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Proposal for the Selection of Materials for Footwear to Improve Thermal Insulation Properties Based on Laboratory Research

DOI: 10.5604/01.3001.0012.2535

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Abstract
The aim of this study was the analysis of the thermal resistance of upper textile materials combined with leather or textile linings. Following a comparative analysis of the combinations of materials tested, the best insulators were recommended. Footwear material packages were created on the basis of the analysis of hygienic properties of textile and leather material-s,which were available on the market. Hygienic properties like water vapour permeability and water vapour absorption gave information about the possibility to apply these materials from a microclimate point of view.

Key words: *thermal insulation, footwear comfort, textile packages, footwear uppers.*

Introduction

The thermal insulation properties of footwear are one of the most important aspects of functionality [1].

The foot is one of the body parts that do not keep the temperature at a constant level all the time [2]. When the external environment is characterised by an elevated temperature, the foot is also going to become hot very fast. By contrast, in a cold environment the foot develops hypothermia and becomes the coldest part of the human body. It is understood that human skin temperature lies between 28 and 34 °C, which are the boundary conditions of the physiological temperature of the foot surface. When it comes to relative humidity, the optimal values lie between 60 and 65% [2]. Even small deviations from these optimal values cause a defensive reaction of the body: peripheral coldness or sweating. These processes are connected with activating sweat production and perspiration from the skin surface [3-5].

The microclimate of shoes is defined as the overall conditions connected with temperature and humidity levels in the shoe interior. The important factor determining the hygienic quality of shoes is the stability of the microclimate over their time of usage. Ideal conditions assume that the foot – shoe system should be isothermal, which means a smooth flow of humidity and temperature towards the external environment in the case of a warm environment. Similarly in cold conditions footwear must become an effective barrier against cooling. The possibilities of automatic regulation of the temperature and humidity of foot skin are limited. Correctly designed footwear can effectively support this mechanism.

One of the most important factors determining the process of circulation between the shoe interior and the environment is the extent to which the foot is covered by the upper. This mechanism has an impact on the hygienic properties of footwear, which are described by a set of parameters, i.e thermal insulation, sorption and desorption of moisture, water vapour permeability, humidification, water absorbency and the passage of water through the layers of the material [2, 6-10]. The group of properties described above establishes a set of mutually dependent relationships. The selection of optimal material packages should, therefore, involve all the elements of the mechanism across the upper, lining and insole. The aspect of combinations of appropriate footwear materials is very important because the relations and processes between the human foot and the environment are transient and depend on individual physiology features [11].

According to [12], the insulate values of footwear (based on ASHRAE 1985) remain between 0.02 clo for sandals and 0.08 for boots, which correspond to thermal resistance between 0.031 and 0.124 m^2KW^{-1}. The rate of heat exchange between the shoe interior and exterior depends on many factors, such as the physical properties of footwear materials (in particular density and porosity) and external environment characteristics (like air temperature, humidity or the velocity of air movement).

As regards footwear materials, upper – lining – sock sets have significant importance and are responsible for the overall thermal insulation index. The ratio between the thermal insulation of the upper and the shoe bottom is another parameter describing the qualitative criterion of warmth retention. It is justified by the fact that during human movement, the upper is surrounded by a gas (or rarely liquid) environment. Therefore, for example, when the upper provides good insulation and the bottom provides poor insulation, the total index of thermal insulation would be unacceptable. In [13] a sufficient level of thermal resistance of footwear is defined as a value below 30 m^2kW^{-1} for a single shoe. The optimal ratio between the upper and bottom is defined as a value between 2.5 and 3.

Lining materials have a significant impact on comfort sensation because they lie in the nearest vicinity of the skin surface. It is a well-known fact that wet materials have poorer insulation properties [14]. In cases where the materials used provide a barrier against moisture transport through the layers, we can observe a rapid growth of humidity in the shoe interior and a discomfort sensation occurs. This causes other problems like the bacterial and fungal contamination of footwear, foot infections and unpleasant odour.

