NANOFIBER ENHANCED LIGHT-WEIGHT COMPOSITE TEXTILES FOR ACOUSTIC APPLICATIONS

Merve Kucukali-Ozturk, Elif Ozden-Yenigun, Banu Nergis and Cevza Candan

Abstract

This paper proposes light-weight textile acoustic structure, wherein electrospun PAN based nanofibers enhance sound absorption properties with no weight and thickness penalty. PAN nanofibers with diameter of 110±7nm were electrospun on spacer knitted fabrics by varying deposition amount and surface coating arrangement. Proposed novel approach eliminated additional processing steps such as handling and post-lamination and provided easy scalability of nanofibers at macro-scale. The results showed that the sound absorption of nano-enhanced specimens was improved drastically when deposited amount of nanofibers or its effective surface area increased. Sound propagation paths in different configurations were interpreted from sound absorption and air permeability measurements. The sound absorption coefficient values up to 0.7 are achieved in the low and medium frequency ranges with no weight and thickness penalty by tuning deposition amount and surface coating arrangement.

Keywords

PAN nanofibers, spacer knitted fabric, sound absorption coefficient, air permeability

Introduction

Textile materials are often preferred for acoustic environment control [1-5]. Among them, spacer knitted fabrics with air trapping ability are good candidates for noise absorption which is one of the growing environmental issues in today's society. Thus, the acoustic behavior of these fabrics has been studied in the literature which verified that these fabrics showed promising acoustic performance [6-10]. Most common traditional acoustic fibrous materials such as wool and glass fibers have good sound reduction abilities in high frequency range (>2000Hz), but exhibit lower sound absorption in low and moderate frequency ranges (250-2000 Hz) where humans are highly sensitive to noise [11-13]. Thus, fibrous materials with enhanced sound absorption properties in the low and medium frequency regime, receive a great deal of attention. Transmission losses and sound absorption coefficient strongly depend on fiber diameter and fiber surface area. For instance, large specific surface area of sub-micron size fibers and nanofibers dramatically increase sound absorption coefficient particularly in the lower frequency band due to the increase of relative density and friction [14]. Therefore, electrospun nanofibers have been studied recently to investigate their potential use as nano-scaled sound absorbers [15-22]. However, there is limited number of studies about acoustic performance of nanofibrous membranes. Kalinova [17] studied the potential use of electrospun polyvinyl alcohol (PVA) based nanofibrous membranes as sound absorbents and focused on the estimation of nanofibrous membranes' resonance frequency from sound absorption coefficient and transmission loss measurements.

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Mohrova *et al.* [18] also investigated the sound absorption properties of PVA nanofibrous membranes with different morphologies. Nanofibrous membranes were exposed to water vapor for 10 to 120 seconds and the changes in the structure of nanofibrous membrane were monitored. The researchers concluded that nanofibrous PVA membranes exhibited the same absorption analogy with that of the thin polymeric foils. However, the regularity and acoustic performance of the membranes were affected when they were treated by water vapor due to the dissolved and merged fibers. Even though, the resonance frequency of membranes was affected by these irregularities, the absorbed frequency range was slightly improved. Jirsak *et al* [19] also demonstrated that the sound absorption coefficient of coated specimens with nanofibrous layers is eminently higher than neat specimens even at lower frequencies. It was also stated that the resonant nanofibrous membrane vibrates and this vibration caused the lower frequency sound absorption. In one of our previous studies, [20] the acoustic performance of PVA nanofibrous resonant membranes produced by needleless electrospinning, was investigated. The sound absorption behavior of these homogenous standalone membranes was predicted by determining its resonance frequency via an experimental set-up with high-speed camera.

Within the light of literature, we implemented novel approach to produce nano-enhanced composite textiles for acoustic applications. As nano-sized sound absorbents, polyacrylonitrile (PAN) based nanofibrous membranes were selected since they were affected less from ambient relative humidity and temperature (T_g~95˚C) changes. Moreover, PAN has been shown to be quite promising as a sound absorber [23]. PAN solution was directly electrospun onto the surface of warp knitted spacer fabrics. This approach eliminates handling, scalability problem of nanofibers and further steps such as lamination. Moreover, it enables us to use the advantages of both spacer fabrics and porous nature of nanofibrous membranes for acoustic applications. The novelty of the current work was based on both the selection of PAN based nanofibers and unique single step application technique in manufacturing.

Materials & Method

Materials

The polyester spacer warp knitted fabric, which was manufactured on E12-gauge Karl Mayer knitting machine, was used as the substrate (Fig. 1a). 167/48 x 4polyester yarns were utilized for knitting front layer of the spacer fabric while 334/72 x 3 polyester yarns were used for the backside. The interconnecting yarn was 100% polyester monofilament with a diameter of 0.243 mm. The samples were conditioned under standard laboratory conditions (relative humidity of 65 ± 4% at a temperature of 22 ± 2 C). Mass per unit area and thickness of the fabrics were determined in accordance with the relevant standards TS 7128 EN ISO 5084 and BS EN ISO 5084:1997, were reported as 850 g/m^2 and 8 mm, respectively. As substrate material, spacer knitted fabric was used. Spacer fabrics are much like sandwich structures which include two complementary slabs of fabric with a third layer tucked in between. The inner layer can take a variety of shapes, which gives the entire three-layer fabric a wide and ever-expanding range of potential applications. There is an air gap between top and bottom layers which helps absorption of sound waves in the use of acoustic applications.

