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Investigation on the Acoustic Characteristics of Multi-Layer Nonwoven Structures. Part 1 - Multi-Layer Nonwoven Structures with the Simple Configuration

Abstract
In this research work the amount of sound absorption in different multi-layer structures made from nonwoven layers and placed in various configurations were measured and analysed. After producing nonwovens with specified geometric characteristics, multi-layer structures with different configurations were made. We investigated the multi-layer structures and found out that when the number of layers in a structure increases, its sound absorption would rise. It was also observed that the increase in sound absorption at lower frequencies only occurs when the thickness of nonwovens is increased. However, at high frequencies the thickness of the nonwoven layers has a slight influence on the sound absorption of the multi-layer structure. It was also seen in the multi-layer structures that, with a less distance between layers, increasing the number of layers in the structures would positively improve the sound absorption. Hence, this property can be improved either by increasing the distance between the layers or simultaneously decreasing the number of layers in the multi-layer structures, although this trend would be true for panels having less than four nonwoven layers and at frequencies up to 1000 Hz.

Key words: *acoustics, nonwoven, coefficient of sound absorption, tube impedance.*

Introduction

Sound pollution is one of the biggest problems concerning people’s health. In the industrial environments, in addition to sound generated by machinary, sound reflection can also intensify this pollution.

In recent years a lot of research work has been carried out on the sound acoustic of nonwoven layers [1 - 10].

Acoustical absorbing materials are often used in the automotive and building industries. At present, the most common materials used are fibrous materials, foam, glass, perlite and concrete. Fibrous materials are considered to be the most ideal because of their low-cost, lightweight, no pollution and high-efficient absorption capability [1].

The studies suggest that the Noise Acoustic Coefficient (NAC) of nonwoven layers is comparable with that of fibre-glass and rock-wool in the frequency range of 2000 Hz [1].

When sound waves enter into fibrous materials, they move due to the vibration of air molecules in the void spaces. These vibrations lead to frictional dissipations. The change in the passage path of the flow of the sound wave as well as the expansion and contraction of the flow of the sound wave throughout the irregular voids cause the movement of the sound waves to decrease. Frictional dissipation appears in the form of temperature variation in the multi-layer structures [1 - 3].

One of the most important properties of nonwovens relevant to their acoustics is the geometry of the fabric used. In the past some research work has been done, as mentioned here.

Recently, Tascan and Vaughan studied the effects of the textile density, fineness and cross section of fibres on sound absorption. The results of their research indicated that finer fibres with an irregular cross section absorb more sound compared with other fibres. It was also found that denser textiles absorb more sound in comparison with textile materials of low density [4].

In another research work on composites consisting of PP and PET, it was shown that when the thickness of composites increases, the NAC will improve somewhat; however, this parameter decreases when the composite becomes denser [5].

Mainly multi-layer structures are used as sound and heat absorbents in buildings. In this study we found that in addition to the geometry of the nonwoven layer, there are other structural factors influencing the sound absorption of multi-layer structures. Despite the significance of this area, few research works have been carried out and only some mathematical formulas have been given by some research workers [6 - 8].

The majority of research workers used two methods to measure the acoustic properties of fabrics. Using tube impedance as the primary method is suitable for small samples (samples of 10 cm diameter), but this trend of measurement is not so appropriate since each frequency is measured in a particular amount. Therefore the frequency range of 1 - 1000 Hz is preferred.

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Table 1. Specifications of the materials and production.

Fibres materials	Fibre fineness, dtex	Punch density	Unit weight of layer, g/m^2	Type of layer surface	Layer thickness, mm
PET	9	180/cm^2	700	Raw felt	50

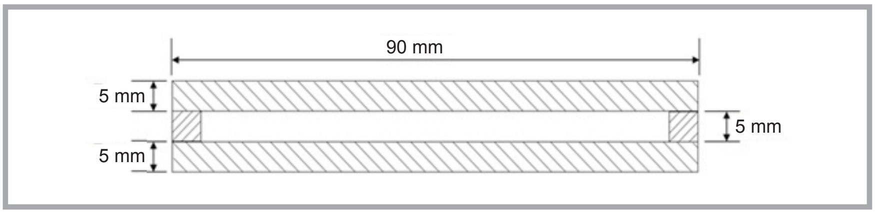

Figure 1. Side view of a two layer structure with a 5 mm distance.

