Wioleta Serweta[1,*], Justyna Wójcik[1], Małgorzata Matusiak[2], Katarzyna Ławińska[1], Beata Szałek[1]

Research on the Possibilities of Polymer Textile Applications as Footwear Packages to Improve Health Properties

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[1] **Łukasiewicz Research Network – Institute of Leather Industry,**
ul. Zgierska 73, 91-463 Łódź, Poland,
* e-mail: w.serweta@ips.lodz.pl

[2] **Lodz University of Technology, Faculty of Material Technologies and Textile Design, Institute of Architecture of Textiles,**
ul. Żeromskiego 116, 90-924 Łódź, Poland

Abstract
In this paper, the authors focused on the examination of the possibility of polymer material applications as upper footwear elements in order to improve the functional properties, which are transposed to the hygienic comfort conditions. The set of materials used in this research were two – layered packages stitched together around the edges. Cotton material formed the outer layer, and polymer fabrics were used as the inner layer. Hygienic properties were identified with the use of water vapour permeability and water vapour absorption characteristics, while the thermal conductivity property was described on the basis of research done with an Alambeta device. Statistical analysis with the use of the t-Student test was conducted and showed that the proposition of material substitution undertaken was able to improve the hygienic characteristics of material packages, which can be implemented in manufacturing practice as upper materials with higher functional properties.

Key words: *polymer materials, footwear comfort, hygienic properties, water vapour permeability, water vapour absorption, thermal insulation*

Introduction

The human foot is adapted to performing a lot of dynamic functions connected with the locomotion process. The general characteristics of the foot condition are described by the physiological parameters: temperature, humidity and the microclimate around the nearest foot – skin neighbourhood [1, 2]. Each of these features are determined by the quality of footwear materials.

Over the period of contact of footwear with human skin, processes of heat and humidity exchange take place in a system: human foot – footwear materials – environment. The ability to permanently absorb and at the same time remove it from the foot surface is one of the basic features of high quality footwear materials. Research on hygienic material properties with respect to water vapour, air permeability and thermal conductivity give a possibility of predicting footwear properties that are important from the user's point of view. The transport of humidity through the material depends on the water vapour pressure differences on both sides thereof. Many papers showed that the positive effect on the improvement of water vapour permeability of materials is connected with increasing of sorption properties [3-5]. Most of the known methods of qualitative estimation of footwear comfort focus on the determination of hygienic properties of materials through their analysis – both individually and in the form of configurations. These simulations are undertaken on a laboratory scale and describe the quality of materials [6, 7]. As a reference, the foot – footwear – environment system is used, where acceptable values of some hygienic properties are described. Results obtained as the effects of laboratory research are compared with the values of temperatures and humidity during real – time simulations of effort [1, 9-11]. Due to this fact, the possibility of drawing conclusions about the optimal materials and their components exists; however, it is important to remember that the comfort sensation is also determined by the individual features of factors like sweat secretion, connected with sweet gland distribution on the foot surface, the metabolic rate, and emotional and anxiety states [12].

Recently, there have been a great number of papers discussing the possibilities of improving the hygienic properties of footwear with the use of innovative materials or their configurations. Most of the known methods of qualitative estimation of footwear comfort focuses on the determination of hygienic properties of materials through their analysis – both individually and in the form of configurations [13-15]. For example, in paper [16] the application of different polymer textile components like PES, PP and CLY translated into greater comfort of fire-fighter footwear use. In paper [17] different ski – boot lining sandwich compositions based on polymers like EVA, PE and PVC were examined from a thermal insulation point of view. In paper [18] spacer textile structures were examined. Cotton, polyester and bioactive polyester were used in certain proportions. The effect of the modifications was observed as changes in the mechanical and hygienic properties but with antimicrobial protection, which is very important from the user's point of view. Polymer materials are also used as components of bioactive insole materials [19, 20]. They can form a hydrophobic layer – used as the top of bioactive insoles. The following package configuration gives good support in the exchange of biophysical mediums between the interior and exterior of shoes. The reason for this is that the hydrophobic layer (polymer fabrics) lies in the nearest neighbourhood of foot skin, has good permeable properties, and is able to transfer t moisture away from the foot surface.

In this paper, the authors show a way to improve the functional properties of footwear uppers by replacing of the cotton lining by synthetic material characterised by high hygienic values. This was undertaken for a cotton – cotton footwear package, which is very popular, especially in cheap footwear for everyday use. The outer layer of this package remained cotton in order to improve the biodegradability and environmental friendliness of the footwear package. Such a way of construction of this package, based on natural cotton material, has two main advantages: from the user's point of view it is more hygienic than the cotton – cotton package, but no more expensive.

