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Investigation of Porosity and Air Permeability Values of Plain Knitted Fabrics

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Abstract
The air permeability of a fabric is defined as the amount of air passed over a surface under a certain pressure difference in a unit time. This value has significance with respect to the usage area. Since knitted fabrics have a loop structure, they have more pores than woven fabrics; therefore, in general, the air permeability of knitted fabrics is higher than that of woven fabrics of the same weight. An experiment to determine the air permeability is very important as it defines the properties of keeping warm, protection against the wind, breathability etc. of knitted fabrics used as clothing. In this study, it has been attempted to establish a theoretical model for the porosity and predicted air permeability of plain knitted fabrics. A theoretical model was created to predict the porosity and air permeability of a knitted structure depending on the geometrical parameters, such as the courses per cm, wales per cm, stitch length, fabric thickness, yarn count, diameter of yarn and fiber density. For this purpose, a theoretical model of porous systems based on D'Arcy's law was used, the validity of which was confirmed by experimental results using 100% cotton plain knitted fabrics produced from ring and compact yarns of different yarn number linear density and tightness.

Key words: *knitted structure, porosity, air permeability, geometric modelling.*

Designations used

A_1 - cross-sectional area of pore, cm^2
A_t - fabric area tested, cm^2
c - number of courses per centimeter
d_h - hydraulic diameter of a pore, cm
d_p - pore diameter, cm
d_y - yarn diameter, cm
f - friction coefficient
m - number of pores per square
n - coefficient indicating the flow regime
Q - total flow rate of the air, m^3/s
R - air permeability, mm/s
Re - Reynolds number
r_p - pore radius, cm
r_y - yarn radius, cm
t - fabric thickness, cm
U_m - mean air flow velocity, m/s
w - number of wales per centimeter
ρ - air density, kg/m^3
ρ_y - yarn density, g/cc
ε - rate of void area
v - kinematic viscosity of the air, m^2/s
η - dynamic viscosity of the air, Pa.s
ΔP - pressure drop, Pa
λ - coefficient of laminar and turbulent flow

Introduction

Knitting is the process of forming fabric by interloping yarn in a series of connected loops using needles. Knit fabrics provide outstanding comfort qualities and have long been preferred in many types of clothing. In addition to comfort imparted by the extensible looped structure, knits also provide lightweight warmth, wrinkle resistance, and ease of care [1].

Such knitted structures have a more open character when compared to other textile fabric structures, such as woven and braided [2].

Air permeability is often used in evaluating and comparing the 'breathability' of various fabrics (coated and uncoated) for such end uses as raincoats, tents and uniform shirtings. It helps evaluate the performance of parachutes sails, vacuum cleaners, air bags, sail cloth and industrial filter fabrics [3 - 6].

Air permeability is defined as the volume of air in liters which is passed through 100 cm^2 (10 cm × 10 cm) of the fabric in one minute at a pressure difference of 10 mm head of water [7].

Due to the manner in which yarns and fabrics are constructed, a large proportion of the total volume occupied by a fabric is usually airspace. The distribution of this airspace influences a number of important fabric properties such as warmth and protection against wind and rain in clothing, and the efficiency of filtration in industrial cloths.

Air permeability is an important factor in the comfort of a fabric as it plays a role in transporting moisture vapour from the skin to the outside atmosphere. The assumption is that vapour travels mainly through fabric spaces by diffusion in air from one side of the fabric to the other [8].

The porosity of a knitted structure will influence its physical properties, such as the bulk density, moisture absorbency, mass transfer and thermal conductivity [2].

Air flow through textiles is mainly affected by the pore characteristics of fabrics. It is quite clear that pore dimension and distribution is a function of fabric geometry. The yarn diameter, surface formation techniques and the number of loop counts per unit area are the main factors affecting the porosity of textiles. The porosity of a fabric is connected with certain of its important features, such as air permeability, water permeability, dyeing properties etc. [9, 10].

