# Incorporation of Nanofiber Layers in Nonwoven Materials for Improving Their Acoustic Properties

Amir Rabbi, Hossein Bahrambeygi, Ahmad Mousavi Shoushtari, PhD, Komeil Nasouri, PhD

Department of Textile Engineering, AmirKabir University of Technology, Tehran IRAN

Correspondence to:
Ahmad Mousavi Shoushtari email: amousavi@aut.ac.ir

**ABSTRACT**
Due to numerous developments in most industries and the increase in the usage of massive and powerful machines in every field, noise has become an unavoidable part of mechanized life and has brought about serious health hazards. The main aim of this work was to investigate the usability of polyurethane and polyacrylonitrile nanofibers for improving sound insulation properties over a wide band of frequencies and reducing weight and thickness of conventional polyester and wool nonwovens. The effect of the number of nanofiber layers and associated surface densities on acoustic properties was investigated. Sound transmission loss and sound absorption analysis using the impedance tube method were carried out as the main factors affecting acoustic behavior of samples. The results show that incorporation of nanofiber layers in nonwoven materials can improve both sound absorption and sound transmission loss simultaneously, especially in mid and lower frequencies, which are difficult to detect by conventional materials.

**Keywords:** Nanofibers; Nonwoven composite; Sound transmission loss; Sound absorption

## INTRODUCTION

The property of a material to oppose sound transfer through its thickness is called sound insulation. In practice, the efforts to reduce noise often involve identifying and analyzing the physical mechanisms involved in the generation and transmission of sound and finding the possible means of noise reduction [1]. A variety of methods have been described for noise reduction which can be basically grouped as passive and active mediums. Active mediums differ from passive mediums in that it is necessary to apply external energy against incident sound waves in the noise reducing process. The absorbing materials and sound barriers are passive mediums. Sound absorbers lower noise by disseminating energy and turning it into heat. The amount of sound energy which is absorbed is described as the ratio of sound energy absorbed to the sound energy incident, and is termed the sound absorption coefficient (α). Sound barriers prevent sound from traveling from one place to another [2]. Nonwoven fabrics are extensively utilized in noise reduction where sound absorption is important. Sound absorption and sound transmission are the main factors affecting acoustic properties and they depend on the interaction of sound wave with the fibers forming the nonwoven fabrics. While nonwoven fabrics are known as good sound absorbers at high frequency, they are less effective at low and middle frequencies, because of their low density [3]. Various parameters can affect the acoustic behavior of fibrous materials: fiber denier [3-5], porosity [6], tortuosity [7], fabric surface area [8], density [9], airflow resistance [10], thickness [11], and fiber cross section [5, 12]. In general, any acoustical treatment requires high performance in both absorption and transmission losses. High absorption can be achieved by using suitable absorbers, while high transmission loss requires heavy barriers. An absorber needs to be porous and light, but a barrier needs to be impermeable and massive. How to best create a combination of these two contradictory properties in a multiple-layer is considered as a big challenge for all acoustical engineers [1].

Many new and light weight acoustical materials have been introduced in recent years. It has been claimed that active carbon fiber composite with a cotton base layer would be lighter in weight, higher in low frequency absorption, and higher in transmission loss in both ranges of frequencies compared to other fibrous composites. These simultaneous behaviors have been attributed to the very high specific surface area and high micro pore volume of the active carbon fibers [13, 14]. In recent years innovative solutions have been derived from electrospun nanofibers. Electrospinning is an approach for providing fibers in nanometer scale, and it is based on applying an electric field between a needle and a collector for drawing a polymer droplet from the tip of the needle toward the collector [15]. Special characteristics of these nanofibers such as high specific surface area, small fiber diameter, and high porosity allow rapid interaction of materials with surrounding media [16]. The effect of nanofiber layers on sound transmission loss has not been discussed in the literature. However, there are a few studies on the effect of nanofiber layers on sound absorption properties [17-20].

The main aim in this work was to investigate the usability of polyurethane (PU) and polyacrylonitrile (PAN) nanofibers as a means of improving sound insulation of conventional polyester and wool nonwoven materials over a wide band of frequencies. Composite samples consisting of nonwoven layers and different numbers of nanofiber layers and their associated surface densities were prepared and their effects on acoustic properties studied.

