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REVIEW PAPER

Effective Parameters, Modeling, and Materials in Sound Absorption: A Review

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***Abstract-* Textiles are used in most industries, due to their specific physical and mechanical characteristics. These materials are used as sound absorbent because of their porous structures. Moreover, textiles are less expensive, lightweight and recyclable. This article reviews the mechanisms, experimental modeling and research that has been done in the last two decades in the field of sound absorption in fibers, carpets, composites, woven fabrics, knitted fabrics, and spacers. There are several parameters affecting the sound absorption of textiles, and the effectiveness of each parameter is specific to each textile. Therefore, the best usage of each kind of textiles can be determined through considering the sound absorption behavior at different frequencies. In this article, it has been tried to provide general and partial specific information about sound absorption properties of textiles. It is noteworthy to mention that some research results are in conflict with each other.**

***Keywords*: sound absorption, nonwoven, woven, knitted, composite, carpet**

I. INTRODUCTION

In the past few years, the importance of acoustic and sound absorption in different environments such as factories, car interior, sound and music recording studios, meeting rooms and amphitheaters, community halls, theaters, cinemas, residential houses and etc. has been noticed. Due to existence of annoying sounds in urban spaces, the use of sound absorbing materials has increased especially in the houses. Moreover, the annoying sounds cause disease like heart failure and hearing issues in human. In the past few years, the usage of building materials for sound insulation has reduced because of their weight and price. According to research, textiles have a high ability to absorb sounds. These materials have low specific weight, high rigidity, good abrasion resistance, chemical resistance, anti-spot ability and their most important feature is their good sound insulation regarding the price. Due to the high cost of preparing samples and experiments, numerical modeling and simulation are also used. Furthermore, in view of preserving the environment, waste textile materials can be used as sound absorbers. Sound absorbents can be used in a wide range of applications which some of them are shown in Fig. 1 [1].

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I. DISCUSSION

A. Sound Absorption Parameters

According to the published works, various parameters affect sound absorption in different ways. By reducing the fiber diameter, the sound absorption coefficient reduces and the larger the fiber diameter, the higher the air resistance, which absorbs more sound [2]. In explanation of this phenomenon, it could be said that sound waves move easier through fibers with less diameters and consequently there is less friction between fibers and waves [3]. Another parameter can be the surface area of the fiber. Based on previous research, the sound absorption of fibers with circular and round surface is less than the ones with serrated surface due to less contact surface [4]. Another parameter that affects sound absorption is called air permeability which is defined as the amount of air passes through an object during a specific time and specific area, and could be calculated by Darsey rule through Eq. (1) [5]:

$$Q_m = k\frac{\Delta p}{\mu d} \qquad (1)$$

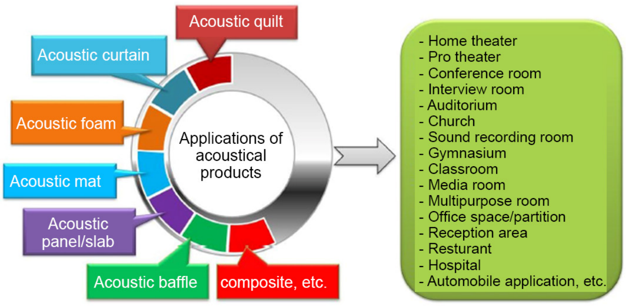


Fig. 1. Application of textiles in sound absorbers [1].

Where, Q_m is the rate of flow (m/s), k is the flow permeability coefficient (non-dimensional), Δp is the pressure drop (Pa), μ is the dynamic viscosity of the air (Pa.s) and d is the thickness of fabric (m). The air flow resistance can be considered as an estimation of sound absorption. In this case, we can calculate how much sound waves have penetrated and how much have been converted into thermal energy and wasted. So that, the air flow resistance parameter can be remarked as a significant factor in sound absorption of a material [6]. Table I shows a brief explanation of experimental and theoretical models for predicting the air flow resistance.

Porosity is one of the most important characteristics of sound absorbent materials as the porous structure causes the sound waves move through the material [14]. Despite the fact that some of materials such as metals absorb sound, they cause sound pollution because of wave reflection. But in textiles, the waves hit the fibers and causing them to vibrate. This vibration is due to the viscosity of the air, which causes the waves to move and collide with the fiber wall and create friction. Eventually, the friction turns into heat. The amount of porosity is different by changing the fiber orientation which can be effective on the fiber distribution and consequently the amount of sound absorption. Moreover, the fiber orientation could be divided into three kinds [15]:

- Parallel orientation (fibers are oriented in the direction of sound waves)
- Vertical orientation (fibers are oriented perpendicularly to the sound waves)
- Random orientation (fibers are oriented randomly).

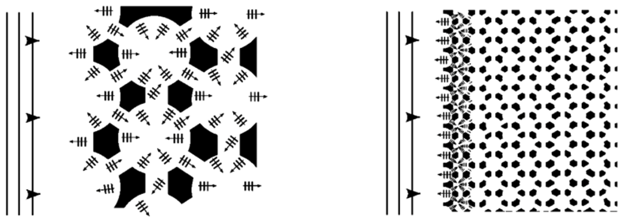
The sound absorption is affected by the size of pores [16]. Generally, the smaller the pores, the less the energy transmitted to the material structure and obviously the more the reflection on the surface and the less the energy absorption. The sound absorption mechanism is shown simply in Fig. 2.

Of course the sound absorption can be quantified with different indexes but one of the most used index is related to impedance model which presented by the Zwikker and Kosten theory shown below as Eq. (2) [17]:

$$\alpha = 1 - \left| \frac{\frac{Z_s}{\rho_0 c_0} - 1}{\frac{Z_s}{\rho_0 c_0} + 1} \right|^2 \tag{2}$$

TABLE I
EXPERIMENTAL AND THEORETICAL MODELS FOR PREDICTING AIR FLOW RESISTANCE

Category	Model	Airflow resistivity
Capillary channel theory	Kozeny–Carman [7]	$\sigma = \frac{180\eta(1-\varepsilon)^2}{d^2\varepsilon^2}$
	Pelegrinis [8]	$\sigma = \frac{180\eta(1-\varepsilon)^2}{d^2}$
Drag force theory	Langmuir [9]	$\sigma = \frac{16\eta(1-\varepsilon)}{d^2\varepsilon\left[-\ln(1-\varepsilon)-1.5+2(1-\varepsilon)-\frac{(1-\varepsilon)^2}{2}\right]}$
	Tarnow [10]	$\sigma = \frac{16\eta(1-\varepsilon)}{d^2\left[-1.280\ln(1-\varepsilon)+0.526-2\varepsilon\right]}$
Empirical method	Garai–Pompoli [11]	$\sigma = \frac{2.83\times10^{-8}\times\rho^{1.404}}{d^2}$
	Manning–Panneton [12]	$\sigma = \frac{1.94\times10^{-8}\times\rho^{1.516}}{d^2}$
	Bies and Hansen [13]	$R = \frac{K}{d^2\rho_m^{-1.53}}$



(a) (b)

Fig. 2. Sound absorption mechanism: (a) with big pores and (b) small pores [16].

Where, α is the sound absorption coefficient, Z_s is the surface characteristic impedance, ρ_0 is the air density at room temperature and c_0 is the sound speed in air media at room temperature. Density should be noted as the other factor [2]. By increasing the density, the sound absorption at medium and high frequencies increases. As the density increases, the number of fibers in the cross section increases, which causes the collision of waves and surface friction. Thickness is another important parameter of sound absorption that directly affects it [18]. Aso and Kinoshita [15] worked on the parameters affecting the amount of sound absorption which including textile characteristics and also absorption mechanism. Generally, there are three mechanisms for sound absorption which are depicted in Fig. 3.

Mechanism type 1 is called resistance against viscosity. There is low sound absorption at low frequencies and significant sound absorption at high frequencies. Sound pressure leads to vibration between fibers and air in empty spaces and these vibrations cause conquering the surface friction and reducing the sound energy and converting to heat energy. This phenomenon is known as viscosity mechanism. In type II, sound absorption increases at low frequencies then a peak is observed and after that by increasing the frequency, the sound absorption decreases and then increases. This mechanism is called resonance.

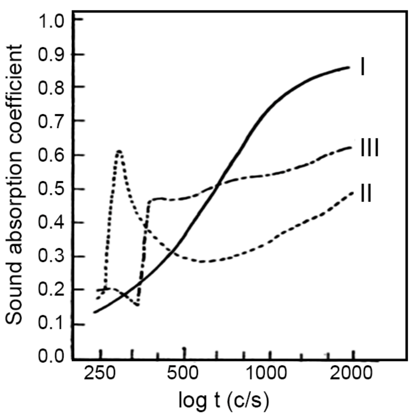


Fig. 3. Different kinds of absorption mechanism, (I) viscosity, (II) resonance, and (III) moderate [15].