Most of the previous studies investigated the relationship between the air permeability and structural characteristics of plain knitted fabrics. For example, Oinuma (1990) showed that the stitch length, porosity and air permeability increase and the thermal retaining property decreases for dry relaxed cotton 1 × 1 rib knitted fabrics [11]. Marmarali (2003) investigated the air permeability of cotton/spandex single jersey fabrics within their dimensional and physical properties and compared results with fabrics knitted from cotton alone. It proved that the air permeability of fabrics containing spandex was lower [12]. Karaguzel (2004) calculated values of pore size and pore volume for plain knitted fabrics. Those of the pore size were measured with image analysis and fluid extrusion procedures. It was found that there was a noticeable difference between the estimated and measured values [8]. On the basis of computer image analysis, the surface porosity of knitted fabrics was evaluated for plain double-layered and lining knitted fabrics by Wilbik-Halgas et al. (2006). It was found that air permeability, contrary to water vapour permeability, is a function of the thickness and surface porosity of knitted fabrics [13]. Benltoufa et al. (2007) investigated methods of determining jersey porosity, which proved that geometry modelling is the most suitable and easiest method of determining poros-

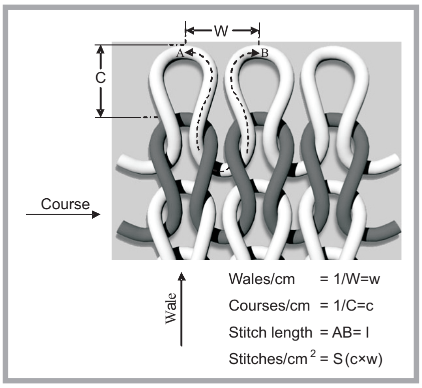

***Figure 1.** Representation of a plain knitted fabric.*

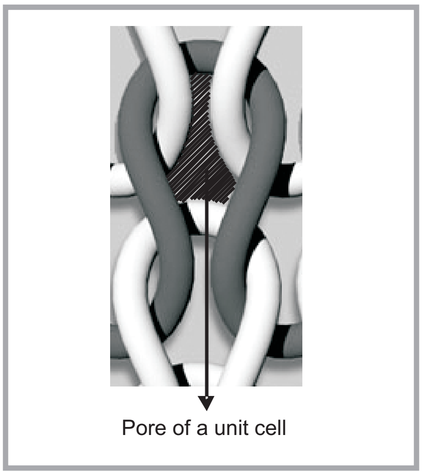

***Figure 2.** Stitch diagram of a plain knitted structure.*

ity [14]. The thermal properties and thermal behaviour of cellulose textile fabrics (air permeability, porosity) were investigated by Stankovic et al. (2008), in which they found that air permeability and heat transfer through fabrics is closely related to both the capillary structure and surface characteristics of yarns [15].

Dias and Delkumburewatte, (2008) created a theoretical model to predict the porosity of a knitted structure. It was determined that porosity depended on fabric parameters and relaxation progression [2].

Mavruz and Ogulata, (2009) investigated air permeability of cotton knitted fabrics. Before manufacturing the fabrics the equation of regression was used to predict air permeability, depending on some fabric properties [16].

Establishing a more complex theory to express air permeability related to all fabric parameters will have difficulties. To simplify the matter, certain important parameters such as the pore of the fabric were taken into account in the calculation of air permeability. Three factors are mainly considered that are related to the pores in fabrics.

1) Cross-sectional area of each pore,
2) Depth of each pore or the thickness of the fabric and
3) The number of pores per unit area or the number of courses and wales per unit area.

In this work, these parameters are considered to develop a theoretical model for porosity and air permeability.

Theoretical Model

A knitted fabric consists of one or more looped yarns. Plain knitted fabric, which is illustrated in ***Figure 1***, is one structure of knitted fabric. In this paper, we consider plain knitted fabrics which are commonly used in many apparel applications. *W* and *C* represent wale and course spacing, whereas *w* and *c* correspond to the number of wales per cm and number of courses per cm, respectively [17]. (Wales per cm: the number of visible loops per unit length in cm measured along a course. Courses per cm: the number of visible loops per unit length in cm measured along a wale. Stitch length: the length of yarn in a knitted loop).