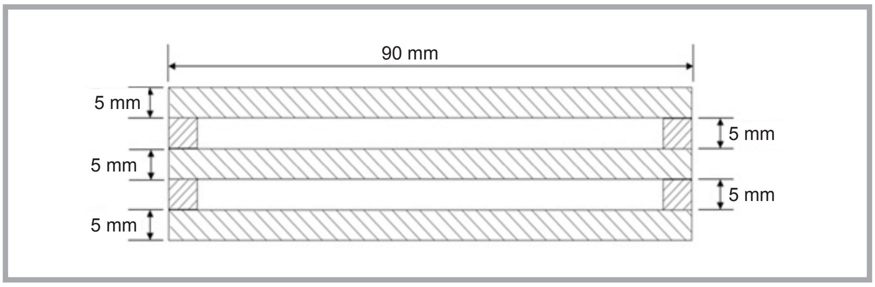

Figure 2. Side view of a three layers structure with a 5 mm distance.

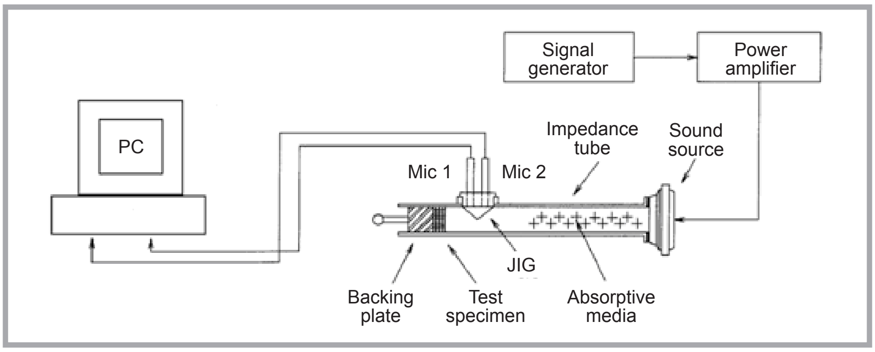

Figure 3. Tube impedance with 2 microphones and the set-up used to measure NAC.

The second method which is suitable for larger samples is the method of reverberation room. This method is a direct way of comparison for sound parameters [4].

On the basis of research work carried out by Youngjoo [9], it was revealed that the sound absorption coefficients of microfibre fabrics, measured by the reverberation room method, is remarkably higher than this property of conventional fabric with the same thickness or weight. It was also shown that the structure of microfibre fabrics plays a vital role in controlling sound absorption [9].

Parikh and Chen studied the reduction of automotive interior noise with natural fibre nonwoven floor covering systems. Natural fibres are noise-absorbing materials that are renewable and biodegradable, making them an effective choice for the automobile industry. Floor coverings using natural fibres (kenaf, jute, waste cotton, and flax) in blends with polypropylene (PP) and polyester (PET) were developed as carded needle-punched nonwovens [10].

The aim of this research work is to find out how the number of layers and space between them in nonwoven multi-layer structures influence the sound absorption of the structures produced.

Materials

The nonwoven layers used in this research were made from 9 dtex PET fibres reinforced by needle punching. Considering the results of previous research works, it was attempted to optimise the parameters to make nonwoven layers with the highest sound absorption.

The fibres were opened by an opener and fed to a card machine and needle loom, model Automatef from Italy. The output web from the card machines were delivered to a cross lapper. The crossed lap layers were then punched by a needle punching machine. Specifications of the fibres, the punching rate, type of layer and thickness of the layers are given in ***Table 1***.

Methods

At present, the NAC of materials is measured by tube impedance. Determination of the NAC using tube impedance can be made in two subordinates of the Standing Wave Ratio and Fast Fourier Transform (FFT) [9].

Russel, using a tube of Standing Wave made by B&K and sound analyzer, measured the minimum and maximum sound pressure in the tube impedance to determine the Standing Wave Ratio of NAC for different materials [11].

In another method applied by Angelo [12], a microphone, which can be placed at different distances along the tube impedance, was used to calculate the transfer function between each couple of locations and the NAC of the samples. This technique is more time consuming in comparison with the transfer function calculated using two microphones. It is necessary to find the precise location of the sensors manually, but it is more accurate in determining absorption specifications at different frequencies.