Moreover, from the ecological point of view, the cotton layer (natural material) is an important factor, which can reduce

Table 1. *Lining material characteristics.*

Sample name	Material description	Mass per square meter, g/m² ± 5%	Thickness, mm ± 6%
D1PES	100% polyester	317	2.71
D2PES	100% polyester	306	3.10
D3PES	100% polyester	265	2.31
D4PES	100% polyester	361	2.50
P1PES/PA	80% polyester, 20% polyamide	271	0.94
P2PES	100% polyester	263	1.20
P3PA	100% polyamide	163	0.61
P4PA	100% polyamide	110	0.80
P5PA	100% polyamide	148	0.40
P6PA	100% polyamide	213	0.60
PCOT	100% cotton	180	0.40

Table 2. *Upper layer material characteristics.*

Sample name	Material description	Mass per square meter, g/m² ± 5%	Thickness, mm ± 6%
WCOT	100% cotton	230	0.48

the total amount of the carbon footprint, which determines environmental friendliness [21]. The concept of the above-mentioned substitution is motivated by the fact that in the woven – woven package, the water produced by the foot during exertion (in both forms: liquid and gas) is trapped in the structure of the material package. This situation may lead to abnormalities in temperature and humidity exchange in a shoe volume interior. These factors are sources of worse hygiene, leading to the multiplication of bacterial flora and disease – causing fungus. Improvement of the hygienic properties of materials is an important step in order to reduce foot pathologies and diseases.

Materials and method

Research was done on a group of textile polymer materials with two and three – dimensional structures. Materials within the D1PES – D4PES group had a three – dimensional spacer structure. The outer and inner polyester layers were connected by monofilament polyester threads. Whereas the rest of materials examined (P1PES/PA to PCOT) were two – dimensional knitted fabrics. The basic characteristics of knitted fabrics used in this research are described in ***Table 1***. In ***Table 2***, the cotton woven used as the outer layer is described. These materials stems from the material database owned by the Łukasiewicz Research Network – Institute of Leather Industry.

The scheme of the research was as follows:
- Step 1 – hygienic analysis of single materials with respect to water vapour permeability, sorption [22], and thermal resistance (according to the method drawn up in papers [23, 24]).
- Step 2 – the abovementioned research was conducted for material packages used as connections of knitted fabric linings with WCOT woven uppers.

As a control sample, the WCOT – PCOT package was adopted. Qualitative changes in hygienic properties related to the control sample were noted.

Water vapour permeability measurement was conducted to determine the mass of water vapour, which permeates from the area with higher vapour pressure to lower vapour pressure in a previously defined amount of time. It is a feature which determines the quality of footwear materials. The application of improper material may cause health issues and discomfort for users. The test method is based on the following scheme: each tested sample was placed on the opened neck of a clean and dry vessel half filled with silica gel. Then each sample were weighted with the vessel and located in a holder. Then the vessel with water and the sample were dried at a temperature of 40 °C. It took 8 hours and the results of the analysis are expressed in mg H_2O/1000 mm^2/8 h. The ***Equation (1)*** applied [22] for water vapour permeability (WVP) calculation is given as follows:

$$WVP = \frac{M_1 - M_2}{t \cdot A}\left[\frac{mg}{cm^2 \cdot h}\right], \qquad (1)$$

where:
M_1 – vessel mass with sample before test procedure, mg,
M_2 – vessel mass with sample after test procedure, mg,
t – procedure time, h,
A – surface area, cm^2.

By comparison, the water vapour absorption (WVA) [22] is determined according to the ***Equation (2)***:

$$WVA = \frac{M_1 - M_2}{A}\left[\frac{mg}{cm^2}\right], \qquad (2)$$

for the same parameters M_1, M_2 and A as previously mentioned.

In order to determine thermo-physical properties of the materials examined, an Alambeta device was used. Samples of 20 cm x 20 cm size were placed between the two plates. The bottom plate was heated to 32 °C, while the lower plate was of room temperature. The total amount of heat conducted away from the material surface per unit of time was measured. The plates adhered to the sample measured with a constant pressure of 200 Pa ± 20 Pa. The measurement stand was placed in normal climate conditions [23]. As a result of this measurement, the thermal ability of the material was ascertained by the following measurements: thermal conductivity and resistance.

Results and discussion

The results and discussion part is divided into two sections: describing the results for single materials, and where the results for packages are examined.

Results of water vapour permeability property for single materials

In order to replace the PCOT material by a polymer knitted fabric counterpart, the water vapour transfer through the single materials was described. The results obtained were placed between 33.3 mg/cm^2h (P1PES/PA) and 44.33 mg/cm^2h (D4PES), and indicate the existence of small intragroup variability – at the level of 11%. The results obtained fulfil the requirements laid down for lining materials. According to the Institute standards, the minimum acceptable value for lining material is 20 mg/cm^2h. In order to determine the hierarchy of materials, water vapour absorption values were obtained (***Figure 1***).

