Indian Journal of Fibre & Textile Research
Vol 45, March 2020, pp. 32-39

Evaluation of air permeability behaviour of warp knitted spacer fabrics

T Palani Rajan[1] & Subrata Das[2,a]

[1]VIT Fashion Institute of Technology, VIT University Chennai, Chennai 600 127, India

[2] Department of Fashion Technology, Bannari Amman Institute of Technology, Sathyamangalam 638 401, India

Received 22 December 2017; revised received and accepted 17 April 2018

The porosity and air permeability of 3D polyester warp knitted spacer fabric has been determined by optimizing the structural parameters and using Box and Behnken experimental design. Spacer fabrics are developed by using polyester multifilament of 80 - 120 denier on the face layer and 30 - 70 denier on the bottom layer. Polyester monofilaments of 20 - 40 denier are used in the middle layer, deciding the third dimension of the fabric. Porosity and air permeability are estimated with respect to the linear density of polyester filaments, and response the surface design is used to predict the optimum linear density. Better air permeability and porosity are observed at the face layer denier of 100 and middle layer denier of 20. The statistical analysis proves that the degree of correlation of F values is 12.44 between the filament linear density and air permeability.

Keywords: Air permeability, Polyester fabric, Porosity, Response surface method, Warp knitted spacer fabric

1 Introduction

Cushioning and comfort are the main aspects of clothing comfort, among which cushioning is a crucial property to the user while seating, walking and sleeping and for impact resistance[1]. For better cushioning, the appropriate material has to be selected with bulkiness and lightweight.

Polyurethane (PU) foam, pile or fleece fabrics and layered fabrics might give cushioning effect, but these are having some undesirable issues concerning comfort and reuse. These textile materials are having necessary bulkiness but, have few undesirable properties like more weight, poor permeability and permanent surface deformation. It is essential to achieve both cushioning and comfort by appropriate selection of fabrics with compression and resilience, besides good air and moisture permeability and thermal conductivity[2]. The permeability character of the fabric directly influences the movement of air, moisture and thermal energy through the fabric[3]. Fabric permeability depends upon the geometrical properties, raw material, thickness and porosity[4]. Porosity is directly connected with certain significant aspects of fabrics such as air permeability, water vapor permeability, and water & dye holding properties[5]. The pore size in the fabric determines the porosity percentage[6]. The number of yarns per unit area, yarn linear density, fabric structure, weight and thickness are the other fabric features that affect the air permeability and porosity. The correlation between porosity and air permeability of different fabrics was investigated and theoretical models were developed[7]. Further, through the analysis on the effect of filament fineness on air permeability of polyester fabrics, it is observed that the air permeability can be reduced by the coarser filament[8-10].

To accomplish a better permeability with good porosity, it is essential to develop a suitable fabric applicable for different apparel and technical applications. Three dimensional spacer fabric is one of the unrivaled fabrics having high porosity and permeability with respect to its fabric characteristics[11,12]. The perfect porous construction of the spacer fabric results in exceptional moisture and thermal comfort properties with greater permeability and conductivity[13]. These properties are customarily connected to the yarn linear density, aerial density, surface structure and thickness of the spacer fabric.

Spacer fabrics are of 3D constructions, having two surface layers and one center connecting layer producing extensive spaces. Among the fabric manufacturing systems, warp knitting is the utmost regularly used technology for engineering warp knitted spacer fabric[14,15]. Most commonly used material in spacer fabric is polyester multifilament

[a]Corresponding author.
E-mail: subratactl@gmail.com

in outer surface layers and monofilaments in middle layer. To preserve the space between the two surface layers and to acquire appropriate cushioning properties, monofilaments are generally used as a connecting spacer yarns to give appropriate fabric thickness. The monofilament has a substantial effect and yields remarkable effect on the compression and resilience performance of the spacer fabrics[16,17]. The face surface layers of the spacer fabric can be plain or open mesh structure but most of the spacer fabric structure has open mesh structure[18,19].

