Research Article • DOI: 10.2478/ftee-2023-0047 FTEE • 31(5) • 2023 • 75–85

Structural and Physiological Properties of Footwear Textiles

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Abstract
Textile uppers in the form of fitted knitted fabrics are now gaining in importance in the production of commercial footwear. The subject of this study was twelve different textile uppers and two reference leather materials. Structural properties and parameters of physiological comfort were characterized for selected variants. In order to analyze the thermo-physiological properties of the upper parts of the footwear, air permeability, thermal insulation properties, water vapor permeability and sorption properties were measured. Among the variants of textile uppers analyzed, the most desirable functional properties were shown by knitted fabrics made on cylindrical crochet machines of large diameters. The varnished cowhide leather variant was characterized by the worst hygienic properties.

Keywords
footwear, comfort, footwear upper, physiological properties.

1. Introduction

The consumption of footwear, growing along with the population, has contributed to the emergence of alternative methods of manufacturing footwear uppers in the form of fitted textile materials [1-3], which is partly related to the increased environmental awareness of users [4-5].

Footwear is part of a person's clothing. Its primary task is to protect the feet against injuries from the ground and ensure comfort while walking. Due to the application, footwear can consist of a variety of materials and components. The shoe can be divided into two main parts: the upper (upper, lining) and the lower (sole, insole) [6-7]. The materials most often used for the upper part are leather and textile materials. In the lower part the following are used: leather, vulcanized rubber, thermoplastic rubber (TPR), polyurethanes (PU), thermoplastic polyurethanes (TPU), ethylene vinyl acetate (EVA), and plasticized polyvinyl chloride (PVC) [8-9]. The selection of materials and components is an important factor affecting the quality of footwear use, its performance properties, and durability. Due to the subject of the work, the focus was on the materials used in the upper parts of footwear.

Leather is one of the oldest materials chemically modified by man. It is produced as a result of a long and complicated tanning process [10]. This process consists in introducing additional cross-linking into collagen, which binds the active groups of tannins with functional groups of the protein (COO- and NH3+), as a result of which raw animal skins gain appropriate strength properties and resistance to physical and biological factors [11]. The exact date when leather was first used to make shoes is not known. In 2010, a shoe made of a single piece of cowhide with a grass lining was found in an Armenian cave. The time of its creation is estimated at the period between the Neolithic Age and the Bronze Age (i.e. around 5500 BC) [12]. Until the late Middle Ages, shoes had been very simple products consisting of a single piece of leather. With the industrial revolution of the 19th century, mass production of footwear began [15]. Technological progress has made it possible to increase production efficiency, which has contributed to clear changes in footwear fashion and the birth of 'fast fashion' [16]. Despite the centuries-old tradition, leather is still one of the most popular footwear materials. It is characterized by shape stability, water resistance, good tensile strength, flexibility, breathability, and air and water vapor permeability. In addition, it retains the listed properties in changing climatic conditions. In terms of environmental issues, the process of tanning hides, unfortunately, contributes to the generation of sewage and emissions of pollutants [17]. More environmentally friendly leather materials have been developed, i.e. BIOnature, BioLeather, EcoLikeTM and Organio Leather [18-19].

Textile materials were used in footwear only at the turn of the 19th and 20th centuries. This involved the use of vulcanizing rubber for the sole in the popularization of sport. Around 1892, the first sneakers with a canvas upper appeared [20]. The first mass-market sneakers were the Converse All Star basketball shoes (1917). A breakthrough in the production of sports footwear was brought about by Puma, Adidas, Nike, and Reebok, which created a trend for innovative footwear with increased physiological values. Linen materials favored the growth of bacteria and fungi, were characterized by poor durability, and sweat caused discoloration in them. They were quickly replaced by leather, and later by synthetic materials. The first nylon uppers were proposed by the Japanese company Onitsuka Tiger (today's ASICS Tiger) [21]. Nylon, despite the higher price, turned out to be lighter, faster drying, more breathable, and resistant to discoloration.

