Beata Grabowska-Polanowska*,
Joanna Kwiecień,
Robert Gajewski**

Lukasiewicz Research Network,
Institute of Leather Industry
ul. Zgierska 73, 91-462 Łódź, Poland,
* e-mail: bmagrabowska@gmail.com,
** e-mail: rgajewski@ips.krakow.pl

Measurement of the Inside Microclimate of Footwear Constructed from Different Material Sets

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Abstract
The aim of the research was to determine the effect of footwear materials used on the microclimate inside shoes and to identify which material set provides optimal comfort to users. The microclimate of the interior of 21 pairs of footwear was tested. Selected nonwovens, natural leather, and leather-like materials were used to make the upper, lining and insole lining. Determined was the amount of water absorbed on the sock fibres, and measurement was taken of the relative humidity and temperature, as well as the permeability and sorption of outer materials and lining elements.Results of the researches carried out showed that in order to ensure adequate footwear comfort, materials for the upper should have high permeability, while lining materials should have both high sorption and permeability.

Key words: *microclimate, footwear comfort, nonwoven fabrics, leathers, leather-like materials.*

Introduction

The selection of the right material for the footwear structure is an important factor affecting the comfort. Knowledge of the hygienic parameters of materials, such as water vapour absorption and permeation is considered crucial during the design process of shoes. It is commonly accepted that some materials are more recommended than others. Generally, natural materials (leather, textiles) are considered optimal. Most consumers are convinced that shoes made of such materials would provide an appropriate microclimate that guarantees comfort to users [1]. However, the ultimate and objective evaluation of material performance can give the temperature and humidity inside shoes, which provides information about the microclimate as well [1-4].

Comfort assessment includes many factors ranging from external conditions to psychological, neurophysiological and ontogenetic traits [2, 5-10].

Moisture inside shoes may change during different activities. The amount of heat and sweat generated may vary depending on the level of physical activity and the type of clothing and footwear and consecutively affect the microclimate inside shoes and thermal comfort [1, 9-15].

Nowadays, footwear is often produced using synthetic materials. The application of synthetic or converted natural materials, often coated with polymer layers, may trigger the deterioration of hygienic and physiological properties of footwear [1, 16].

When assessing the quality of footwear, one should take into consideration its comfort and health-promoting features. Comfort assessment is a complex task because many factors affect it, including both subjective (individual physiological and mental characteristics of users, their sensitivity to stimuli exerted on the foot) as well as objective, physical parameters of a given pair of shoes (construction, selection of appropriate materials). The footwear manufacturer may influence only the last subgroup of factors. Particularly important is the selection of a correct last and materials used for the uppers, linings, and soles as well as the appropriate construction.

Determination of footwear microclimate is a difficult and complex issue due to the number of factors affecting it. In previous researches various methods were used [3, 17]. The method named The Satra Comfort Index was developed at the SATRA Laboratory in the UK. The method was allowed to determine both the sorption and water vapour permeability rates for insoles and innersoles. This method could also be used to predict the properties of materials and their performance during use. Research was also carried out on the relationship between the type of outer material and the accumulation of moisture and its spread in various parts of shoes during use [1, 2, 16-20].

Several comparative studies were made of the physiological impact of footwear made of artificial and natural leather on the foot [21]. There were data collected on changes in temperature and humidity inside shoes. It is assumed that the best feeling of comfort is perceived at the temperature (24-26 °C) [1]. The comfort range of humidity is up to 80%. Exceeding the threshold gives a feeling of discomfort, and exceeding 90% gives a feeling of total discomfort [22]. The relative humidity measured inside footwear made of natural leather was 64.33% on average, while for footwear made of synthetic leather, higher values of moisture were observed. It was noticed that full grain leather exposed to water vapour has the ability to pass moisture into the surrounding environment and has low absorption, while varnish-finished leather itself has a much lower water vapour permeability coefficient while increasing the absorption capacity [1, 2, 16].