The 3rd type is a combination of the two first mechanisms which there are no peaks. The reason is that absorption in the high frequency range follows a resonant frequency and the absorption coefficient is due to the high viscosity of the air. This mechanism is called moderate. It has been practically proven that the mechanism of fiber absorption is the friction between the fibers and the air.

B. Modeling

Due to time and cost producing and performing different tests, modeling is needed in some cases in order to predict the sound absorption of samples based on the identified characteristics. Generally, models are divided into two groups named experimental and microstructural. Experimental models use a non-acoustic input factor which is the resistance to air flow and they are obtained by fitting the curve on a vast amount of data. The Delany-Bazlay model is the oldest and most comprehensive experimental model [19,20]. Despite the fact that this model was effective in predicting the sound absorption, there are some defects. The most important issue is that in this model, at low frequencies, the coefficients are reported with errors and also negative in some cases. The Delany-Bazlay relation is explained through Eqs. (3) to (6):

$$Z_f = \rho_a c_a [1 + c_1 (\frac{\rho_a f}{\sigma})^{c_2}) - ic_3 (\frac{\rho_a f}{\sigma})^{c_4}] \quad (3)$$

$$\gamma_f = k_0 [1 + c_5 (\frac{\rho_a f}{\sigma})^{c_6}) - ic_7 (\frac{\rho_a f}{\sigma})^{c_8}], \quad k_0 = \frac{2\pi f}{c_a} \quad (4)$$

$$\Gamma_f = Z_f \coth(\gamma_f t_f) \quad (5)$$

$$\alpha = \frac{4R_f / \rho_a c_a}{(1 + R_f / \rho_a c_a)^2 + (X_f / \rho_a c_a)^2} \quad (6)$$

Where, ρ_a is the air density, c_a is the sound velocity, σ is the flow resistivity, f is the frequency, t_f is the thickness, Γ_f is the surface acoustic impedance, R_f and X_f are the real and imaginary components of Γ_f, α is the sound absorption coefficient and c_i (i=1, 2, … , 8) are constants.

The coefficients related to the Delany-Bazlay model were reexamined by other researchers to obtain better results. For example, the Delany-Bazlay model was improved by Miki [21] to show better performance at low frequencies. Table II shows the coefficients reported by researchers. Moreover, Dunn and Davern [22] explained that the Delany-Bazlay model is suitable for fibrous materials and reformed the model for materials such as foams with cellular structure.

There are some factors used in the microstructural models including curvature, longitudinal factors, pore cross-sectional shape, airflow resistance and porosity. For example, Yoon [24] prepared a microstructural model based

TABLE II
C_1 TO C_8 COEFFICIENTS OF DIFFERENT MODELS

Model	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8
Delany and Bazley [19]	0.057	-0.754	0.087	-0.732	0.098	-0.7	0.189	-0.595
Dunn and Davern [22]	0.114	-0.369	0.099	-0.758	0.136	-0.491	0.168	-0.715
Miki [21]	0.07	-0.632	0.107	-0.632	0.16	-0.618	0.109	-0.618
Garai and Pompoli [11]	0.078	-0.623	0.074	-0.66	0.121	-0.53	0.159	-0.571
Ramis, Alba, Del Rey, Escuder, and Sanchís [23]	0.046	-0.255	0.112	-0.967	0.039	-0.541	0.06	-1.256

on geometrical properties as mentioned above. In general, it is difficult to calculate these factors, which makes this type of modeling less used by researchers. But experimental models can effectively predict sound absorption without the need for complex geometric models. In microstructural models, there is a precise need to recognize the exact material's geometry, and a slight misconception leads to incorrect prediction. Moreover, in experimental models, the only required factor is the air flow resistivity that can be easily calculated (Table II).

C. Fibers

Natural and synthetic fibers can be used as sound absorbents. There are various published review articles related to the sound absorption property of fibers. Different fibers can be used as sound absorbent including rice straw, coconut, palm, tea leaf, jute, bamboo, cotton, wool, kapok, hemp, and polyester fibers [1,6,25-27]. There has not been observed much difference between the sound absorption of natural and synthetic fibers based on previous researches. The advantages of using natural fibers over synthetic fibers in sound absorbers include recyclability, environmental friendliness and cost reduction.

Hur *et al.* [28] made aluminum fibers using melt extraction method. Sample masses with 3, 5, 8, and 10 mm thicknesses and 0.3, 0.4, and 0.6 g/cm^3 densities were tested. To produce samples, fibers were inserted into the metal cylinders with 102 mm diameter and pressed under 100 kgf pressure. Based on the results published, by increasing the thickness and relative density, the sound absorption raises significantly. The sample with a 0.6 g/cm^3 density and a 10 mm thickness showed the highest noise reduction coefficient (NRC) of 0.73. Kino and Ueno [29] examined the effect of cross-sectional shape of polyester fibers (circular, hollow, flat and triangle) on the sound absorption. All samples had 11 mm thickness. The results showed that the cross-sectional shape has no significant effect on the sound absorption. In other words, the sound absorption of 0.22 tex polyester fibers with triangle and flat cross sections and 0.175 tex polyester fibers with circular cross section were almost the same.

Maderuelo-Sanz *et al.* [30] worked on a new material. Using recycled materials especially fibers solves the environmental and sound absorption problems simultaneously. In this experiment, linen and rubber fibers were used. The results proved that this type of material has a good ability to absorb sound at low and high frequencies. It can be said that these materials are a good alternative to synthetic materials like glass. In general, porosity and thickness are reduced due to pressing, which reduces sound absorption, but adding a rubber layer can solve this problem. This increases the thickness and consequently, increases the sound absorption. Alba, Del Rey, Berto, and Hervás [31] blended fibers with nanofibers to improve the sound insulation property. They used nanofibers to cover wool and polyester fibers and placed these blends in the perforated panels then conducted a sound absorption test using impedance method. Wool/polyester sample thickness was 4 mm and wool/polyester nanofiber sample thickness was 0.2 mm. To be a good soundproof, fibers should have air resistance ability at least 5 kPa.s/m^2, of which the mentioned blend has an air resistance of 9 kPa.s/m^2. They emphasized a 30% increase in sound absorption at some frequencies with a width increase of only around 0.5%. In

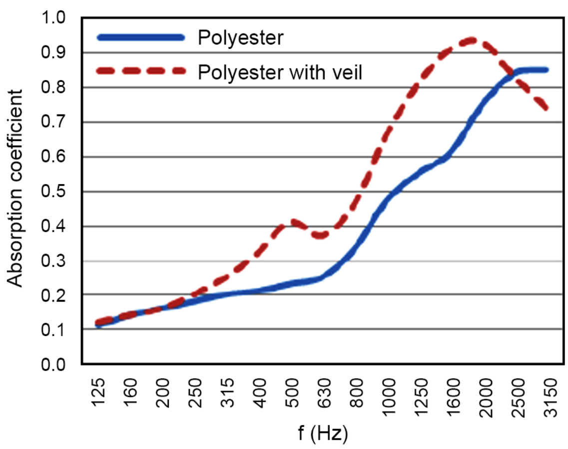


Fig. 4. Curves related to the sound absorption of polyester/wool samples with and without nano coating [31].

general, the use of this blend had better results than the use of current mineral wool products. The effect of nano coating on the sound absorption in polyester/wool samples with and without nanofiber coatings are shown below in Fig. 4.

Firsa *et al.* [32] investigated a study on the ABACA and coconut fibers sound absorption. A reverberation room was used in order to perform the sound absorption test. Eq. (7) was used to obtain sound absorption coefficient:

$$\alpha = \alpha_o + \frac{55.3V}{cS_b}\left[\frac{1}{T_2} - \frac{1}{T_1}\right] \quad (7)$$

Where, the volume of the test room is V, the speed of sound propagation in the drone chamber is c, the surface area of the test sample is S_b, and the absorption coefficient at different frequencies is α_o. The highest sound absorption was observed in ABACA banana and coconut fibers in the frequency range of 160-250 and 1600-6300 Hz. Moreover, the lowest sound absorption in ABACA fibers is at 315 and 250 Hz for coconut fibers.

Taban *et al.* [33] investigated a study on the sound absorbing properties of jute fibers at different thicknesses and densities. The impedance tube has been used in order to perform the sound absorption test. The results showed that the increase in the density leads to an increase in air flow resistance, which causes more sound absorption. To study the effect of thickness on sound absorption, samples with a density of 200 kg/m^3 and different thicknesses were used and the sound absorption coefficient was measured in the 800-1600 Hz frequency range. Based on the results, the sound absorption coefficients were 0.24 and 0.94 for samples with 15 and 45 mm thicknesses, respectively. According to the results, with increasing thickness, the sound absorption coefficient also increases at low frequencies.