When considering fluid flow through textiles, the shape arrangement and size distribution of voids through which the fluid flows are of great importance. The fabric thickness and differential pressure between the two surfaces of a fabric are the other dominant factors that affect permeability. The pressure gradient through a textile is a function of the viscosity, density, rate of fluid flow and porosity, as in the case of flow through a pipe [9].

The dependence of the friction coefficient, *f*, on the Reynolds Number, *Re*, for laminar and turbulent flow is described by the Blasius equation:

$$f = \lambda \cdot Re^{-n} \tag{1}$$

where λ is the coefficient of laminar or turbulent flow, and n is a coefficient indicating the flow regime.

Laminar flow: λ = 64, n = 1
Turbulent flow: λ = 0.3164, n = 0.25

The type of flow depends on the Reynolds number. The Reynolds number represents the ratio of the inertia force to the viscous force [4].

The Reynolds number is calculated as follows:

$$Re = \frac{U_m . d_h}{\nu} \tag{2}$$

where U_m is the mean flow velocity, d_h the hydraulic diameter of a pore, and ν is the kinematic viscosity of the air [4, 18].

The pressure drop of the flow through a duct over the thickness of the fabric is related to the friction factor *f* through D'Arcy's formulation.

$$\Delta P = f \frac{t}{d_h} \rho \frac{U_m^2}{2} \tag{3}$$

where t is the thickness of the fabric, and ρ is the air density [19].

Knitted fabric has a porous structure. For this reason, the air velocity in pores must be taken into consideration.

$$U = \frac{U_m}{\varepsilon} \tag{4}$$

where *U* is the air velocity through pores, and ε is rate of the void area (porosity) [4].

Figure 2 shows the pore within a loop. Our theoretical model was created by considering one repeating unit cell of a knitted structure. By determining the course (*c*) per cm, wale (*w*) per cm, thickness (*t*), yarn diameter (d_y) and loop length (*l*), the porosity can be shown as follows [14]:

$$\varepsilon = 1 - \frac{\text{Yarn volume}}{\text{Total volume}} \tag{5}$$

$$\text{Yarn volume} = \frac{\pi d_y^2 2l}{4} = \frac{\pi d_y^2 l}{2} \tag{6}$$

$$\text{Total volume} = \frac{1}{c}\frac{1}{w} t = \frac{t}{cw} \tag{7}$$

Finally,

$$\varepsilon = 1 - \frac{\pi d_y^2 lcw}{2t} \tag{8}$$

The air velocity through pores of the fabric does not usually have a high value. Therefore, the fluid flow in the pores is laminar. According to kinetic theory, if the Reynolds number is below 2320, the flow in the tube is laminar [4, 18]. For this reason, the mean air velocity through one pore can be expressed as:

$$U_m = \left(\frac{d_h^2}{32 \eta t} \right) \Delta P \tag{9}$$

The flow rate of air for a fabric of porous material, *Q*, becomes:

$$Q = m \cdot A_1 \cdot U \qquad (10)$$

where m is the number of pores, and A_1 is the cross-sectional area of the pore [4]

$$A_1 = \pi \frac{d_p^2}{4} \qquad (11)$$

where, d_p is the pore diameter (In this study, the loops are assumed to be composed of ideal yarns which are circular in cross-section and have a constant diameter throughout their length. Yarn deformation at the crossover points is omitted, hence it is accepted that $d_p = d_h$).

