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Air Permeability and Costructional Parameters of Woven Fabrics

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Abstract
The main aim of this paper is to look into the relationship between the structure and air permeability of a woven fabric, and discuss the possibility of the prediction of fabric air permeability. With respect to the relationship between the air permeability and structure of woven fabrics it is not possible to describe fabric only by its porosity. Generally porosity indicates how many air gaps a textile material contains. For a description of airflow through textile materials, further details about the configuration of pores in textiles (the pore size, shape, texture, arrangement etc.) are very important. In this paper the influence of the type of weave is eliminated by using only fabrics with a plain weave, where inter-yarn pores have approximately the same shape. The size of these pores, however, varies considerably, which has a significant influence on the air permeability of the fabric. This fact complicates the possibility of the prediction of air permeability.

Key words: *woven fabric, air permeability, porosity, set of yarns, yarn linear density, structure.*

Introduction

the geometrical characteristics of textile fabrics are very important for evaluating and simulating a lot of fabric properties, one of which is air permeability. The permeability of fabric is closely linked to its structure. A number of authors, e.g. [1 – 5] have dealt with the possibility to predict the value of the permeability of fabrics based on their structural parameters. In some applications woven fabrics are used as filters or protective barriers whose function is to prevent the penetration into the human body of various microparticles or microorganisms. The elements of the structure which decide whether a woven fabric is capable of performing such a function are the inter-yarn pores, which are dependent on the weave and structural parameters of the fabric. These factors need to be pre-determined in the designing phase and realised in the weaving process [3, 4, 6]. Moreover the permeability of fabrics is correlated with many other properties. An inverse relation was shown between the air permeability of woven fabrics and their mechanical properties, such as the bending rigidity, shear rigidity and strength [14].

The structure of a fabric is usually characterised by its porosity, e.g. [4, 5, 7, 8]. The total porosity of woven fabrics usually comprises two type of porosity, i.e. the micro porosity (or intra-yarn porosity) caused by the void spaces between fibres in yarns, and the macro porosity (or inter-yarn porosity) caused by the void spaces between yarns. Constructional parameters, such as the linear density of yarns, sets of yarns, type of weave and the production technology used can be combined in various ways. The structure of fabrics made can be very similar or very different, but the permeability of two fabrics which have an apparently very similar structure may be very different. The fabric air permeability is mainly determined by its inter-yarn pores (their size, shape, texture, mutual arrangement, etc.). This issue has already been described in several papers. However, most of them completely eliminate the effect of yarn hairiness,e.g. [4, 5, 7 – 9, 11] – considering mono- or multi- filaments or neglecting it. The air permeability of a fabric is also highly influenced by its type of weave. Any weave can be created using the four basic inter-yarn pores described by Backer [1]. Some authors, e.g. [5, 7 – 10] describe the effect of the number and shape of these four pore cells in the air permeability of fabric.

This paper is focused on plain weave fabrics made of staple yarns. The influence of the type of weave is eliminated.

Methods used

One of the main aims of this research was to discuss the possibility of the prediction of the air permeability of fabrics on the basis of their constructional parameters. The following basic constructional parameters were considered:

- D_O, D_U, in 1/m – sets of warp and weft yarns, respectively,
- T_O, T_U , tex – linear density (fineness) of warp and weft yarns, respectively,
- Type of weave (it was eliminated).

The linear density (fineness) of yarns is a parameter which is usually specified by the manufacturer of the fabric. This parameter is replaced by the yarn diameter to describe geometrical characteristics of the fabric structure. Then d_O, d_U [m] are diameters of warp and weft yarns respectively. The diameter of yarn can be determined by calculation or the experimental use of various methods, e.g. [12, 13].

