Detection of Fabric Structure Irregularities Using Air Permeability Measurements

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ABSTRACT

In this paper we demonstrate the possibility of using the close relationship between structure and air permeability of a woven fabric for the detection of the non-uniformity (or defects) in the structure of the fabric. Air permeability of fabrics is a principal property of the structure of a textile material. A very small change in the structure of the fabric at a given location causes a change in the permeability at that location. First we measure the air permeability at defined locations of the fabric. The method allows us to detect areas with an extreme value of permeability – the locations "suspected" of extreme unevenness of fabric's structure. Second, we explore the structure of the fabric in these areas of extreme values of the permeability and attempt to determine the causes of the irregularities in the fabric's structure. To quantify and describe the degree of these irregularities we applied methods of image analysis and statistical processing on acquired data. For our experiment, woven fabrics in the plain weave made from 100% staple yarn polyester were used. Results of our research confirm that significantly greater permeability variations occur in the weft direction of the fabric. Subsequent analysis of the structure of the fabric shows the bimodal nature or the data corresponding to the measurement of width of inter-yarn pore in the place of the maximal value of permeability. The observed higher value of permeability can be attributed to the irregularity of warp yarns at a given location of fabric. Initial permeability measurements enabled us to detect locations of its extreme values. Further close examination of these "suspected" locations of the fabric by a detailed analysis of the structure lead to the determination of the causes of the related irregularities.

INTRODUCTION

Physical and mechanical properties of textiles are determined primarily by their structure. A demanded requirement in several application areas of textiles is the homogeneity of their physical and mechanical properties. One of such physical properties is the air permeability. Permeability of textile materials is generally understood as the ability of air-permeable fabric to transmit air under given well specified conditions. The property of the textile's permeability is closely connected with the structure of the given textile material. The structure of the fabric is usually characterized by its porosity ([1, 2 or 3]). The total porosity of woven fabric usually comprises two types of porosity: the micro porosity (or intra-yarn porosity) is caused by the void spaces between fibers in yarns, the macro porosity (or inter-yarn porosity) is caused by the void spaces between yarns. Even very small change in the structure of the fabric causes a change in the permeability at the given location of the fabric. Therefore, it is necessary to keep a high degree of uniformity of the fabric structure to ensure stable values of the permeability throughout the entire fabric area.

As suggested in some earlier contributions ([4, 5, and 6]), assessment of the uniformity of fabric permeability in a given area can be performed by three-dimensional (3-D) surface graphs and some statistical methods (for example, the analysis of variance [7] or method specified in the work by Cherkassky [8]). In this work, in addition to these basic methods, the relationship between the variations in the air permeability value and the changes (or irregularity) of the woven fabric structure is studied in more detail.

METHODOLOGY

Measurement of the Permeability

Permeability measurement was carried out according to the standard ISO 9237. Permeability *AP* [mm/s] is expressed as the speed of air flowing through the given sample of fabric. Conditions of the measurement have to be well defined, namely, the clamping area of sample *S* [cm^2] and the pressure difference Δp [Pa].

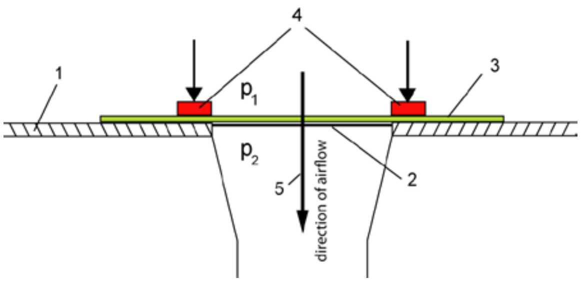


FIGURE 1. Method of clamping of a sample to perform a measurement of the permeability; 1 – desktop of device, 2 – sample support (wires), 3 – sample of fabric, 4 – circular clamping jaw, 5 – airflow ($p_1 > p_2$).