A breakthrough in the production of textile uppers took place in 2012 when Nike introduced Flyknit technology, which was developed for the Summer

Olympic Games in London. It was the first method of producing uppers in the form of fitted knitted elements [22]. At the same time, Adidas developed its Primeknit technology. Both technologies used Stoll flat knitting machines. The main advantages of uppers made in this technology were: good fit to the foot, low weight, breathability, and reduction of production waste. Since then, uppers in the form of fitted textile elements have gained increasing commercial value. They are used both in recreational footwear, specialized sports footwear, as well as rehabilitation footwear and footwear for special purposes (e.g. for medical or uniformed services). Currently, fitted uppers are produced using only knitting technologies due to the possibility of producing elements with fitted shapes (waste-free technologies), as well as unlimited design. Textile elements of footwear are manufactured on warp knitting machines, cylindrical crochet machines of large and small diameters, and flat crochet machines [40].

This work aimed to analyze the functional characteristics of the physiological comfort of textile and leather materials used in commercially produced footwear by Puma, Reebok, Under Armour, The North Face, Adidas, and Nike. This work is a continuation of research on the performance properties of footwear textiles, which was previously published in the journal: Materials on 'Design Methodology and Technology of Textile Footwear' [23].

2. Materials

Fourteen different footwear materials were the subject of the research. Twelve of them were fitted uppers made by knitting technologies (variants 1 to 12). Variants 11 and 12 were textile elements obtained from commercial footwear by Adidas (Figure 1) and Sprandi (Figure 2). The last two variants (13 and 14) were reference leather materials (varnished and unvarnished cowhides). The characteristics of each variant, with a photo of the top and bottom sides of the material, are presented in Table 1.

3. Methods

For the research material presented, tests were carried out to characterize structural parameters and to analyze and compare selected parameters of physiological comfort. All tests were carried out in normal climate conditions, i.e. air temperature 20 °C ± 2 °C, relative air humidity 65 % ±4 %.

3.1. Structural parameters

The structural parameters that were determined for all the variants analyzed are as follows:

- thickness (h),
- mass per square meter (Mp).

For knitted elements additionally specified:

- course (Pr) and wale (Pk) density,
- flat loop dimensions (A - width, B - height)
- and loop shape coefficient (C).

The thickness (h) of the variants was determined in accordance with the PN-EN ISO 5084:1999 standard [24], while the mass per square meter (Mp) was determined in accordance with the PN-P-04613:1997 standard [25].

3.2. Parameters of physiological comfort

In order to determine the functional parameters of physiological comfort, the variants were subjected to the following tests:

- air permeability - ISO 9237:1995 standard [26],
- thermal insulation properties – Alambeta device,
- water vapor permeability - Permetest device,
- sorption properties - M290 Moisture Management Tester.

3.2.1. Air permeability

The air permeability was determined according to the ISO 9237:1995 standard for a pressure difference of 10 daPa.

Fig. 1. Adidas footwear model used for the research

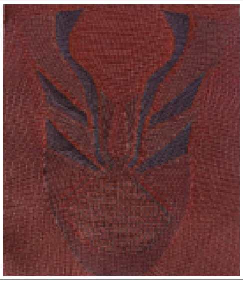
Fig. 2. Sprandi footwear model used for the research

3.2.2. Thermal insulation properties

Thermal insulation properties of the variants analyzed were measured using an Alambeta device. The Sensora Alambeta device is a two-plate device, in which the upper plate simulates dry human skin (32 °C), and the lower plate simulates the ambient temperature (20 °C). The device uses the phenomenon of steady heat exchange [27-30]. The measurement result of thermophysical properties of the material tested is given on the basis of the measurement of heat flow under the influence of the temperature difference between the plates of the device flowing through the sample over time.

The parameters measured by the Alambeta device are the: sample thickness (h), thermal conductivity (λ), thermal diffusion (a), thermal absorption (b), thermal resistance (r), maximal and stationary heat flow quotient (I) and stationary heat flow density at the contact point (s).

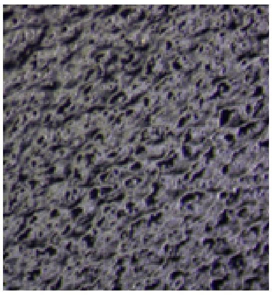
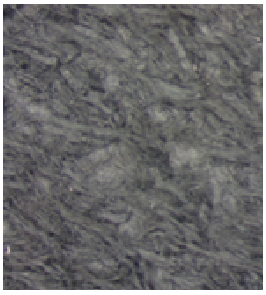
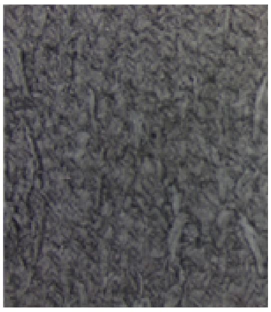
Particular attention should be paid to thermal conductivity (λ) and thermal resistance (r) from the point of application of materials in the footwear industry. Thermal conductivity describes the transport of energy in the form of heat through a sample of a certain mass