The polymer materials used in this research allowed to conclude that the method of improvement of hygienic properties of footwear materials with the use of polymer materials is effective. Materials which are placed in a nearest foot neighbourhood should show high values of water vapour permeability, whilst minimalizing water vapour absorption. All the polymer materials can successfully replace cotton knitted fabric (PCOT). The most effective solution can be obtained for materials with minimal water vapour absorption, i.e.: P4PA, P5PA (0.02), P6PA (0.04), P2PES, D2PES (0.04), D3PES and D4PES (0.05). From the water vapour permeability point of view, the polymer materials were also more hygienic. Differences between the values for cotton and polymer fabrics reached a value of 155% for P1PES/PA to 207% for D4PES. This fact indicates better hygienic properties and higher level of ability to take water and water vapour away from the skin surface.

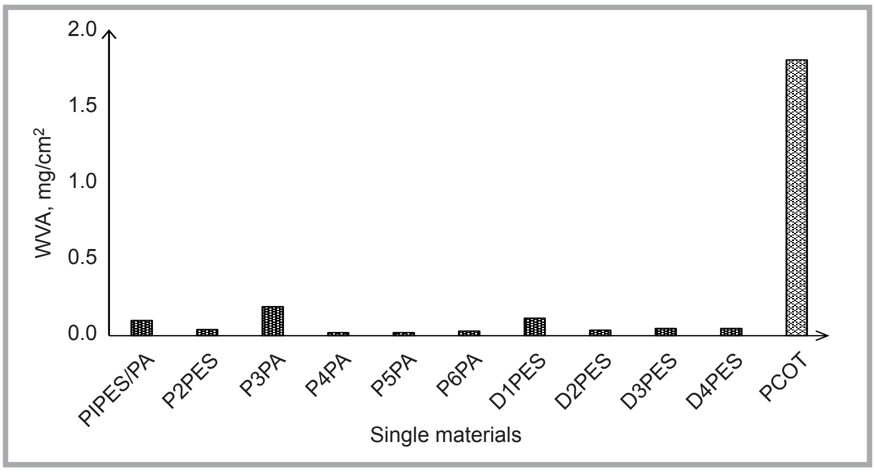

Figure 1. *Water vapour absorption property for samples tested.*

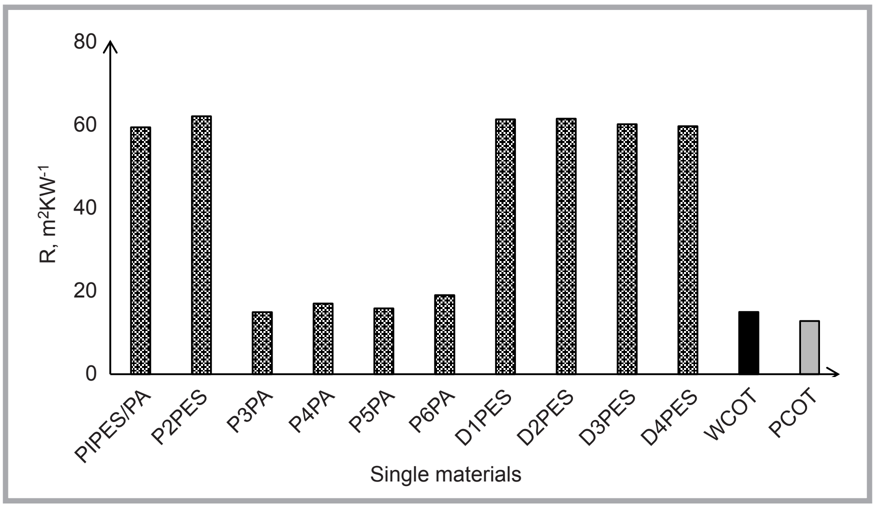

Figure 2. *Values of thermal resistance (R) for samples measured.*

Results of thermal resistance property for single materials

The thermal insulation of footwear materials is important, because it describes the ability of materials to transfer heat to the surrounding environment by the following processes: conductivity, convection and radiation. This property depends on the material porosity, specific volume, thickness, moisture content and the way of merging materials into packages. An important aspect is also the number of layers in the upper package, connected with the number of air layers and gaps, which determines the thermal insulation properties. Moreover the texture of layers, especially in the contact surface, affects the airtightness of adhesion, which is important from an insulation point of view.

In this paper, the thermal insulation property was described in terms of thermal resistance (*R*), given as the following ***Equation (3)*** [23]:

$$R = \frac{h}{\lambda}\left[\frac{m^2K}{W}\right], \qquad (3)$$

where, *h* is the sample thickness and λ – the thermal conductivity of the material.

