AIR PERMEABILITY, WATER VAPOUR PERMEABILITY AND SELECTED STRUCTURAL PARAMETERS OF WOVEN FABRICS

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Abstract: *This paper is primarily focused on the description of the relationship between the structural parameters of woven fabric and its permeability for air and for water vapour. There are significant differences between the two phenomena. Consequently, there are also differences in the relationship between the structure and each of these phenomena. In this paper the influence of the weave type is eliminated by using only fabrics with a plain weave, and influence of material is eliminated by using only polyester fibres. Then two parameters of the fabric – the fineness of the yarns used and diameter of inter-yarn pores – are shown to play a very important role. With the use of the multivariate linear regression method equations for predicting air permeability and relative water vapour permeability have been proposed on the base of the structural parameters of the woven fabrics – yarn fineness and inter-yarn pore diameter. The correlations between calculated and measured values were high.*

Keywords: *air permeability, relative water vapour permeability, woven fabric, porosity, inter-yarn pore.*

1 INTRODUCTION

Air permeability and water vapour permeability are very important properties of textile materials, which significantly contribute to the physiological comfort felt by a dressed person. Both the properties are due to the porous structure of textile materials. However, the number, size, shape and distribution of the pores in the fabric may be varied within a wide range. The aim of a number of research papers [e.g. 1-15], therefore, is to identify the relationships between structural parameters of textile material and its air permeability or water vapour permeability. Understanding these relationships can lead to a targeted designing of clothing materials with very specific comfortable properties (e.g. sports, outdoor, medical or professional clothing). Some studies indicate that there are differences in relations between the structure of the fabric and its permeability for air or for water vapour [e.g. 12-15].

2 AIR PERMEABILITY

Air permeability (*AP*) of textile materials is generally understood as the ability of air-permeable fabric to transmit air under the well specified conditions given. Permeability measurement is carried out according to the standard ISO 9237. Air permeability *AP* [mm/s] is expressed as the speed of air flowing through the sample of fabric given. The measurement conditions have to be defined properly, namely the clamping area of sample S [cm^2] and the pressure difference Δp [Pa]. Standard measurement devices create a negative pressure inside the device, which leads to sucking air through the tested fabric. The air permeability of fabric is closely connected with the structure of the given textile material. Therefore, a number of contributions [e.g. 1-10, 12-15] are focused on finding the relationship between the structure and air permeability of fabrics.

In these works, the structure of the fabric is usually characterized by its porosity [1, 3, 4, 6-10, 12, 13]. In the case of woven fabrics, a number of authors also discuss the effect of weave on air permeability of the fabric [e.g. 1-5, 7]. An even a very small change in the structure of the fabric causes a change in the air permeability. This fact can be used in assessing the quality of fabrics. In earlier papers [8, 10] it was shown that air permeability measurement can be used for detection of fabric structure irregularities. There is also an assumption [1] that if the inter-yarn pores in woven fabric (i.e. pores between the yarns – see Figure 1) are large enough and the air has enough space for free passage, it will mostly flow just in that way. Based on this assumption, most authors dealing with the air permeability of fabrics consider yarns as an impermeable body. The question of whether it is right to consider yarns in fabric as impermeable body was also addressed in an earlier paper [9]. In this paper, for most of the evaluated knitted fabric, this assumption was confirmed as possible.

The conclusions of the contributions that deal with the relationship between the structure of the fabric and its air permeability are fairly consistent. According to them, the air permeability is very closely associated with properties such as porosity or the average size of one inter-yarn pore (e.g. diameter, area, perimeter) – regardless of whether it is a woven or knitted fabric [1-4, 6-7, 9, 10, 12, 13]. These properties, such as the porosity of the fabric or the size of the individual inter-yarn pores in the fabric, depend on its constructional parameters and on the production technology used.