On the basis of the subjects' experiences during the use of trekking footwear in paper [15], optimal sets of lin-

Table 1. Basic properties of upper textile materials.

Sample name	Material	Mass per square meter, g/m^2	Water vapour permeability, g/m^2 · h (acc. to [21])	Water vapour absorption, g/m^2 (acc. to [21])
MW1	three-layered material, 100% cotton	645.8	163.0	36.0
MW2	three-layered material, cotton bound together with the use of polyurethane foam (2 mm)	550.2	127.0	11.0
MW3	three-layered material, cotton bound together with the use of polyurethane foam (5 mm), 100% polyamid + polyurethane coating	639.9	14.6	14.5

Table 2. Basic properties of textile lining materials.

Sample name	Material	Mass per square meter, g/m^2	Water vapour permeability, g/m^2 · h (acc. to [21])	Water vapour absorption, g/m^2 (acc. to [21])
TS1	knitted fabric: 56% polyester, 46% – modified polyamide + polyurethane foam	275.0	136.0	0.4
D1	knitted fabric open weave 3D, 100% polyamide	342.1	355.0	14.1
D3	knitted fabric 3D, 100% polyamide	354.8	374.0	8.6
TS5A	knitted fabric, 100% polyamide	162.2	414.0	1.9
TS5B	knitted fabric, 100% polyamide	110.3	383.0	0.2
TS5D	knitted fabric, 80% polyester, 20% modified polyamid	212.8	379.0	0.3

Tabela 3. Basic properties of leather lining materials.

Sample name	Material	Thick-ness, mm	Water vapour permeability, g/m^2 · h (acc. to [21])	Water vapour absorption, g/m^2 (acc. to [21])
S3	cowhide lining leather	3.00	96.1	86.8
SW3	pig lining grain leather	2.20	178.0	44.0
SW4	pig lining leather split	2.42	163.0	45.0

ing materials have been proposed. For the development of inner layer fabrics, a set of fibres was selected from cotton, polylactic acid, soybean or bamboo, which are a part of the hydrophilic layer, as well as polypropylene and polyester, which are considered hydrophobic fibres. The analysis carried out in this paper showed that the identification of thermal discomfort zones of the foot is an important issue for the design of footwear, which is possible with the use of fabrics with differentiated thermal behaviour in these sensitive areas.

Similar research was done with the use of sports footwear in [4]. A broader spectrum of different parameters including physiological (i.e. heart rate, oxygen consumption, foot temperature) was compared with subjective sensitivities.

On the other hand, an attempt to find an optimal and comfortable set of shoe materials for uppers and linings for army boots was made in [16]. The dependence of the temperature of the foot surface on the type of lining material was investigated. Similar research with the use of permeable membranes like Gore-Tex or Outdry as linings was done with the use of a human manikin in [17]. The impact of cotton lining and cotton – polyamide socks was tested with the use of firefighter rubber footwear in [18].

As shown by the literature review, studies of the dependence between shoe design and comfort due to physiological aspects are important for establishing the needs of users. Multiple publications in this area reveal the complexity of these problems.

The main objective of this work was the analysis of the thermal insulation properties of combinations of footwear material packages in order to make a selection of those that could improve insulation properties. The materials were chosen on the basis of initial tests of a wide spectrum of materials according to their hygienic properties, i.e. water vapour permeability and absorption.

Materials and methods

The parameters which describe thermal insulation properties, like thermal conductivity and resistance, were measured using an Alambeta Measuring Device [19, 20]. Using this instrument, the heat flow through the two layers: the upper and the lining due to the different temperature of the bottom measuring plate was registered. The measuring head was heated up to 32 °C, because that is the temperature of the human skin surface. 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 adhere to the measured sample with a constant pressure of 200 Pa ± 10%. The measurement stand was placed in normal climate conditions [1].

The measurements were made with two kinds of materials:
- used for linings,
- used for uppers.