In other researches, estimation of footwear comfort was carried out using the method developed at C.T.C. in France. In this method the speed of transportation and absorption of water vapour as well as changes in these rates were determined. In this method the hygienic properties of various lining and upper materials for shoes were tested. In the range of lining materials tested, it was found that the most beneficial properties, closest to those of natural leather, are possessed by linings containing a layer of natural leather and those characterised by high water vapour permeability [2].

In the present article the parameters related to footwear microclimate were determined in order to identify the best material sets for footwear which would provide optimal microclimate comfort. For this purpose measurements were made of the relative humidity and temperature inside the shoes as well as of the quantity of sweat emitted.

Materials and methods

For the tests, one model of shoes was chosen: ankle boots. This model was multiplied into 21 various versions differing in material composition. Specifications of the material sets are presented in ***Table 1***. For every subject their own collection of shoes of identical construction and material composition was prepared.

The upper materials and lining elements selected were characterised with respect to permeability and sorption. For this purpose values of the water vapour permeability and water vapour absorption were determined according to PN-EN ISO 20344:2012 (point 6.6. and 6.7) [13].

These parameters were estimated for samples cut out from the test material in an air-conditioned room at a temperature of 20 ± 2 °C and relative humidity of 50 ± 5%. Values of vapour permeability were determined for circle-shaped samples of 34 mm diameter. Values of permeability were calculated based on the ***Equation (1)*** below:

$$\textit{water vapour permeability} = \frac{m}{At} = \frac{m}{\pi r^2 t} \quad (1)$$

Where,
water vapour permeability, g/m^{2}24 h; m – mass of sample, g; calculated as ($m_2 - m_1$), where m_1 – initial & m_2 – final mass of sample; $A = \pi r^2$ area tested, m^2; r – radius of area tested, cm; t – time estimated between first and second weighing of sample, h.

The values of water vapour absorption were expressed as a percentage of the mass increase. The percentage of water absorption was calculated according to the ratio of the difference between the final (m_2) and initial (m_1) mass of the test piece to the initial mass of the piece (m_1), according to ***Equation (2)***.

$$\textit{water vapour absorption} = \frac{m_2 - m_1}{m_1} \times 100 \quad (2)$$

Where,
water vapour absorption is expressed as a percentage of the mass, %;
m_1 – the initial mass of the test piece, g;
m_2 – the final mass of the test piece, g.

Measurement of sweat absorbed by the sock materials was estimated by the weight method. Additionally, a sensor was used in order to determine the relative humidity and temperature inside the shoes; there were two sensors in one housing. The sensor was placed on the medial side of the foot midfoot in the area corresponding to the medial cuneiform and navicular bones (above the longitudinal arch). The sensor was produced by Novasina AG company (Switzerland).

The study involved three adult men aged 24 ± 2 years with a BMI in the range of 23.7 ± 0.8. Each pair of shoes was tested nine times (every subject tested the same pair of shoes three times), with the measurements repeated three times (8:00, 10:00, 12:00). The total time of a single test was 100 min, and included: treadmill walking (1h) and two resting periods – 10 min before walking and 30 min after walking. The tests were carried out in an air-conditioned room at a temperature of 20 ± 2 °C and relative humidity of 50 ± 5%.