## EXPERIMENTAL

### Materials

Polyacrylonitrile powder (PAN, $\bar{M}_w = 10^5\ g/mol$) and polyurethane granule (commercial PU; $\bar{M}_w = 65000\ g/mol$) were supplied from Iran Polyacryl Co. and Bayer Co., respectively. N, N-dimethylformamide (DMF, EMPARTA) and tetrahydrofuran (THF, EMPLURA) were obtained from Merck as solvents. In order to prepare polymer solutions for electrospinning, PU was dissolved in DMF and THF in proportion of 40:60; and PAN was dissolved in DMF at the ambient temperature. Nonwovens were produced by a carding machine, followed by needle punching. The properties of the used nonwoven layer are shown in *Table I*.

TABLE I. Properties of nonwoven layers.

| Properties | Nonwoven | |
|---|---|---|
| | PET | Wool |
| Fiber length(cm) | 6-8 | 12-10 |
| Fiber Fineness(µm) | 19 | 33 |
| Average Weight ($g/m^2$) | 100 | 96 |
| Average Thickness(mm) | 2.53 | 3.01 |
| Average of Porosity | 97% | 99% |
| Punch Density ($punch/cm^2$) | 228 | 228 |
| Origin | Iran | |

### Electrospinning Apparatus

As shown in *Figure 1*, a horizontal electrospinning apparatus with a cylindrical collector (with take-up speed of 100 RPM) was used. A 22 G needle (inner diameter: 0.4 mm and length: 34 mm) was chosen. For creating an electric field between the needle and the collector, a high-voltage power supply which can generate DC voltage up to 40 kV was utilized. This leads to polymer ejection of drops from the tip of the needle toward the collector. The solution flow rates were controlled by a pump at a rate of 0.25 ml/h. The electrospinning process parameters were adjusted to: solution concentrations of 10 and 9 w/v %, and applied voltages of 12 and 16 kV for providing PAN and PU nanofiber, respectively. Tip to collector distance was fixed at 12 cm.

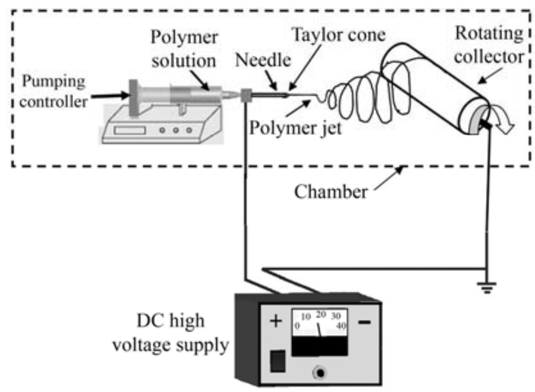


FIGURE 1. Schematic of electrospinning apparatus.

### Sample Preparation

Nanofiber webs with determined surface densities of 1, 3, and 5 $g/m^2$ were placed within nonwoven layers. The properties of all nonwoven samples were the same as listed in *Table I*. After layering 1, 2 or 3 nanowebs within four nonwoven layers, a sandwich structure was produced. The schematic of prepared sample is shown in *Figure 2*. 1, 3 and 5 $g/m^2$ nanofiber webs were obtained in 3, 8, and 12 hrs and 3, 9, and 15 hrs for PAN and PU, respectively by the electrospinning apparatus. The structures of all samples together with their codes are given in *Table II*.

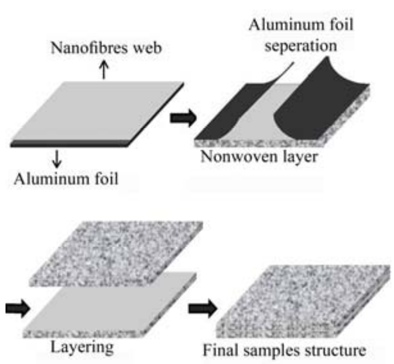


FIGURE 2. Schematic of prepared sample.

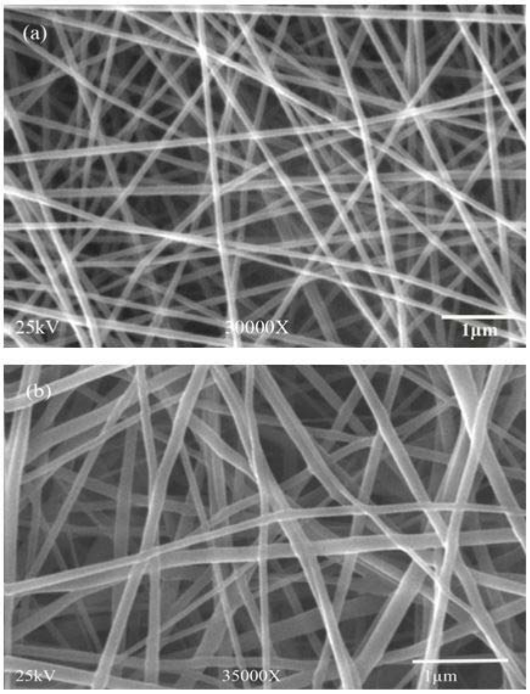


FIGURE 3. SEM micrograph of surface morphology of (a): PAN and (b): PU nanofibers.