The values of thermal resistance obtained in this research were placed between 12.7 m^2KW^{-1} for cotton knitted fabric PCOTT and 78.95 m^2KW^{-1} for knitted fabric DKF5 with a three-dimensional structure (***Figure 2***). The results obtained for the materials examined can be divided into two subgroups: materials with lower thermal resistance in the range of 14.85 (P3PA) – 18.9 (P6PA) and with higher values in the range of 59.05 (P1PES/PA) – 61.7 (P2PES). The first group comprised plain materials with the smallest loop height (from 0.63 to 0.67 mm) and mass per square meter (from 110 to 213 g/m^2). This conclusion is connected with the research done in papers [25] and [26], where the relations between eye dimension and thermal conduction and resistance were described.

For fabrics, the main factor in creating thermal resistance properties is the thickness of the fabric and type of weave [27].

It is worth noting that the maximum values of thermal resistance were reached for materials with the spacer structure [28, 29] (between 59.35 for D4PES and 60.95 for D1PES) and plain materials – P2PES (61.7) and P1PES/PA (59.05). Other materials are not recommended due to this parameter. The cause of this situation are the air gaps entrapped in the materials or packages examined, influencing the heat capacity and inducing an increase in the thermal resistance of materials.

Results of the water vapour permeability property for the packages

Based on the characteristics obtained for single materials, the cotton lining layer was replaced by a polymer synthetic one. It was possible to improve the hygienic properties of footwear without a strong lack of environmental friendliness. The application of sustainable or safe materials in combination with other materials with a higher level of functionality during the footwear design process is important to ensure that greenhouse gas emissions are minimised [30].

According to the values of water vapour permeability obtained (***Figure 3***), the replacement of cotton lining material (PCOTT) by polymer materials improved the water vapour property of the packages.

The statistically significant differences (***Table 3, 4, 5***) between WCOTT – PCOTT gave a possibility to place these

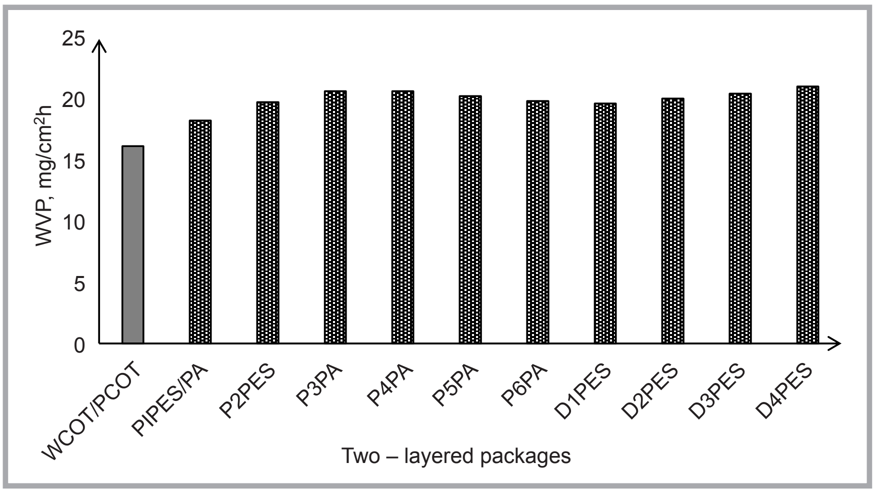

Figure 3. *Water vapour permeability for packages connected with polymer linings.*

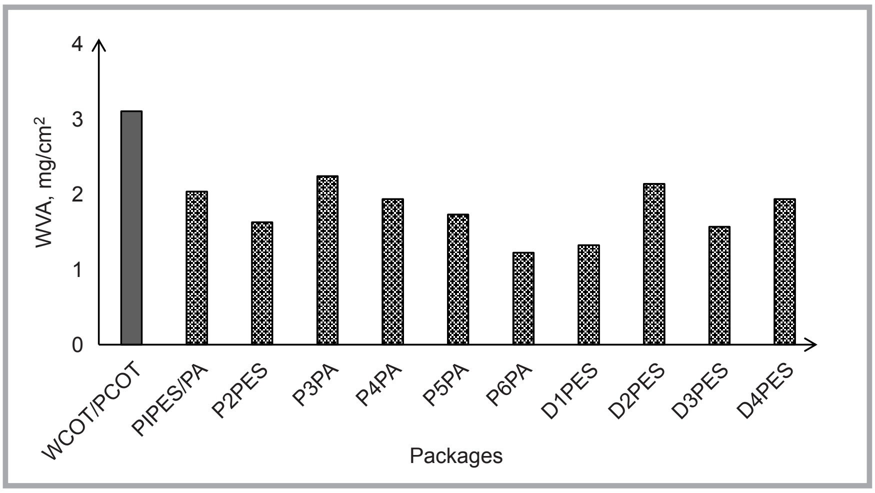

Figure 4. *Water vapour absorption for packages connected with polymer linings.*

materials at a qualitatively and quantitatively higher level than knitted cotton.

