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INVESTIGATION AND PREDICTION THE PERMEABILITY OF WOOLLEN FABRICS

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Abstract: The water vapor and air permeability properties of fabrics are the determining factors for thermal comfort. It is stated in the literature that the hygroscopic structure of wool fibre and the fibre surface properties improve the water vapor permeability property, thus increasing the sense of comfort. In this study water vapor and air permeability of 16 woollen fabric were investigated. It was shown that the effect of finishing process, weave type and raw material on air permeability is significant. In case of water vapor permeability, the effect of finishing process and weave type was found to be significant in the 95% confidence interval, while the effect of raw material was not found to be significant. Furthermore, permeability properties of woollen fabrics were predicted both multiple linear regression and artificial neural network. The R^2 values of the models were 0.989 and 0.485 obtained with multiple linear regression and 0.988 and 0.773 obtained with artificial neural network, for air and water vapor permeability, respectively. Results of the artificial neural network were quite good especially for water vapor permeability.

Keywords: Air permeability, Water vapor permeability, Artificial neural network, Linear regression, Woollen fabric

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1. Introduction

Physiological comfort is expressed as ensuring the thermal balance between the human body and the environment and keeping the body within certain temperature limits. Under extreme conditions where the body cannot provide this balance with its own thermoregulation mechanism and cannot regulate body temperature, clothing selection is very important to provide comfort. In this case, clothing helps to maintain thermal balance by preventing or facilitating heat exchange between the body and the environment (Varshney et al., 2010; Bogusławska-Bączek and Hes, 2013). Since environmental and human factors affecting the microclimate cannot be directly intervened, it is possible to provide a feeling of comfort only by changing the properties of the clothing (Erenler and Oğulata, 2015).

For ideal clothing comfort, clothing design should consider high thermal resistance to protect from cold, low water vapor resistance for efficient heat transfer under mild thermal stress, and fast liquid transport properties to improve heat transfer under high thermal stress conditions (Bedek et al., 2011). Clothing should have good water vapor and liquid moisture transmission properties to ensure thermophysiological wearing comfort (Maqsood et al., 2016).

People produce heat rapidly during activities such as resting, exercising and working, and the body's cooling system begins to sweat to remove this excess heat produced in the body. When sweat evaporates from the skin or fabric surface, water vapor transmisses this excess heat; thus, the body's comfort is maintained. The transfer of sweat from the skin surface by clothing depends on two main factors. The first is that the clothing allows sweat to evaporate from the skin surface during activities, and the other is that the moisture contained in the clothing is removed for rapid drying at the end of the activity (Das et al., 2007; Öner et al., 2013).

Textile clothing is a capillary and porous material system with different pore sizes and can be saturated with both liquid and gaseous water during wear. The transfer of sweat through this material system at different temperatures is a very complex process that includes convection, capillary flow, penetration, molecular diffusion, evaporation and solidification (Das et al., 2012).

Water vapor permeability is the ability to transport water vapor out of the body. It also indicates the amount of moisture passing through a textile material. The fabric must allow sweat to pass through, otherwise it will be uncomfortable. It is also important to reduce the reduction of thermal insulation caused by moisture accumulation. When the amount of evaporated sweat is very small compared to that produced, moisture accumulates in the inner layer of the fabric system, reducing the thermal insulation of the garment and causing undesirable body heat loss. Therefore, moisture transport through textiles plays an important role in ensuring comfort in both hot and cold weather and during normal and high activity (Benltoufa et al., 2024).

Structural and geometrical properties of fibres, yarns and fabrics can affect the water/moisture vapor transmission of textiles. Water vapor resistance mainly depends on the air permeability of the fabric and is an important parameter in determining thermal comfort. Studies have shown that fabric properties such as fibre type, yarn count, weave pattern, fabric weight, fabric thickness, fabric density, porosity and air permeability are related to water vapor resistance (Bedek et al., 2011; Das et el., 2012; Karaca et al., 2012).

Air permeability is defined as the volume flow rate per unit area when there is a certain pressure difference between the two sides of the fabric and this property affects the comfort sense of the wearer. Many factors such as fibre cross-section, yarn twist, yarn crimp, fabric cover factor, thickness, porosity, fabric texture and the amount of finishing and coating applied to the fabric can affect air permeability. Thermal properties are mainly affected by air permeability (Bedek et al., 2011; Das et el., 2012; Karaca et al., 2012). Due to the structure of yarns and fabrics, a large part of the total volume of a fabric is usually air voids. Air flow within textiles is mainly affected by the pore properties of the fabrics. It is quite obvious that the pore size and distribution are a function of the fabric geometry. Yarn diameter, surface formation techniques, and the number of loops per unit area are the main factors affecting the porosity of textiles. The porosity of a fabric is related to some important properties such as air permeability, water permeability, dyeing properties etc. (Ogulata and Mavruz, 2010).

