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Model of Vertical Porosity Occurring in Woven Fabrics and its Effect on Air Permeability

Abstract
The main focus of this paper is aimed at a description of the relationship between the air permeability of woven fabric and its structure. The porosity of the fabric is divided into two basic types: horizontal and vertical porosity. The horizontal porosity is considered as a complement to the woven fabric cover factor – it is a two-dimensional model of porosity which is a projection of the fabric onto the horizontal plane. An elliptical model of the vertical pore is proposed for the description of vertical porosity, being a two-dimensional model of porosity as well, but it is a projection of the fabric onto the vertical plane. Two sets of woven fabrics (made of staple yarns) with different types of weave were used for the experiment. The correlation between the permeability values measured and vertical porosity values calculated was high. The method of multiple linear regression was used to derive a regression equation that allows to calculate the permeability based on the horizontal and vertical porosity. Then the correlation between the values of permeability measured and calculated was also high.

Key words: *porosity, porosity horizontal, porosity vertical, woven fabric, floating yarn, air permeability.*

Introduction

Air permeability is one of the most important properties of textile materials. It is generally understood as the ability of air-permeable fabric to transmit air under given well-specified conditions. In the case of clothing materials, permeability is an important aspect of comfort. In the case of technical materials, permeability can be even the property that is essential in terms of fabric function (e.g. filters, parachutes, airbags etc.). The air permeability of fabrics is the principal property of textile material structure. A very small change in the structure of fabric causes a change in its permeability. Therefore a number of authors have researched the relationship between the structure and permeability of a woven fabric, e.g. [5, 7 – 10]. The property usually given by the description of the structure of the fabric is the porosity, e.g. [1, 3, 6]. The size of the pores in textile as well as their shape arrangement and distribution are decisive characteristics of the fabric from the air permeability point of view. All models that lead to the determination of the porosity of woven fabric include some simplifying assumptions, which introduce some inaccuracies into the result. Therefore it is very difficult to find the optimal method that predicates the permeability of the woven fabric best.

In some research (e.g. [1, 4, 5]), textile woven fabric is compared with metal woven nets, but metal materials have quite different properties. The structure of a metal woven net is unchangeable in airflow (in a range of pressure differences usually used on textile materials). In textiles exposed to airflow, some deformations exist and the textile structure is changed. For that reason the relationship between the air permeability and structure of textile woven fabric is much more complicated.

The structure of fabric with a plain weave is still relatively simple to describe. Fabrics with another type of weave (e.g. twill or satin) are more complicated because the type of weave is the parameter that also significantly affects the value of the woven fabric permeability. Therefore a number of authors (e.g. [3, 6 – 8]) have performed research on the influence of the type of woven fabric weave on its air permeability. These authors often characterise the type of weave using a parameter that expresses the degree of yarn interlacing, e.g. parameters crossing-over firmness factor (CFF) or floating yarn factor (FYF), or they take into account the shape of four different types of pore cells, defined by Backer [12]. It was found in [7] that differences in air permeability between different weave types are more pronounced among samples of fabrics with lower warp and weft density, while for fabrics with higher warp and weft density, this difference is less pronounced.

However, in woven fabric there are also pores in locations of longer non-interlaced segments of yarns in the vertical direction. These pores (can be very small) are formed in the vertical direction between the warp and weft thread systems and one such pore passes through several pore cells. The above-mentioned deformation of woven fabric caused by airflow is strongly dependent on the degree of interlacing of yarns. Flowing air can cause a movement of the non-interlaced parts of yarns (~ floating yarn) and "new pores" appear in textiles. This paper deals with a description of this type of vertical porosity and its influence on the permeability of woven fabric.

Porosity of woven fabrics

Generally all spaces that are filled with air can be considered as pores in fabric. The porosity can be expressed as a portion of air in the fabric (in % or as a dimensionless number). For example, porosity can be calculated as density based porosity P_W [11]:

$$P_W = 1 - \rho_W / \rho_F \qquad (1)$$

where ρ_F in kg/m^3 is the density of fibres and ρ_W in kg/m^3 = m/V is the volumetric density of the fabric. m in kg is the weight of the fabrics and V in m^3 is the volume of the fabric with a surface of 1 m^2. Using the values of fabric planar weight W_P in kg/m^2 measured as well as the fabric thickness t in m and density of fibres ρ_F known, it is simple to calculate the porosity:

