An Investigation into Acoustic Properties of Lightly Needled Estabragh Nonwovens Using the Taguchi Method

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ABSTRACT

Sound pollution has become an important issue that has been addressed by scientists of various disciplines. Control of sound in areas of transport and building industries is of paramount importance. Textiles are widely used as sound insulators. Among the broad spectrum of textiles, nonwoven fabrics due to their technical merits and wide acceptance are extensively used as sound controlling media.

In this work, various blends of polypropylene and naturally grown hollow Estabragh fibers were used to prepare sound absorptive nonwoven layers. The fiber blends were fed to a laboratory scale carding machine. Carded webs were lightly needled on a laboratory scale needling machine. Acoustic properties of needled samples were evaluated using the Impedance tube method. The Taguchi method was used to analyze the effective parameters influencing fabric acoustic properties. Results show that the proportion of Estabragh fibers in the blends strongly affects the noise absorption coefficient (NAC). Frequency is the second effective factor and is followed by nonwoven layer mass (areal density) and punch density, respectively. It was concluded that layers comprised of 100% Estabragh fibers achieved the highest value of NAC. The results also pointed to existence of a direct correlation between noise absorption coefficient and the amount of punch density exerted during needling process. It was found that the increase in the amount punch density resulted in higher values of NAC.

Keywords: Acoustic, Estabragh fibers, needling, noise absorption, nonwoven, punch density, Taguchi method

INTRODUCTION

Sound insulation is a challenging issue, faced by both transport and building industries [1]. Enhancement of passenger comfort in car cabins and interiors of buildings by reduction of noise has become one of the main criteria in designing buildings and various types of transport equipment [2]. Development of new materials in accordance to acoustic principles to be used as sound barriers is a challenging task for scientists and engineers. Sound control can only be successful when sound intensity is reduced to a level that is comfortable for humans. This reduction in noise level can only be achieved by employment of relevant techniques and scientifically designed materials. Absorption of sound by textile structures is both technically and economically one of the most extensively means of noise reduction. Fibrous structures due to their porosity, low mass, and cost are capable of noise absorption, and thus are widely accepted as noise absorptive materials [3]. Reviews of literature [4, 5 and 6] indicate that nonwoven fabrics are the fastest growing segment of the global textile industry [7] and are the preferred textile structures used for noise control.

In general, insulation and absorption properties of various types of nonwoven fabrics depend on fiber geometry and fiber arrangement within the fabric structure. According to Koizumi et al [8] fabric noise absorption coefficient increases as fiber diameter reduces. Fine fibers have better mobility than coarse fibers when subjected to sound wave pressure. Therefore, presence of finer fibers in a fibrous structure leads to the higher tortuosity and airflow resistance. [3].

Voids inherently formed within a nonwoven structure are called pores. The sound energy can be damped through these pores. For this reason, the geometry of pores in a nonwoven structure can affect fabric sound insulation properties [2]. Pore size and its distribution within the fabric affect sound insulation capability. The relation between the thicknesses of materials and noise absorption properties was studied by Ibrahim et al. [9]. It was concluded that at low frequencies, the noise absorption coefficient increases as material thickness increases, while at high frequencies the increase in fabric thickness hardly affects fabric sound insulation. Fabric density also governs noise absorption behavior of materials. In nonwoven fabrics, the number of fibers per unit area increases with apparent fabric density. This in turn enhances frictional resistance offered by the fibers which correspond to improved noise absorption capacity of the fabric [3]. Additionally noise absorption properties of nonwoven fabrics are significantly affected by the structural properties of the constituent fibers. Compared to solid fibers, hollow fibers enhance the absorption properties of fabrics.

Estabragh fiber is a cultivable plant of the Aclepiadacae family. This plant grows wild and produces silky, lustrous, and acicular fibers [10]. Apart from the great geotechnical function of Estabragh shrub such as soil reinforcement especially on hillsides, the extracted fibers from the plant have unique properties in comparison with all other natural fibers. This fiber is very similar to Milkweed fiber of the Asclepia-Syriace family [10, 11] which grows in the United States of America or Rux fiber of the Calotropis-Gigantea family [6, 12] which grows in Southeast Asia. Estabragh fibers have salient properties not associated with man-made or other natural fibers. *Figure 1* shows Estabragh fibers with their pods. *Figure 2* depicts the hollow structure of an Estabragh fiber [13, 14].

FIGURE 1. Estabragh fibers.