Polyacrylonitrile polymer (PAN) was purchased from Sigma-Aldrich Co. (M_w 150,000 g/mol) were selected and dissolved in *N,N*-Dimethylformamide (Sigma-Aldrich Co.). All products were consumed without any further purification. During the preliminary studies, the solution were electrospun at three polymer concentration levels (4 wt %, 6 wt % and 8 wt %) by focusing on the homogeneity and reproducibility of membrane coating, PAN polymer solution at 8 wt

% concentration was selected for the current study since optimal bead-free fiber production were achieved.

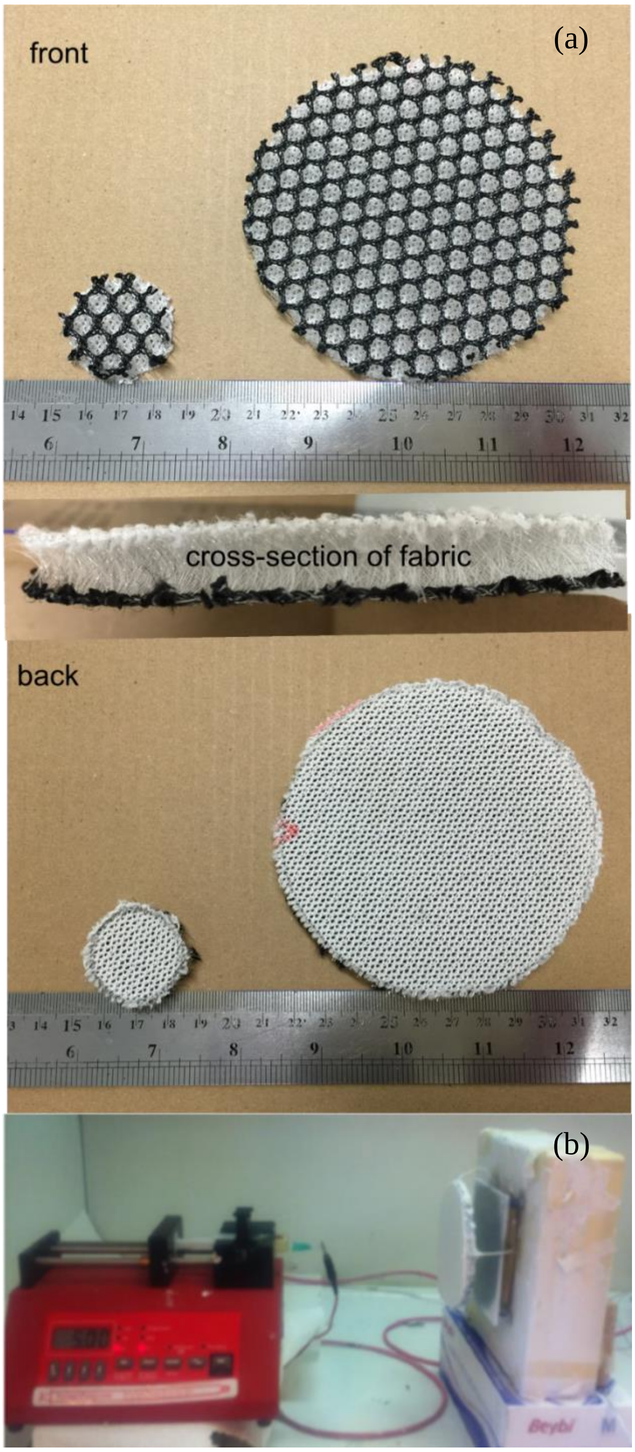


Figure 1. (a) Front, back and cross-section view of spacer warp knitted fabrics **(b)** Lab-scale electrospinning setup

