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RESEARCH ARTICLE

# Thermal insulation and sound absorption properties of fibrous layered structures

Canan Sarıçam, Nazan Okur*, Nuray Uçar, Nevin Çiğdem Gürsoy

Istanbul Technical University, Department of Textile Engineering, Istanbul, Türkiye

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## Abstract

In this study, the effects of the addition of Activated carbon powder (ACP), Polyacrylonitrile nanofiber web (PAN), application of Plasma treatment (P), and the number of treatment layers on thermal insulation and sound absorption properties of fibrous structures have been examined and compared to each other. Bamboo and E-glass fibers have been used to produce fibrous layered structures. E-glass-based fibrous structures had slightly higher thermal resistance than that of bamboo fiber-based fibrous structures. However, sound absorption of bamboo-based fibrous layered structures was higher than that of E-glass fiber-based fibrous layered structures. The results revealed that plasma treatment, nanofiber web application, and activated carbon powder insertion increased the thermal resistance of fibrous layered structures made of bamboo fiber and E-glass fiber. In particular, the plasma treatment on three layers provided the highest thermal resistance for the E-glass fiber fibrous layered structure, however, PAN nanofiber application between three layers resulted in the highest thermal resistance for the bamboo fiber fibrous layered structure. Concerning sound absorption, the PAN nanofiber web provided the highest improvement for both the bamboo fiber-based layered structures and the E-glass-based layered structures.

## 1. Introduction

Sound absorption and thermal insulation are vital for some industries such as construction and automotive for insulation of high-speed rotating mechanical parts to increase the comfort level of the interior environment and energy savings by eliminating disturbances. Whereas, thermal insulation is significant in energy saving since it abates heat transfer between a medium and its environment [1,2]; sound absorption decreases noise pollution, which causes annoyance and sleep disturbance that can even contribute to heart attacks, learning disabilities, and tinnitus [3].

Other than the high-density materials that could insulate the sound efficiently, fibrous materials are preferred for acoustical applications; because the rigid materials do not allow the sound waves to get through and reflect the sound waves into the environment [4]. In fibrous materials, the number of boundaries of the material is directly proportional to the number of fibers. Meeting these boundaries, some sound waves are reflected, some are transmitted through the boundary and some are absorbed [4]. Fibrous materials are efficient in sound absorption because of their characteristics such as porosity, tortuosity, density, airflow

* Corresponding author (okurn@itu.edu.tr)

resistance, and thickness [5]. On the other hand, fibrous materials are also used for thermal insulation because of their inherent characteristics of high tortuosity and porosity [6]. Thus, the porosity of the material is an important property that influences both thermal insulation and sound absorption.

Besides, some treatments such as plasma can improve both the sound absorption and thermal insulation of the porous materials. Plasma is a technique that modifies surface characteristics [7]. Argon plasma and Oxygen plasma result in fiber surface etching [8]. However, this etching effect may not be observed by SEM (Scanning Electron Microscopy) because of some setup problems, the quality and the magnification properties of the equipment, and its effect may be noticed by increased surface roughness through the AFM (Atomic Force Microscopy) analysis [9]. Investigating the sound absorption and the viscoelastic property of the automotive nonwovens and the plasma treatment, Na and Choo studied the effect of plasma treatment on the needle-punched fabrics including 2 polyester fabrics made of hollow polyester fibers or solid polyester fibers and 2 polypropylene-composite cellulose fabrics made of jute fibers or kenaf fibers. The authors stated that the plasma treatment increases the surface area of the fibers due to the etching effect and the sound waves of high frequency have a higher possibility to interact with fibers when there are smaller and more pores in the web with high porosity [10].

Having a very high specific surface area of up to 2500 $m^2/g$ and a high micro-pore volume of up to 1.6 ml/g [11], activated carbon materials and their integration into the material were found to improve the sound absorption ability of nonwovens significantly [12]. Activated carbon fiber (ACF) is stated to be an ideal porous material for sound absorption due to the developments in production processes and the decrease in the cost of production. Since it is light, fire-resistant, and anticorrosive, they can be preferred in the insulation of buildings, automobile interiors, and road barriers [13].

