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Predicting the Air Permeability of Polyester/Cotton Blended Woven Fabrics

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Abstract: The aim of this study was to model the air permeability of polyester cotton blended woven fabrics. Fabrics of varying construction parameters i.e. yarn linear densities and thread densities were selected and tested for air permeability, fabric areal density and fabric thickness. A total of 135 different fabric constructions were tested among which 117 were allocated for development of prediction model while the remaining were utilized for its validation. Four variables were selected as input parameters on basis of statistical analysis i.e. warp yarn linear density, weft yarn linear density, ends per 25 mm and picks per 25 mm. Response surface regression was applied on the collected data set in order to develop the prediction model of the selected variables. The model showed satisfactory predictability when applied on unseen data and yielded an absolute average error of 5.1 %. The developed model can be effectively used for prediction of air permeability of the woven fabrics.

Keywords: Air permeability, Modeling, Response surface regression, Cover factor, Woven fabric

Introduction

The role of clothing is very important for effective thermoregulation process in human beings. The comfort of human body is related to the type of clothes used and their compatibility with external weather conditions. Comfort can be defined as “a pleasant state of psychological, physiological and physical harmony between a human being and the environment” [1]. The clothes used in higher temperature conditions must be able to provide reasonable evaporation to the sweat which is possible by circulation of air between the clothing layer and human body. During winter, the clothes must be able to provide insulation to human body in order to retain its generated heat by minimizing the circulation of air between external environment and human body. This particular behaviour of clothing regarding exchange of air is related to its air permeability. Air permeability of a material can be described as its ability to allow air to pass through it. It has been defined as “the degree to which a fabric, coating or laminate allows air to pass through its construction” [2]. The air permeability of fabrics also significantly affects the technical performance of textiles. Air bags, parachutes, industrial and domestic filters are the areas where air permeability holds critical importance with respect to their performance [3,4].

Various studies are reported in the past which focused on the modeling of the air permeability of different fabric structures. The developed models can be categorized as theoretical models, geometrical models, statistical models and artificial neural network based models. The limitation of these models is narrower range of materials, fewer input parameters and their levels, non-generalizable prediction, smaller data sets used for model development and higher error of validation [5-16]. Also the contribution percentage of the input factors is not quantified with the air permeability of the woven fabrics which can effectively screen out the most influencing input parameters.

In this study, response surface regression has been applied to develop a statistical model for prediction of air permeability of woven fabrics. Certain fabric related parameters had been taken as input variables and a huge data set was utilized for development and validation of the model. The effect of input variables on the air permeability was observed in context of the developed model and sensitivity analysis has been carried out to quantify the influence of the input variables on the air permeability of polyester/cotton blended woven fabrics.

Materials and Methods

One hundred and thirty five fabric samples were woven on a Sulzer weaving machine (P 7150). The polyester/cotton blended (52:48) yarns were utilized for production of fabrics. Fabrics were developed with controlled variation in yarn linear densities and fabric thread densities. Three different levels of yarn linear density i.e. 15, 20 and 25 tex while five different levels of thread densities i.e. 40, 50, 60, 70, 80 per 25 mm were used. The fabric constructions are given in Table 1. The highlighted cells represent the data set used for validation of the model. The weave pattern of the fabrics is 3/1 S Twill weave. The desizing of the fabrics was done by enzymatic desizing method. After desizing, all the fabric

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Table 1. Fabric constructions used for modeling the air permeability of woven fabrics