Methods

Electrospinning method was used to produce PAN based nanofibers. This set-up mainly has three components: a high voltage supplier (0-30 kV), polymer reservoir, and metal collecting screen (rotating drum, mandrel or flat screen). In the electrospinning process high voltage is used to create an electrically charged jet of polymer solution out of the needle. Before reaching the collecting screen, the solution jet evaporates or solidifies, and is collected as an interconnected web of small fibers. Positively charged electrode is placed into the spinning solution and grounded cable is attached to the collector. In the current study, lab-scale single nozzle electrospinning device was used (Fig. 1b). The distance between the collection surface and the needle tip was set to 10 cm, while the feed rate of 300 μl/hr and the applied voltage of 15kV was adjusted. The surface morphologies and average diameter of electrospun PAN fibers were determined using scanning electron microscope SEM LEO 1530 VP. Two-microphone Impedance Measurement Tube Type 4206 was used to measure the absorption coefficient of the samples in the frequency ranges 50 Hz to 6.4 kHz according to ISO 10534-2. Sound absorption capacities of coated and uncoated specimens were determined. For the uncoated sample as well as for the single and double faces coated ones, the front side of the fabric (Fig. 1a) was exposed to the sound generator. The air permeability of the samples in mm/sec was measured according to the method specified by TS 391 EN ISO 9237. This test method which is applicable to most fabrics, covers the measurement of the air permeability the rate of air flow passing perpendicularly through a pre-defined cross-sectional area under a prescribed air pressure differential between the two surfaces of textile fabrics.. Circular fabric is clamped into the tester through vacuum pressure, the air pressure is applied on one side of the fabric. Airflow will take place from higher air pressureto lower air pressure. From air flow rate changes, the air permability of the fabric is calculated. The measurements were performed at a constant pressure drop of 100 Pa (per 20 cm^2 test area). In each test level, five specimens were tested and the average values were reported.

PAN Nanofiber Coatings at Different Deposition Levels

PAN polymers were deposited on the surface of the spacer fabrics at two different deposition levels (at 0.1 and 0.2 mass fractions). All models are given in Table 1, their air permeability values are also provided. Herein, sample name coding is done according to the number of surfaces coated and deposited amount of nanofiber on the surface of fabric. For instance, in *Sample I-a*, only front surface of spacer warp knitted fabric was coated with 10 g/m^2 PAN nanofibrous membrane. Fig 2 shows *Sample I-a* and *Sample I-b* which were coated with 10g/m^2 and 17 g/m^2 PAN nanofibrous membranes, respectively.

Table 1. Different studied models, sample name coding is given according to deposited amount of nanofiber and number of coated surfaces.

Sample Number	**Deposition Amount**	**Number of Coated Surfaces**	**Air permeability, mm/sec**
Uncoated Spacer Fabric (SF)	-	-	324±1
Sample I-a	10g/m^2	1 (front)	30±1
Sample I-b	17g/m^2	1 (front)	11±1
Sample II-a	10g/m^2	2 (front& back)	10±1
Sample II-b	17g/m^2	2 (front& back)	8±1

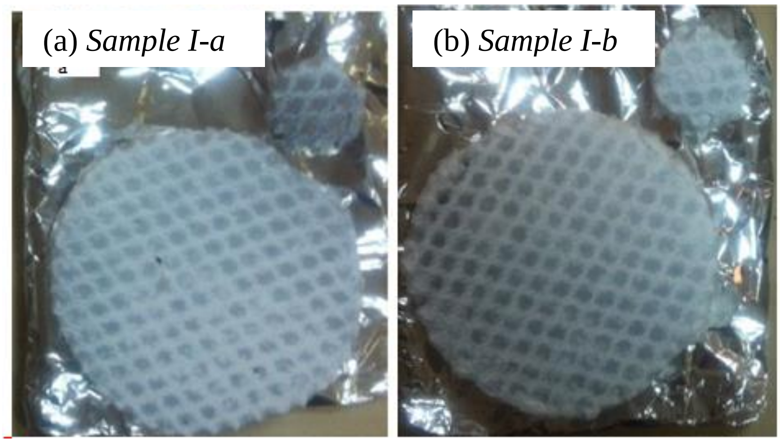


Figure 2. The spacer fabric coated with **(a)** 10g/m^2 PAN nanofibrous membrane, *Sample I-a* **(b)** 17g/m^2 PAN nanofibrous membrane, *Sample I-b*.

The previous studies [17-19] demonstrated that air trapping capability of nanofibers also has remarkable influence on sound absorption properties. As a further step, PAN nanofibers were deposited on both faces of the spacer fabrics, so that air trapping could be enhanced. Fig. 3 displays *Sample II-a* and *Sample II-b* where both side of fabrics were coated with 10 g/m^2 and 17g/m^2 PAN nanofibrous membranes, respectively.

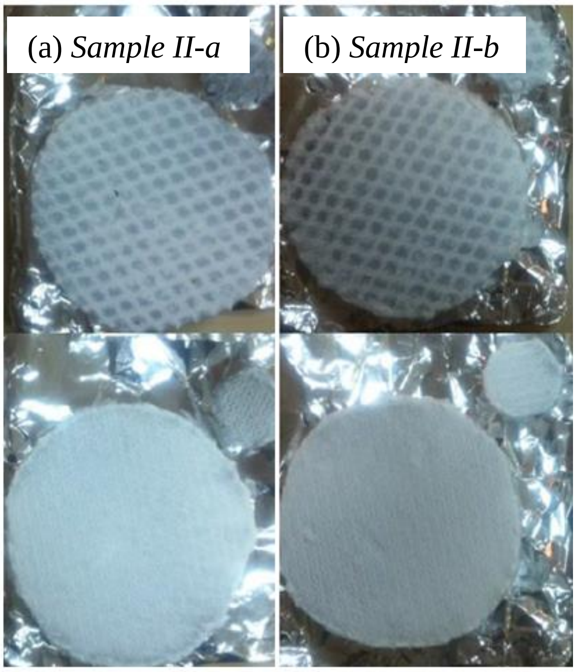


Figure 3. The spacer fabric coated with **(a)** 10g/m^2 PAN nanofibrous membranes, *Sample II-a* **(b)** 17g/m^2 PAN nanofibrous membranes, *Sample II-b*, on both sides.