Table 1. *Materials used in the preparation of footwear tested.*

Number of set	Symbol of set	Type of material			
		Upper	Lining	Insole lining	Inner insole
1	1	cattle leather	pig lining	pig lining	cellulose material
2	2	cattle leather	pig lining	pig lining	bonded leather
3	3	cattle leather	synthetic material 1	synthetic material 1	cellulose material
4	4c	cattle leather	polyamide nonwoven fabric	polyamide nonwoven fabric	cellulose material
5	4w	cattle leather	polyamide nonwoven fabric	nonwoven 60% viscose/ 40% polyester	cellulose material
6	5	cattle leather	three-layered material set	three-layered material set	cellulose material
7	6	cattle leather	engrained polyamide knitted fabric	engrained polyamide knitted fabric	cellulose material
8	7	cattle leather	knitted frotte	knitted frotte	cellulose material
9	8	leather-like material 1	pig lining	pig lining	cellulose material
10	9	leather-like material 1	pig lining	pig lining	bonded leather
11	10c	leather-like material 1	polyamide nonwoven fabric	polyamide nonwoven fabric	cellulose material
12	10w	leather-like material 1	polyamide nonwoven fabric	nonwoven 60% viscose/ 40% polyester	cellulose material
13	11	leather-like material 2	pig lining	pig lining	cellulose material
13	12	leather-like material 2	polyamide nonwoven fabric	polyamide nonwoven fabric	cellulose material
14	13	split laminated PVC	pig lining	pig lining	cellulose material
15	14	split laminated PVC	pig lining	pig lining	bonded leather
16	15c	split laminated PVC	polyamide nonwoven fabric	polyamide nonwoven fabric	cellulose material
17	15w	split laminated PVC	polyamide nonwoven fabric	nonwoven 60% viscose/ 40% polyester	cellulose material
18	16	split laminated PU	pig lining	pig lining	cellulose material
19	17	split laminated PU	polyamide nonwoven fabric	polyamide nonwoven fabric	cellulose material
20	18	split coated PU	pig lining	pig lining	cellulose material
21	19	split coated PU	polyamide nonwoven fabric	polyamide nonwoven fabric	cellulose material

Results

Measurement of permeability and sorption

The values of water vapour permeability (WVP) and water vapour absorption (WVA) estimated for selected materials applied for preparation of the footwear tested are presented below (***Table 2***).

Measurement of relative humidity and temperature inside of footwear

Values of relative humidity measured inside footwear made of different material sets are presented in the diagrams (***Figure 1***). In the case of shoes marked 1-7, the uppers were made of cattle leather. The lining and lining insole were made from six kinds of materials, as described in the Materials and Method section.

In the group of shoes marked 8-19, the uppers were made from two kinds of leather-like materials ("1", "2") and also from split leather laminated with PVC or PU. The lining and insole lining were made from pig lining or polyami-

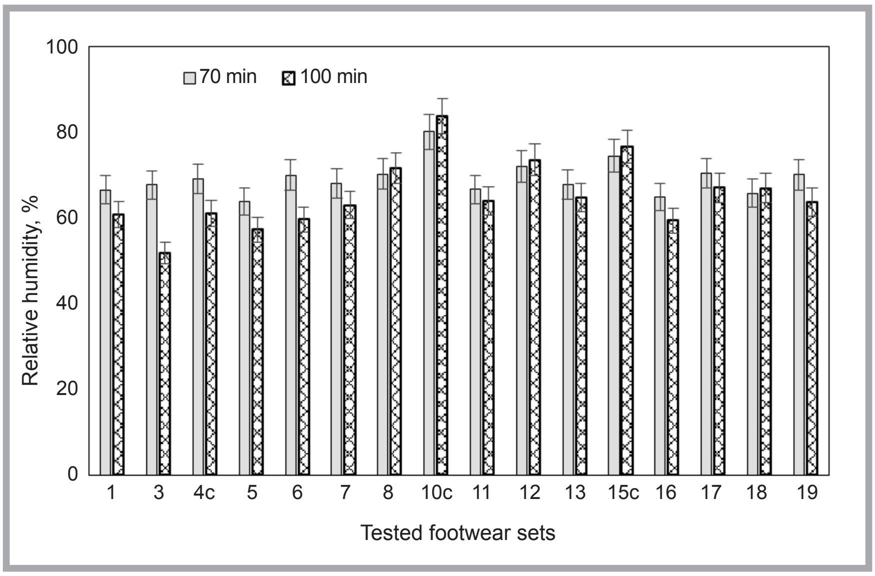

Figure 1. *Values of humidity measured inside footwear prepared with different material sets of the upper/ lining/insole lining and with an innersole made from cellulose material. The uppers were made from cattle leather (sets 1-7), from leather-like material – 1 (8-10c), from leather-like material – 2 (11, 12), and laminated split (13-19). In sets (1-7) different materials were used as the lining and insole lining: pig lining (1), synthetic material (3), polyamide nonwoven fabric (4c), material sets – type nonwoven (5) polyamine knitted fabric (6), and cotton knitted fabric (7). In sets (8-19) different kinds of upper materials were used: leather-like materials (8, 10c, 11, 12), PVC laminated split (13-17), and PU coated split (18, 19). Pig lining was used as lining or insole lining in sets 8, 11, 13, 16 & 18, whereas in sets 10c, 12, 15c, 17 & 19 polyamide nonwoven fabric was used.*