Textile and leather materials were used as linings, while textiles were used for uppers.

Each type of upper and lining material together with their basic hygienic properties (according to ISO standard [21]) is set out in ***Tables 1-3***.

The phenomenon of heat exchange between the shoe materials and the environment was described by two physical quantities: thermal conductivity (λ) and thermal resistance (R). Thermal conductivity (1) describes the amount of heat which passes through surface A at time with the temperature decreasing by $\Delta t = 1\ K$ per thickness unit h.

$$\lambda = \frac{Q}{A\tau\frac{\Delta t}{h}}\left[\frac{W}{mK}\right] \quad (1)$$

On the other hand, thermal resistance R describes the ratio between the sample thickness (h) and thermal conductivity (λ):

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

The thermal insulation properties of a shoe are described by the following elements:
- thermal insulation of lining materials
- thermal insulation of a set of materials in the combination upper – bottom;
- air temperature, air humidity and velocity of air movement;
- ground temperature and ground moisture [2].

Results

Analysis of the experimental results provided information on the thermal insulation properties of the combination upper – textile or leather lining. ***Figures 1*** and ***2*** describe thermal conductivity values for the linings tested combined with uppers.

On the basis of the results obtained, we can observe (***Figure 1***) that the lowest values of thermal conductivity occurred for the three-layered material, with cotton bound together with the use of a polyurethane foam upper (MW2), irrespective of the type of lining material. Greater diversity was observed with the use of leather linings S3, SW3 & SW4 (***Figure 2***). In this case the weakest composition is MW3 – S3 (λ = 0.0753).

As the thickness of the material (or package) is the main factor in the evaluation of thermal insulation properties, the thermal resistance was calculated. ***Figures 3*** and ***4*** describe the values of thermal resistance for particular combinations of materials.

With regard to ***Figure 3***, it can be observed that the highest values of thermal resistance were obtained for MW3. The maximum value (0.1737) is an effect of the material package used in the analysis: MW3 and textile knitted fabric of the following composition: 56% polyester, 46% modified polyamid with polyurethane foam (TS1). Additional content in the form of polyurethane foam with high density improves the insulation properties of the upper – lining package [22].

For leather linings the best insulation properties were observed (***Figure 4***) for combination MW3 and SW4 (0.1111). Moreover for an MW1 upper combined with an S3 lining, the insulation properties were marginally weaker (about 2%) than for the previous one.

In order to establish the qualitative differences between individual materials, a statistical analysis with the use of the t-Student test was done. For the zero hypothesis almost no significant differences between the means of two independent data sets were verified at a confidence level of 95%. The following groups were examined: MW1 – MW2, MW2 – MW3 and MW1 – MW3 (for uppers), TS1 – D1, TS1 – D3, TS1 – TS5A, TS1 – TS5B, TS1 – TS5D, D1 – D3, D1 – TS5A, D1 – TS5B, D1 – TS5D, D3 – TS5A, D3 –

