

Technical note

Acoustic and thermal properties of a cellulose nonwoven natural fabric (barkcloth)



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ABSTRACT

The desire to mitigate climate change due to greenhouse gas emissions has led to the exploration of plant fibers as alternative materials for various industrial applications, sound absorption inclusive. In this investigation, sound absorption properties of *Antiaris toxicaria* barkcloth, and the thermal insulation properties of the barkcloth epoxy laminar composites were characterized. Theoretical sound absorption models were utilized to validate the experimental data and the empirical models were in agreement with experimental data. The lowest thermal conductivity was achieved by the *Antiaris toxicaria* epoxy composites.

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1. Introduction

Rapid industrialization and growth of metropolis come with challenges such as noise pollution. According to the new World Health Organization report, traffic related noise accounts for over one million healthy years of life lost annually to ill health, disability, or early death. Furthermore, among the environmental factors contributing to disease in Europe, environmental noise leads to a disease burden that is only second in magnitude to that from air pollution. Noise pollution causes or contributes to not only annoyance and sleep disturbance, but also heart attacks, learning disabilities, and tinnitus [1].

The use of sound absorbing materials is the most effective means used in buildings, automotive, aerospace, and other transport vehicles to abate noise and vibrations through the absorption of the acoustic energy of the acoustic wave as it propagates through the sound absorber [2]. Synthetic materials such as polymer foams, glass fiber, polyester, mineral wool are the leading sound absorption or noise reduction materials used. However, the biggest drawback is that most of the raw materials sources are from fossil fuels.

In order to create a new class of materials, sustainable, renewable material sources are being explored as a consequence of the

Kyoto protocol on global climate change [3]. A comparison based on the Ecoinvent database [4] between the environmental impacts of some traditional and natural sound insulation materials from cradle to gate shows that vegetable fibers need less energy for production and contribute minimum greenhouse gas emissions.

The acoustic properties of jute felt and rubber composites were investigated by Fatima and Mohanty [5]. The addition of rubber was found to reduce the noise reduction coefficient whereas treatment with alkali had no significant change in the sound absorption coefficient. Na and Cho [6] investigated the sound absorption and viscoelastic property of automotive nonwovens and the effect of treatment with plasma. It was observed that jute nonwoven of 5.62 mm thickness used in car headliner felts had good sound absorption at higher frequencies (3000–5000 Hz) whereas treatment with plasma led to the reduction of the sound absorption property of jute nonwovens. A blend of jute-polypropylene nonwoven performed well as a sound absorber and was found to be suitable materials for car flow coverings [7,8]. Yang and Li [9] showed that Jute, Ramie and Flax nonwovens of thickness, 40 mm exhibited better sound absorption performance in comparison to synthetic fibers. Arenga pinnata bast fiber samples of thickness, 40 mm exhibited the sound absorption coefficient within the range of 0.75–0.90 with respect to the frequency 2000–5000 Hz [10].

Zulkifh et al. [11] studied the acoustic properties of multilayer coir fiber panels and found out that the developed panels had a sound absorption coefficient of 0.70–0.80 in the frequency range of 1000–1800 Hz. Fouladi et al. [12] showed that fresh coir fiber

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felt of thickness, 20 mm exhibits an average sound absorption coefficient of 0.8 above the frequency of 1360 Hz. Increasing the thickness improved the sound absorption in lower frequencies, having the same average sound absorption at a frequency greater than 578 Hz and with the thickness of 45 mm. The addition of recycled tyre rubber to coir reinforced polyurethane resin composites produced a positive effect of the composite boards under investigation [13]. Xiang et al. [14] showed that kapok fiber has excellent acoustical damping performance due to its natural hollow structure, and the sound absorption coefficients of kapok fibrous assemblies were significantly affected by the bulk density, thickness and arrangement of kapok fibers but less dependent on the fiber length. Compared with assemblies of commercial glass wool and de-greasing cotton fibers, the kapok fiber assemblies with the same thickness but much smaller bulk density may have similar sound absorption coefficients.