In this research a set of 58 fabrics were used for experiments. These experimental blended fabrics (cotton/polypropylene) were used in a grey state for the experiment. The yarns used were produced by ring spinning technology. A summary of the fabric parameters is shown in ***Table 1***. The air permeability was measured

Table 1 *Parameters of fabrics used*

T_O, T_U = 20 tex	T_O, T_U = 29.5 tex	T_O, T_U = 45 tex
Material: 100% CO 65% CO/35% PP 50% CO/50% PP 35% CO/65% PP	Material: 100% CO 65% CO/35% PP 50% CO/50% PP 35% CO/65% PP 100% PP	Material: 100% CO 65% CO/35% PP 50% CO/50% PP 35% CO/65% PP 100% PP
D_O ≈ 26 yarns/cm	**D_O ≈ 21.2 yarns/cm**	**D_O ≈ 18 yarns/cm**
D_U: ≈ 10.4 yarns/cm ≈ 15.6 yarns/cm ≈ 20.8 yarns/cm ≈ 26 yarns/cm ≈ 28 yarns/cm	D_U: ≈ 8.6 yarns/cm ≈ 12.8 yarns/cm ≈ 17 yarns/cm ≈ 21.2 yarns/cm ≈ 23 yarns/cm	D_U: ≈ 7.2 yarns/cm ≈ 10.8 yarns/cm ≈ 14.4 yarns/cm ≈ 16 yarns/cm
Plain weave		

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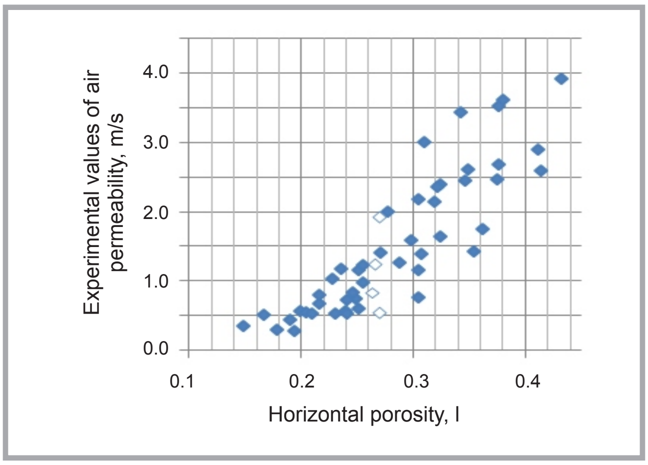

Figure 1. *Comparison of air permeability values and horizontal porosity of the fabrics.*

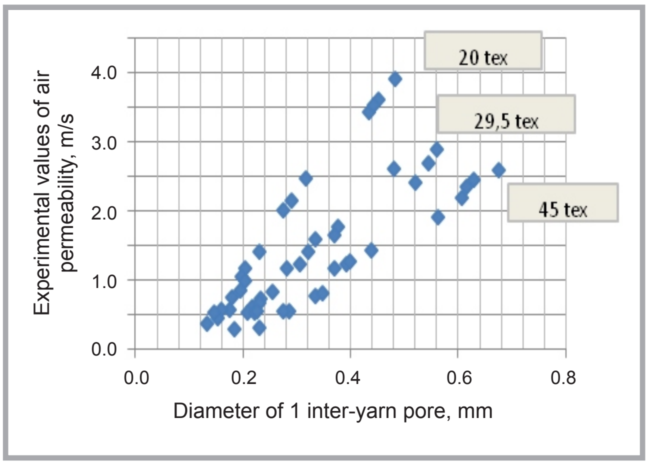

Figure 4. *Comparison of air permeability values and values of the pore diameter.*

using a digital tester - FX 3300 according to the 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 the D_O and D_U values were determined experimentally according to the standard ČSN EN 1049 – 2. The original intention

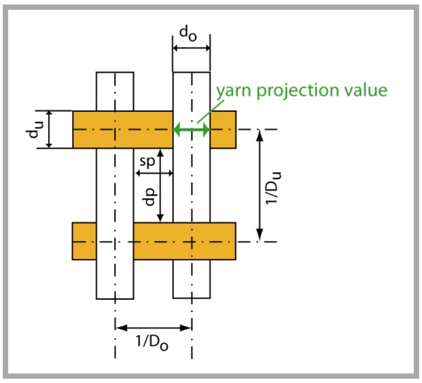

Figure 2. *Scheme of dimensional characteristics of the one inter-yarn pore.*

was to produce experimental fabrics that always have the same warp and differ only in the set of weft yarns (at the same linear density of yarns); however, this was not fully achieved as D_O values varied relatively significantly, which should be taken into account. The diameters of yarns were determined experimentally using USTER apparatus. The fibre material was mixed by the mass method, which means that the yarn diameter varied depending on the proportion of cotton and polypropylene fibres.