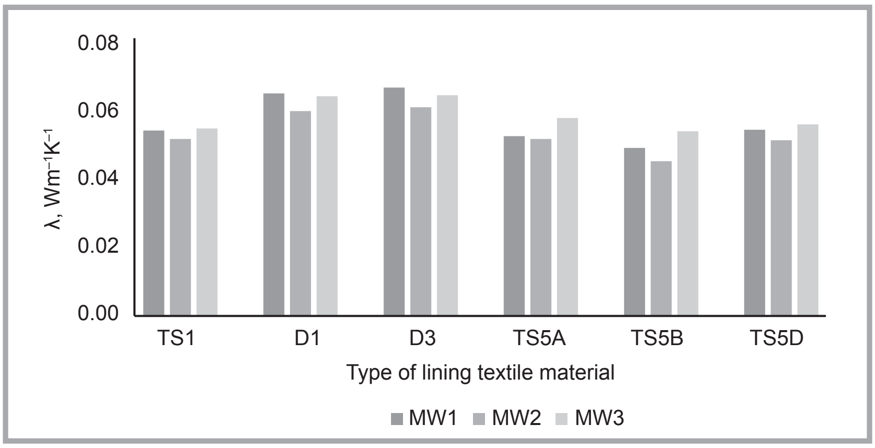

Figure 1. *Thermal conductivity λ for the upper – textile lining combination.*

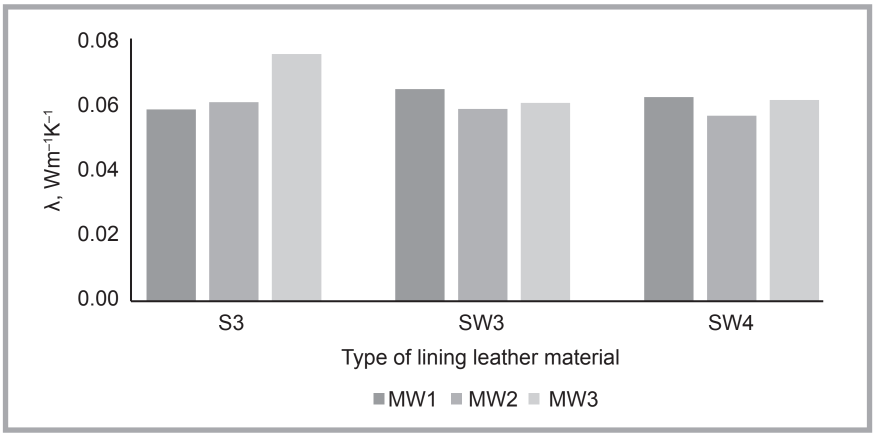

Figure 2. *Thermal conductivity λ for the upper – leather lining combination (where MW1, MW2 and MW3 are upper materials, and S3, SW3 & SW4 are leather linings).*

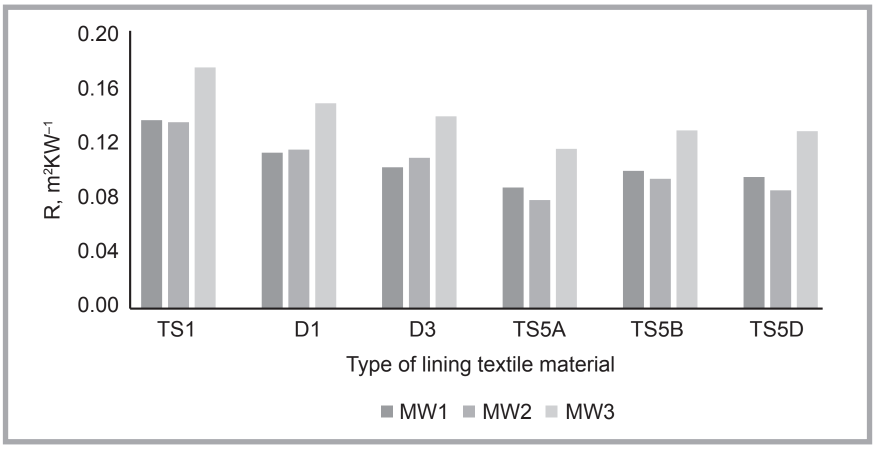

Figure 3. *Thermal resistance R for textile linings (where MW1, MW2 and MW3 are upper materials, and TS1, D1, D3, TS5A, TS5B and TS5D are textile linings)*

Table 4. *Post-hoc analysis values for uppers ((*) statistical significance of differences was obtained at a confidence level of α = 0.05)*

Pair of uppers tested	With leather lining		With textile lining	
	t	p	t	p
MW1 – MW2	1.00834	0.370334	0.25879	0.80
MW2 – MW3	-6.82425	0.002411(*) d-Cohen's>2	-3.04627	0.01 (*) d-Cohen's = 0.40
MW1 – MW3	-2.56816	0.0621	-3.07193	0.01 (*) d-Cohen's = 1.77