Textile materials					
Variant number	**Top side**	**Bottom side**	**Knitting technology**	**Yarns**	**Weave**
1			large diameter cylindrical crochet machine (Mayer & Cie, OVJA 1.6 EE 3/2 ET)	PES dtex 167 f 32/1 x 3, PES dtex 330 f 72/4	modified incomplete four-color jacquard with a filling in the form of a thread in each row
2			large diameter cylindrical crochet machine (Mayer & Cie, OVJA 1.6 EE 3 WT)	PES dtex 167/1, Elastan dtex 44	full two-color jacquard (in some areas there is a jacquard with a modified structure causing an openwork effect)
3			large diameter cylindrical crochet machine (Mayer & Cie, OVJA 1.6 EE 3/2 ET)	PES dtex 167/1	incomplete four-color double-sided jacquard
4			large diameter cylindrical crochet machine (Mayer & Cie)	PES dtex 167/1	incomplete three-color jacquard (in some areas there is a jacquard with a modified structure causing an openwork effect)
5			small diameter cylindrical crochet machine	PES 450 dtex	striped jacquard (alternating left-right and jacquard weave stripes)
6			flat knitting machine (CMS 502 HP B multi gauge E7.2)	PES dtex 167/32/1, Elastan dtex 156	two-layer knitted fabric with a tuck stitch system

Continued *Table 1. List of materials with characteristics*

Textile materials					
Variant number	Top side	Bottom side	Knitting technology	Yarns	Weave
7			flat knitting machine (CMS ADF-3 E7.2)	PES dtex 167/32/1, Elastan dtex 156, Hot Melt 220 dtex	two-layer knitted fabric composed of three weave systems: jacquard, openwork and tuck stitches
8			flat knitting machine (CMS 330 HP W TT sport E7.2)	PES 167 dtex, Lycra 156 dtex	two-layer knitted fabric with openwork weave areas
9			flat knitting machine (CMS 330 HP W TT sport E7.2)	PES 167 dtex, Lycra 156 dtex	two-layer knitted fabric with openwork and jacquard weave areas
10			flat knitting machine (CMS 502 HP+ multi gauge E7.2)	PES 167 dtex, Lycra 156 dtex	two-layer knitted fabric composed of jacquard (positive-negative) and openwork weave systems
Commercial textile uppers					
11			The upper consists of two knitted fabrics connected with an embroidery thread, the upper part is made of a two-layer knitted fabric joined with tucks, the bottom is an interlock knitted fabric		
12			Two-layer knitted fabric combined with tuck stitches and an openwork weave		

Continued *Table 1. List of materials with characteristics*

Leather materials			
Variant number	Top side	Bottom side	Description
13			Chrome-tanned cow leather, vegetable-syntan retanning, polished face finished by pouring using roll coater, fixed with a water-based polyurethane varnish
14			Chrome-tanned cow leather, chrome-syntan retanning

Continued Table 1. List of materials with characteristics

as a result of an external temperature difference. It is expressed by the formula:

$$\lambda = \frac{Q \cdot h}{S \cdot \Delta T}, \mathrm{W \cdot m^{-1} \cdot K^{-1}} \quad (1)$$

where: Q – heat flux, S – material surface, ΔT – temperature difference on both sides of the material, h – material thickness.

The lower the value of the coefficient λ, the less susceptible the material is to heat loss, thus better insulating the foot from the cold. The thermal resistance (r) is the ratio of the thickness of the material to its thermal conductivity coefficient λ. It determines the material's ability to resist heat loss.

3.2.3. Water vapor permeability

The water vapor permeability of the materials was tested using the Permetest instrument. The device works on a similar principle to the 'artificial skin model' (ISO 11092) [31]. The test sample is placed in a ventilated chamber on a heating plate covered with a membrane. The test sample is placed in a ventilated chamber, then, based on the measurements of the temperature of the measuring plate and the temperature and relative humidity in the chamber, the relative water vapor permeability RWVP and water vapor resistance R_{et} [34] are measured.

The relative water vapor permeability (RWVP) for the Permetest instrument is calculated from the formula:

$$RWVP = 100 \frac{q_v}{q_o}, \% \quad (2)$$

where: q_v - heat flux determined with the sample, q_o - heat flux determined without the sample.