$$P_W = 1 - W_P/(\rho_F \times t) \qquad (2)$$

However, the porosity determined in this way is usually not very suitable in terms of the exploration of the relationship between the permeability of the fabric and its structure. It only indicates how much air is contained in the fabric, and says nothing about its placement – the shape of pores, their size and distribution. Just these characteristics, however, are very important in terms of fabric permeability. Therefore many models (e.g. [2, 3, 5, 6]) try to describe the geometric structure of pores in woven fabric, some of which simplify the three-dimensional structure of fabric into a two-dimensional one (e.g. [3, 4]). In woven fabric a distinction between the porosity of yarns (inter-yarn porosity) and that between fibres inside yarns (intra-yarn porosity) should be made. There is an assumption [4] that if the inter-yarn pores are large enough and air has enough space for free passage, it will flow mostly just that way. Therefore in terms of air permeability evaluation, intra-yarn porosity is usually neglected.

The porosity P_V [1] can also be calculated based on the volumetric filling of woven fabric [11]:

$$P_V = 1 - V_Y/V \qquad (3)$$

where V in m^3 is the volume of fabric with a surface of 1 m^2 and V_Y in m^3 is that of yarns in 1 m^2 of the fabric. V_Y is equal to the sum of the volume of warp yarns V_{YO} and that of weft yarns V_{YU}:

$$V_{YO} = D_O \times V_{1mO},\ V_{YU} = D_U \times V_{1mU}$$

V_{1mO} in m^3 and V_{1mU} in m^3 are the volumes of warp and weft yarn in a 1m portion of the fabric, respectively, and D_O & D_U in 1/m are setts of warp and weft yarns, respectively. Assuming a circular cross-section of yarn with diameter d, in m can be V_{1mO} calculated as the volume of a cylinder:

$$V_{1mO} = 1/4\ \pi\ d_O^2 \times l_O \qquad (4)$$

where l_O in m is length of warp yarn in a1m portion of the fabric. For V_{1mU} indexes O are replaced by indexes U. The length of yarn in woven fabric l in m can generally be determined experimentally or can be calculated based on the percentage of shortening s in % of yarns in the fabric. Many authors also deal with a theoretical description of binding weaves and with the cross-sectional properties of yarns in woven fabric (e.g. [15, 17]).

It should be noted that the value of yarn diameter d in m is used in a number of models that describe the porosity of fabric. At the same time, in woven fabrics, yarn flattening and distortion of the yarn cross-section take place as a result of normal forces between yarn systems as they occur during the usual weaving process [18]. The initial, approximately circular cross-section of the yarn is thus deformed. For a description of the deformed cross-section of yarn, there are several models – for example ellipse or lens. Moreover it was shown [9, 16 – 18] that the yarn cross-section shape is variable along the yarn length. The spatial geometry of woven fabric is generally affected by the weave type, the material and fineness of the yarn, the setting, but also by the type and adjustment of the weaving loom [9, 15, 17]. The problem of the determination of yarn diameter can also be complicated by yarn hairiness. It was shown [14, 19] that yarn hairiness also affects air permeability.

Experimental evaluation of the cross-section parameters of fabric is relatively complicated and time-consuming, but it allows measurement of the deformed cross-section yarn in both directions (horizontal diameter d_1 and vertical diameter d_2 – see ***Figure 1.b***). Measuring the fabric's plane characteristics is much easier. The measurements in [9] were carried out using a PC with a scanner. This method allows the measurement of only horizontal diameter d_1. Then vertical diameter d_2 can be evaluated theoretically assuming that the cross-section shape of yarns in the fabric is known. The relationship between air permeability and the projections of warp yarns is investigated in [10], showing that air permeability is not constant in the fabric width and depends on the distance from the fabric edge. Thus for precise calculation of the horizontal porosity diameter d_1 is important, and for calculation of the vertical porosity both diameters are important – d_1 & d_2. However, from the above it is evident that for the determination of average values d_1 and d_2 there will always be a number of simplifying assumptions.