During the measurement, it is necessary to avoid the crumpled locations. Distance of measured location must be at least 10 cm from edge of the fabric. Average permeability is calculated from at least 10 measurement values that are acquired at different locations of the tested fabric. Standard devices can be equipped with different circular clamping jaw (5 cm^2, 20 cm^2, 50 cm^2, 100 cm^2). The clamping jaw with the diameter area of 20 cm^2 is the most used one. The orientation of the fabric sample (in direction of the warp – weft) does not influence the outcome of the measurement because the measured area is always circular. The pressure difference *Δp* is recommended to be 100 Pa for apparel fabrics and 200 Pa for technical fabrics.

It should be noted, that the value of the permeability may vary considerably across the entire area of the fabric. This can be observed when measurements are performed across the “entire area” of the given fabric. However, it is not realistic to consider such a detailed set of measurements using standard measurement devices (for example, FX 3300), because one measured value corresponds to the area given by the area defined by the size of the clamping jaw of 20 cm^2. In such a detailed approach when the entire area of the fabric is examined the time for an experiment increases significantly.

Variability of the Permeability

To perform our measurements we selected a regular mesh with the number of rows i = 7 and equal number of columns j = 7 (see *Figure 2*). The resulting number of locations in which the measurement has been made therefore equals to N = 49. The used clamping area was 20 cm^2.

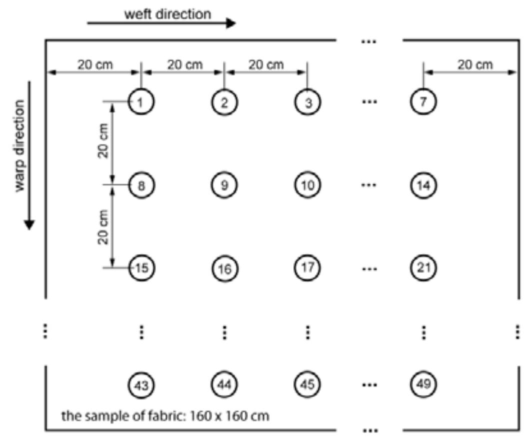


FIGURE 2. Schematic of the fabric samples used for the measuring of the air permeability.

Generally it is possible select a different mesh (different clamping area of sample *S* [cm^2], different spacing distance). In such a case, however, the obtained results will be different. We chose a mesh with spacing 20 cm, which choice was based on the experience with previous experiments [see also 4, 5 or 6]. When using the selected spacing, the variability of the permeability is sufficiently detected and the time required for an experiment is acceptable. A regular mesh is used for simplicity of the measurements, description of the data and their statistical processing.

For the description of the uniformity in the weft and warp directions the decomposition of the total coefficient of variation *CV* can be used. In the work [8] it is derived that *CV* can be expressed by means of the forms:

$$CV^2 = CV_O^2 + CV_{OU}^2 \quad \text{or} \quad CV^2 = CV_U^2 + CV_{UO}^2 \tag{1}$$

Symbol CV_O^2 denotes the variation coefficient in the warp direction and CV_U^2 denotes the variation coefficient in the weft direction. CV_{OU}^2 and CV_{UO}^2 coefficients are cross products of the variation coefficients. Then the total coefficient of variation *CV* has the same value in both cases expressed in Eq. (1), the individual components, however, are different.

The uniformity of the air permeability can be estimated by the two-way ANOVA model described in [9] and expressed by:

$$AP_{ij} = m + \alpha_i + \beta_j + c\alpha_i\beta_j \quad (2)$$

where m is total mean value, α_i describes effects of rows (warp direction), β_j describes effects of columns (weft direction) and c is one degree of non-additivity parameter. By using ANOVA the following hypotheses can be tested:

H_0: α_i=0, i.e. uniformity in the warp direction
H_0^*: β_j=0, i.e. uniformity in the weft direction
H_0^{**}: $c\alpha_i\beta_j = 0$, i.e. whether interaction is zero

Variability in Inter-yarn Pore Size

Two fabrics may have the same value of the surface porosity, however, their air permeability can be significantly different. Such fabrics may have a larger number of smaller pores or smaller number of larger pores. Therefore, in this paper we applied the analysis of the individual inter-yarn pores in relation to the permeability of the fabric.