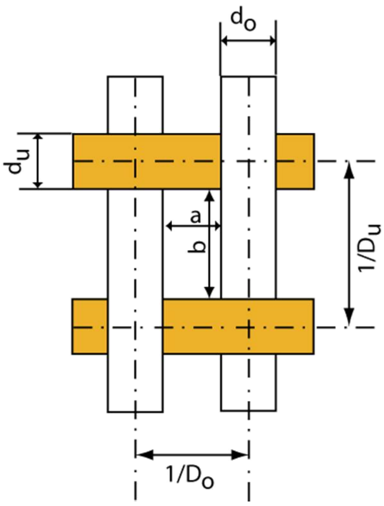

Figure 1 Scheme of dimensional characteristics of the one inter-yarn pore in woven fabric

3 WATER VAPOUR PERMEABILITY

Water vapour permeability (*WVP)* of textile materials is generally understood as the ability of permeable fabric to transmit water vapour through textile structure – usually expressed in units [g/m^2/24h]. Water vapour permeability measurement can be carried out according to the cup method [14, 15], or according to the standard ISO 11092. Similar procedure to that given by this standard is measurement using a PERMETEST apparatus, which measures the amount of heat passing through the thermal model of human skin [16, 17]. Relative water vapour permeability *RWVP* [%] of textile sample is a non-standardized but useful parameter that represents the relative heat flow responsible for the cooling of the body [16, 17], in the isothermal steady state is measured by the given equation:

$$RWVP = \frac{q_S}{q_0} \times 100 \qquad (1)$$

where q_S [W/m^2] is the heat flow passing through the measuring head covered by the sample and q_0 [W/m^2] is the heat flow passing through the measuring head without sample.

Unlike air permeability, water vapour permeability is significantly influenced by the material composition of fabric. There are different ways for transfer of water vapour through fabrics. One of them is transfer of water vapour through the void spaces in the fabric – intra-yarn and inter-yarn pores, and the other one is the diffusion through individual fibres [11, 12, 14, 18]. In the case of hygroscopic fibres (cotton, wool, viscose etc.) water vapour transfer also occurs by diffusion through the fibres themselves. So, the water vapour permeability is much more closely connected with the properties of the fibre material itself [11, 12, 14] than the air permeability. The geometrical parameter, which appears to be the most significant for the water vapour permeability, is the fabric thickness [11, 15].

Lee and Obendorf [11] searched relationship between the structural parameters of woven fabrics and their water vapour permeability using a statistical modelling. They tested fifteen woven fabrics with various fabric thickness, weight, fabric construction and fibre material. Statistical analysis revealed that it was fabric thickness, fabric cover factor, mean flow pore diameter of fabric, and moisture regain of fibre that proved to be significant parameters affecting water vapour transmission through woven fabrics. The yarn twist factor and yarn packing factor were found to be insignificant.

A number of authors investigated the influence of fabric constructional parameters on both of these comfort properties. For example, Polipowski et al. [12] confirmed the above mentioned that a strong correlation with the thickness of the woven fabric was obtained for the water vapour resistance and very strong correlation of the air permeability was found with the channel clearance area. At the same time, it was stated that there is a lack of correlation of air permeability with fabric thickness. The correlation between air permeability and water vapour resistance was only 0.44.

The attention of a number of papers, which are focused on evaluation of comfort properties, is paid to knitted fabrics [e.g. 13-15]. The reason is practical because the knitted materials are very often intended for garments that are in direct contact with human skin (e. g. underwear, sportswear). Wilbik-Halgas [13] and similarly Bivainyte [14] investigated the air and water vapour permeability of double-layered weft knitted fabric. Wilbik-Halgas [13] shows that air permeability, contrary to water vapour permeability, is a function of the thickness and surface porosity. The vital lack of correlation between water vapour permeability and the thickness and surface porosity is accounted for by a different character of media transport by free convection and by generally high porosity of knitted fabrics. Similarly, Bivainyte [14] established that knitting structure parameters, such as the loop length, area linear filling rate and pattern have a significant influence on the air permeability. It is the raw material that has the main influence on the water vapour permeability. To predict water vapour permeability using the loop length or area linear filling rate is impossible. There is no correlation between water vapour permeability and air permeability because the water vapour permeability depends on the structure of knits in the order different from air permeability. Coruh [15] examined single jersey knitted fabrics. His investigation shows that an increase in the loop length of the fabric investigated increases its permeability for air and for water vapour, likewise an increase in the linear density of yarns decreases its permeability to air and water vapour.

Based on the above mentioned facts, water vapour transport through porous textile materials is governed by various factors. Diversity and complexity of the involved parameters makes it hard to describe moisture vapour transport in relation to these factors [11]. In order to investigate the influence of individual structural parameters, it is necessary to eliminate the influence of others. Therefore, our experiment is focused only on woven fabrics with plain weave made of 100% polyester staple yarns. The influence of fibre composition, as well as the effect of the type of weave is eliminated.