Whereas the water vapor resistance (R_{et}) is obtained from the formula:

$$R_{et} = (t_m - t_o)(q_v^{-1} - q_o^{-1}), \mathrm{Pa \cdot m^2 \cdot W^{-1}} \quad (3)$$

where: t_m - measuring head surface temperature, t_o - air temperature in the measuring channel, q_v - heat flux density passing through the tested material, q_o - heat flux density passing from the head surface without the sample to the air in the measuring channel.

3.2.4. Sorption properties

The sorption properties of the materials were tested on an M290 Moisture Management Tester by SDL Atlas, according to AASTCC standards [35]. To measure the dynamic moisture transport process, a material sample is placed horizontally between two sensors. Then, a solution corresponding to human sweat is administered to the center of the upper sensor [36,37]. The measurement results are given based on changes in electrical resistance during wetting of the sample.

The parameters measured by the device are the wetting time of the top surface (WTT) and bottom surfaces (WTB), the absorption rate of the top (TAR) and bottom surface (BAR), the maximum wetting radius for the top (MWRT) and bottom surface (MWRB), the spreading speed on the top (TSS) and bottom surface (BSS), the accumulative one-way transport index (R) and the overall moisture management capacity (OMMC) [38].

The most important metrics when evaluating uppers for wicking ability are the last two : the accumulative one-way transport index (R) and the overall moisture management capability (OMMC). The accumulative one-way transport index (R) is used to rate a fabric's one-way moisture transport from the bottom to the top side. This parameter can take both negative and positive values. The higher the value of this parameter, the better the material wicks away sweat. The value of the OMMC parameter is the result of three measured properties: the absorption rate of the bottom surface (BAR), the accumulative one-way transport index (R), and the spreading speed on the bottom side (BSS). OMMC values range from 0 to 1. The higher the OMMC value, the better the moisture-wicking ability of the tested material [39].

$$OMMC = 0.25\,BAR + 0.50\,R + 0.25\,BSS \quad (4)$$

4. Results

4.1. Structural parameters

The results of structural parameters measurements for the variants analyzed are included in Table 2. For variant 11, due to the two-layer construction, the parameters of the knitted fabric structure were determined separately for each of the two component fabrics (11a, 11b). For leather variants, the thickness and mass per square meter were determined.

The mass per square meter (Mp) of the tested textile materials obtained ranged from 348 g/m^2 to 1219 g/m^2. The tested variants can be divided into three groups: with a low mass per square meter below 700 g/m^2, an average mass per square meter below 1000 g/m^2 and a high mass per square meter above 1000 g/m^2. The variants with a low mass per square meter included variants: 2, 3 and 4 (single-layer knitted fabrics made on cylindrical crochet machines), and the variants with a medium mass per square meter were variants: 1, 5, 8 and 11. The variants with a high mass per square meter were 6, 7 , 9, 10, 12 (knitwear mostly made on flat crochet machines). The mass per square meter for reference leather materials are at a high level, reaching 1000 g/m^2.

The course density of the tested knitted variants ranged from 37 to 198 courses/dm. Variant 1 was characterized by the lowest value of course density, and the highest value of the bottom knitted fabric was for variant 11 (11b). The wale density of the tested variants ranged from 52 to 162 wales/dm. The lowest value of wale density was obtained for the upper fabric of variant 11 (11a), while the highest value for the lower knitted fabric of this variant (11b). In most cases, the surface density is at a similar level, with an average of 8942 loops/dm^2.

In the assessment of the construction of materials used for footwear, no significant differences in the size of structural parameters are visible, i.e. the variants analyzed are comparable.

4.2. Air permeability

Results of the air permeability test according to the PN-P-04618:1989 standard are included in Table 3.