Thus, equation (10) can be written as follows:

$$Q = \frac{m}{\varepsilon} \pi \frac{d_p^4}{128\eta t} 10^{-6} \Delta P \text{ (m}^3\text{/s)} \qquad (12)$$

The value of air permeability (R) is calculated according to the following equation

$$R = \frac{Q}{A_t} \qquad (13)$$

where A_t is the fabric area tested [7].

d_p is calculated from ***Figure 3*** (yarn representation) and ***Figure 1***.

$$r_y = \sqrt{\frac{T}{\pi p_y 10^5}} \qquad (14)$$

$$\text{Volume of yarn in 1 cm}^2 = Sl\pi r_y^2 \qquad (15)$$

$$\text{Volume of free space } (cm^3) \text{ in } 1\ cm^2 \text{ of fabric} = 1 \times 1 \times t = t - Sl\pi r_y^2 \qquad (16)$$

$$\text{Area of free space } (cm^2) \text{ in } 1\ cm^2 \text{ of fabric} = \frac{t - Sl\pi r_y^2}{t} \qquad (17)$$

$$\text{Area of open space within one loop} = \frac{t - Sl\pi r_y^2}{tS} \qquad (18)$$

As mentioned beforehand, if the area occupied by a pore is transformed to that of a circle, the pore radius (r_p) can be written as equation 19 [8].

$$r_p = \sqrt{\frac{t - Sl\pi r_y^2}{\pi t S}} \qquad (19)$$

As indicated by equation 19, when the stitch density, stitch length or yarn diameter increases, pore size values decrease. The equations developed in this study will be used to predict the pore size and air permeability of plain knitted fabrics.

Materials and methods

In order to compare the values of air permeability from theoretical modelling and those from experiments of air permeability, we produced 18 (eighteen) knitted samples with various knitting parameters. The yarns were made of cotton fibers, and the bonding type of each sample was plain. Plain knitted fabrics were knitted with three different tightnesses (slack, medium and tight) on a circular knitting machine using ring and compact yarns of 19.72, 14.79 and 11.83 tex.

The knitted samples were conditioned for 48 hours in atmospheric conditions of 20 ± 2 °C temperature and 65 ± 2% relative humidity before the tests were performed. The air permeability of the samples in mm/s was measured according to the method specified by Standard TS 391 EN ISO 9237 [8], using a Textest FX 3300 air permeability tester. The measurements were performed at a constant pressure drop of 100 Pa (20 cm^2 test area). For each one of the 18 fabric types, we repeated this measurement for ten (10) samples, thus obtaining a body of (18 × 10 =) 180 measurements. Furthermore, the loop length, wales per cm, courses per cm, thickness and weight of the fabrics were measured according to the relevant standards [20 - 23].

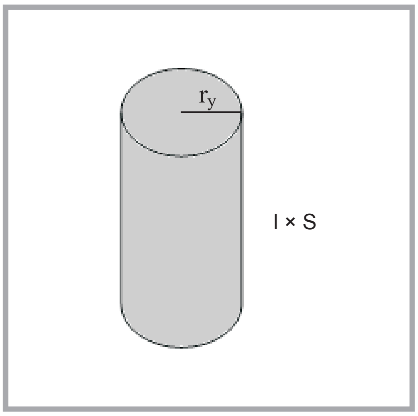

Figure 3. *Representation of yarn in 1 cm^2 of fabric; r_y - yarn radius, r_p - pore radius, ρ_y - yarn density (Pierce used a value of 0.909 g/cc for cotton yarn), T - yarn linear density in tex.*