Palani *et al.*[20] established that the long loops in open mesh hexagonal net structure with an optimum thickness of 3 mm show reputable porosity with superior air and water vapour permeability than the Locknit and Rhombic mesh structures. In spacer fabrics, even though polyester multifilament is used as raw material and open mesh structure is used as face layer structure, it is essential to optimize the linear density of polyester filament with respect to fabric properties. This study investigates the influence of polyester filament linear density on air permeability with respect to porosity.

2 Materials and Methods

2.1 Materials

Different linear densities of polyester multifilament and monofilament for the two surface layers and middle layer respectively were selected for the manufacturing of warp knitted spacer fabric (WKSF). Polyester multifilament was used on face and bottom layers and monofilament was used in the middle layer. The range of deniers was selected from courser to finer, aimed to assess the impact of filament linear density on permeability of spacer fabrics. The space between the two outer surface layers was maintained at around 3mm through the middle layer. The details of the polyester filaments are given in Table 1.

2.2 Methods

Karl Mayer RD 6 model Raschel double needle bed warp knitting machine was used to produce spacer fabric samples with 170 inches width and machine gauge of 22 E. The machine was equipped with 3 pairs of ground guide bars; front and back pair forms stitches on the face and bottom layers of fabrics. The middle pair connects the face and bottom layers and forms the spacer fabric with a defined thickness. The thickness of the WKSF can be adjusted by changing the face and back needle bar distance. Different structures can be used on each needle bar, for example fabric developed with hexagonal net structure at face layer and locknit at bottom layer. The structure of the WKSF surfaces and stitch notations are given in Fig. 1.

The thickness of the WKSF was measured at 50 Pa pressure over KES-F evaluation system when estimating the compression of spacer fabric samples. Areal density was measured using weighing balance (ASTM D 3776 - 07) and the fabric bulk density was calculated based on the fabric thickness and areal density. The researchers[21,22] made an attempt to test the porosity of different fabrics and attained a theoretical model as well as standard equation for the fabric porosity. Fabric porosity was estimated by using the following formula can be stated either as a fraction or as a percentage:

$$\text{Porosity (\%)} = 1 - [\text{Fabric density (g/m}^3) / \text{Filament density (g/m}^3)] \times 100 \quad \text{... (1)}$$

The air permeability of all the WKSF was tested according to BIS IS 11056:1984 (R1999) at 10 cm water head and 3% accuracy of full scale range with test area of 4 cm^2.

2.3 Design of Experiment

Box and Behnken design of experiment was used to develop the samples and this design is an effective tool to study the effect of variables on the response and its optimization[23-25].

A sequence of experiments was conducted based on three-factorial Box and Behnken design to find out the effects of different combinations of face, middle and bottom layer polyester filament denier. The effect of face, middle and bottom layer denier was quantitatively evaluated using response surface method (RSM). The details of the layer and filament denier are shown in Table 2.

Table 1 — Polyester yarn particulars

Yarn particular	Polyester								
	Multifilament						Monofilament		
Filament linear density, den	30	50	70	80	100	120	20	30	40
Number of filaments	24	24	24	36	36	36	1	1	1
Diameter, mm	0.041	0.061	0.069	0.088	0.113	0.128	0.033	0.048	0.054

