

Barrier Properties of Footwear Packages against Water Vapour Transport and Thermal Resistance

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Abstract

In this paper the authors focused on the analysis of relations between the material (such as knitted fabrics with a two and three dimensional structure) configurations and hygienic parameters of packages. In order to measure hygienic properties, the water vapour permeability and absorption were both used with the thermal resistance capacity. The connector role in the packages measured was played by air (in the case of two – layered package), polyurethane foam and three – dimensional knitted fabric with similar characteristics to polyurethane foam in respect of the mass per square metre and thickness. On the basis of the results obtained, a statistical model of the barrier was created and the changes in water vapour transport process described.

Key words: footwear upper packages, sandwich structures, water vapour absorption, water vapour permeability, thermal resistance.

higher pressure occurrence [1]. Mechanical parameters can affect resistance to destructive forces, which are common during the footwear life cycle. The lining materials participate in ensuring optimal temperature and humidity conditions inside a shoe interior [2]. Additionally, the mode of connection between the lining and outer layer is also an important determinant in improving the hygienic parameters of a shoe. The set of properties which can affect footwear comfort includes high air and water vapour permeability (especially in a hot environment), good thermal insulation (especially in cold conditions [3]), optimal abrasion and tear resistance. In cases where footwear is not hygienic, the mechanism of sorption from the skin and desorption to the external environment of sweat is disturbed. The drying processes of footwear materials are delayed and may cause the occurring of a discomfort sensation. The water and air permeability properties depend on the porosity of the material, which is described by the presence of open spaces between fibres [4]. Other authors found a correlation between water vapour permeability and loop length or linear density [5]. The water vapour permeability was higher for fabrics made from finer yarns. When the mass per square metre and thickness were lower, the easy passage of water vapour through the fabrics was possible. One possibility of improving the water vapour permeability parameter is putting microporous membranes made from polytetrafluorethylene (i.e. Gore – Tex), polyurethane (i.e. Porelle, Seyntex), polyester (i.e. Sympatex) or a blend based on polyester and polyamide (i.e. Tepor). In the most cas-

es, the abovementioned membranes are joined with other materials (textiles or leather) by lamination processes, which is an effective way to create innovative footwear materials [6-7].

Research on the possibilities of optimising physiological footwear comfort properties has raised innovative solutions both in respect of materials and combinations. The water vapour transport mechanism from the skin surface was also improved [8]. In paper [9] the authors showed that support textile materials (liners, insoles, socks or inserts) with good heat and moisture transport properties can play an important role in removing sweat from the foot surface. In paper [10] the authors showed that sock – like liners and lining materials joined in a specific way could create conductive and diffusive layers. Research conducted with the use of subjects confirmed a reduction in the discomfort index of 40%.

In the following paper, the authors developed and investigated innovative material packages based on polyester fibres for hygienic properties. Depending on the footwear type, the packages had two or three layers. As a joining medium, air, polyurethane foam (with water vapour permeability at the level of 29.1 mg/cm²h) and three – dimensional knitted fabric (42.61 mg/cm²h) were used. The motivation behind using polyurethane foam was that this material is commonly used in footwear manufacturing [11], due to being adhesively compatible with most materials, like fabrics, plastics and leathers, both in the lamination and coating processes [12-13].

Introduction

The footwear upper is – in most cases – a composition of different materials – of natural or synthetic origin. The most important task in designing footwear upper packages is appropriate selection. Moreover, the right configuration of packages, should be able to create an optimal microclimate in a shoe volume as well as mechanical parameters which are connected with the possibility of the reduction of the probability of

In addition, polyurethane foam improves the insulation properties. The model of material composite proposed might be – after suitable modification – applied in a wide spectrum of cases – from footwear, through industrial textiles to personal protective equipment [14-15]. The outer layer of this composite was formed of woven cotton with a view to reducing CO₂ emissions during the footwear life cycle [16-17]. The composite packages designed in this work were tested for water vapour permeability, absorption and thermal resistance. This was the basis to establish a hierarchy of materials intended for future research.

Materials and methods

The research material consists of a group of polymer materials with a two and three – dimensional structure. The basic characteristics of the materials used are given in *Tables 1* and *2*.