The air permeability (P) of the tested textile uppers ranged from 264 dm^3/m^{2}s to 1688 dm^3/m^{2}s. The lowest value of air permeability was obtained for variant 10, which was a two-layer knitted fabric composed of jacquard and openwork weave systems, produced on a Stoll flat knitting machine. From the presented variants produced by this technology, it

Variant number	Thickness, h mm	Mass per square meter, Mp g/m^2	Course density, Pr number of courses/dm	Wale density, Pk number of wales/dm	Loop width, A mm	Loop height, B mm	Loop shape coefficient, C
1	1.91	730	37	71	1.41	2.70	1.92
2	1.56	372	98	93	1.08	1.02	0.95
3	1.70	488	77	89	1.12	1.30	1.16
4	1.48	348	97	86	1.16	1.03	0.89
5	3.55	973	122	72	1.39	0.82	0.59
6	3.18	1219	88	59	1.69	1.14	0.67
7	3.15	1024	89	59	1.69	1.12	0.66
8	3.44	984	122	80	1.25	0.82	0.66
9	3.48	1173	108	76	1.32	0.93	0.70
10	3.49	1089	106	79	1.27	0.94	0.75
11	2.42	915	-	-	-	-	-
11a	1.74	750	70	52	1.92	1.43	0.74
11b	0.68	165	198	162	0.62	0.51	0.82
12	2.47	1147	118	68	1.47	0.85	0.58
13	1.80	1009	-	-	-	-	-
14	1.45	905	-	-	-	-	-

Table 2. Results of measurements of structural parameters

Variant number	Air permeability, P dm^3/m^2s
1	417.36
2	1422.80
3	1014.93
4	1588.79
5	275.08
6	882.14
7	1688.39
8	882.14
9	1432.29
10	264.64
11	986.48
12	327.25
13	0.00
14	0.86

Table 3. Results of measurements of air permeability

was this variant that was characterized by the smallest share of the openwork spot. The highest value of air permeability was shown by variant 7, produced by the same technology, but with a greater share of openwork spots, which proves the great influence of the perforation of the upper on the ventilation of the footwear. According to the results presented, knitted fabrics can be divided into two groups: one with high air permeability (from 882 dm^3/m^2s to 1688 dm^3/m^2s) and another with low air permeability (from 264 dm^3/m^2s to 417 dm^3/m^2s). The variants with high air permeability include are 2, 3, 4, 6, 7, 8, 9 and 11, while those with low air permeability are 1, 5, 10 and 12.

Very low air permeability results were obtained for the reference leather materials. Variant 13 (patent leather material) was shown to be entirely airtight . For variant 14, a very low value of less than 1 dm^3/m^2s was obtained.

Fitted knitting uppers, therefore, have several times better air permeability than leather, which makes them more attractive in terms of physiological comfort. Textile uppers contribute to the improvement of footwear ventilation, facilitating air circulation in the system of footwear interior - external conditions and vice versa.

4.3. Thermal insulation properties

Thermal insulation properties were determined according to methodology referring to the Alambeta device. The results are summarized in table 4.

An average thermal conductivity (λ) of $52.75 \cdot 10^{-3}$ W/mK was obtained for the tested textile variants. The highest value was obtained for variant 10 ($66.3 \cdot 10^{-3}$ W/mK), and the lowest for variant 2 ($42.4 \cdot 10^{-3}$ W/mK). Variant 10 (a two-layer knitted fabric composed of a jacquard and openwork weave made on a flat crochet machine) will therefore best dissipate heat from the inside of the footwear. Variant 2 (one-layer jacquard knitted fabric made on a large-diameter cylindrical crochet machine), on the contrary, will insulate the foot better from external conditions. It should be noted that the values of thermal conductivity (λ) were at a very similar level. The average value of thermal conductivity (λ) of leather materials was 55.6 10^{-3} W/mK. Therefore, it can be concluded that the thermal conductivity of textile materials is similar to the thermal conductivity of leather materials.

The average value of thermal resistance (r) for textile uppers was $60.42 \cdot 10^{-3}$ $K \cdot m^2/W$, and for leather materials it was $26.9 \cdot 10^{-3}$ $K \cdot m^2/W$. This means that fitted knitted elements will protect the feet against heat loss to a greater extent than leather materials. Variants 9 (double-layer knitted fabric made on a flat crochet machine) and 12 (shoe uppers of Sprandi commercial shoes) deserve attention as they showed the best thermal insulation, more than three times higher than leather variants.

In order to determine the influence of the structure of materials on the thermal resistance (r), the relative thermal resistance is determined relative to the material thickness unit (r_{rel}). The highest value of the relative thermal resistance in relation to the thickness of the material (r_{rel}) was obtained for variant 2, and the lowest for variant 10. This means that the value of thermal resistance of knitting materials depends not only on the thickness (h), but also on structural parameters, i.e. the weave , linear mass of yarn and surface filling, among others.