4 STRUCTURAL PARAMETERS OF FABRICS

One of the main aims of this research is to discuss the possibility of predicting the air and water vapour permeability of fabrics on the basis of their structural parameters. The basic structure of the woven fabric may be described as follows: the weave, weft and warp diameter or the linear masses of these yarns, the density of the warp and weft, the thickness of the product or its surface mass [12, 20]. The fabric structure parameters can be divided into primary and secondary parameters [2]. Primary parameters of fabric structure are dependent variables, where the choice of one parameter influences the effect of the others – it is yarn thickness, density of yarns, type of weave. All others fabric structure parameters depend on primary parameters. These are secondary parameters. In our experiment the following primary and secondary structural parameters are considered:

- D_O, D_U [1/m] – setts of warp and weft yarns, respectively
- T_O, T_U [tex] – fineness of warp and weft yarns, respectively
- t [m] – fabric thickness
- W_P [g/m^2] – planar weight.

Porosity P [-] expresses the proportion of air voids contained in the textile. It can be considered as a secondary parameter of fabric structure. The porosity inside textile materials is usually divided into inter-yarn porosity (includes pores between the yarns from which the fabric is made) and intra-yarn porosity (includes pores inside the yarns, which are formed between the fibers) [4, 5, 11, 19].

There exist several different techniques for characterization of the idealized fabric porosity based on some constructional parameters of woven fabrics. Each of these techniques involves some simplifying assumptions. In our research the following will be considered:

Density based porosity P_D [-], which is calculated as [4, 10, 11]:

$$P_D = 1 - \frac{\rho_W}{\rho_F} = 1 - \frac{W_P}{\rho_F * t} \quad (2)$$

where ρ_F [kg/m^3] is the density of fibres and ρ_W [kg/m^3] is the volumetric density of the fabric, W_P [kg/m^2] is the planar weight and t [m] is the fabric thickness.

Porosity determined in this way indicates how much air is contained in the fabric, however, says nothing about its placement – the shape of pores, their size, distribution etc. It includes both types of pores – inter-yarn pores and intra-yarn pores.

Area filling base porosity P_S [-], which is calculated as [4, 6, 7, 10, 11]:

$$P_S = 1 - (D_O d_O + D_U d_U - D_O d_O D_U d_U) \quad (3)$$

where d_O, d_U [m] are the diameters of warp and weft yarn, respectively, and D_O, D_U [1/m] are setts of warp and weft yarns, respectively (see Figure 1).

The diameter of yarn can be determined by calculation or the experimental use of various methods. This model of porosity completely neglects the third dimension of the fabric and includes only inter-yarn pores.

As shown previously [6], 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. The value of the pore diameter is not well defined because pores do not have regular shapes. In a simple approach it is possible to assume that the diameter of a rectangular pore d_P [m] (see Figure 1) equals to an average of its width a [m] and length b [m]:

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

In an earlier paper [6] it was shown that the pore diameter d_P [m] calculated according to equation (4) can be considered as the characteristic dimension of the one inter-yarn pore of woven fabric. This parameter itself is well applicable to the prediction of the air permeability value in the case that fabrics are made from yarns of the same fineness, because there is a strong positive linear dependence between air permeability and the inter-yarn pore diameter value.

5 MATERIALS AND EXPERIMENT

In this research a set of 13 woven fabrics was used for the experiment. The yarns used were 100% polyester and were produced by the ring spinning technology. The fineness of yarns was 16.5, 25 or 40 tex. All fabrics were woven in a plain weave. A summary of some fabrics parameters is shown in Table 1.