The sound absorption coefficient of rice straw-wood particle composite boards was higher than wood-based materials in the frequency range of 500–8000 Hz [15]. Generally, because agricultural waste such as rice straw and sawdust have low porosity after compaction with binders, the sound absorption properties are lower compared to nonwovens [16]. Doost-hoseini et al. [17] investigated the sound absorption coefficients of insulating boards made of bagasse with the thickness of 12 mm. Urea–formaldehyde and melamine–urea–formaldehyde were used to produce homogeneous as well as three-layered insulating boards with three densities of 0.3, 0.4, and 0.5 g/cubic cm. The obtained results indicated that resin-type affected the sound absorption coefficients. The maximum absorption coefficient was found at 2000 Hz of frequency (in the multi-layered board of 0.50 g/cm³ of density, produced with urea–formaldehyde resin), and the minimum was observed at 500 Hz (homogeneous board of 0.50 g/cm³ produced with urea–formaldehyde resin). Ersoy and Küçük [18] showed that

tea leaf fiber can be used as a sound absorption material, the results showed a beyond average absorption coefficient with a backing of cotton.

Incorporation of an air gap between sound absorption materials has a positive effect on the absorption behavior of the material assemblies [19,20].

In this investigation, sound absorption and thermal insulation properties of barkcloth, a nonwoven fabric from *Antiaris toxicaria* were characterized. Theoretical sound absorption models available in literature were utilized to validate the experimental data.

2. Materials and methods

Barkcloth from *Ficus natalensis* and *Antiaris toxicaria* fabrics was extracted using the method described by Rwwiire et al. [21]. Table 1 shows an overview of physical, chemical and mechanical properties of Barkcloth. Using vacuum assisted resin transfer molding, synthetic Epoxy resin LG285 and amine hardener HG 285 supplied by GRM systems, Czech Republic was utilized in the production of composite panels.

2.1. Acoustic properties

The acoustic properties of barkcloth were investigated using a type 4206 Brüel&Kjær impedance tube according to ISO10534-2 standard using two quarter-inch condenser microphones type 4187 (Fig. 1A). The principle of measurement works in such a way that the sound source is generated by a loudspeaker at the end of the impedance tube; the sound waves are transmitted to the surface of the material sample (Fig. 1B). The tube measures the physical sound absorption coefficient (the fraction of acoustic energy not reflected by the material surface), which is a quotient of acoustic energy absorbed by the material to the energy of the incident wave.

The material samples with a diameter of 29 mm; thickness ranging from 1 to 1.4 mm were studied in the frequency range of 500–6400 Hz. The airflow resistivity was measured utilizing the air resistance meter and the value of airflow resistivity was calculated utilizing the equation below:

$$\sigma = \frac{\Delta P}{Ud} \quad (1)$$

where ΔP is the set pressure difference between the surfaces; U is the air flow velocity and d is the thickness of the sample.

2.2. Thermal properties

Alambeta thermal conductivity measuring device [22] which measures the thermal conductivity of specimens of up to 8 mm was used under room temperature. The composites (Fig. 2) were ground using sandpaper so as to achieve a uniform smooth surface for thermal conductivity tests. Chemical silicon paste was used to condition the samples, thus serving a dual purpose of a lubricant to prevent damage to the device's measuring probes and the fastening of the device heating plate to the samples.

Table 1
Overview of barkcloth material properties [22–24].

| Property | Unit | Value |
|---|--|--------|
| <i>Physical and mechanical properties</i> | | |
| Areal weight | g/m ² | 123 |
| Average thickness | mm | 1.12 |
| Fabric strength | | |
| Fiber direction | N | 101.7 |
| Transverse | N | 23.5 |
| <i>Chemical composition</i> | | |
| α -Cellulose | % | 68.69 |
| Hemicellulose | % | 15.07 |
| Lignin | % | 15.24 |
| <i>Thermo-physiological properties</i> | | |
| Thermal conductivity coefficient | W/m K | 0.0357 |
| Thermal absorptivity | W s ^{1/2} /m ² K | 0.197 |
| Thermal resistance | m ² K/W | 81.4 |
| Thermal diffusivity | m ² s ⁻¹ | 0.034 |
| Peak heat flow density | [W m ²] × 10 ⁻³ | 0.234 |
| Relative water vapor permeability | % | 66 |
| Evaporation resistance | Pa m ² | 4.4 |



