Development of the Predictive Models for the Fabric Water Vapor Resistance

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ABSTRACT

The water vapor transport properties of textile fabrics are of considerable importance in determining thermal comfort properties of clothing systems. There are different standard test methods available for measuring water vapor transport properties of fabrics. They are either time consuming or expensive methods. Objective of this work is to determine water vapor transmission resistance of the fabric using other properties of the fabric in such a manner that one can predict water vapor resistance. Both linear and nonlinear models were considered and different measures of model adequacy including residual sum of square, maximum absolute deviation and average absolute deviation were calculated. Using linear regression techniques, several statistically acceptable linear models were developed. The results revealed that several non-linear models can predict the water vapor resistance better than linear models.

INTRODUCTION

Comfort is fundamental to daily human life. This universal need, however is such a nebulous quantity that unanimous agreement on a definition of comfort is almost impossible to achieve.

Four different aspects for comfort may be defined, thermal comfort, sensorial comfort, garment fit, and psychological comfort. Among these, thermal comfort is of primary importance, since clothing is worn in various thermal conditions. Again four properties are suggested as critical for thermal comfort of a clothed body: (a) effectiveness to stagnant air, (b) thermal resistance, (c) vapor transfer rate, (d) liquid water transport properties. In this paper special attention is paid to water vapor transfer properties of fabrics.

In order to provide comfort for wearer, it is necessary for clothing to transmit water vapor from the body to the environment as fast as possible. Many researchers have investigated effect of properties such as weave or knit structure [1- 4], fiber type and blend level [1, 2, 5, 6], porosity [2, 5, 7], tightness factor [2, 6, 7], etc., on water vapor transmission rate.

Yoon and Buckley [5], showed the importance of construction variables on moisture vapor transmission characteristics of fabrics. They described the resistance to water vapor transmission R in terms of fabric thickness L, optical porosity β and water vapor diffusivity of air D_a as;

$$R = \frac{L}{D_a \beta} \tag{1}$$

Özdil et al. [7] described the regression equation between water vapor permeability (*WVP*) and fabric parameters of the 1×1 rib fabrics with correlation coefficient of 98% as;

$$\text{WVP} = 39.6 + 2.10a_e + 7.28\text{L} - 12.2h \tag{2}$$

Where α_e is twist coefficient, L is loop length and T is fabric thickness. Using "Eq. (3)." the conversion of WVR into R can easily be made.

$$R = D\frac{(C_2 - C_1)}{WVP} \tag{3}$$

Where, R is diffusion resistance, described as the thickness of still air layer, which has the same resistance to water vapor diffusion as the fabric. C_2-C_1 is difference in water vapor concentration between two surfaces of the fabric (Kg/m^3). D is coefficient of moisture vapor in the air and WVP, is the rate of water vapor transmission ($kg/s/m^3$).

Whelan et al. [8] developed a relationship between water vapor resistance of fabric, against fabric thickness and fiber volume as follows:

$$R = \frac{100}{100 - V_f}(0.9 + 0.034V_f)T + 0.5 \qquad (4)$$

Where, R is fabric's water vapor resistance, V_f is ratio of fiber volume in fabric and T is fabric thickness. In their work, other factors such as ends and pick per inch, warp and weft yarn count, weight, and air permeability are also measured.

Whelan et al. divided their report into three parts. The first part dealt with the method of measurement and included results and discussion of external air associated with laminar materials [8]. The second part dealt with results of a study of the transmission of water vapor by diffusion through perforated metal plates and mathematical consideration of the problem [9]. From empirical relations, they derived the general expression of:

$$R = \frac{T}{\beta} + 0.71d\left(\frac{1}{\beta} - \frac{1}{\sqrt{\beta}}\right) \qquad (5)$$

Where T is plate's thickness, d is diameter of hole and β is percentage area of perforation. The third part was concerned chiefly with the resistance to the diffusion of water vapor offered by fabrics [10]. Objective of this paper is to link fabric properties like yarn count to water vapor transmission rate.

DATA MANIPULATION

Since, Whelan et al. thoroughly measured almost all operative parameters influencing fabric's water vapor resistance, the data which they measured was considered as the basis of this work. They chose 57 different samples, including felts. However, there were only 36 samples with all parameters measured, which are elicited in *Table I*. Also for convenience all yarn counts are converted to denier. Using statistical analysis of these data, different models were also developed to predict fabric's water vapor resistance.