Flat covering & surface porosity

The area covering values were calculated as:

$$Z = D_O d_O + D_U d_U - d_O d_U D_O D_U \quad (1)$$

Values of D_O ,1/m, D_U ,1/m, d_O ,m & d_U, m were determined experimentally.

Surface (or horizontal) porosity (as an "open area of the fabric") was then considered as an additional area to the area covered:

$$P_S = 1 - Z \quad (2)$$

Characteristic dimension of the one inter-yarn pore

As already mentioned above, two fabrics can have the same value of the flat covering, but their air permeability is significantly different (see ***Figure 1***). Such fabric may have a larger number of smaller pores or a smaller number of larger pores. Therefore this paper deals with an analysis of individual inter-yarn pores in relation to the permeability of the fabric.

The area of perpendicular projection of one inter-yarn pore is calculated as:

$$A_1 = \left(\frac{1}{D_O} - d_O\right)\left(\frac{1}{D_U} - d_U\right) \quad (3)$$

The perimeter of the perpendicular projection of one inter-yarn pore is calculated as:

$$O_1 = 2\left(\frac{1}{D_O} - d_O\right) + 2\left(\frac{1}{D_U} - d_U\right) \quad (4)$$

The value of the pore diameter is not clear due to the fact that the pores do not have a regular shape. For a simple approach it is possible to think of the pore diameter as the average of its width *sp,* m and length *dp,* m (see ***Figure 2***):

$$d_p = \frac{1}{2}\left[\left(\frac{1}{D_O} - d_O\right) + \left(\frac{1}{D_U} - d_U\right)\right] \quad (5)$$

Effect of yarn hairiness & effect of the irregularity of setts

In the case of fabrics made from staple yarns, the space of each inter-yarn pore is more or less affected by the area of yarn hairiness. There is an assumption [11] that if the inter-yarn pores are large enough and the air has enough space for free passage, it will flow mostly just that way. The photos of fabrics captured, however, show (e.g. ***Figures 3.a*** or ***Figure 9***) that the area of yarn hairiness overlaps the inter-yarn pore area significantly. Neither can this area be regarded as completely impermeable nor quite freely permeable, it forms a kind of "transition zone" (see ***Figure 3.b***). In case where a monofilament thread is used, the border between the thread and inter-yarn pore is clear. When staple yarn is used, the determination of the border is only a matter of intuition. Usually it is located in the space which corresponds to the radius of the yarn. As mentioned above, there exist

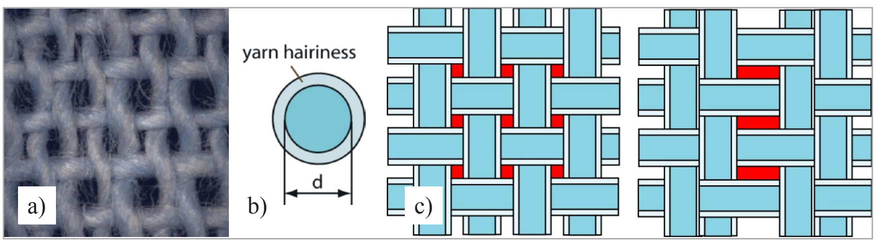

Figure 3. *Effect of yarn hairiness on the air permeability of a woven fabric.*

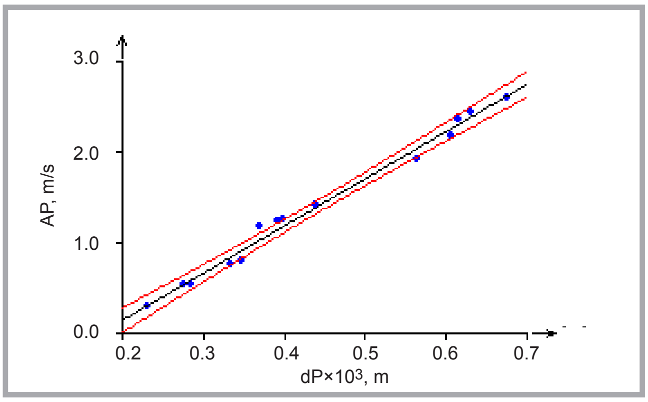

Figure 5. *Dependence of the permeability on the diameter of the pore (fabrics with 45 tex yarns).*

