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Investigation of the Water Vapour Transfer Properties of Textile Laminates for Footwear Linings

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Abstract
Textile laminates with breathable membranes are used extensively in waterproof clothing items such as jackets, footwear and gloves. The polymer membranes act as a barrier to liquid water and soil entry from the environment, but they are sufficiently permeable to water vapour to allow significant amounts of sweat to evaporate through the clothing system and greatly affect the comfort of the wearer. In this paper the influence of the multifold water vapour resorption/desorption process on the hygienic properties of textile footwear lining laminates is presented. The water vapour resorption/desorption process was carried out by the repeating of three-cycle water vapour absorption and drying. It was shown that the water vapour absorption behaviour of textile laminates can be classified as Fickian. The equilibrium of water uptake increases with an increase in the resorption/desorption process. The resorption/desorption process influences not only the absorption parameters of laminates, but also changes the character of sorption kinetics – it influences the water uptake and drying times of laminate. It was determined that the moisture transport properties textile lining laminates are history-dependent.

Key words: *textile lining laminates, breathable membrane, water vapour permeability, absorption, desorption.*

Introduction

A microclimate is created in the human body by water and air permeability, as well as by the heat insulation of clothing materials. There are a great number of publications discussing the relations between yarns, textile structure and properties [1].

Recently, new textile laminates have been produced that are simultaneously permeable to water vapour from the inside but waterproof from the outside. Semi-permeable membranes increase the resistance of laminates to water, wind, micro-organisms, and the penetration of various chemicals [2 - 5]. Improving the resistance causes unwanted effects of laminate properties, often making their comfort features worse, such as water vapour permeability, water vapour absorption and desorption [6].

Water vapour transfer through multilayered materials strongly depends on their specific structure and can be very different from that of discrete materials. Each of the components affects moisture transfer differently [7, 8]. Therefore, the hygienic properties of multilayer materials are greatly influenced by the character of water vapour transfer across the layers of materials, which have different properties and influence the mechanism of water vapour absorption and desorption differently.

Commonly an increase in resistance to water reduces the water vapour permeability of materials and increases vapour concentration; as a consequence a liquid layer can originate due to water vapour condensation [2]. Not all accumulated moisture is removed when a material is dried, as the result of which the sensation of clothing system discomfort increases. Thus, water vapour transfer through the clothing system directly affects the comfort of a human.

A wide range of semi-permeable polymeric membranes gives the possibility to create multilayered textile laminates with unique properties [9, 10 - 12]. Two types of breathable polymer membranes – hydrophilic or microporous – are mostly used for textile laminate production. Microporous membranes from polytetrafluorethylene or polyurethane and hydrophilic membranes from polyester or polyester/polyamid blend are applied. These membranes are often joined with a protective layer of polyamide or polyester woven, knitted or non-woven fabrics [6, 8].

With an extensive range of semi-permeable membranes, waterproof, breathable and highly durable multiple textile laminates for footwear lining were developed in order to maintain equilibrium in feet thermo-regulation processes over a long period of time [4, 6, 9]. Such laminates are engineered to meet specific requirements in lining materials for military, professional, sports and leisure wear, as well as daily footwear.

Footwear lining comes into direct contact with moisture excreted by the human body. For this reason the absorption of water vapour or liquid moisture and their elimination to the environment is very important for ensuring human comfort [3 - 5].

The internal climate, next to the skin, is warm and damp because the human body is generating heat and moisture. The external climate is much drier and cooler; consequently, water vapour is driven from the inside outside. During wearing, moisture transport – water vapour diffusion, absorption and desorption – continuously takes place. For evaluation of the hygienic properties of footwear materials, it is very important to know their moisture transport properties after a long period of exposure in humid conditions. Thus, investigations of water vapour transfer through multiple systems and its influence on the water vapour resorption/desorption process are of great significance for footwear with good hygienic properties and an understanding of diffusion mechanisms [13].

The aim of this work was to investigate the influence of the properties of textile lining layers on comfort properties and to determine the laws of sorption and desorption alteration in the multiple processes of vapour sorption and drying.