Bhingare and Prakash [34] experimented the sound absorption of coconut fibers with various thicknesses and densities using an impedance tube. The results of the obtained sound absorption coefficients are shown in Fig. 5. As it can be seen, the sound absorption increases by increasing the thickness and the highest sound absorption coefficient equals to 0.84 obtained at the 35 mm thickness in the 2700-3100 Hz frequency range.

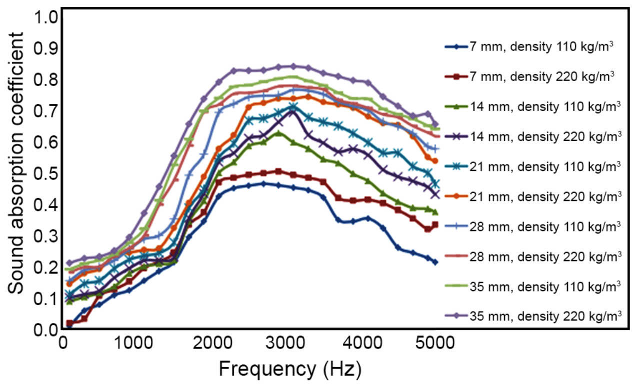


Fig. 5. Sound absorption coefficients for samples with different thicknesses and densities [34].

D. Nonwovens and Carpets

Parikh *et al.* [35] made nonwovens by natural fibers using punching method and studied the sound reduction in car interior. They used kenaf, jute, cotton waste and synthetic fibers such as polyester and polypropylene and showed that using these textiles leads to reduction in car interior sound. For example, using a cotton or PU foam layer under the needle punched kenaf nonwoven (678.11 g/m^2) can increase the absorption coefficient from 0.54 to 0.81-1.0 at 3200 Hz frequency and also using a lower cotton layer and PU (1017.17 g/m^2) can alternate the absorption sound from 0.79 in to 0.98 the same frequency area. In all cases, good results were obtained, which was better in the PU layer.

Yilmaz *et al.* [36] studied the effect of fibers fineness, porosity and the way of putting nonwoven layers on the sound absorption coefficient and air resistance. Hemp, glass, polylactic acid (PLA) and polypropylene fibers have been used to make nonwovens. The order of placement of textile layers in this study was different and layered samples were made with layers of different fibers. According to the obtained results, reduction in fibers amount, diameters and porosity leads to an increase in air resistance. Moreover, how the layers are placed on top of each other is effective in air resistance, so that the air flow resistivity increases with placing the glass layer on the surface, which also affects the sound absorption coefficient.

In addition to current nonwoven production methods, two methods of vibration and roller can also be used. Thermal compliments are used to obtain a 3D nonwoven form for use in automobiles. Küçük and Korkmaz [37] worked on the effect of physical parameters of nonwovens on sound absorption. To produce composites, nonwovens made of different fibers and different blending proportions were tested. Beside sound absorption, thickness, weight and air penetration have been investigated. With reference to the results, by increasing the thickness, the air penetration decreased and consequently the sound absorption increased. Samples made of 70% cotton and 30% polyester, in medium to high frequency range have the best sound absorption. Moreover, adding acrylic and polypropylene to cotton-polyester blend led to an increase in sound absorption at low frequencies. Sound absorption coefficients for some samples are shown in Fig. 6.

Yilmaz *et al.* [38] produced nonwoven samples using

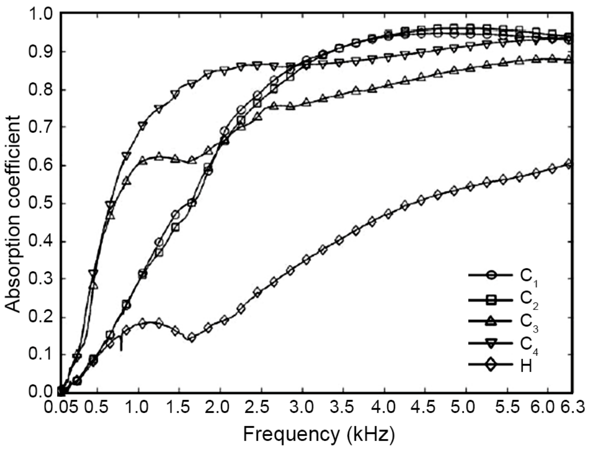


Fig. 6. Sound absorption coefficients of samples; H is a commercial sample and C_1 to C_4 are samples with 1300, 1400, 2800, and 2900 g/m^2 surface area made by 70% acrylic/cotton/polyester and 30% polypropylene [37].

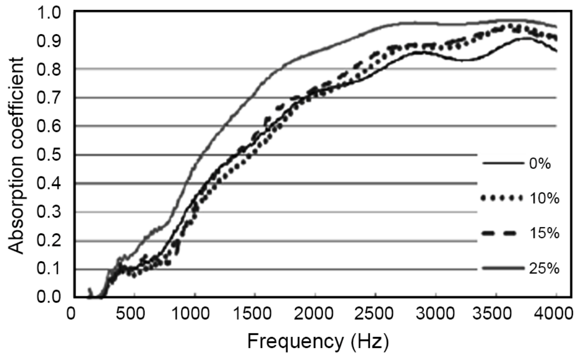


Fig. 7. Sound absorption permeability for composite samples with different weight proportions [39].

polypropylene, jute, PLA, glass and glass/polypropylene (33% glass and 66% PP). Then the samples were put on each other using thermal operation and a hydraulic press. The structural parameters of nonwovens, fibers size and porosity and also the finishing parameters such as temperature and time duration have been studied and regarding the results, temperature and time duration were effective on sound absorption. Heat affects air flow resistivity and temperature should be chosen considering the fibers melting point. By increasing temperature and time duration, sound absorption decreased which is a similar behavior in all composites. Huang *et al.* [39] made inquiries about the sound absorption properties of nonwovens made of coconut fibers. First, the nonwovens were produced using hollow polyester fibers. Then the coconut fibers were placed on nonwovens using punching method so composite panels were made. According to the results, sound absorption increased by increasing the amount of coconut fibers. By increasing the coconut fibers weight to 25%, sound absorption increased significantly according to Fig. 7 and moreover by considering the constant thickness of samples (10 mm), it makes the samples to be more compressed. However, from Table III, there are low changes in sound absorption.

Seddeq *et al.* [40] studied the sound absorption of nonwovens made up by recycled natural and synthetic fibers. To this aim, the number of nonwoven layers varied to four layers (S1 to S4) which led to change in sample thickness. Generally, the produced samples show high and low sound absorption in the frequency range of 2000-63000 and 100-400 Hz, respectively. Based on the results shown in Table IV, an increase in number of layers and consequently the thickness led to increase in sound absorption.

In some applications, like fire-fighting, a series of shields such as perforated metal or wood sheets are used behind sound-absorbing insulators. In this study, perforated wooden plates were used behind the samples. Adding these plates increases the air behind the sample, which causes the frequencies to be transmitted at shorter wavelengths. Although this improves the sound absorption coefficient at low frequencies, it reduces the sound absorption at high frequencies. Liu *et al.* [41] produced nonwovens made of polypropylene and glass and performed the sound absorption test on them. In this study, the goal was to anticipate the sound absorption coefficient using regression and neural network. The sound absorption test was conducted at 6 different frequencies including 125, 250, 500, 1000, 2000, and 4000 Hz. The minor and major reported errors between experimental and modeling data was 6.3×10^{-4} and 6.3×10^{-3}, respectively, and the average predicting error was 2×10^{-3}. Liu *et al.* [42] investigated the sound absorption of nonwovens made of kapok fibers mixed with different proportions by hollow polyester fibers and polypropylene fibers at low frequencies between 100 and 2500 Hz. Based on the obtained results, at low frequencies, the higher proportion of kapok fiber causes

TABLE III
AIR PERMEABILITY (CM^3/(CM^2/S)) FOR COMPOSITE SAMPLES WITH DIFFERENT WEIGHT PROPORTIONS [39]

Polyester fiber length (mm)	Coconut fibers (wt%)			
	0	10	15	25
51	10.2±0.2	11.5±0.3	10.3±0.6	9.8±0.2
66.3	30.7±0.8	30.5±0.6	34.8±0.3	30.3±0.8

TABLE IV
AVERAGE SOUND ABSORPTION COEFFICIENT OF NONWOVEN SAMPLES AT LOW, MEDIUM AND HIGH FREQUENCIES [40]