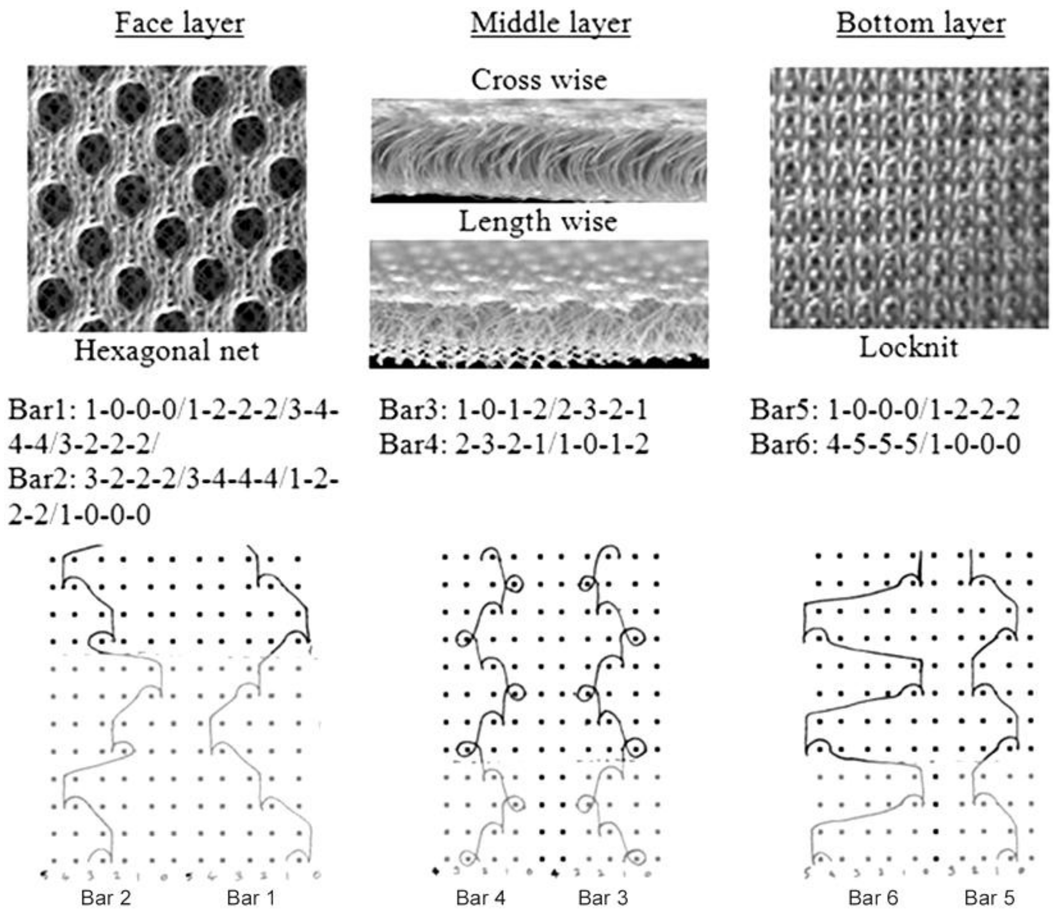

Fig. 1 —- Polyester warp knitted spacer fabric

Table 2 — Design of WKSF using Box and Behnken model

Factor	Minimum	Maximum	Mean	Std. dev.
A - Face layer	80	120	100	15.12
B - Middle layer	20	40	30	7.56
C - Bottom layer	30	70	50	15.12

Analysis of variance (ANOVA) and response surface method (RSM) were used for the optimization of porosity and air permeability. A second-order polynomial equation was developed to analyze the experimental data and to finalize the suitable model based on the following responses:

$$Y = \beta_0 + \beta_i\ A + \beta_i\ B + \beta_i\ C + \beta_{ii}\ A^2 + \beta_{ii}\ B^2 + \beta_{ii}\ C^2 + \beta_{ij}\ AB + \beta_{ij}\ AC + \beta_{ij}\ BC \qquad \text{... (2)}$$

where Y is the predicted response (porosity and air permeability); β_0 the constant coefficient; β_i the ith linear coefficient of the input factor; β_{ii} the ith quadratic coefficient of the input factor; β_{ij} the different interaction coefficients between input factors and variables coded as A (face layer denier), B (middle layer denier) and C (bottom layer denier). The fitness of the model was established based on the coefficient of determination (R^2), and the F-tests were used to investigate the statistical significance of the executed models.