Experimental

Footwear multilayer lining material *Dryliner* (L), composed of two textile layers (PES knitting fabric and non-woven cotton fabric) and a foamed polyurethane layer was used for the investigation. In order to increase the lining's resistance to water penetration, the semi-permeable polyurethane membrane *Puratex* (M) (Freudenberg Vliesstoffe KG) was hot laminated on the bottom of lining L at a temperature of (90 ± 5) °C and pressure of (35 ± 2) kPa for (20 ± 2) s. The structure of the membrane is presented in ***Figure 1, a***, and the structure of the whole laminated system (L+M) is given in ***Figure 1, b***. Some characteristics of the materials investigated are given in ***Table 1***.

The water vapour permeability and absorption of the textile laminates investigated were determined according to the requirements of standard methods. Beforehand all the test specimens were conditioned for at least 48 h in a standard atmosphere (T = 23 ± 2 ºC, RH = 50 ± 5%, i.e. 23/50), in accordance with LST EN 12222. The water vapour permeability was measured according to LST EN ISO 14268 at conditions of 23/50. A circular specimen of material was placed over a jar containing a solid desiccant i.e. silica gel. This unit was placed in a strong current of air in a conditioned atmosphere of 23/50 for 16 h. Then the container was weighed in order to determine the mass of moisture that had passed through the test piece and absorbed by the desiccant. The permeability to water vapour was calculated according to:

$$P = \frac{7639M}{d^2 \cdot t}, \qquad (1)$$

where M is the increase in mass of the container with the test piece and silica gel, d - the average diameter of the neck of the container, t - the time between the first and second weighing.

Water vapour absorption was measured according to LST EN ISO 17229. For the determination of water vapour absorption, an impermeable material and the specimen were clamped above the opening of the container, which contained 50 ml of water, for the duration of the test [4]. The duration of water vapour absorption was determined as the absorption time up to a constant weight of the damp specimen. The water vapour absorption A_i of the laminate after a set time was defined as the mass difference before and after the water vapour absorption:

Table 1. Characteristics of materials investigated.

Materials	Thickness h, 10^{-3} m	Density ρ, 10^2 kg/m^3	WV permeability P, 10^{-6} kg/m^2·s	WV absorption A, 10^{-3} kg/m^2
L (lining Dryliner)	2.82	7.90	368.3	22.5
M (semi-permeable membrane Puratex)	0.15	3.00	25.4	12.4
L+M (Dryliner + Puratex)	2.95	6.20	4.2	22.0

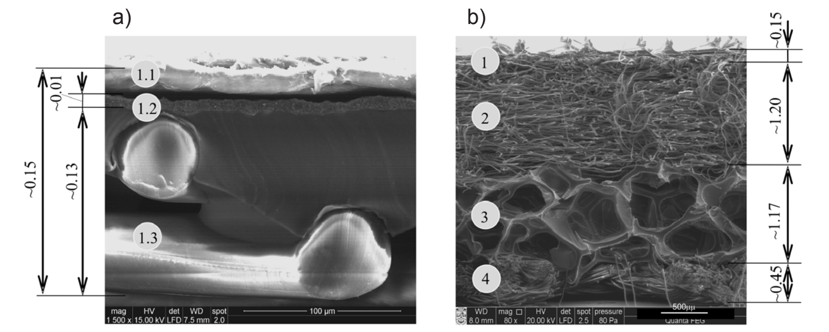

Figure 1. *Cross-section of textile linings: a – semi-permeable polyurethane membrane; (1.1 – adhesive layer, 1.2 – microporous PU membrane, 1.3 – PES protective layer); b – laminate (1 – membrane, 2 – PES knitted, 3 – PU foam, 4 – cotton non-woven).*

$$A_i(\tau) = \frac{M_\tau - M_0}{M_0}, \qquad (2)$$

where M_0 is the initial mass of the specimen, and M_τ is the mass of the specimen in cycle i after time τ of absorption.