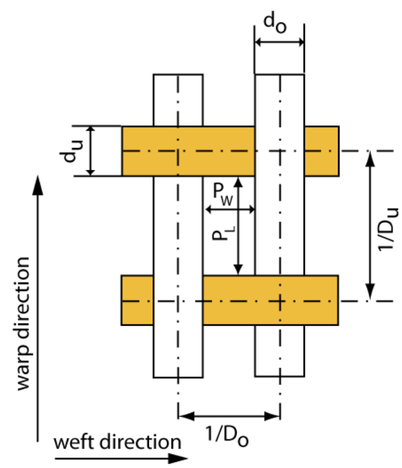


FIGURE 3. Schematic of the dimensional characteristics of an inter-yarn pore (P_W – width of the pore, P_L – length of the pore).

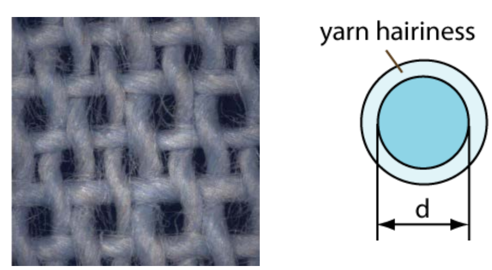
The value of the pore diameter is not well defined because pores do not have a regular shape. In a simple approach it is possible to assume that the diameter of a pore P_D [m] equals to an average of its width P_W [m] and length P_L [m]:

$$P_D = (P_W+P_L)/2=[(1/D_O - d_O)+(1/D_U - d_U)]/2 \quad (3)$$

where, d_O, d_U are diameters of the warp yarn and the weft yarn, respectively, and D_O, D_U are sets of warp yarns and weft yarns, respectively (see *Figure 3*).

In the case of fabrics made of staple yarns, the space of each inter-yarn pore is more or less affected by the area of the yarn hairiness. There is an assumption [10] 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 captured photos of fabrics, however, show (see for example *Figure 4 – a*) 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. The area forms a kind of a "transition zone" (see *Figure 4 – b*). In the case that mono-filament thread is used, the border between the thread and the inter-yarn pore is clear. In the case when a staple yarn is used, the determination of this border is only a matter of an intuition.

The effect of the yarn hairiness on the air permeability of a fabric increases in the context of irregularity of warp and weft yarn setts. A number of performed theoretical calculations of the structural characteristics of the fabric [1, 2, 11 or 12] automatically accept the assumption that the inter-yarn pores in the fabric are all of the same size – as a rule of an "average pore". However, the real fabric may not look like that.



a **b**

FIGURE 4. (a) Fabric view (b) Yarn hairiness.

The area and the perimeter of the perpendicular projection of the average inter-yarn pore will not change by mutual displacement of individual yarns in the fabric, but only in the case when the yarn hairiness is neglected. As a result of the close position of two adjacent yarns their areas of hairiness overlap (are depressed). Then, due to unevenness of the fabric structure the size of one pore is increased while the adjacent pore size is reduced (*see Figure 5*).

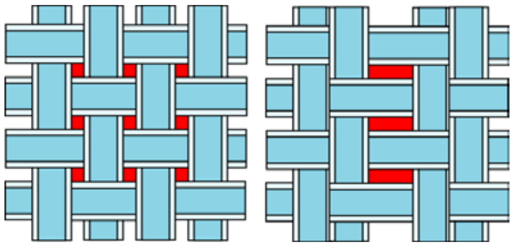


FIGURE 5. Schematic of the mutual displacement of an individual yarns in the fabric. Fabric on the left has regularly spaced warp threads. Fabric on the right has irregularly spaced warp threads – in some cases the hairiness of two adjacent yarns may overlap.

Consequently, in the case of fabrics made from the staple yarns, the distribution of the inter-yarn pore size is significant. This phenomenon has very strong effect on the air permeability of woven fabric.

MATERIAL AND EXPERIMENT

In this research a set of 9 woven fabrics was used for the experiment. These experimental 100% polyester fabrics were used in the greige state. The yarns used were produced by the ring spinning technology. A summary of some fabrics parameters is shown in *Table I* (T [tex] is fineness of warp and weft yarns, D_O [1/cm] is the sett of warp yarns, D_U [1/cm] is the sett of weft yarns):

TABLE I. Constructional parameters of used experimental fabrics.