Table 2. *Values of water vapour permeability (WVP) and absorption (WVA) determined for materials used for the construction of the upper and insole of the footwear.*

Material to make upper	Cattle leather	Leather-like material 1	Leather-like material 2	Split laminated PVC	Split laminated P	Split coated PU
WVA, %	11.5 ± 0.115	0.6 ± 0.009	2.5 ± 0,03	8.6 ± 0,086	8.7 ± 0.1218	8.0 ± 0.088
WVP, $g/m^2 \cdot 24h$	439.5 ± 4.395	28.0 ± 0.42	227.0 ± 2.724	77.0 ± 0.77	188.7 ± 2.6418	188.7 ± 2.0757
Material for insole	pig lining	synthetic material	polyamide nonwoven fabric	three-layered material	engrained polyamide knitted fabric polyamide	knitted fabric frotte
WVA, %	10.7 ± 0.1605	4.5 ± 0.045	2.4 ± 0.0288	3.5 ± 0.0385	1.5 ± 0.015	5.5 ± 0.0715
WVP, $g/m^2 \cdot 24h$	403.0 ± 6.045	316.0 ± 3.16	340.0 ± 4.08	437.0 ± 4.807	410.0 ± 4.1	400.0 ± 5.2

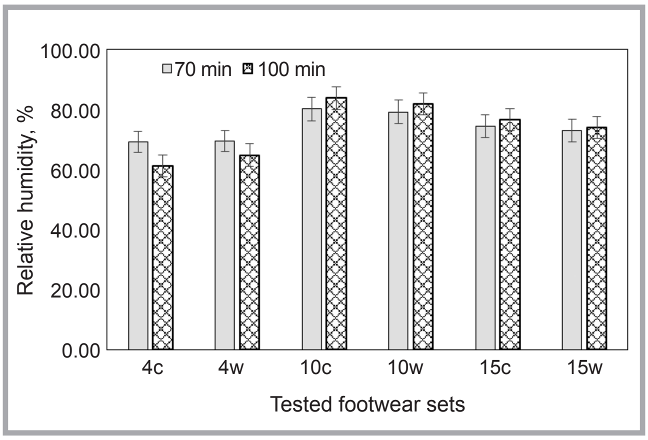

Figure 2. *Comparison of the relative humidity measured inside footwear with the use of nonwoven (60% viscose and 40% polyester) or polyamide nonwoven fabric as the insole lining. In all footwear sets the lining was made from polyamide nonwoven fabric. In the case of 4c, 10c & 15c, polyamide nonwoven fabric was also applied as the insole lining. The uppers were made of cattle leather (4c, 4nw), leather-like material – 1 (10c, 10w), and PVC laminated split leather – 1 (15c, 15w). The innersole was made of cellulose material.*

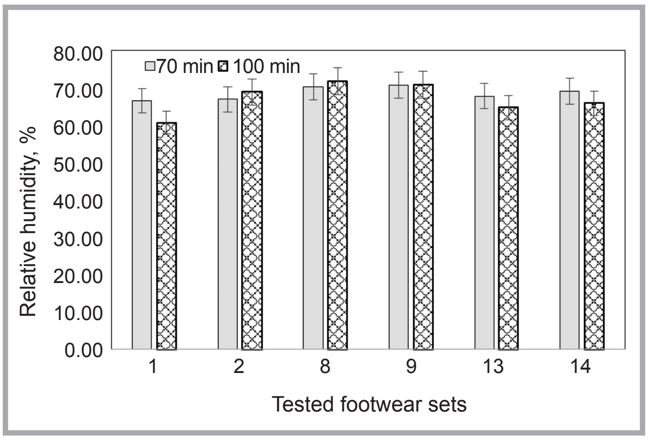

Figure 3. *Comparison of relative humidity measured after 70 and 100 minutes of tests of inside footwear with the innersole made of cellulose material or bonded leather. The linings in all cases were made of pig lining. The uppers were made of cattle leather (1, 2), leather-like material – 1 (8, 9), and laminated split leather – 1 (13, 14). The innersole was made of cellulose material.*