Sample	Frequency range (Hz)	1 layer	2 layers	3 layers	4 layers
		Thickness (mm)			
		3.7	7.4	11.1	14.8
S1	Low (100-400)	0.02	0.04	0.07	0.18
	Mid (500-1600)	0.11	0.31	0.51	0.79
	High (2000-6300)	0.67	0.95	0.94	0.94
		Thickness (mm)			
		3.7	7.3	11	14.6
S2	Low (100-400)	0.04	0.04	0.09	0.12
	Mid (500-1600)	0.10	0.20	0.44	0.66
	High (2000-6300)	0.61	0.79	0.92	0.94
		Thickness (mm)			
		2.5	5	7.6	10.1
S3	Low (100-400)	0.06	0.09	0.13	0.18
	Mid (500-1600)	0.18	0.42	0.68	0.81
	High (2000-6300)	0.58	0.88	0.96	0.97
		Thickness (mm)			
		5.6	11.3	16.7	22.6
S4	Low (100-400)	0.03	0.06	0.09	0.12
	Mid (500-1600)	0.10	0.26	0.44	0.64
	High (2000-6300)	0.47	0.87	0.92	0.95

higher sound absorbing due to its hollow structure. By increasing the number of fibers in volume unit, there would be more interaction between fibers and sound waves, and consequently sound absorption increases. However, if density increases excessively, the material become dense and sound absorption decreases. Furthermore, the highest sound absorption obtained for the kapok/hollow polyester (90/10%) sample was 0.84 at 2500 Hz. Lin *et al.* [43] firstly, produced nonwovens by kevlar/nylon/polyester fibers. Then, they produced other nonwovens using polypropylene wastes and as it is shown in Fig. 8, it has been placed on the primary nonwovens in different angles.

After that, the sound absorption coefficients of samples before and after thermal pressing were measured. As using polypropylene nonwovens makes the samples denser, it has improved sound absorption, especially in the 1000 Hz to 4000 Hz frequency range. This may cause an increase in air flow resistance and sound absorption. But after thermal pressing, due to melting, the space between the two layers of nonwovens becomes less, which causes the sample becomes tough, so waves penetrate into the samples with difficulty and sound absorption falls (Fig. 9). In the sample with a 0/0 angle, because of the finer pores, there is more bonding, so that better sound absorption occurs rather than other samples.

Liu *et al.* [44] represented a study about the relation between the sound absorption loss and parameters such as density, pore diameter and porosity in a nonwoven made of kapok. The kapok fibers used have 1.25 dtex, 8-32 mm diameters and 290 kg/m^3 density and the polyester fibers show 6.67 dtex and 32 mm length. According to the obtained results, whatever the pores are smaller, the absorption of sound at lower frequencies increases. Moreover, the sound absorption reduces at low frequencies by decreasing density. Ganesan and Karthik [45] studied on sound absorption of nonwovens produced by kapok and milkweed blended fibers. They introduced a new device for sound absorption testing as shown in Fig. 10. The body of

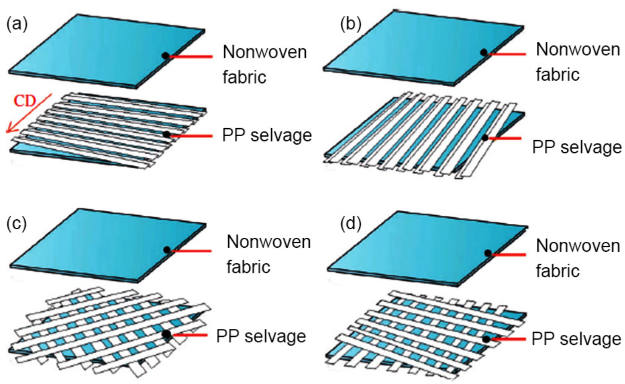


Fig. 8. Placing polypropylene waste nonwovens on primary nonwovens in different directions [43].

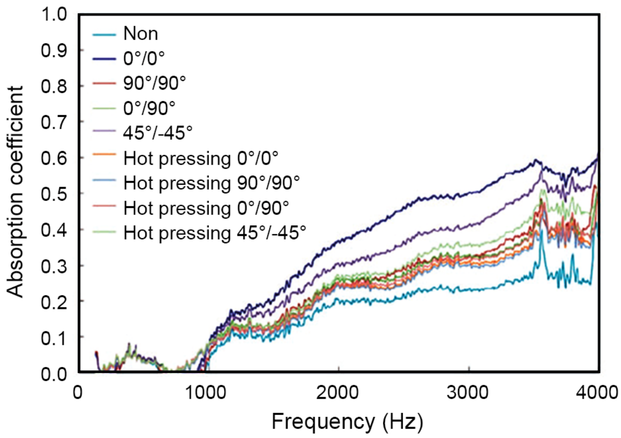


Fig. 9. Sound absorption coefficients in different samples [43].

this device is made of a thick and strong cardboard box with 3 grooves at different distances. The audio source is located on one end of the device. Three movable plates are placed at different distances inside the grooves to adjust the distance of the sample to the sound source. A decibel meter is used coaxially with the sound source inside the device and the volume is controlled by an electric panel.

Because of short lengths of fibers, they cannot be used lonely, so cotton fibers with different ratios were used in fiber blends. The sample made of 40% cotton and 60% milkweed had the highest sound absorption. Moreover, by increasing the distance between sample and sound source, the sound absorption decreased. In general, the percentage of sound absorption increases with increasing the percentage of kapok/milkweed mixture.

Kucukali Ozturk *et al.* [46] investigated on the increase of nonwoven sound absorption made of jute and wool covered by polyacrylonitrile nano fibers. To produce the nanofibers and proceed sound absorption test, electrospinning and impedance tube method were used, respectively. Based on the obtained results, the nanofiber covering on wool nonwovens was uniform and homogenous and made the air penetration harder (better air trapping ability) which leads to increase in sound absorption. The same behavior was observed in jute nonwovens covered by nanofibers at low and medium frequencies. So it can be said that nanofiber covering causes increase in sound absorption for both wool and jute nonwovens however the effect was more considerable in wool samples rather than jute ones.

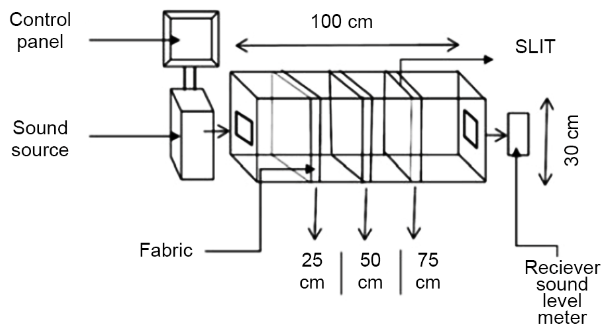


Fig. 10. Schematic view of sound absorption apparatus [45].

Mvubu *et al.* [47] Produced nonwovens using agave fibers, linen, and wool fiber wastes. In this research, different ratios of polyester fibers were mixed with each of the mentioned fibers. Then the effects of fiber type, blending ratio and size of air pores on sound absorption were investigated using an impedance tube. The results showed that all three parameters had significant effect on the sound absorption. Because of morphological structure of wool fibers which have scales on their surface, there is good entangling between them which leads to more friction between fibers that consequently results in better sound absorption. On the other hand, for agave fibers, because of bulkiness and less surface contacts, less amount of sound is absorbed. So, sound absorption becomes less in the polyester/agave mixture samples. As jute fibers are finer than agave fibers, the mixture of jute/polyester fibers shows better result in sound absorption than agave/polyester. In general, wool/polyester mixture has better sound absorption than other samples. Generally, it can be deduced that an increase in polyester fiber in the blend causes sound absorption increase. The results are shown in Fig. 11. Moreover, it was observed that by increasing the air gap (distance between sample and impedance tube end) to 15 mm, sound absorption increased while for bigger air gaps, sound absorption decreased.

Küçük and Korkmaz [48] tested the sound absorption properties of the acrylic carpet with two different pile densities and four different pile lengths. In general, acrylic carpet with longer pile has better sound absorption. Also, the density of the loop is an effective factor in sound absorption. Increasing the pile length to 10 and 12.5 mm had a good improvement in sound absorption and the best result was obtained at length of 14 mm. The more the number

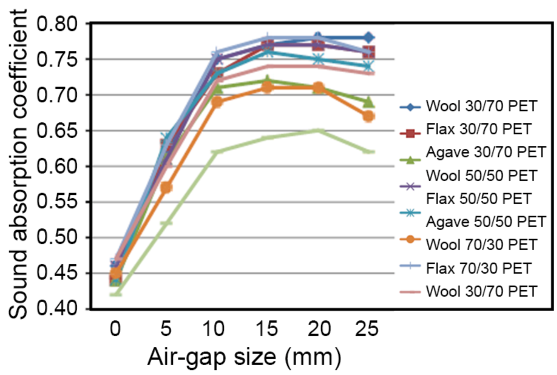


Fig. 11. Sound absorption coefficient in different samples and various air gaps [47].