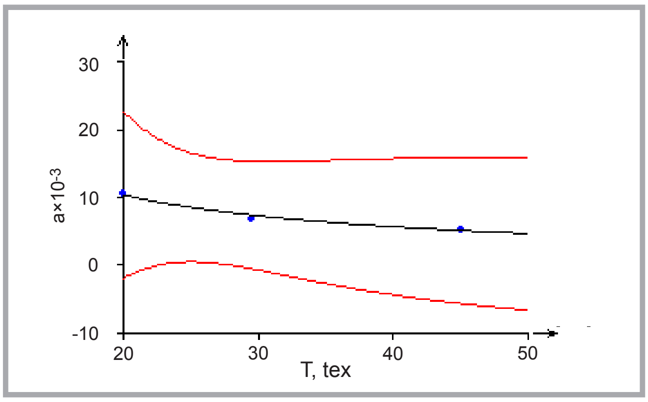

Figure 6. *Comparison of the values of parameter a and those of the linear density of the yarns used.*

several methods for determining the radius (or diameter) of yarn. When using the analysis of the radial filling of the yarns [13], the radius is localated at the place where the filling value drops to 0.15.

The effect of yarn hairiness on the air permeability of fabric even increases in the case of the irregularity of sets of warp and weft yarns. Theoretical calculation of the structural characteristics of the fabric is based on the automatically accepted assumption that the inter-yarn pores in the fabric are all the same size, with the "average pore" always being assumed. However, the real fabric may not be like that.

The area A_1 and perimeter O_1 of the perpendicular projection of one average inter-yarn pore will not change by mutual displacement of individual yarns in the fabric, except when the yarn hairiness is neglected. As a result of the close position of two adjacent yarns their areas of hairiness overlap. Then, due to the unevenness of the fabric structure, the size of one pore is increased, while the adjacent pore size is reduced (see ***Figure 3.c***).

The distribution of the inter-yarn pore size is significant. This phenomenon has a very strong influence on the air permeability of woven fabric.

Experiment

Comparison of the air permeability and horizontal porosity values (see ***Figure 1***) shows that this structural characteristic is not sufficient for the prediction of air permeability values.

When comparing the permeability values with dimensional characteristics of one inter-yarn pore (see ***Figure 4***), it is clear that the values can be divided into three groups: fabrics made with 20 tex, 29.5 tex and 45 tex yarns. ***Figure 4*** shows a comparison of the air permeability values and values of the pore diameter d_P in m (according to ***Equation 5***).

Similar results were shown by the comparison of the air permeability and perimeter or area of one inter-yarn pore. The dependence of the air permeability values on the diameter of one inter-yarn pore was tested for each group of values separately using regression analysis (software QC. Expert), the results of which are shown in ***Table 2*** and one graph in ***Figure 5***. The linear dependence was tested in the form:

$$AP = a \times d_p + b \qquad (6)$$

It is possible to consider the parameter b (displacement of the regression line on the y-axis) as its average value: b = - 0.94, but the value of parameter a (slope of the regression line) varies in dependence on the corresponding value of the linear density of yarns. It is clear that (see ***Figure 4***):

- at the same value of d_P the air permeability of the fabric "20 tex" is higher than that of the fabric "45 tex".
- at the same time, the fabric "20 tex" has a higher sett of warp yarns D_O than the fabric "45 tex".
- the fabric "20 tex" has a greater number of pores of size d_P than the fabric "45 tex".

Then the value of parameter a of the regression line decreases in dependence on the linear density of the yarns used. However, statistical analysis of this dependence is very problematic because they are only three points (see ***Figure 6***).