No.	T = 16.5 tex		T = 25 tex		T = 40 tex	
	D_O	D_U	D_O	D_U	D_O	D_U
6	29.00	24.70				
7			23.20	19.75		
8	29.30	28.35				
9			23.65	22.25		
10					19.10	15.15
11			26.55	19.35		
12					19.80	18.10
15			27.65	26.60		
16					22.05	18.35
All samples are plain weave						

First, the permeability was measured for all fabrics. Then the geometry measurements were performed. The measurement of the air permeability was acquired in agreement according to the standard ČSN EN ISO 9237 with the use of standard measuring instrument FX 3300. We used the clamping area 20 cm^2 and the pressure difference 100 Pa. Each sample was measured 49 times in the position presented in *Figure 2*. An example of measured values is given in *Table II* (sample No. 15). The surface graphs (see *Figure 6* and *Figure 7*) are based on the acquired values of the air permeability to illustrate the variation of the air permeability in the fabric area.

TABLE II. Air permeability values (*AP* [mm/s]) acquired for sample No. 15; minimum and maximum values are marked by red and blue, respectively.

	1	*2*	*3*	*4*	*5*	*6*	*7*
1	196	243	323	311	294	227	199
2	201	267	306	315	297	227	207
3	209	275	309	351	319	234	216
4	204	270	313	322	293	231	205
5	216	275	319	317	297	243	221
6	202	273	311	298	290	260	221
7	204	268	310	318	316	244	232

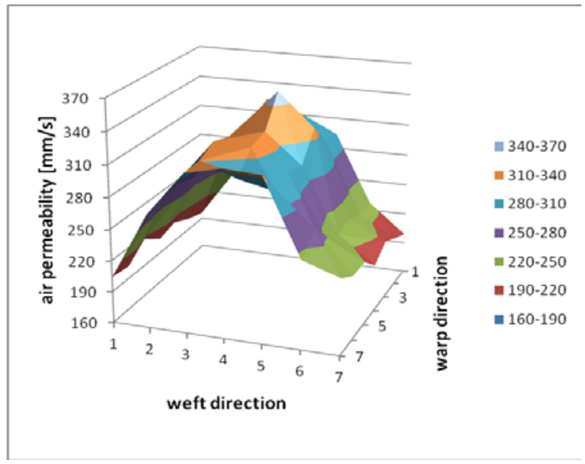


FIGURE 6. Surface diagram of the air permeability – side view (sample No. 15).

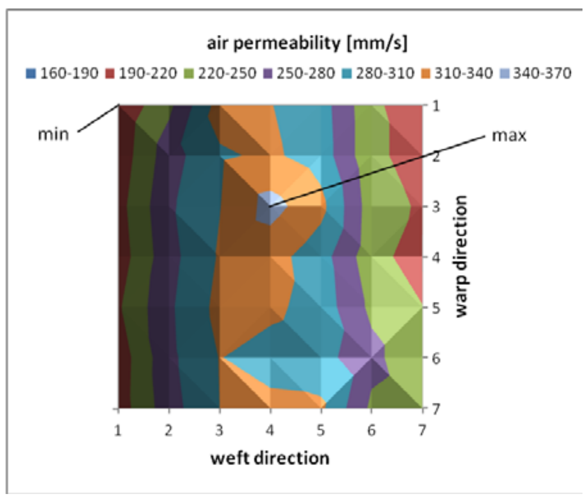
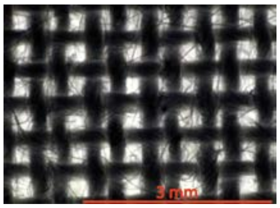


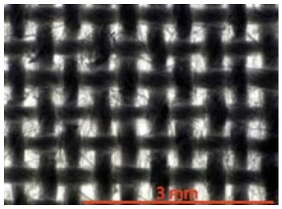
FIGURE 7. Surface diagram of the air permeability – top view; sites corresponding to the maximum and minimum value of permeability are marked (sample No. 15).