Fig. 1. Sound absorption measurement procedure: (A) Brüel&Kjær impedance tube set up; (B) sample of the barkcloth layers studied.

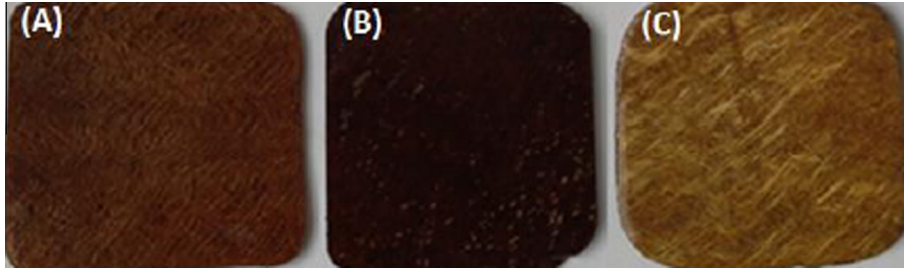


Fig. 2. (A) *Ficus brachypoda*; (B) *Ficus natalensis* and (C) *Antiaris toxicaria*.

2.3. Theoretical sound absorption models

Existing sound absorbing models aim to describe the characteristic wave impedance and the characteristic sound propagation constant utilizing laboratory measurable physical properties of the materials, such as the porosity, the tortuosity, and the airflow resistance.

2.3.1. Delany and Bazley model

In 1970, Delany and Bazley (DB) introduced the first empirical model for determining the bulk acoustic properties of porous substrates [23]; the model is only applicable if and only if the frequency is higher than 250 Hz [24].

$$Z_c = \rho_o c_o [1 + 0.057X^{-0.754} - j0.087X^{-0.732}] \quad (2)$$

$$k = \omega/c_o [1 + 0.0978X^{-0.700} - j0.189X^{-0.595}] \quad (3)$$

$$X = \frac{\rho_o f}{\sigma} \quad (4)$$

$$\alpha = 1 - |R|^2 \quad (5)$$

$$R = \frac{Z_s - \rho_o c_o}{Z_s + \rho_o c_o} \quad (6)$$

$$Z_s = -jZ_c \cot(kd) \quad (7)$$

where ρ_o is density of air; c_o is Speed of sound in air; Z_c is characteristic impedance; k is propagation constant; f is frequency; ω is angular frequency; σ is airflow resistivity; $j = \sqrt{-1}$; R is sound pressure reflection coefficient; Z_s is the surface impedance; d is the thickness

The DB model was formulated for fibers with diameter 1–10 μm . However, that notwithstanding, the DB model has had subsequent modifications so as to be applied to other fibers with larger diameters. Garai and Pompoli revised the model and applied it to polyester fibers with diameter 20–50 μm [25].

$$Z_c = \rho_o c_o \left[1 + 0.078 \left(\frac{\rho_o f}{\sigma} \right)^{-0.623} - j0.074 \left(\frac{\rho_o f}{\sigma} \right)^{-0.66} \right] \quad (8)$$

$$k = \omega/c_o \left[1 + 0.121 \left(\frac{\rho_o f}{\sigma} \right)^{-0.53} - j0.159 \left(\frac{\rho_o f}{\sigma} \right)^{-0.571} \right] \quad (9)$$

The DB models are based on a host of experimental results and a curve fitting approach. Various others researchers such as Miki, Mechel etc. have come up with various coefficients to the DB model [26].