There are studies in the literature that investigate the properties that affect the water vapor and air permeability of woven fabrics. Das et al. investigated the effect of blend proportion, yarn count and twist level on moisture transmission properties of polyester/viscose blended fabrics. They showed that fabrics produced with finer yarns had lesser air and water vapour permeability. Also, with increase in polyester proportion and decrease in twist level, the air and water vapour permeability of fabrics decrease. Moreover, the response surface equations have been derived by the authors for all properties (Das et al., 2009). Karaca et al. (2012) investigated effects of fibre cross sectional shape and weave pattern on thermal comfort properties. The results of their study showed that because of the higher thickness, lower porosity and closer structure of the fabrics produced with hollow fibres the water vapour permeability and air permeability were lower than fabrics produced from solid fibres. The water vapour permeability and air permeability values of fabrics woven from trilobal fibres were higher than fabrics woven from round fibres in relation with compact structure of the yarns from these fibres. Also, they showed that twill fabrics had higher water vapour and air permeabilities than the plain fabrics due to their higher porosity. Erenler and Ogulata (2015) also indicated that, fabric weight and fibre type were most influential parameters, respectively for relative water vapor permeability (RWVP) and for air permeability. They also predicted RWVP and air permeability by using artificial neural network (ANN). They selected fibre type of weft yarn, weaving pattern, weight, thickness, weft yarn count and weft yarn density as input parameters. They predicted RWVP and air permeability with 0.83 and 0.94 regression values respectively. Maqsood et al. (2016) investigated the effect of weave type and fabric thread density of mechanical and comfort properties of woven fabrics. The results showed that the air permeability of 3/1 twill weave higher than plan fabrics. Also, they concluded that air permeability of the fabrics reduced with increased threads density. Otherwise, they indicated that moisture management capacity of twill fabrics greater than plain fabrics due to better wicking property. Also, moisture management capacity improved with increased threads density. Havlová (2020) concluded that porosity and weight of the fabric were very important for air permeability. Whereas the most important parameters for water vapour permeability were weight of the fabric, thickness of the fabric and yarn fineness. Benltoufa et al. (2024) proposed two mathematical models to predict water vapour resistance of fabrics by using their structural parameters. They validated the models with different weave pattern, weft density and material type.

Although the parameters affecting the water vapor and air permeability properties of fabrics have been investigated in detail in the literature, there are not many studies examining these properties for woollen fabrics. Monika Bogusławska-Bączek and Lubos Hes (2013) evaluated the water vapor transmission properties of wool and wool blend fabrics in both dry and wet conditions. As a result of the study, it was observed that the water vapor resistance increased with the increase in fabric weight, and the increase in the moisture content in the fabric decreased the water vapor permeability. The researchers stated that the hygroscopic structure of wool increased the water vapor permeability. In their study, Zhou et al. (2007) measured the moisture transmission properties of six types of jersey or vanized fabrics produced by combining wool and wool with polyester or cotton. As a result of the study, it was stated that the moisture transfer and distribution properties could be improved with fabric design and finishing processes. In addition, it was stated that the moisture spreading property of the fabric produced as wool/cotton vanized was better than other fabrics and showed good moisture management properties. Li (2005) stated in his study that participants felt warmer, drier and more comfortable when wearing woollen clothes compared to acrylic clothes in rainy conditions. Tashkandi et al. (2013) examined the thermal comfort properties of plain-woven fabrics that were dyed black and chemically treated to reflect solar energy. The fabrics used in the study were made of 100% wool and two different ratios of polyester/wool blends. It is stated that the water vapor resistance value of the 100% wool fabric was the highest among the three fabrics due to it being the thickest and heaviest fabric. Behera and Mishra (2007) stated that water vapor permeability is affected by fabric thickness and weight. It is stated that 100% wool and combinations of wool with protein fibres such as silk show higher water vapor transmission. The researchers explained this with the fineness of the fibre used and suggested that the high specific surface area of the fine fibres increases vapor permeability. In the study, it was found that synthetic blends generally show low permeability. It is stated that the hygroscopicity and curled structure of wool fibre provides openness in the fabric and therefore wool fabrics have higher permeability values. Atmaca et al. (2015) investigated the air permeability properties of woollen fabrics. They concluded that increase warp and weft frequency increase air permeability, and as weft density increases, porosity decreases. Also, they expressed increasing air permeability can cause a reduction in water vapor permeability values.

