester fabrics. This may be explained by the higher absorption and thickness of the 100% and blended cotton fabrics compared to ones of the 100% and blended polyester fabrics. A minor increase in the vapor resistance of cotton and polyester knitted fabrics was observed as a result of the use of antistatic polyester fibers in their structure. Similar tendencies were also confirmed in previously published research, which stated that air permeability and thermal and water vapor resistance depended on the structural parameters of the fabrics.

In the current investigation, it was determined that the resistance to water vapor R_{et} decreased when the porosity of the fabric *P* increased (Figure 2a) and showed a tendency to increase due to the increase in the *TF* tightness of the fabric (Figure 2b).

Relative water vapour permeability p_{wv} was found slightly higher for cotton blended fabrics than 100% cotton and similarly for polyester (blended polyester > 100% polyester) knitted fabrics (Table 4). Thus, the embedded carbon black polyester fibers influenced the increase in the vapour permeability p_{wv} of 100% cotton and 100% polyester knitted fabrics. Supposedly, it occurred because of the small diameter of antistatic polyester fibers compared to cotton fibers, which caused high porosity leading to high vapor permeability.

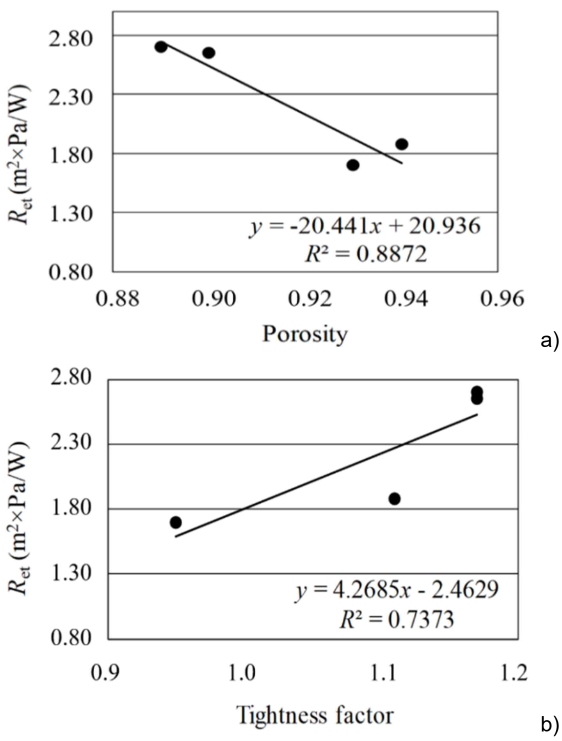

Figure 2 Dependence of the water vapor resistance R_{et} on the porosity *P* (a) and the tightness factor *TF* (b) of the knitted fabrics

Thermal resistance R_t is defined as the temperature difference between the two faces of a knit fabric divided by the resulting evaporative heat flux per unit area in the direction of the gradient [21]. The thermal resistance R_t is generally related to the thickness of the fabric, but the composition also influences the thermal resistance of the fabrics. The thermal resistance R_t of the cotton and cotton/antistatic polyester knitted fabrics was lower than that of the polyester and polyester/antistatic polyester knitted fabrics. Carbon black influenced the decrease in thermal resistance R_t of both cotton and polyester knitted fabrics (Table 4). It was supposed that due to the inherent nature of carbon being conductive that there was more heat conductance in the material. It was also previously determined that the thermal conductivity of carbon was high and the thermal resistance low, and the covering of the cotton fabric by carbon also influenced the increase in its thermal conductivity.

In this investigation, the electrical resistance R_m of the investigated knitted fabrics was measured to predict their antistatic properties. From the results presented in Table 4 it can be seen that the electrical resistance R_m of 100% polyester knitted fabrics was highest due to the non-conductive nature of the polyester fibers. Therefore, they tend to accumulate electrical charge for a long time. The electrical resistance of 100% cotton knitted fabric and blended polyester knitted fabrics was lower than that of 100% polyester knitted fabrics. Furthermore, 4% of antistatic polyester fibers embedded in the structures of polyester and cotton fabrics significantly decreased their electrical resistance R_m, as previously determined similarly. Thus, the research results showed that the presence of 4% antistatic polyester fibers in cotton and polyester knitted fabrics positively influenced their antistatic behavior. Telipan et al. [25] and Varnaitė Žuravliova et al. [26, 27] stated that textiles having 10^{10}-10^{12} Ω vertical resistance could be defined as antistatic textiles.

Thus, in the current research, it was shown that the use of antistatic polyester fibers for the purpose of reducing the static electricity of knitted fabrics improved or almost did not alter the comfort properties of the knitted fabric.

4 CONCLUSION

In the current research, the influence of antistatic polyester fibers containing 4% carbon black on the antistatic and comfort properties of 100% and blended cotton as well as on 100% and blended polyester single jersey knitted fabrics was evaluated. The research results revealed that the behaviour of 100% and blended cotton fabrics was different from one of 100% and blended polyester knitted fabrics. The tensile strength and elongation of the cotton and polyester yarns used to manufacture knitted fabrics were determined to increase due to the presence of antistatic polyester fibers in their structure. These mechanical characteristics of 100% and blended polyester yarns were almost two times higher than ones of 100% cotton and cotton/antistatic polyester yarns, respectively. The research results also revealed that the higher fiber density and the wale and course counts of 100% and blended cotton knitted fabrics influenced their higher area densities compared to those of 100% and blended polyester knitted fabrics, respectively. A small decrease in area density and an increase in porosity of cotton/antistatic polyester knitted fabric were determined compared to those of 100% cotton fabric.

The antistatic properties of the knit fabrics involved in this investigation were evaluated on the basis of their electrical resistance. The electrical resistance of 100% cotton knit fabric and blended polyester knit was lower than that of 100% cotton knit fabrics and blended polyester knit, and the use of 4% antistatic polyester fibers in polyester and cotton fabrics significantly decreased their electrical resistance. The carbon black used to enhance the antistatic properties of the fabrics positively influenced the air permeability of the polyester/ /antistatic polyester knitted fabric. The air permeability of 100% and blended cotton fabrics was approximately 3.5 times compared to both 100% and blended polyester fabrics, respectively.

The thermal resistance of the cotton and cotton/antistatic polyester knitted fabrics was shown to be lower than that of the polyester and polyester/antistatic polyester knitted fabrics. Carbon black influenced the decrease in thermal resistance of both cotton and polyester knitted fabrics. The relative permeability of the water vapour was slightly higher for 100% and blended polyester knitted fabrics mixed compared with those of 100% and blended cotton fabrics, respectively. Also, the embedded carbon black influences the increase in the vapour permeability of the 100% cotton and 100% polyester knitted fabrics. The water vapor resistance of cotton and cotton/antistatic polyester knitted fabrics was significantly higher than that of polyester and polyester/antistatic polyester fabrics. A minor increase in the vapor resistance of cotton and polyester knitted fabrics was observed as a result of the use of antistatic polyester fibers in their structure. The resistance to water vapor decreased as the porosity of the fabric increased and showed a tendency to increase as a result of an increase in the tightness of the fabric.

Therefore, the research results showed that the presence of 4% antistatic polyester fiber in cotton and polyester knitted fabrics positively influenced their antistatic behavior. Furthermore, it was shown that the use of antistatic polyester fibers for the purpose of reducing static electricity of knitted fabrics improved or almost did not alter the comfort properties of the knitted fabric investigated.

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