4.4. Water vapor permeability

Water vapor permeability through the variants analyzed was measured using the Permetest instrument. Results of the relative water vapor permeability and water vapor resistance are presented in table 5.

Textile variants in terms of the value of relative water vapor permeability (RWVP) can be separated into: those with a high level of RWVP, from 41.4 % to 61 % (variants: 1, 2, 3, 4 and 6), and variants with a low level of RWVP, from 22 .7 % to 33.2 % (variants: 5, 7, 8, 9, 10, 11, 12). Among the textile materials, the best results were obtained for elements mostly produced on large-diameter cylindrical crochet machines. The worst RWVP results were obtained for knitted fabrics from small-diameter cylindrical crochet machines, from flat crochet machines and for commercial shoe uppers. The number 13 leather variant was shown to be non-permeable to water vapor as its surface had been sealed with varnish. Variant 14, on the other hand, was characterized by a RWVP value similar to that of textile variants (31.1%).

The average water vapor resistance (R_{et}) for the tested textile variants was 12.2 $Pa \cdot m^2/W^{-1}$. The lowest value of water vapor transmission resistance (Ret) of 4.4 Pa m^2/W^{-1} was recorded for variant 2 (single-layer knitted fabric with a full double-sided jacquard weave), which means that this variant will have the lowest resistance to water vapor, i.e. it will be the best for transporting it from the inside of the shoe to the environment. The highest value of water vapor resistance (R_{et}), equal to 23.2 $Pa \cdot m^2/W^{-1}$, was obtained by variant 5 (strip jacquard knitted fabric made by sock and hosiery technology), which will be the least hygienic among the tested textile variants. For the leather variant, an R_{et} value of 14.6 $Pa \cdot m^2/W^{-1}$ was obtained, which is commensurate with the average R_{et} obtained for the textile variants.

Variant number	**Thickness, h**	**Thermal conductivity, λ**	**Thermal diffusion, a**	**Thermal absorption, b**	**Thermal resistance, r**	**Relative thermal resistance related to material thickness, r_{rel}**	**Maximal and stationary heat flow quotient, I**	**Stationary heat flow density at contact point, s**
	mm	10^{-3} W · m^{-1} · K^{-1}	10^{-6} m^2 · s^{-1}	W · m^{-2} · $s^{1/2}$ ·K^{-1}	10^{-3} W^{-1} · K ·m^2	W^{-1} · K ·m	-	W · K · m^{-2}
1	2.44	51.2	0.243	104.0	47.6	19.51	2.01	0.295
2	1.53	42.4	0.179	100.0	36.1	23.59	1.87	0.359
3	1.73	55.6	0.182	130.0	31.0	17.92	2.16	0.477
4	1.53	48.8	0.175	117.0	31.3	20.46	1.96	0.457
5	4.21	55.3	0.836	60.5	76.2	18.10	1.98	0.181
6	3.25	59.0	0.772	67.1	55.1	16.95	1.52	0.190
7	3.59	51.9	0.145	136.0	69.3	19.30	3.10	0.305
8	4.21	53.2	0.321	93.9	79.2	18.81	1.76	0.163
9	4.77	50.9	0.495	72.4	93.6	19.62	1.51	0.118
10	3.50	66.3	0.452	98.7	52.8	15.09	1.50	0.195
11	2.78	51.4	0.162	128.0	54.0	19.42	3.13	0.392
12	4.65	47.0	0.630	59.2	98.8	21.25	1.55	0.109
13	1.58	55.1	0.078	197.0	28.6	18.10	1.90	0.466
14	1.41	56.1	0.062	226.0	25.2	17.87	2.41	0.663

Table 4. Results of measurements of thermal-insulating properties measured on the Alambeta device

Variant number	**Relative water vapor permeability, RWVP %**	**Water vapor resistance, R_{et} Pa · m^2 · W^{-1}**
1	41.4	10.0
2	61.0	4.4
3	52.1	6.4
4	56.1	5.3
5	22.7	23.2
6	51.0	6.2
7	33.2	12.9
8	31.1	14.2
9	22.7	22.0
10	24.2	10.1
11	28.0	16.6
12	29.5	15.3
13	0.0	0.0
14	31.1	14.6

Table 5. Results of measurements of water vapor permeability

4.5. Sorption properties

The results of sorption property measurements for selected variants are presented in tables 6a and 6b. The test results are presented in two tables to illustrate the absolute values of the parameters and their relative values in relation to the scale (from 1 to 5). Due to the too small surface area of the tested material, it was not possible to obtain the result for four variants - variants 6, 7, 10 and 13. For these reasons, the results of sorption properties for these variants will not be discussed.