Results and Discussion

In sound absorption mechanism, the friction between fibers and air increases with fiber surface area and results in higher sound absorption [14]. Herein, first aim was to produce homogenous and reproducible nanofibrous coatings (with 50µm thickness). Fig 4 shows the surface morphology and structure of electrospun PAN nanofibers, which were taken from the surface of *Sample I-a*. The average diameter of PAN nanofibers, which are calculated by *ImageJ* *software*, was at around 110±7 nm. In an attempt to provide air-trapping, producing nano and micro scale fibrous coating is also essential. Hur *et al.* [24] explained that the sound absorption in porous material is governed by the viscosity of air pressure in the pores or the friction of pore wall. Therefore, sound absorption increases with specific surface area of fibers and elevated relative density and friction of pore walls. In this current study, the nano-size fibers increase specific surface area with an increase of relative friction while they do not bring thickness or weight penalty.

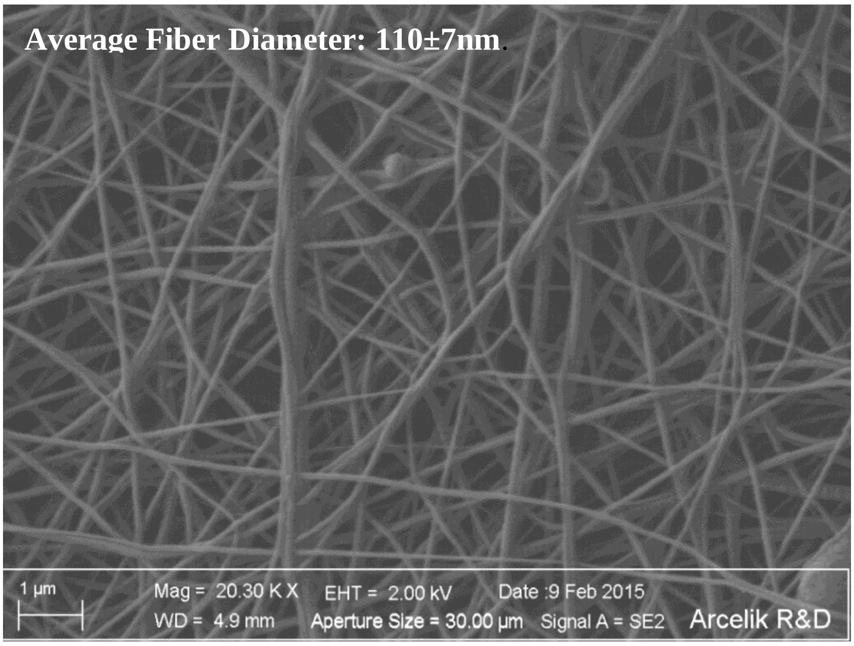


Figure 4. SEM images of PAN nanofibers at 20kX magnification, images are taken from *Sample I-a.*

The incorporation of nanofibrous webs significantly improved the sound absorption coefficients, as seen in Figs 5-8. Fig 5 demonstrates the typical sound absorption curve of uncoated spacer warp knitted fabric as well as coated *Sample I-a* and *Sample I-b* specimens. The sound absorption curve of substrate (Fig 5) displays the porous nature of spacer fabric structure and its low sound absorption performance. *Sample I-b* coated with 17 g/m^2 PAN nanofibrous membrane showed a drastic change in sound absorption coefficient, while *Sample I-a* coated with 10 g/m^2 PAN nanofibrous membrane exhibited a slight increase in acoustic response. Fig 5 pointed out that the increase in deposition amount also alters sound absorption ability. It is worthy to note that, specific flow resistance per unit thickness of the materials is one of the defining quality that influence the sound absorbing characteristics. In this current study, there is no thickness and weight penalty in nanofiber enhanced spacer fabrics. Therefore, we assumed that the difference in thickness between *Sample I-a* and *Sample I-b* specimens is negligible. However, increased surface area with higher nanofiber amount also increases friction. It is predicted that when sound waves enters these materials, its amplitude is decreased by friction as the waves try to move through the tortuous passage [24]. Therefore, the difference between *Sample I-a* and *Sample I-b* in sound absorption mechanism is observed to be quite remarkable. Furthermore, as seen in the Fig. 5, the sound absorption of *Sample I-b* reaches its peak value at around 2000 Hz and decreases at around 4200 Hz. Having absorption peaks is a characteristic behavior of membrane absorbers. The first significant peak in the sound absorption coefficient α has been displaced in the direction of lower frequencies with increasing mass per unit area of coating material [17].