There are limited scientific reports on the use of Estabragh fibers in production of commonly defined textile structures. Louis and Andrews [10, 15] believe that Milkweed fibers suffer from low cohesion due to lack of crimp. Thus extreme processing difficulties are encountered during conventional textile operations. These difficulties can be overcome by blending Milkweed with other fibers. Andrews et al. [10, 16] investigated the mechanical and physical properties of cotton/ Milkweed blends. The work of Drean et al. [10, 17] deals with spinning and characterization of yarn using Milkweed fibers.

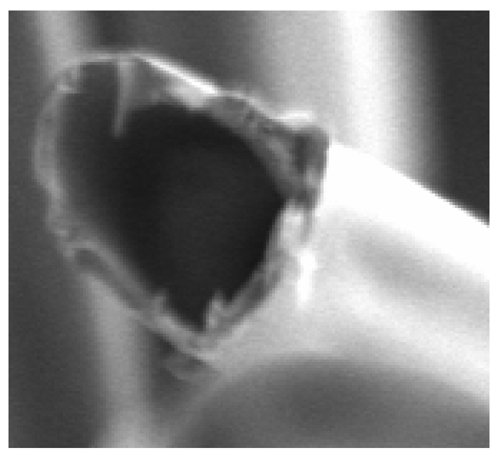

FIGURE 2. Cross section of Estabragh fiber.

In this work, the effect of an Estabragh fiber component in nonwoven fabrics on their noise absorption coefficients was investigated using the Taguchi method.

Taguchi's experimental design is often used for analyzing experiments involving several variables with the aim of predicting the optimum processing adjustments according to the individual weight of each controllable parameter on a particular response. This method emphasizes a mean performance characteristic value close to the target value, rather than a value within certain specification limits, and eventually improving the product quality. Additionally, the Taguchi method is an easy and simple tool that can be used for experimental design in various engineering applications. It uses available data to quickly narrow the scope of a research project or to identify problems in a manufacturing process [18]. The controllable factors considered in this research project were blend ratio, nonwoven layer mass, punch density, and sound frequency.

EXPERIMENTAL

Preparation of Samples

Approximately 1Kg of Estabragh fibers were blended with polypropylene staple fibers. In order to prevent breakage of Estabragh fibers, the blending operation was carried out manually. *Table I* shows the specifications of fibers used in the blends.

TABLE I. Fibers specification.

Properties	*Estabragh*	*Polypropylene*
Fiber length $_{mm}$	27.9 ±6.1	40.15±2.6
Fiber diameter $_{\mu m}$	22.14	16.13
Fiber fineness $_{dTex}$	3.75	2.50
Linear density $^{g}/_{cm^3}$	0.89	0.91
Breaking elongation $_{\%}$	2.6	30
Tenacity $_{g/Tex}$	38.3	40.5
Crimp $_{per\ cm}$	0	8

Since Estabragh is a crimp-less fiber, it had to be blended with polypropylene as carrier fibers during carding. In order to improve blend cohesion, 10% by weight of valid spinning oil was applied to the blends two days before carding operation. Four blends of 100g containing 100%, 75%, 50% and 25% Estabragh were prepared and designated as 100_{ES}, $75_{ES}/25_{PP}$, $50_{ES}/50_{PP}$ and $25_{Es}/75_{PP}$. Fibrous webs were produced using a laboratory scale carding machine. The carding operation was carried out at 60-70% relative humidity and ambient temperature of 20-25°C. In *Figure 3*, the SEM image of fiber arrangement within a 100% Estabragh nonwoven sample is shown.

Carded webs were lightly needled on a laboratory scale needling machine equipped with Groze-Beckert felting needles 15×18×32×3. Details of the needle loom are given in *Table II*. Needling was adjusted so that punch densities of 15.2, 20.3, 25.4 and 30.5 punch/cm^2 according to Eq. (1) were imparted to the webs.

$$P.D=W/A \tag{1}$$

Where (P.D.), (W) and (A) are punch density, needle density and the layer advance respectively.

TABLE II. Needling Machine details.

Parameters	Value
Machine width $_{cm}$	100
Needle board width $_{cm}$	60
Needle density $_{per\ cm}$	8
Feeding roller speed $_{cm/min}$	31.5
Delivery roller speed $_{cm/min}$	31.5

TABLE III. Specifications of nonwoven samples.