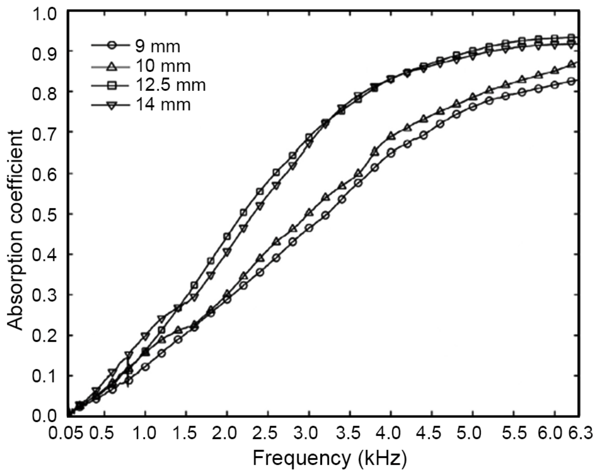


Fig. 12. Sound absorption coefficients of samples with 2400 loops/dm^2 at different pile heights [48].

of loops, the higher the sound absorption. Moreover, the optimum amount of sound absorption obtained in sample with 2400 loops/dm^2 and 12.5 mm pile height. Fig. 12 shows the sound absorption coefficients of sample with 2400 loops/dm^2 at different pile heights.

Paknejad *et al.* [49] conducted a study on acrylic carpets with different densities and pile lengths. At first, the samples were subjected to dynamic load with different number of shocks, and the sound absorption test was performed on them using impedance tube method. Then, the artificial intelligence algorithm such as ANN, ANFIS, GA, and a combination of them were used to predict the sound absorption coefficients. According to statistical analysis, all parameters are effective on the sound absorption. The prediction accuracy of ANN-GA and ANFIS-GA models with mean error percentage were compared with the traditional regression model. The results obtained from the models are 11.85, 17.68, and 61.82%, respectively.

E. Composites

Parikh *et al.* [50] investigated the thermoset composites made of kenaf and other cellulosic fibers inside the car. To make the 255 g/m^2 samples, blends of jute, flax and cotton fibers with polypropylene in different fractions were used. Table V presents the sound absorption coefficients for samples of 700 g/m^2 at frequencies heard inside the car. As it can be seen, all samples show good sound absorption. According to the obtained results, using cellulosic fibers such as kenaf, jute, and other inexpensive plant fibers in the structure of punched nonwovens has a great effect on increasing sound absorption and reduction noise inside the car.

Lou *et al.* [51] produced a sound-absorbing composite using cutting waste of polypropylene and polyester punched nonwovens. To produce nonwovens, blend of 25% ordinary polyester fibers, 15% of polyester fibers with 110 °C melting point and 60% of high temperature polyester fibers was used. The initial weight of nonwoven and average thickness were 700 g/m^2 was 2.9 mm, respectively. The melted polypropylene fibers were used as the matrix part of composite. Based on the obtained results, sound absorption was good at high frequencies more than 2000 Hz while it was less at frequencies less than 1000 Hz. Furthermore, despite sound absorbing increase as a result of increasing the thickness (Table VI), by increasing density, sound absorption decreases due to compactness of composite.

Chen and Jiang [52] firstly, investigated nonwovens containing activated carbon as highly efficiency sound absorbent. To this aim, three layers of nonwovens made of cotton, rami and polypropylene as the basic layer and activated carbon fibers (ACF) and glass fibers as coating for those layers were prepared. An impedance tube was used in order to perform sound absorbing test. Generally, using ACF caused more sound absorption in the 100-6400 Hz frequency range rather than glass fibers. The use of ACF indicates good effect on all kind of nonwovens, for example the effects of two kinds of coatings on polypropylene nonwoven are shown in Fig. 13.

Tascan and Vaughn [53] studied on the effect of fiber density, cross-sectional shape and sample density on sound absorption in produced nonwoven composites made of 65% polyester fibers and 35% adhesive (melted 4-denier polyester fibers). To produce specimens, fibers with 2, 3, and 15 den and three cross-sectional shapes including

TABLE V
SOUND ABSORPTION COEFFICIENTS FOR SAMPLES OF 700 G/M^2 AT DIFFERENT FREQUENCIES [50]

Frequency (Hz)	Target* (%)	Flax/PP 50/50	Jute/pp 50/50	Kenaf/pp 50/50	Cotton/PET/PP 35/35/30
800	9	15	15	17	18
1000	16	20	20	20	25
1600	35	32	35	34	36
2000	51	53	66	63	52

* Target absorption reference for automotive noise reduction (ASTM C384 method).

TABLE VI
SOUND ABSORPTION COEFFICIENTS AT DIFFERENT THICKNESSES AND FREQUENCIES [51]

Thickness (mm)	Frequency (Hz)						
	α_{125}	α_{250}	α_{500}	α_{1000}	α_{2000}	α_{4000}	α
17	0.10	019	0.17	0.37	0.86	0.91	0.43
34	0.10	0.39	0.35	0.87	0.90	0.92	0.59
51	0.10	0.12	0.67	0.97	0.85	0.95	0.61
68	0.24	0.45	0.90	0.85	0.93	0.94	0.72

circle, triangle and 4DG were used. Then the samples were put on each other perpendicularly. The results showed that samples made of 3 den fibers have better sound absorption than sample made of 15 den fibers because of larger surface area filing (Fig. 14). Also, samples made of 15 den fibers with triangular cross-sectional shape and 4DG had better sound absorption than circular cross-sectional shape.

Gliścińska *et al.* [54] conducted a study on the sound absorption of nonwoven and composites made of PLA and viscose mixtures with different mixture percentages (50% to 90% for PLA fibers and 10% to 50% for viscose fibers). In order to produce composite samples, the nonwoven layers were placed on top of each other by exposing to heat and pressure. The sound absorption coefficient in composite samples are slightly lower than corresponding nonwoven ones. Furthermore, it was observed that in the nonwoven and composite samples, the ones with PLA/viscose by proportion of 90/10 and 80/20 indicate higher sound absorption, respectively. Krucińska *et al.* [55] used very short and fine cellulosic fibers as the spinning waste in order to produce composite. From the obtained results, the use of natural cellulosic fibers in the structure of thermoplastic polymers increases sound absorption. The best results are related to the use of very short cotton fibers and very fine cotton, respectively. According to the experiments performed by gravimetric method and tensile strength, it was concluded that cotton fibers with short and fine lengths give better results. The nonwoven layers were put on top of each other while cotton and linen fibers were used between each layer. PLA was used as the resin and a layer of teflon foil was wrapped around it to remove the resin during compression. Three different types of composites including resin/cotton, resin/linen, and resin/cotton-linen blended fibers were produced. The results exhibited that the fibers absorb sound well and the resin is responsible for compacting and enhancing the sound absorption of the composite. The best result is related to the composite, which was reinforced with a mixture of 50% cotton and linen fibers. The sound absorption coefficient in the wide frequency range between 2000 and 6400 Hz was 0.7-0.8. Pan *et al.* [56] investigated the sound absorption of spacer fabric/polyethylene (PU) foam composites. At first, the produced polyester/kevlar nonwoven (20/80) was combined with glass fiber fabric through needle punching process and then was laminated. Then, it was combined with laminated warp knitting spacer fabric through PU foam to form composite samples. As it shows in Fig. 15, the best sound absorption coefficient in the 1500-2500 Hz frequency range is 0.8 and in the 2500-4000 Hz frequency range is 0.9, while for nonwoven samples they are 0.2 and 0.3, respectively.

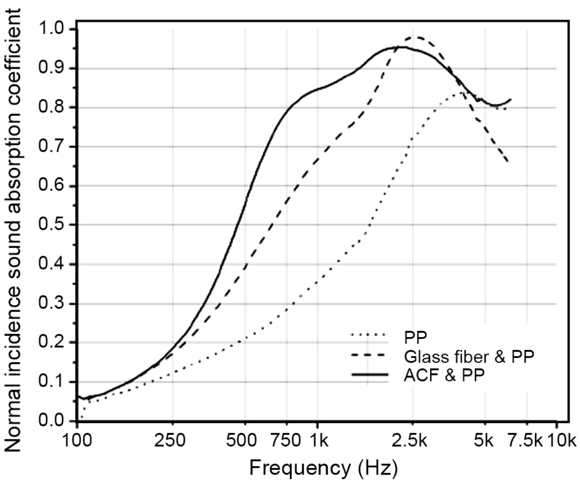


Fig. 13. Sound absorption coefficients of polypropylene nonwovens with different coatings [52].