The way of preparing the material packages is as follows: in all cases, as the outer layer woven cotton of plain weave was used. As the layers placed in the nearest foot neighbourhood, three – dimensional knitted fabrics: D1 – D4 and two – dimensional polyamide, polyester and cotton knitted fabrics: P1 – P6 and PCOT were used. As the connecting layer, polyurethane foam (PUfoam) [18] and knitted fabric D1 were used.

The water vapour permeability and absorption were obtained by using the procedure described in PN – EN ISO 20344: 2012 p. 6. 6 and 6. 7. The measurement time was equal to 8 hours. The thermal resistance was determined with the use of the Alambeta (SENSORA) tool according to methodology described in papers [19-21].

In order to measure the transient and steady state thermo-physical properties of the upper and lining footwear materials, the Alambeta device was also used. Sample sized 20 cm x 20 cm were placed between 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 being measured with a constant pressure of 200 ± 20 Pa. The measurement stand was placed in normal climate conditions [22]. As a result of this measurement, the thermal ability of the

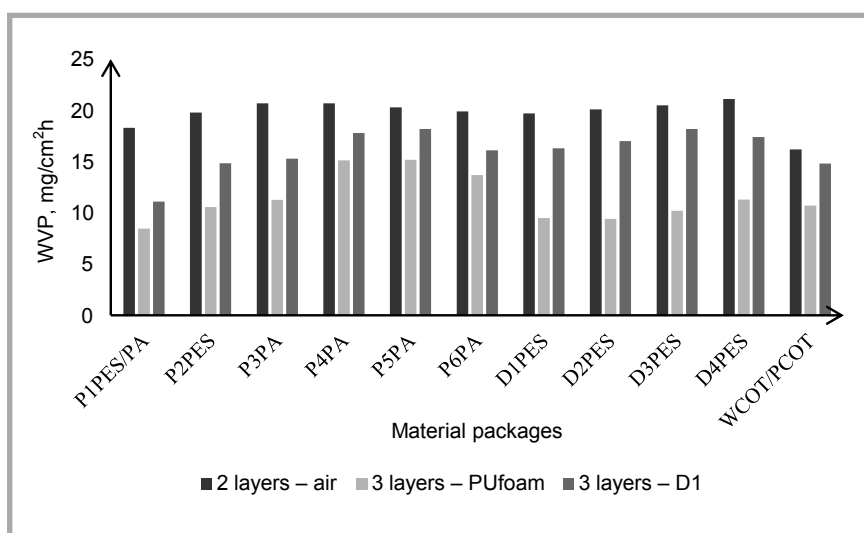


Figure 1. Water vapour permeability for material packages.

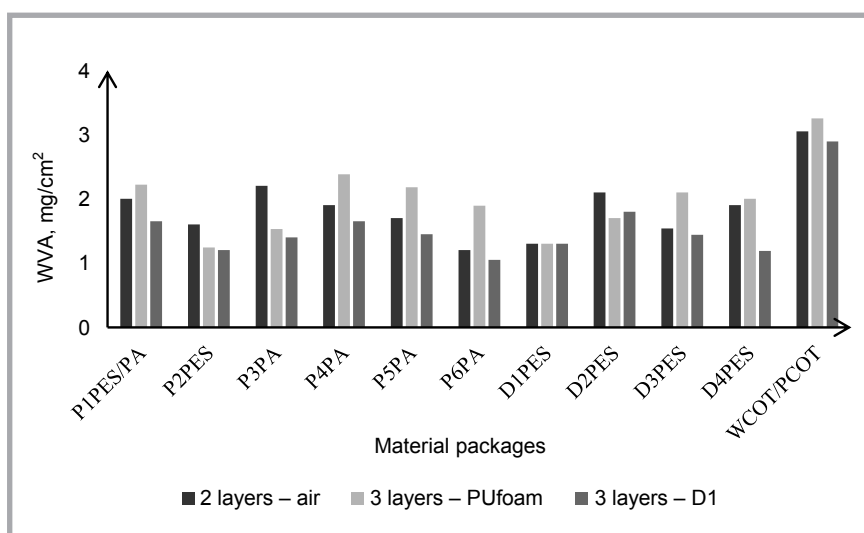


Figure 2. Water vapour absorption for material packages.

Table 1. Basic material characteristics of materials used as an inner layer.

Sample name	Fibre composition	Mass per square metre, g/m ² ± 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. Characteristics of the material for the outer layer and those of polyurethane foam.