S No.	Set 1	Set 2	Set 3	Set 4	Set 5	Set 6	Set 7	Set 8	Set 9
1	*15×15/ 40×40	15×20/ 40×40	15×25/ 40×40	20×15/ 40×40	20×20/ 40×40	20×25/ 40×40	25×15/ 40×40	25×20/ 40×40	25×25/ 40×40
2	15×15/ 50×40	15×20/ 50×40	15×25/ 50×40	20×15/ 50×40	20×20/ 50×40	20×25/ 50×40	25×15/ 50×40	25×20/ 50×40	25×25/ 50×40
3	15×15/ 50×50	15×20/ 50×50	15×25/ 50×50	20×15/ 50×50	20×20/ 50×50	20×25/ 50×50	25×15/ 50×50	25×20/ 50×50	25×25/ 50×50
4	15×15/ 60×40	15×20/ 60×40	15×25/ 60×40	20×15/ 60×40	20×20/ 60×40	20×25/ 60×40	25×15/ 60×40	25×20/ 60×40	25×25/ 60×40
5	15×15/ 60×50	15×20/ 60×50	15×25/ 60×50	20×15/ 60×50	20×20/ 60×50	20×25/ 60×50	25×15/ 60×50	25×20/ 60×50	25×25/ 60×50
6	15×15/ 60×60	15×20/ 60×60	15×25/ 60×60	20×15/ 60×60	20×20/ 60×60	20×25/ 60×60	25×15/ 60×60	25×20/ 60×60	25×25/ 60×60
7	15×15/ 70×40	15×20/ 70×40	15×25/ 70×40	20×15/ 70×40	20×20/ 70×40	20×25/ 70×40	25×15/ 70×40	25×20/ 70×40	25×25/ 70×40
8	15×15/ 70×50	15×20/ 70×50	15×25/ 70×50	20×15/ 70×50	20×20/ 70×50	20×25/ 70×50	25×15/ 70×50	25×20/ 70×50	25×25/ 70×50
9	15×15/ 70×60	15×20/ 70×60	15×25/ 70×60	20×15/ 70×60	20×20/ 70×60	20×25/ 70×60	25×15/ 70×60	25×20/ 70×60	25×25/ 70×60
10	15×15/ 70×70	15×20/ 70×70	15×25/ 70×70	20×15/ 70×70	20×20/ 70×70	20×25/ 70×70	25×15/ 70×70	25×20/ 70×70	25×25/ 70×70
11	15×15/ 80×40	15×x20/ 80×40	15×25/ 80×40	20×15/ 80×40	20×20/ 80×40	20×25/ 80×40	25×15/ 80×40	25×20/ 80×40	25×25/ 80×40
12	15×15/ 80×50	15×20/ 80×50	15×25/ 80×50	20×15/ 80×50	20×20/ 80×50	20×25/ 80×50	25×15/ 80×50	25×20/ 80×50	25×25/ 80×50
13	15×15/ 80×60	15×20/ 80×60	15×25/ 80×60	20×15/ 80×60	20×20/ 80×60	20×25/ 80×60	25×15/ 80×60	25×20/ 80×60	25×25/ 80×60
14	15×15/ 80×70	15×20/ 80×70	15×25/ 80×70	20×15/ 80×70	20×20/ 80×70	20×25/ 80×70	25×15/ 80×70	25×20/ 80×70	25×25/ 80×70
15	15×15/ 80×80	15×20/ 80×80	15×25/ 80×80	20×15/ 80×80	20×20/ 80×80	20×25/ 80×80	25×15/ 80×80	25×20/ 80×80	25×25/ 80×80

samples were first preconditioned at a temperature of 47 °C and relative humidity of 10 to 25 % for 4 hours in a hot air oven. Afterwards the conditioning of the fabric samples was carried out for 24 hours in standard atmosphere according to ASTM D 1776 [17]. The fabric areal density and fabric thickness were also measured through standard test methods ASTM D 3776 and ASTM D 1777 respectively [18,19].

Standard test method used for determination of air permeability of textile fabric is ASTM D 737 [20]. Fabrics were tested on SDL air permeability tester. A testing head of 20 cm^2 was selected for testing the fabric samples on air permeability tester. A constant air pressure of 100 Pascal was maintained for fabric testing on the tester. The results acquired from the tester were taken in units of l/m^2/min.