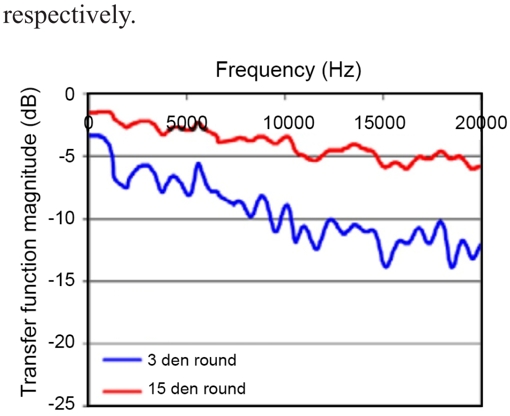


Fig. 14. Sound absorption coefficients related to 3 and 15 den samples [53].

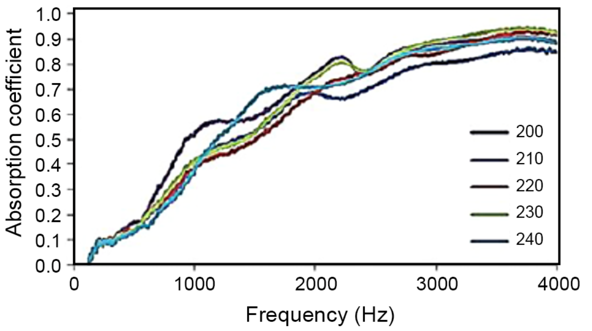


Fig. 15. Sound absorption coefficients in spacer/PU foam composite samples at different densities of PU foam [56].

Canbolat *et al.* [57] conducted a study to investigate the effect of stone powder on sound absorption. In this study, Pumice stone (54.29% oxygen, 26.50% calcium, 11.91% silicon, 4.79% carbon, 1.33% aluminum and 1.27% iron) powder was used to cover samples. First, a nonwoven layer of four-slotted polyester (SPET) was produced and a plain woven fabric (warp was regular polypropylene yarn and weft was texturized polypropylene (TPP) and hollow texturized polypropylene (HTPP) yarns) was considered as the top layer. It should be mentioned that before placing the top layer on SPET nonwoven, Pumice stone powder at different concentrations and sizes using PU was coated on nonwoven sample. The results showed that with increasing the amount of stone powder, the sound insulation property of the fabric increases, and this composite can be used in buildings for sound absorption. As it is shown in Fig. 16, nonwoven with HTPP as top layer and 15% stone powder at 150 μm size represented the best sound absorption. Existence of silicate, calcium oxide, ferrite oxide and aluminum oxide roughen the surface of fibers. This phenomenon led to more surface friction with waves and consequently more sound absorption.

Lee *et al.* [58] researched on the sound absorption properties of glass/epoxy and flax/epoxy. They tested the unidirectional and cross-ply samples and found that sound absorption at low (less than 500 Hz) and high (more than 3150 Hz) frequencies are, respectively, low and high due to the lower sound frequencies i.e., longer wavelength and shorter propagation path. Moreover, in all specimens, it was observed that increasing the sample thickness reduces sound energy. The noise reduction coefficients (NRC) for unidirectional and cross-ply samples were 0.095-0.11 and 0.1, respectively. Mohd Azhar and Wahid [59] studied sound absorption of panels produced using 10 different kinds of fibers. Fig. 17 shows that the obtained sound absorption coefficient for each sample and the tests have been done using an impedance tube. Pineapple and hemp fibers seem to be good substitutions to sound absorbent panels. So that, they showed the sound absorption coefficients of

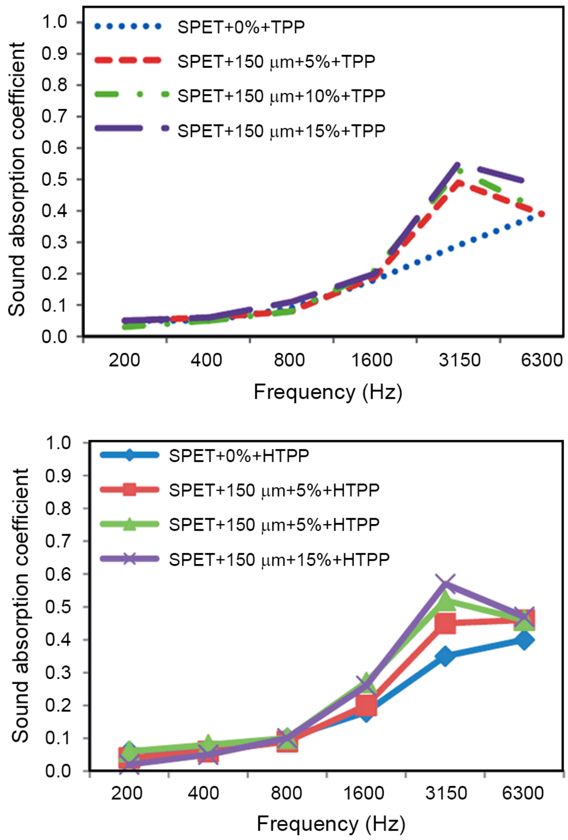


Fig. 16. Sound absorption coefficients at different percentages of Pumice stone [57].

0.95 and 0.97 in the 500 Hz to 2048 Hz frequency range, respectively.

F. Spacers and Knitted Fabrics

Kim *et al.* [60] worked on the acoustic properties of polyester warp knitted fabrics. To this aim they prepared seven samples; three reverse locknit, two double denbigh and two sharkskin stitches and measured level pressure of total sound (LPT), amplitude range, frequency range (Δf) and autoregressive constant (ARC). Moreover, they calculated the Zwicker's psychoacoustic parameters such

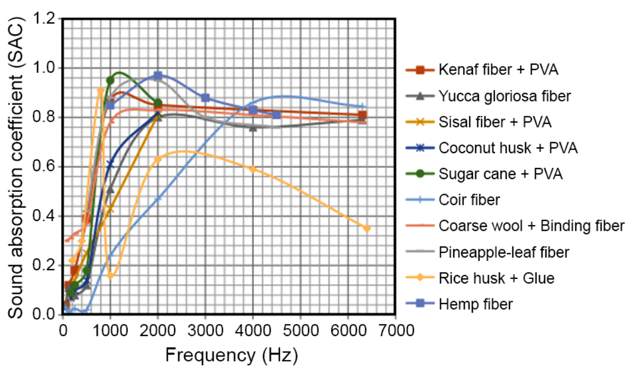


Fig. 17. Sound absorption coefficient for different panels [59].

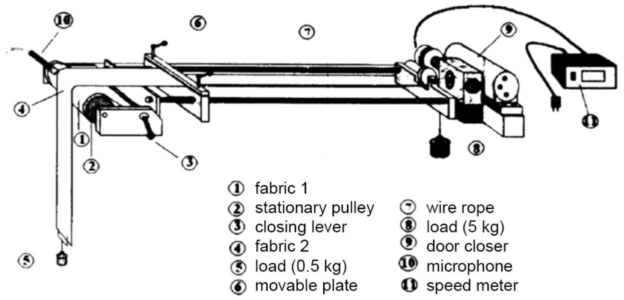


Fig. 18. Sound generator [60].

as loudness, sharpness, roughness and fluctuation strength using sound spectra obtained from Fast Fourier transform analysis at frequencies between 0 Hz to 18,750 Hz. The sound was generated and recorded with a fabric sound generator as shown in Fig. 18. They found that the sharkskin stitch shows the highest LPT, Δf, ARC, loudness and fluctuation strength values and roughness is similar for all samples. The open lap is louder, sharper and has greater fluctuation strength compared to the closed one. Furthermore, all mentioned parameters depend on the construction type, lap form, and direction of mutual guide bar movement on knitting machine.

Dias and Monaragala [61] worked on the sound absorption of different structures of knitted fabrics made from the same polyester yarn using an impedance tube. According to the results, knitted fabrics with smaller pores have less porosity hence show better sound absorption. To examine the thickness effect, several layers of fabrics have been placed on each other. So, sample A1 is a single-layer fabric with a thickness of 0.6 mm, sample A1(4) is a 4-layer fabric with a thickness of 2.5 mm and sample A1(5) is a 5-layer fabric with a thickness of 3.1 mm. For sound absorption test, pore radius and porosity for

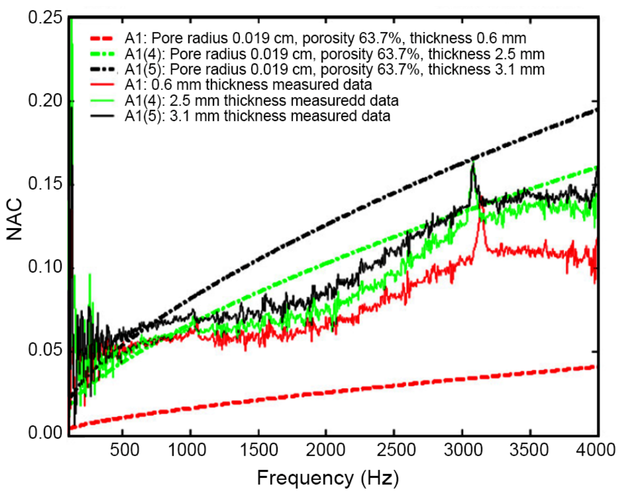


Fig. 19. NAC measured experimentally (dotted) and mathematical theoretically (solid line) [61].