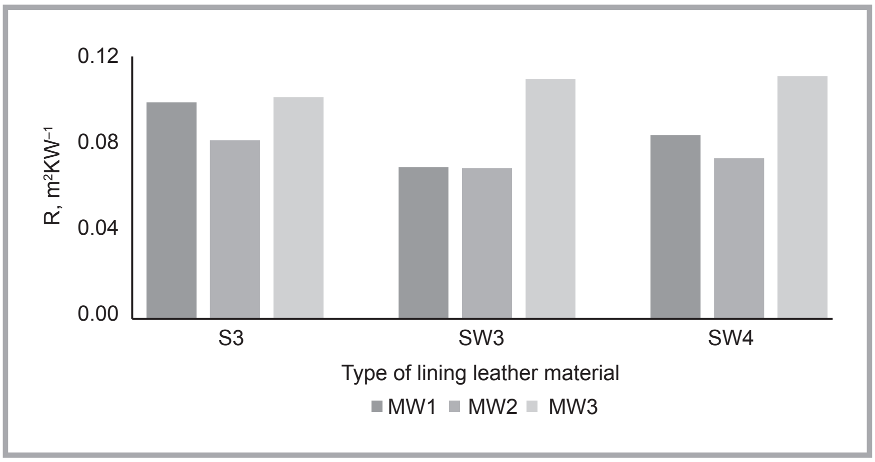

Figure 4. *Thermal resistance R for leather linings.*

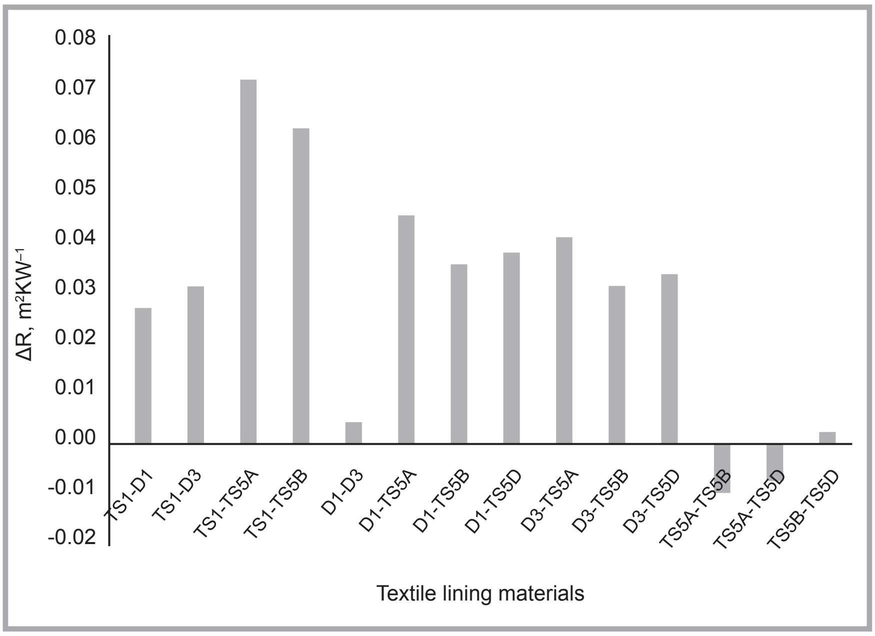

Figure 5. *Differences in thermal resistance for textile lining materials.*

Table 5. *Post-hoc analysis values for textile linings ((*) statistical significance of differences was obtained at a confidence level of α = 0.05).*