As is expected, the specimens having coatings on both surfaces (*Sample II-a* and *Sample II-b*) have better sound absorption properties than the corresponding one layer coated samples (i.e. *Sample I-a* and *Sample I-b*) (see Fig. 5 and 6). This may be explained by the propagation of wave through nanofibrous membrane and spacer fabric. It may be assumed that incoming sound waves are precluded when they interact nanofibrous coatings on the spacer fabric, and in turn damp each other as a result of collision within the fabric and the coatings. Coating of two surfaces creates enough meso-scale pores on the surface of the specimens (as seen in Fig 4), for the sound waves to pass through and get dampened. As seen in Fig 5-8, deposition amount has greater effect than the number of coated surfaces. Even though, *Sample II-a* has two coated surfaces, it is not able to exhibit membrane like sound absorption behavior which is observed in *Sample I-b* and *Sample II-b*.

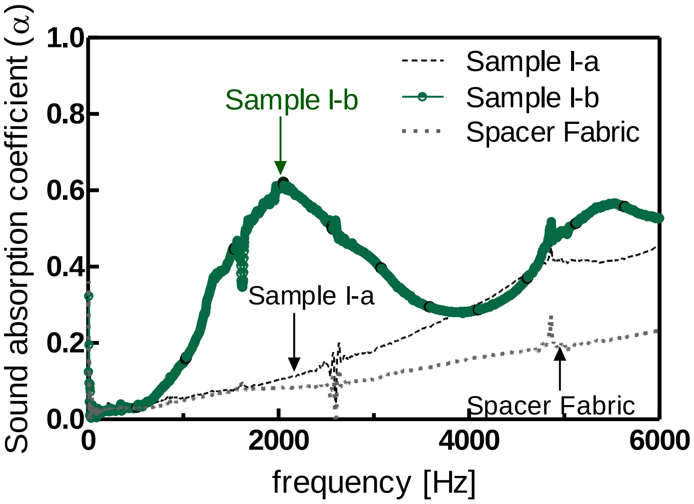


Figure 5. Comparison of the sound absorption coefficients of spacer warp knitted fabrics coated with PAN nanofibers (*Sample I-a* and *Sample I-b*) and uncoated spacer fabric.

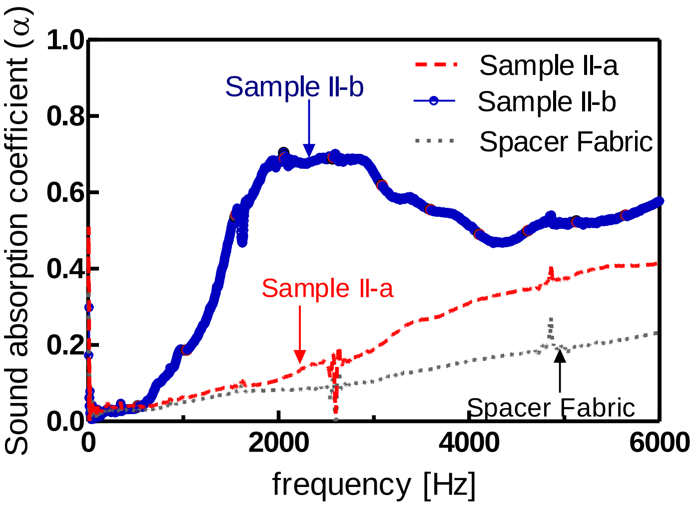


Figure 6. Comparison of the sound absorption coefficients of spacer warp knitted fabrics whose both layers are coated with PAN nanofibers (*Sample II-a* and *Sample II-b*) and uncoated spacer fabric.

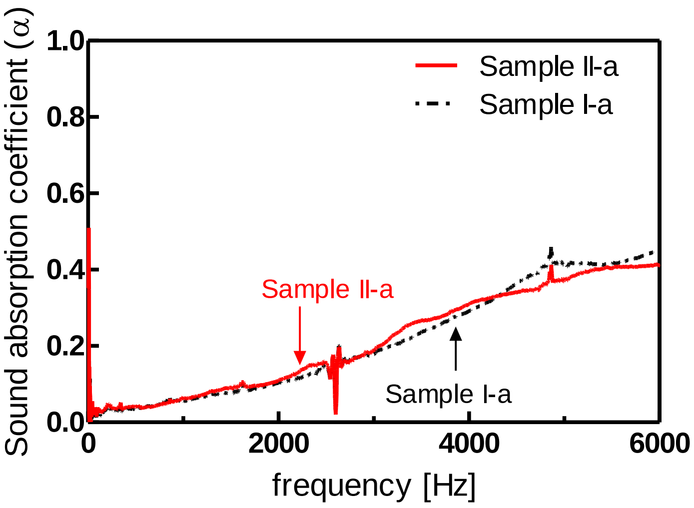


Figure 7. Comparison of the sound absorption coefficients of spacer warp knitted fabrics whose one layer and both layers coated with 10g/m^2 PAN nanofibers.