Moreover, the application of innovative nanofibers is efficient in noise control at lower frequencies because of having porous structures [14]. Investigating the sound absorption characteristic of electrospun materials, Rabbi et al. found out that the sound transmission loss was improved by increasing the number and weight per unit area of nanofiber layers which provide high surface area due to fiber in nanoscale [5]. In addition to good sound absorption properties, producing nanofibers with electrospinning also enables the production of highly porous structures with very small pore sizes [6,15]; which results in lower thermal conductivity and thus, higher thermal insulation. Nonetheless, the influence of the applications and treatments mentioned above were not investigated comparatively and in detail covering both thermal insulation and sound absorption.

Recently, natural fibers, as fibrous porous materials, were investigated for their sound absorption characteristics and proposed as an alternative for other conventional synthetic fibrous materials, like glass fiber and mineral wool [16] because of use the same mechanism of sound absorption and are lighter in weight. Besides, natural fibers are also advantageous in eliminating some health concerns related to some common synthetic materials such as glass fiber, which adheres to the body during processing. Other than kenaf, jute, and coir fibers [17-20], bamboo was also investigated as a sound-absorbing material [21]. Koizumi et al. [21] have compared the sound absorption coefficient of the bamboo fiber to that of glass wool and found that the acoustic characteristics, sound absorption coefficient, characteristics impedance, and propagation constant of the bamboo fiber are similar to that of glass wool. Thilagavathi et al investigated the sound absorption properties of nonwovens made of bamboo, banana, and jute fibers blended with polypropylene in a ratio of 50: 50. They observed that the bamboo/polypropylene nonwoven showed, higher tensile strength, higher stiffness, and lower elongation, lower thermal conductivity, lower air permeability, and good absorption coefficient when compared to others and they stated that it is suitable for the automotive interior noise control [22]. Similarly, Buyukakinci et al. observed that adding cotton, bamboo, or wool fibers to polyurethane foam improved the sound absorption coefficient [23].

Sound and thermal insulator materials can be used in many areas such as generators, engines, etc. To the best of our knowledge, in the literature; the comparisons of these two fibers (bamboo and E-glass) for thermal insulation were not made and the effect of plasma treatment, activated carbon insertion, and nanofiber web application on both sound absorption and thermal insulation properties of fibrous layered structures were not compared to each other. Given these limitations and the gaps in the literature, the purpose of this study is to contribute to the literature by providing novel comparative results regarding the effects of activated carbon powder (ACP), polyacrylonitrile nanofiber web (PAN), and plasma treatment (P) in different amounts on the sound absorption and thermal insulation properties of fibrous layered structures, made up of two fibers as bamboo and E-glass. Besides, the originality of the present study lies also in the comparison of the given properties of bamboo fiber with that of E-glass fiber, since the use of bamboo is relatively new and the knowledge about its potential in that area is quite limited, against the use of E-glass fiber.

## 2. Material and method

### 2.1. Material

E-glass fiber and bamboo fiber were obtained from Cam Elyaf Sanayi AŞ and Karteks from Turkey. The activated carbon powder was purchased from Grafen Chemicals in diameter < 100nm, Polyacrylonitrile (PAN), ($M_w$ = 150000 g/mol) was purchased from Sigma Aldrich, and N, N-Dimethylformamide (DMF) was purchased from Merck.

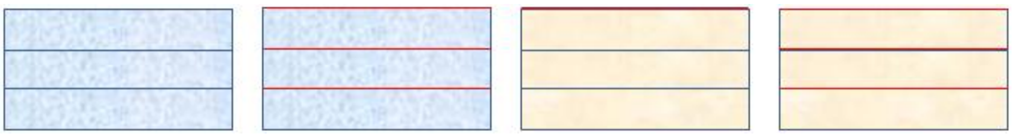
### 2.2. Method

E-glass and bamboo fibers were processed in a laboratory-type carding machine (Mesdan Laboratory Carding Machine, 337A) and fibrous structures were produced. All fibrous structures were aimed to be produced in the same thickness. The production of the samples was made by spreading three layers of fibrous structures which were obtained from the carding machine. The thicknesses of E-glass and bamboo fiber structures were measured as 4.474+0.41 mm and 4.511+0.15 mm respectively.