The next parameter, which is important from a footwear user's point of view, was the sorption property (***Figure 4***). All of the packages with polymer substitutions had observable lower absorption, which is very positive from the user's point of view.

The changes in basic hygiene parameters (with respect to both thermal resistivity and water vapour transport) had a statistically significant nature (***Table 3, 4, 5***). This fact was examined with the use of the t-Student test at the confidence level α = 0.05. The null hypothesis H_0 rules that for the independent means, the two unrelated groups are equal. The alternative hypothesis H_1, says the contrary.

The statistical analysis results showed that the replacement operation was important from the hygienic parameter improvement point of view. All differences were highly significant, which is evidence of the legitimacy of such changes in material packages in order to improve their properties from a hygienic point of view.

The less amount of water which is stored in the package structure is important also from a drying point of view. Polyester materials improve quick dry properties, and the water trapping processes are eliminated [31], which is important from the footwear point of view, because water trapping inside a material structure can increase the probability of moulding the materials and cause the risk of foot diseases. In cases of good moisture holding by footwear materials, an environment for the growth of mould appears. Typically moulds which can grow on footwear are, for example, xerophilic fungi, which can thrive on low relative humidity or low levels of water. Hence, even a small amount of trapped water is able to give negative effects on human health.

Results of the thermal resistance property for the packages

In order to describe the thermal resistance property, as noted in [23], the sum of thermal resistance can be approximated by the algebraic sum of the resistance for a single material. The effective thermal conductivity of a two – layered package can be expressed as [23]:

Table 3. *T-Student comparison between the control sample with PCOTT and samples with polymer materials with regard to the water vapour permeability parameter.*

Treatment pair	t-value	p-value
WCOTT – D1PES	-9.531	0.005
WCOTT – D2PES	-19.482	0.001
WCOTT – D3PES	-9.318	0.006
WCOTT – D4PES	-7.050	0.001
WCOTT – P1PES/PA	-10.522	0.004
WCOTT – P2PES	-18.019	0.002
WCOTT – P3PA	-22.518	0.001
WCOTT – P4PA	-22.518	0.001
WCOTT – P5PA	-20.519	0.001
WCOTT – P6PA	-18.519	0.001

Table 4. *T-Student comparison between the control sample with PCOTT and samples with polymer materials with regard to the water vapour absorption parameter.*

Treatment pair	t-value	p-value
WCOTT – D1PES	10.815	0.004
WCOTT – D2PES	16.978	0.002
WCOTT – D3PES	13.506	0.003
WCOTT – D4PES	13.368	0.003
WCOTT – P1PES/PA	20.796	0.001
WCOTT – P2PES	28.757	0.001
WCOTT – P3PA	16.816	0.002
WCOTT – P4PA	22.786	0.001
WCOTT – P5PA	26.767	0.001
WCOTT – P6PA	36.717	0.001

Table 5. *T-Student comparison between a control sample with PCOTT and samples with polymer materials with regard to the thermal resistance parameter.*

Treatment pair	t-value	p-value
WCOTT – D1PES	-211.085	0.0001
WCOTT – D2PES	-131.463	0.0001
WCOTT – D3PES	-147.897	0.0001
WCOTT – D4PES	-188.600	0.0001
WCOTT – P1PES/PA	-5.573	0.0200
WCOTT – P2PES	-24.008	0.0010
WCOTT – P3PA	2.683	0.0600
WCOTT – P4PA	-12.969	0.0030
WCOTT – P5PA	-2.655	0.0600
WCOTT – P6PA	-12.528	0.0030

$$\lambda_{ef} = \lambda_w \cdot \frac{h_w}{h_w+h_z} + \lambda_z \cdot \frac{h_w}{h_w+h_z}, \quad (4)$$

where:
λ_{ef} – effective thermal conductivity for two – layered package, $Wm^{-1}K^{-1}$;
λ_w – thermal conductivity of inner layer, $Wm^{-1}K^{-1}$;
λ_z – thermal conductivity of outer layer, $Wm^{-1}K^{-1}$;
h_w – thickness of inner layer, mm;
h_z – thicknes of outer layer, mm.

Thus, in this case, the thermal resistance is directly proportional to the sum of the thickness and inversely proportional to the sum of thermal conductivities of each layer. In the present case, the best insulators were spacer fabrics (***Figure 5***).