Run	*Blend Ratio* %	*Punch Density* Punch/cm^2	*Nonwoven layer mass* g/m^2	*Thickness* mm	*Porosity* %
1	$25_{ES}/ 75_{PP}$	15.2	84	0.75	89.0
2	$25_{ES}/ 75_{PP}$	20.3	100	0.77	87.2
3	$25_{ES}/ 75_{PP}$	25.4	256	1.81	86.0
4	$25_{ES} / 75_{PP}$	30.5	256	1.72	85.3
5	$50_{ES} / 50_{PP}$	20.3	260	2.17	89.4
6	$50_{ES} / 50_{PP}$	15.2	260	2.23	89.7
7	$50_{ES} / 50_{PP}$	30.5	88	0.88	91.1
8	$50_{ES} / 50_{PP}$	25.4	88	0.83	90.6
9	$75_{ES} / 25_{PP}$	25.4	88	1.05	93.4
10	$75_{ES} / 25_{PP}$	30.5	88	1.03	93.3
11	$75_{ES} / 25_{PP}$	15.2	216	2.08	91.8
12	$75_{ES} / 25_{PP}$	20.3	224	2.05	91.4
13	100_{ES}	30.5	160	1.92	94.3
14	100_{ES}	25.4	164	2.16	94.8
15	100_{ES}	20.3	80	1.05	94.8
16	100_{ES}	15.2	84	1.18	95.1

The two methods which are commonly used for measuring sound absorption performance are ASTM E–1050 (Normal Incidence Sound Absorption) and ASTM C–423 (Random Incidence Sound Absorption). The former is a relatively inexpensive method which requires the use of a small circular test sample. A schematic of this method is illustrated in *Figure 4*.

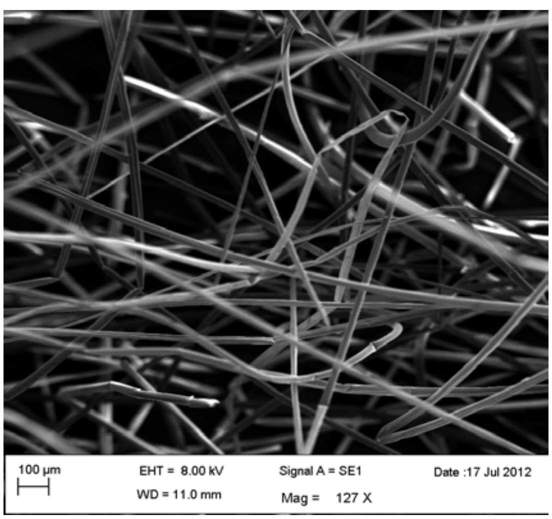

FIGURE 3. SEM image of a 100% Estabragh non-woven.

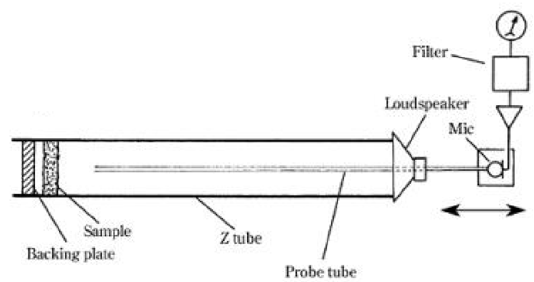

FIGURE 4. Impedance tube.

The sound absorption coefficient essentially depends on the amount of original energy of incident sound waves and the remaining unabsorbed energy of reflected waves. The ratio of remaining unabsorbed sound energy to the initial energy of the incident sound, leads to the measurement called noise absorption coefficient (NAC). Among various measurement techniques that can be used to determine NAC of porous materials, the impedance tube method equipped with a moveable microphone is preferred. In the present work this technique which schematically is shown in *Figure 4* was used. A loudspeaker serving as sound source was connected to one end of the tube while the test sample was mounted on the other end. The loudspeaker was employed for generating the broadband random plane waves in frequency range of 250 to 4000 Hz. The waves were monitored on an oscilloscope display. A digital voltmeter was used to collect the data. Each sample was tested three times and the average of the three measurements was used.

Design of Experiments

Table IV represents the layout of the experimental design based on assignments of the selected factors and their levels to appropriate columns of L16 orthogonal array. The response values (noise absorption coefficient) of three replicates for each design point are reported in *Table IV*. *Table V* shows the Levels of four selected controllable factors. An orthogonal array L16 was chosen since only sixteen runs were required for combinations of four controllable factors, three of which varied at four levels and the fourth remained at two levels (*Table IV*). The numbers in each column indicate the levels of the specific factor. In order to avoid the unidentified noise sources during experiments, test run order were randomly chosen. Mini-tab software was used to determine the effect of each parameter on sound absorbency.

TABLE IV. Taguchi array (L16) used for experiment design.