Definition of horizontal porosity

In the theory of the classical 2-D model, porosity P_{hor} is derived from the pure geometry of the yarn projection (see ***Figure 1.a***) and is defined as a complement to the woven fabric cover factor CF [6]:

$$P_{hor} = 1 - (d_O D_O + d_U D_U + \\ - d_O d_U D_O D_U) \qquad (5)$$

where d_O & d_U in m are the diameters of a warp and weft yarn, respectively, and D_O, D_U in 1/m are setts of warp and weft yarns, respectively. This model of poros-

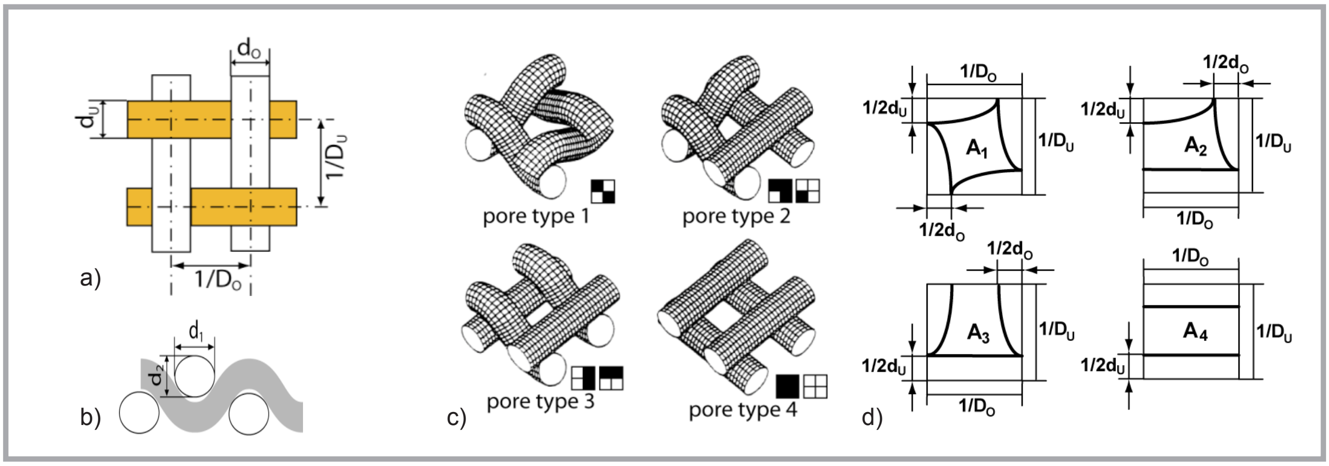

Figure 1. *Unit cells for woven fabric: a – pure geometry of the projection of yarns, b – cross-section of woven fabric, c – three-dimensional models [12], d – modified two-dimensional models [3].*

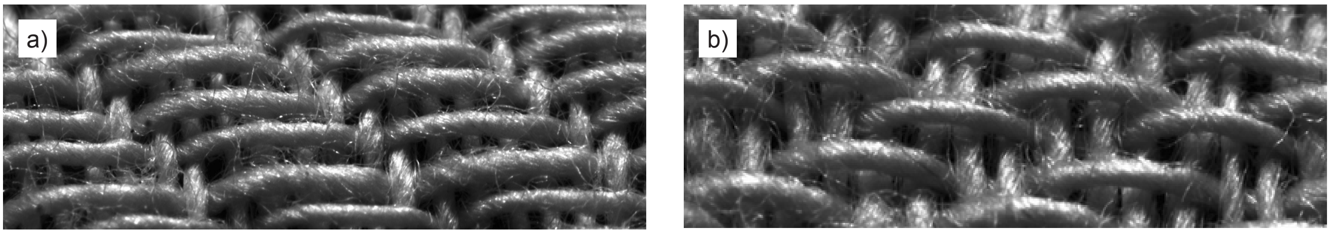

Figure 2. *Images (taken at an angle of 45°) of the woven fabric, in which the existence of vertical pores is evident: a) twill 1/5, b) satin 2/4.*

