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Influence of Relative Humidity on Electrical Properties of Textile Laminates

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The aim of this paper is to determine the influence of relative humidity on the comfort and electrical resistance properties of textile laminates in order to predict possible changes in footwear protection levels. Four textile laminates of different structure and fibre nature were selected for the study. It was determined that water vapour absorption of textile laminates strongly depends on the humidity of the storage environment. The absorption ability of laminates increases about 1.8 – 3 times as relative humidity increases from 65 % up to 95 %. The degree of increase depends on the textile laminate structure and the nature of the materials layers. The electrical properties of protective footwear can be influenced by the structure, thickness, relative humidity, and voltage of textile laminates. For textile laminates composed of natural and synthetic fibres and polymer foam as insulators, the resistivity increases with the thickness of the synthetic fibre and polymer layer. At low voltage (U = 100 V), the textile laminates tested became insulating materials, as the electrical resistivity exceeded the threshold values for antistatic materials in all relative humidity ranges. At high voltage (U = 500 V) the electrical resistivity of textile the laminates drops dramatically when the relative air humidity increases and the level of protection of the laminates depend on the amount of moisture absorbed and the nature of the layer materials. The laminates possessed insulating properties in environments of up to 65 % relative humidity. In a high humidity of the environment, the insulating properties of textile laminates turned to antistatic, except for laminate without a polymeric membrane, which became conductive.

Keywords: textile laminate, atmosphere humidity, water vapour absorption, electrical resistance.

1. INTRODUCTION

The main function of protective equipment for occupational use is protection from the risks posed by workplace hazards [1, 2]. Employees' productivity and satisfaction with the workplace can increase greatly when they work with the reassurance of protection against injury. While working with and around electricity, special attention must be paid to footwear that may reduce the possibility of electrocution or other electricity-related incidents [3 – 5]. Among all the materials used in the production of personal protective equipment, an important category is represented by materials for the protection and control of any electrostatic discharge (ESD) phenomena, where the electrostatic charges can dissipate over their surfaces or their volumes [6]. ESD protective materials can be grouped, according to their electrical conductivity, into several categories: ESD anti-static materials, ESD static-dissipative materials or ESD conductive materials. A basic electrical parameter for ESD protective materials is electrical resistivity. It is a generally accepted statement that materials are antistatic if the resistivity measured is in the range of $10^5\ \Omega < R < 10^9\ \Omega$, which is an acceptable compromise between conductive and insulation requirements [3].

The resistivity of semi-insulating, antistatic, static dissipative, ESD protective materials depends strongly on the relative humidity of the environment [6, 7 – 9]. As a result, the protective properties of materials may vary during wear due to moisture absorption and the level of protection may also change. It was found [7, 8, 10] that the electrical resistivity of ESD protective materials increases, materials have a highly restricted capability to charge dissipation at a relative humidity below 20 – 40 % and they may become insulators in a low humidity environment. At low humidity the risk of ESD increases [7, 8, 10, 11]. Conversely, higher moisture amount absorbed by the material could contribute to free charge carriers and influence the conductivity of the material. As a result, the resistivity of the material decreases with increasing relative humidity [8, 9, 12, 13].

At higher human activity the feet release a large amount of sweat. They can sweat around 30 g/h, and in some cases up to 50 g/h, which can increase the microclimate humidity and lead to the accumulation of moisture in the materials [14 – 16]. The surface resistivity of materials containing adsorbed moisture decreases due to the presence of a continuous layer of moisture on the surface [17]. Safe wearing conditions and a comfortable microclimate for personal protective equipment can be ensured by using appropriate materials [18, 19].

Especially the hygienic properties and comfortability of protective footwear are improved by using laminates for the footwear lining made from textile fabrics and nonwoven with desirable hydrophilic and hydrophobic characteristics. They have good hygienic properties and ensure a comfortable microclimate, but the electrical conductivity of most of these polymers is so low that they are considered insulators [6, 20]. This is an advantage up to a certain extent for electric safety reasons and to avoid short-circuits occurring in dangerous working environments. Still,

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personal protective equipment materials must not be "perfect" insulators, e.g. to prevent the accumulation of static charges [20]. The specific resistivity of textile materials increases with an increase in the synthetic fibre amount because many synthetic fibres used for textile fabrics are insulators with a resistivity in order of 10^{15} Ω [12, 21, 22]. Textile materials are known for their ability to accumulate electrical charge; therefore, it is important to understand how to minimise the detrimental influence of static electricity. Recently, new breathable and highly durable textile laminates have been produced for protective clothing to maintain equilibrium in thermo-regulation processes over a long period [23, 24]. Such laminates are engineered to meet specific requirements for military, sports and leisurewear, as well as for daily footwear.