The water vapor and air permeability properties of fabrics are the determining factors for thermal comfort. It is stated in the literature that the hygroscopic structure of wool fibre and the fibre surface properties improve the water vapor permeability property, thus increasing the sense of comfort (Zhou et al., 2007). In order to determine the fabric parameters for manufacturing fabrics with demanded properties, predicting properties of fabric before production is important. Linear (Manshahia and Das, 2014; Neway, 2021; Asfand et al., 2024) and nonlinear regression (Irandoukht and Irandoukht, 2011), response surface (Afzal et al., 2014 a, b) and ANN (Shabaridharan and Das, 2013; Erenler and Oğulata, 2015; Ghorbani et al., 2015; Baghdadi et al., 2016; Li et al., 2020) methods have been used for predicting permeability properties of textile fabrics in the literature. However, it has been observed that there are limited studies on the permeability properties of wool fabrics and the estimation of these properties.

In the study, the water vapor permeability properties and air permeability values of some woollen fabrics obtained from YÜNSA A.Ş. were evaluated together with their fabric constructions. 16 different woollen fabrics were used in the study. The yarn count and twist values, fabric weight, warp and weft densities, fabric thicknesses and weave patterns of these fabrics, where different raw materials were used and different finishing processes were applied, were determined, and porosity and covering factor values were calculated. The water vapor permeability and air permeability values of the fabrics were measured and the relationship between the obtained values and the fabric parameters was investigated. The effects of raw material, weave type and finish on the permeability values of the fabrics were statistically examined. In addition, these values were estimated with the structural parameters of the fabrics using multiple linear regression (MLR) and ANN.

2. Materials and Methods

16 different wool and wool blend fabrics were used in the study. The wool fibres used in the fabrics are in the range of 18-21 microns. Fabric parameters are shown in Table 1. Type 1 and Type 2 finishes given in the table are the processes of YÜNSA A.Ş. The workflows for finishing processes were given below.

Type 1: Washing- Drying- Singeing- Washing- Drying- Fixation- Autoclave decatizing- Steaming-

Type 2: Washing- Drying- Singeing- Washing- Drying- Fixation- Autoclave decatizing- Superfinish

Table1. Fabric parameters

Fabric Code	Raw Material	Finishing Type	Weave Type	Warp Yarn Count (Nm)	Warp Yarn Twist (t/m)	Weft Yarn Count (Nm)
1	Wool	Type1	Plain	26	550S	37
2	Wool	Type1	Plain	30	667S	37
3	Wool	Type1	Plain	32	667S	37
4	Wool	Type1	Plain	32	667S	37
5	Wool	Type1	Twill 3/1	32	667S	37
6	Wool	Type1	Twill 2/1	32	667S	37
7	Wool	Type1	Twill 3/1	38	667S	37
8	Wool	Type1	Twill 2/1	38	667S	37
9	Wool	Type1	Cross Twill	45	667S	56
10	Wool	Type1	Twill 2/2	32	667S	48
11	Wool	Type1	Cross Twill	32	667S	48
12	Wool /PES	Type1	Cross Twill	38	667S	56
13	Wool/ PES/ PA	Type1	Hopsack 2/2	45	750S	56
14	Wool/ PES/ PA	Type2	Twill 2/1	45	750S	56
15	Wool/ PES/ PA	Type2	Twill 2/2	45	750S	56
16	Wool/ PES/ PA	Type2	Twill 2/2	45	750S	56

The yarn count and twist used in the fabrics were obtained from YÜNSA A.Ş. The twist of the weft yarns was fixed as 600Z (t/m). The fabric weight, thickness and weft and warp density measurements of the fabrics were carried out after the fabrics were conditioned for 24 hours under standard atmospheric conditions (20°C ±2 temperature, 65% ±4 relative humidity).

Fabric weights were determined according to the TS EN 12127:1999 and fabric density according to the TS EN ISO 7211-2: 2024 standard. The fabric thickness values were measured on the SDL Atlas brand digital fabric thickness tester according to TS 7128 EN ISO 5084:1998 standard.