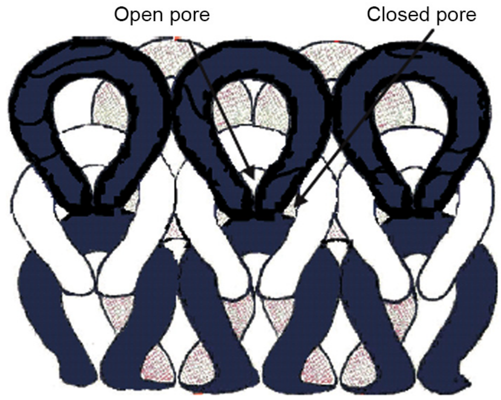


Fig. 20. Structure of knitted fabric with rib pattern [62].

all samples were considered fixed and equal to 0.019 cm and 63.7%, respectively. As shown in Fig. 19, the noise absorption coefficient (NAC) value increases with increasing thickness. It can be said that sound absorption increases by reducing porosity and increasing density and the effect of density on sound absorption is more than that on thickness. The mentioned parameters have good results at frequencies over 2000 Hz and more studies should be done for the frequencies less than 2000 Hz. Additionally, a mathematical model for predicting sound absorption was presented and a good adaptation has been seen between the experimental and modeling results. It should be noted that in modeling all pores were considered cylindrical, however in fact this is not true.

Honarvar, Jeddi, and Amani Tehran [62] investigated the sound absorption of knitted fabrics made by acrylic yarn with rib pattern. The first group includes 7 samples with different number of knit and miss-knit stitches and the second group includes 5 samples with different number of knit and Tuck-knit stitches. Then, using the impedance tube method, the sound absorption coefficient of the samples was evaluated. All pores in the knitted fabrics are not open, as shown in Fig. 20, the knitted fabric is composed of open and closed stitches, which affect sound absorption.

Statistical results show that structural and frequency changes are effective in NAC. Since the structure of the fabric is a random mixture of fibers and air, a combination of the two models should be used. Dent model [63] was used for closed pores and Allard model [64] was used for open pores. The correlation coefficient between the measured NRC and the model results for the samples of the first and second group were obtained 0.875 and 0.9, respectively.

Liu and Hu [65] produced two samples of warp and weft knitted spacer fabrics and used impedance tube method for sound absorption test. A series of oval holes were made in the weft knitted spacer in order to improve sound

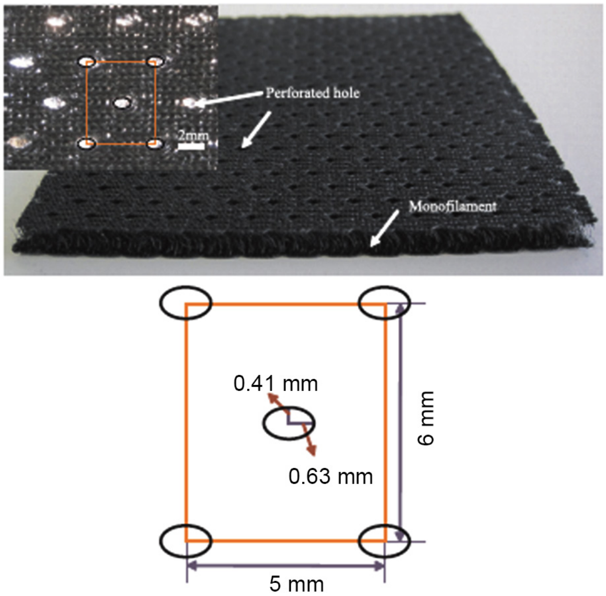


Fig. 21. Weft knitted spacer sample [65].

absorption (Fig. 21). The sound absorption coefficients of the weft single-layer spacer sample (A) at frequencies of 500, 1000, and 2000 Hz were 0.06, 0.14, and 0.35, respectively, and in the warp spacer sample (B) at the same frequencies they were 0.035, 0.05, and 0.07, respectively. In sample A, by placing the fabrics on top of each other up to 4 layers, sound absorption increases at low frequencies but has no effect on improving sound absorption at high frequencies. In sample B, the sound absorption coefficient increases at all frequencies as the number of layers increases. The results showed that the sequence of layers and their number have a great effect on sound absorption. When sample B is placed under sample A, sample B acts as an amplifier which improves sound absorption at all frequencies. When sample A is placed under sample B, it leads to an increase in the thickness of the sample, and as a result at low frequencies sound absorption increases, but at high frequencies it decreases.

Yang and Ye [66] worked on 6 different kinds of knitted fabrics (2 single-cylinder fabrics, 2 two-cylinder fabrics and 2 spacers) in size of 20×17.5 cm. They established their own test system as shown in Fig. 22 and tested the samples at frequencies of 31.5, 63, 125, 250, 500, 1000, 2000, and 4000 Hz. In all samples, the best sound absorption occurred at 125 and 500 Hz frequencies, respectively. Moreover, they observed that the samples with tight structure indicate better insulation performance.

Chen *et al.* [67] worked on polyurethane-based spacers composite using impedance tube method and studied different warp knitting parameters such as inclination angle of spacer yarn, thickness, yarn diameter and surface layer

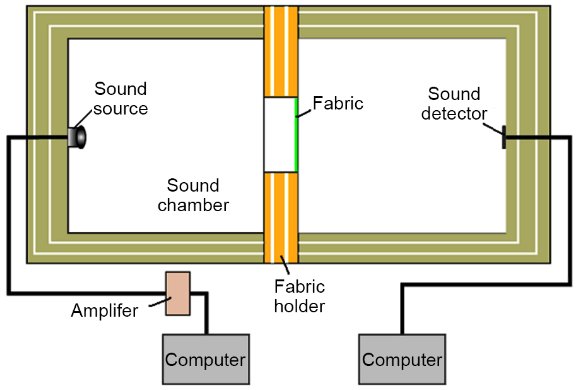


Fig. 22. Sound absorption test results [66].

structure. According to the obtained results, at frequencies less than 3000 Hz, samples showed better sound attenuation. Besides, the amount of sound absorption of composites is highly dependent on knitting parameters.

Arumugam *et al.* [68] investigated the factors affecting the sound absorption of warp knitted spacer fabrics. Samples were produced using polyester fibers at different thicknesses, besides two different knitting patterns such as locknit and hexonal were used for surface layers. The impedance tube method was implied to measure sound absorption. Based on the results, samples with lower thickness were denser which causes more resistance against air penetration and consequently less sound absorption. Considering the pores shapes in hexonal pattern comparing to locknit, sound absorption in hexonal pattern is less than locknit. Moreover, by decreasing porosity, sound absorption increases.

Davoudabadi Farahani *et al.* [69] researched on the sound absorption of weft knitted spacers made of polyester fibers. In this research, 75 den polyester yarns were used for lower and upper layers and 30 den monofilament polyesters were implied as connecting yarns. In order to investigate the effect of thickness, samples were produced in 4.5 and 7.5 mm thicknesses and for sound absorption test, the

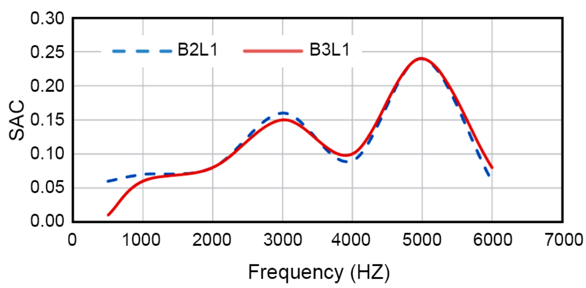


Fig. 23. Effect of connecting yarn angle on the sound absorption coefficient (SAC), B2L1: surface area=430.35 g/m^2, thickness=7.85 mm, porosity=95.78%, B3L1: surface area=439.26 g/m^2, thickness=7.57 mm, porosity=95.50% [69].

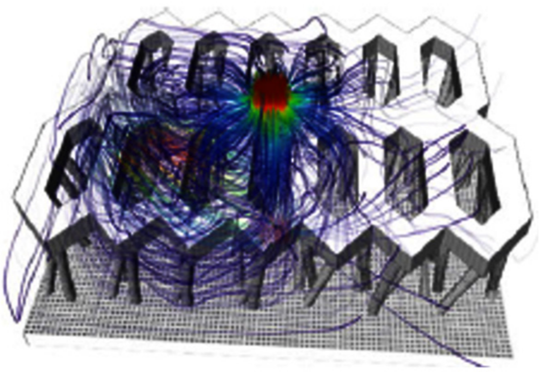


Fig. 24. Fluid flow lines through weft-knitted spacer [70].