Sample name	Fibre composition	Mass per square meter, g/m ² ± 5%	Thickness, mm ± 6%
WCOT	100% cotton	230	0.48
PUfoam	100% polyurethane	313	1.98

Table 3. Results of ANOVA for water vapour permeability within a group of flat textiles (P1PES/PA, P2PES, P3-P6PA).

Source of variance	SS	df	MS	F	p-value	Test F
Between groups	185.84	2	92.92	18.84	3.85E-05	3.55
Within group	88.77	18	4.93			
Total	274.6	20				

Table 4. Results of the ANOVA for water vapour absorption within a group of spacer textiles (D1-D4PES).

Source of variance	SS	df	MS	F	p-value	Test F
Between groups	220.79	2	110.40	188.98	4.46E-08	4.26
Within group	5.26	9	0.58			
Total	226.05	11				

Table 5. Scheffe results within a group (P1PES/PA, P2PES, P3-P6PA, PCOTT).

Treatment pair	Scheffe T-statistic	Scheffe p-value	Scheffe interference
2 layers – air versus 3 layers – PUfoam	6.13	0.00004	**p<0.01
2 layers – air versus 3 layers – D1	3.34	0.01304	*p<0.05
3 layers – PUfoam versus 3 layers – D1	2.79	0.03931	*p<0.05

Table 6. Scheffe results within a group (D1-D4 PES).

Treatment pair	Scheffe T-statistic	Scheffe p-value	Scheffe interference
2 layers – air versus 3 layers – PUfoam	18.97	0.00000005	**p<0.01
2 layers – air versus 3 layers – D1	5.78	0.00009319	**p<0.01
3 layers – PUfoam versus 3 layers – D1	13.18	0.00000013	**p<0.01

material was ascertained by conducting measurements of the following: thermal resistance, conductivity, absorptivity and diffusivity. The thermal resistance parameter R is directly proportional to the sample thickness (h) and inversely proportional to the thermal conductivity (λ). The thermal resistance of footwear materials is a result of the sum of heat transfer caused by the following phenomena: conduction, convection and radiation.

■ Results and discussion

The results of water vapour permeability and absorption and thermal resistance were used to make a selection of materials in order to create optimal packages from a hygienic point of view. The values of water vapour permeability and absorption are shown in **Figures 1** and **2**.

The best characteristics in the field of water vapour permeability are possessed by two – layered packages, which obvious because the diffusion of water vapour molecules occurs automatically due to the lack of a barrier. The values of water vapour permeability were between 16.2 mg/cm²h for the control cotton sample and 20.7 mg/cm²h for packages with polyamide fabric (P3PA

and P4PA). The open – work structure of P3PA and P4PA supported the migration of water vapour through the empty spaces between fibres. Moreover, the polyamide fibres are characterised by a high level of hydrophobicity, consequently vapour was not trapped in the material structure and migration through the next layers was possible. In the case of the cotton material, the opposite situation took place. Cotton fibres are characterised by a high level of hydrophilicity, hence a part of water vapour was trapped through the penetration process, and the rest of the vapour migrated slowly to the next neighbouring layer. The implementation of such materials as polyurethane foam and three – dimensional knitted fabric caused that an additional barrier occurs between the outer and inner layer of the package. In consequence of this, the total amount of water vapour transferred through the layers is reduced, as a result of the diffusion resistance of the barrier, which depends on their thickness and water vapour coefficient. In the case of polyurethane foam used as the inner layer, the values of water vapour permeability were between 8.5-15.2 mg/cm²h. A high level of degradation of this parameter was observed for P1PES/PA. In this case, the integrity between the poly-

urethane layer and textile layer was very strong, causing the blocking of pores for both the foam and fabric. The inverse effect was observed for materials based on polyamide fibres (P5PA and P4PA). In the case of knitted fabric which was used as an additional layer between the separated outer and inner, the degradation of the water vapour property was reduced compared to packages with polyurethane foam. However, in the case of polyurethane foam, the degradation of vapour transmission was between 54% for P1PES/PA and 34% for the control package WCOT/PCOT; the use of three – dimensional knitted fabric caused the proportions and degradation of water vapour to decrease from 39% for P1PES/PA to a level of 8% for the cotton package. The influence of the barrier type on the water vapour transmission property was confirmed with the use of the ANOVA procedure for two groups: two – and three – dimensional knitted fabrics. At the level of confidence α , which was equal to 0.05, hypothesis H_0 states that there is no difference in the means of water vapour due to barrier type. And the alternative hypothesis H_1 indicates the inequality of means. **Tables 3** and **4** contain the results of the ANOVA procedure.