Another technique used by researchers to measure NAC is using tube impedance with two fixed microphones. In this system, both the Standing Wave Ratio and Transfer Function methods can be applied.

We used a tube impedance with two fixed microphones to measure the NAC of the nonwoven multi-layer structures.

In order to measure the NAC of the samples, we cut the multi-layer structures into the form of disks of 90 mm diameter. It should be mentioned that the samples were put loosely, adjacent to each other. Then the multi-layers were inserted inside the sample holder perpendicular to the tube. ***Figures 1*** and ***2*** display the side views of two samples of the multi-layer structures.

This method of measuring NAC based on ASTM E 1050 [13] is used for measuring the absorption of sound waves. The equipment was designed and manufactured at the Textile Engineering Department of Yazd University. ***Figure 3*** shows this equipment and the set-up used to measure NAC. The equipment includes a steel tube of 80 centimetres length and 10 centimetres diameter, a signal generator, two microphones, a speaker and a PC/Laptop. At the end of the tube, there is a cylindrical part functioning as a sample holder. Using this holder reduces the amount of transit sound waves remarkably. In fact, when the sound waves collide with the sample surface, there is only the possibility of the absorption and reflection of the sound waves.

As can be seen from ***Figure 3***, the speaker is installed on one side of the tube and the samples are put inside the sample holder on the other side of the steel tube. The sample holder, which is securely fitted inside the tube, can move in the tube. The distance between the sample and the microphones changes due to this movement.

To measure NAC, sound waves within a frequency range of 200 - 1600 Hz were produced by a signal generator. The sound waves sent into the tube affected the samples and were sensed by the microphones. Then these signals were digitised and processed by a digital frequency analyser and PC. Each sample was tested three times, and finally the mean value was considered as the NAC of the relevant specimen.

To determine the NAC, the standing wave method and ***Equation 1*** is used. It should be added that the equation can be applied for all materials.

$$S = \frac{|P_{\max}|}{|P_{\min}|} \qquad (1)$$

where:

S - Ratio of Standing Wave

P_{max} - maximum sound pressure in the tube

P_{min} - minimum sound pressure in the tube

$$|P_{max}| = |P_i| \cdot (1 + |r|)$$

$$|P_{min}| = |P_i| \cdot (1 - |r|)$$

The reflection factor, r, of the sound can be obtained from ***Equation 2*** [14].

$$S = \frac{1+|r|}{1-|r|} \qquad (2)$$

The NAC can be calculated from ***Equation 3***:

$$\mathrm{NAC} = 1 + |r^2| \qquad (3)$$

In practice, to measure the amplitude of sound wave, the amplitude of the pressure is measured in the Impedance Tube.

As the pressure level of the sound is expressed in dB, the sound absorption can be obtained from ***Equation 4***:

$$S = 10^{\frac{\Delta L}{20}} \qquad (4)$$

To obtain the dimensionless NAC, α, we can use equation (5)

$$\alpha = \frac{4\times 10^{\frac{\Delta L}{20}}}{\left[10^{\frac{\Delta L}{20}} + 1\right]^2} \qquad (5)$$

where α is the NAC and ΔL is the difference between the maximum and minimum level of pressure [14].

Results and discussion

Application of nonwovens in order to reduce sound pollution is based on two major advantages: a low cost of production and low specific weight. Therefore a wide of range of these products can be used as acoustics in buildings. The range of frequencies applied in this research work was 200 to 1600 Hz on the basis of the diameter of the impedance tube [14].

The samples were tested at frequencies of 250, 500, 1000 and 1600 Hz, generated by the signal generator. However, we repeated the experiments for the same samples at other frequencies such as 300, 400, 700 and 1200 Hz, and the results obtained followed similar trends to those of 250, 500, 1000 and 1600 Hz. The phenomena and signals reflected in the tube were recorded by the PC, and then the maximum and minimum pressure of the sound was measured in the impedance tube. The NAC of each sample is calculated from ***Equation 5***, the results of which are displayed as curves of the NAC-frequency dependence. The primary results suggest that the trend of sound absorption in the different samples is alike when the frequency changes.