3 Results and Discussion

Design-expert software version 10 has been used to develop the response surface plots from the regression models for optimizing the polyester filament denier on each layer of WKSF that influence the porosity and air permeability. To investigate the effect of variables on the response, one variable was kept constant as a center point and the other two parameters were varied within a limit.

The second order polynomial was fitted from the data and the porosity and air permeability were estimated using multiple linear regressions. The predicted level of porosity and air permeability calculated using the following equations are given in Table 3:

$$\text{Porosity} = 88.41 - 1.75\ A - 0.828\ B - 0.373\ C - 1.82\ AB + 0.1AC - 0.318\ BC - 3.011\ A^2 + 0.170\ B^2 + 0.457\ C^2 \qquad \text{… (3)}$$

Table 3 — Actual and predicted values of porosity and air permeability

Runs	Polyester filament, denier			Fabric thickness mm	Fabric weight g/m^2	Porosity, %		Air permeability cc/s/cm^2	
	Face layer	Middle layer	Bottom layer			Actual value	Predicted value	Actual value	Predicted value
1	80	30	30	3	253.4	88.48	88.08	167.1	166.5
2	100	30	50	2.9	277.3	88.41	88.41	172.3	170.2
3	120	40	50	3.1	292.5	81.63	81.17	147.6	144.8
4	120	20	50	3	276.1	86.01	86.47	166.7	167.3
5	100	30	50	2.9	277.3	88.41	88.41	169.2	170.2
6	80	30	70	3.1	257.6	86.74	87.13	157.9	156.3
7	100	30	50	2.9	277.3	88.41	88.41	169.2	170.2
8	100	40	30	2.9	286.1	88.04	88.9	163.8	164.9
9	120	30	70	2.8	286.7	83.43	83.83	154.5	155.1
10	80	40	50	3.1	264.2	88.77	88.31	161.9	161.4
11	120	30	30	2.9	281.8	84.78	84.38	154.5	156.1
12	100	20	70	2.8	273.4	90.67	89.81	172.3	171.5
13	80	20	50	2.9	248.9	85.87	86.33	159.5	162.3
14	100	20	30	3	271.5	89.98	89.92	177.4	175.2
15	100	40	70	3.1	294.6	87.46	87.52	155.7	157.9

$$\text{Air permeability} = 170.23 - 2.89\,A - 5.86\,B - 2.8\,C - 5.36\,AB + 2.3\,AC - 0.75\,BC - 10.05\,A^2 - 1.24\,B^2 - 1.68\,C^2 \quad \ldots (4)$$

The ANOVA values clearly indicate that the regression model based on Eqs (3) and (4) are significant ($F_{crit} > F_{actual}$) with actual F values of 6.363. The model $F_{(2,\ 14)}$ values porosity (15.162) and air permeability (12.44) imply that the model is significant with a probability of 95%. In Table 4, values of “p" (< 0.05) specify that the model terms are significant and the P -value larger than 0.10 shows that the model terms are not significant. In this correlation, A, B, AB and A^2 are significant model terms for both porosity and air permeability. The term AB evidently points out that there is sufficient interaction among the face layer denier as well as middle layer denier with both responses. Factor C has a moderate impact on air permeability rather than on porosity.

In Table 5, the R^2 of the quadratic model is 0.965 for porosity and 0.957 for air permeability and there are fewer chances for changes in the model. These specified model equations have an effectively significant connection between the variables in deliberation. The CV % shows the degree of precision on responses, and the low values of CV % suggest a high consistency of the experiment. Adequate precision measures the signal to noise ratio and a ratio greater than 4 is desirable. The ratio of 13.951 and 12.993 indicates an adequate signal and this model may be used to navigate the design of responses.

