Nazan Avcioğlu Kalebek

Sound Absorbing Polyester Recycled Nonwovens for the Automotive Industry

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University of Gaziantep, Fine Art Faculty, Fashion and Textile Design Department
27310 Gaziantep, Turkey
E-mail: nkalebek@gantep.edu.tr

Abstract
The subject of noise has received an increasing amount of attention from scientists, technologists and the public as a whole because a high noise level may determine the quality of human life. Therefore acoustic insulation is an essential need for both driver and passengers in order to reduce noise related problems. The use of recycled materials in nonwovens provides alternatives for the production of ecologically friendly acoustic products for the automotive industry. Recently noise absorbent textile materials, especially nonwoven structures or recycled materials, have been widely used because of the low production costs and their being aesthetically appealing. This paper reports the acoustic behaviour of needle-punched nonwoven fabrics which were produced with different thickness and mass per unit area. Comparison of the physical properties such as thickness, density, mass per unit area, air permeability, tensile strength and elongation was performed for all samples and data obtained from tests were statistically analysed with Design Expert software. In conclusion, it is observed that air permeability decreases with an increase in the mass per unit area of fabric. Higher air permeability results in higher sound transmission, and therefore less sound insulation.

Key words: *Needle-punched nonwoven, recycled polyester fibers, air permeability, sound absorption coefficient, impedance tube.*

Introduction

Sound is an important part of our life, but unpleasant and unwanted sound is considered as noise [1]. The increase in electromechanical systems in the automotive industry with the development of new technologies has resulted in an increase in noise pollution. Noise pollution poses a significant threat to human comfort. Noise greatly affects day-to-day activities and can even cause various health problems such as sleep disturbance, hearing loss, a decrease in productivity/learning ability/scholastic performance, and an increase in stress related hormones and blood pressure [2, 3]. Therefore it is very important to control or reduce noise from traffic and vehicles [4]. Unwanted and uncontrolled noise should be reduced using a noise barrier and noise absorbers. Recently, recycled nonwovens, as one of the most common textile products, have become important sound absorption materials [5 - 7] because the waste generated from the nonwoven industry has increased gradually every year and caused many serious problems. Factories that manufacture nonwovens normally dispose of the selvages by burying and burning, often leading to environmental pollution and destruction. Recycling and reusing fibrous waste is one of the most important environmental tasks that face the world, to reduce environmental loading and promote the most effective use of resources.

Sengupta [2] (2010), studied the effect of density, fabric type, source intensity, the number of layers, the distance of the fabric from the sound source, the distance of fabric from the receiver, and fibre type on the sound reduction of various needle-punched nonwoven fabrics by using a sound insulation box. As a result, higher area density is responsible for higher sound reduction. There is a negative correlation between the area density or bulk density of needle-punched nonwoven and sound reduction. With an increase in the number of layers of nonwoven fabric, the sound reduction through the fabric increases initially, but after the maximum it remains almost unaltered. Carvalho [8] et al (2012) report a qualitative analysis of the acoustic insulation behavior of thermo-bonded nonwoven fabrics performed in an insulating box. Nonwoven fabrics were produced from mineral wool and recycled fibres, which was a mixture of polypropylene, acrylic, cotton and polyester. The mass per unit area, thickness and density of the samples were different. Some samples were laminated with aluminum foil. In conclusion, that laminated with aluminum foil exhibited better sound reduction performance than other single layered nonwovens made from recycled fibres and even better performances than those made from mineral wool. According to the studies carried out by Dias and Ozturk, thick spacer knitted fabrics are used for the reduction of interior noise in automobiles. These textiles materials are used in the headliner, carpets, seats, door panels and other interior parts. Thick spacer fabrics are used because of being lighter and less expensive. Furthermore their thickness remains unaltered with moisture and compression, unlike porous sound absorbing materials. Sound absorption coefficients of fabrics were tested with the impedance tube method. It was found that knitted structures can be suitable materials to absorb sound in the passenger space within an automobile [9 - 11]. Fibre reinforced composites generally have materials such as glass wool, foam, mineral fibres and their composites. Natural fibre mixed composites have recently been widely studied. The main purpose of these researches was to investigate the effects of ramie, natural fibre and micro fibre on the sound absorption property [12 - 15]. Nonwoven fabrics are ideal materials for use as acoustical insulation products because they have a high total surface. The acoustical properties of fabrics were measured by the impedance tube method, developed to determine the ability of materials for absorbing normal incidence sound waves. The effects of physical parameters on the sound absorption properties of nonwoven fabrics were investigated. In addition to the acoustical properties, the thickness, mass per unit area, strength and elongation, porosity, air permeability and thermal conductivity were measured. According to the studies, the thickness, mass per unit area, density, fibre type, fibre diameter, fibre mixture ratio and production type significantly contribute to sound absorption characteristics of the materials [1, 4, 5, 16 - 22].