In *Table II*, the mean and standard deviation of the independent variables are tabulated. Considering the mean values and standard deviations of the fabric properties one can observe that they differ widely from each other. To overcome this difficulty the values of all of the independent variables are modified in such a manner that their average value and standard deviation became zero and one respectively. The standardized independent values are shown in *Table III*

LINEAR REGRESSION MODELS

The Pearson product moment correlation coefficient is expressed as follows:

$$r = \frac{\sum (x - \bar{x})(y - \bar{y})}{\sqrt{\sum (x - \bar{x})^2 \sum (y - \bar{y})^2}} \qquad (6)$$

Where x stands for any independent fabric property and y signifies water vapor resistance of any sample. The Pearson product moment correlation coefficient, or simply r is a dimensionless number that ranges in [-1, 1] and is a measure of extend of a linear relationship between water vapor resistance and the fabric properties.

Table IV shows that the correlation coefficient between water vapor resistance and ends and picks per inch, and also air permeability are negative numbers. This means that, by increasing the amount of them, the water vapor resistance will decrease. On the other hand, for the remaining properties the Pearson correlation coefficients are positive values. So, by increasing the value of such properties, the water vapor resistance will also increase. Another important point is that r for fabric's weight against water vapor resistance has the highest positive value; it implies that there is a strong direct relationship between weight and water vapor resistance of the fabrics.

For all fabric properties as independent variable, and water vapor resistance as dependent variable, regression calculations are performed and their ANOVA tables are obtained. Although the Pearson correlation coefficient is an adequate measure for determination of linear relationship between fabric water vapor resistance and any other fabric property, but in some cases, one may want to add extra variables to his/here model. When the amount of independent variables exceeds than one, the analyst should use other statistical parameters such as the multiple coefficient of determination for investigation of the amount of variation of water vapor resistance accounted for the mixture of independent variables. Appendix shows the statistical parameters used in regression analysis in brief. The third and fourth columns of *Table IV* indicate R^2 and *F-ratio,* for each model having only a single independent variable as shown in the first column of the table. Considering these measures of model adequacy, one could see that the highest correlation coefficient between water vapor resistance and all fabric properties is due to weight of fabric (0.87328). On the other hand the R^2

for this variable is (0.75226) which means that variable weight accounts 75.2226 percent of the total variance of the water vapor resistance. This variable also showed the highest F- ratio (103.239).

TABLE I: Data used for development of models for prediction of water vapor resistance