Development of the Model

The total data consisted of 135 sets of input/output patterns. Among the total experimental datasets, 117 sets were selected for development of the air permeability model while the remaining 18 sets were separated for validation of the developed model. Minitab statistical software was utilized for the analysis of data and development of the response surface regression model.

Initial statistical investigations on the collected data revealed that fabric areal density, fabric thickness and fabric cover factor were not the significantly affecting variables. The P-value of all these parameters was found more than 0.05 representing their non-significant effect on the air permeability of woven fabrics. The reason lies in the fact that these three parameters were actually the dependent variables and get influenced by variation in fundamental independent variables i.e. yarn linear densities and thread densities. So, these three variables were separated and were not included in development of the air permeability model.

In order to make sure the selection of the significant variables for development of model, best subset regression was applied on the data prior to development of the model. Best subset regression is a statistical tool used to sort out the

Table 2. Best subset of regression models

S. No	Vars	R^2	R^2 (Adj)	C-P	S	Wp LD	Wf LD	EPL	PPL
1	1	60.10	59.70	684.70	611.62			X	
2	1	57.50	57.10	736.40	631.10				X
3	2	76.20	75.80	363.90	473.98			X	X
4	2	73.00	72.60	428.00	504.96	X		X	
5	3	89.50	89.30	100.00	315.78	X		X	X
6	3	81.30	80.80	264.10	421.94		X	X	X
7	4	94.40	94.20	5.00	232.22	X	X	X	X

non-significant variables from the input data and make possible the development of the model by fewer variables. Subsets produced in this analysis were compared with full model in terms of data fitting and future responses to determine the best combination of the variables. The results of best subset regression carried out on the data are given in Table 2. There are total 7 combinations of input variables tested for most appropriate variable selection.

The results obtained by the best subset regression suggest that the most suitable combination of the variables for the development of air permeability model is taking Wp LD (warp linear density), Wf LD (weft linear density), EPL (ends per 25 mm) and PPL (picks per 25 mm) as input parameters because it shows the highest values of R^2 and R^2 adjusted. R^2 value represents the accuracy of data fitting while R^2 (Adj) assures the selection of appropriate variables combination for the model. Higher the values of R^2 and R^2 (Adj) better is the developed model. Also the value of C-P suggests taking the four variables as inputs as Mallows C-P value is used to avoid over fitting of the model. The value of C-P should be less than double of the number of input variables in the subset which is only valid in subset of four input variables. S is the standard deviation of the data which is also least in case of particular subset model which comprise of all four input parameters. This method is often applied after the selection of vital few input parameters on the basis of knowledge and expertise to screen out non-significant variables and their interactions from the model.

In the attempt to model the air permeability of the woven fabrics, warp linear density, weft linear density, ends per 25 mm and picks per 25 mm have been taken as input parameters. The data was then analyzed with response surface regression to develop the model for air permeability. The reason for selection of response surface regression rather than multiple linear regression lies in the fact that response surface regression is a fully capable tool to model the linear as well as nonlinear relationships of the variables which is not possible in multiple linear regression.

The fitting of the developed model was observed quite satisfactory with an R-square value of 99.02 % which showed satisfactory fitting of data in the model. Initially the developed model highlighted a few interactions of the input variables with a P-value more than 0.05 which showed their non-significance. These terms were deleted from the model and newly developed model showed all contributing terms having a P-value less than 0.05 confirming their significant contribution in the model. The finally developed model is shown in following equation.

$$
\begin{aligned}
AP = {} & 17135.5 - 186.096\ \text{Wp LD} - 194.530\ \text{Wf LD} \\
& - 121.156\ \text{EPL} - 140.318\ \text{PPL} + 0.413\ \text{EPL} \times \text{EPL} \\
& + 0.301\ \text{PPL} \times \text{PPL} + 4.171\ \text{Wp LD} \times \text{Wf LD} \\
& - 1.253\ \text{Wp LD} \times \text{EPL} + 1.968\ \text{Wp LD} \times \text{PPL} \\
& + 1.379\ \text{Wf LD} \times \text{EPL} - 0.605\ \text{Wf LD} \times \text{PPL} \\
& + 0.537\ \text{EPL} \times \text{PPL}
\end{aligned}
$$