Then the experimental data were processed by the methods of the statistical analysis introduced above. Results of this analysis are summarized in *Table III*.

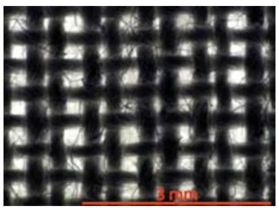
Using an image analysis (software LUCIA G) the size of inter-yarn pores was determined (namely, the values “pore width” P_W [m] and „pore length“ P_L [m] – see *Figure 3*). The measurement was performed by one person and pore boundaries were chosen subjectively. *Figure 8* shows some images of measured fabrics.



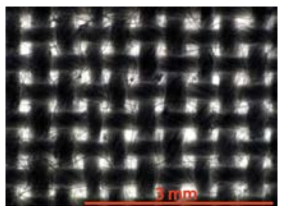
a – sample No. 7



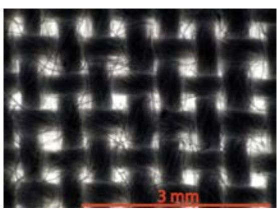
b – sample No. 7



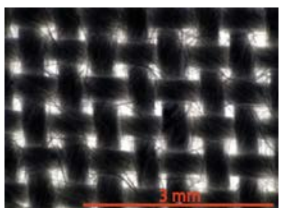
c – sample No. 9



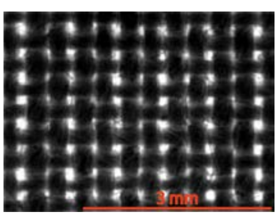
d– sample No. 9



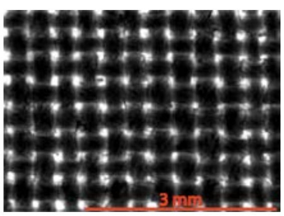
e – sample No. 12



f – sample No. 12



g – sample No. 15



h – sample No. 15

FIGURE 8. Images of locations on the fabric, which correspond to the maximum (a, c, e, g) and minimum (b, d, f, h) value of air permeability.

RESULTS AND DISCUSSION

The data obtained by measuring the permeability of fabrics were processed using the software QC Expert. The results obtained using the ANOVA statistical method is presented in *Table III*. Acceptance of hypothesis H_0 corresponds to the uniformity of the fabric in the warp direction. This hypothesis was rejected in most cases. Acceptance of hypothesis H_0* corresponds to uniformity in the weft direction. This hypothesis was rejected in all cases. Moreover, the values given in last column of *Table III* very significantly exceed criterion 2.364. Consequently, the irregularity of the fabric sample in the weft direction is very important. These results show that the fabric exhibits significantly greater permeability variations in the weft direction (as seen from *Figure 6* and *Figure 7*) and indicate a possible irregularity in the structure of the fabric.

TABLE III. Results of the statistical analysis of the acquired values of air permeability.

No.	CV_O [%]	CV_U [%]	H_0	H_0^*
6	6.4	1.94	**2.382**>2.364 *rejected*	**81.268**>2.364 *rejected*
7	8.83	2.02	**1.853**<2.364 *accepted*	**135.291**>2.364 *rejected*
8	9.58	2.73	**3.830**>2.364 *rejected*	**113.149**>2.364 *rejected*
9	12.67	2.90	**4.316**>2.364 *rejected*	**184.018**>2.364 *rejected*
10	4.91	2.30	**4.359**>2.364 *rejected*	**38.479**>2.364 *rejected*
11	11.51	2.29	**1.619**<2.364 *accepted*	**185.9**>2.364 *rejected*
12	8.09	2.52	**1.646**<2.364 *accepted*	**56.165**>2.364 *rejected*
15	18.10	4.07	**2.641**>2.364 *rejected*	**155.878**>2.364 *rejected*
16	11.56	3.32	**6.552**>2.364 *rejected*	**135.423**>2.364 *rejected*

The data obtained by measuring the dimensions of individual inter-yarn pores (length of the pore – P_L [m], width of the pore – P_W [m]) were also statistically processed using the software QC Expert. In this case the method of comparing two choices was used – one choice in the location of the fabric that corresponds to the maximum value of permeability (~ A) and one choice in the location with the minimum value of permeability (~ B). Some results are shown in *Table IV*.