	Identification	Ends per inch	Picks per inch	Warp-den	Weft-den	Weight (oz/sq yd)	Air-perm.	Thickness (mm at p=0.05 psi)	% Fiber volume	WV R (mm of air)
1	Cotton-Plain	72	60	231.0652	265.725	4.5	18	0.31	32	1.3
2	Cotton-2/1Twill	97	70	156.3088	221.4375	4.4	65	0.41	24	1.5
3	Cotton-Plain	78	57	265.725	265.725	5.5	42	0.51	24	1.5
4	Cotton- 3/1Twill	115	53	295.25	442.875	8.3	12	0.6	31	2.2
5	Cotton- 3/1Twill	114	56	295.25	442.875	8.2	16	0.69	27	1.9
6	Cotton- 5/1Twill	96	40	442.875	442.875	8.8	18	0.81	24	2.2
7	Cotton-Sateen	97	44	408.8077	759.2143	9.9	21	0.94	24	2.5
8	Cotton-Oxford	170	65	73.8125	106.29	6.7	1.2	0.53	28	1.8
9	Cotton-Plain	88	31	590.5	590.5	10.2	4.2	0.83	27	2.7
10	Cotton-Plain	52	32	354.3	354.3	8.2	20	0.91	20	2.5
11	Cotton-Plain	52	38	408.8077	332.1563	10.2	5.8	0.94	24	3.1
12	Cotton-Plain	51	35	408.8077	408.8077	12.5	3.1	0.95	29	3.1
13	Cotton-Plain	49	33	408.8077	408.8077	15.3	2	1.19	29	3.4
14	Cotton- 3/1 herringbone	79	64	442.875	442.875	8.6	15	0.94	21	2.4
15	Cotton-Plain	46	38	196.8333	590.5	4.6	80	0.99	10	1.9
16	Cotton-Plain	46	27	408.8077	408.8077	12.5	5.5	0.97	29	2.5
17	Cotton, Viscose and Hair-Plain	47	23	885.75	1062.9	8.3	20	1.17	16	2.8
18	Cotton,Wool-2/2Twill	62	38	306.6	996.47	10.7	42	1.05	27	2.9
19	Wool-2/2Twill	64	64	265.72	362.35	10	18	1.35	19	2.9
20	Acetate- Sateen	202	94	75	75	2.7	66	0.13	53	1.3
21	Acetate, Viscose-Plain	110	69	125	150	3.7	86	0.25	35	1.1
22	Viscose-Plain	77	64	150	150	2.9	139	0.19	34	0.9
23	Viscose- 2/2Twill	116	66	150	150	3.6	38	0.19	43	1.5
24	Viscose-Plain	77	66	177.15	177.15	3.8	192	0.43	19	1.3
25	Viscose-Plain	48	40	332.1563	531.45	7.1	116	0.57	28	2.1
26	Viscose-Matt	40	36	1650	1650	19	33	0.84	52	4.9
27	Viscose-Sateen	148	70	150	295.25	5.2	41	0.44	26	1.5
28	Nylon-Plain	88	87	70	70	1.5	323	0.13	35	0.7
29	Nylon-Plain	160	88	70	70	2.6	6.9	0.16	48	1.9
30	Nylon-Plain	155	84	70	70	2.3	12	0.17	41	1.1
31	Nylon-Sateen	315	104	40	70	3.1	220	0.25	37	1.2
32	Nylon- 3/1Twill	238	72	70	70	4.7	60	0.3	46	1.8
33	Nylon- Open Net	60	56	260	260	3.9	392	0.44	27	1.3
34	Orlon- Plain	54	30	1100	1100	12.8	2.2	0.94	39	5.8
35	Polyethylene- 3/1 Twill	93	34	540	540	9.1	188	0.75	45	2.8
36	Glass-Plain	43	32	664.31	664.3125	6.6	2.5	0.22	40	3

TABLE II. Average value and standard deviation of fabric properties

No.	Fabric Property	Mean value	Standard deviation
1	Ends per inch	97.19444	60.330906
2	Picks per inch	54.4444	21.11931
3	Warp denier	348.3478	322.24452
4	Weft denier	416.6293	347.80443
5	Weight	7.2777	4.02358
6	Air permeability	64.6222	92.25696
7	Thickness	0.62472	0.35542
8	Fiber volume	30.9166	10.19909

TABLE III. The standardized variables of fabric properties

Ends per inch	Picks per inch	Warp-denier	Weft-denier	Weight	Air-perm	Thickness	Fiber volume%
-0.4176	0.2631	-0.3640	-0.4339	-0.6904	-0.5054	-0.8855	0.1062
-0.0032	0.7366	-0.5959	-0.5612	-0.7152	0.0041	-0.6041	-0.6782
-0.3182	0.1210	-0.2564	-0.4339	-0.4418	-0.2452	-0.3228	-0.6782
0.2951	-0.0684	-0.1648	0.0755	0.2541	-0.5704	-0.0696	0.0082
0.2786	0.0737	-0.1648	0.0755	0.2292	-0.5270	0.1837	-0.3840
-0.0198	-0.6839	0.2933	0.0755	0.3783	-0.5054	0.5213	-0.6782
-0.0032	-0.4945	0.1876	0.9850	0.6517	-0.4728	0.8871	-0.6782
1.2068	0.4998	-0.8519	-0.8923	-0.1436	-0.6875	-0.2665	-0.2860
-0.1524	-1.1101	0.7515	0.4999	0.7263	-0.6549	0.5776	-0.3840
-0.7491	-1.0627	0.0185	-0.1792	0.2292	-0.4837	0.8027	-1.0704
-0.7491	-0.7786	0.1876	-0.2429	0.7263	-0.6376	0.8871	-0.6782
-0.7657	-0.9207	0.1876	-0.0225	1.2979	-0.6669	0.9152	-0.1879
-0.7988	-1.0154	0.1876	-0.0225	1.9938	-0.6788	1.5905	-0.1879
-0.3016	0.4525	0.2933	0.0755	0.3286	-0.5379	0.8871	-0.9723
-0.8486	-0.7786	-0.4702	0.4999	-0.6655	0.1667	1.0277	-2.0508
-0.8486	-1.2995	0.1876	-0.0225	1.2979	-0.6408	0.9715	-0.1879
-0.8320	-1.4889	1.6677	1.8581	0.2541	-0.4837	1.5342	-1.4625
-0.5834	-0.7786	-0.1296	1.6671	0.8505	-0.2452	1.1966	-0.3840
-0.5502	0.4525	-0.2564	-0.1561	0.6766	-0.5054	2.0406	-1.1684
1.7372	1.8730	-0.8483	-0.9822	-1.1377	0.0149	-1.3919	2.1652
0.2123	0.6892	-0.6931	-0.7666	-0.8892	0.2317	-1.0543	0.4004
-0.3347	0.4525	-0.6155	-0.7666	-1.0880	0.8062	-1.2231	0.3023
0.3117	0.5472	-0.6155	-0.7666	-0.9141	-0.2886	-1.2231	1.1847
-0.3347	0.5472	-0.5313	-0.6885	-0.8643	1.3807	-0.5479	-1.1684
-0.8154	-0.6839	-0.0502	0.3301	-0.0442	0.5569	-0.1540	-0.2860
-0.9480	-0.8733	4.0393	3.5462	2.9134	-0.3428	0.6057	2.0672