2.3.2. Miki model

Miki [27] proposed a new model based on the Delany – Bazley equations that would address the negative real part of the surface impedance at low frequencies for multi-layer membranes:

$$Z_c = \rho_o c_o \left[1 + 5.50 \left(10^3 \frac{f}{\sigma} \right)^{-0.622} - j8.43 \left(10^3 \frac{f}{\sigma} \right)^{-0.632} \right] \quad (10)$$

$$k = \omega/c_o \left[1 + 7.81 \left(10^3 \frac{f}{\sigma} \right)^{-0.618} - j11.41 \left(10^3 \frac{f}{\sigma} \right)^{-0.618} \right] \quad (11)$$

2.3.3. Mechel model

Mechel and Ver [28] proposed a theoretical model for low frequencies as follows:

$$\Gamma = i \frac{\omega}{c_o} \sqrt{1 - i \frac{\gamma}{2\pi X}} \quad (12)$$

$$Z_k = -i \frac{c_o^2 \rho_o}{\omega \gamma \phi} \quad (13)$$

where $\gamma = 1.4$ is the adiabatic constant of air; ϕ is the porosity

For the mid and high frequencies, Mechel proposed the following formulas:

$$Z_c = \rho_o c_o [1 + 0.06082X^{-0.717} - j0.1323X^{-0.6601}] \quad (14)$$

$$k = \omega/c_o [0.2082X^{-0.6193} - j0.1087X^{-0.67311}] \quad (15)$$

2.3.4. Allard and Champoux model

Allard and Champoux [29] postulated a model that is based on the assumption that the thermal effects are dependent on frequency. The model describes a porous layer as a mixture of air and elastic frame.

$$\rho(\omega) = \rho_o \left[1 - i \left(\frac{\sigma}{\rho_o \omega} \right) G_1 \left(\frac{\rho_o \omega}{\sigma} \right) \right] \quad (16)$$

$$K(\omega) = \gamma P_o \left(\gamma - \frac{\gamma - 1}{1 - \left(\frac{i}{4P_r} \right) \left(\frac{\sigma}{\rho_o \omega} \right) G_2 \left(\frac{\rho_o \omega}{\sigma} \right)} \right)^{-1} \quad (17)$$

where P_r is the Prandtl's number

$$G_1 \left(\frac{\rho_o \omega}{\sigma} \right) = \sqrt{1 + \frac{i}{2} \left(\frac{\rho_o \omega}{\sigma} \right)} \quad (18)$$

$$G_2 \left(\frac{\rho_o \omega}{\sigma} \right) = G_1 \left(\frac{\rho_o \omega}{\sigma} \right) [4P_r \left(\frac{\rho_o \omega}{\sigma} \right)] \quad (19)$$

where $\rho(\omega)$ is the effective density and $K(\omega)$ is the bulk modulus.

2.4. Empirical thermal conductivity models

Various models have been formulated to study and predict the effective thermal conductivity (k_e) of heterogeneous materials. The models presented here take the heterogeneous material as macroscopically heterogenic [30].

The effective thermal conductivity models are based on measurable quantities such as thermal conductivity of matrix (k_m); thermal conductivity of the reinforcing fiber preform (k_f) and corresponding volume fraction of the composite (Φ).

2.4.1. Series model

$$k_e = \frac{k_m k_f}{\Phi k_m + (1 - \Phi) k_f} \quad (20)$$

Heat flow in the series model is assumed to flow perpendicular to the layers and therefore gives the minimum value of thermal conductivity [31].

2.4.2. Parallel model

$$k_e = \Phi k_f + (1 - \Phi)k_m \quad (21)$$

The parallel model assumes the layers are arranged parallel and gives the maximum thermal conductivity of the composite since heat flows proportionally through the layers [32].

2.4.3. Geometric mean model

$$k_e = k_f^\Phi k_m^{(1-\Phi)} \quad (22)$$

2.4.4. Maxwell model

$$k_e = k_m \frac{k_f + 2k_m + 2\Phi(k_f - k_m)}{k_f + 2k_m - 2\Phi(k_f - k_m)} \quad (23)$$

Maxwell postulated the effective thermal conductivity of randomly distributed spheres in a matrix [33]. The Maxwell model is based on the assumption that the volume fraction of the composite is less than 25%.