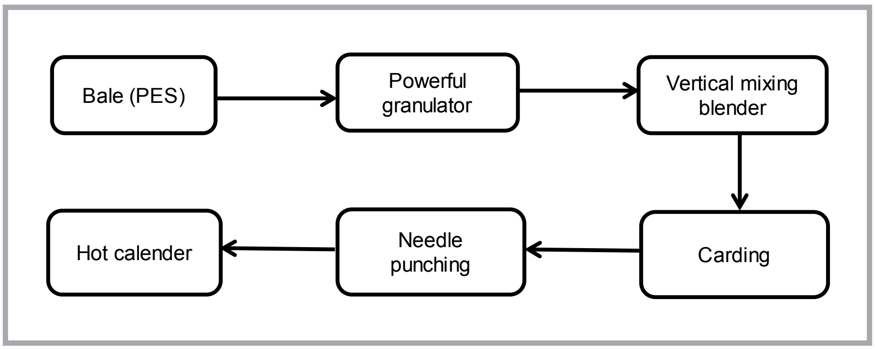

__Figure 1.__ Scheme of production line.

In this research, recycled polyester nonwoven selvages were investigated. Using recycled nonwoven selvages to produce sound absorption composites can reduce the textile waste problem and also help to reuse resources more efficiently. The main purpose of the research was to investigate the effects of the mass per unit area and thickness on the sound absorption property of recycled polyester nonwoven selvages.

Materials and methods

Materials

The use of textiles (Sarıkılıc Textile STS Nonwoven Factory, Usak, Turkey), especially recycled felts, is based on two advantages: low production costs and excellent noise absorption capacity. Before production (***Figure 1***), the bales in the processing area were kept at 23.9 °C temperature and 55% relative humidity. At these conditions, the moisture content on the surfaces of the fibres provided trouble-free processing e.g. low fibre sticking to card wires. Also production lines were cleaned before running the PES fibres to prevent contamination and not lead to the over bonding of fibres. Recycled polyester was shredded into fragments with particles of an appropriate size using a powerful granulator. Afterwards PES nonwoven fragments were weighted on an electronic balance and physically blended in a vertical mixing blender. The first step to prepare the fibres for carding and web formation was carding. The objective was to break down the big pieces of the bundle from the bale into a small manageable size to be fed to a fine opener to further separate it into individual fibre. The carding process was performed 3 times for better evenness, orientation and successful web formation. The webs were then fed to a needling loom containing 4000 needles per running meter. The needle loom was arranged to get a punch density of 100 punch/cm^2. The depth of needle penetration was kept at 12 mm and the type of needles was Groz-Beckert 15×18×32×3 R333 G3027 for all samples. This kind of materials was formed by needle punching nonwovens into several card webs and using a hot calendar for smoothing to produce an automotive nonwoven floor covering. Needle-punching technology was chosen to produce the samples because it was best suited to mouldalibity and good fitting of the floor coverings. Also the physical characteristics of needle-punched nonwoven fabrics, such as softness, bulkiness, conformability, fibrousness, and high strength without a binder make this process unique among those for nonwovens. A good fit is essential for acoustical control. Each sample is produced with different thickness, density and mass per unit area. The ten samples prepared and properties are listed in ***Table 1***.