The purpose of this paper is to determine the influence of relative environment humidity on the comfort and electrical resistance of multilayer textile laminates to predict possible changes in materials protection levels.

2. EXPERIMENTAL

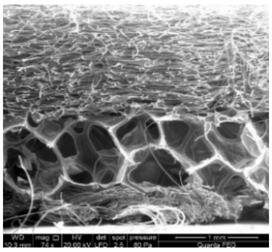
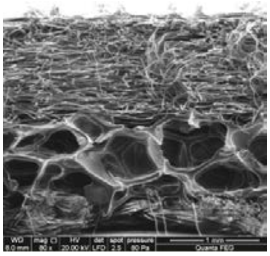
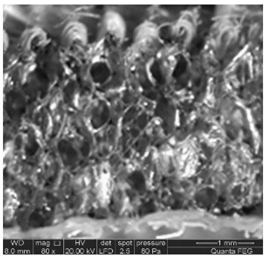
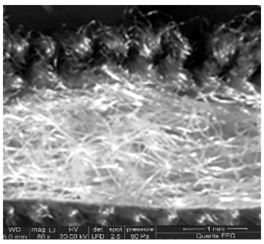
2.1. Materials

For the investigation, four different commercially available textile laminates typically used for footwear lining were selected. The chosen textile laminates are composed of three or four layers with different chemical compositions, structure, and thickness. The structures and characteristics of investigated laminates are presented in Table 1.

The laminates L1, L3, and L4 consist of top and bottom layers from knitted or nonwoven fabrics, a middle layer from polyurethane foam, or nonwoven fibre with a large number of microscopic open pores allowing air to circulate. These layers provide cushioning and create good hygienic properties of lining and a comfortable micro-climate around the foot. The textile laminates L3 and L4 contain water vapour permeable microporous or hydrophilic membranes in their structure: L3 by *Tepor*, and L4 by *LTI*. The permeable membranes act as a barrier to liquid water and soil from the environment but are permeable enough to allow significant amounts of perspiration [24].

The laminate L1 does not contain a membrane in its structure.

Table. 1. Characteristics of investigated textile laminates

Code	ρ, g/cm^3	P_{wv}, mg/cm^{2}h	Cross-section views of laminates	Layer compositions		Thickness h, mm
L1	0.11	133.00		Microliner	CO non-woven fabric	1.30
					PU foam	1.00
					PES and PU blend knit *DryLiner*	0.50
L2	0.14	15.1		Hydrophilic PU membrane *Puratex*		0.20
				Microliner		2.8
L3	0.16	4.26		PA knit		0.75
				PU foam		2.90
				Nonporous hydrophilic PES membrane *Tepor*		0.015
				PES knit		0.35
L4	0.22	3.20		PA knit		1.10
				PES non-woven		1.30
				PU membrane, microporous		0.030
				PES knit		0.60

Notes: CO – cotton; PU – polyurethane; PES – polyester; PA – polyamide; P_{wv} – water vapour permeability

To determine the influence of permeable membrane on the properties of textile laminates, microporous polyurethane membrane *Puratex* was hot laminated on the bottom of laminate L1 at the temperature of (90 ± 5) °C and pressure of (35 ± 2) kPa for (20 ± 2) s to obtain a laminate L2, which consists of laminate *MICROLINER* and membrane *Puratex*.

2.2. Testing methods

The test specimens with the dimension of 100 mm × 100 mm were conditioned for at least 48 h in a standard atmosphere (temperature T = 23 ± 2º C, relative humidity RH = 50 ± 5 %, i.e. 23/50) in accordance with LST EN 12222: 1997.

In order to investigate the effect of relative humidity on the properties of textile laminates the specimens were stored in airtight containers at the temperature of 20º C ± 2º C and different relative humidity (50 ± 5) % – (95 ±5) %. After 7 days' storage, the water vapour absorption and electrical resistance of samples were measured. The water vapour absorption and electrical resistance were measured for four different textile laminate test groups (L1 – L4). Tests at different relative humidity environments were performed using three samples of the same laminate and the average result value for each laminate was calculated. The coefficient of variation for water vapour absorption and electrical resistance did not exceed 5 and 7 percent, respectively.