### 2.3. Plasma treatment of fibrous layered structures

The plasma treatment of fibrous structures was performed on a Plasmatek device. Samples were placed in the plasma chamber and a vacuum of about 600-800 mTorr was provided. Samples were exposed to $O_2$ (0.05 liters per minute) and Argon (0.5 liters per minute) gasses under 80 volts for 60 seconds. Both Oxygen and Argon plasma were used since both of them have an etching effect. Whereas Oxygen plasma is effective in the formation of functional groups, Argon Plasma increases the etching effect when both Oxygen and Argon are used together [24,25].

The fibrous layered samples were prepared to have three layers. Only the surface of the uppermost layer of the samples G1P and B1P was treated by the plasma; while the surfaces of the three layers of the samples G3P and B3P were treated by plasma application. The applications were demonstrated schematically in Fig. 1. The thicknesses of plasma-treated E-glass fiber layered structures and bamboo fiber layered structures were measured as 5.105±0.90 mm and 5.559±0.01 mm respectively.



a b c d

Fig. 1. Demonstration of samples with plasma treatment, a: E-glass fiber sample with plasma treatment on one layer, b: E-glass fiber sample plasma treatment on three layers, c: bamboo fiber sample with plasma treatment on one layer, d: bamboo fiber sample with plasma treatment on three layers

### 2.4. Plasma treatment of fibrous layered structures

The fibrous layered samples were prepared to have three layers. Activated carbon powder was deposited manually between only the first and second layers for the samples G1ACP and B1ACP and between all layers for the samples G3ACP and B3ACP. The applications were demonstrated schematically in Fig. 2. The thicknesses of ACP-applied glass fiber fibrous layered structures and bamboo fiber fibrous layered structures were measured as 5.309±0.38 mm and 5.567±0.13 mm respectively. The amount of ACP within the fiber-layered structures was tried to be kept at the percentages of 5% and 10% with one-layer and three-layer ACP treatments respectively.

### 2.5. PAN nanofiber production and application to fibrous layered structures

Polyacrylonitrile has been dissolved by Dimethylformamide (DMF) as 10 w% by using a magnetic stirrer at 60 C°. Nanofiber webs were produced on a horizontal electrospinning apparatus, which was equipped with a syringe pump, a high-voltage power supply, and a grounded rotating collector covered by aluminum foil. DMF-PAN solution was added to a 20 ml syringe with a blunt needle and fed with the flow rate of 2 ml/h towards the tip of the needle. A voltage of 15.6 kV was applied to create an electrical field between the nozzle and the rotating cylindrical collector, where the distance was set to 12 cm. The average diameter of nanofibers within the web was found to be 198.2 nm. The SEM image of the PAN nanofiber is shown in Fig. 3. As in the case of Active carbon powder application, PAN nanofibers were put between the first and second layers for the samples G1PAN and B1PAN and; between all layers for the samples G3PAN and B3PAN. The thicknesses of E-glass fiber layered structures and bamboo fiber layered structures containing PAN nanofiber were measured as 5.325±0.19 mm and 5.181±0.43 mm respectively. The amount of PAN nanofiber within the fiber-layered structures was tried to be kept at the percentages of 10% and 20% within one-layer and three-layer PAN insertion respectively. Demonstration and images of samples with PAN insertion were shown in Fig. 4 and 5 respectively.

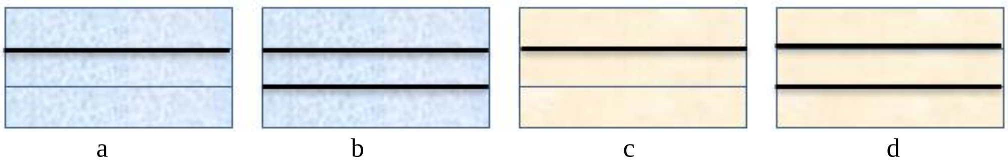



Fig. 2. Demonstration of samples with ACP insertion, a: E-glass fiber sample with one layer ACP, b: E-glass fiber sample with ACP between three layers, c: bamboo fiber sample with one layer ACP, d: bamboo fiber sample with ACP between three layers