Fabric porosity consists of micro gaps between yarns and micro gaps between fibres. In the study, porosity was calculated by the ratio of fabric density to fibre density (Equation 1) (Çay and Tarakçıoğlu, 2008).

$$\varepsilon = 1 - \frac{\rho_a}{\rho_b} \quad (1)$$

where, ρ_a is the fabric density (g/cm^3) and ρ_b is the fibre density (g/cm^3). Fabric density is found by the ratio of fabric weight to fabric thickness. Cover factor of the fabric is the part of the fabric surface covered with yarn and calculated according to equation (Equation 2).

$$CF= (Dc \times dc+Dm \times dm-dc \times dm \times Dc \times Dm)x100 \quad (2)$$

where, CF is the cover factor, Dc is the weft density (1/cm), Dm is the warp density (1/cm), dc is the weft yarn diameter (cm) and dm is the warp yarn diameter (cm), respectively (Militký et al., 2001). For the calculation of the cover factor according to equation (Equation 2), required yarn diameters were obtained from the formula below (Equation 3):

$$\nu_y = \pi \frac{d^2}{4} 100\ N_m \quad (3)$$

Here ν_y is the specific volume of the yarn (cm^3/g), d is the diameter of yarn in cm and Nm is the yarn number in Nm. Yarn specific volumes were calculated according to the Equation 4, assuming that Pierce's 0.59 packing constant is valid for all fibre types (Önder, 1995).

$$\text{Packing constant} = \rho_c/\rho_b \quad (4)$$

where, ρ_c is the yarn density and ρ_b is the fibre density. While calculating the yarn densities, the weighted ratio was used for fibre density in blended yarns [31]. Also, moisture content of fabrics calculated with the weighted ratio of equilibrium moisture content of fibres. Moisture content values were used for different raw materials in predicting models. In the covering factor calculations, the possible effects of finishing processes on the yarn diameter were neglected.

The water vapor permeability tests of the fabrics were carried out in accordance with BS 7209:1990 standard on the PRO-SER Testing Technologies, K032 Model Water Vapor Permeability Tester. According to this standard, fabrics are placed on containers containing distilled water and the device head is rotated at a speed of 2 rpm for at least 1 hour to balance. At the end of 1 hour, the weight of each fabric, including the container and water, is recorded. Then, the containers are placed in the device in the same way and rotated at the same speed for at least 5 hours, and at the end of the process, their weights are measured again. The water vapor permeability values of the fabrics are calculated according to the Equation 5.

$$\text{WVP} = 24M/At \quad (5)$$

where, WVP is the water vapor permeability value of the fabric in g/m^2/day, M is the mass loss at time t (g), A is the area of the container (m^2) and t is the time (h). Three measurements were performed from each fabric used in the study and the water vapor permeability values of the fabrics were calculated by taking the average of the mass losses (M).

The air permeability of the fabrics was measured in accordance with the TS 391 EN ISO 9237: 1999 standard in the unit of l/m^2/s under 100 Pa pressure using a 20 cm^2 measuring head on the PRO-SER Testing Technologies, Prowhite Airtest II. Tests were performed from front of the fabrics and the average of 10 tests were taken for each fabric.

Variance analyses and regression analyses were performed with SPSS. For ANN models MATLAB®R2022a was used. ANNs are preferred in many textile applications due to their flexibility and performance in solving nonlinear problems.

3. Results and Discussion

The experimental results of the fabrics used in the study are shown in Table 2, water vapor permeability and air permeability values are shown in Figures 1 and 2.

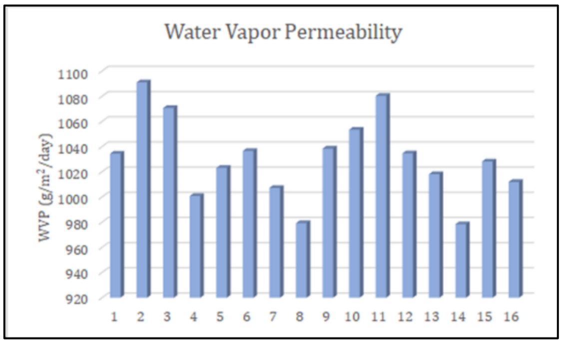


Figure 1. Water vapor permeability values.

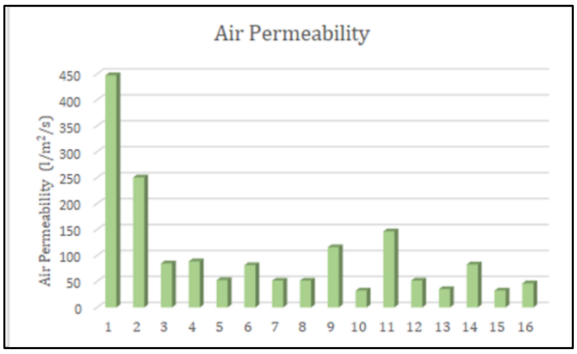


Figure 2. Air permeability values.