Results and Discussion

The validation data set is not used during the development of the model and was used to evaluate the performance of the model. Observed and predicted values of the air permeability showed a good agreement with each other. An absolute error was also calculated to determine the difference between the actual and predicted values of air permeability by means of following formula.

$$Absolute\ error = \frac{Actual\ value - predicted\ value}{Actual\ value} \times 100$$

The results of air permeability validation along with the absolute error are given in Table 3. The average absolute error of 5.1 % was obtained which confirms good predictability of the model on unseen data set. A fitted line plot is also given in Figure 1 which shows good agreement between actual and predicted values.

Surface plots have been made between different input variables and the air permeability to study the effect of input variation on the output. Surface plots are basically three dimensional plots which provide a picture of effect of input factors with the output variable. The surface plots of variable interactions based on the developed model are shown in Figures 2-7.

The results obtained from surface plots of various parameters with air permeability agree the logical relationships of input parameters with air permeability characteristics of the

Table 3. Actual and predicted values of air permeability

S. No	Planned fabric construction	Actual fabric construction	Actual air permeability (l/m^2/min)	Predicted air permeability (l/m^2/min)	Absolute error (%)
1	15×15/70×50	15.05×15.05/75×54	2436	2313	5.05
2	15×15/80×60	15.05×15.05/83×65	1730	1678	3.01
3	15×20/70×60	15.05×20.68/74×64	1533	1511	1.44
4	15×20/80×50	15.05×20.68/82×53	1842	1893	2.77
5	15×15/70×50	15.05×25.90/72×54	1730	1695	2.02
6	15×25/80×70	15.05×25.90/83×74	662	704	6.34
7	20×15/70×60	20.68×15.05/75×63	1353	1388	2.59
8	20×15/80×50	20.68×15.05/82×53	1390	1493	7.41
9	20×20/70×50	20.68×20.68/73×53	1584	1574	0.63
10	20×20/80×70	20.68×20.68/83×72	690	748	8.41
11	20×25/70×60	20.68×25.90/75×65	935	849	9.20
12	20×25/80×60	20.68×25.90/83×65	717	760	6.00
13	25×15/70×50	25.90×15.05/76×51	1170	1145	2.14
14	25×15/80×70	25.90×15.05/84×73	442	476	7.69
15	25×20/70×60	25.90×20.68/73×63	817	842	3.06
16	25×20/80×60	25.90×20.68/82×63	676	597	11.69
17	25×25/70×50	25.90×25.90/75×51	1103	1037	5.98
18	25×25/80×50	25.90×25.90/83×51	892	835	6.39

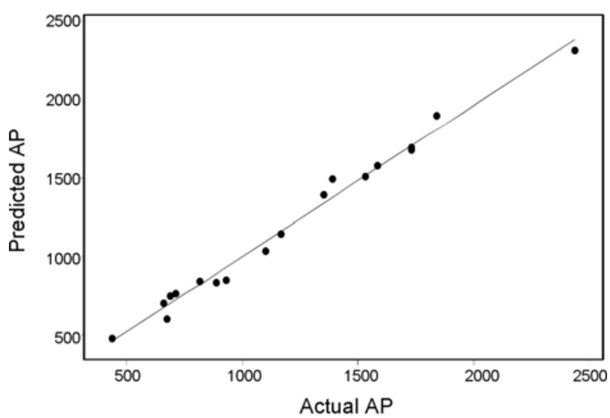

Figure 1. Fitted line plot between actual and predicted air permeability of woven fabrics.