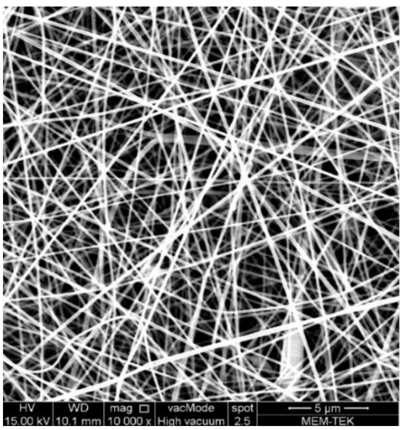
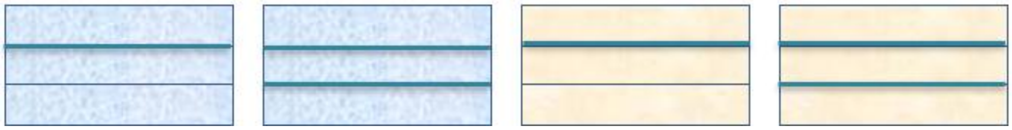
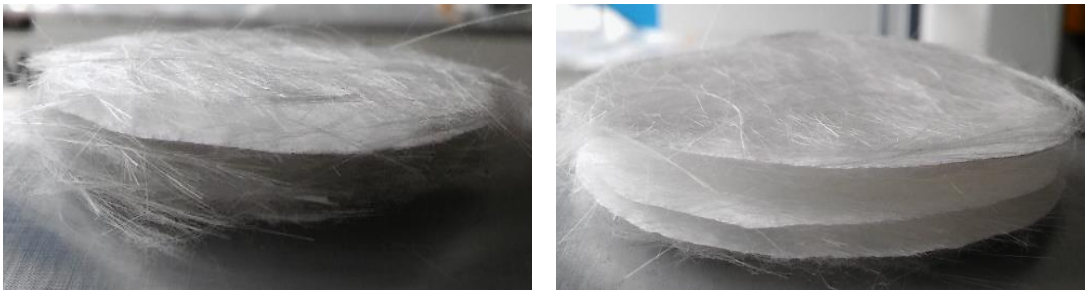



Fig. 3. SEM image of PAN nanofiber



a b c d

Fig. 4. Demonstration of samples with PAN insertion, a: E-glass fiber sample with one layer PAN insertion, b: E-glass fiber sample with PAN insertion between three layers, c: bamboo fiber sample with one layer PAN insertion, d: bamboo fiber sample with PAN insertion between three layers



a b

Fig. 5. Images of samples with PAN insertion, a: E-glass fiber sample with one layer PAN insertion, b: E-glass fiber sample with PAN insertion between three layers

The samples were coded as shown in Table 1.

## 2.6. Testing procedure

The thermal resistance, which is an indication of the thermal insulation property of a material, and the thicknesses of the samples were measured using Alambeta Instrument according to ISO 11092:2014 standard [26]. Alambeta Instrument uses two plates, one is a hot plate and the other is a cold plate. The hot plate, located at the upper part, contacted the sample at a pressure of 200 Pa. The convection of the heat from the hot plate to the cold plate through the sample was detected by the heat flux sensors inside. The thicknesses of the samples were also measured by a sensor. The flux of heat, which is the energy per unit area per unit time, was measured in the instrument was divided by the temperature gradient, and by using Eq. 1, the thermal conductivity of the samples was determined [27].

$$\lambda(\mathrm{W}m^{-1}K^{-1}) = \frac{Qh}{A\Delta Tt} \tag{1}$$

where; $Q$ is the amount of conducted heat ($J$); A is the area through which the heat is conducted ($m^2$); t is the time of conductivity ($s$); ΔT is the drop of temperature ($K$); h is the fabric thickness ($m$). Then the thermal resistance, which is the difference of the temperature across a unit area of the samples of unit thickness when a unit of heat energy flows through the sample in unit time, was defined by using Eq. 2 [28]:

$$R = h/\lambda \tag{2}$$

where; $R$ is the thermal resistance of the sample, $h$ is the sample thickness and $\lambda$ is the thermal conductivity of the sample.

Sound absorption coefficients ($\alpha$) of the samples were measured by using the TestSENS SOUNDTUBE testing device and TestSENS acoustic material testing software using ISO 10534-2 standard [29]. Measurements were performed within the frequency range of 100 Hz and 3900 Hz. Thermal resistance values and sound absorption coefficients were measured on the samples, which of their production and application procedures were explained above. All the tests were performed under standard atmospheric conditions (20±2 °C and 65%RH).