Table 1 Parameters of used experimental fabrics

No.	D_O [1/m]	D_U [1/m]	$T_{O,U}$ [tex]	t [mm]	W_P [g/m^2]	P_S [-]	P_D [-]	d_P [mm]	AP [mm/s]	$RWVP$ [%]
P_1	2060	2020	25	0.326	108	0.288	0.760	0.263	1469	78.3
P_2	2820	2800	16.5	0.260	90	0.253	0.749	0.179	1680	83.0
P_3	1585	1510	40	0.415	132	0.279	0.770	0.342	1516	73.4
P_4	3060	2720	16.5	0.267	99	0.238	0.731	0.170	1252	82.8
P_5	2420	2160	25	0.334	119	0.230	0.741	0.211	1157	77.1
P_6	3040	3020	16.5	0.291	108	0.215	0.730	0.153	758.8	79.3
P_7	2420	2340	25	0.313	128	0.211	0.705	0.193	832.7	76.7
P_8	1940	1540	40	0.432	151	0.217	0.747	0.277	975.1	73.0
P_9	2560	2680	25	0.339	131	0.164	0.720	0.155	791.7	76.5
P_10	2060	1840	40	0.401	168	0.163	0.696	0.209	612.3	70.6
P_11	2880	2860	25	0.332	158	0.121	0.655	0.121	229.5	73.3
P_12	2020	2240	40	0.451	181	0.122	0.710	0.166	225.5	71.0
P_13	2260	2160	40	0.431	199	0.106	0.666	0.148	200.4	69.7

For each fabric D_O [1/m] and D_U [1/m] values were determined experimentally according to Standard EN 1049 – 2. The fabric thickness t [mm] was measured according to the Standard EN 5084 (1 kPa, 20 cm^2). The planar weight W_P [g/m^2] was measured according to the Standard EN 12 127. The air permeability AP [mm/s] was measured using a digital tester FX 3300 according to the standard EN 9237 (20 cm^2, 100 Pa). The relative water vapour permeability $RWVP$ [%] was measured with the use of apparatus PERMETEST (at 23.0±0.5°C), which is consistent with the Standard EN 11092. 10 measurements were always taken for each parameter, Table 1 shows average values.

The area filling based porosity P_S [-] according to equation (3), density based porosity P_D [-] according to equation (2) and diameter of one inter-yarn pore d_P [mm] according to equation (4) were calculated for each woven fabric. These values are also shown in Table 1. The values of yarn diameters $d_{O,U}$ [mm] were measured using USTER apparatus before weaving.

6 RESULTS AND DISCUSSION

The data were processed with the use of linear regression analysis (using software QC Expert). First, the correlation coefficients between the air permeability AP and selected parameters of woven fabrics structure and correlation coefficients between the relative water vapour permeability $RWVP$ and selected parameters of woven fabrics structure were determined. These results are shown in Table 2 (correlation coefficients in bold are significant at $p<0.05$).

Table 2 shows there is relatively high positive linear dependence (R=0.69) between $RWVP$ and AP. However, other correlation coefficients that are shown in Table 2 confirm differences in relations between the structure of the fabric and its permeability for air or for water vapour. A strong positive linear dependence is between air permeability and porosity of both the types – density based porosity P_D (R=0.87) and area filling based porosity P_S (R=0.95). In contrast to this, in the case of relative water vapour permeability these correlation coefficients are lower – R=0.50 for P_D and R=0.64 for P_S. And on the contrary, a strong negative linear dependence is between $RWVP$ and thickness of the fabric t (R=-0.92) and fineness of yarn $T_{O,U}$ (R=-0.91). In contrast to that, in the case of AP these correlation coefficients are low – R=-0.47 for t and R=-0.39 for $T_{O,U}$. A strong negative linear dependence is between AP and planar weight W_P (R=-0.82) and between $RWVP$ and W_P too (R=-0.95).

These results indicate that while the parameters of fabric that reveals information on the void spaces in the fabric are important for air permeability, the parameters indicating the filling of fabric by yarns are more significant for the water vapour permeability. It is a very interesting finding corresponding to the differences between the two phenomena described above. While in the case of passage of air through the fabric the assumption that the yarns are impermeable bodies and air flows predominantly through inter-yarn pores is accepted, in the case of water vapour permeability water vapour passes through the mass of yarns itself.

Table 2 Correlation coefficients between AP, $RWVP$ and selected structural parameters of woven fabrics

	AP [mm/s]	$RWVP$ [%]	$T_{O,U}$ [tex]	D_O [1/m]	D_U [1/m]	t [mm]	W_P [g/m^2]	P_D [-]	P_S [-]	d_P [mm]
AP [mm/s]	1	**0.69**	-0.39	-0.05	-0.15	-0.47	**-0.82**	**0.87**	**0.95**	**0.61**
$RWVP$ [%]	**0.69**	1	**-0.91**	**0.65**	**0.56**	**-0.92**	**-0.95**	0.50	**0.65**	-0.10

Very important information is also provided by spot diagrams shown in Figures 2 and 3. Figure 2 shows a comparison of the *AP* values and values of the pore diameter d_P. It is evident that the values can be divided into three groups: fabrics made with 16.5 tex, 25 tex and 45 tex yarns. Points in one group are spaced approximately along a straight line. This finding is consistent with the findings from the earlier paper [6] and shows that when the fabrics are woven from yarns of the same fineness, a strong linear dependence is between air permeability and the diameter of one inter-yarn pore (Figure 2 and Table 3).