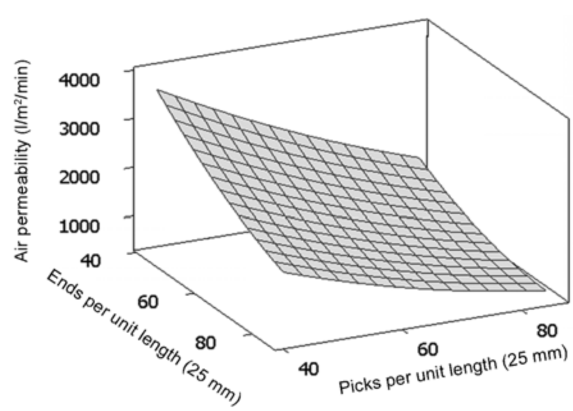

Figure 2. Surface plot of picks per 25 mm (PPL) and ends per 25 mm (EPL) versus air permeability

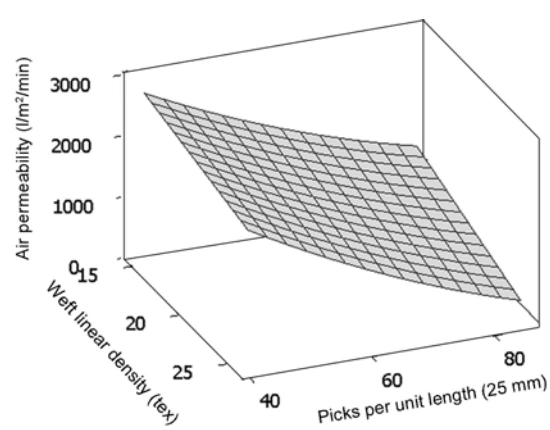

Figure 3. Surface plot of picks per 25 mm (PPL) and weft linear density (Wf LD) versus air permeability.

fabrics. Increments in thread density either warp wise or weft wise, significantly enhances the cover factor of the fabrics resulting in reduction of inter yarn spacing. Once the yarns are closer to each other, the porosity is reduced providing more hindrance to the air flow resulting in reduction of air permeability.

The linear densities of warp and weft i.e. Wp LD and Wf LD are also found negatively correlated with the air permeability. This finding also complies with established facts of fabric structural characteristics that once the yarn diameter is increased it covers more space in a unit length as compared to a finer yarn. Increment in yarn diameter with linear density causes the pore size reduction in the fabric and

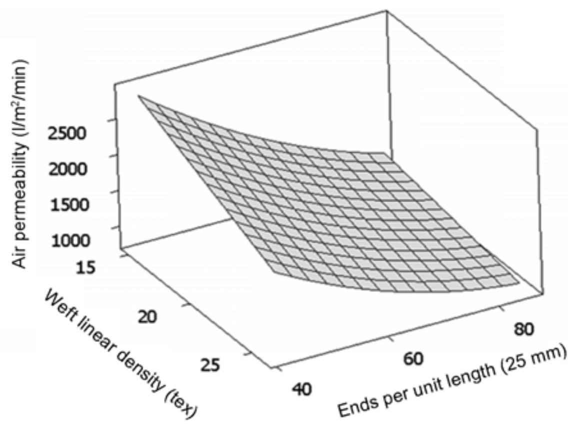

Figure 4. Surface plot of ends per 25 mm (EPL) and weft linear density (Wf LD) versus air permeability.