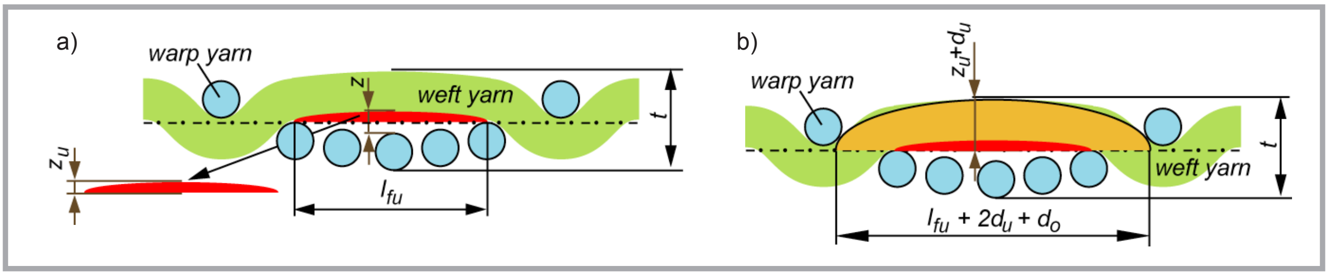

Figure 3. *Two-dimensional elliptical model of vertical porosity (cross-section through woven fabric along weft yarn): a) one vertical pore in the woven fabric, b) projection area of one floating yarn.*

ity completely neglects the third dimension of the fabric and differences in pore forms due to the various types of weave. As shown earlier [14], in regard to the description of the relationship between the permeability of woven fabric and its structure, the model of horizontal porosity is insufficient.

The model suggested by Gooijer [3] partly includes the three-dimensional structure of pores in woven fabric. This model of porosity is based on the idea that air flows around yarns and not only in a perpendicular direction. Any weave can be created using the four basic inter-yarn pores described by Backer [12] (see ***Figure 1.c***). Gooijer calculated a projection of the wetted perimeter of a pore consisting of four yarns at its narrowest cross section onto the plane of the fabric (see ***Figure 1.d***) and derived four equations for calculation of the effective open areas $A_1 – A_4$ of pore types 1 – 4. Gooijer takes into account the shape difference between individual types of pores, but does not consider their mutual arrangement. However, it is not only the number of the different pore types but also their relative positions that create the type of weave, which is very significant in terms of the permeability of woven fabric. Therefore some articles (e.g. [7, 8]) research the influence of the type of weave on the permeability of woven fabric.

Parameter *CFF* – crossing-over firmness factor was used in [8] and [13]:

$$CFF = N_c / N_i \qquad (6)$$

where N_c is the number of crossing-over lines in a complete repeat and N_i the number of interlacing points in a complete repeat.

Parameter *FYF* – floating yarn factor was used in [8] and [13]:

$$FYF = (type_{I \sim IX} - 1) \times E_n / N_i \qquad (7)$$

where E_n is the number of types of floating yarn $type_{I \sim IX}$ in a complete repeat.

Definition of vertical porosity

Vertical pores are formed in locations of longer non-interlaced segments of yarns between warp and weft yarns in the vertical direction. These pores include the space in the fabric that is filled up by air, thus contributing to the inter-yarn porosity. The size of these pores is very closely connected with the mechanical properties of threads (bending rigidity, elasticity). It is clear that in the case of fabric with a plane weave, this type of porosity does not occur. In the case of other fabric (twill, satin), vertical pores can occur in locations of longer non-interlaced segments of yarns (~ floating yarns) due to the bending thereof (see ***Figure 2***). However, also in these locations, warp and weft yarns can lie close to each other (for example due to the calendaring of the fabric). Then during the measurement of permeability, these non-interlaced segments of yarns float in the air flow and the size of the vertical pores may fluctuate.

The elliptical model of the vertical pore proposed describes one vertical pore – the projection of the pore onto the vertical plane – as one half of an ellipse. The basic geometry of this model is introduced in the ***Figure 3***.

The area E_{U1} in cm^2 of the one vertical pore that is created under weft yarn is:

$$E_{U1} = 1/2\ \pi \times l_{fU} \times z_U \qquad (8)$$

where l_{fU} in cm is the length of the floating weft yarn:

$$l_{fU} = 1/D_O \times p_{IU} \qquad (9)$$

where p_{IU}, - is the number of non-interlaced segments in this floating yarn (e.g. for the floating yarn in ***Figure 3*** $p_{IU} = 4$). The number of these floating weft yarns in one pattern repeat is p_{fU}, - and the number of pattern repeats in 1 cm^2 p_S, - is calculated as:

$$p_S = D_O D_U / (n_{SO}\, n_{SU}) \qquad (10)$$

where D_O in 1/cm & D_U in 1/cm are setts of warp and weft yarns, respectively, and n_{SO}, - & n_{SU}, - are the numbers of warp and weft yarns in the pattern repeat, respectively. The total area of the all vertical pore cross sections under weft yarns in 1 cm^2 is possible to calculate as:

$$E_U = \\ = \pi/2 \times p_{IU}/D_O \times z_U\, p_{fU} \times D_O D_U / (n_{SO}\, n_{SU}) \qquad (11)$$