Table 4 — ANOVA for quadratic model of porosity and air permeability

Factor	F value		p-value	
	Porosity %	Air permeability cc/s/cm^2	Porosity %	Air permeability cc/s/cm^2
Model	15.162	12.44	0.004	0.01
A	41.528	8.12	0.001	0.04
B	9.290	33.46	0.029	0.00
C	1.889	7.63	0.228	0.04
AB	22.456	14.06	0.005	0.01
AC	0.067	2.57	0.806	0.17
BC	0.688	0.27	0.445	0.62
A^2	56.767	45.42	0.001	0.00
B^2	0.180	0.71	0.689	0.44
C^2	1.309	1.27	0.304	0.31

Table 5 — Statistical information of porosity and air permeability

Parameter	Porosity %	Air permeability cc/s/cm^2
R-squared	0.965	0.957
Adjusted R-squared	0.901	0.881
Adequate Precision	13.951	12.993
Standard deviation	0.768	2.867
Coefficient of variation, %	0.881	1.755

3.1 Optimization of Porosity

Porosity optimisation results by Palani *et al.*[26] state that the denier of face layer polyester WKSF is the primary cause for higher porosity. The range between 92 den and 96 den multifilament on face layer with other two layers has been observed by means of RSM and the same is found to have high points of porosity. The RSM plots help to optimise the polyester monofilament denier for the middle layer as 21 and multifilament denier at bottom layer as 33. Further, the face layer denier is significant in two aspects for porosity identification. The productive connection between denier and porosity of the face layer is highlighted as the first presumption. However, small diameter and fine denier of polyester multifilament (80) on face layer occupy more area, resulting in modest porosity. While the heavy and coarser denier (120) produces bulkiness and occupies more surfaces in the spacer fabric, thus confirms low porosity. This can be supported by RSM plots and the optimum porosity attained is between 92 den and 96 den on the face layer. During interaction of the face layer with other two layers, middle layer facilitates better result than the bottom layer. The finer monofilament (20) in middle layer stands like thin rod and connects the face and bottom layer of WKSF. It provides additional space to allow more air to pass through than in fabrics of other deniers (30 - 40). The change in denier of the bottom layer does not show much influence on the porosity.

The second postulation deals with the fabric structure and the loops per unit area. The face layer structure of WKSF is kept as an open skin hexagonal net structure, which obviously produces high porosity. In addition to that, the number of stitch loops in a defined area of hexagonal net structure influences the bigger pore size and porosity.

3.2 Optimization of Air Permeability

The RSM and contour plots have been developed to study the effect of linear density of polyester mono and multifilament of spacer fabric layers on air permeability. Among the variables, one variable is kept constant and other two are changed within their range.

The effect of polyester denier of the face and middle layers on air permeability of spacer fabric is shown in Fig. 2, keeping the bottom layer denier value constant at 50. A gradual increase in the filament denier of the face layer accompanied by an increase in the filament denier of the middle layers has resulted in higher air permeability value of 173.6. Specifically, face and middle layers having filament denier values of 102 and 23 respectively provide optimum air permeability. Both layers influence the air permeability values to increase by increasing denier, to attain the maximum point and then to start descending. Finer denier occupies more filaments and coarser deniers accommodate more spaces in a defined area; both conceal more space and restrict the air movement. The RSM clearly indicates that the combination of 40 and 120 deniers on the face and middle layers respectively show low air permeability.

Figure 3 shows the impact of the linear density of face and bottom layers on air permeability of WKSF. The most favorable level of air permeability (171) is achieved with the denier of 98 at face layer and denier of 44 at the bottom layer. It is interesting to note that the increase in the linear density of polyester filament of spacer fabric layers leads to an initial increase in the air permeability and a decrease thereafter. The 30 denier polyester was kept as constant on the middle layer of WKSF.