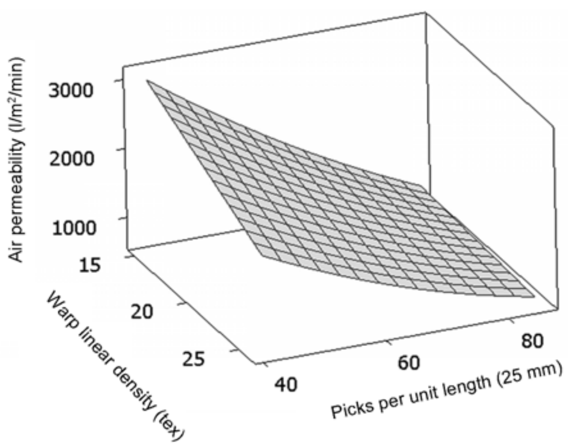

Figure 5. Surface plot of picks per 25 mm (PPL) and warp linear density (Wp LD) versus air permeability.

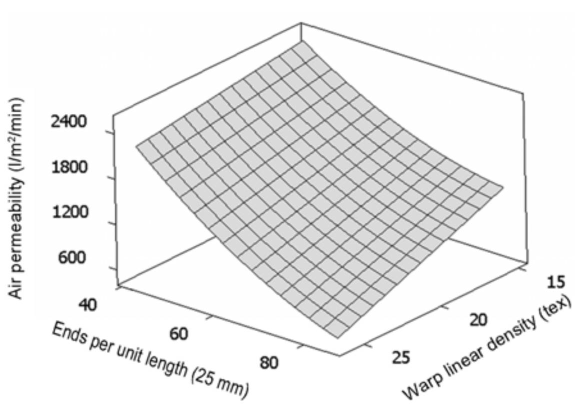

Figure 6. Surface plot of ends per 25 mm (EPL) and warp linear density (Wp LD) versus air permeability.

enhancing its cover factor. This effect provides more hindrance to the air flow resulting in reduction of air permeability of

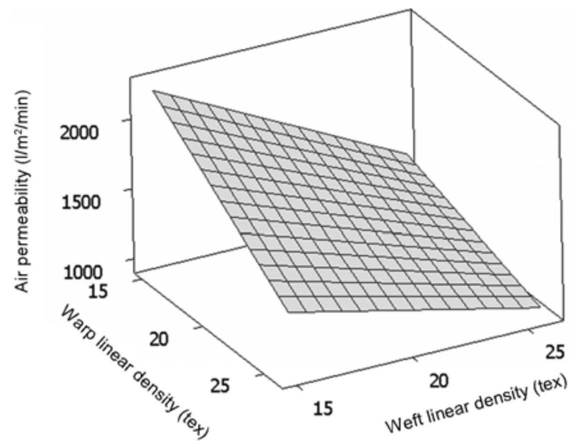

Figure 7. Surface plot of weft linear density (Wf LD) and warp linear density (Wp LD) versus air permeability.

woven fabrics. However as the steeping of surface is relatively less in case of linear densities Wp LD and Wf LD as compared to thread densities EPL and PPL, it can be inferred that effect of linear densities is not as influential as that of thread densities.

There exists a certain degree of non-linearity in the relationship of input and output variables which can be seen due to presence of curvatures in the surface plots instead of straight lines. The basic reason of curvature in the graphs is utilization of non-linear terms during the model development in addition to linear terms i.e. interaction terms and squared terms. Without the addition of non-linear terms, model was unable to accurately understand the relationships of the variables resulting in higher prediction error. Though addition of non-linear terms enhanced the complexity of equation by making it second order equation but it provided a better data fitting as well as validation.

Sensitivity Analysis

To judge the relative importance of input parameters on air permeability of woven fabrics, sensitivity analysis was carried out by utilizing the response surface regression based air permeability model. All the parameters were kept at their middle level values except for the parameter whose sensitivity was to be evaluated. The parameter under consideration was varied from its minimum to maximum level and the corresponding change in the fabric air permeability as suggested by the model was recorded. This change was expressed as a percentage of full range of air permeability values. Different levels of the input variables considered in the sensitivity analysis are given in Table 4.