As we know, sound is a mechanical disturbance that travels through a gas, liquid, or solid. As sound waves pass through a material, each particle in the material oscillates back and forth repetitively. Nearby, atoms and molecules move in unison, creating regions of high and low density in the material. Although the atoms and molecules themselves do not move very far, the regions of altered density travel through the medium at the speed of sound. These compressed and rarefied regions contain energy, and this energy also travels through the medium.

Effect of the number of layers in the multi-layer structure

To investigate the effect of this parameter, the NAC of the multi-layer structures with different layers previously prepared were measured.

Figure 4 shows the NAC of the multi-layer structures with different layers placed adjacent each other, i.e. the distance between the layers is zero.

As can be observed from ***Figure 4***, at a frequency of 250 Hz, when the number of layers in the multi-layer structures is increased up to three layers, their NAC increases, whereas the NAC of the multi-layer structure with four layers will drop to a value between those of the multi-layer structures of one and two layers. Therefore an increase in the layers of the multi-layer structures causes the NAC to rise and then drop. It can also be seen that when the frequency of the sound increases to 500 Hz, the NAC of the multi-layer structures becomes somewhat higher; however, it will decrease significantly at 1000 Hz in all the multi-layer structures. However, the NAC of the multi-layer structures will increase at 1600 Hz. The increase in sound absorption at low frequencies only occurs when the layers become thicker. Moreover the thickness of the layers in the multi-layer structures have little influence on the sound absorption at high frequencies.

The NAC of the structures can be improved using several layers put nearby with orwithout a space between. Among the samples, the three layer multi-layer structure, had the best performance at low frequencies, with an NAC of about 0.8. i.e. this multi-layer structure can absorb 80% of the incident sound waves.

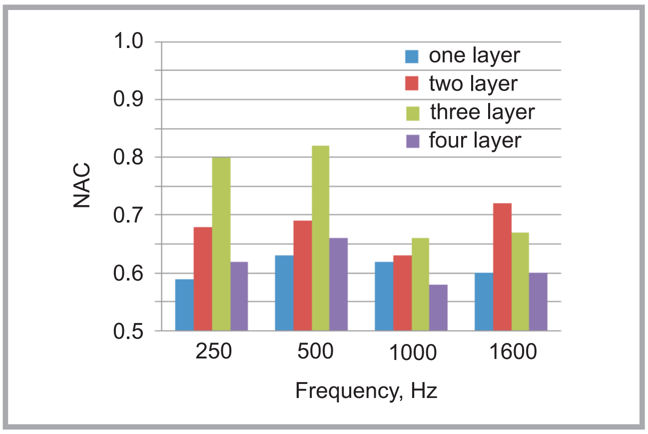

Figure 4. *Effect of the number of layers in the multi-layer structures, placed without a gap.*

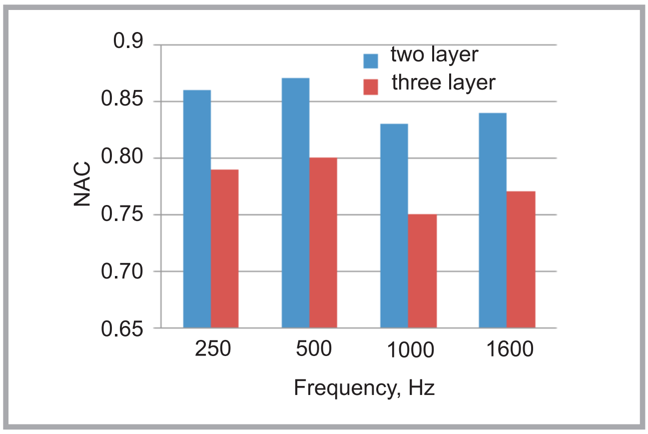

Figure 5. *Effect of the number of layers in the multi-layer structures, placed with a distance of 15 mm.*