2.4.5. Cheng and Vachon Model

$$k_e = - \left[\frac{2}{\sqrt{C \cdot (k_f - k_m)(k_m + B)(k_f - k_m)}} \tan^{-1} \left[\frac{B}{2} \sqrt{\frac{C \cdot (k_f - k_m)}{k_m + B(k_f - k_m)}} \right] + \frac{1 - B}{k_m} \right]^{-1} \quad (24)$$

$$B = \sqrt{\frac{3\Phi}{2}} \text{ and } C = -4\sqrt{\frac{2}{3\Phi}}$$

The Cheng and Vachon model endeavors to solve the effective thermal conductivity of a two phase solid mixture using distribution functions [34].

3. Results and discussion

3.1. Thermal and acoustic properties

The amount of heat transmitted through a unit area of the material was measured as the thermal conductivity coefficient (k). There is dependence between the thermal conductivity of a material and its sound absorption. When sound waves propagate through a porous fiber network like barkcloth; the sound waves cause vibration in the pores of the fiber network. The vibration causes thermal and viscous heat build up in the fibers due to friction. Therefore a good absorbing material absorbs the thermal energy of the sound waves and less heat is generated. At low frequencies, the heat losses are limited and isothermal whereas, at high frequencies of sound, the heat is adiabatic and significant [2]. The case is somewhat different with solid composite materials. The compaction of the barkcloth nonwoven felt results in reduced porosity, therefore increasing flow resistivity and reduced vibration of the fibrous network, therefore, a reduced sound absorption coefficient and higher thermal conductivity. The combination of several nonwoven fabric layers allows the realization of different absorption degrees in one composite structure, which can then absorb sound in a wide range of frequencies. High values of thickness and fabric density facilitate sound insulation. Microstructure parameters such as fiber orientation, tortuosity, pore structure, influence the sound absorption efficiency [35].

3.1.1. Thermal insulation behavior of BFRPs

The ficus species had a higher thermal conductivity among the measured specimens whereas Antiaris had the lowest thermal conductivity (Fig. 3). The high thermal conductivity coefficient is attributed to the epoxy polymer used whose thermal conductivity is approximately 0.2 W/m K. A lower value of k is characterized as a better thermal insulation material due to the fact that it helps in resisting outside heat transmitted through the fibrous network.

The *Ficus natalensis* composite laminate was used for the purpose of prediction of thermal conductivity of fiber reinforced composite. It is observed that the Cheng and Vachon empirical model was in agreement with the experimental data (Fig. 4). The exceptional performance of the model is based on the fact that it puts

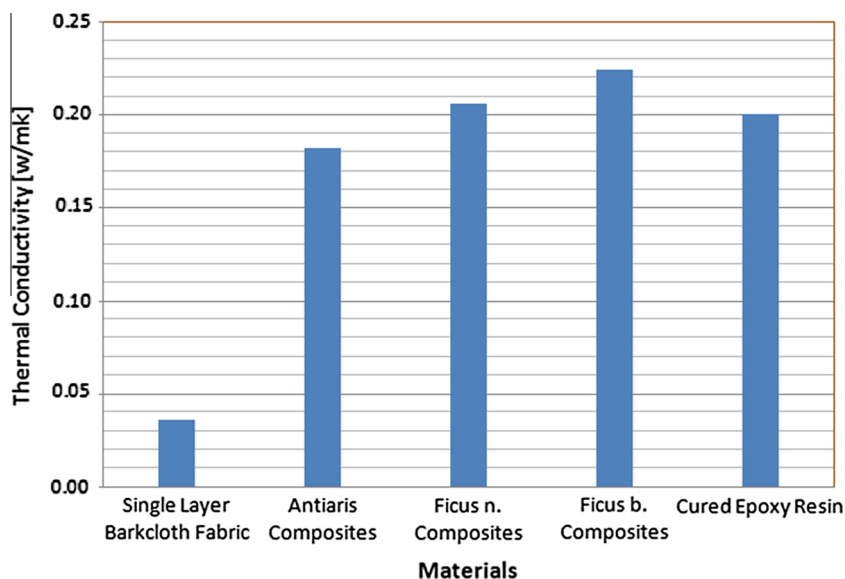


Fig. 3. Thermal conductivity of composites.