Methods

Acoustical properties of fabrics are measured by the impedance tube method according to TS EN ISO 10534-2. The equipment used in this experiment consisted of a two-microphone impedance measurement tube type 7758 (PULSE Acoustic Material Testing Bruel & Kjaer and Computer System, Denmark), PULSE Acoustic Material Testing Bruel & Kjaer and computer system, as shown in ***Figure 2***. The sample was fastened to the tube's left rigid wall by a sample holder, and a loudspeaker that can emit sound waves of well-defined frequencies was attached to the right rigid wall. The nodes and anti-nodes of the standing waves emitted by the loudspeaker and those reflected from the sample were detected by a small microphone that can slide along the axis of the tube. In other words, the analyser generates a random signal which is then amplified. Then the frequency weighting unit in the tube was applied to the sound source. Finally the analyser measured the response of the two microphones and calculates the frequency response function between the two microphone channels. From this frequency response function, all test sample data were calculated. The diameter of the tube d is smaller than the wavelength of the emitted sound wave (typically d = 10 cm for f < 1600 Hz and d = 3 cm for f > 1600 Hz), hence the wave can be thought of as a plane wave propagating along the axis of the tube. The value of the sound absorption coefficient is given from 0 to 1, which means sound absorption is zero a at value of 0, reaching the maximum at a value of 1. The sound absorption coefficient indicates how much of the sound is absorbed in the materials. All sound absorption measurements

*__Table 1.__ Technical properties of nonwovens; *MD = machine direction, CD = cross directon.*

Fabric aode	Mass per unit area, g/m^2	Density, g/m^3	Thickness, mm	Porosity, %	Tensile strength, N/5 cm		Elongation at break, %	
					MD	CD	MD	CD
RCP 100	100	0,087	1,15	96,10	59,39	75,00	42,69	54,40
RCP 150	150	0,075	1,99	93,92	60,78	107,68	52,27	71,71
RCP 250	250	0,095	2,62	93,20	72,12	125,00	50,14	75,28
RCP 300	300	0,093	3,21	88,85	76,26	214,87	44,12	79,34
RCP 400	400	0,096	4,15	80,88	137,53	276,43	51,19	81,56
RCP 500	500	0,113	4,41	68,56	161,98	353,36	51,45	87,33
RCP 600	600	0,124	4,82	68,56	313,20	611,60	65,00	89,12
RCP 700	700	0,130	5,40	66,39	458,20	789,40	77,19	92,10
RCP 800	800	0,131	6,12	53,35	574,03	980,47	78,00	95,16
RCP 900	900	0,134	6,73	62,04	793,10	1170	78,23	96,47

were performed 3 times for each sample and the frequency analysis system was set from 100 to 6300 Hz. Test samples (3 cm and 10 cm) were cut randomly at a considerably distance from the fabric selvedges.

In this study, standard test procedures were used to measure the physical properties of the nonwoven fabrics. Mechanical properties of the nonwovens were tested according to ISO standards. The fabric thickness was measured using a thickness tester at a pressure of 0.5 kPa according to ISO 9073-2: 1995, Textiles–Test Methods for Nonwovens-Part 2: Determination of Thickness. The fabric weight was measured according to ISO 9073-1: 1989, Textiles–Test Methods for Nonwovens–Part 1: Determination of Mass Per Unit Area. Fabric strength and elongation were measured inn accordance with ISO 9073-3: 1989, Textiles-Test Methods for Nonwovens, Part 3: Determination of Tensile Strength and Elongation. Air permeability is associated with the porosity of fabric, and thus it was also necessary to calculate the porosity. The theoretical fabric porosity was calculated as follows using the fabric bulk density and fibre density:

$$\Phi = \rho_{fabric}/\rho_{fibre} \times 100 \text{ in } \% \qquad (1)$$

$$\varepsilon = (1 - \Phi) \times 100 \text{ in } \% \qquad (2)$$

where, ε is the fabric porosity in %, Φ the volume fraction of solid material in %), ρ_{fabric} in g/m^3 the fabric bulk density, and ρ_{fibre} in g/m^3 is the fibre density. Recycled polyester fibre density is accepted approximately as 0.138 g/m^3.

All tests were performed under standard atmospheric pressure, 20 ºC and relative humidity of 63 % for 48 h.