Table 2: Fabric properties

Fabric Code	Fabric Weight (g/m²)	Warp Density (ends/cm)	Weft Density (picks/cm)	Thickness (mm)	Porosity (ε) %	Cover Factor
1	146.07	21	24	0.290	61.26	76.94
2	154.63	25	23	0.275	56.75	78.89
3	172.47	28	27	0.285	53.45	84.50
4	177.50	28	28	0.295	53.72	85.27
5	190.77	31	29	0.325	54.85	88.67
6	176.10	32	26	0.315	57.00	87.83
7	211.80	42	30	0.355	54.11	95.56
8	212.13	46	28	0.375	56.49	98.44
9	189.20	34	28	0.310	53.05	82.04
10	184.13	32	33	0.308	53.94	89.54
11	197.20	33	36	0.440	65.52	91.80
12	163.93	38	36	0.250	50.95	91.58
13	156.90	38	38	0.220	44.94	91.00
14	152.80	38	33	0.230	48.52	88.52
15	158.97	38	38	0.215	43.37	90.58
16	160.07	30	39	0.250	50.96	85.99

3.1. Statistical Analysis

Firstly, it was examined whether the raw material, weave type and finishing process had an effect on the water vapor and air permeability values of the fabrics. For this purpose, independent t-test and univariate analysis were performed using SPSS. Analysis results according to 95% confidence interval are given in Table 3-5. When Table 3-5 is examined, it is seen that the effect of finishing process, weave type and raw material on air permeability is significant. In case of water vapor permeability, the effect of finishing process and weave type was found to be significant in the 95% confidence interval, while the effect of raw material was not found to be significant.

When we compare the fabrics with codes 1, 2 and 3, which have the same raw materials, finishing and weave types and similar weights, it is possible to say that there is a dramatic decrease in the air permeability value with the increase in the fabric density and therefore the cover factor and the decrease in porosity. This result is also consistent with the literature. Porosity and cover factor are known as the most important parameters for air permeability. When the water vapor permeability of the same fabrics is examined, it is possible to say that the water vapor permeability value decreases with the increase in thickness. When we make the same comparison between the fabrics with codes 14, 15 and 16, which have different weave types with same raw materials and finishing types and similar weights, it is seen that the water vapor permeability value of the fabric with code 15, which has the lowest thickness, is the highest. The fact that the fabric with code 14 has a higher air permeability value despite similar porosity and cover factor values can be explained by the difference in weave type. Since Twill 2/1 has more connection points than Twill 2/2 in equal report sizes, air permeability is higher in similar fabric density.

When we compare the weave types of fabrics with codes 4, 5, 6, 9 and 10, with the same weight, raw material and finishing process, it is seen that twill 2/2 has the highest cover factor and the lowest air permeability value with the least connection points in equal report size. It is possible to say that cross twill fabric has a lower cover factor and higher air permeability value due to thinner yarns. Water vapor permeability value of plain fabric is lower than twill fabrics according to the literature (Karaca et al., 2012). This is followed by Twill 3/1, Twill 2/1, Cross twill, Twill 2/2, respectively. Here, parameters such as thickness, porosity, cover factor and yarn fineness are effective.

In order to evaluate the difference in the finishing process, fabrics with the same raw material, similar weights, and equal float numbers in the texture report were compared with coded 13 and 15. Although the density, thickness, porosity and covering factor values were close, the water vapor permeability of the type 1 finish was found to be lower and its air permeability was found to be higher. The difference between the air permeability values was significant according to the 95% confidence interval (P:0.002<0.005).

Table3. Results of independent t-test regarding finishing process for water vapor permeability and air permeability at 95 % confidence level

Test Variable	t	df	P-value
Water Vapor Permeability	2.254	46	0.029*
Air Permeability	5.732	155.928	0.000*

*= Statistically significant according to α=0.05

Table 4. Results of univariate variance analyses in interaction model for water vapor permeability at 95 % confidence level

Source	Sum of Squares	df	Mean Square	F	P-value
Raw Material	5185.300	2	2592.650	2.469	0.098
Weave Type	17048.431	5	3409.686	3.247	0.015*
Raw Material * Weave Type	14.463	1	14.463	0.014	0.907
Error	40956.223	39	1050.160		
Total	51030000	48			