The water vapour absorption A_{RH} was calculated according to the formula:

$$A_{RH} = \frac{M_{RH} - M_{50\%}}{S_a}, \quad (1)$$

where $M_{50\%}$ is the initial weight of the dry sample at relative humidity RH = 50 %; M_{RH} is the weight of the sample after 7 days of exposure in tested relative humidity (RH); S_a is the specimen area.

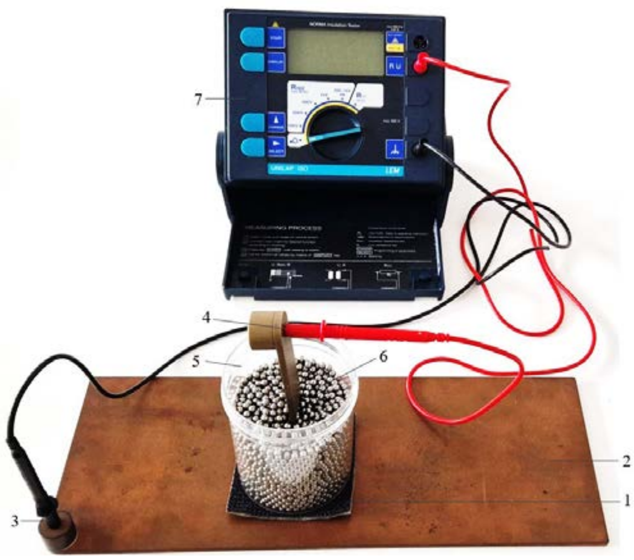


Fig. 1. Electrical resistance testing set: 1 – test specimen; 2 – copper contact plate; 3 – external electrode; 4 – internal electrode; 5 –nonconductive plastic cylinder; 6 – stainless steel balls; 7 – insulation tester

The electrical resistance was measured using multifunctional insulation tester Unilap ISO (LEM Norma GmbH, Austria) with the electrical resistivity measurements from 10 Ω up to 30 GΩ and measuring voltage in the range of 50 – 1000 V DC at a measuring current of 1 mA (Fig. 1.).

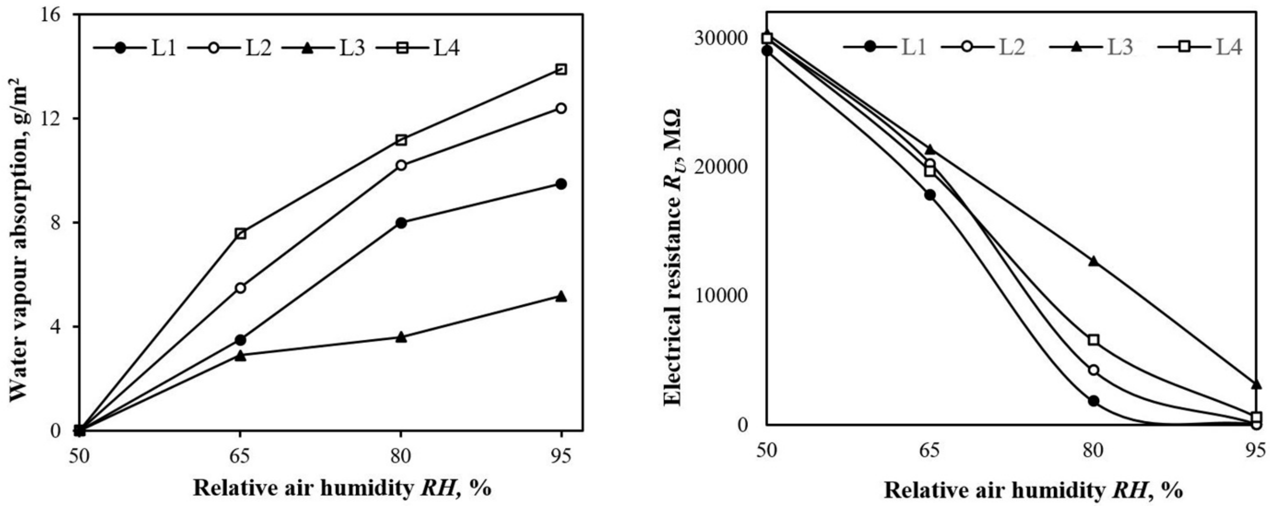
Test specimen 1 was placed on a copper contact plate 2 connected to an external electrode 3 and to internal electrode 4. This electrode was inserted into a plastic cylinder 5 filled with a conductive material of 5 mm diameter stainless steel balls 6. The insulation resistance values were measured between the copper plate and the steel balls by applying a test voltage of (100 ± 2) V DC and (500 ± 2) V DC for about 1 min.