After each water vapour absorption test, the water vapour desorption (rate of desiccation) of the materials was also investigated. In this case, after the absorption test, the damp specimen was dried to a constant weight in a horizontal position in standard conditions (23/50). In this case the weight of the specimen was monitored until its constant weight was obtained. Then the same specimen was used in a subsequent absorption test. The same procedure was followed in several cycles. At a fixed time interval, the water vapour desorption was determined as the change in specimen weight using:

$$D_i(\tau) = \frac{m_\tau - m_0}{\Delta m_\tau}, \qquad (3)$$

where m_τ is the mass of the specimen after time τ of desorption, m_0 - the mass of the dry specimen after the desorption process, and Δm_τ is the mass of full moisture desiccated after the desorption process.

The resorption/desorption process was carried out for all the materials investigated by way of repetitive water vapour absorption and desorption cycles [4].

Results and discussion

As can be seen from ***Table 1***, footwear lining material L shows the highest water vapour permeability (368.3·10^{-6} kg/m^{2}s). The lamination of the semi-permeable polyurethane membrane M decreases the water vapour permeability of textile laminate L + M down to 4.2·10^{-6} kg/m^{2}s. An earlier investigation showed [14] that the membrane only marginally worsens the moisture transfer of the laminate, while the adhesive layer, used to bond this film, decreases the water vapour permeability and increases its absorption due to the formation of a non-porous barrier [14]. However, the water vapour permeability of the laminate remains high enough, meeting the requirements defined for these types of materials. On the other hand, the lamination of the polymeric membrane M barely changes the water vapour absorption of the laminate. As can be seen (***Table 1***), the water vapour absorption of lining L and laminate L+M is similar (22.5·10^{-3} kg/m^2 and 22.0·10^{-3} kg/m^2, respectively).

Water vapour absorption was carried out by keeping the materials investigated in humid conditions (23/90) for a long duration (up to 120 h) until a constant weight was reached. Generally, the water vapour absorption is normally presented by plots of the absorption rate as a function of time or the square root of time. As can be seen from ***Figure 2***, water vapour absorption depends on the cycle number i – the curves in each cycle have a different slope and values. The rate of water vapour absorption of lining materials increases with an increase in the number of cycles. Water vapour absorption equilibrium in cycles i = 1 and 2 is reached after ca. 40 h for L and L + M, whereas in cycle i = 3 water vapour uptake is higher for laminate L+M, and equilibrium is reached after ca. 90 h. From ***Figure 2*** it is also evident that the dependence between the water vapour absorption and resorption/desorption cycle number in the case of L is not significant. As regards the character of changes in the absorption plots, it may be assumed that the water vapour absorption of the lining materials investigated may be classified as Fickian [15, 16].

The water vapour absorption character of lining L in all cycles is quite similar for laminate L+M and may be described by the exponential law:

$$A_i(\tau) = k_{ip} - k_{ig} \exp(\tau_a), \qquad (4)$$

where τ_a is the time of water vapour absorption, k_{ig} - constant of the water vapour absorption rate, and k_{ip} is the constant of the water vapour absorption equilibrium. The values of these constants are presented in ***Table 2.***

Comparing the data in the different absorption cycles, it can be concluded that the higher diffusivity and water uptake of the materials investigated are characteristic in cycles i = 2 and 3. From the data given in ***Table 2***, it can be stated that the water vapour absorption rate for both

Table 2. *Values of absorption constants (Equation 4).*

Cycle i	Lining L			Laminate L+M		
	k_{ip}, 10^{-2} kg/kg	k_{ig}, 10^{-2} kg/kg·$h^{1/2}$	R^2	k_{ip}, 10^{-2} kg/kg	k_{ig}, 10^{-2} kg/kg·$h^{1/2}$	R^2
1	5.17	5.18	0.995	4.62	4.67	0.922
2	5.30	5.31	0.994	5.28	5.30	0.994
3	5.59	5.61	0.991	6.44	6.53	0.931