In both cases the value of the test statistic far exceeds the critical value. Moreover, the test's probability is much higher than the confidence level, thus signifying that the null hypothesis is false. In order to make a qualitative evaluation of the differences between groups of barriers, the Scheffe test was implemented, the results of which are shown in **Tables 5** and **6**.

On the grounds of Scheffe test results, three groups with the strongest diversity can be isolated. In the case of flat materials, the highest differences ($p<0.01$) were observed between two – and three – layered packages where polyurethane foam was the connecting element. In the case of linking with three – dimensional knitted fabric, within all groups strong diversity was observed, which means that the type of barrier decided the water vapour characteristics. The inherent element of the analysis of the hygienic parameters of materials is water vapour absorptivity measurement.

Lower values of water vapour absorption through the material packages were obtained in the case of the cotton package, whereas high values occur for three – dimensional knitted fabric – 2.9 mg/cm²

and the package with polyurethane foam – 3.3 mg/cm². Thus, this leads to conclude that the cotton package is not optimal, because of the probability of water accumulation inside the footwear material. This is very dangerous from a hygienic point of view, especially in a hot environment, because the temperature inside the footwear volume rises and a discomfort sensation appears. Moreover, when the footwear is used in cold temperature conditions, hypothermia occurs, because of moisture trapped in the material. In most cases the implementation of three – dimensional spacer fabric reduced the total amount of water vapour absorbed by the materials. This is related to the additional layer, which is rich in open spaces, which in turn are able to trap air in the gaps, causing that the water vapour diffuses through the layers to the external circulation as a vapour flux, according to the mass balance law. In the case of two – layered packages, where the role of connecting medium is played by air, the water vapour absorption values were between 1.2 mg/cm² for the package with polyamide fabric P6PA and 3.1 mg/cm² for cotton fabric PCOT. On the other hand, using polyurethane foam as a connector causes the increasing of absorptivity due to the blocking of open pores. Thus, in effect, a part of water vapour passing through the sample was trapped in the material structure. The values of water vapour were between 1.2 mg/cm² for P2PES and 3.3 mg/cm² for cotton fabric. The application of spacer fabric as a connecting layer effected a reduction in the total amount of water vapour absorbed in the packages. Values from the interval between 1.1 mg/cm² (for P6PA) and 2.9 mg/cm² (for cotton material) were in most cases the smallest for the package variants considered. The ANOVA statistical analysis carried out did not reveal any statistically significant differences due to the barrier type.

The last stage of the research conducted was thermal resistance analysis of the material packages (Figure 3). In stationary conditions, the thermal resistance is directly proportional to the material thickness. In the case of non – stationary conditions, when air movement appears, the thermal resistivity of the materials is a function of air permeability. The air which passes through the material removes the trapped air, which – with the structure of the material – plays the role of thermal insulator. The results of thermal resistance analysis confirmed the fact

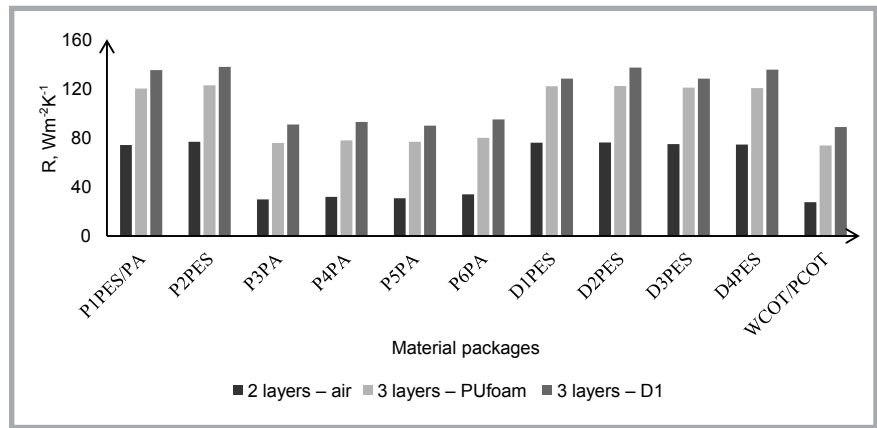


Figure 3. Thermal resistance values for material packages.

that using materials with open, or partially open spaces, improves the thermal insulation of packages, which is very important from the footwear point of view.