Estabragh %	Frequency	Punch Density	Nonwoven Layer Mass	Noise Absorption Coefficient		
				R1*	R 2	R3
1	1	1	1	0.15	0.12	0.19
1	2	2	1	0.32	0.22	0.21
1	3	3	2	0.70	0.61	0.58
1	4	4	2	0.57	0.62	0.60
2	1	2	2	0.42	0.39	0.45
2	2	1	2	0.47	0.50	0.62
2	3	4	1	0.5	0.46	0.49
2	4	3	1	0.58	0.51	0.46
3	1	3	1	0.36	0.32	0.39
3	2	4	1	0.40	0.45	0.45
3	3	1	2	0.95	0.92	0.92
3	4	2	2	0.91	0.86	0.98
4	1	4	2	0.66	0.73	0.72
4	2	3	2	0.75	0.70	0.71
4	3	2	1	0.68	0.70	0.59
4	4	1	1	0.55	0.67	0.53

* R: Replication

TABLE V. Controllable factors Levels.

Parameter	Level 1	Level 2	Level 3	Level 4
Estabragh *%*	25	50	75	100
Frequency *(HZ)*	250	500	1000	4000
Punch density *(Needle/cm^2)*	15.2	20.3	25.4	30.5
Nonwoven Layer mass *(g/m^2)*	89.6	230.1		

Three readings (corresponding to the three replications) were recorded for each experimental condition in the Taguchi technique; the variation of the response was also examined using an appropriately chosen S/N ratio. Broadly speaking, the S/N ratio is the ratio of the mean (signal) to the standard deviation (noise). Generally, three standard S/N equations are widely used to classify the objective function as: 'larger the better', 'smaller the better', or 'nominal the best'. However, regardless of the type of performance characteristic, a larger S/N ratio is always desirable. Noise absorption coefficient belongs to the larger-the-better quality characteristics. The loss function of the larger-the-better quality characteristics can be expressed as [19].

$$L_j = (\frac{1}{n}\sum_{k=1}^{n}\frac{1}{y_i^2}) \quad (2)$$

$$\eta_j = -10\log L_j \quad (3)$$

where n is the number of tests, and y_i the experimental value of the i_{th} quality characteristic, L_j overall loss function, and η_j is the S/N ratio. By applying Eq. (2) and Eq. (3), the η corresponding to the overall loss function for each experiment of *L16* was calculated.

RESULTS AND DISCUSSIONS

A level S/N ratio analysis was adopted to identify the strongest effects and determine the best factor levels for the nonwoven layer that absorbs considerably noise. The empirical relationships between NAC and the controllable factors were analyzed using Minitab software [20]. Moreover, the optimum conditions were determined.

This analysis is based on combining the data associated with each level for each factor. The difference between the highest and the lowest S/N ratio measures the effect of that factor on NAC. The greatest value of this difference is related to the strongest effect of that particular factor. The results are given in *Table VI*. According to the S/N ratio analysis, the factor related to Estabragh ratios shows the strongest effect on NAC with a delta of 5.83. Frequency is the second factor with a delta of 5.41 and is followed by other factors nonwoven layer mass and punch density with delta of 4.63 and 1.66 respectively.

TABLE VI. Signal to noise ratios response.

Factors	Ratios (larger is better)						Optimal level
	Level 1	Level 2	Level 3	Level 4	Delta	Rank	
Estabragh %	-9.11	-6.36	-4.44	-3.62	5.83	1	4
Frequency	-6.97	-7.08	-3.69	-3.99	5.41	2	3
Nonwoven layer mass	-8.28	-3.65	-	-	4.63	3	2
Punch density	-8.286	-6.145	-5.463	-5.305	1.66	4	4

In order to investigate whether the controllable factors had a significant effect on the NAC of nonwoven layers, results of variance analysis are shown in *Table VII*. The findings show that apart from punch density, other controllable factors have significant effects on the NAC.

TABLE VII. Analysis of Variance for SN ratios.

Variable	DF	SS (Sum of Square)	MS (Mean Square)	F-value	P-value
Estabragh %	3	80.53	26.84	36.75	0.001
Frequency	3	80.78	26.92	36.87	0.001
Punch density	1	6.920	2.307	3.160	0.124
Nonwoven layer mass	3	85.78	85.78	117.46	0.00
Residual error	5	3.650	0.730	-	
Total	15	257.67	-	-	

Generally, the noise absorption coefficient of fibrous materials is affected by various factors such as porosity, thickness, fiber size, density, and fiber composition. *Figure 5* shows the relation between the controllable factors (Estabragh ratio, nonwoven layer mass, punch density, and sound frequency) and the response (noise absorption coefficient).