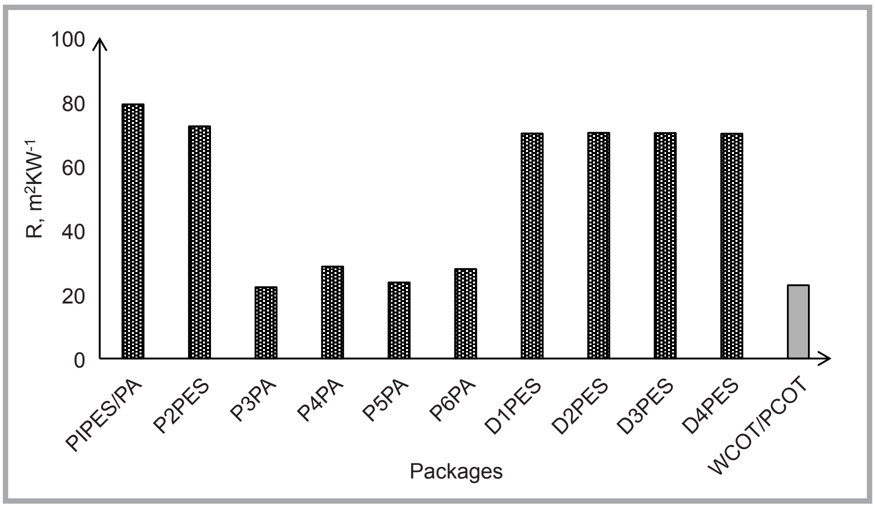

Figure 5. *Thermal resistance of packages connected with polymer linings.*

When we strive to create optimal material packages, the above-mentioned hygienic parameters must be involved to draw final conclusions with respect to the hierarchy of materials. It should be noted that all materials with a spacer structure are better than the cotton (WCOTT) – cotton (PCOTT) combination. These materials were also extremely hygienic from the water vapour permeability point of view. Some doubts occurred with regard to polyamide materials. All polyamide fabrics, except P6PA, were characterised by a higher level of water vapour absorption and, therefore, not recommended as a lining material. Moreover, the thermal resistance is also lower than for other materials. Hence, when we want to create materials for indoor use at a low level of physical effort (for example, light seated manual work or short walking periods, where standing and sitting take place), polyamide materials can be also used with no risk of discomfort condition occurrence. However, when the activity is more pronounced, better hygienic properties in a shoe interior can be created with the use of more permeable and less absorbable lining materials. It should be underlined that the total insulation depends on the sweating rate [32]. The reduction of insulation depends on the wetting of material layers, because determines the increase in heat conductivity throughout the composition. Thus in this case, the materials with better insulation are more recommended, because in cases with a high level of sweating, the foot is protected to a greater extent.

Results obtained from the statistical analysis showed that the vast majority of differences in the hygienic parameters measured between the control sample based on cotton materials (both outer and inner) and samples where the cotton lining was replaced by polymer linings were statistically significant. A lack of significance was observed only for two cases: P3PA and P5PA. These materials had a similar structure to that of cotton knitted fabric with regard to the mass per square meter, thickness, number of rows and columns, column width, row height and eye loop shape [33]. Hence, it was a cause of the non – significant differences.

Summary and conclusions

The implementation of new materials in footwear compositions is a difficult task. Footwear comfort is a multidimensional issue and depends also on subjective sensations during use. Even though custom footwear with specific hygienic properties with respect to perspiration by evaporation or absorption – essential to foot comfort – is made, the comfort and fit may not be optimal for the different kinds of activities and differently shaped feet of individuals. The mechanism of discomfort condition occurrence is very complicated and finding a compromise between feet expectations and footwear designers seems to be impossible [34]. The following conclusions can be formulated:

- polymer materials like polyester and polyamide can be used as lining materials as an effective replacement for those commonly used, especially in cheap footwear;
- an increase in polymer material content in the footwear package from 32% (for P4PA) to 61% (for D4PES) in respect of the total mass per square meter of the package gave an improvement in hygienic properties in terms of vapour permeability in the range between 113% for P1PES/PA to 130% for D4PES. The statistically significant probability of the replacement effect lay between 0.001 and 0.006, which suggests a strong improvement;
- statistically significant changes were also observed for packages with respect to the water vapour absorption property – when the polymer material content rises, water vapour absorption by the material composition falls. This effect was observed most strongly for P6PA (254%) and D1PES (235%). The statistically significant probability of the replacement effect was also very strong, lying between 0.001 and 0.004.
- a significant effect was also observed for the thermal resistance parameter – here we can observe a strong improvement – especially for spacer fabrics, i.e. within the D1PES – D4PES group.