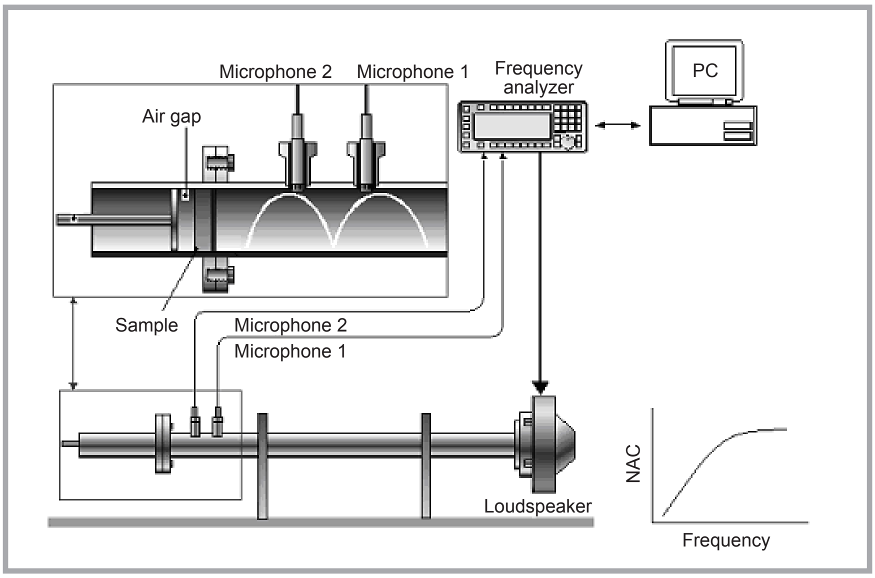

Figure 2. *Impedance tube [1].*

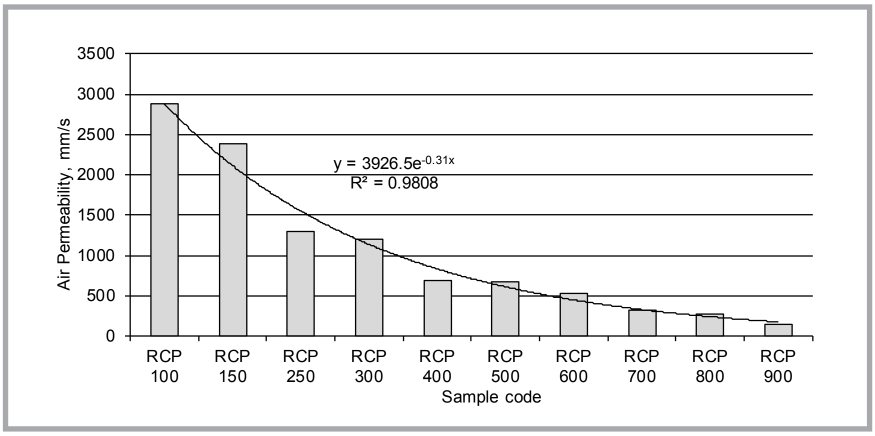

Figure 3. *Air permeability of nonwovens.*

Test results

Air permeability test

One of the most important qualities that influence the sound absorption characteristics of a nonwoven material is the specific flow resistance per unit thickness. Air permeability was obtained by taking the average of 10 samples using an SDL Atlas Air Permeability Tester (USA), the results of which are shown in ***Figure 3***. The tests were conducted according to the EN ISO 9237: 1995 standard by applying 200 Pa constant air pressure to each sample attached to a 20 cm circular holder.

Figure 3 shows the relationship between the air permeability and mass per unit area of the fabric.

As can be seen in ***Figure 3***, air permeability values range from 675 to 2880 mm/s. Obviously the air permeability of nonwoven fabric RCP 100 had the highest value at every fabric area density. The lowest air permeability was found for nonwoven fabrics RCP 900. The increase in fabric mass per unit area causes a reduction in air permeability. By increasing the fabric mass per unit area, the number of fibres in both thw fabric direction (MD and CD) increases and resists the air flow through the fabric. The trend observed was consistent with results reported [23 - 26].

To describe the results in terms of air permeability dependence on the mass per unit area, a polynomial equation is used because it shows the highest determination coefficient. In the equation, x is the fabric surface mass in g/m^2 and y is the air permeability in mm/s. In ***Figure 3***, the dependence of air permeability on the area density is presented. The determination coefficient of the equation obtained is R^2 = 0.9808. As mentioned earlier, these results confirm that air permeability decreases with the increasing density of the samples.

Sound absorption coefficient (α)

Needle-punched nonwoven fabrics used for automotive applications were measured for sound absorption properties, the results of which are shown in ***Figure 4***. The minimum frequency for the sound absorption coefficient is 100 Hz, and a 6300 Hz maximum frequency was used.