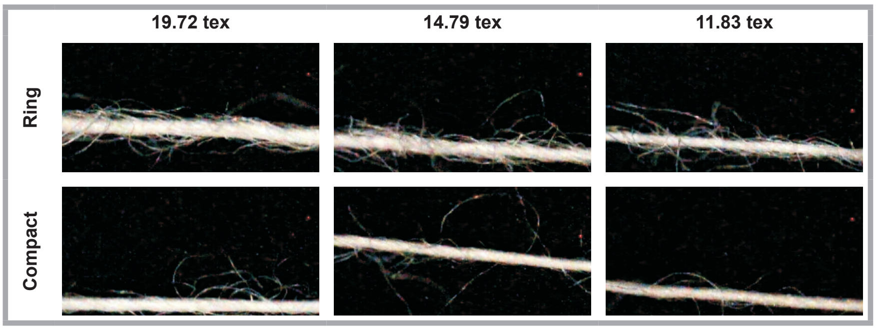

Figure 4. *Microscopic views of the yarns.*

Table 1. *Fabric properties and experimental air permeability values.*

Sample number	Yarn type R: Ring C: Compact	Yarn number, tex	Loop length, cm	Course count per cm	Wale count per cm	Thickness, cm	Weight, g/m^2	Experimental air permeability, mm/s
1	R	19.72	0.255	23.0	12.3	0.0069	161.38	1193
2	R	19.72	0.285	18.0	12.3	0.0057	136.78	1562
3	R	19.72	0.320	16.0	12.1	0.0068	136.90	1562
4	C	19.72	0.260	24.0	13.0	0.0060	159.48	1532
5	C	19.72	0.286	19.0	13.0	0.0058	143.72	1647
6	C	19.72	0.330	15.0	13.0	0.0062	134.22	1948
7	R	14.79	0.256	24.0	12.2	0.0063	120.88	2020
8	R	14.79	0.284	19.0	12.0	0.0059	105.72	2077
9	R	14.79	0.320	15.0	12.0	0.0052	87.22	3059
10	C	14.79	0.261	24.0	13.0	0.0059	126.10	2459
11	C	14.79	0.280	18.0	13.0	0.0060	118.24	2966
12	C	14.79	0.250	15.0	13.0	0.0065	107.16	3708
13	R	11.83	0.250	23.0	13.0	0.0053	86.98	2938
14	R	11.83	0.280	18.0	14.0	0.0053	75.86	3502
15	R	11.83	0.320	16.0	12.0	0.0061	76.62	3680
16	C	11.83	0.251	24.0	13.0	0.0052	98.30	3128
17	C	11.83	0.290	18.0	13.0	0.0056	89.58	3306
18	C	11.83	0.330	15.0	12.0	0.0060	76.82	4616