The impact of middle and bottom layers on air permeability of WKSF samples is shown in Fig. 4;

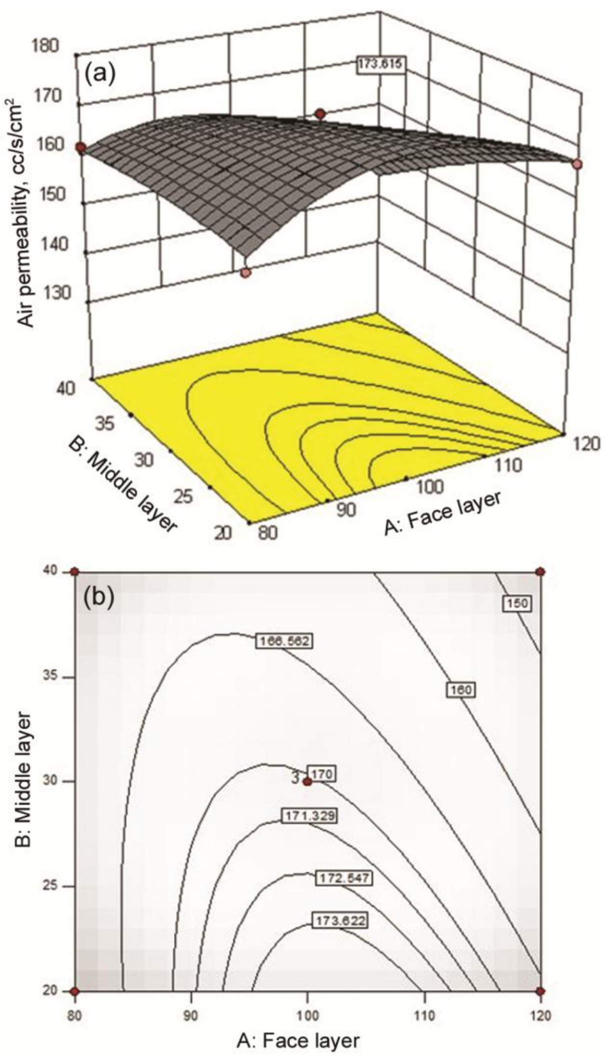

Fig. 2 — Contour and RSM of WKSF face layer and middle layer polyester filament denier on air permeability

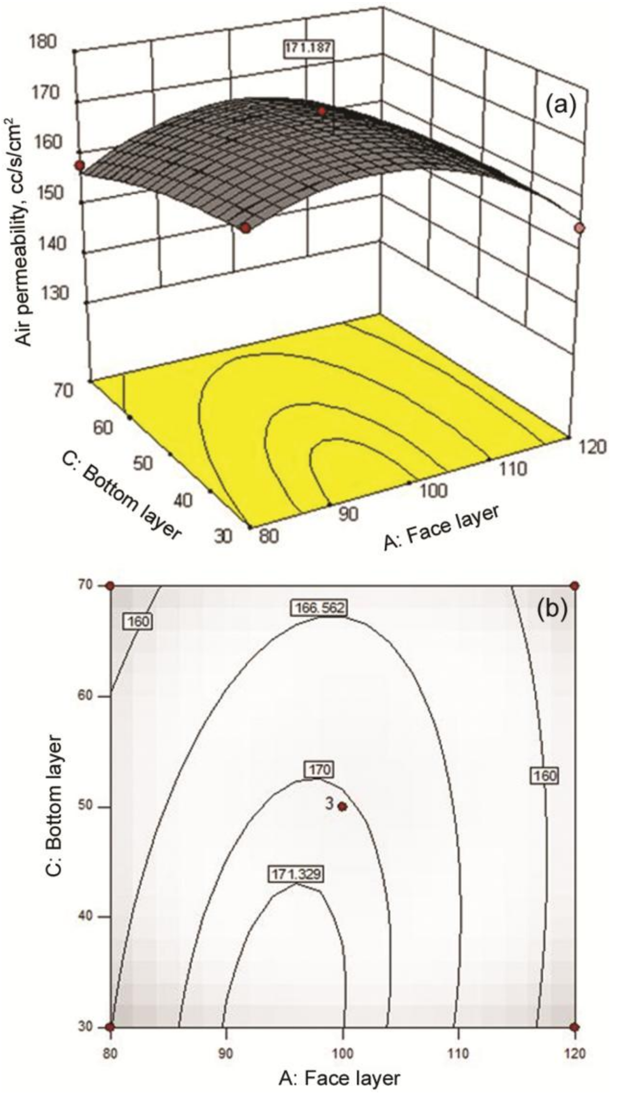

Fig. 3 — Contour and RSM plot of WKSF face layer and bottom layer polyester filament denier on air permeability