TABLE IV. The results of the Average Conformity Test (level of significance is 0.05).

No.	P_L	P_W
6	8.497>1.964 different	1.862<1.964 **identical**
7	0.268<1.964 identical	0.129<1.964 **identical**
8	6.527>1.964 different	3.765>1.964 different
9	12.403>1.964 different	1.523<1.964 **identical**
10	8.047>1.964 different	2.428>1.964 different
11	6.785>1.964 different	1.894<1.964 **identical**
12	7.847>1.964 different	0.803<1.964 **identical**
15	7.116>1.964 different	3.747>1.964 different
16	12.096>1.964 different	2.614>1.964 different

The results shown in the *Table IV* demonstrate that the average pore size varies across the given fabric. However, for the values of P_W the average conformity was demonstrated for most fabrics. Yet it is also important to note that the coefficient of variation for the measurement of P_W is significantly greater than for the measurement of P_L (see *Table V*).

TABLE V. Results of the statistical analysis (the measuring of the size of pores) and some parameters of fabrics.

No.	Location corresponds to the max. AP		Location corresponds to the min. AP		Fabric density [g/cm^3]	Ratio $1/D_O$ to $1/D_U$
	CV_{PL} [%]	CV_{PW} [%]	CV_{PL} [%]	CV_{PW} [%]		
6	8.42	59.2	7.58	60.3	0.379	0.852
7	9.01	55.0	6.74	30.3	0.374	0.851
8	9.91	61.9	10.8	46.4	0.398	0.968
9	9.00	63.0	9.56	28.5	0.416	0.941
10	7.99	60.4	7.61	51.3	0.374	0.793
11	6.85	57.4	7.89	44.6	0.399	0.729
12	8.84	56.3	10.8	28.9	0.434	0.914
15	15.75	56.6	18.4	43.0	0.466	0.962
16	7.41	67.6	8.57	55.7	0.437	0.832

It is evident that the value of P_W (cross pore size) varies significantly, which indicates uneven distribution of warp threads in the fabric. We have constructed histograms from the measured values of P_W and P_L. These histograms confirmed the bimodal nature of the data corresponding to the measurement of P_W values in the place of maximum value of permeability. This bimodal character of distribution is also consistent with the images shown in *Figure 8*.

Some examples of graphs obtained using the software QC Expert are shown in *Figure 9 – Figure 15*. They show that in the case of the same average values of the pore size (characteristic dimension), the permeability can be very different. A summary of the important data is presented in *Table VI* and *Table VII*.

TABLE VI. Maximum and minimum values of air permeability.

No.	AP_{max} [mm/s]	AP_{min} [mm/s]	Difference [%]*
6	1520	1200	23.02
7	1470	1130	25.56
8	1060	749	33.84
9	985	634	41.79
10	1260	1040	19.13
11	1070	760	34.29
12	770	569	29.60
15	351	196	58.05
16	444	310	34.90

**Difference is related to the average value of permeability.*

TABLE VII. Average inter-yarn pore size.

No.		Place of AP_{max}		Place of AP_{min}	
		average	standard deviation	average	standard deviation
6	P_L [mm]	0.233	0.020	0.220	0.017
	P_W [mm]	0.139	0.082	0.127	0.076
7	P_L [mm]	0.295	0.027	0.295	0.020
	P_W [mm]	0.165	0.091	0.166	0.050
8	P_L [mm]	0.177	0.018	0.167	0.018
	P_W [mm]	0.125	0.077	0.102	0.049
9	P_L [mm]	0.239	0.022	0.218	0.021
	P_W [mm]	0.157	0.099	0.147	0.042
10	P_L [mm]	0.360	0.029	0.342	0.026
	P_W [mm]	0.236	0.142	0.211	0.108
11	P_L [mm]	0.309	0.021	0.297	0.024
	P_W [mm]	0.133	0.076	0.122	0.055
12	P_L [mm]	0.253	0.022	0.238	0.026
	P_W [mm]	0.185	0.104	0.191	0.055
15	P_L [mm]	0.102	0.016	0.093	0.093
	P_W [mm]	0.072	0.041	0.062	0.026
16	P_L [mm]	0.245	0.018	0.227	0.019
	P_W [mm]	0.117	0.079	0.102	0.057