0.8421	0.7366	-0.6155	-0.3490	-0.5164	-0.2560	-0.5197	-0.4821
-0.1524	1.5415	-0.8638	-0.9966	-1.4360	2.8006	-1.3919	0.4004
1.0410	1.5889	-0.8638	-0.9966	-1.1626	-0.6257	-1.3075	1.6750
0.9581	1.3995	-0.8638	-0.9966	-1.2372	-0.5704	-1.2794	0.9887
3.6102	2.3465	-0.9569	-0.9966	-1.0383	1.6842	-1.0543	0.5965
2.3339	0.8313	-0.8638	-0.9966	-0.6407	-0.0501	-0.9136	1.4789
-0.6165	0.0737	-0.2742	-0.4503	-0.8395	3.5485	-0.5197	-0.3840
-0.7160	-1.1574	2.3326	1.9648	1.3725	-0.6766	0.8871	0.7926
-0.0695	-0.9680	0.5947	0.3547	0.4529	1.3373	0.3525	1.3808
-0.8983	-1.0627	0.9805	0.7121	-0.1685	-0.6734	-1.1387	0.8906

TABLE IV. Statistical parameters of the models with single independent variable

Independent Variable	Pearson Correlation Coefficient, r	Multiple Coefficient of Determination, R^2	F- Ratio
Ends per inch	-0.45131	0.20368	8.69647
Picks per inch	-0.68427356	0.46823	29.9375
Warp denier	0.847801246	0.71877	86.8962
Weft denier	0.805238858	0.64841	62.7034
Weight	0.867328	0.75226	103.239
Air perm	-0.43874	0.19249	8.10499
Thickness	0.668254	0.44656	27.4343
Fiber volume %	0.06764	0.00458	0.15628

All of these measures reveal the weight of the fabric can be selected as the first important variable for prediction of water vapor resistance in a model. The equation of this model is as follows:

$$WVR1 = 2.20278 + weight\,(0.91988) \quad (7)$$

Now the first variable is fixed for weight and the next important variable is searched in turn. *Table V* shows the results of the regression analysis for all of the models with two independent variables. Comparing the R^2 for the models, one can easily observe the weight and warp denier account 83.2203 percent of the water vapor resistance.

The F-ratio which is another measure of appropriateness of the model is 81.83304. Finally, this model can be considered as another suitable model for prediction of water vapor resistance where weight and warp- den was independent variables. The regression equation for this model is as follows:

$$WVR2 = 2.202778 + weight\,(o.558957) + warp\ \ den(0.469244) \quad (8)$$

TABLE V. Statistical parameters of the models with two independent variables

Independent Variable in Addition of Weight	Multiple R	Multiple Coefficient of Determination, R^2	F- Ratio
Ends per inch	0.867591	0.752715	50.22459
Picks per inch	0.869928	0.756775	51.33832
Warp denier	0.912252	0.832203	81.83304
Weft denier	0.898095	0.80574	86.8039
Air perm.	0.89129	0.755384	50.9528
Thickness	0.867653	0.752822	50.2535
Fiber volume %	0.877836	0.770597	55.42571

Further investigation showed that the addition of a third variable for WVR2 model does not improve the adequacy of this model significantly. Using statistical technique of backward elimination regression, some other suitable models for prediction of water vapor resistance can also be obtained. In *Table VI* and *VII* the analysis of variance data and also coefficients for the models developed, using backward elimination regression are tabulated.