TABLE II. Sample description and codification.

| Sample Code | Nanofiber Layers No. | Nanofiber Surface Density | Nanofiber Layer | Nonwoven |
|---|---|---|---|---|
| P-PAN1 | 3 | 1 | PAN | Polyester |
| P-PAN3 | 3 | 3 | PAN | Polyester |
| P-PAN5 | 3 | 5 | PAN | Polyester |
| P-PU1 | 3 | 1 | PU | Polyester |
| P-PU3 | 3 | 3 | PU | Polyester |
| P-PU5 | 3 | 5 | PU | Polyester |
| W-PAN1 | 3 | 1 | PAN | Wool |
| W-PAN3 | 3 | 3 | PAN | Wool |
| W-PAN5 | 3 | 5 | PAN | Wool |
| W-PU1 | 3 | 1 | PU | Wool |
| W-PU3 | 3 | 3 | PU | Wool |
| W-PU5 | 3 | 5 | PU | Wool |
| P-PANI | 1 | 5 | PAN | Polyester |
| P-PANII | 2 | 5 | PAN | Polyester |
| P-PANIII | 3 | 5 | PAN | Polyester |

**Morphology of Nanofibers**

Scanning electron microscopy (SEM; model AIS 2100, Seron Technology, Korea) at an accelerating voltage of 25 kV was used to investigate the surface morphology of nanofiber webs. Samples were gold-coated before SEM. The nanofiber diameter was determined by 100 measurements using Image J software.

**Acoustic Properties**

The transfer function method (ASTM E 1050) covers the use of an impedance tube (model: 4206, B&K, Denmark), with two microphone locations and a digital frequency analysis system (model: 550 & BZ5051, B&K, Denmark) for measuring the normal incidence sound absorption coefficients. Transmission Loss factor (TL) is the loss as sound passes through a barrier. In particular, TL can be defined as the difference between the sound pressure level (SPL) on the source side of the barrier and the SPL on the receiver side. ASTM E 2611-09 (Standard test method for measurement of normal incidence sound transmission of acoustical materials based on the transfer matrix method) was used for measuring of TL factor. An additional tube extension impedance tube with four microphone and different setup was utilized. By measuring the sound pressure at the four microphones (two microphones located in front of samples and the other placed behind it) location, the TL value of the material can be determined. To measure over the complete frequency range from 50 Hz to 6.4 kHz, the components can be assembled into two different setups: a 100 mm diameter tube (for frequencies from 50 Hz to 1.6 kHz) and a 29 mm diameter tube (for frequencies from 500 Hz to 6.4 kHz). A loudspeaker (sound source) is mounted at the one end of the impedance tube, and the test sample is installed at the middle of the tube. In the impedance tube method, sound waves are confined within the tube and thus the size of the sample required for test needs to be only large enough to fill the cross-section of the tube properly.

**Measurement of Air Permeability**

Air permeability of samples was measured according to BS 5636 (standard test method for determination of permeability of fabrics to air) with a pressure of 100 Pa after and before placing the nanofiber layers within nonwoven layers.

## RESULTS AND DISCUSSION

**Nanofiber Diameter**

*Figure 3* (a, b) shows the surface morphology of nanofibers. The average diameter of PAN and PU nanofibers are 121 and 203 nm, respectively. As can be seen from *Figure 3*, a narrower fiber diameter distribution was observed in case of the PAN sample.