## 3. Results and discussion

### 3.1. Thermal resistance values

In Fig. 6, the comparison of the thermal resistance values of E-glass fiber and bamboo fiber layered structures and the effect of each application on thermal resistance values was shown. The test results revealed that E-glass fiber layered structures have generally higher thermal resistance than that of bamboo fiber layered structures. This can be attributed to the lower thermal conductivity of E-glass materials when compared to the regenerated bamboo fiber materials [30, 31]. In addition, Fig. 6 supports that all the applications such as plasma treatment, application of nanofiber web, and presence of activated carbon powder resulted in an increase of thermal resistance values for both E-glass fiber and bamboo fiber layered structures namely G1P, G1ACP, G1PAN, B1P, B1ACP, B1PAN compared to the fibrous layered structures with no application G and B. Even the increase in the thermal resistance of the samples G3P, G3ACP, G3PAN, B3P, B3ACP, and B3PAN was observed to be more remarkable. The positive effect of plasma treatment on thermal resistance can be attributed to the abrasion and increased roughness of the fiber surface as pointed out in the literature [8] which enables an increase in the number of gaps for capturing more dead air inside the structure as pointed in the literature [30]. The integration of activated carbon powder may increase the amount of micropore volume within the structure which leads to higher air capturing and better thermal insulation performance [11]. Finally, the influence of the application of the PAN nanofiber layer can be explained by the fact that the diameters of fibers produced by using the electrospinning method are lower than that of conventional fibers. Because noticeable thermal insulation is possible for nanofibers, which have nano diameters and higher surface densities and nanopores [1].

Table 1. Sample and application code

| Sample Code | Sample Description |
|---|---|
| G | E-glass fiber with no application or treatment |
| B | Bamboo fiber with no application or treatment |
| G1P | E-glass fibrous structure with plasma treatment on one layer |
| B1P | Bamboo fibrous structure with plasma treatment on one layer |
| G3P | E-glass fibrous structure with plasma treatment on three layers |
| B3P | Bamboo fibrous structure with plasma treatment on three layers |
| G1ACP | E-glass fiber with ACP application in one layer |
| B1ACP | Bamboo fiber with ACP application in one layer |
| G3ACP | E-glass fiber with ACP application between three layers |
| B3ACP | Bamboo fiber with ACP application between three layers |
| G1PAN | E-glass fiber with PAN application in one layer |
| B1PAN | Bamboo fiber with PAN application in one layer |
| G3PAN | E-glass fiber with PAN application between three layers |
| B3PAN | Bamboo fiber with PAN application between three layers |

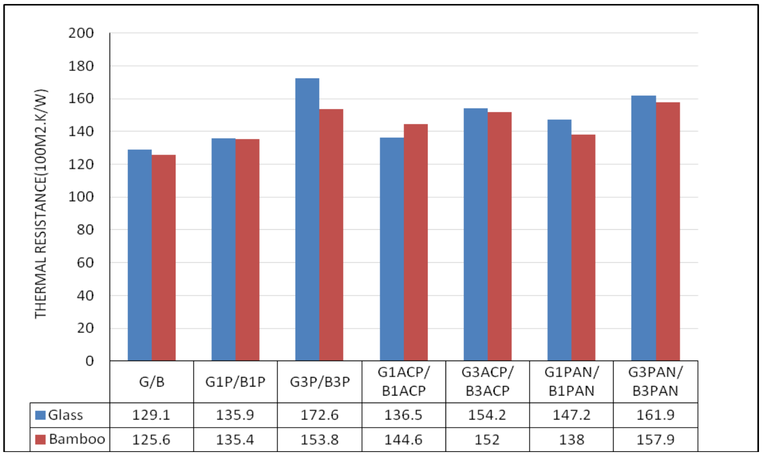



Fig. 6. Comparison of thermal resistance values of E-glass fiber and bamboo fiber layered structures

When the effects of different applications are compared, it can be concluded that the greatest increase in thermal resistance property was achieved by the plasma treatment on three layers on the E-glass fiber-based fibrous layered structures and by three-layer PAN nanofiber application on the bamboo fiber-based fibrous layered structures.