into consideration the underlying assumptions of heterogeneous composite mixtures. The other empirical models were inferior due to the fact they utilize less material parameters to predict effective conductivity.

3.1.2. Modeling of acoustic properties

The ability to predict a material behavior using models offers a fast time-saving economical design of structures without prototype production and the rigorous experimental series needed to refine a material. Fig. 5 shows the Delany – Bazley model as applied to the one layer *Antiaris toxicaria* (AT) Barkcloth fabrics, it

is observed that the model is in agreement at least for the frequency below 3000 Hz, however, beyond this frequency, the Delany – Bazley model is incapable of modeling sound absorption behavior of one layer AT barkcloth fabrics. This phenomenon is typical for the Delany – Bazley model as reported elsewhere showing that the model is inadequate for very low and very high frequencies [36].

Four other empirical models (Fig. 6) were employed with four layers AT fabrics so as to compare the behavior of the predicted models, it was observed that the models are in agreement with experimental data up to the frequency of 3500 Hz

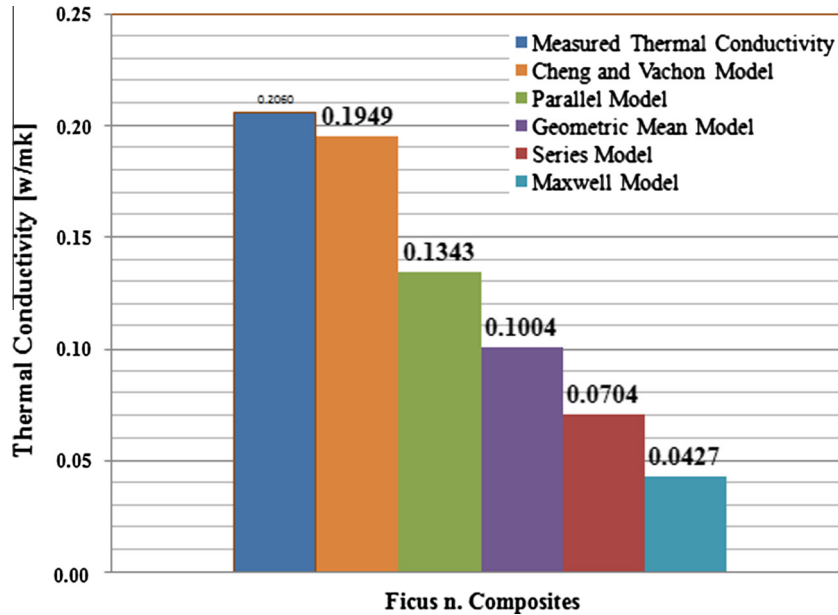


Fig. 4. Predicted thermal conductivity of barkcloth reinforced composite laminate.