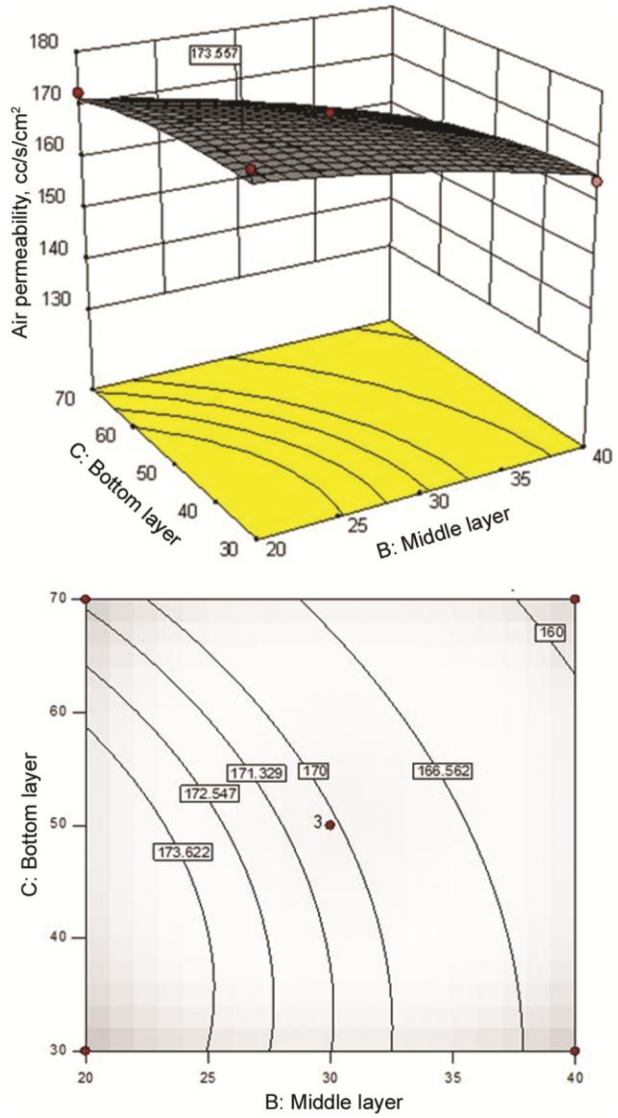

Fig. 4 — Contour and RSM plot of WKSF middle layer and bottom layer polyester filament denier on air permeability

face layer denier maintained at 100. The highest air permeability of 174 is found with the combination of middle and bottom layers denier at of 24 and 47 respectively. It is apparent from the RSM plots that the interaction between bottom layer with other two layers is not up to appreciable level and it is already confirmed in the ANOVA Table 4.

The RSM plots confirm that the yarn linear density is one of the factors affecting the porosity and air permeability of WKSF. The optimum air permeability is estimated from the model Eq. (4) and the peak values of air permeability recorded with the fabric combination of face, middle and bottom layers constructed with filament denier values of 98-102, 23-24 and 44-47 respectively. Even though all the three layers contribute to the air permeability and porosity, it is observed from ANOVA and RSM plots that the face layer of WKSF is the primary cause for changes in air permeability. Face layer is having the positive relationship with other two layers. There is a definite relationship identified between the denier of polyester filament yarns and the pore size of the face layer. Consequently, once the air gets penetrated through the face layer it will pass through the other layers. On considering the constraints of middle and bottom layers, the middle layer seems to play a vital role. The diameter of spacer yarn and the density of yarn occupied in the middle layer comprehensively influence the permeability characteristics of WKSF. The coarser filament denier occupies more space and