The results showed that the possibility of improving the thermal resistance property in stationary conditions exists through the implementation of spacer fabric as a connecting material between the layers. As for the two – layered package, the increases in values of the thermal insulation property reached a level from 45% to 69%, whereas in the case of the three – layered package with polyurethane foam, the improvement was weaker – between 5 and 17%, depending on the material type. Statistical analysis confirmed that the barrier type affected the thermal resistance of the material packages significantly (Table 7 and Table 8).

By using of the Scheffe test, the differences between two – layered packages and three – layered ones with polyurethane foam were placed at the level of 0.004 of test probability. In the case of the package with three – dimensional knitted fabric as a connector, the probability value was 0.0003. When the knitted fabrics

were compared between groups thereof, the differences were also significant at a level of probability less than 0.01.

In order to verify the possibility of making a forecast in the field of water vapour absorption and permeability values, the multivariate regression procedure was applied. A regression model was created according to the following Equation (1):

$$Y: f(X, \xi) \quad (1)$$

Where, Y – is a dependent variable (it is the water vapour permeability of the material package), and X is a combination two or three elements – $X = [X_1, X_2]$ or $X = [X_1, X_2, X_3]$, where indexes 1, 2 and 3 correspond to the numbers of layers. Moreover, it is assumed that the random component ξ has a standard normal distribution. For water vapour permeability, the determination coefficient R^2 obtained was equal to 0.8 within the group of spacer fabrics and 0.7 within the flat textiles. It was a quite satisfactory result for these cases, but in the other variants, it does not exceed the value 0.3, which proves that this model is poor matching. A similar situation was also observed for the water vapour absorption of two

Table 7. Results of ANOVA for thermal resistance within a group of flat textiles (PIPES/PA, P2PES, P3-P6PA)

Source of variance	SS	df	MS	F	p-value	Test F
Between groups	14016.58	2	7008.29	14.61	0.00017	3.55
Within group	8634.04	18	479.67			
Total	22650.62	20				

Table 8. Results of ANOVA for thermal resistance within a group of spacer textiles (D1-D4PES).

Source of variance	SS	df	MS	F	p-value	Test F
Between groups	7275.92	2	3637.96	460.07	8.66E-10	4.26
Within group	71.17	9	7.91			
Total	7347.09	11				

layered packages, where the determination coefficient R^2 was equal to 0.9 for flat fabrics and 0.8 for spacer fabrics. However, the high level of estimation error in all cases examined does not allow for formulating equations of forecast functions. The addition of a subsequent layer caused the degradation of the determination coefficient on a large scale. The necessary element which should be taken into account is the structure of the materials and physico – chemical parameters of fibres, which will induce the increasing of predictor variables; but the determination coefficient will be more satisfactory. A different approach can be executed by recording the water vapour flux continuously in time and using of partial differential equations. In these cases, the boundary conditions should be set in such a way that the initial conditions for the next layer will be equal to the end conditions obtained for the previous neighbouring layer. The number of iterations will be equal to $n - 1$, where n denotes the number of layers.

Summary

The hygienic properties of materials and their packages which can be used as footwear components are some of the most important criteria which affect suitability. The quantitative assessment of the influence of footwear materials on the thermal and humidity exchange between the foot surface and surrounding environment largely depends on the number of layers and the configuration pattern as much as on the hygienic properties of particular materials [23, 24]. The results confirmed the relevance of this attempt due to the possibility of replacing some of the worst materials used and achieving significant effects. The application of hydrophobic materials with good water vapour permeability characteristics causes that in use conditions water from the foot surface can be removed very fast and the material will not be loaded with sweat. From a hygienic point of view, according to research conducted under stationary conditions, the best recommendation will be received by those materials which are characterised by the highest water vapour permeability values with simultaneously low as possible absorption. Also, high values of thermal resistance are favourable. In the case of two – layered packages, these criteria are fulfilled for P6PA and DIPES used as linings. Moreover, when the material analysed has the form of a three – layered package with poly-

urethane foam, optimal hygienic conditions are shown by knitted fabrics with a spacer structure, despite insignificant degradation of water vapour permeability in comparison to that of polyamide materials P4PA and P5PA. In the latter case, when used as a joining element with knitted fabric D1, the best hygienic properties were obtained for the package with D4PES lining.

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