## 3.2. Sound absorption coefficients

The measured sound absorption coefficients of the samples are shown in Fig. 7-12. In Fig. 7, the sound absorption coefficients of E-glass and bamboo fiber layered structures as the functions of frequency are shown. Both E-glass and bamboo fiber layered samples showed steadily increasing sound absorption characteristics between the frequency range of 100-3900 Hz. While the sound absorption coefficient of E-glass and bamboo fiber layered samples were close to each other at a lower frequency range of 100-600 Hz, the sound absorption coefficient values of bamboo fiber layered samples were higher when compared to that of E-glass samples within the frequency range of above 600 Hz, this may be due to the creased, serrated surface and porous structure of bamboo fiber as mentioned in the literature [33,34].

The effect of plasma treatment on the sound absorption coefficients of the samples is shown in Fig. 8. It was found that plasma treatment improved the sound absorption property of the layered samples, particularly at the frequency above 600 Hz, this may be attributed to the abrasion and increased roughness of the fiber surface due to the etching effect of plasma [9]. The improvement in the sound absorption property for E-glass fiber layered samples was observed to be more obvious for the sample G3P (sample with plasma treatment on three layers) when compared to the G1P sample (sample with plasma treatment on one layer). On the other hand, the plasma treatment on one layer had a noticeable improvement in the sound absorption property of the bamboo fiber layered sample.

Fig. 9 shows the effect of activated carbon application on the sound absorption coefficients of the samples. According to the results, it can be stated that activated carbon application positively affected the sound absorption property of the fibrous layered samples, regardless of the fiber type. The integration of pores into the fibrous layered samples by using activated carbon powder might have provided an increase in the sound absorption coefficient, as stated in previous studies [35, 36]. The positive effect was obvious mainly at the frequency above 600 Hz. However, the application of activated carbon between the three layers of the samples did make a slight difference in sound absorption property when compared to the application onto only one layer of the samples.

The graph in Fig. 10 illustrates the effect of PAN application on the sound absorption coefficients of the samples. The graph reveals that one-layer PAN application improved the sound absorption property of the

E-glass fiber layered samples, and PAN application between three layers of the E-glass fiber layered samples provided a further improvement on the sound absorption property compared to one-layer PAN application. Concerning bamboo fiber layered samples, one-layer PAN application had a slightly positive effect on the sound absorption property; whereas, the application of PAN between three layers of the bamboo fiber layered samples considerably enhanced the sound absorption property. The improvement in sound absorption properties with PAN application can be attributed to the higher surface area and lower fiber size of nanofibers [5] and highly porous structures with very small pore sizes [6, 15]. In the literature [5], it has been pointed out that the incorporation of nonwoven materials with polyurethane and polyacrylonitrile nanofiber layers was stated to improve sound absorption performance. As stated for the effects of plasma treatment and ACP application, the improvements were obvious at a frequency above 600 Hz.

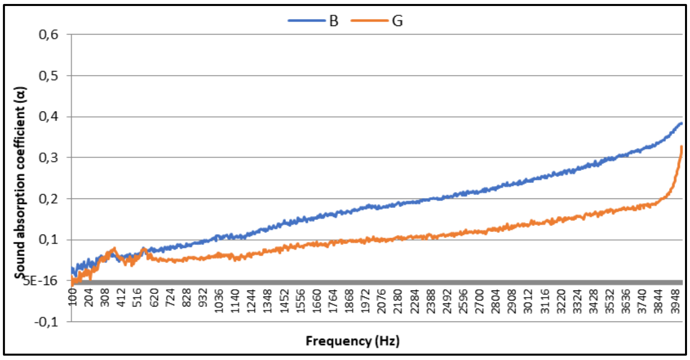



Fig. 7. Comparison of sound absorption coefficients of E-glass fiber and bamboo fiber layered structures