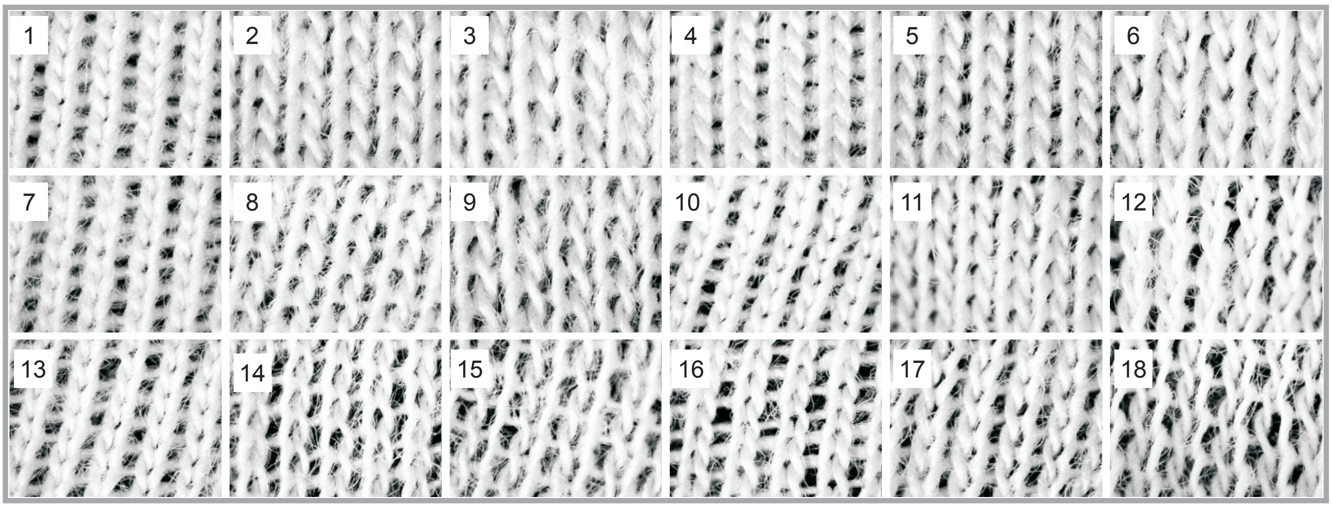

Figure 5. *Microscopic views of the knitted structure.*

Results and discussion

Fabric properties (yarn number, loop length, course count per cm, wale count per cm, thickness, weight) and the (experimental) air permeability values measured are presented in ***Table 1***.

It can be seen that the fabrics differed in terms of the yarn linear densities, yarn type, courses per cm and loop length. The thickness of the fabrics varied with the loop length and course count. Since the wale count per cm usually depends on the machine settings, a constant range from 12 - 13 should be maintained.

According to ***Table 1***, the fabric with the lowest course count per cm and yarn number in tex has the highest air permeability values. Therefore, the rising loop length resulted in a looser surface on the fabric, thereby increasing the air permeability.

In order to predict air permeability values for the knitted fabrics, the following were used: values of the porosity, the radius of pores and yarns, and the flow rate calculated using the newly developed equations expressed in the theoretical model.

Moreover, we observed microscopic views of the yarns and pores in the knitted fabrics from pictures taken using an image analysis device (***Figure 4*** and ***5***). Sample numbers were marked on the pictures in ***Figure 5***.

In ***Figure 4*** it can be seen that as the yarn count decreased, yarn hairiness values fell in general. Furthermore, microscopic views revealed that the surface of knitted samples produced from thin yarns (both ring and compact yarns) is highly non-uniform with deformations (especially in loose fabrics) because of the bigger pore dimensions (***Figure 5***). As is widely known, the compact spinning method forms a different yarn structure. The most evident properties of these yarns are their high breaking strength, high elongation and low hairiness. Moreover, other yarn properties such as yarn unevenness, thin/thick places etc. are comparable to those of conventional ring yarn. As the surface of compact yarns is smoother and less hairy, fabrics produced from such yarns cannot block air, thus indicating high air permeability. However, the difference between compact and conventional ring yarns is not too great.

In order to simplify the theoretical calculations, loops are assumed to be composed of ideal yarns but with great variability in pore size distribution. Thus samples produced with 14.79 and 11.83 tex yarns have pore dimensions which are highly variable across the fabric. It is difficult to estimate the porosity of fabrics by calculating the pore dimensions and yarn diameter. As is known, yarns in the structure of the fabric do not have a smooth surface nor a solid construction. There is also a lot of emptiness in the yarns. Consequently, in order to obtain closer results, the value of the pore diameter of knitted fabrics produced from 14.79 and 11.83 tex yarns was increased by 15%, and these new values were used for calculations.

Comparing the theoretical model method (Equation 13) and that using experimental air permeability values, we obtained the result shown in ***Figure 6*** (see page 109).

The match is close, which is also indicated by the high values of correlation coefficient, R^2, obtained from the statistical analysis. ***Figure 7*** shows correlation plots between the predicted and measured values (x axis-measured values, y axis-predicted values).

The values in ***Figure 7*** indicate that the correlation for fabrics produced from 19.72 tex yarn is superior to that for fab-

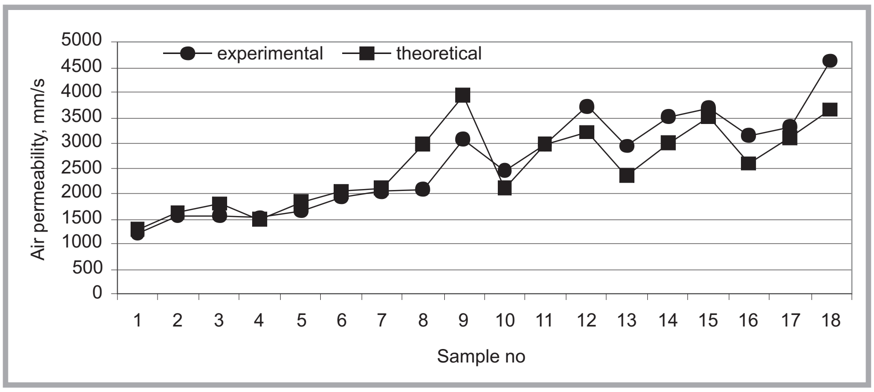

Figure 6. *Air permeability values according to the experimental and theoretical models.*