As shown in ***Figure 4***, needle-punched nonwoven test material RCP 900 was a better sound absorber at every fabric mass per unit area. The lowest sound ab-

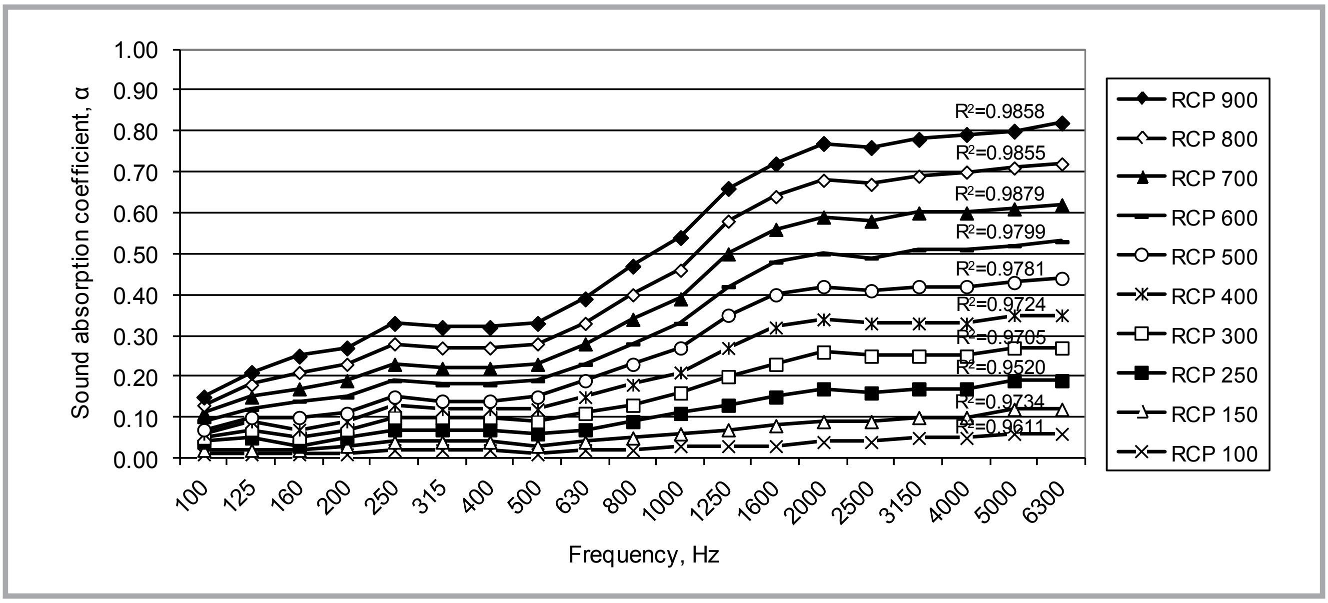

Figure 4. *Sound absorption coefficient of nonwovens.*

sorption coefficient was found from nonwovens fabric RCP 100. In other words, it is apparent that for all samples, while the maximum value of the absorption coefficient occurs at a frequency of 6300 Hz, the minimum value of the absorption coefficient is obtained at a frequency of 100 Hz. At a higher mass per unit area, such as 900 g/m^2, smaller fabric pores are created. As higher pores are emptied, the sound absorption coefficient through the sample increases, and air and sound flow is recorded as a function of acoustic properties. This results in higher overall fabric mass per unit area, which in turn causes a greater portion of the incident sound to be reflected from the fabric, thus preventing the transmission of sound through the material, and hence decreasing the absorption of sound by the fabric. Poor fabric sound absorption at low frequency bonds is due to the complete transmission of sound through the fabrics, which technically can be described as having a tissue-like thickness. The sound absorption of all the nonwoven fabrics rose steadily up to the maximum value at 6300 Hz. The sound absorption of the sample with a mass per unit area of 100 g/m^2 increases steadily up to 0.06 at a frequency of 6300 Hz. For the sample with a 600 g/m^2 mass per unit area and 528 mm/s air permeability, the sound absorption coefficient attains a local peak value of 0.04 at 250 Hz. After a slight decrease between 315 and 630 Hz, the sound absorption of the materials increases steadily up to a maximum value of 0.09 at a frequency of 6300 Hz.