*= Statistically significant according to α=0.05

Table 5. Results of univariate variance analyses in interaction model for air permeability at 95 % confidence level

Source	Sum of Squares	df	Mean Square	F	P-value
Raw Material	43929.133	2	21964,567	3.685	0.027*
Weave Type	609369.625	5	121873.918	20.447	0.000*
Raw Material * Weave Type	288.300	1	288.300	0.048	0.826
Error	900036.625	151	5960.507		
Total	3431760.000	160			

*= Statistically significant according to α=0.05

3.2. Linear regression

In this section, the water vapor and air permeability of 16 woollen fabrics used in the study were tried to be estimated by linear regression. In the air permeability estimation, the categorical variables were initially selected as finishing and weave types, and the numerical variables were moisture content, warp count, warp twist, weft count, fabric weight, warp and weft density, fabric thickness, porosity, cover factor. In addition to these variables, air permeability was also used as a numerical variable in the estimation of water vapor permeability values.

For modelling, predictors should be in numeric form, so categorical variables as finishing and weave types were converted to dummy variables. Finishing type can take only two values, and "0" indicates Type 1 and "1" indicates Type 2 (Malik et. al, 2014).

Due to weave types of fabric has six categories, five dummy variables (D1, D2, D3, D4, D5) for weave types were defined (Hristian et. al., 2017). The dummy variables are given in Table 6.

Table 6. Definition of dummy variables

Weave Type	D1	D2	D3	D4	D5
Plain	1	0	0	0	0
Twill 2/1	0	1	0	0	0
Twill 3/1	0	0	1	0	0
Twill 2/2	0	0	0	1	0
Hopsack 2/2	0	0	0	0	1
Cross Twill	0	0	0	0	0

The model with five dummy variables is given below. Y represents dependent variable and X's represent independent variables.:

$$Y = a_0 + a_1 D_1 + a_2 D_2 + a_3 D_3 + a_4 D_4 + a_5 D_5 + b_1 X_1 + b_2 X_2 + \cdots + b_k X_k + \varepsilon \quad (6)$$

Regression equation (7) for cross twill fabrics is (D_1, D_2, D_3, D_4, D_5=0):

$$Y = a_0 + b_1 X_1 + b_2 X_2 + \cdots + b_k X_k + \varepsilon \quad (7)$$

Regression equation (8) for plain fabrics is (D_1= 1; D_2, D_3, D_4, D_5=0):

$$Y = (a_0 + a_1) + b_1 X_1 + b_2 X_2 + \cdots + b_k X_k + \varepsilon \quad (8)$$

Regression equation (9) for Twill 2/1 fabrics is (D_2= 1; D_1, D_3, D_4, D_5=0):

$$Y = (a_0 + a_2) + b_1 X_1 + b_2 X_2 + \cdots + b_k X_k + \varepsilon \quad (9)$$

Regression equation (10) for Twill 3/1 fabrics is (D_3= 1; D_1, D_2, D_4, D_5=0):

$$Y = (a_0 + a_3) + b_1 X_1 + b_2 X_2 + \cdots + b_k X_k + \varepsilon \quad (10)$$

Regression equation (11) for Twill 2/2 fabrics is (D_4= 1; D_1, D_2, D_3, D_5=0):

$$Y = (a_0 + a_4) + b_1 X_1 + b_2 X_2 + \cdots + b_k X_k + \varepsilon \quad (11)$$

Regression equation (12) for Hopsack 2/2 fabrics is (D_5= 1; D_1, D_2 D_3, D_4=0):

$$Y = (a_0 + a_5) + b_1 X_1 + b_2 X_2 + \cdots + b_k X_k + \varepsilon \quad (12)$$

In the modelling performed with the "Enter method", the variables with a Pearson coefficient less than 0.3 were removed from the equation in the next stage. Beside this, for avoiding multicollinearity some independent variables (>0.8) were neglected from the analyses. The R^2 values of the regression equations obtained in this way were found as 0.987 and 0.485 for air and water vapor permeability, respectively. With these results, it can be said that the relationship between fabric parameters and WVP values is not linear. Although there is a certain correlation between air permeability and water vapor permeability, they do not represent the same physical phenomenon. Water vapor permeability depends not only on the porosity of the fabric but also on additional parameters such as the hygroscopic nature of the fibers, moisture transfer mechanisms, and capillary interactions. Therefore, while a high coefficient of determination (R^2) may be obtained for air permeability, a comparatively lower R^2 value for water vapor permeability is considered normal. The regression equations (13 and 14) and the variance analysis tables of the models are given below (Table 7and 8).