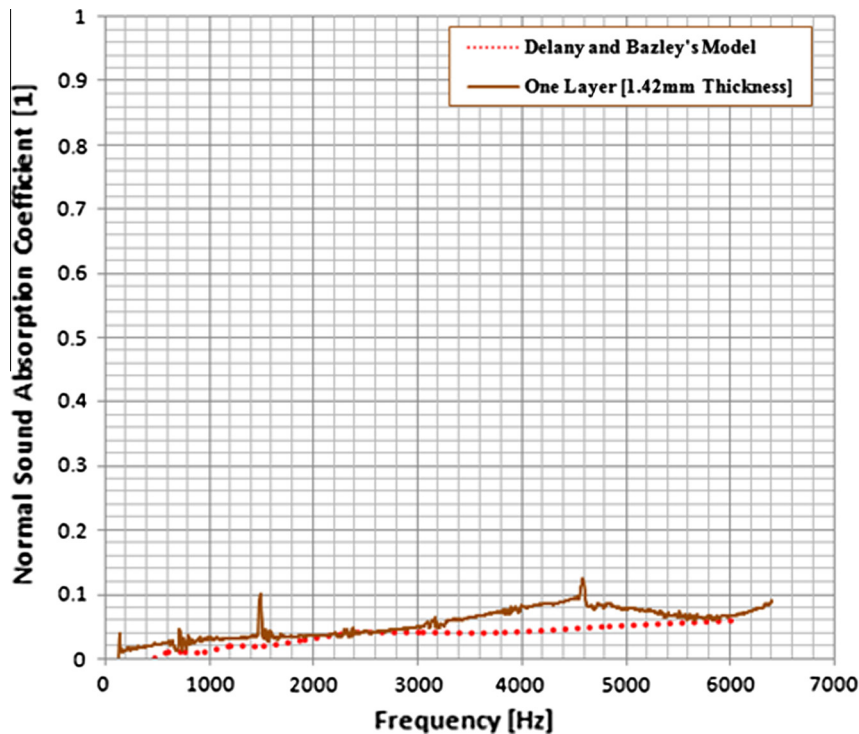


Fig. 5. Delany – Bazley model with one layer *Antiaris toxicaria* fabrics.

and thereafter the models' under predicted the sound absorption behavior.

The underprediction of the models could be due to the fact that barkcloth is a highly anisotropic material with not uniform fiber distribution network that rendered the underprediction at higher frequencies. A review on the theoretical modeling of natural fibers showed that modeling of natural fibrous assemblies is majorly influenced by the microscopic structure of the substrates and because there's a lot of variability, the models tend to be inaccurate [2].

3.1.3. Effect of air gap on the acoustic properties

Since barkcloth is a new material and with prospects of sound absorption applications, another material design parameter was

implemented in the model whereby an air gap was incorporated between the two material layers.

The Allard – Champoux model was utilized for prediction of the behavior of two layers *Antiaris toxicaria* (AT) fabrics. It's observed that the model is in good agreement with the experimental data.

Incorporation of an air gap between the two AT fabrics was observed to have positive effects on the sound absorption properties. The larger the distance between the airgap, the higher the absorption at lower frequencies and reduction in the absorption at higher frequencies (Fig. 7).

In the long run, the introduction of a small air gap between the layers gradually increase the sound absorption of two layers AT

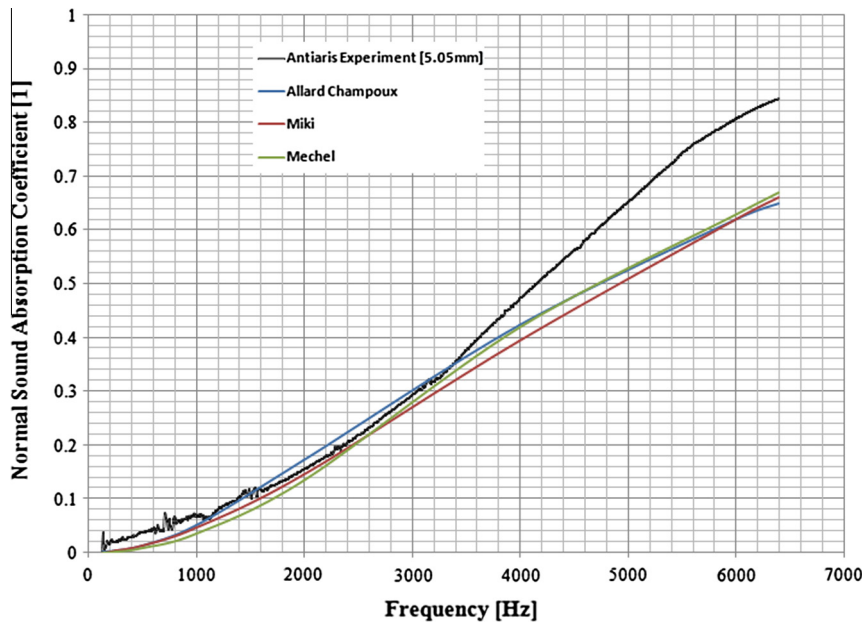


Fig. 6. Sound absorption models of *Antiaris toxicaria* 4-layer fabrics.