Table 2. *Statistical significance analysis of sound absorption coefficient.*

Source	Sound absorption coefficient					
	Sum of squares	Degree of Freedom (DF)	Mean squares	F-V	P-V	Significance
Model	0.12	14	8.868E-003	116.89	< 0.0001	Significant
M	3.007E-005	1	3.007E-005	0.40	0.5298	
D	2.361E-005	1	2.361E-005	0.31	0.5777	
T	2.598E-005	1	2.598E-005	0.34	0.5591	
F	2.875E-003	1	2.875E-003	37.89	< 0.0001	Significant
M^2	1.817E-005	1	1.817E-005	0.24	0.6252	
D^2	2.741E-004	1	2.741E-004	3.61	0.0590	
T^2	7.649E-006	1	7.649E-006	0.10	0.7512	
F^2	0.024	1	0.024	313.25	< 0.0001	Significant
MD	1.597E-004	1	1.597E-004	2.10	0.1487	
MT	8.730E-006	1	8.730E-006	0.12	0.7348	
MF	5.957E-004	1	5.957E-004	7.85	0.0056	Significant
DT	8.922E-005	1	8.922E-005	1.18	0.2797	
DF	3.116E-004	1	3.116E-004	4.11	0.0442	Significant
TF	7.036E-004	1	7.036E-004	9.27	0.0027	Significant
Residual	0.0130	175	7.587E-005			
Cor Total	0.1400	189				
R^2	0.9034					
R_a^2	0.8957					
R_p^2	0.8806					

Higher air permeability results in higher sound transmission, and hence less sound absorption. The influence of the mass per unit area and frequency can be described by a linear equation with the coefficient of determination approximately R^2 = 0.97. By increasing the mass per unit area and frequency, the sound absorption coefficient of the fabrics increases, which could also be explained by the fact that when the number of fibres in the fabric increases, the fibres get closer to each other in the fabric because of the lack of space between each fibre in the fabric.

Statistical significance analysis

The experimental results were statistically evaluated by using Design Expert Anaysis of Variance (ANOVA) software (USA) with F values of a significance level of α = 0.05, with the intention of exploring whether there is any statistically significant difference between the variations obtained. We evaluated the results based on the F-ratio and its probability (prob > F). The lower the probability of the F-ratio, *i* the contribution of the variation *s* stronger and the variable more significant. The best models for each fabric were obtained and the corresponding regression equations and regression curves fitted. The test results of the related fabrics were entered into the software for analysis of the general design [23, 27].

Table 2 summarises the statistical significance analysis for all the data obtained in the study except the air permeability, which was evaluated separately. In the table, variables are the mass per unit area in g/m^2, density in g/m^3, thickness in mm and sound absorption frequency in Hz. Morever the abrevations in ***Table 2*** are as follows: F-V is the f-value, P-V the p-value, M - the mass per unit area in g/m^2, D - the density in g/m^3, T - the thickness in mm, F - the sound sbsorption frequency in Hz, R_a^2 – the adjusted R^2, and R_p^2 - the R^2 predicted. Here p values of the models smaller than 0.05 are considered to be significant. The ANOVA table also indicates significant interactions between fabric properties and the sound absorption coefficient. The terms M, D, T and F in this table are independent variables (numerical factors), whereas the sound absorption coefficient is a dependent parameter. The term "model" is the sum of the model terms in the ANOVA table. In addition, the "corrected total" (cor total) is the sum of the model and pure error. The regression equations were also developed by considering the ANOVA table.

When ANOVA Table (***Table 2***) is examined, it can be seen that the F of nonwoven fabrics have a significant impact on the sound absorption coefficient values. In addition, when the interaction between and within factors M, D, T and F are examined, it can be said that F^2, MF, DF and TF have significant impacts, whereas M^2, D^2, T^2, MD, MT and DT do not have any significant impacts. The explanatory percentage of the model which confirms data R_a^2 has to be calculated. According to ***Table 2***, the R_a^2 value of the model turned out to be approximately 0.89, in which case the terms in the model can be explained almost 89%. This case shows that the model established for the sound absorption coefficient describes the relation between dependent variables and independent variables with considerably high accuracy and that the experimental study is accepted as accurate.

In the lack of fit test, the model with the highest p value must be chosen. Accordingly the quadratic model with a 0.9565 p value was chosen, which can be seen from ***Table 3***.