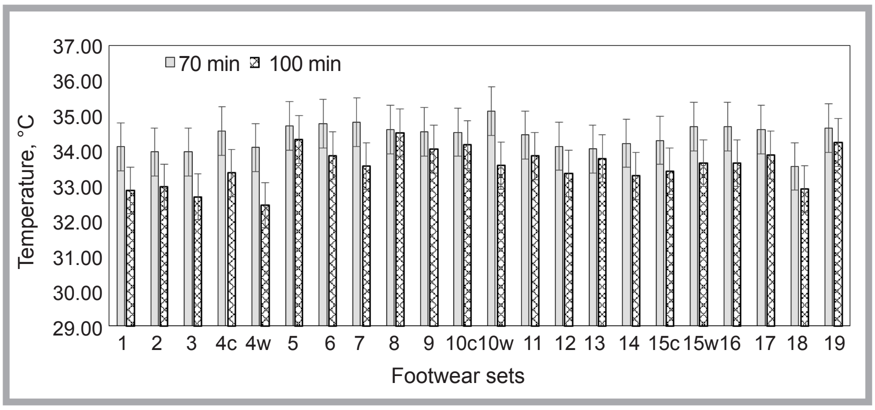

***Figure 4**. Comparison of temperature values measured for the inside of the tested footwear sets after 70 and 100 minutes.*

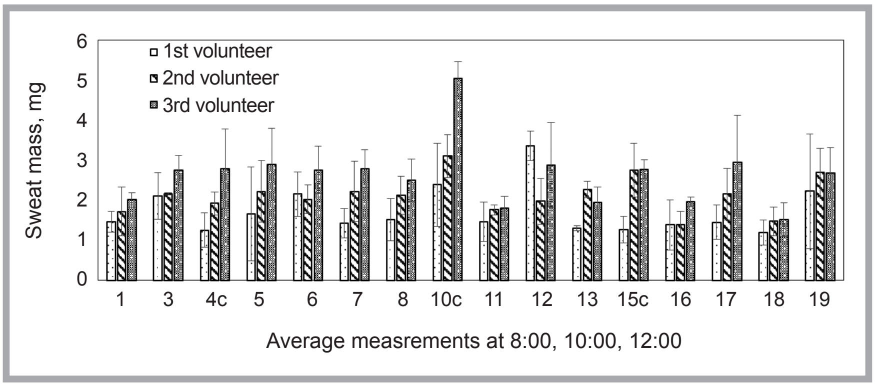

***Figure 5.** Comparison of results of water absorbed by sock material obtained for three volunteers testing different footwear sets. Average results of nine measurements for every volunteer (every set was tested threefold at 8:00, 10:00, 12:00).*

de nonwoven fabric. Cellulose material or bonded leather were applied for preparing the innersoles. In the case of sets 1-7, in which the uppers were prepared using cattle leather, the values of humidity amounted to less than 70%. For these sets humidity values measured after 70 minutes of the test were lower than after 100 minutes.

For the sets numbered from 8 to 19, the highest values of relative humidity were measured for sets 10c, 15c, 12, 17 and 8 (***Figure 2***). In the case of sets 8, 10c, 12 & 15c, higher values of RH were measured after 70 minutes than after 100 minutes of the test.

Additionally, the use of nonwoven (60% viscose and 40% polyester) as insole lining material was assessed. For this purpose, six sets of footwear were prepared, where the uppers were made from cattle leather (4c, 4w), leather-like material 1 (10c, 10w) and split leather laminated by PVC (15c, 15w). The linings were made from polyamide nonwoven fabric in all six cases, and insole linings were produced from polyamide nonwoven fabric or nonwoven (60% viscose and 40% polyester).

In the case of footwear with uppers made of cattle leather (4c and 4w), values of RH measured at 70 minutes were a little bit higher than those measured at 100 minutes. For shoes made of leather-like materials and laminated split leather, RH values were higher than for natural leather. The highest RH values were observed in sets 10c and 10w. Additionally, higher RH values at 100 minutes of measurement were reported in shoes with leather-like materials and laminated split leather (***Figure 2***).