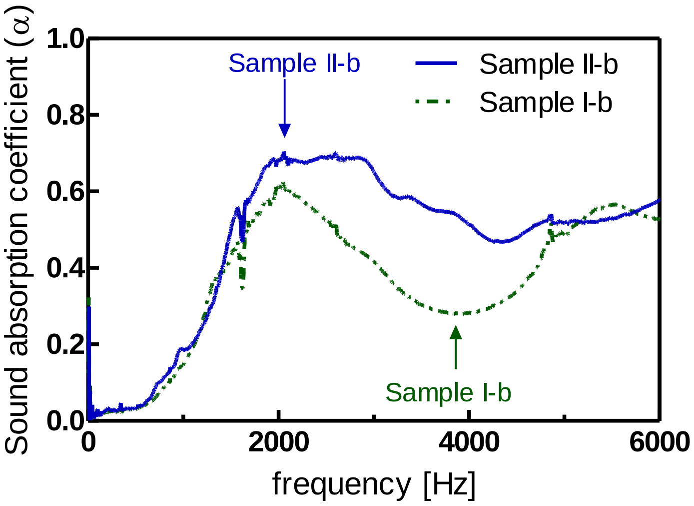
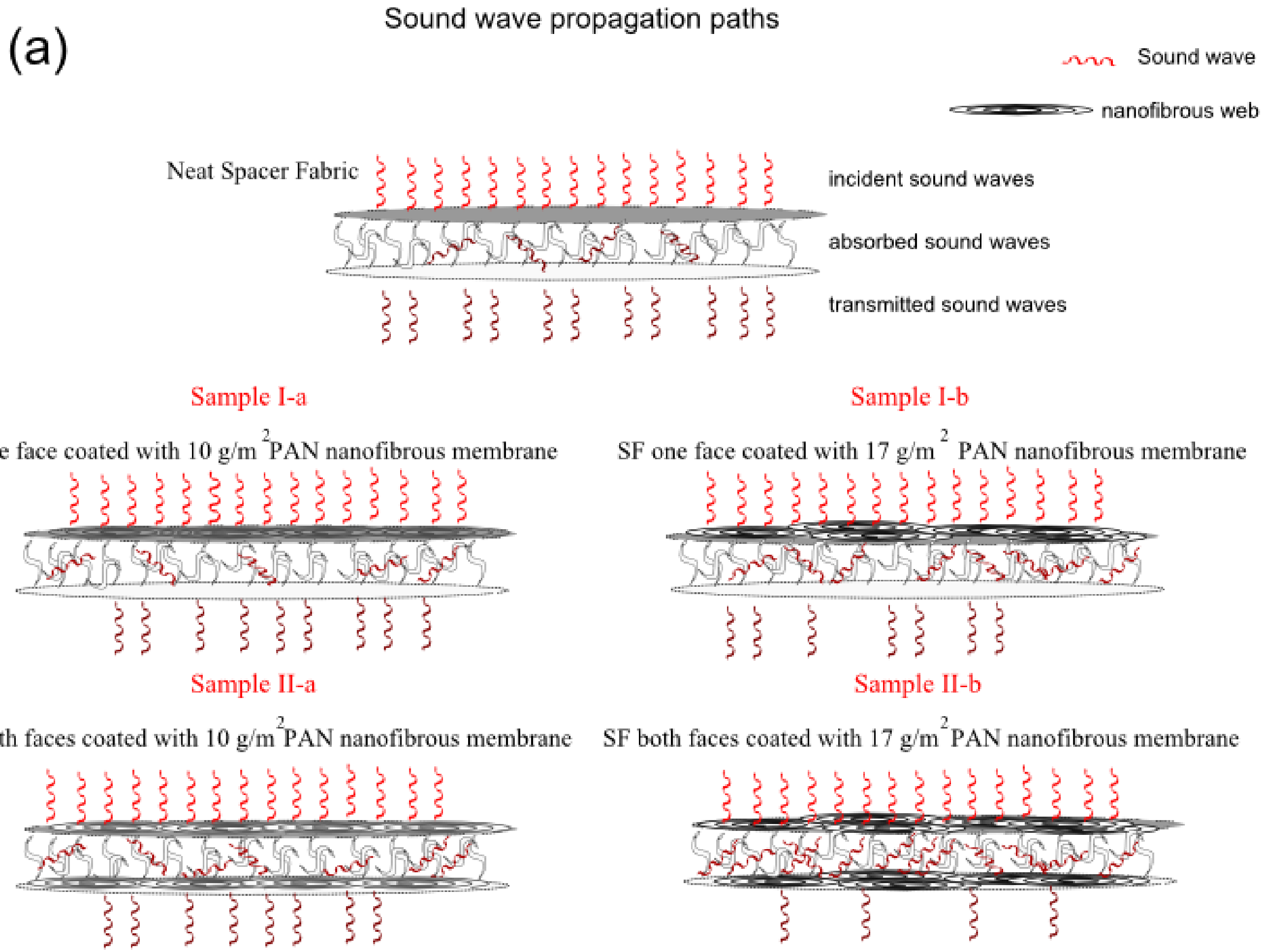


Figure 8. Comparison of the sound absorption coefficients of spacer warp knitted fabrics whose one layer and both layers coated with 17g/m^2 PAN nanofibers.