Value E_U in cm^2 is necessary to quantify for each type (respective length) of floating yarn in case that different types of the floating yarns are in the pattern repeat (e.g. twill 2/4, twill 3/4). The total area of the warp vertical pores E_O [cm^2] can be calculated applying the same process (see ***Equation 8*** to ***11***).

z_U & z_O are values of the deflection of weft and warp yarns, respectively. This parameter is not a constructional parameter of the woven fabric. It is possible for value $z = z_O + z_U$ to be considered for the experimental fabrics as approximately:

$$z = t - (d_O + d_U) \qquad (12)$$

where t in cm is the fabric thickness, and d_O in cm & d_U in cm are the diameters of warp and weft yarns, respectively. The fabric thickness must be measured under minimum pressure of the measuring device.

The term ‘porosity of woven fabric’ expresses the portion of the total volume or area in the woven fabric that is not filled with fibres. In the classical two-dimensional model of the horizontal porosity (see ***Equation 5*** and ***Figure 1.a***) the projection area of one pore is related to that of one-unit cell of the woven fabric. In the case of two-dimensional vertical porosity the projection area of one vertical pore E_{U1} and E_{U2} , respectively, is related to the projection area of one floating yarn, S_{FU} and S_{FO} , respectively (see ***Figure 3.b***). The projection area of one floating yarn is considered as a half ellipse, whose axes are simply expressed as:

$$a_U = l_{fU} + 2d_U + d_O \qquad (13)$$

$$b_U = z_U + d_U \qquad (14)$$

Then the total projection area of floating weft yarns in 1 cm^2 of the woven fabric is:

$$S_{FU} = \pi/2(p_{lU}/D_O + 2d_U + d_O) \times$$
$$\times (z_U + d_U) \times p_{fU} \times D_O D_U/(n_{SO}\, n_{SU}) \qquad (15)$$

The total projection area of floating warp yarns in 1 cm^2 S_{FO} is calculated according to ***Equation 15*** with the substitution of index $U \rightarrow O$. Then the vertical porosity P_{ver} can be calculated as:

$$P_{ver} = (E_O + E_U)/(S_{FO} + S_{FU}) \qquad (16)$$

Material and experiments

In this research two sets of woven fabrics were used for the experiment. The first was 100% polyester woven fabrics made of 40 tex staple yarns, and the second was 100% cotton woven fabrics made of 20 tex yarns. The yarns used were produced by ring spinning technology. All fabrics in one set were produced with the same D_O & D_U in 1/cm – setts of warp and weft yarns, respectively, and with the same T_O & T_U in tex – linear density of warp and weft yarns, respectively. Only the type of weave was different – see ***Figure 4***. These fabrics were used in the grey state. A summary of the fabric parameters is shown in ***Table 1***.

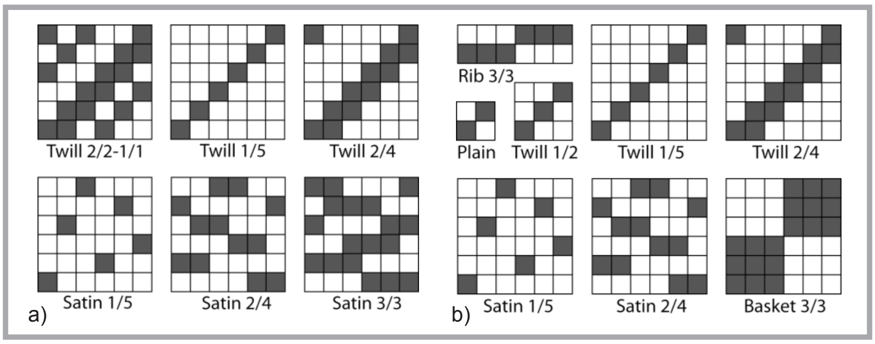

Figure 4. *Weave structures of experimental fabrics; a –first, b –second set of fabrics.*

The air permeability was measured using a digital tester – FX 3300 according to Standard ČSN EN ISO 9237 (20 cm^2, 100 Pa). The values of D_O and D_U introduced in ***Table 1*** are only approximate (specified by the manufacturer). For further use, for each fabric D_O and D_U values were determined experimentally according to Standard ČSN EN 1049 – 2. The diameters of yarns introduced in ***Table 1*** were determined experimentally with the use of USTER apparatus (before weaving). The fabric thickness was measured with the use of an automatic thickness-tester - FF – 27 (0.1 kPa, 25 cm^2, 30 s).