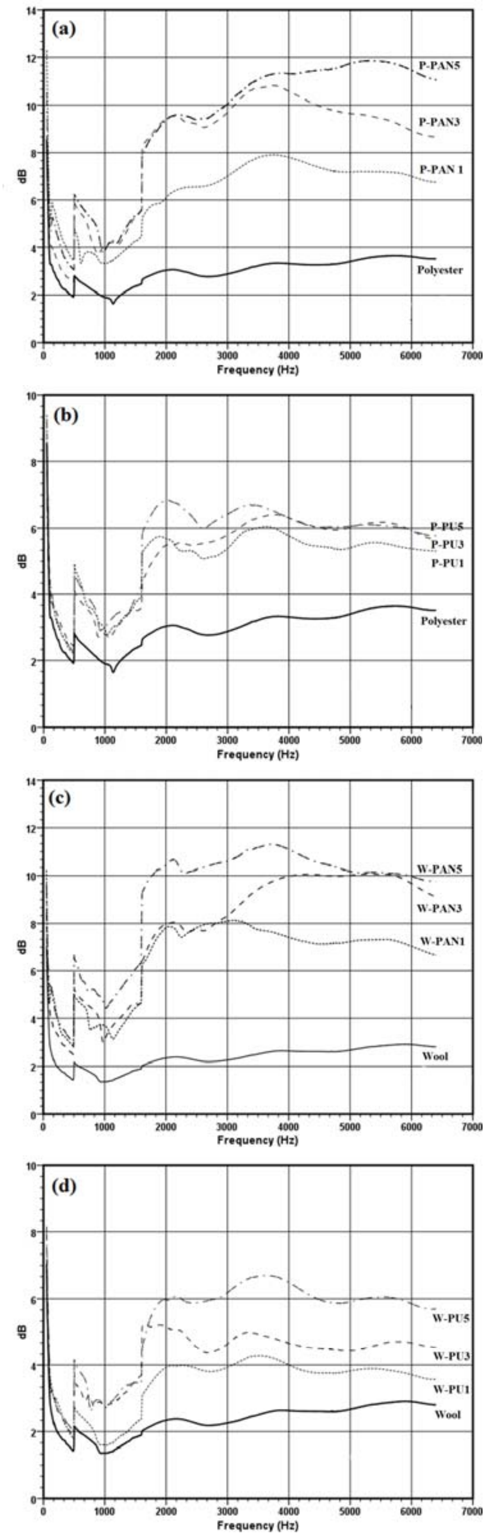


FIGURE 4. Changes of sound transmission loss against frequency (a): PAN nanofiber layers within polyester layers, (b): PU nanofiber layers within polyester layers, (c): PAN nanofiber layers within Wool layers, (d): PU nanofiber layers within wool layers.

**Effect of Surface Density**

The ability of a material to resist the flow of sound energy through its structure is termed as sound insulation and this is largely determined by its mass. According to the mass law in acoustics Eq. (1), heavy materials stop more noise passing through them than light materials. For any impermeable material there will be an increase in its noise stopping ability of approximately 6 dB for every doubling of mass per unit area (*m*) or frequency (*f*). [21].

$$TL = 20\log(fm) - 33 \quad (1)$$

However, increasing the mass of an insulator for improving nonwoven sound transmission loss is not acceptable in most industries. *Figure 4 (a-d)* shows transmission losses of PAN and PU nanofiber layers placed within polyester and wool nonwovens layers. As shown, TL was increased by the presence of PAN or PU nanofiber layers. Moreover, increasing the surface density of both nanofiber layers resulted in higher sound transmission loss in both wool and polyester nonwoven substrates. Higher sound transmission loss was observed in the case of samples produced from PAN nanofiber layers.

**Effect of the Number of Nanofiber Layers**

*Figure 5* shows the enhancement of sound transmission loss by increasing the number of PAN nanofibers layers within the polyester nonwoven layers from one to three. While sound waves pass through the first to the last (third) layer, their intensity is suppressed step by step. By comparing of the results presented in *Figure 5* and *Figure 4*(a), it can be concluded that increasing in the number of nanofiber layers is more effective than increasing in the mass per unit are of the layers. For example, the sample of P-PAN3 demonstrates better sound transmission loss than the sample of P-PANII.

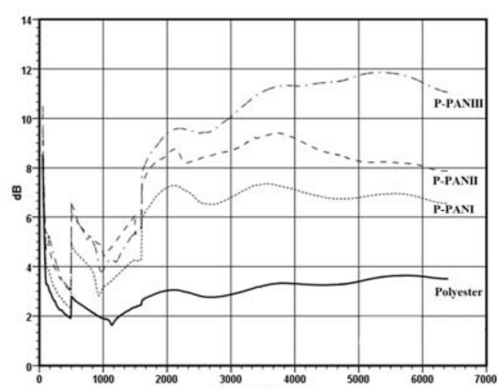


FIGURE 5. Changes of sound transmission loss against frequency; different number of PAN nanofiber layers within polyester layers.