For further works on this topic, it should be kept in mind that also the parameters of knitting technological processes can influence some parameters of knitted fabrics, like air and water vapour permeability [35], or mechanical properties [36, 37]. Hence, this way is also suitable for optimising material parameters, which is important from the footwear manufacturer's point of view.

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References

1. Irzmańska E. The Microclimate in Protective Fire Fighter Footwear: Foot Temperature and Relative Humidity. *AUTEX Research Journal* 2016; 16 (2): 75-79.
2. Ławińska K, Serweta W, Jaruga I, Popovych N. Examination of Selected Upper Shoe Materials Based on Bamboo Fabrics. *FIBRES & TEXTILES In Eastern Europe* 2019; 27, 6(138): 85-90. DOI: 10.5604/01.3001.0013.4472.
3. Gulbiniene A, Jankauskaite V, Kondratas A. Investigation of the Water Vapour Transfer Properties of Textile Laminates for Footwear Linings. *FIBRES & TEXTILES in Eastern Europe* 2011, 19, 3 (86): 78-81.
4. Irzmańska E, Dutkiewicz J K, Irzmański R. New Approach to Assessing Comfort Use of Protective Footwear with a Textile Liner and its Impact on Foot Physiology. *Textile Research Journal* 2014; 84 (7): 728-738.
5. Langmaier F. Hygiena A Komfort Obute Nohy, *Kozarstvi* 1990; 40 (12): 345-349.
6. Serweta W, Matusiak M, Olejniczak Z, Jagiełło J, Wójcik J. Proposal for the Selection of Materials for Footwear to Improve Thermal Insulation Properties Based on Laboratory Research. *FIBRES & TEXTILES in Eastern Europe* 2018; 26, 5(131): 75-80. DOI: 10.5604/01.3001.0012.2535.
7. Ławińska K, Serweta W, Gendaszewska D. Applications of Bamboo Textiles in Individualised Children's Footwear. *FIBRES & TEXTILES in Eastern Europe* 2018; 26, 5(131): 87-92. DOI: 10.5604/01.3001.0012.2537.
8. Serweta W, Olejniczak Z, Matusiak M. Improve of Footwear Comfort Sensation with Material Packages and Knitted Fabrics. FIBRES & TEXTILES in Eastern Europe 2019; 27, 3(135): 85-90. DOI: 10.5604/01.3001.0013.0747.
9. Arezes PM, Neves MM, Teixeira SF, Leao CP, Cunha JL. Testing Thermal Comfort of Trekking Boots: an Objective and Subjective Evaluation. *Applied Ergonomics* 2013; 44 (4): 557-565.
10. Diebschag W, Mueller-Limmroth W, Mauderer V. Influence of Several Socks and Linings on the Microclimate in Shoes with Upper Material of Leather or Synthetic. *Journal of the American Leather Chemists Association* 1976: 71 (6): 239-306.
11. Kawabata A, Tokura H. Effect of Shoe Type on the Thermoregulatory Response and Clothing Microclimate in Women During Walking and Resting. *Journal of Home Economics of Japan* 1993; 44 (8): 665-670.
12. Taylor NAS, Caldwel JN, Mekjavic IB. The Sweating Foot: Local Differences in Sweat Secretion During Exercise – Induced Hyperthermia. *Aviation, Space and Environmental Medicine* 2006; 77 (10): 1020-1027.
13. Ławińska K, Serweta W, Modrzewski R. Qualitative Evaluation of the Possible Application of Collagen Fibres: Composite Materials with Mineral Fillers as Insoles for Healthy Footwear. *FIBRES & TEXTILES in Eastern Europe* 2018; 26, 5(131): 81-85. DOI: 10.5604/01.3001.0012.2536.
14. Ławińska K, Serweta W, Modrzewski R. Studies on Water Absorptivity and Desorptivity of Tannery Shavings-Based Composites with Mineral Additives. *Przemysl Chemiczny* 2019; 98(1): 106-109.
15. Ławińska K, Modrzewski R, Serweta W. Tannery Shavings and Mineral Additives as a Basis of New Composite Materials. FIBRES & TEXTILES in Eastern Europe 2019; 27, 5(137): 89-93. DOI: 10.5604/01.3001.0013.2906.
16. Irzmańska E. The Impact of Different Types of Textile Liners Used in Protective Footwear on the Subjective Sensations of Firefighters. *Applied Ergonomics* 2015; 47: 34-42.
17. Colonna M, Moncalero M, Nicotra M, Pezzoli A, Fabbri E, Bortolan L, Pellegrini B, Schena F. Thermal Behaviour of Ski – Boot Liners: Effect of Materials on Thermal Comfort in Real and Simulated Skiing Conditions. *Procedia Engineering* 2014; 72: 386-391.