$$Air\ Permeability = -586.320 + 143.284 * D1 + 25.467 * D2 + 150.415 * D3 + 26.415 * D4 + 29.960 * D5 + 4211.479 * Moisture\ Content + 7.845 * Warp\ Count - 1.073 * Warp\ Twist + 5.629 * Weft\ Count - 8.290 * Fabric\ Weight + 15.034 * Warp\ Density + 1.867 * Weft\ Density + 19.624 * Porosity \quad (13)$$

$$Water\ Vapor\ Permeability = 806.521 - 35.759 * Moisture\ Content + 0.396 * Warp\ Twist - 2.409 * Warp\ Density + 2.195 * Porosity - 0.807 * Cover\ Factor - 41.840 * Finishing\ Type + 0.012 * Air\ Permeability \quad (14)$$

Table 7. Variance analysis of air permeability model

	Sum of Squares	df	Mean Square	F	Sig.
Regression	521813.264	13	40139.482.469	275.638	0.000*
Residual	4951.216	34	145.624		
Total	526764.479	47			

*= Statistically significant according to 95%confidance interval

Table 8. Variance analysis of water vapor permeability model

	Sum of Squares	df	Mean Square	F	Sig.
Regression	7641.075	7	1091.582	1.077	0.454
Residual	8107.208	8	1013.401		
Total	15748.283	15			

*= Statistically significant according to 95%confidance interval

While the value obtained by MLR for air permeability was quite good, the R^2 value of water vapor permeability was found to be quite low. As stated in the literature, it can be said that there is no linear relationship between water vapor permeability and fabric parameters. In addition, it was observed that the regression equation obtained for water vapor permeability was not statistically significant.

3.3. Artificial Neural Network (ANN)

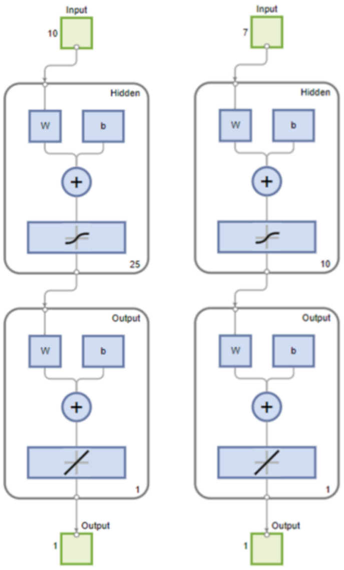
When we examine the coefficients of determination, it is clear that MLR analysis can be suitable for air permeability values, but another method should be used for water vapor permeability values. For this reason, ANN, which is also suitable for non-linear problems, was used to estimate.

Multi-layered back propagation feed forward neural network was used to predict the WVP and Air permeability properties of woollen fabrics. Neural Net Fitting App (Nftool) of MATLAB®R2022a was used for prediction using ANN. The same predictors in regression models were chosen as inputs. 60% of samples was used for training, 20% was used for validation and 20% was used for testing. The training set is used to determine the adjusted weights and biases of ANN. Levenberg-Marquardt training algorithm with back propagation was chosen in accordance with the literature [27]. Due to its modified architecture feedforward multilayer perceptron (MLP) is the most widely used algorithm. In the backpropagation algorithm which is usually used to train the MLP, the values of the weights and bias variables were adjusted backward from the output to the input layer according to the calculated prediction error (Malik et al., 2017). Root Mean Square Error (RMSE) and coefficient of determination (R^2) values were used for evaluate the performance of models. RMSE is given by following equation (15):

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(Y_e - Y_p)^2}{n}} \quad (15)$$

where n is the number of data-sets for training or testing, Ye is the experimental value and Yp is the predicted output. Lower Root Mean Square Error (RMSE) and higher R^2 values indicate higher model accuracy and better prediction performance respectively.

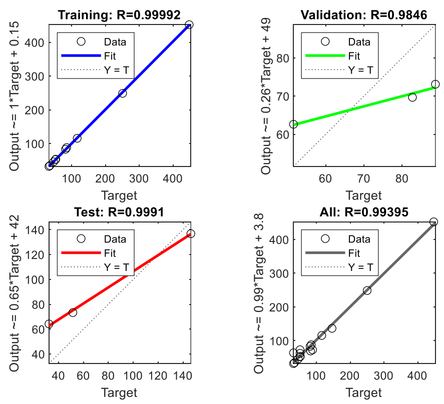
Two-layer feed-forward ANN models were built with one hidden layer and one output layer. Sigmoid function was chosen as transfer function for hidden layer and linear function for output layer (Figure 3). Trials were done for determine hidden neuron numbers and 25 hidden neurons for air permeability model and 10 hidden neuros for water vapor permeability model were selected.