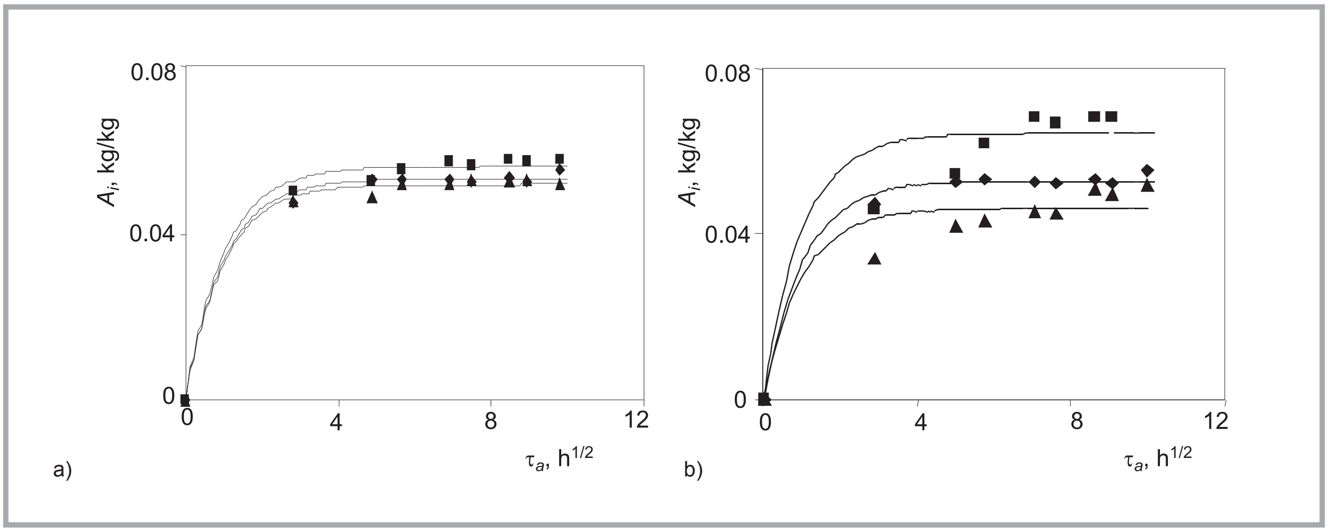

Figure 2. *Changes in water vapour absorption A_i for lining L (a) and laminate L+M (b) in the different resorption/desorption cycles: ▲ – i = 1; ♦ – i = 2; ■ – i = 3.*

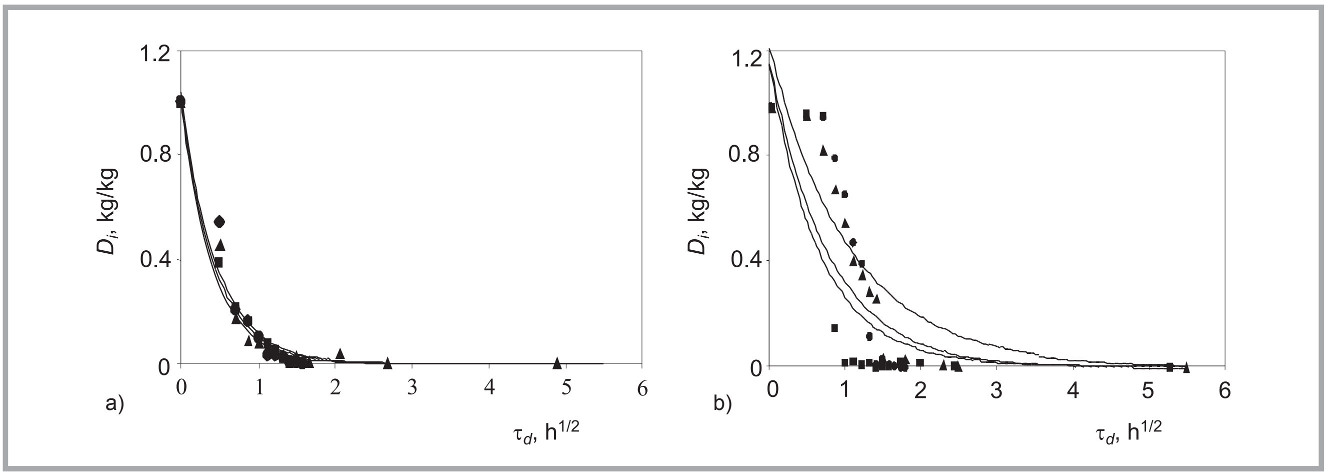

Figure 3. *Changes in water vapour desorption D_i for lining L (a) and laminate L+M (b) in the different resorption/desorption cycles: ▲ – i = 1; • – i = 2; ■ – i = 3.*