These graphs (see *Figure 9 – Figure 15*) show the difference between arrangement of the warp and weft yarns. *Figure 10*, *Figure 11* and *Figure 12* show that the average value of P_L (~ distance between two adjacent weft yarns) slightly varies but the distribution has only one mode. In the case of the value P_W the bimodal distribution is often observed – always on the fabric location corresponding to the AP_{max} and only in some cases on the locations corresponding to the AP_{min}. *Figure 13* shows that a greater difference in values of each mode leads to a higher value of permeability (which confirms the initial assumption). *Figure 9* shows clearly how a higher frequency of “the small pores” leads to a lower value of the permeability and a higher frequency of “the larger pores” leads to a higher value of permeability.

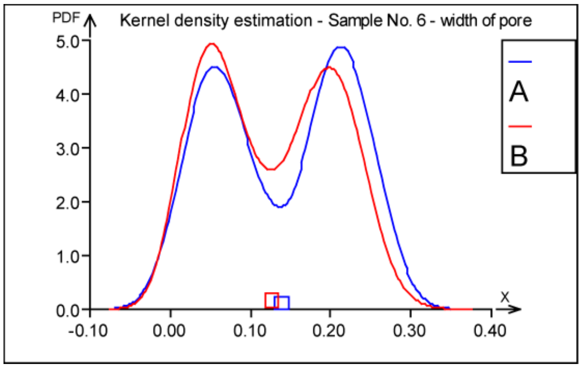


FIGURE 9. Kernel density estimation (sample No. 6 – measurement of the P_W [mm] dimension). The blue curve corresponds to measurement at the AP_{max} and the red curve corresponds to measurement at the AP_{min}.

CONCLUSION

The aim of our contribution is to demonstrate a very close relationship between the air permeability and the structure of a fabric. The adopted measuring method of the fabric permeability is a very simple and non-destructive test that can detect non-uniformity (or defects) in the structure of the fabric. The method can be used for assessment of the quality of fabrics, especially of those for which permeability is one of the vital characteristics (such as fabrics for air bags, parachutes, and barrier fabrics), but also others. The subsequent detailed analysis of fabric structures carried out directly in the location of the extreme values of the air permeability can then help us to find and determine the cause of the defects.

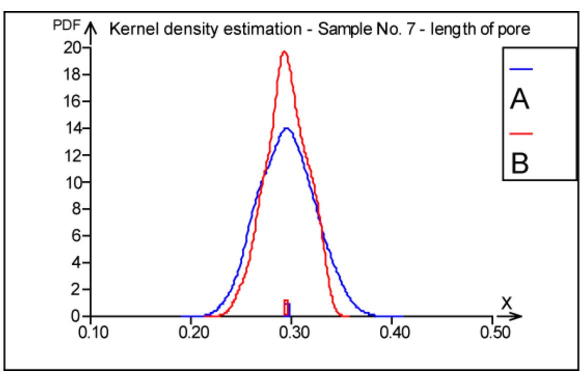


FIGURE 10. Kernel density estimation (sample No. 7 – measurement of the P_L [mm] dimension). The blue curve corresponds to measurement at the AP_{max} and the red curve corresponds to measurement at the AP_{min}.

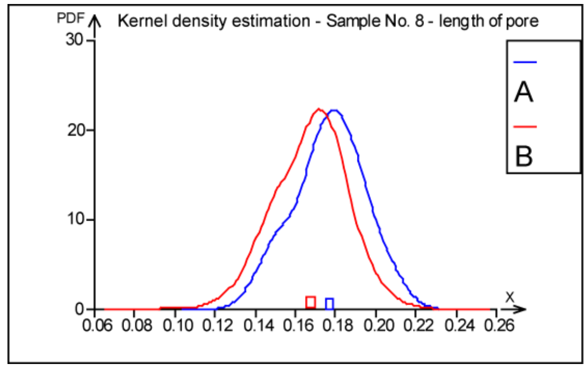


FIGURE 11. Kernel density estimation (sample No. 8 – measurement of the P_L [mm] dimension). The blue curve corresponds to measurement at the AP_{max} and the red curve corresponds to measurement at the AP_{min}.