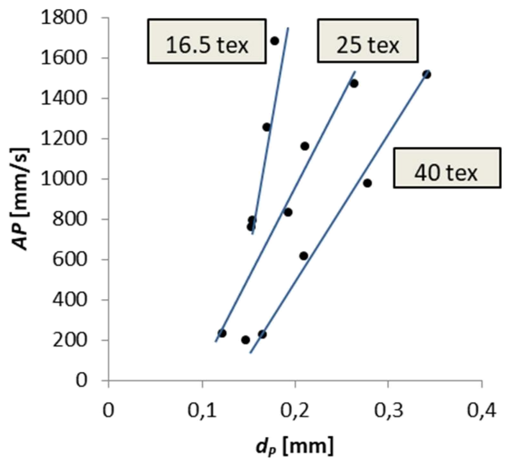

Figure 2 Relationship between *AP* and diameter of one inter-yarn pore d_P

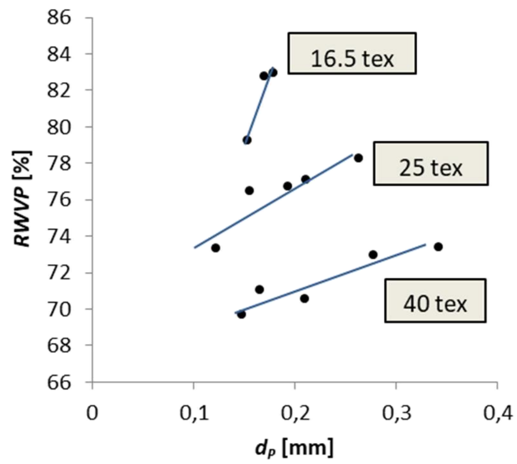

Figure 3 Relationship between *RWVP* and diameter of one inter-yarn pore d_P

Figure 3 shows a comparison of the *RWVP* values and values of the pore diameter d_P. It is evident that the values can be divided into three groups too: fabrics made with 16.5 tex, 25 tex and 45 tex yarns. This confirms the importance of yarn fineness value for the relative water vapour permeability. However, the value of d_P appears to be very well applicable to the prediction of *RWVP*, provided that the fabrics are made from yarns of the same fineness (Figure 3 and Table 3). In this case, a close linear relationship between *RWVP* and d_P is evident, as in the case of *AP*, but the slope and displacement of the individual lines on the y-axis are different. Table 3 shows the correlation coefficients between the air permeability and inter-yarn pore diameter values and between relative water vapour permeability and inter-yarn pore diameter values when evaluating individual groups of fabrics with different yarn fineness separately. The values of all these correlation coefficients are very high.

Table 3 Correlation coefficients between *AP*, *RWVP* and inter-yarn pore diameter values

	T=16.5 tex		*T*=25 tex		*T*=40 tex	
	AP	***RWVP***	***AP***	***RWVP***	***AP***	***RWVP***
d_P	0.99	0.96	0.96	0.90	0.99	0.94

Based on the findings described above the method of multivariate linear regression was used and model was tested in the shape:

$$y = a_1 * x_1 + a_2 * x_2 + a_0 \quad (5)$$

where air permeability *AP* [mm/s] was chosen as a dependent variable, and yarn fineness *T* [tex] and diameter of one inter-yarn pore d_P [mm] were chosen as independent variables.

Then, the predictive model in the form:

$$AP \approx -39.5 * T + 7517 * d_P + 543 \quad (6)$$

is suitable for prediction of the air permeability (R^2=0.86), see Figure 4. Similarly, the predictive model in the form:

$$RWVP \approx -0.46 * T + 23.5 * d_P + 84.5 \quad (7)$$

is suitable for prediction of the relative water vapour permeability (R^2=0.92), see Figure 5. The method of the least squares was used, all tests were performed at a significance level 0.05. Both models – (6) and (7) were identified as significant, all parameters in equations (6) and (7) were identified as significant.