Results and discussion

Based on the values of warp and weft setts – D_O & D_U, yarn diameters – d_O & d_U and fabric thickness t established (see ***Table 1***), the values of horizontal and vertical porosity were calculated (according to ***Equations 5*** and ***16***). The relationship between the values of air permeability and porosity is shown in ***Figure 5***. A comparison of air permeability and porosity values (horizontal and vertical – see ***Figure 5***) shows that when using fabrics with the same constructional parameters as setts of warp and weft yarns and yarn diameter but with different types of weave, the P_{hor} values are approximately the same, but those of air permeability differ; the values of vertical porosity P_{ver} vary as well. The correlation between air permeability and vertical porosity is relatively significant (R^2 = 0.88 in the case of the first set of fabrics and 0.83 in that of the second set, respectively). This means that vertical porosity is important in terms of the air permeability of woven fabrics. Of course, the horizontal poros-

Table 1. *Parameters of fabrics used.*

Textile weave	Sett of warp, 1/cm	Sett of weft, 1/cm	Yarn diameter, μm	Fabric thickness, mm	*CFF*, -	P_{hor}, -	P_{ver}, -	*AP*, dm^3/m^2s
S 2/4	21.2	21.2	305	0.878	1.00	0.1019	0.1019	835
S 1/5				0.854	0.67	0.1036	0.1528	1179
T 2/2-1/1				0.661	1.33	0.1047	0.0155	410
T 1/5				0.885	0.67	0.1106	0.1685	1085
T 2/4				0.844	0.67	0.1071	0.1381	1048
S 3/3				0.758	1.10	0.1056	0.0559	823
S 2/4	25.0	26.0	180	0.640	1.00	0.2550	0.1757	1698
S 1/5				0.610	0.67	0.2605	0.2588	1960
T 1/2				0.490	1.33	0.2576	0.0706	1130
T 1/5				0.640	0.67	0.2514	0.2761	1919
T 2/4				0.600	0.67	0.2587	0.2303	1836
R 3/3				0.600	1.33	0.2558	0.0994	1571
B 3/3				0.620	0.67	0.2587	0.2414	1591
P 1/1				0.489	2.00	0.2420	0.0000	561

Table 2. *Correlation coefficients between the air permeability and selected parameters of woven fabrics.*

Fabric property	P_{ver}	P_{hor}	P_W	**CFF**
Air permeability, dm^3/m^2s	0.89	0.67	0.91	-0.59

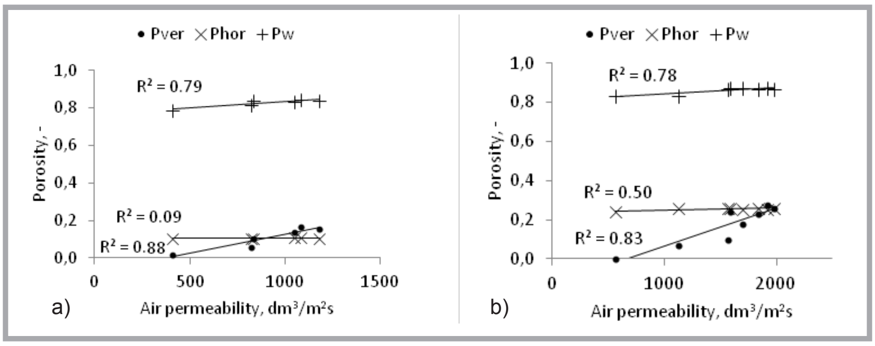

Figure 5. *Comparison of air permeability values and porosity of the fabrics (P_{hor}, P_{ver} & P_W) – data for each set of fabrics were processed separately; a –first, b –second set of fabrics.*