## Air Permeability

Air permeability is a very important parameter for thermal and acoustical insulation of nonwoven fabrics. Lower air permeability causes lower sound transmission; consequently, more sound insulation [9]. The air permeability of samples is shown in *Table III.* According to the table; samples containing PAN nanofiber layers presented less air permeability. This behavior can be attributed to the finer diameter of PAN nanofiber compared to PU nanofiber diameter.

TABLE III. Air permeability of samples.

| Sample | Before layering ($cm^3/s/cm^2$) | After layering ($cm^3/s/cm^2$) |
|---|---|---|
| W | 334 | — |
| P | 297 | — |
| P-PAN1 | 289 | 29 |
| P-PAN3 | 292 | 20 |
| P-PAN5 | 295 | 13 |
| P-PU1 | 300 | 44 |
| P-PU3 | 286 | 38 |
| P-PU5 | 297 | 31 |
| W-PAN1 | 338 | 27 |
| W-PAN3 | 331 | 21 |
| W-PAN5 | 340 | 15 |
| W-PU1 | 339 | 50 |
| W-PU3 | 333 | 41 |
| W-PU5 | 337 | 34 |
| P-PANI | 302 | 31 |
| P-PANII | 291 | 19 |
| P-PANIII | 295 | 13 |

As can be seen, by increasing the number of nanofiber layers, lower air permeability was achieved, confirming the relation of this important parameter with sound insulation ability [9].

Generally, some sound energy is radiated by the vibration of the nanofiber layer [21]. Because of the high elasticity of PU nanofiber [22], more sound energy can be created by PU nanofiber vibration; therefore, less sound transmission loss was achieved by PU layers compared to PAN layers. Moreover, samples with polyester nonwoven substrates presented higher sound transmission loss because of their lower porosity (97%) in comparison with wool substrate (99%).

The TL test shows improvement in sound insulation ability of samples containing lightweight nanofiber layers. Although sound reflection can restrict sound waves to pass, sound intensity in front of a hard surface is enhanced because the reflected wave adds to the incident wave [21]. Impedance tube measurements show that adding of nanofiber layers within nonwoven layers leads to a considerable increase in the sound absorption coefficient. Specifically, the polyester nonwoven layers sound absorption coefficient of 0.40 increased to 0.67 and 0.71 by the presence of PAN and PU nanofiber layer, respectively at a frequency of 2000 Hz. At the present time, intensive studies of sound absorption by nanofiber layers are in progress by the authors [23], and the detailed results will be published in a separate paper.

According to the above results, it seems that these innovative composite materials can introduce a new branch of acoustic materials that can improve both sound absorption and sound transmission loss simultaneously, especially at low and mid frequencies which are difficult to detect by conventional materials. Additionally, weight and thickness can be reduced by the presence of nanofiber layers, which provide potential economic benefits through the use of these materials. Moreover, because of the easier electrospinning, affordably and easier solubility of PAN compared to PU polymer, PAN nanofiber is preferred.

## CONCLUSIONS

The effects of applying polyurethane and polyacrylonitrile nanofibers within polyester and wool nonwoven layers on sound proofing behavior were studied. The results show enhancement in sound transmission loss by increasing the number and the weight per unit area of both nanofiber layers. Higher sound transmission loss was observed in the case of samples containing PAN nanofiber layers, which can be attributed to the higher air permeability and elasticity of PU compared to PAN nanofiber layers. Samples with polyester nonwoven layers presented higher sound transmission loss due to their lower porosity (97%) compared to wool nonwoven layers (99%). Moreover, Sound absorption coefficient measurements show that adding nanofiber layers within nonwoven layers leads increased sound absorption. We have shown in this study that our experimental acoustic material can enhance both sound transmission loss and sound absorption, simultaneously, especially in low and mid frequencies which are difficult to detect by conventional materials. Furthermore, weight and thickness can be reduced by means of nanofiber layers.

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**AUTHORS' ADDRESSES**

**Amir Rabbi**
**Hossein Bahrambeygi**
**Ahmad Mousavi Shoushtari, Ph.D.**
**Komeil Nasouri, Ph.D.**
Department of Textile Engineering,
AmirKabir University of Technology,
Tehran 15875-4413, Iran.
IRAN, ISLAMIC REPUBLIC OF