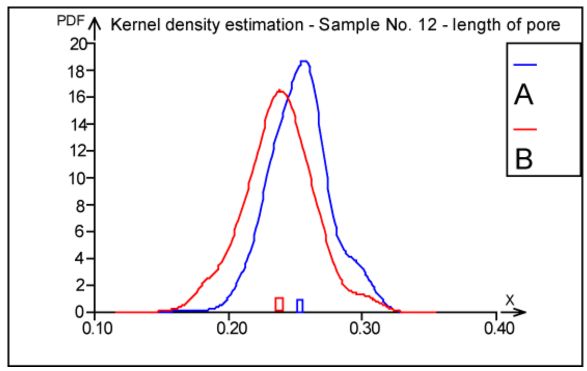


FIGURE 12. Kernel density estimation (sample No. 12 – measurement of the P_L [mm] dimension). The blue curve corresponds to measurement at the AP_{max} and the red curve corresponds to measurement at the AP_{min}.

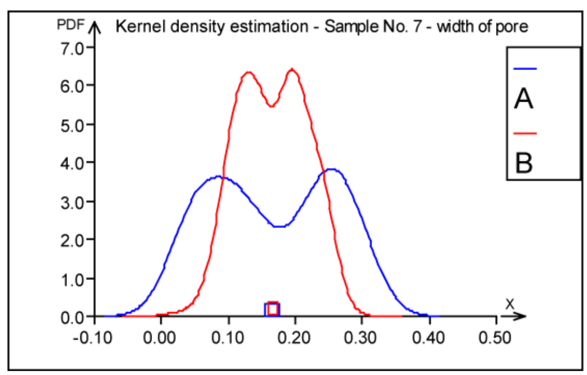


FIGURE 13. Kernel density estimation (sample No. 7 – measurement of the P_W [mm] dimension). The blue curve corresponds to measurement at the AP_{max} and the red curve corresponds to measurement at the AP_{min}.

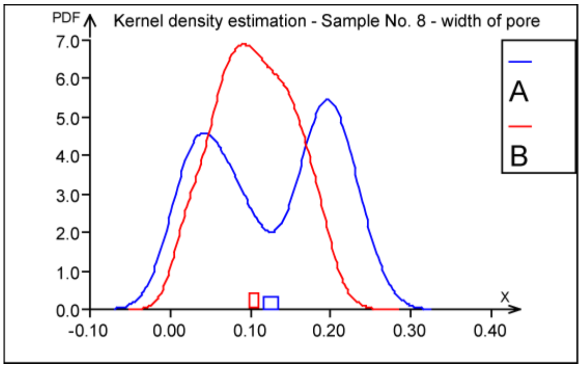


FIGURE 14. Kernel density estimation (sample No. 8 – measurement of the P_W [mm] dimension). The blue curve corresponds to measurement at the AP_{max} and the red curve corresponds to measurement at the AP_{min}.

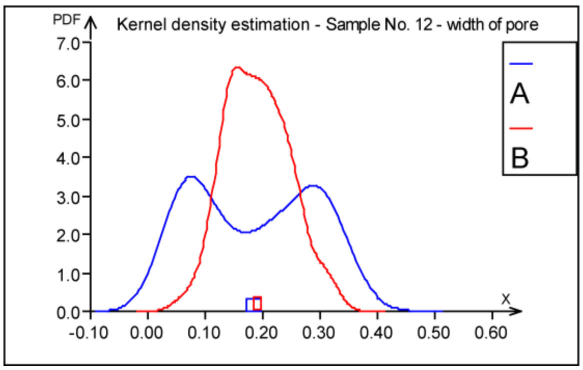


FIGURE 15. Kernel density estimation (sample No. 12 – measurement of the P_W dimension). The blue curve corresponds to measurement at the AP_{max} and the red curve corresponds to measurement at the AP_{min}.

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