Pair of textile liningst ested	t	p
TS1 – D1	1.32309	0.26
TS1 – D3	1.83953	0.14
TS1 – TS5A	3.18078	0.03(*) d-Cohen's > 2
TS1 – TS5B	2.41595	0.07
TS1 – TS5D	2.47695	0.07
D1-D3	0.53335	0.62
D1 – TS5A	1.95395	0.12
D1 – TS5B	1.12518	0.32
D1 – TS5D	1.28767	0.27
D3 – TS5A	1.43636	0.22
D3 – TS5B	0.58967	0.59
D3 – TS5D	0.79953	0.46
TS5A – TS5B	-0.26578	0.80
TS5A – TS5D	0.00000	1.00
TS5B – TS5D	0.26578	0.80

TS5B, D3 – TS5D, TS5A – TS5B, TS5A – TS5D, TS5B – TS5D (for textile linings), S3 – SW4, S3 – SW3, SW3 – SW4 (for leather linings).

Statistical analysis of thermal resistance experimental results of the materials examined showed that statistical significance exists between upper materials MW2 and MW3. This fact was discovered irrespective of the lining material. The source of these significant differences is that these materials have a different structure. The MW3 material was made of two layers of polyamide material bound together by polyurethane foam (5 mm). Additional polyurethane coating improved the thermal resistance. Moreover this package of materials was characterised by low water vapour permeability, thereby, in conjunction with impregnation coating, providing higher thermal resistance for this material.

From a hygienic comfort point of view, polyamide fibres have very good sorption properties, which is important for storing moisture accumulated from the skin surface. By contrast, the MW2 material was made from two cotton layers bound together with the use of thinner polyurethane foam (2 mm). This material had a looser structure with larger pores, and this was the cause of heat escaping through the layers.

In the case of textile lining, statistically significant differences appeared only for TS1 (knitted fabric: 56% polyester, 46% – modified polyamide + polyurethane foam) and TS5A (polyamide knitted fabric). Material TS1 combined with MW1 or MW2 gives large differences in values of thermal resistance (over 36% and 42%, respectively). The main source of such considerable diversity is the thickness of these materials (in packages of upper lining between 38 and 42% and for single textiles over 83%). As thermal resistance is directly proportional to thickness, when we assume windless conditions, as in the experiment, large differences were obtained [2].

In ***Figure 5***, the differences in thermal resistance for textile materials are shown, with the ellipse indicating the pivotal materials – TS1 and TS5A.

For leather linings, statistical significances were not observed.

Based on the previous analysis, a table with optimal proposals (due to thermal insulation and hygienic properties) can be created. This diagram is connected with hygienic properties of the materials chosen. For this purpose, the water vapour coefficient (W_{VC}), which is the relation between water vapour permeability (W_{VP}) and water vapour absorption (W_{VA}), was calculated as follows:

$$W_{VC} = 8 \cdot W_{VP} + W_{VA},$$

where:
W_{VP} – water vapour permeability,
W_{VA} – water vapour absorption.

This is an important factor because a higher moisture content in footwear materials is connected with lower thermal insulation properties. The most optimal conditions are when this factor has the highest values and when the ratio

Table 6. Post – hoc analysis values for leather linings ((*) statistical significance of differences was obtained at a confidence level of α =0.05).

Pair of leather linings tested	t	p
S3 – SW3	0.76371	0.49
S3 – SW4	0.35135	0.74
SW3 – SW4	0.3923	0.71

Table 7. Diagram with optimal material proposals in respect to hygienic properties.

Upper	Textile linings	Leather linings
MW3 (water vapour coefficient is equal to 135.0 g/m^2)	TS5B (water vapour coefficient is equal to 3064.0 g/m^2)	SW4 (water vapour coefficient is equal to 1349.0 g/m^2)
	TS5D (water vapour coefficient is equal to 3032.0 g/m^2)	SW3 (water vapour coefficient is equal to 1468.0 g/m^2)

between water vapour absorption and water vapour permeability is as minimal as possible (in our case for textile linings TS5B and TS5D it was about 0.006% and 0.009% and for leather linings SW3 and SW4 – 3.1% and 3.2%), because a small level of vapour absorption gives a small possibility of precipitation of footwear materials. In view of this fact, a diagram of a optimal material hierarchy can be given as follows (***Table** 7*).