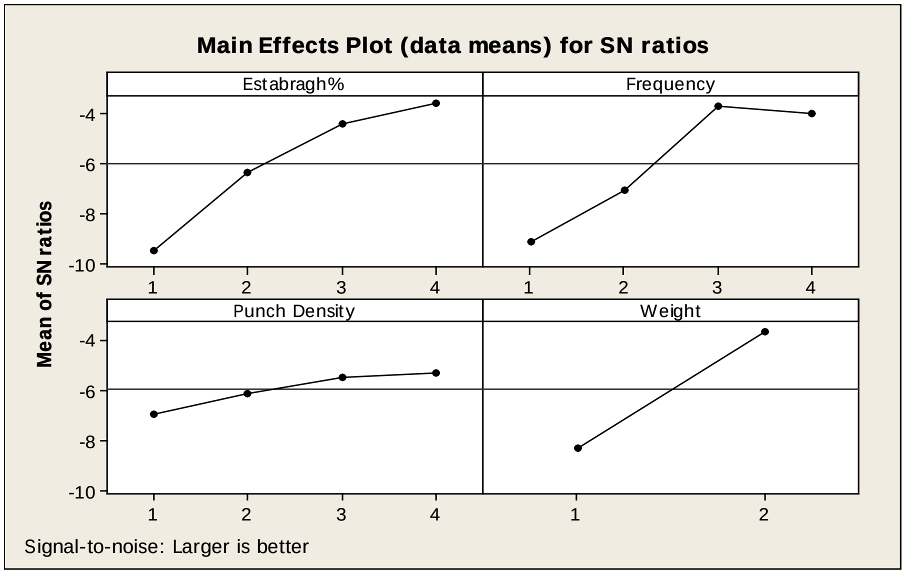

FIGURE 5. Interaction of controllable factors with NAC.

Considering *Figure 5*, it can be stated that increases in percentage of Estabragh fibers in the blend results in enhancement of noise the absorption of the samples. This is confirmed by higher values of NAC as depicted in *Figure 5*. This trend is common among the samples produced with various punch densities. The presence of an axial channel along the length of Estabragh fibers allows air to flow. The air flow enables the fabric to absorb more noise [3]. The finding of previous researchers [8] points to the existence of a direct relation between fiber fineness and NAC values. Measurement of fiber diameter indicated that polypropylene fibers are finer than Estabragh by 37.3%. It can be seen that despite the fact that polypropylene fibers were finer than Estabragh fibers, the latter fibers had a higher absorbency. This result can only be associated with the hollow structure of Estabragh fibers, which facilitates the flow of air in the fiber channel. This enhances the sound insulation property of fibers.

The findings show that the nonwoven layer mass had significant effect on the noise absorption of the nonwoven. An increase in mass of nonwoven layer corresponds to the existence of more fibers per unit area of the fabric. Thus, greater energy losses which resulted in higher noise absorbency would occur [9].
As far as the effect of punch density is concerned, an increase in punch density correspondingly results in an increase the value of NAC. This is because of increase in the intensity of fiber entanglement that occurs as direct result of higher amount of punch density and the subsequent changes in the porosity of the fabric [3]. It can be seen that an increase in punch density does not show a significant effect on the NAC of Estabragh nonwoven samples. It should be stated that the increase in punch density causes excessive breakage of fibers. Intensive needling of Estabragh fibers results in reduced fibers length. Reduction in fibers length decreases the degree of fiber entanglement and, consequently, the NAC values decrease.

Harris [21] reported that the noise absorption coefficient is affected by the frequency of the sound wave. Moreover, Seddeq [22] reported that while noise absorption occurs at high frequencies in dense structures, similar phenomenon takes place at low frequencies in more open structures. Since needling was carried out lightly, it can be considered that the samples had less dense structures than normally needled fabrics. This can be the reason behind the maximum value of NAC which was measured at a frequency of 1000 Hz.

CONCLUSION

Through this research, it was established that blends of Estabragh and polypropylene fibers in form of lightly needled nonwoven fabrics can be successfully used as means of sound pollution control. This can mainly be attributed to hollow structure of Estabragh fiber component of the blends. Results show that fabric NAC value increases with increasing percentages of Estabragh fibers in the blend. The findings show that the nonwoven layer mass has a significant effect on fabric noise absorption. Increases in the nonwoven mass lead to increases in the number of fibers per unit area which results in changing the porosity of the fabric. Subsequently, the fabric absorbs more sound. Additionally it was found that the effect of punch density is insignificant as far as sound absorption is concerned. Because of the less dense structure of lightly needled samples, maximum value of NAC was obtained at frequency of 1000 Hz.

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