Dominated sound absorption mechanisms may be illustrated in the way given in Figure 9 (a). Our hypothesis is that this phenomena correlates with percolation theory as given in Figure 9 (b) where hypothetical points are generated for better description [25-27]. The sound absorption coefficients of *Sample I-a&b* and *Sample II-a&b* measured at 2000 Hz are, for instance, displayed in the same graph. It is clear that *Sample I-a* and *Sample II-a* are not efficient enough to trap sound waves throughout fabric. On the other hand, *Sample I-b* and *Sample II-b* respond at a different regime, which was beyond percolation limit. These results emphasized that the total amount of coating (or nanofibers deposited) were not solely dominant players in sound absorption mechanism. Manipulation of sound waves propagation by tuning surface morphology such as roughness would also affect sound absorption characteristics. For instance, having same chemical compositions, nanofiber surfaces exhibit higher roughness compared to dip-coated surfaces [28]. Thus, nanofiber coating has high level tortuosity which damps sound waves, more effectively. Besides, low frequency sound absorption, which has direct relationship with thickness and roughness of coated surfaces, is improved in nanofiber enhanced composite structures. Since deposited nanofibers are able to behave as porous absorbers and enable to damp sound waves whose wavelength is one tenth of thickness. Sound absorption results also correlates with air permeability values which is provided in Table 1. Since the air permeability of fabric influences the acoustical absorption capability of materials such that lower air permeability capacity causes lower sound transmission; and as a consequence, more sound absorption.



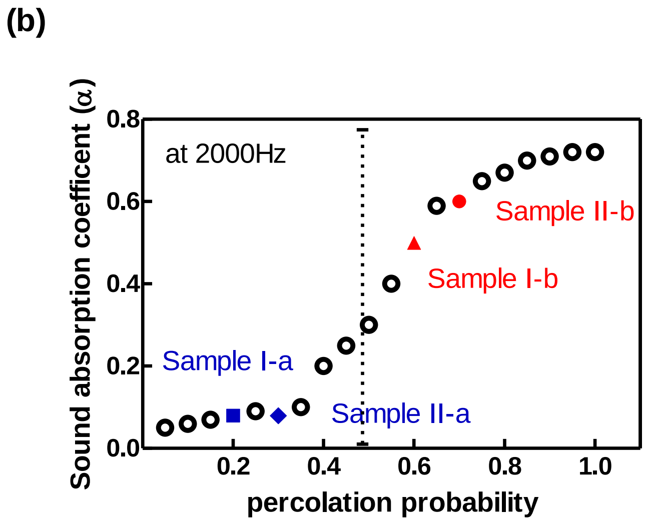


Figure 9. (a) Predicted sound waves propagation paths through coated and uncoated fabrics.**(b)** Sound absorption coefficient (α) vs percolation probability graph of *Sample I-II-a* (colored in blue) and *Sample I-II-b*(colored in red). Hypothetical hollow circular points colored in black were generated for better description of percolation theory.

Conclusion

In this study, we proposed a novel approach to produce nanofibrous coated composites. This method eliminated additional processing steps like post-lamination process and handling of nanofibrous membrane and provided the applicability of nanofibers even at macro-scale. The acoustic performance of polyacrylonitrile (PAN) based nanofibrous membranes which were electrospun over spacer fabrics, were investigated. .As substrate material, spacer knitted fabric was used, which has better sound absorption properties than conventional knitted structures due to having two face layers which are connected to each other by an interconnecting yarn. The experimental results showed that the deposition amount of PAN nanofibers as well as the number of coated layers (single or double) have an influence on sound absorption performance and dominated sound absorption mechanism. Finally, the sound absorption coefficient values for the samples having coatings of 17 g/m^2 on both surfaces reached up to 0.7 for the frequency range of 1000 Hz – 3200 Hz with no weight and thickness penalty.