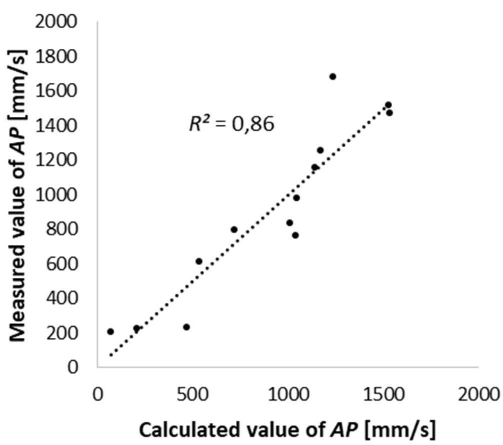

Figure 4 Relationship between calculated and experimental values of *AP*

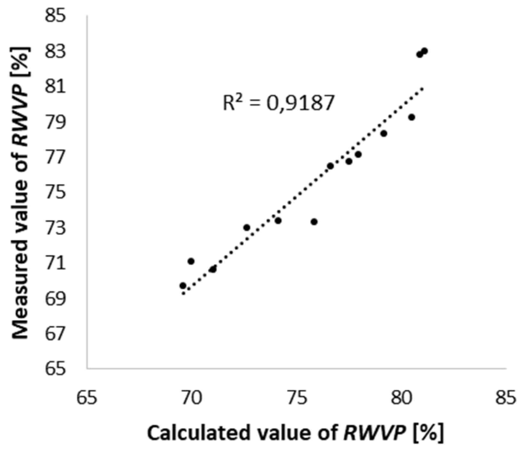

Figure 5 Relationship between calculated and experimental values of *RWVP*

7 CONCLUSIONS

The main aim of this paper was to demonstrate and discuss the relationship between fabric structure and its permeability for the air and for the water vapour using woven fabric made of polyester staple yarns. Some important differences between the two phenomena were discussed. Both phenomena – air permeability and water vapour permeability – are based on the porous nature of textile materials and, therefore, both closely related to their structure. However, apparently each of them in a different way. In the case of air permeability, the yarn is usually considered as an impermeable body and only the pores between yarns are considered as important. Then conclusions of many published works are quite consistent. Air permeability is very closely associated with inter-yarn porosity of textile materials, which can be determined by various methods. In the case of water vapour permeability significantly less publications aimed at studying the relationship between water vapour permeability and the structure of textile material are available, and their findings are not always consistent. It is obvious that an important role is played by the material of the fibres themselves. However, the role played by the inter-yarn pores and intra-yarn pores is still a matter of discussion.

In our research the set of 13 woven fabrics with plain weave was chosen for experiment. Fabrics were made of polyester staple yarns. For these fabrics the air permeability and relative water vapour permeability were measured as well as some other parameters of structure. Subsequently, the mutual relations were evaluated:

- Relatively high linear dependence was found between air permeability and relative water vapour permeability. The correlation coefficient was *R*=0.69.
- In the case of air permeability, the strongest linear dependence was demonstrated with planar weight of fabric (*R*=-0.82), with density based porosity (*R*=0.87) and with area filling based porosity (*R*=0.95). This indicates that the information about void spaces in the fabric is very important for air permeability. This conclusion is consistent with previous findings of other authors.
- In the case of water vapour permeability, the strongest linear dependence was demonstrated with planar weight of fabric (*R*=-0.95), with thickness of the fabric (*R*=-0.92) and with yarn fineness (*R*=-0.91). This indicates that the information about the filled spaces is very important for relative water vapour permeability.
- It was further demonstrated strong linear relationship between each of the properties – *AP* and *RWVP* – and the inter-yarn pore diameter values in the case when the yarns used are of the same fineness.
- Using the multivariate linear regression method enabled equations for prediction air permeability and relative water vapour permeability of fabric to be proposed based on the yarn fineness and inter-yarn pore diameter values.

In our experiment some important factors of the fabric structure were eliminated by using only fabric with plain weave and polyester fibres. It allowed showing the important aspects of relationships especially between relative water vapour permeability and the structural parameters of woven fabric such as yarn fineness, inter-yarn pore diameter and porosity.

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