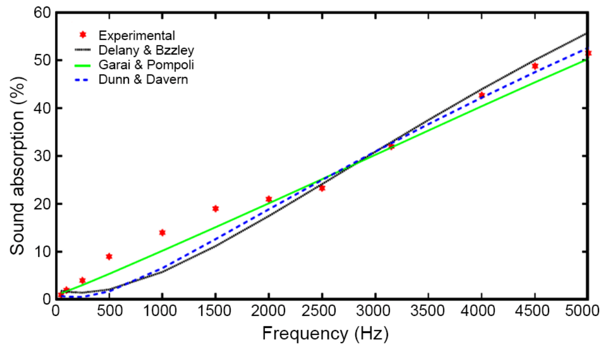


Fig. 25. Difference between sound absorption coefficient and frequency [70].

impedance tube method was used. The sound absorption coefficient increased by increasing frequency. Moreover, the sound absorption coefficient decreases at 4000 Hz because of resonance phenomenon. Samples with 7.5 mm thickness showed better sound absorption comparing to those with lower thicknesses. Furthermore, in producing samples, the angle of connecting yarns was varied while the other structural parameters remained constant. Based on the obtained results, change in connecting angle does not show much difference in sound absorption (Fig. 23). The effect of polyacrylonitrile nanofiber covering was also investigated. Increasing a small amount of nanofibers on the samples surfaces significantly improved the sound absorption coefficient at all frequencies, but excessive increase of nanofibers reduced the sound absorption coefficient due to the closure of pores and reducing porosity.

Abedkarimi *et al.* [70] tried to predict flow resistivity of woven spacers made by multi-filament polyester fibers. Firstly, air flow resistance was measured experimentally using a Shirley M021S air permeability tester and then the upper and lower sample layers were scanned. Structural parameters such as porosity, pore size, geometry, and pore shape were extracted using the image processing method in mesoscale. Then, using CAD-based technique the air flow resistance was simulated (measured and simulated flow resistivity are obtained 59054 and 56980 kg/m^3.s, respectively). In Fig. 24, the air passing track is shown in 3D.

Moreover, sound absorption was modeled using different models. The results showed that at high and medium frequencies, Dunn and Davern [22] model was more consistent with the obtained data while at low frequencies, the [11] models had more accurate results (Fig. 25).

G. Effect of Woven Fabrics

Soltani and Zerrebini [71] conducted a study on the sound absorption of woven fabrics using ring yarns. To perform the sound absorption test, the impedance tube method was used and samples with several different types of weaving patterns including plain, twill, satin and rips were produced. The maximum absorption coefficient was observed in all samples at a frequency of 1000 Hz and between 0.107 to 0.530. Due to the greater thickness of the satin fabric, the minimum absorption coefficient was observed at a frequency of 2000 Hz, but in the other samples it was obtained at 250 Hz. Unlike thickness, weight and density have a large effect on sound absorption. The maximum and minimum NAC were obtained in plain and satin fabrics, which is due to the difference number of yarn contacts in the fabric. In plain fabric, there are most contacts between the yarns, so NAC increases. According to the obtained results, with decreasing the fineness of the yarn, sound absorption increases, so that in the produced sample with a yarn of 24.5 tex, the highest sound absorption was obtained.

Soltani and Zarrebini [72] produced woven fabrics using spun yarn and measured their sound absorption coefficient at frequencies of 250, 500, 1000, and 2000 Hz using the impedance tube method and the average of these values were represented as NRC values. To investigate the effect of compactness, samples with different warp and weft compactness were produced and according to the results, sound absorption increases up to 1000 Hz and then decreases. Excessive compactness reduces sound absorption due to more yarn adhesion. To determine the effect of thickness on sound absorption, the number of fabric layers have been increased. As shown in Fig. 26, with increasing thickness due to the increase in resistance to air flow, the sound absorption coefficient increases. Also, NRC decreases with increasing twist per meter due to more compactness in yarn structure.

Tang *et al.* [73] investigated the sound absorption coefficient of cotton woven fabrics with different densities using the impedance tube method. The variation in air permeability was obtained very small in samples and the multiple regression was used to analyze the results. Due to the low coefficient of determination between sound

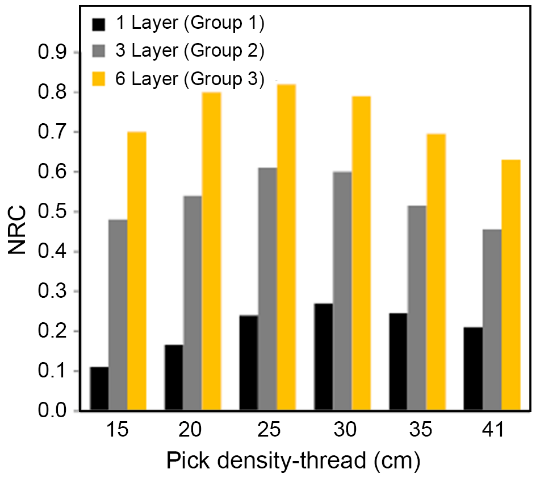


Fig. 26. Effect of compactness and number of layers on NRC [72].

absorption coefficient and the parameters of thickness, diameter, weight and stiffness, it has been concluded that these factors do not have significant effect on sound absorption. The coefficient of determination between the sound absorption coefficient and pore ratio in the air gap of 1, 2, and 3 cm were 0.655, 0.729, and 0.686, respectively, and 0.681, 0.696, and 0.687 for the air permeability, respectively. Therefore, it has been concluded that the pore ratio and air permeability are the most important factors in sound absorption.

Li *et al.* [74] using polyester fibers with two round and triangular cross-sectional shapes produced woven fabrics with three plain, twill and honeycomb patterns. The impedance tube method was used to perform the sound absorption test. At medium frequencies, samples with twill weaving pattern and round cross-section and at high frequencies, samples with plain weaving pattern and triangular cross-section had the highest sound absorption. Moreover, despite previous works [61,75-81], it has been observed that thickness, density, air permeability and porosity are not related to sound absorption. On the other hand, the size and shape of pores are the most important factors in the sound absorption of woven fabrics.

Segura-Alcaraz *et al.* [82] produced polyester samples of woven fabrics with plain weaving pattern and nonwoven fabrics, then investigated the effect of the number of layers on sound absorption. By changing the compactness of the warp and weft, the number of layers and the ratio of warp and weft in each layer, the pore size between the yarns can be changed. Adding a nonwoven layer on the back of the woven sample improves sound absorption, but increasing the nonwoven thickness does not have remarkable effect on sound absorption, so that in the best case by changing the nonwoven thickness from 15 to 45 mm, the sound absorption coefficient changes from 0.86 to 0.9. By increasing the weft density in the fabric, the mass increases, so pore size decreases, and consequently sound absorption increases.

CONCLUSION

Textiles have always been considered in many applications because of their unique physical and mechanical properties. One of their most important applications is in sound absorbents due to their high porosity and lightweight, so they can be used in buildings as sound insulants easily. Effective parameters on sound absorption include fiber diameter, porosity, thickness, pore size and airflow resistance. Due to the high cost of producing samples and measuring the sound absorption, experimental models can be used. The oldest and most comprehensive of these models is referred to the Delaney Bazley model and other researchers try to change the coefficients of this model regarding the textile they studied. Fibers which are the main constituents of textiles seem to be good sound absorbents regardless their origin which can be natural or synthetic. It has been tried to use natural fibers such as jute, hemp and kapok due to the environment issues. The reason for using more kapok is that this natural fiber is hollow in which sound waves are trapped. Other useful textiles are nonwovens and carpets used for flooring in cars, homes and halls. In nonwovens and carpets, porosity and thickness play an important role on sound absorption. To improve their sound absorption, possible solutions could be increasing the number of layers and also nano-coating. In composites, in addition to thickness, density is a more important factor, so that as density increases, sound absorption decreases. In warp and weft knitted fabric, unlike nonwoven fabrics, thickness does not have much effect on sound absorption, while knitting pattern plays an important role. Different knitting patterns create pores with different numbers and shapes in the fabric, and this is effective on the air flow resistance and is directly related to sound absorption. Thickness and airflow resistance are very important in spacer fabrics. To improve the sound absorption coefficient, more layers can be used. It should be noted that in some studies, the combination of textiles such as nonwoven and woven fabrics have been used simultaneously; some textiles absorb sound at lower frequencies and some at higher frequencies. Therefore, depending on the type of consumption and final application of sound absorbent, different textiles or their combinations can be used.

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