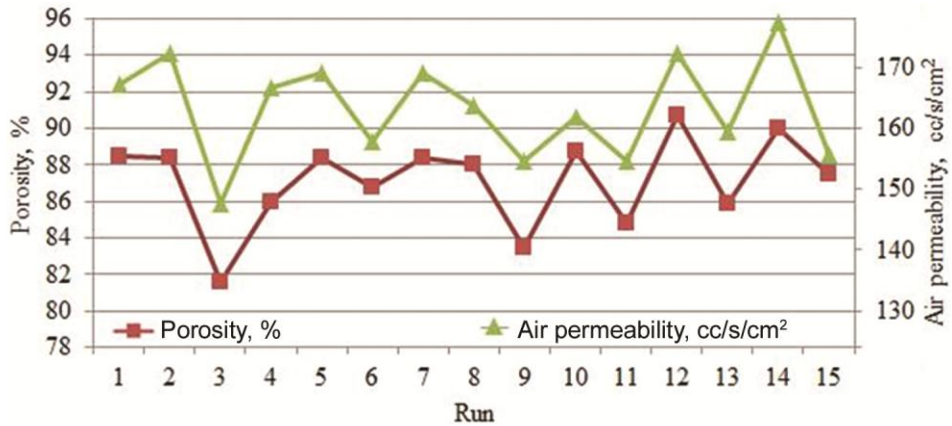

Fig. 5 — Relationship between air permeability and porosity

reduces the porosity and consecutively the air permeability. The finer filament denier of 23 in the middle layer has created more space among the loops and has allowed the air to escape freely than in the middle layer constructed with coarser filaments. In bottom layer, denier of polyester does not have significant influence on permeability with the combination of other two layers and this permits the air from face layer to pass through it.

3.3 Effect of Fabric Porosity and Air Permeability

Porosity and air permeability of WKSF have been found to be strongly inter-connected. The airflow through the fabric is mainly enhanced by the pore size and pore characteristics. An open skin hexagonal net structure constructed with larger pore size will exhibit higher porosity and contribute to good permeability.

Figure 5 shows the relationship between air permeability and porosity of the experimental values. The diameter of the filament, the spacing between the layers and pore shape are the parameters that decide the relationship between porosity and air permeability. The higher and lower values of air permeability are directly correlated with corresponding porosity values of WKSF. In addition to hexagonal net structure on face layer, the contribution of middle and bottom layers on permeability are also found significant. The degree of void within the fabrics created by middle layer supplements the air permeability.

4 Conclusion

The experimental results indicate that the porosity of WKSF has a very strong correlation with air permeability and increase in porosity results in increase in air permeability. The face and middle layer show excellent influence on porosity and air permeability. Both the layers independently and reciprocally contribute to the significant impact on air permeability. The finer filament denier of the middle layer has resulted in enough space to escape the air freely through it. The effects of bottom layer deniers on the responses are quite uncertain because of low interaction with face and middle layers, and locknit structure at bottom layer could be the reason. RSM plots have been assessed and the test results clearly indicate that the deniers ranging 92 - 102 on face layer and 21 - 24 on middle layer exhibit optimum result. In bottom layer denier, two stages of optimum outcome are produced i.e. around 33 and 47 deniers for porosity and air permeability respectively. From the observations, the optimum values of 100 denier of polyester multifilament on face layer, 20 denier polyester mono filament on the middle layer and either 30 or 50 denier on the bottom layer are found with optimal porosity and air permeability values. The result of this investigation will certainly have an impact on the manufacturing of textile goods such as car seat covers, shoe insoles and inner jackets where the cushioning, permeability to air & moisture and thermal characteristics are linked directly to porosity.

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