It was then considered approximately:

$$a = 1.36\times10^5 T^{-0.86} \qquad (7)$$

Table 2. *Results of the regression analysis.*

T, tex	D_O, 1/m	a	b	R^2
20.0	2702	10540	-1.0820	0.9917
29.5	2305	6720	-0.8540	0.9804
45.0	1885	5206	-0.8965	0.9946

Table 4 *. Results of the correlation of the measured and estimated values.*

Set	a	b	R^2
Initial	1.003	0.0583	0.98
Control	0.848	0.0020	0.82

Table 3. *Some parameters of the control fabrics.*

	AP, m/s experiment	T, tex	D_O, 1/m	D_U, 1/m	AP, m/s calculation	Deviation, %
1	0.610	16.5	3365	3175	0.605	4.1
2	0.296	25.0	2765	2660	0.244	-8.6
3	1.877	25.0	1930	1910	1.514	-16
4	1.918	16.5	2535	2425	1.770	-4.9
5	0.957	25.0	2700	1960	0.968	-7.9
6	1.370	25.0	2370	1950	1.226	-18
7	0.723	40.0	1890	1800	0.453	-43
8	1.655	40.0	1570	1500	1.070	-37
9	1.438	16.5	2900	2460	1.588	3.2
10	0.994	16.5	2900	2840	1.247	16
11	1.231	40.0	1880	1500	0.762	-40
12	0.910	25.0	2360	2264	0.893	-10
13	0.419	40.0	2120	1800	0.140	-41

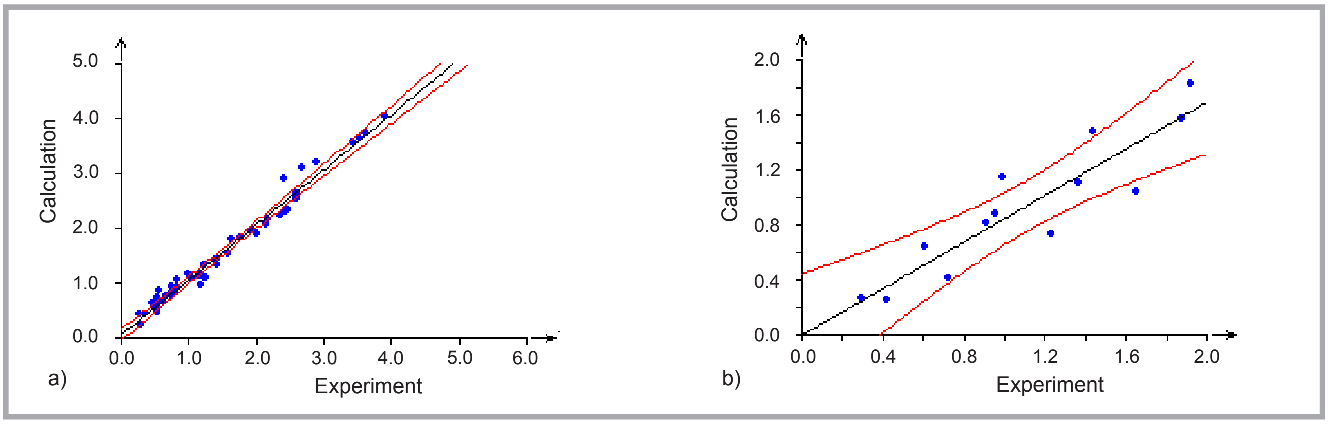

Figure 7. *Comparison of the measured and predicted values of the air permeability AP in m/s: a – initial set of fabrics, b – control set of fabrics.*

And the air permeability value can be predicted according to:

$$AP \approx (1.36 \cdot 10^5 T^{-0.86}) d_p - 0.94 \quad (8)$$

Equation 8 was applied to a set of initial fabric (see ***Table 1***) and also to a set of 13 additional control fabrics. These fabrics were made from 100% polyester yarns produced by ring spinning technology. The yarn diameters were determined experimentally using the USTER apparatus. Some parameters of these fabrics are introduced in ***Table 3***. The results are shown in ***Table 4*** and ***Figure 7***.

The results indicate that the correlation between predicted and experimental values of permeability in the control group is relatively good, but the predicted values are significantly undervalued – see the deviation in % in ***Table 3***. The highest negative deviation is achieved in the case of fabrics manufactured with yarn linear density 40 tex (~ - 40%).

Discussion

There are two questions:

1. What deviation value is still regarded as acceptable at the predicted values?
2. As a result, what was the understatement of the estimated values?

It should be noted that the value of permeability can vary quite considerably in the area of the fabric. ***Figure 8*** shows the results of measurement of the air permeability at defined points in the area of the fabric (boundary points are 20 cm from the fixed edges of the fabric and the mutual distance between them is always 15 cm in the warp and weft directions).