The absolute values (Table 6a) of the cumulative one-way transport index (R) obtained for textile materials can be divided into positive and negative. Variants 2, 3, 4, 5 and 12 were characterized by positive values, and: 1, 8, 9 and 11 by negative values. Based on this division, it can be assumed that variants with positive results are materials that wick away moisture well (single-layer knitted fabrics made on large diameter cylindrical crochet machines and a variant of the upper of commercial footwear by Sprandi). According to the ranking scale (Tab. 6b), the best textile variants in terms of moisture transport are variants 3 and 4 (3.75 and 3), while the worst are variants 8 and 11, i.e. a two-layer knitted fabric made on a flat crochet machine and a variant of a commercial upper manufactured by Adidas. The other variants showed satisfactory results, from 2 to 2.5. For the leather variant, the absolute value of the cumulative one-way transport index (R) of 6.717 was obtained, which in the ranking scale also corresponds to a satisfactory value of 2.

With regard to the absolute (Table 6a) and relative (Table 6b) results of the overall moisture management capacity (OMMC), four textile variants with high sorption properties can be distinguished, namely, variants 2, 3, 4 and 12 (variants of knitted single-layer and fabric of Sprandi's commercial footwear). The remaining variants, including the leather variant, showed poor OMMC values (from 0 to 0.1), which translates into a score of 1 on the ranking scale.

Variant number	Wetting time of top surface, WTT s	Wetting time of bottom surface, WTB s	Absorption rate of top surface, TAR, %/s	Absorption rate of bottom surface, BAR %/s	Maximum wetting radius for top surface, MWRT mm	Maximum wetting radius for bottom surface, MWRB mm	Spreading speed on top surface, TSS mm/s	Spreading speed on bottom surface, BSS mm/s	Accumulative one-way transport index, R -	Overall moisture management capacity, OMMC -
1	8.658	12.823	13.604	12.506	7.500	7.500	1.234	1.127	-45.566	0.076
2	1.742	9.828	26.865	36.422	12.500	10.000	0.666	0.696	261.570	0.420
3	21.528	8.517	41.943	51.433	10.000	10.000	0.484	0.741	129.866	0.315
4	3.464	3.604	40.290	42.022	20.000	20.000	3.546	3.433	13.622	0.362
5	7.676	11.326	18.379	21.517	10.000	10.000	1.489	0.899	9.422	0.100
6	-	-	-	-	-	-	-	-	-	-
7	-	-	-	-	-	-	-	-	-	-
8	6.271	120.000	78.578	0.000	5.000	0.000	0.774	0.000	-936.689	0.000
9	5.897	14.040	6.918	8.558	10.000	5.000	1.176	0.351	-29.673	0.023
10	-	-	-	-	-	-	-	-	-	-
11	7.020	50.544	81.606	5.012	5.000	5.000	0.694	0.099	-941.899	0.000
12	4.212	4.587	20.884	25.140	10.000	15.000	1.665	2.106	97.732	0.298
13	-	-	-	-	-	-	-	-	-	-
14	120.000	120.000	0.000	0.000	0.000	0.000	0.000	0.000	6.717	0.060

Table 6a. Results of sorption properties of tested variants - absolute values

Variant number	Wetting time of top surface, WTT 1-5	Wetting time of bottom surface, WTB 1-5	Absorption rate of top surface, TAR, 1-5	Absorption rate of bottom surface, BAR 1-5	Maximum wetting radius for top surface, MWRT 1-5	Maximum wetting radius for bottom surface, MWRB 1-5	Spreading speed on top surface, TSS 1-5	Spreading speed on bottom surface, BSS 1-5	Accumulative one-way transport index, R 1-5	Overall moisture management capacity, OMMC 1-5
1	3.25	3	1.5	1.5	2	2	2	2	1.25	1
2	3	3.25	2.5	2.75	2.5	2	1	1	3.75	2.75
3	2.5	3.5	3	3.5	2	2	1	1	3	2
4	4.25	4.25	3	3	4	4	4	4	2	2.25
5	3.5	3	2	2	2	2	2	1	2	1
6	-	-	-	-	-	-	-	-	-	-
7	-	-	-	-	-	-	-	-	-	-
8	3.5	1	4	1	1	1	1	1	1	1
9	3.5	3	1	1	2	1	1.5	1	1.5	1
10	-	-	-	-	-	-	-	-	-	-
11	3.5	2	4	1	1	1	1	1	1	1
12	4	35	2	2.5	2	3	2	2.5	2.5	2
13	-	-	-	-	-	-	-	-	-	-
14	1	1	1	1	1	1	1	1	2	1