3. RESULTS AND DISCUSSION

The electrical properties of textile laminates depend not only on their nature and structure, but also on their ability to absorb moisture in environments with different relative humidity [6 – 8, 12]. The dependence of water vapour absorption and electrical resistance of the textile laminates on the relative humidity is shown in Fig. 2. It is evident (Fig. 2, a) that laminates absorbed water vapour content increases intensively as the humidity of the environment increases from 50 % up to 95 %. At all different relative humidity levels, laminate L3 with a PU foam layer absorbs the least and laminate L4 with a non-woven PES layer absorbs the most water vapour. After exposure to high humidity, L4 laminate water vapour absorption reaches 13.9 g/m^2, while in the case of L3, only 5.2 g/m^2. It may be related to the peculiarities of the PU foam layer in a laminate L3 structure. Such foam has a closed pores structure, therefore water vapour molecules cannot penetrate the structure of the inner layer and cannot absorb moisture. In the case of non-woven PES, water vapour is able to penetrate freely through the layers and water molecules are absorbed at the surface of the hydrophilic polyester fibres of laminate L4.

The laminate L1 with a CO non-woven and knitted DryLiner® fabric has better absorption properties than laminate L3. After exposure to high relative humidity L1 laminate water vapour absorption reaches 9.5 g/m^2. The incorporation of the semi-permeable microporous membrane in the laminate L1 structure increases the water vapour absorption ability of the textile laminate. It is evident that the water vapour absorption capacity of *Puratex* microporous PU membrane adhering to the Microliner increases about 1.3 times. The adhesive layer, used to bond this microporous membrane, decreases the water vapour permeability (Table 1) and increases its absorption due to the formation of a non-porous barrier.

It is known [22] that the electrical resistance of textile laminates with polymer layers is extremely high (in the order of 10^{15} Ω). It was found that at low voltage (U = 100 V), electrical resistance values of all investigated textile laminates tested were found to be above the insulation tester's measurement limits (30000 MΩ) at relative humidity levels of 50 – 95 % [3]. However, at a voltage of U = 500 V the increase of relative humidity from 50 % to 95 % considerably decreases the electrical resistance of the textile laminates (Fig. 2, b).



a b

Fig. 2. Dependence of the textile laminates upon the relative humidity: a – water vapour absorption; b – electrical resistance

The electrical resistance of textile laminates increases with the thickness of the synthetic fibre and polymer layer in all relative humidity ranges. As expected, laminates electrical resistivity decreased with increasing relative humidity of the environment. The highest electrical resistance was characteristic for laminate L3 with the highest thickness, consisting of four layers from synthetic fibres: knitted PA, PES fabrics, a non-porous hydrophilic water vapour permeable PES membrane and a PU foam layer.

The electrical resistivity of this laminate decreased up to 21400 MΩ when the relative humidity was increased from 50 % to 65 % and about 1.5 times (from 21400 MΩ down to 12700 MΩ) when the relative humidity was changed from 65 % to 80 % and remained an insulator. Only in an environment of 95 % relative humidity does this laminate acquire antistatic properties.

The lowest electrical resistance was characteristic of laminate L1 without a polymeric membrane and which had the lowest thickness (Table 1). The electrical resistance of this laminate's decreases significantly (R_U = 7 MΩ) at 95 % humidity. In a high humidity environment, the laminate almost loses its antistatic properties and becomes conductive [3].

The incorporation of the semi-permeable microporous membrane in the laminate structure increases the electrical resistivity of the textile laminate. The *Puratex* membrane decreases the changing intensity of the laminate electrical resistance: when the relative humidity change from 65 % up to 95 %, the electrical resistance of the L2 laminate decreases from 20300 MΩ up to 490 MΩ. Even when wet laminate L2 with the membrane *Puratex* retains its antistatic properties.