Table 3. *Model summary statistics (Sound Absorption Coefficient).*

Source	F-V	Model Summary Statistics				
		Standard deviation	R-squared	Adjusted R-squared	Predicted R-Squared	PRESS
Linear	< 0.0001	0.015	0.7130	0.7068	0.6980	0.041
2FI	0.2398	0.015	0.7254	0.7101	0.6871	0.043
Quadratic	**< 0.0001**	**8.710E-003**	**0.9034**	**0.8957**	**0.8806**	**0.016**
Cubic	< 0.0001	6.019E-003	0.9565	0.9502	0.9383	8.481E-003

Table 4. *Statistical significance analysis of air permeability.*

Source	Air Permeability (mm/s)					
	Sum of squares	Degree of freedom (DF)	Mean Square	F-V	P-V	
Model	7.561E+006	3	2.520E+006	110.66	< 0.0001	Significant
M	7.927E+005	1	*7.927E+005*	34.8	0.0011	
D	3.954E+005	1	*3.954E+005*	17.36	0.0059	
T	1.442E+006	1	*1.442E+006*	63.29	0.0002	
Residual	1.367E+005	6	22777.32			
Cor Total	7.698E+006	9				
R^2	0.9822					
R_a^2	0.9734					
R_p^2	0.9449					

Table 5. *Model summary statistics (Air Permeability).*

Source	F-V	Model Summary Statistics				
		Standart deviation	R-squared	Adjusted R-squared	Predicted R-squared	PRESS
Linear	**< 0.0001**	**150.92**	**0.9822**	**0.9734**	**0.9449**	**4.244E+005**
2FI	0.4016	138.72	0.9925	0.9775	0.6791	2.471E+006
Quadratic	0.6723	22.24	0.6729	0.6310	0.5846	1.030E+002
Cubic	0.8713	12.76	0.4578	0.4714	0.4200	1.005E+008

A normality test (normal distribution test) was also applied to the data obtained from sound absorption test by changing M, D,T and F. The result is demonstrated in ***Figure 4***. In general, probability plotting is a graphical technique for determining whether the sample data conform to a hypothesised distribution based on a subjective visual examination of the data. The assessment is very simple: From the data, which are scattered around the normality line, as shown in ***Figure 5***, we can see that they conform to normal distribution. This analysis also supports the conformity of the model chosen.

Regression ***Equation 1*** for determining the sound absorption coefficient is presented below.

$$\begin{aligned}\text{Sound absorption coefficient} = \\ + 0.21 + 0.45\times M - 0.087\times D + \\ -0.34\times T + 0.017\times F + \\ - 0.47\times M^2 - 0.120\times D^2 - 0.21\times T^2 + \\ - 0.036\times F^2 + 0.50\times M\times D + \\ + 0.570\times M\times T - 0.050\times M\times F + \\ - 0.39\times D\times T + 0.014\times D\times F + 0.042\times T\times F\end{aligned}$$

A similar analysis was made on the relation between the fabric air permeability, fabric mass per unit area in g/m^2, density in g/m^3 and thickness (mm) properties for all samples obtained from experimental studies for air permeability using the Design Expert 6.01 statistical package program. When the ANOVA Table (***Table 4***) is examined, it can be seen that M, D and T of the nonwoven fabrics have a significant impact on the air permeability values. The statistical analysis indicates that the sound absorption frequency has a significant influence by having a 63.29 F-value. The explanatory percentage of the model which confirms data R^2 has to be calculated. According to ***Table 4***, R_a^2 of the model turned out to be 0.97, in which case the terms in the model can be explained almost 97%. This case shows that the model established for air permeability describes the relation between dependent and independent variables with