To create a complete view of the thermal insulation properties of whole footwear, the following steps should be taken:

- evaluation of thermal insulation of sock material;
- evaluation of thermal insulation of the upper – and sole combination (whole footwear volume);
- environmental conditions;
- temperature and moisture content in the ground.

These analyses will be undertaken in the next part of these investigations, with use of a thermal foot model (first two steps), and last two steps with the use of subject testing methodology (as, for example, in the previous work of authors [23].

Summary

The analysis of thermal insulation properties of footwear materials and compositions there conducted for this paper give the possibility to pick the best and worst in view of hygienic and usage characteristics. From only an insulation point of view, the best materials for lining were TS5B and TS5D, because these materials have good insulation properties along with high hygienic characteristics. The values of water vapour absorption for these lining materials (TS5B – 0.2 and TS5D – 0.3) allow to recommend this composition, which could provide better microclimate properties.

As regards leather linings, the best insulation characteristics were found for the following compositions: lining S3 with uppers MW1 and MW2 and for SW4 with upper MW3. By contrast, the weakest was lining SW3 with uppers MW2 and MW3 and S3 with upper MW1.

In conclusion, the choice of materials is of great importance for footwear consumers. As of yet, natural leather has better hygienic properties than other materials, and it can be used for uppers and each element of a shoe interior.

The porous structure of leather results in a high capacity of water absorption and desorption, which improves hygiene comfort of use. In contrast to a situation where all materials establish a barrier against circulation between the foot and the environment, leather has better water vapour permeability and stops an increase in temperature and humidity inside footwear. It is worth noting, however, that the thermal insulation of packages with leather lining was weaker than for textile linings. The possibility of improving the thermal insulation properties of leathers occurs during the tanning processes, when the semi-finished product is subjected to hydrophobisation. This treatment, however, results in the deterioration of some utility properties of the finished product [24, 25].

In order to minimise the negative impact of hydrophobisation on micro-climate conditions in the footwear interior, hydrophilic materials with a highly developed porous structure should be applied [26]. The same effect is possible with the use of materials with open porous spaces. Because of the experimental results obtained, we can select optimal packages of materials in the lining – upper combination. From the insulation properties point of view, textile combinations are better than leather – textile sets.

The issue of the insulation properties of footwear or footwear materials is very important in the creation an optimal microclimate in a shoe interior, especially for long periods of working in a frozen environment or for the elderly. Commonly used to study the insulation properties of footwear is a thermal foot model [5] with various sweating rates due to individuals. But this method is adapted to the analysis of the final shoe. The authors of this paper focused on the creation of two-layered textile packages (upper – lining), which could give guidelines for footwear constructors. By using of the analogous method with an Alambeta device, textile packages for thermal protective clothing were examined in [27]. In paper [28], similar analysis with regard to clothing materials was made with the use of an alternative measuring device. On the other hand, the authors of paper [29] determined the recommendable thickness of garment packages for environments with unsteady heat exchanges. In [30] the relationships between the thermal insulation properties of single and multi-layered materials for winter outdoor clothing were investigated. The optimal configuration of layers was found.

As regards footwear materials in articles [31, 32], optimal textile packages for footwear were examined, but only with respect to some physico – mechanical properties, not thermal insulation.

The problem of footwear comfort is very difficult, because a lot of factors, in particular hygienic, insulation or physico – mechanical properties of materials, must be harmoniously integrated. The complex evaluation of thermo-physiological comfort conditions will be the next step of these investigations. Wider analysis of selected materials with respect to their hygienic properties in packages is necessary to construct of a final shoe consistent with the specification developed.

Acknowledgements

The study presented in this paper was carried out as a part of research project Cornet/5/20/2016 titled: "Development of a ho-

listic footwear concept based on user – centred design and integrated self-management tools for the elderly (60+)" financially supported by the National Centre for Research and Development.

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Received 27.04.2018 Reviewed 11.07.2018