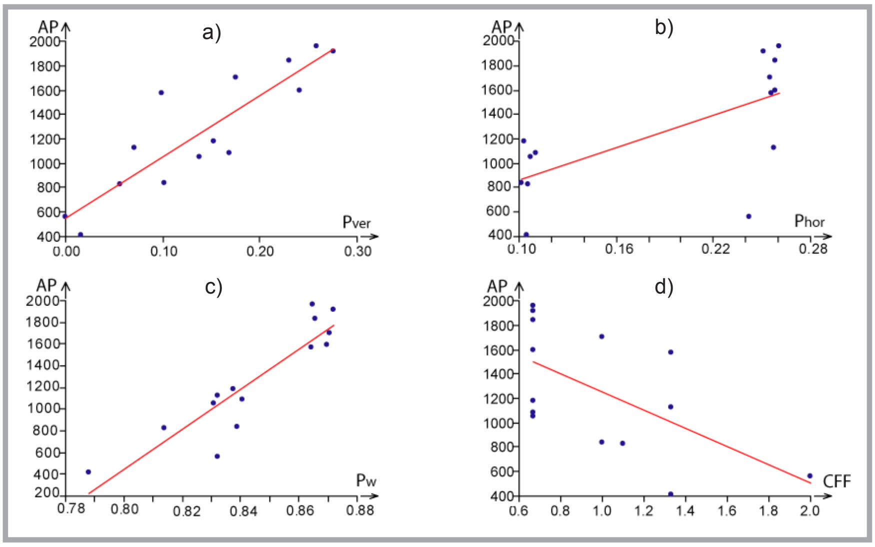

Figure 6: *Relationship between air permeability and selected parameters of fabrics (data of both sets of fabrics processed together): a – vertical porosity P_{ver}, b – horizontal porosity P_{hor}, c – density based porosity, d – CFF.*

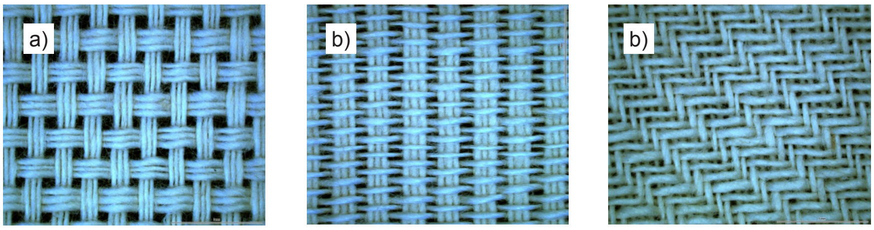

Figure 7. *Images of experimental fabrics: a – basket, b – rib, c – twill 2/4.*

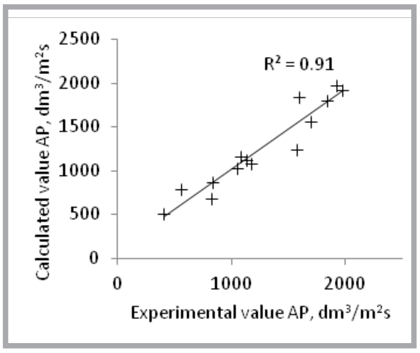

Figure 8. *Relationship between calculated and experimental values of air permeability (including panama and rep).*

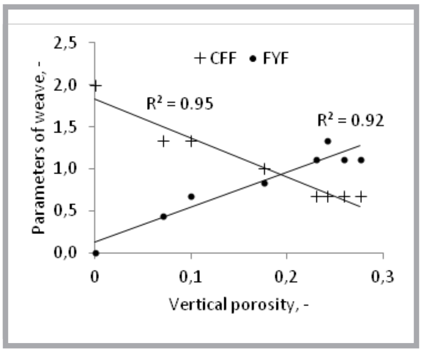

Figure 9. *Relationship between parameters of weave (CFF, FYF)- only the second set of fabrics and vertical porosity.*

ity is important in terms of the air permeability of woven fabric as well.

Therefore in the following evaluation, data from both sets of fabrics were evaluated together. The data were processed with the use of correlation analysis and linear regression analysis (software QC Expert). First correlation coefficients between the air permeability and porosity (P_{hor}, P_{ver} and P_W) of the fabrics were determined, the results of which are shown in ***Table 2*** (significance level - 0.05). ***Figure 6*** shows the relationship between air permeability and selected parameters of fabrics (P_{ver}, P_{hor}, P_W and *CFF*).