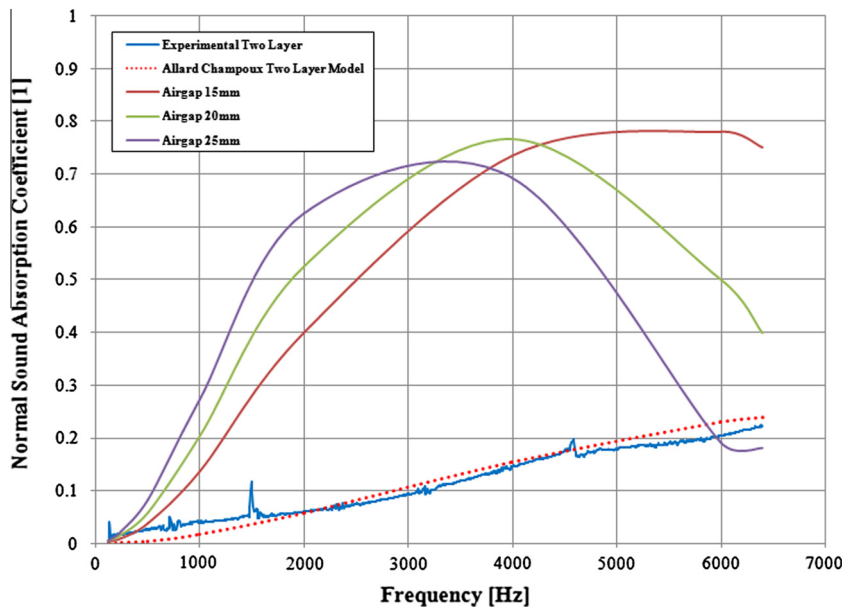


Fig. 7. Prediction model of behavior of fabrics with incorporation of an air gap in between.

fabrics reaching a sound absorption coefficient of 0.78 at frequencies of above 4000 Hz.

3.2. Automotive applications

Layered Barkcloth *Antiaris toxicaria* fabrics can find applications in car headliners. Headliners are materials installed on the ceilings inside of vehicles and are intended for the purpose of occupant protection through thermal insulation and sound absorption. A good headliner should be able to keep outside heat out of the vehicle and also preserve interior heat for the best comfort of the occupants. Typical car headliners have 200–220 g/m² [37]. Barkcloth has a low thermal conductivity and yet has high sound absorption properties; therefore, its application in car headliners is a novel concept that will serve the triple purpose of decoration, thermal insulation through restriction of heat migration and sound absorption through reduction of noise inside the vehicle.

4. Conclusions

In this investigation, the thermal and acoustic properties and prediction models were presented. Barkcloth had a low thermal conductivity and this has a multiplier effect which results in good sound absorption behavior. The results show that barkcloth non-woven fabric has good sound absorption properties and can be used as an alternative replacement for the synthetic commercial fibers which are widely used in the industry. The investigated sound absorption properties showed that *Antiaris toxicaria* barkcloth has higher sound absorption properties at higher frequencies. Increasing the barkcloth fiber layers showed a positive trend towards sound absorption coefficient, therefore giving a prediction of multi-layer products of antiaris barkcloth with potential to provide positive results even at low frequency ranges. Incorporation of an airgap using prediction models had a positive impact on the overall sound absorption properties of the fabrics. The fabrics can therefore be designed at absorbing particular frequencies depending on the sound absorption.

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