It is evident that in the direction of the length of the fabric the air permeability value is relatively stable, but in the direction of the width of the fabric this value varies considerably, probably caused by irregularities in the sett of warp yarns. The minimum measured value was 1.12 m/s and the maximum 1.52 m/s. The difference between these two values related to the average value represents a deviation of 30%. Does this mean that such deviation could be explicitly considered acceptable at the predicted values?

Also other authors have investigated the irregularity of some fabric constructional parameters over the width of fabric. Frontczak-Wasiak [15] deals with an analysis of the process of creating a non-uniform distribution of the weft take-up over the width of woven fabrics manufactured with the use of jet looms. Milašius et al. [16 – 19] investigated the unevenness of some fabric cross-section parameters and the influence of these structural inequalities on some fabric properties – including fabric permeability. He says that the character of inequality in the width of all fabrics has the same tendency and air permeability varies

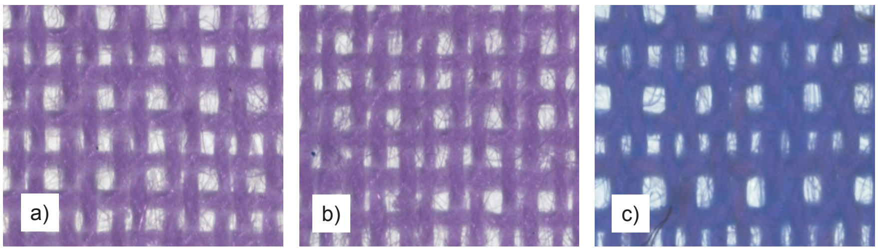

Figure 8. *Structure of one control fabric: a – Sample 6 (the centre of the fabric, AP =1.5 m/s); b – Sample 6 (the border of the fabric, AP = 1.21 m/s) and one initial fabric: c – Sample 29/17 (the centre of the fabric, AP = 0.905 m/s).*

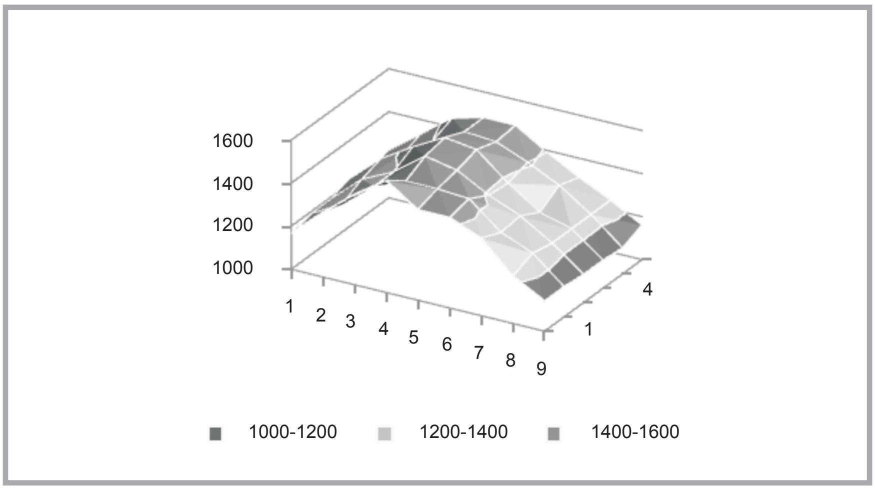

Figure 9. *Variation of the air permeability value in the area of fabric.*

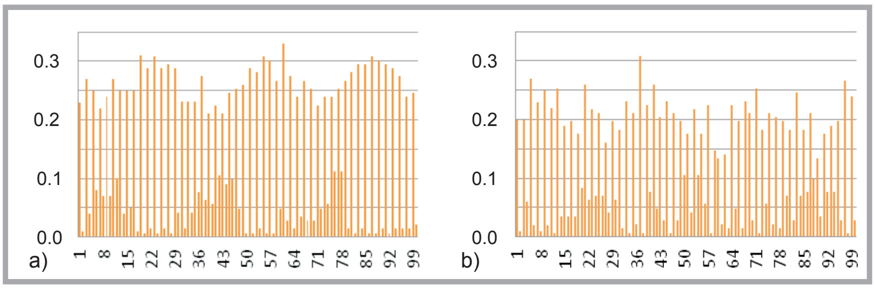

Figure 10. *Measured values of sp in mm; a – about in the centre of the fabric, b – about 20 cm from the hard edges of the fabric.*