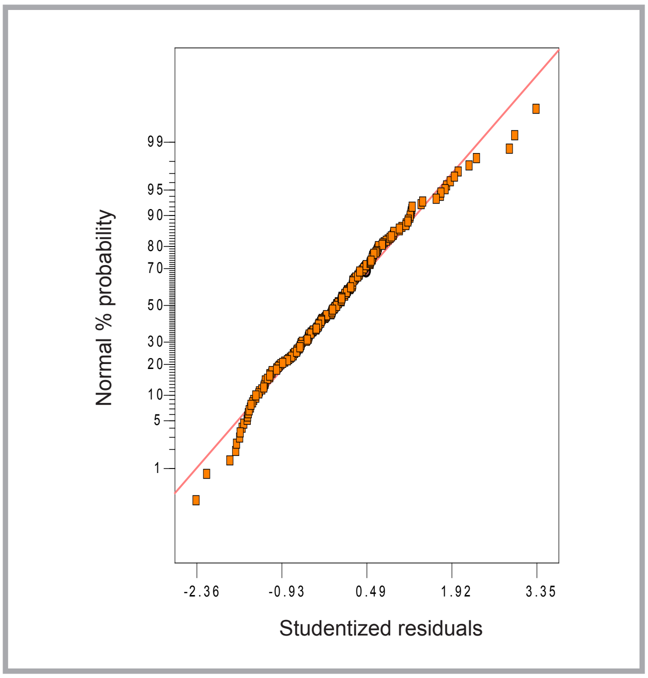

Figure 5. *Normality test for sound absorption coefficient of samples.*

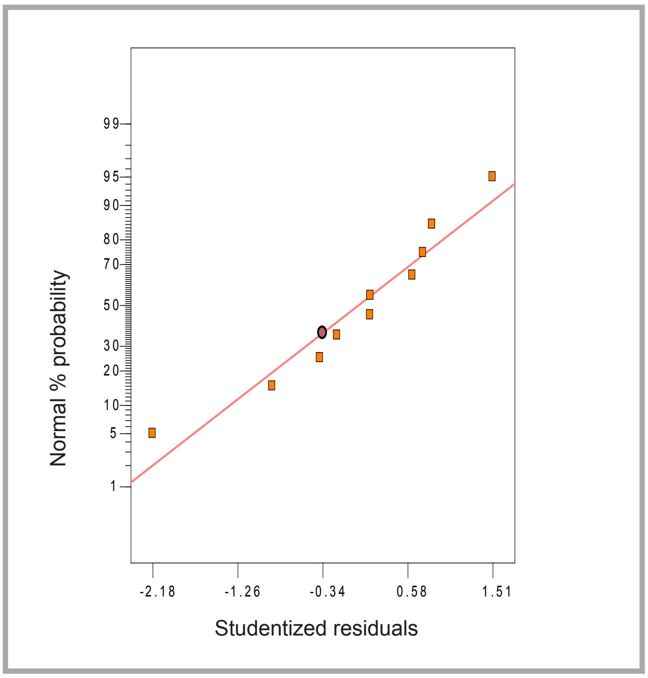

Figure 6. *Normality test for air permeability of samples.*

considerably high accuracy and experimental study is accepted as accurate.

In the lack of fit test, the model with the highest R_a^2 value must be chosen. Accordingly the linear model with 0.95 was selected, which can be seen in ***Table 5***.

Figure 6 gives a normal distribution graph of residuals for the linear model. As can be seen from the figure, no problems were observed in the normal distribution in the model chosen. This analysis also supports the confirmity of the model chosen. Consequently the regression equation of the model determined was found as

$$\text{Air permeability} = +6989.91779 + \\ +10.45554 \times M - 39003.36283 \times D + \\ -1643.43877 \times T$$

where, M express the mass per unit area, D express density and T express thickness in the equation.

Discussion and summary

Textile products, especially nonwoven fabrics, can help to control the effects of noise pollution. Acoustic comfort has become more important for human health recently [10]. The automotive materials market exhibits high potential because of the requirements for increased driving comfort and the search for alternative environmentally recycled materials [16].

A variety of nonwoven fabrics were produced with different physical parameters and evaluated in terms of their acoustic property for sound absorption. The Impedance tube instrument was used to measure the sound absorption coefficient.

The research on the air permeability and sound absorption coefficient of samples with different structure parameters can be summarised as follows;

- The fabric mass per unit area and thickness in needle-punched nonwoven fabrics affected the sound insulation positively.
- Porosity and air permeability have a significant correlation. A high porosity structure leads to an increase in air permeability.
- Fabric air permeability is a very important parameter for acoustical insulation of nonwoven fabrics. As the fabric mass per unit area increased, the air permeability decreased due to increased resistance to air flow caused by consolidation of the web. Therefore there is a good relation between the area density and air permeability for all kinds of nonwoven samples. The experimental results are best described by a polynomial equation for the function of air permeability to area density. The determination coefficient of the equation obtained is $R^2 = 0.9808$.
- There is a strong correlation between the air permeability, sound absorption coefficient and mass per unit area for all samples.
- At low fabric mass per unit area and thickness, minimal sound absorption occurs. This is due to the ease of sound waves through the fabric and vice versa for high fabric mass per unit area. Because at high mass per unit area, there is a lack of space between each fibre in the fabric.
- Sound absorption of all materials increases steadily up to a maximum value at 6300 Hz.
- Results show that sound absorption ability of all fabric samples is influenced sound absorption frequency, thickness and density.

It is recommended that the same nonwovens can be used for auditoriums, theatres and general rooms.

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