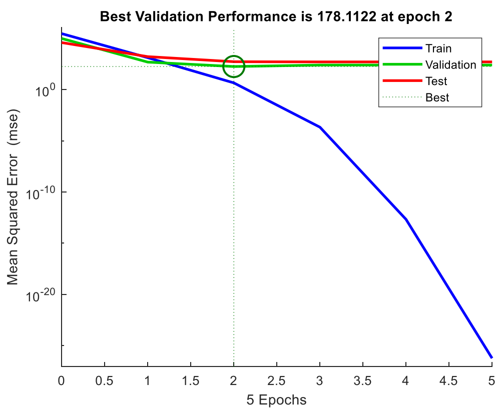
a b

Figure 3. ANN architectures (a) air permeability model (b) water vapor permeability model.

Root Mean Square Error (RMSE) of the selected models were13.346 and 11.699; coefficient of determination (R^2) values of the selected models were 0.988 and 0.773 for air permeability and water vapor permeability, respectively. These results were quite good when compared with MLR model, especially for water vapor permeability. Prediction performances of the models were shown in Figure 4 and 5

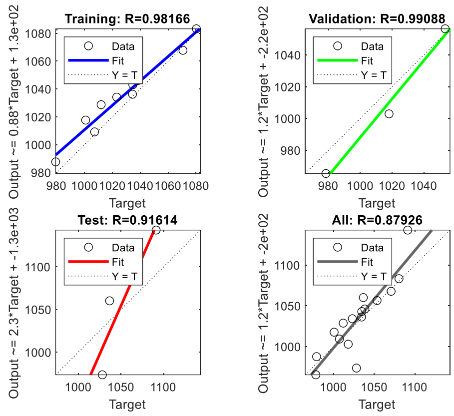


a

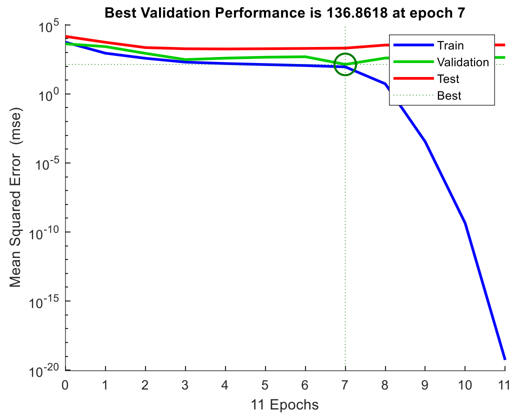


b

Figure 4. Prediction performance of air permeability model (a) R values of model (b) MSE value of model.



a



b

Figure 5. Prediction performance of water vapor permeability model (a) R values of model (b) MSE value of model.

4. Conclusion

In this study, the effect of fibre, yarn and fabric parameters on permeability properties of woven fabrics were investigated. It was shown that the effect of finishing process and weave type were important for both water vapor and air permeability properties. The effect of raw material was significant just in case of air permeability. It was clear that the most important parameters that effect the water vapor permeability was fabric thickness. Porosity and cover factor of the fabrics were prominent for the air permeability. These findings were in accordance with the literature.

Permeability properties of woollen fabrics were predicted by both multiple linear regression (MLR) and artificial neural network (ANN). The R^2 values of the models were 0.987 and 0.485 obtained with MLR and 0.988 and 0.773 obtained with ANN, for air and water vapor permeability, respectively. Results of the ANN were quite good especially for water vapor permeability. Since the ANN is suitable for non-linear problems, results of water vapor permeability were more fitted. The results can be improved by using larger data sets in further studies.

Author's Contributions

The percentages of the author' contributions are presented below. The author reviewed and approved the final version of the manuscript.

	Z.E.K.
C	100
D	100
S	100
DCP	100
DAI	100
L	100
W	100
CR	100
SR	100
PM	100
FA	100

C=Concept, D= design, S= supervision, DCP= data collection and/or processing, DAI= data analysis and/or interpretation, L= literature search, W= writing, CR= critical review, SR= submission and revision, PM= project management, FA= funding acquisition.

Conflict of Interest

The author declared that there is no conflict of interest.

Ethical Consideration

Ethics committee approval was not required for this study because of there was no study on animals or humans.

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