18. Soares G, Magalhaes A, Vasconcelos A, Pinto E, Santos J. Comfort and Antimicrobial Properties of Developed Bamboo, Polyester and Cotton Knitted Spacer Fabrics. *Cellulose Chemistry and Technology* 2018; 52 (1-2): 113-121.
19. Troynikov O, Wardiningsih W. Moisture Management Properties of Wool/Polyester and Wool/Bamboo Knitted Fabrics for the Sportswear Base Layer. *Textile Research Journal* 2011; 81 (6): 621-631.
20. Irzmańska E, Brochocka A. Influence of the Physical and Chemical Properties of Composite Insoles on the Microclimate in Protective Footwear. *FIBRES & TEXTILES in Eastern Europe* 2014; 22, 5(107): 89-95.
21. Serweta W, Gajewski R, Olszewski P, Zapatero A, Ławińska K. Carbon Footprint of Different Kinds of Footwear – a Comparative Study. *FIBRES & TEXTILES in Eastern Europe* 2019; 27, 5(137): 94-99. DOI: 10.5604/01.3001.0013.2907.
22. PN-EN ISO 20344:2012. Personal protective equipment – Test methods for footwear.
23. Matusiak M. *Ciepłochronność tkanin odzieżowych*, Textile Research Institute, Lodz, 2011.
24. Matusiak M, Kowalczyk S. Thermal Insulation Properties of Multilayer Textile Packages. *Autex Research Journal* 2014; 14 (4): 299-307.
25. Chidambaram P, Govind R, Venkataraman K C. The Effect of Loop Lenght and Yarn Linear Density on the Thermal Properties of Bamboo Knitted Fabric. *Autex Research Journal* 2011; 11 (4): 102-105.
26. Majumdar A, Mukhopadhyay S, Yadav R. Thermal Properties of Knitted Fabrics Made from Cotton and Regenerated Bamboo Cellulosis Fibres. *International Journal of Thermal Science* 2010; 40 (10): 2042-2048.
27. Frydrych I, Dziworska G, Bilska J. Comparative analysis of the thermal insulation properties of fabrics made of natural and man – made cellulose fibres, *FIBRES & TEXTILES in Eastern Europe* 2002; 10, 4(39): 40-44.
28. Wang Y, Lu Y, Li J. Effects of Air Gap Entrapped In Multilayer Fabrics and Moisture on Thermal Protective Performance. *Fibers and Polymers* 2012; 13 (5): 647-652.
29. Schacher L, Adolphe DC, Drean JY. Comparison Between Thermal Insulation and Thermal Properties of Classical and Microfibres Polyester Fabrics. *International Journal of Clothing Science and Technology* 2000; 12 (2): 84-95.
30. Herva M, Alvarez A, Roca E. Sustainable and Safe Design of Footwear Integrating Ecological Footprint and Risk Criteria. *Journal of Hazardous Materials* 2001; 192 (3): 1876-1881.
31. Wang F, Zhou X, Wang S. Development Processes and Property Measurements of Moisture Absorption and Quick-Dry Fabrics. *FIBRES & TEXTILES in Eastern Europe* 2009; 17 2(73): 46-49.
32. Kuklane K, Holmer I, Giesbrecht G. Change of Footwear Insulation at Various Sweating Rates, *Journal of Physiological Anthropology* 1999; 18 (5): 161-168.
33. Frydrych I, Sybilska W, Wajszczyk M. Analysis of Selecte Physical Properties of Membrane Fabrics Infl uencing the Utility Comfort of Clothing. *FIBRES & TEXTILES in Eastern Europe* 2009, Vol. 17, No. 6 (77) pp. 50-55.
34. Goonetilleke RS, Luximon A. Designing for Comfort: a Footwear Application, *Proceedings of the Computer – Aided Ergonomics and Safety Conference* 1, 2001: 1-6.
35. Wilbik-Hałgas B, Danych R, Więcek B, Kowalski K. Air and Water Vapour Permeability in Double – Layered Knitted Fabrics with Different Raw Materials. *FIBRES & TEXTILES in Eastern Europe 2006;* 14, 3(57): 77-80.
36. Kłonowska M, Kowalski K. Optimising Knitting Process Conditions on the Basis of Controlled Robbing – Back of Yarn. *FIBRES & TEXTILES in Eastern Europe* 2006; 14, 1(55): 47-51.
37. Kłonowska M, Kowalski K. Assessment of Knitting Conditions and States of Discontinuous Robbing Back in the Knitting Zone on Weft – Knitting Machines. *FIBRES &TEXTILES in Eastern Europe* 2002; 10, 3(38): 50-52.

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