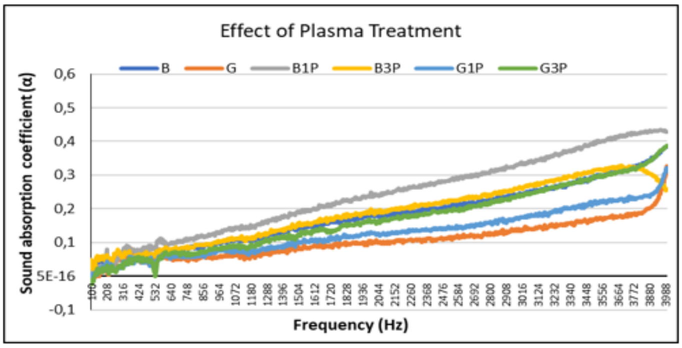



Fig. 8. Effect of plasma treatment on the sound absorption coefficient of the samples

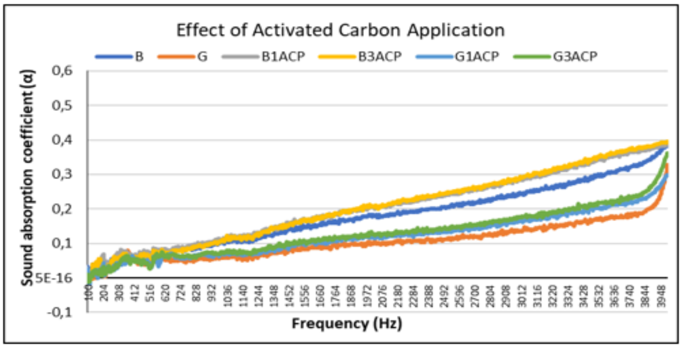



Fig. 9. Effect of activated carbon application on the sound absorption coefficient of the samples

As a result, the analysis showed that the samples with plasma treatment, activated carbon application, and PAN application absorbed all sound frequencies better than untreated samples. To evaluate the effects of these treatments and applications, the comparative results were analyzed in the graphs in Fig. 10 and 11 for bamboo and E-glass fiber samples respectively. The graphs were generated for the samples G3P, G3ACP, G3PAN, B3P, B3ACP, and B3PAN since the influences of all treatments and applications as mentioned above were much more apparent for the mentioned samples.

Fig. 11 shows the effects of plasma treatment, ACP, and PAN nanofiber applications on bamboo fiber-based samples. It was observed that plasma treatment had a very slight impact on enhancing the sound absorption property for the bamboo fiber layered samples. However, the application of ACP and PAN nanofiber proposed greater improvements, and the most significant improvement was provided by PAN nanofiber for bamboo fiber layered structures. The effects of the treatment and applications were obvious at a frequency above 2000 Hz.

Fig. 12 shows the effects of plasma treatment, ACP, and PAN nanofiber applications on E-glass fiber-based samples. It was observed that ACP application had the least effect on improving the sound absorption property for glass fiber layered structure. On the other hand, plasma treatment resulted in a higher improvement on E-glass fiber, while PAN nanofiber application had the greatest improvement in sound absorption properties. The improvements were observed at a frequency above 600 Hz.

Noteworthily, the results revealed that bamboo fiber-based samples continued to perform better sound absorption properties when compared to the E-glass fiber-based samples, except the sample G3PAN. The application of PAN between three layers of the E-glass fiber layered samples showed similar and even better performance when compared to the sample B3PAN. While plasma provides an improvement in sound absorption for both types of fiber, it is more effective for glass fiber than bamboo fiber. The positive effects of the treatment and applications were apparent mainly above the frequency of 600 Hz.

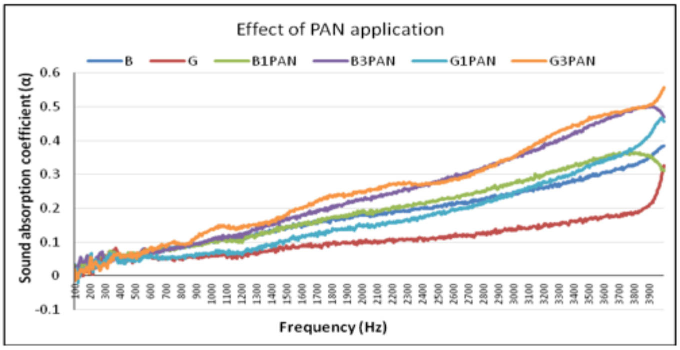



Fig. 10. Effect of PAN application on the sound absorption coefficient of the samples