Table 3. *Values of desorption constants (Equation 5).*

Cycle i	Lining L			Laminate L+M		
	k_{1i}, kg/kg	k_{2i}, $h^{1/2}$	R^2	k_{1i}, kg/kg	k_{2i}, $h^{1/2}$	R^2
1	1.01	0.43	0.971	1.14	0.67	0.802
2	1.01	0.40	0.978	1.20	1.06	0.845
3	1.04	0.45	0.923	1.17	0.78	0.827

linings increases with an increase in the number of cycles. For lining L the values of constant k_{ig} in cycles i = 1 and 2 differ only slightly (only in 2.5%), while in cycles i = 3 this difference increases by more than 8 %. However, this is not distinct, and it may be assumed that the resorption/desorption process practically does not influence the properties of lining L. For laminate L+M the constant of the water vapour absorption rate k_{ig} in cycles i = 1 and 2 differs marginally compared to that of lining L. Meanwhile, the water vapour uptake of laminate L+M changes significantly with an increase in the number of absorption/desorption cycles. Comparison of the values of water vapour absorption rate constants for all cycles shows that in cycles i = 2 and 3 constant k_{ig} is about 13% and 39% higher than that in cycle i = 1. It may be supposed that the water vapour absorption rate increases because of changes in the properties of the laminate layers during the water vapour sorption and drying processes. Due to the moisture adsorbed in the first cycle, the lining structure becomes more open and accessible for additional water vapour penetration [13]. Therefore, the water vapour absorption uptake in cycles i = 2, 3 increases for both linings. Moreover the water vapour absorption of the textiles investigated is history-dependent.

The water vapour absorption equilibrium constant k_{ip} of both lining materials also increases with an increase in the number of resorption/desorption cycles. It is supposed that the relaxation process which takes place in the textile lining after the first water vapour resorption/desorption cycle accelerates the rate of gain of the absorption equilibrium in subsequent cycles [17].

It is known [13] that water vapour absorption and desorption influence the relaxation processes of polymeric materials as well as their hygienic properties. The linings used for footwear must not only possess high ability to pass and absorb water vapour but also an ability to remove accumulated moisture. Therefore, changes in the water vapour desorption of the textile lining materials were investigated.

As can be seen from ***Figure 3***, lining L is charectised by a higher drying rate than that of laminate L+M. In the case of L, half of the moisture absorbed evaporates at the beginning of drying (after 0.3 h), whereas in the case of L+M this occurs after more than 1h of drying. Thereinafter, the drying rate slows down, and lining materials reach a constant weight after ca. 3 h of drying.

The investigations show that the water vapour desorption process of lining materials during the resorption/desorption process may be described by the exponential law [17]:

$$D_i(\tau) = k_{1i} \exp\left(-\frac{\tau_d}{k_{2i}}\right), \qquad (5)$$

where τ_d is the time of water vapour desorption, k_{1i} - constant of the initial water vapour desorption rate, and k_{2i} is the constant of the water vapour desorption rate at time τ_i. The values of constants are presented in ***Table 3***.

As can be seen, the higher diffusivity and desiccation rate of lining L is characteristic compared to that of laminate L + M. The resorption/desorption process barely influences the drying properties of lining L, but the constant k_{2i} of laminate L + M is markedly higher than that of lining L. Thus, it can be supposed that the semi-permeable polymeric membrane retards the drying process of the laminate.

Conclusions

A microporous membrane decreases the ability of water vapour transfer but does not change water vapour absorption in textile lining laminates.

The multifold resorption/desorption process of textiles laminates is history-dependent. Fickian behaviour is characteristic for the water vapour absorption kinetics of textiles materials. Water vapour absorption and diffusion depend on the vapour sorption and drying cycles. The absorption rate and equilibrium uptake increase with an increase in the number of resorption/desorption cycles. During the resorption/desorption process, changes in the absorption parameters of the linings are observed. A semi-permeable polymeric membrane decreases the water vapour desorption rate and retards the drying process of footwear textile laminate.

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