Materials made from the fibre of different nature have different values of electrical resistance due to different water vapour absorption [12, 18, 25]. The effect of the accumulated moisture content in the textile laminates on their electrical resistance (at a voltage of U = 500 V) is shown in Fig. 3.

It is evident that the decrease in the electrical resistance depends on the absorbed amount of moisture and the nature of the layers of laminates [17]. Laminate L3 absorbed the lowest amount of water vapour. Although the electrical resistance of laminate L3 decreased intensively, it had the highest electrical resistance due to the low content of the absorbed moisture.

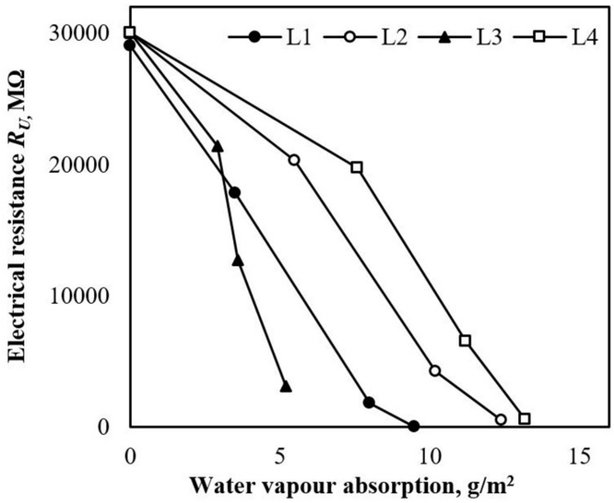


Fig. 3. The effect of the accumulated moisture content in the textile laminates on their electrical resistance

Laminate L4 absorbed the highest amount of moisture, due to the hydrophilic non-woven PES and knitted PES, PA layers in this laminate, which provide better water vapor penetration and water absorption. On the other hand, the electrically insulating properties of these polymers and PU microporous membrane, provided high electrical resistance. The electrical resistance decreased about 1.5 and 4.5 times when laminate accumulated about 55 % and 85 % of moisture, respectively. This laminate has been shown to have anti-static properties at any humidity tested.

The effect of the accumulated moisture content on the decrease of electrical resistance was higher in laminate L1 without a membrane, with the decrease of about 1.7 and 17 times when accumulating moisture content of about 35 % and 85 %, respectively. This laminate became conductive when absorbed moisture at high relative humidity.

The incorporation of a microporous hydrophilic membrane into the L1 structure of the laminate resulted in a simultaneous increase in water vapour absorption and electrical resistance. The intensity of the decrease in the electrical resistance of laminate L2 as a function of accumulated moisture was slower than laminate L1 without a membrane and similar to laminate L4. The decrease in electrical resistance was about 1.5 and 7 times for laminates with a moisture content of about 45 % and 80 % respectively. This laminate also exhibited antistatic properties regardless of the moisture content.

4. CONCLUSIONS

The comfort properties of protective footwear in terms of water vapour absorption can be influenced by the structure, nature and thickness of lining materials. The water vapour absorption of textile laminates increases about 1.8 – 3 times as relative humidity increases from 65 % to 95 %. The degree of the increase depends on the structure of the laminate and the nature of the material layers.

The electrical properties of protective footwear can be influenced by textile laminates' structure, thickness, relative humidity, and voltage. The resistance of laminates composed of natural and synthetic fibres and polymer foams as insulators increases with the thickness of the synthetic fibre and polymer layer.

At low voltage (U = 100 V), the textile laminates tested became insulating materials, as the electrical resistivity exceeded the threshold values for antistatic materials at relative humidity levels of 50 – 95 %.

At high voltage (U = 500 V) the electrical resistivity of textile the laminates drops dramatically when the relative humidity of the environment increases and the level of protection of the laminates depends on the amount of moisture absorbed and the nature of the layer materials.

At high voltage (U = 500 V) the electrical resistivity of textile the laminates drops dramatically when the relative air humidity increases and the level of protection of the laminates depend on the amount of moisture absorbed and the nature of the layer materials. The laminates possessed insulating properties in the environments of up to 65 % relative humidity. In a high-humidity of environment, the insulating properties of textile laminates turned to antistatic, except for laminate without a polymeric membrane, which became conductive.

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