TABLE VI. Statistical parameters for the models using backward elimination technique

Name of the Model	Multiple R	Multiple Coefficient of Determination, R^2	F- Ratio
WVR3	0.93664	0.877295	24.12999
WVR4	0.936634	0.877283	28.59532
WVR5	0.936584	0.87719	34.52288
WVR6	0.936204	0.876477	42.57409
WVR7	0.935261	0.874712	54.10767
WVR8	0.929269	0.863541	67.50094

The prediction of water vapor resistance using above models and also original Whelan et al correlation "Eq.(1)." ,in all cases are calculated and tabulated in *Table VIII*. *Table IX* show the comparison of the models concerning their sum of squared error, average absolute deviation and maximum absolute deviation. All of the models from WVR-1 to WVR-8 are acceptable from statistical point of view, however due to the form of the models; they belong to the linear regression category.

TABLE VII. Coefficients of variables in different models for water vapor resistance

Model Coefficients	WVR-3	WVR-4	WVR-5	WVR-6	WVR-7	WVR-8
Constant	2.202778	2.202778	2.202778	2.202778	2.202778	2.202778
Fib volume%	0.333966	0.336076	0.33565	0.364094	0.345437	0.376265
Weft den	-0.02795	-0.0273	-	-	-	-
Air perm	-0.10992	-0.11058	-0.11039	-0.11697	-0.12366	-
Ends	0.006261	-	-	-	-	-
Weight	0.077382	0.077255	0.082	-	-	-
Picks	-0.07282	-0.06849	-0.06674	-0.07793	-	-
Thickness	0.51285	0.514099	0.506769	0.565944	0.589758	0.655488
Warp den	0.501655	0.499826	0.476242	0.497898	0.537838	0.533591

TABLE VIII. Comparison of the water vapor resistance predicted using different models with that of experimental values

No	Whelan	WVR1	WVR2	WVR3	WVR4	WVR5	WVR6	WVR7	WVR8	Resist Exp.
1	1.3479	1.568	1.817	2.149	2.1494	2.1462	1.9217	1.7930	1.7776	1.3
2	1.3739	1.545	1.803	2.147	2.1475	2.1441	1.9116	1.7783	1.7623	1.5
3	1.5871	1.796	1.956	2.169	2.1686	2.1665	2.0229	1.9405	1.9307	1.5
4	2.0913	2.436	2.345	2.222	2.2224	2.2236	2.3062	2.3536	2.3592	2.2
5	2.1163	2.414	2.331	2.221	2.2205	2.2216	2.2961	2.3388	2.3439	1.9
6	2.2266	2.551	2.414	2.232	2.2320	2.2338	2.3568	2.4273	2.4358	2.2
7	2.5037	2.802	2.567	2.253	2.2531	2.2562	2.4681	2.5896	2.6041	2.5
8	1.7808	2.071	2.123	2.192	2.1917	2.1910	2.1443	2.1175	2.1143	1.8
9	2.4442	2.871	2.609	2.259	2.2589	2.2623	2.4985	2.6338	2.6500	2.7
10	2.2063	2.414	2.331	2.221	2.2205	2.2216	2.2961	2.3388	2.3439	2.5
11	2.5037	2.871	2.609	2.259	2.2589	2.2623	2.4985	2.6338	2.6500	3.1
12	2.8683	3.397	2.928	2.303	2.3030	2.3092	2.7312	2.9731	3.0021	3.1
13	3.4666	4.037	3.317	2.357	2.3568	2.3663	3.0146	3.3861	3.4306	3.4
14	2.3205	2.505	2.386	2.228	2.2282	2.2297	2.3366	2.3978	2.4051	2.4
15	1.8200	1.591	1.831	2.151	2.1514	2.1482	1.9318	1.8078	1.7929	1.9
16	2.9182	3.397	2.928	2.303	2.3030	2.3092	2.7312	2.9731	3.0021	2.5
17	2.4221	2.436	2.345	2.222	2.2224	2.2236	2.3062	2.3536	2.3592	2.8
18	2.9596	2.985	2.678	2.269	2.2685	2.2725	2.5491	2.7076	2.7266	2.9
19	2.9500	2.825	2.581	2.255	2.2550	2.2583	2.4783	2.6043	2.6194	2.9
20	1.1887	1.156	1.567	2.115	2.1149	2.1095	1.7395	1.5275	1.5021	1.3
21	1.2500	1.385	1.706	2.134	2.1341	2.1299	1.8407	1.6750	1.6552	1.1
22	1.0527	1.202	1.595	2.119	2.1187	2.1136	1.7598	1.5570	1.5327	0.9
23	1.2300	1.362	1.692	2.132	2.1322	2.1278	1.8306	1.6603	1.6399	1.5
24	1.2804	1.408	1.720	2.136	2.1360	2.1319	1.8508	1.6898	1.6705	1.3
25	1.8775	2.162	2.178	2.199	2.1994	2.1992	2.1848	2.1766	2.1756	2.1
26	4.8050	4.883	3.831	2.428	2.4279	2.4417	3.3890	3.9319	3.9969	4.9
27	1.4989	1.728	1.914	2.163	2.1629	2.1604	1.9925	1.8963	1.8848	1.5
28	0.8900	0.882	1.400	2.092	2.0918	2.0850	1.6181	1.3505	1.3185	0.7
29	1.2200	1.133	1.553	2.113	2.1130	2.1074	1.7294	1.5128	1.4868	1.9
30	1.1137	1.065	1.511	2.107	2.1072	2.1013	1.6991	1.4685	1.4409	1.1
31	1.2976	1.248	1.622	2.122	2.1226	2.1176	1.7800	1.5865	1.5634	1.2
32	1.7667	1.613	1.845	2.153	2.1533	2.1502	1.9419	1.8225	1.8082	1.8