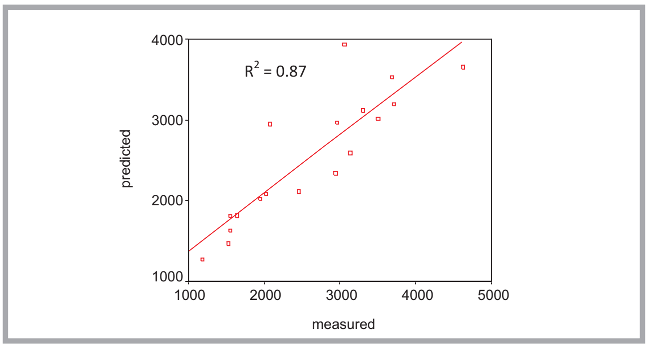

Figure 7. *Correlation plots for predicted and measured values.*

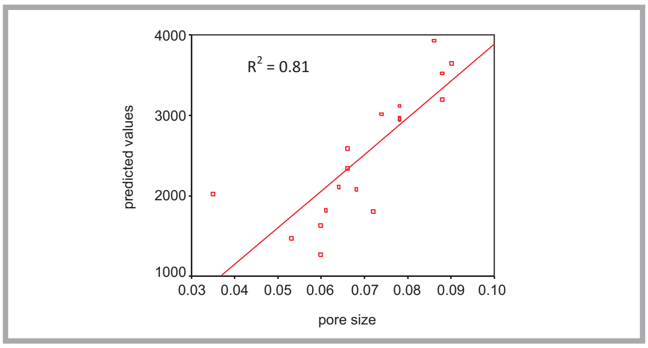

Figure 8. *Relationship between predicted air permeability values and pore size.*

rics produced from 14.83 and 11.92 tex yarns. Air permeability in knitted fabrics is related to pore size. As discussed earlier, variability in pore size affects permeability values.

Moreover, as demonstrated in ***Figure 8***, there is a near positive linear relationship between pore size and predicted air permeability values. Thus, the higher the pore sizes, the higher the air permeability.

Conclusion

An experimental study was carried out to develop a theoretical model to predict air permeability values for knitted fabrics. The theoretical model predicts the value of the air permeability using the pore size and some fabric properties before manufacturing.

D'Arcy's formulation was used to establish an equation expressing the relationship between the air permeability of knitted fabrics and fabric structure parameters.

According to the experimental results, the fabric with the lowest course count per cm and yarn number in tex has the highest air permeability values. Moreover, increasing the loop length produced a looser surface in the fabric and increased air permeability. As the yarn gets thinner and the pores between loops get larger, the air permeability will increase accordingly. According to some formulations, when the stitch density, stitch length or yarn diameter increase, pore size values decreases.

Due to the differences between ideal and real geometry and the random variation of the fabric structure, there are no exact dependences between experimental air permeability and predicted air permeability values. However, the closeness of the results of predictions based on calculated values from the theoretical model and experimental values show that our model can be successfully used for the prediction of the air permeability of knitted fabrics ($R^2 = 0.87$). This model is simple and efficient.

Permeability and porosity are strongly related to each other. If a fabric has very high porosity, it can be assumed that it is permeable. It was also found that there is a near positive linear relationship between pore size and air permeability values ($R^2 = 0.81$), hence tt could be assumed that the model developed is applicable for predicting the air permeability of plain knitted fabrics produced with different fiber types.

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