similarly in both the left and right fabric borders [17, which was more or less confirmed by our experiment also (see ***Figure 9***). Images of fabric presented in [18, 19] at distances of 5, 25 and 70 cm from its edge show that in the centre of the fabric (70 cm from edge) threads are arranged in pairs, which agrees with our images (see ***Figure 8*** – the arrangement of yarns in pairs is significant at the centre of fabric). However, Milašius does not discuss the mutual arrangement of yarns. He also does not measure the size of the pore unit cells, but he does measure the yarn projection values (see ***Figure 2***). Milašius's results show that the variation of air permeability over the width of the fabric is very similar to that in values of warp projection. The linear regression equation describes the dependence of air permeability on projections of warp yarns with coefficients of determination R^2 = 0.7882 to 0.9577. A different linear regression equation is expressed for each fabric. These papers ([16 - 19]) they do not deal with the issue of the prediction of permeability for a set of control fabrics, and those used for the experiments were mainly made from multifilament yarns.

When using staple yarns the possibility of predictions of the fabric air permeability is clearly complicated by their hairiness. The regular non-uniformities in the structure of the fabric have a significant influence on the permeability value (mainly due to the effects described above – see ***Figure 3***).

Figure 8.a, 8.b shows photographs of Sample 6 (one from the control set). These photographs were taken approximately in the middle of the fabric and 20 cm from the hard edges thereof. In these locations the air permeability was also measured. The size of inter-yarn pores (the values "pore width" *sp* ,mm and „pore length" *dp,* mm – see ***Figure 2***) was measured with the use of image analysis (software LUCIA G). The pore boundaries were chosen subjectively and in the case some pores intuitively (= the pores through which no light passes). ***Figure 10*** shows the *sp* in mm values measured. The data are sorted as they were measured – one pore after the other as they followed in the textile.

Figures 8.a, 8.b and 10 give evidence that in the centre of the fabric there are greater differences (extremes) in pore size. There is also a larger number of "fictive pores" (measured only intuitively). In contribution [20] it was shown that if these fictive values are excluded from the data set, the correlation between the values of permeability of the fabrics and the average perimeter O_1 are higher. These facts confirm the assumption about the great influence of yarn hairiness & mutual displacement of yarns on the fabric.

Figure 8.c shows the structure of one sample with the initial set of fabrics (for the parameters, see ***Table 1***). It is evident that the structure of this fabric also shows "regular irregularity", but different to that of Sample 6.

While in Sample 6 all "rows of pores" are approximately the same, in the sample in ***Figure 8.c*** two types of "rows of pores" are periodically repeated. This phenomenon (ripple of yarns) is also evident in the fabric in ***Figure 3.a***. This may be one of the causes of the undervaluation in the case of the predicted permeability values (control set of fabrics).

Conclusion

The main aim of this paper was to demonstrate and discuss the relationship between permeability and fabric structure using fabrics made from staple yarns. The experiment was relatively large and complex because a set of 58 experimental fabrics and another experimental set of 13 control fabrics were used.

The assumption that the mutual relationship between permeability and fabric structure cannot be researched only on the basis of fabric porosity characterisation was confirmed. This parameter says how much air is contained in the fabric but says nothing about individual pores – size, relative positions. It is these structural characteristics that are decisive for fabric permeability. It was shown that the characteristic dimension of one inter-yarn pore (diameter, area or perimeter) correlates with the values of permeability much better.

A relationship for predicting fabric permeability was proposed. Then on the basis of the values of linear density of the yarns used and the diameter of one inter-yarn pore, it is possible to predict approximate permeability values. This relationship was subsequently tested on a control set of 13 fabrics.

The subsequent detailed analysis of the fabric structure showed that if the fabric structure is not quite regular, the use of the characteristic dimension of one "average pore" may not be even sufficient for the prediction of air permeability. The average pore size is not decisive, but the actual size of individual pores is (size distribution).

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