33	1.5307	1.431	1.734	2.138	2.1379	2.1339	1.8610	1.7045	1.6858	1.3
34	3.6898	3.465	2.970	2.309	2.3088	2.3153	2.7616	3.0174	3.0480	5.8
35	3.5682	2.619	2.456	2.238	2.2378	2.2399	2.3872	2.4716	2.4817	2.8
36	1.2700	2.048	2.109	2.190	2.1898	2.1890	2.1342	2.1028	2.0990	3

TABLE IX. Comparison of the models for prediction of water vapor resistance. SSE, MAD and AAD designate for sum of squares of residuals, maximum absolute deviation and average absolute deviation respectively for linear models.

parameter	**Whelan**	**WVR1**	**WVR2**	**WVR3**	**WVR4**	**WVR5**	**WVR6**	**WVR7**	**WVR8**
SSE	9.775	9.7535	14.312	34.596	34.604	34.324	18.954	13.481	12.989
MAD	2.110	2.3347	2.8300	3.4910	3.4911	3.484	3.03840	2.7826	2.752
AAD	0.278	0.3232	0.4203	0.7336	0.7337	0.7301	0.5067	0.4014	0.3913

Non-linear Regression Models

In this part there are some non-linear models developed. It has been found that when water vapor resistance is plotted against the fiber volume percent, air permeability, and ends per inch, graphs show hyperbolic like patterns. Hence the following models for any possible improvement will be studied.

$$\text{nonlinear model} = \frac{\text{a} + \text{hyperbolic variable}}{\text{b} + \text{hyperbolic variable}}(\text{c} + \text{d}(\text{linear variable})) \quad (9)$$

Nonlinear regression analysis is performed and the constants of *a, b, c* and *d* for each model are calculated and reported here.

$$WVR9 = \frac{6.39239 + Fibvol}{374579.1 + Fibvol} \times (5225.718 + 29605.87 Thickness) \quad (10)$$

$$WVR10 = \frac{137.793 + Fibvol}{16471.08 + Fibvol} \times (57.99676 + 21.69941 Weight) \quad (11)$$

$$WVR11 = \frac{9504.033 + Fibvol}{9842.634 + Fibvol} \times (1.274529 + 0.002889 Warp\ den) \quad (12)$$

$$WVR12 = \frac{-6.50808 + Fibvol}{-4.33786 + Fibvol} \times (1.310098 + 0.002737 Weft\ den) \quad (13)$$

$$WVR13 = \frac{6.118789 + Air\ perm}{3.208771 + Air\ perm} \times (0.971501 + 1.423612 Thickness) \quad (14)$$

$$WVR14 = \frac{2.047391 + Air\ perm}{1.486078 + Air\ perm} \times (0.598065 + 0.205709 Weight) \quad (15)$$