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References

1. Schmid F, Haase W, Sobek W, Veres E, Mehra SR, Sedlbauer K. Noise protection and acoustic behaviour of multi-layer textile facade systems. *Bauphysik*. 2014;36:1-10.
2. Bashkova G, Bashkov A. Analysis Acoustic Absorption Capability of Innovative Textile Materials. *Let's Build the Future through Learning Innovation!*, 2014; 4:285-288.
3. Del Rey R, Alba J, Blanes M, Marco B. The acoustic absorption of textile curtains on the function of the fullness. *Mater. Construcc.*, 2013;63:569-580.
4. Curtu I, Stanciu MD, Cosereanu C, Ovidiu V. Assessment of Acoustic Properties of Biodegradable Composite Materials with Textile Inserts. *Mater. Plast.*, 2012;49:68-72.
5. Perepelkin KE, Ivanov MN, Lavrova ZI. Acoustic emission in investigation of the characteristics of fracture of complex viscose fibres and textile materials based on them. *Fibre Chem.*, 1997;29:388-391.
6. Dias T, Monaragala R and Lay E. Analysis of thick spacer fabrics to reduce automobile interior noise, *Meas. Sci. Technol.*, 2007; 18: 1979–1991.
7. Dias T, Monaragala R, Needham P and Lay E. Analysis of sound absorption of tuck spacer fabrics to reduce automotive noise, *Meas. Sci. Technol.*, 2007; 18: 2657–2666.
8. Kucukali Ozturk M., Nergis B. and Candan C. A Study on the Influence of Fabric Structure on Sound Absorption Behavior of Spacer Knitted Fabrics, *7th Textile Science conference*, Liberec, Czech Republic, September 6-8, 2010.
9. Kucukali Ozturk M., Nergis B and Candan C. A Study on the Influence of Polyester Yarn Structure on Sound Absorption Properties of Spacer Knitted Fabric, *AUTEX 2012*, Zadar, Croatia 2012.
10. Kucukali Ozturk M, Nergis B and Candan C. Effect of Face Fabric Layer Structure on Sound Absorption of Spacer Knitted Structure, In: *19th International Conference, Structure and Structural Mechanics of Textiles*, Liberec, Czech Republic, December 3rd-4th 2012.
11. ISO 10534-2: Acoustics – Determination of sound absorption coefficient and impedance in impedance tubes – Part 2: Transfer-Function Method. 1998. International Standardization Organization
12. Özgüven H. N., 2008. Gürültü Kontrolü, Endüstriyel ve Çevresel Gürültü, Türk Akustik Derneği - Teknik Yayınları, İstanbul
13. Product Data: Impedance Measurement Tube Type 4206, available from www.bksv.com (accessed: 31 August 2015).
14. Shahani F, Soltani P and Zarrebini M. The Analysis of Acoustic Characteristics and Sound Absorption Coefficient of Needle Punched Nonwoven Fabrics, *J. Eng Fiber Fabr.*, 2014; 9(2): 84-92.
15. Rabbi A, Bahrambeygi H, Nasouri K, Shoushtari AM and Babaei MR. Manufacturing of PAN or PU Nanofiber Layers/PET Nonwoven Composite as Highly Effective Sound Absorbers, *Adv. In Poly. Tech.*, 2014; 33(4): 1-8.
16. Mazrouei-Sebdani Z, Khoddami A, Hadadzade H and Zarrebini M. Synthesis and performance evaluation of the aerogel-filled PET nanofiber assemblies prepared by electro-spinning, *RSC Advances*, 2015; 5(17): 12830-12842.
17. Kalinova K., Nanofibrous Resonant Membrane for Acoustic Applications, *J.Nanomater.*, 2011
18. Mohrova J.and Kalinová K. Different Structures of PVA Nanofibrous Membrane for Sound Absorption Application, *J. Nanomater.*, 2012

19. Jirsak O, Kalinova K and Stranska D. Nanofibre Technologies and Nanospider Applications, In: *5th Int. Nanotechnology Symposium*, Karlsruhe, Germany, November 21-22, 2006.
20. Kucukali Ozturk M, Kalinova K, Nergis B and Candan C. Comparison of Resonant Frequency of Nanofibrous Membrane and Homogenous Membrane Structure, *Text. Res. J.*, 2013; 83(20): 2204–2210.
21. Li F, Zhao Y and Song Y. Core-Shell Nanofibers: Nano Channel and Capsule by Coaxial Electrospinning, In: Ashok Kumar (Ed.), *Nanofibers* 2010, In Tech, 419-438.
22. Kucukali Ozturk M, Nergis B, Candan C and Kalinova, K. The Effect of Mass Per Unit Area on the Sound Absorption Behavior of the Combined Structures from Nanofibrous Membrane and Porous Material, *14th AUTEX World Textile Conference,* Bursa, Turkey May 26th to 28th 2014.
23. Xiang Hai-fan, Tan Shuai-xia, Yu Xiao-lan, et al. Sound absorption behavior of electrospun polyacrylonitrile nanofibrous membranes. *Chin J Polymer Sci*., 2011; 29: 650–657.
24. Hur B.Y, Park B.K, Ha D.I and Um Y.S. Sound Absorption Properties of Fiber and Porous Materials, *Mater. Sci. Forum.,* 475-479: 2687-2690.
25. Lam PM, Bao W, Yang YS. Renormalization-Group Study of Anomalous Acoustic Behavior in Critical Percolation Network. *Z. Phys. B-Con. Mat.,* 1985;61:283-287.
26. Ohtsuki T, Keyes T. Anomalous Acoustic Behavior and Backbone Structure of Percolation Clusters. *J. Phys. A.Math. Gen.,* 1984;17:L137-L142.
27. Ohtsuki T, Keyes T. Enhancement of Acoustic-Wave Attenuation near a Percolation-Threshold. *J. Phys. C-Solid State.,* 1984;17:L317-L320.
28. Ozden-Yenigun E, Menceloglu YZ, Papila M. MWCNTs/P(St-co-GMA) Composite Nanofibers of Engineered Interface Chemistry for Epoxy Matrix Nanocomposites. *ACS Appl. Mater. Inter.,* 2012;4:777-784.