Table 2 and ***Figure 6*** show that the vertical porosity P_{ver} is strongly related to the air permeability and there is a clear positive correlation. The density-based porosity P_W is also strongly related to the air permeability and there is a clear positive correlation. The correlation between air permeability and horizontal porosity P_{hor} is smaller, but it is generally known that in the case of the open fabrics made of staple yarns, air flows, to a great extent, only through these horizontal pores . The correlation between air permeability and *CFF* values is the smallest and is a negative correlation. Therefore in terms of woven fabric permeability, horizontal porosity is certainly an important parameter. However, as mentioned above, the horizontal porosity cannot distinguish between fabrics with different types of weave. Therefore the importance of both horizontal and vertical porosity is obvious. Then the method of multiple linear regression was used and the resulting regression equation is introduced below:

$$AP = 4200\times P_{ver} + 2520\times P_{hor} + 180 \quad (17)$$

The regression accuracy is shown in ***Figure 8***. The coefficient of determination is relatively high – $R^2 = 0.91$, and both parameters in ***Equations 17*** – P_{ver} and P_{hor} are found to be significant.

If two fabrics (with basket and rib weave) were excepted from the whole set of 14 fabrics evaluated, the coefficient of determination was even $R^2 = 0.97$. The values of basket and rib fabrics were the furthest outliers. ***Figure*** *7* shows that basket and rib fabrics have significantly uneven horizontal inter-yarn pores (unlike twill 2/4). As previously demonstrated [19], the distribution of horizontal pore size has a significant effect on the permeability of woven fabric. When the yarns in the fabric are arranged unevenly, extremely small and extremely large pores occur (as in the case of basket and rib – see ***Figure 7.a** & **7.b***). The permeability of such fabrics will be greater than the permeability of a fabric that has an average area of one inter-yarn pore but at the same time all its pores have the same size (as in the case of twill – see ***Figure 7.c***). It is therefore probable that in terms of air permeability evaluation, the vertical and horizontal pores interact with each other, which may comply with the findings presented in paper [7]; namely that in the case of dense fabrics, the effect of the type of weave on the air permeability of woven fabrics is not so pronounced. If the threads are too close to each other, the effect of vertical porosity may be lower due to the tight overlap of adjacent vertical pores.

Figure 9 shows the relationship between the vertical porosity and parameters of the weave (only the second set of fabrics) – crossing-over firmness factor (*CFF*) and floating yarn factor (*FYF*). These parameters are given, for example, in [8] or [13]. There is a clear positive correlation between vertical porosity and *FYF* – the vertical porosity becomes larger with a greater *FYF*. There is a clear negative correlation between vertical porosity and *CFF* – the vertical porosity becomes larger with a smaller *CFF*.

Conclusions

Air permeability is one of the important properties of fabrics. Especially in the area of technical textiles air permeability can be a decisive parameter in terms of the function of the fabric. The air permeability of a woven fabric is very closely linked to its structure. Therefore many authors have described the relationship between the air permeability and structure of woven fabrics. In different models, they take into account the constructional parameters of woven fabric, such as setts of warp and weft yarns, the diameter of yarns and different types of weave. In this work two types of inter-yarn pores are considered: horizontal and vertical. The vertical pore is formed in the woven fabric "under yarn" in the location of longer non-interlaced segments of the yarn. A model for calculation of the cross sectional area of one vertical pore is outlined in this paper. Then the relationship between vertical porosity and air permeability is studied. It is shown that both parameters – horizontal and vertical porosity are significant in terms of air permeability. The results of correlation and multiple linear regression analyses show that the vertical porosity is strongly related to air permeability, for which there is a clear positive correlation. The horizontal porosity model completely neglects the effect of weave type. On the other hand, the vertical porosity model takes into account the effect of weave type. The regression equation, which allows calculation of the air permeability value based on the vertical and horizontal porosity values, shows good results.

The relationship between vertical porosity and weave structure parameters such as the crossing-over firmness factor (*CFF*) and floating yarn factor (*FYF*) is shown too. When using only one set of fabric (with the same setts of warp and weft yarns, as well as the same yarn diameter), the correlation between these characteristics is very good. But when using both sets of fabric, the correlation is very small. The correlation is also low in the case of the relationship between air permeability and weave structure parameters (*CFF* and *FYF*) when using both sets of fabrics (the settings of yarns and the yarn diameter is not the same). The vertical model of the inter-yarn pore allows, unlike *CFF* and *FYF*, to quantitatively describe the dimensional characteristics of pores formed between yarns in the vertical direction, which can be very useful in designing fabrics such as filters. For example, the pressure loss can be reduced while maintaining some filtering capability.

The correlation between air permeability and density based porosity P_W is very good. However, density-based porosity also does not describe the geometrical structure of the fabric.

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