Table 5 presents the output parameter i.e. air permeability (AP) of the woven fabric with the range determined by the difference of the maximum and minimum values of AP in the data. Relative contribution percentages of all the input parameters were calculated by keeping all other parameters

Table 4. Input parameters along with levels and means for sensitivity analysis

Input parameter	Levels	Minimum level	Maximum Level	Mid-level (mean)
Warp yarn linear density (Wp LD)	3	15.05	25.9	20.48
Weft yarn linear density (Wf LD)	3	15.05	25.9	20.48
Ends per 25 mm (EPL)	3	42	85	63.48
Picks per 25 mm (PPL)	3	41	85	63.32

Table 5. Output parameter along with range used in sensitivity analysis

Output parameter	Minimum value	Maximum value	Range
Air permeability of woven fabric (AP) (l/m^2/min)	206	4490	4284

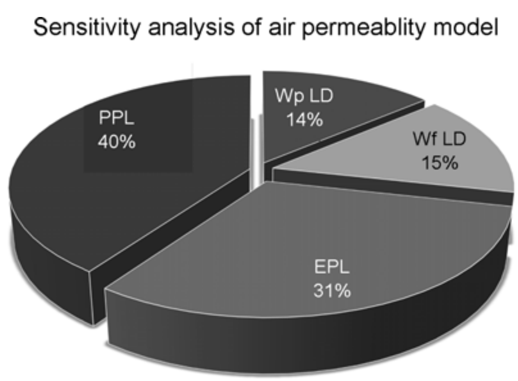

Figure 8. Relative contribution percentages of input variables on air permeability as determined by sensitivity analysis.

at their mean values and dividing the range of input parameter to the output parameter as mentioned in the following equation.

$$C_{EPL}\,(\%) = \text{Predicted range of AP by the factor} \times 100 \,/\, \text{Overall range of AP}$$

Where, C_{EPL} (%) represents the contribution of ends per 25 mm (EPL) in determination of air permeability. Similarly, this formula is applied for determination of contribution of other variables as well. The resultant contribution of the factors is plotted in form of a pie diagram as shown in Figure 8.

The quantification of the variables using sensitivity analysis of the developed model resulted in contribution percentages of 40 %, 31 %, 15 % and 14 % of picks per 25 mm (PPL), ends per 25 mm (EPL), weft yarn linear density (Wf LD) and warp yarn linear density (Wp LD) respectively. The concluded results fully comply with the established logics that thread densities EPL and PPL play a vital role in determination of cover factor and slight variation in it can cause significant effect on air permeability because of change in pore size of the fabric. Similarly the yarn linear densities Wp LD and Wf LD significantly affect the cover factor of the fabric but its influence is not as impacting as that of thread densities and due to this reason its relative contribution is lower than thread densities. The quantification of the input variables and their relative contribution determination for air permeability of the fabric can serve for accurate prediction and optimization of this important comfort parameter of woven fabrics.

Conclusion

Air permeability of the polyester/cotton blended woven fabrics has been predicted using response surface regression. The developed model showed a good predictability with a low error of around 5.1 %. The surface plots of input variables on the air permeability showed that ends and picks density of the fabrics play a vital role in deciding the air permeability of woven fabrics. Also the warp and weft linear densities are secondary parameters that help decide the air permeability of woven fabrics. Fabric thickness, areal density and cover factor do not hold a significant importance in predicting the air permeability of woven fabrics because of their dependence on the basic fabric geometry characteristics. This fact is also supported by the sensitivity analysis conducted on the model to determine the contribution percentage of input variables.

The future work in this regard can be the application of other modeling techniques to reduce the prediction error. The different materials with wider range of input variables and their levels can be used to develop a more generalized air permeability model. The fabrics used in this study for development of model are gray fabrics but in daily life the dyed, printed and finished fabrics are used for clothing, so the same model can be replicated for the other types of wearable clothing. Also the yarn evenness and hairiness are important factors which can apparently affect the air permeability of the woven fabrics. In future, these parameters should also be taken in consideration while developing the air permeability model for woven fabrics.

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