$$WVR15 = \frac{6.365658 + Air\ perm}{3.419404 + Air\ perm} \times (1.107612 + 0.002149 Warp\ den) \quad (16)$$

$$WVR16 = \frac{8.147479 + Air\ perm}{3.722217 + Air\ perm} \times (0.968375 + 0.001872 Weft\ den) \quad (17)$$

$$WVR17 = \frac{-37.1951 + ends\ per\ inch}{-38.6697 + ends\ per\ imch} \times (1.013088 + 1.56728 Thickness) \quad (18)$$

$$WVR18 = \frac{21.95359 + ends\ per\ inch}{8.506506 + ends\ per\ imch} \times (0.592567 + 0.176595 Weight) \quad (19)$$

$$WVR19 = \frac{-39.3849 + ends\ per\ inch}{-39.124 + ends\ per\ imch} \times (1.040423 + 0.003593 Warp\ den) \quad (20)$$

$$WVR20 = \frac{15077.64 + ends\ per\ inch}{15368.06 + ends\ per\ imch} \times (1.202235 + 0.002503 Weft\ den) \quad (21)$$

In *Table X*, the statistical parameters of the models are tabulated and compared with that of original Whelan model.

TABLE X. Comparison of the models for prediction of water vapor resistance. SSE, MAD and AAD designate for sum of squares of residuals, maximum absolute deviation and average absolute deviation respectively for nonlinear models

MODEL	SSE	MAD	AAD
WVR9	9.001208	1.794705	0.332211
WVR10	9.017661	2.204736	0.316082
WVR11	11.07242	1.49986	0.433535
WVR12	12.69117	1.750061	0.470104
WVR13	17.73178	2.558481	0.457802
WVR14	9.224577	2.076831	0.338436
WVR15	6.557548	1.018804	0.341355
WVR16	6.141136	0.917819	0.334423
WVR17	15.84945	3.074517	0.410999
WVR18	9.410892	2.333259	0.305563
WVR19	9.280349	0.956994	0.395928
WVR20	13.84239	1.919194	0.488697
Whelan	9.123689	1.86977	0.293088

Considering average absolute deviation (AAD), as a measurement of model adequacy, one can see that the corresponding value for Whelan model (i.e. 0.293088) is the smallest between all models.

On the other hand the maximum absolute deviation (MAD) for models WVR9, WVR11, WVR12, WVR15, WVR16 and WVR19 present lower values than that of original Whelan model (1.86977). Considering the residual sum of squares (SSE) which is the most important value of model adequacy in comparison with other two values of MAD and AAD, one can easily observe that the models WVR9, WVR10, WVR15 and WVR16 have lower SSE that that of original Whelan correlation.

It is also important to note that both WVR9 and Whelan models used the same variables (fiber volume and thickness), but due to some differences in the form of WVR9, it is a little bit better model. The best model among all is WVR 16 with 6.14136 SSE.

CONCLUSION

Water vapor resistance of the fabric is a very important property for human's body comfort. We developed twenty models to connect water vapor resistance with structural properties of the fabric. Although eight statistically acceptable linear models were developed, none of them were comparable to original Whelan correlation.

On the other hand using non-linear regression models, fiber volume percent, air permeability and ends per inch were considered as hyperbolic variables and, thickness, weight, warp denier, and weft denier as linear variables. Twelve acceptable models were developed. Some of them from different measures of model adequacy such as, AAD, MAD and SSE, revealed that they can predict the water vapor resistance even better that that of original Whelan model.

APPENDIX

The multiple coefficient of determination can be calculated as follows:

$$R^2 = \frac{SSreg}{SStotal} \tag{22}$$

The other parameters for example the amount of total sum of squares, sum of squares due to regression, sum of squares due to residual and F-ratio can be calculated using the following formulae:

$$SStotal = \sum_{i=1}^{n} (y_i - \bar{y})^2 \tag{23}$$

$$SSreg = \sum_{i=1}^{n} (\hat{y}_2 - \bar{y})^2 \tag{24}$$

$$SSresidual = SST - SSregression \tag{25}$$

$$MSregression = \frac{SSregression}{DF_{regression}} \tag{26}$$

$$MSresidual = \frac{MSregression}{DF_{residual}} \tag{27}$$

$$F - Ratio = \frac{MSregression}{MSresidual} \tag{28}$$

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