Table 6b. Results of the sorption properties of the tested variants - relative values in the ranking scale 1-5

5. Discussion

1) A breakthrough in the production of textile uppers took place in 2012 when Nike introduced Flyknit technology, the first method of upper production carried out on Stoll flat knitting machines. The main advantages of uppers made by this technology are a good fit to the foot, low weight, breathability and reduction of production waste. Fitted uppers have been used both in recreational footwear, specialized sports footwear, as well as rehabilitation footwear and special purpose footwear.

2) The subject of the tests was fourteen different footwear materials, including twelve fitted uppers made by knitting technologies and two reference leather materials. For selected materials, tests were carried out to determine the structural parameters, including thickness

and surface mass, as well as functional parameters of physiological comfort, i.e. air permeability, thermal insulation properties, water vapor permeability, and sorption properties. These parameters are measured according to Polish (European ISO) standards, as well as the recommendations of the manufacturers of Alambeta, Permetest and M290 Moisture Management Tester devices.

3) The analysis of structural parameters showed that:

– The thicknesses of the fitted textile elements ranged from 0.68 mm to 3.55 mm. Representative leather materials had a thickness of 1.80 mm and 1.45 mm, comparable to the tested textile materials.
– The mass per square meter of the tested textile materials ranged from 348.4 g/m^2 to 1218.6 g/m^2. Variants of low mass per square meter included single-layer knitted fabrics made on cylindrical crochet machines, while knitted fabrics with a high mass per square meter were mostly variants made on flat crochet machines. The surface weights of reference leather materials are at a high level, reaching 1000 g/m^2.
– The structures of knitted fabrics differ in the density of surface density, which ranges from 2627 to 9760 loops/dm^2.

4) As part of the physiological comfort tests conducted, it was found that:

– The air permeability of the tested textile uppers ranges from 264 dm^3/m^{2}s to 1688 dm^3/m^{2}s. The lowest value of air permeability was obtained for a two-layer jacquard knitted fabric made on a flat crochet machine. The highest value of air permeability was obtained for the knitted fabric with an openwork weave with a small volumetric filling, causing the perforation of the upper to ventilate the footwear well. For the reference leather materials, very low air permeability results were obtained (the varnished leather variant is not air permeable). Fitted knitting uppers, therefore, have several times better air permeability than leather, which makes them more attractive in terms of physiological comfort.
– A two-layer knitted fabric composed of a jacquard (positive-negative) and openwork weave system will best dissipate heat from the inside of the footwear (λ = 66.3·10^{-3} W/mK). The variant of single-layer jacquard knitwear, on the contrary, better insulates the foot from external conditions (λ = 42.4 ·10^{-3} W/mK). The thermal conductivity of textile materials is similar to that of leather materials. It was also shown that fitted textile elements protect against heat loss to a greater extent than leather materials.
– Textile variants with a high level of relative water vapor permeability are mostly single-layer knitted fabrics made on large-diameter cylindrical crochet machines, while variants with a low level of relative water vapor permeability are made on small-diameter cylindrical crochet machines and on flat crochet machines. The lowest water vapor resistance value of 4.4 Pa·m^2/W^{-1} was recorded for a single-layer knitted fabric with a full double-sided jacquard weave, which means that this variant will have the lowest resistance to water vapor, i.e. it will transfer it best from the inside of the shoe to the environment. The highest value of water vapor permeation resistance was obtained by the strip jacquard fabric produced by sock and hosiery technology (23.2 Pa·m^2/W^{-1}).
– According to the ranking scale, in terms of sorption properties, the best textile variants are those produced on large-diameter cylindrical crochet machines, the worst on flat crochet machines as well as the variant of the Adidas commercial upper. With regard to the absolute and relative results of the overall moisture management capacity, four textile variants with high sorption qualities can be distinguished, namely variants of single-layer knitted fabrics and the knitwear of Sprandi's commercial footwear.

Acknowledgments

This work was completed while the first author was a doctoral candidate at the Interdisciplinary Doctoral School at the Lodz University of Technology, Poland.

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