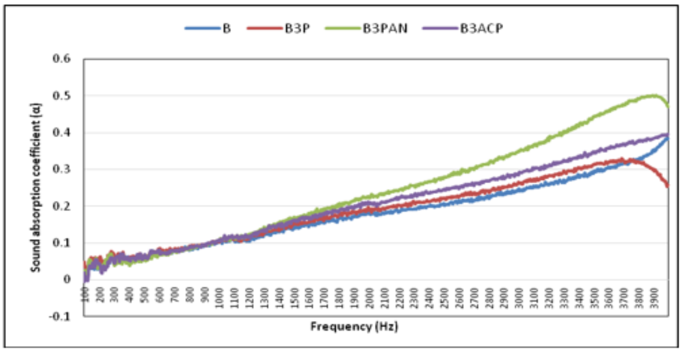



Fig. 11. Comparative results for bamboo fiber samples

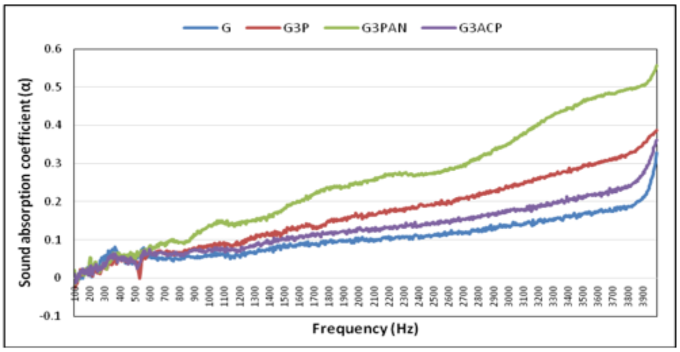



Fig. 12. Comparative results for E-glass fiber samples

## 4. Conclusion

This study explored the thermal insulation and sound absorption properties of fibrous layered structures made of E-glass fiber and bamboo fiber comparatively. The effect of activated carbon and plasma treatment and nanofiber web on both sound absorption and thermal insulation for E-glass fiber layered and bamboo fiber layered structures were analyzed and compared.

According to the results, it was observed that while E-glass fiber layered structures have slightly higher thermal resistance than that of bamboo fiber-based, sound absorption of bamboo fiber layered structures is higher than that of E-glass fiber-based. Based on the observations, the lighter bamboo fiber can be an alternative to E-glass fiber, especially in terms of sound absorption.

Plasma treatment, nanofiber web, and activated carbon powder resulted in an increase of thermal resistance and an increment in the thermal resistances of three-layer samples was more remarkable than that of the one-layer sample. The positive effect can be attributed to the increased roughness of the fiber surface due to plasma etching an increased micropore volume due to activated carbon and nano diameters and high surface densities with nanopores due to the nanofiber web.

The greatest increase in thermal resistance property was achieved by three-layer plasma treatment for the E-glass fiber layered structures and by three-layer PAN nanofiber application for the bamboo fiber layered structures. Among ACP, PAN, and plasma applications, the order for the enhancement of the sound absorption property is the PAN, ACP, Plasma for the bamboo fiber layered samples and PAN, Plasma, and ACP for the E-glass fiber layered samples. Consequently, the addition of PAN nanofiber into the fibrous layered structure, independent of fiber type, can be suggested for improvement in thermal insulation and sound absorption. However, depending on the fiber type, integration of activated carbon powder into the fibrous layered structure made of bamboo fiber can be suggested for a reasonable level of improvement; while plasma treatment can be suggested for the layered structure made of glass fiber.

The fibrous layered structures proposed in the present study can be used in many areas where sound absorption and thermal insulation are needed. Choosing such materials with improved thermal resistance can be an effective solution for decreasing the energy demand for heating in buildings. Besides, for insulating the noise generated in vehicles and in industrial or household equipment and machines such as generators, compressors, and air-pressure water tanks, fibrous structures with improved sound absorption properties can be used. The sound absorption property of such structures can make them efficient solutions in buildings for insulating noise through walls, floors, and ceilings. The ease of manufacturing and light weight of these fibrous structures can make them ideal substitutes for conventional and heavier products.

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## Conflict of interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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## Data availability statement

No new data were created or analyzed in this study.

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