The occurrence of possible differences between innersoles made of cellulose material and bonded leather was researched (***Figure 3***). Six pairs of shoes were prepared with uppers made from cattle leather (sets 1, 2), leather-like material 1 (sets 8, 9) and laminated split 1 (sets 13, 14). Comparing sets with the innersole made from cellulose material or bonded leather, no significant differences were observed.

Temperature measurement

The results of temperature measurements after 70 minutes and 100 minutes of the tests are presented in ***Figure 4***. The highest average values of temperature were noticed at the 70th minute in the case of such footwear sets as 5, 6, 7, 10w, 15c, 15w and 19. In the case of sets 1, 2, 3, 4c & 4w, relatively large differences between the measurement after 70 minutes and after 100 minutes were observed. The biggest differences (1.65 degrees) between both temperature measurements occurred in the case of set 4w, in which polyamide nonwoven fabric and nonwoven material were used.

Sweat absorption measurement

Measurement of sweat was made using the weight method. The sweat was absorbed by sock cotton material. The average results of three measurements made at 8:00, 10:00 and 12:00 o'clock for three volunteers are shown below (***Figure 5***).

The level of perspiration is an individual feature of every person, therefore among the volunteers differences in the tendency to sweat were observed. The highest sweating was noticed in case of the 3rd volunteer, while the 2nd volunteer had less sweating and the 1st volunteer the least. The person with the highest rate of perspiration showed a consistent tendency to reach the highest level of humidity in the majority of measurements (***Figure 5***).

Results and discussion

Based on the tests results, the quality of the materials used for the upper and interior elements of the shoes was analysed and their effect on the microclimate was determined. Comfort is an important factor in shoe design, which depends on the appropriate selection of materials. The function of materials used for uppers is protection of the foot against external factors, but also the channeling of water vapour outside footwear. The parameters of footwear materials considered crucial for ensuring comfort are water vapour permeability and water vapour absorption [2, 16, 17, 19, 20, 23].

Among the test materials used as uppers, the highest permeability parameters were found for cattle leather (403 g/m^{2}24 h), while lower values were measured in the case of leather-like material "2", polyurethane coagulum with an engrain layer

(227 g/m^{2}24 h), as well as in the case of split leather laminated with a polyurethane coating and split leather coated with a polyurethane layer. The values of permeability observed for split leathers were 188.7 and 188.0 g/m^{2}24 h, respectively. Leather-like material “1” with a PCV engrain layer showed significantly lower permeability values (28 g/m^{2}24 h). The highest values of water vapour absorption were observed in natural materials – cattle leather (11.7%) and laminated or coated split (8.75%; 8.7%; 8.0%).

Among materials used for internal footwear elements, i.e. insole and insole lining, the most appropriate were pig lining, three-layered textile material, engrained polyamide knitted fabrics and cotton knitted fabrics, which had the highest parameters of permeability, amounting to 403 g/m^{2}24 h for pig lining, 437 g/m^{2}24 h for three-layered material, 410 g/m^{2}24 h in the case of engrained polyamide, and 400 g/m^{2}24 h in the case of cotton knitted fabrics, respectively.

The highest water vapour absorption was measured in the case of pig lining. Other internal materials tested indicated water vapour adsorption in the range from 2.4% to 5.5%.

Based on the analysis of water vapour permeability and absorption, it was found that natural leather is the best material for the upper. Leather modifications, e.g. by coating or lamination of split leather, significantly affect water vapour permeability. Among the materials dedicated for the internal elements of shoes, pig lining, polyamide knitted fabric, 100% cotton knitted fabric (frotte), and split leather laminated with PVC indicated a high value of permeability and water absorption.

A comparison of the humidity values measured in different footwear sets indicated that for the majority of sets the results were similar (***Figure 2***). Different materials were applied as internal elements, but none influenced humidity significantly. However, in the case of sets with cattle leather (1-7), the humidity measured after 100 minutes of the test was lower than after 70 minutes. The highest values of humidity were measured for sets where the insole was made of leather-like material and polyamide nonwoven fabrics. Additionally, in the case of pairs of footwear 8-19, in which leather-like materials, laminated or coated split leathers were used as the upper, the humidity measured after 100 minutes of the test was higher than after 70 minutes. The results obtained indicated that the application of natural leather as the upper enables to remove moisture from the footwear more effectively than in the case of footwear made of artificial leather.

This observation that the humidity inside shoes made of artificial materials recorded after 70 minutes (end of walking) was higher than after 100 minutes (end of rest) indicates that the hygienic parameters of these materials are insufficient to remove moisture outside when the march stops, and consecutively the pumping effect of the movement of the longitudinal arch is “switched off” and moisture accumulates inside the shoes, whereas in the case of natural leather and textiles, moisture is effectively removed and humidity decreases despite the lack of the “longitudinal arch pump”.

Sweat glands are located mostly on the plantar part of the foot, therefore the role of the insole’s lining is the channeling of sweat into the innersole. Most of the sets presented had insole lining and innersoles made of the same material.

During the investigations described, in three per six measurements, the polyamide nonwoven fabric lining was replaced with nonwoven material consisting of 60% viscose and 40% polyester, however, this did not significantly affect the humidity measurement results. It was observed that only in the case of the upper made of cattle leather did the introduction of nonwoven lining bring about a reduction in humidity measured after 100 minutes as compared to the result after 70 minutes. However, in the case of the upper made of split leather or leather -like material, the humidity measured after 100 minutes of the test was higher than after 70 minutes, despite the use of nonwoven material. On the other hand, the application of nonwoven material improved the channeling of water emitted from the feet only in the case the upper made of cattle leather.

A comparison of footwear sets with two kinds of innersole made of cellulose material and bonded leather was carried out (***Figure 3***) and significant differences observed.

The temperature inside the shoes was measured after 70 and 100 minutes of the test (during the rest). Lower temperature in the second measurement (after 100 minutes) and higher differences between both measurements may indicate a lower insulation coefficient. The changes in temperature at the 100-th minute of the test, when the subjects had rested, may be treated as an indicator of the materials’ parameters.

The measurement of water (sweat) emitted from the feet allowed to compare several footwear sets. Average values of sweat absorbed by cotton socks obtained for the volunteers are presented in ***Figure 4***. The lowest values of absorbed water were measured in the case of samples 1-7 with natural leather as the upper and for 8,11,13,16 & 18. Footwear sets 1 to 7 had an upper made from cattle leather, 8 and 11 from leather-like material, and 13, 16 & 18 from laminated or coated split leather. The application of natural leather as an upper ensured better sweat absorption regardless of the kind of materials applied for internal materials. Small values of sweat emitted from the skin in the case of samples 8, 11, 13, 16 & 18 resulted from the application of pig leather for insole linings.

Somewhat surprising may be the result for set 10c, in which leather-like material was applied as the upper and polyamide nonwoven fabric as internal elements of the footwear. Polyamide nonwoven fabric is a modern material which offers a combination of abrasion resistance and good channeling of moisture to keep the feet cool and dry, and provides comfort even in extreme conditions [19]. Despite the positive characteristics of polyamide nonwoven fabric, in the case of sample 10c values of water absorption are significantly higher than in other samples. The same relates to relative humidity: Shoes 10c were the only samples where there was relative humidity recorded exceeding a value of 80% – the upper limit of the comfort range. The reason for the impaired footwear comfort observed is probably the minor sorption of the lining/polyamide nonwoven fabric applied.

In conclusion, lower values of humidity and sweat absorbed by the socks indicated better footwear comfort – the feet had no contact with a humid surface. The comfort of footwear could be improved when natural material is used for the upper and insole. Values of relative humidity measured in shoes made of natural materials confirmed that the application of such as the upper or insole will ensure footwear comfort. The use of pig lining as the insole and insole lining reduce values of humidity inside shoes and prevents the accumulation of sweat near the skin of the feet. Therefore, these footwear sets allow to obtain shoes of a higher level of footwear comfort.

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