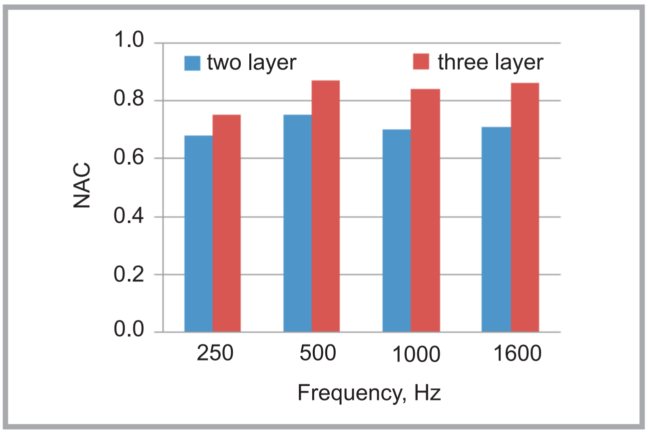

Figure 6. *Effect of the number of layers in the multi-layer structures, placed with a distance of 5 mm.*

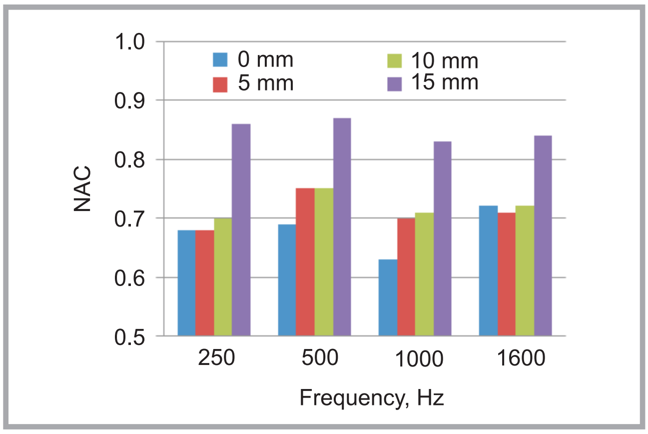

Figure 7. *Effect of the distance between two layers in the multi-layer structures.*

Figures 5 and ***6*** also illustrate the NAC of multi-layer structures with the layers placed at 15 and 5 mm, respectively. It can be seen from ***Figures 5*** that we used only multi-layer structures with two and three layers because it was found from ***Figures 4*** that in these cases the NAC is higher than for the multi-layer structures of one and four layers. According to this figure, when the frequency rises, the NAC of both multi-layer structures increases. It is obvious that multi-layer structures with two layers placed at a 15 mm distance show higher sound insulation in comparison with a similar multi-layer structure with two layers placed at 5 mm. The results suggest that at higher distances better insulation will be achieved with a lower number of layers in the multi-layer structure.

Effect of the distance between layers in the multi-layer structure

Generally speaking, the effect of both factors, the number of layers and distance between them, in the multi-layer structures can be explained using the diffraction of sound. Sound diffraction occurs when a sound wave passes through a multi-layer structure whose material changes. When a sound wave gets to one of the multi-layer structures, it passes through the nonwoven layers, enters the new material (air) and passes into the nonwoven layer and so on. When the material changes the velocity of the wave, this causes the NAC of the multi-layer structures to be different from that of homogenous multi-layer structures. In fact, part of the sound energy within the different materials is reflected. As is known, the sound waves are transferred by air molecules. On this basis the distance between layers or the gaps between them in the multi-layer structures can improve the insulation thereof. It is necessary to mention that the nonwoven layers are not quite homogenous, since there are some voids trapping air inside. The frequencies of 250 and 500 Hz, although not unpleasant, have a long wavelength. But frequencies over 1000 Hz, with a short wavelength, are considered as shocking frequencies. Due to these properties of these frequencies, the maximum and minimum sound pressure constantly change. Therefore the acoustic behaviour of the multi-layer structures also vary.

The value of the sound absorption factor in individual walls (TL) is measured using ***Equation 6***. According to this formula, with an increase in TL in a wall, its acoustic insulation improves. The acoustic characteristic of the multi-layer structure acts as insulation at the walls of two- or multi-layers [15].

$$TL = 14.5 \log (m \times f) - 26 \text{ dB} \quad (6)$$

In which m is the weight of the unit area of the wall (kg/m^2) and f the frequency(Hz).

Figure 7 indicates the NAC of multi-layer structures with 2 layers placed at different distances from each other. As can be observed from this figure, the multi-layer structure with two layers placed at a 15 mm distance has the highest NAC in comparison with other samples.

Conclusions

In this research work, it was attempted to investigate the effect of the number of layers and the distance between them in the multi-layer structures on the sound absorption of multi-layer structures made from nonwoven. Therefore some nonwoven layers with the best structural and geometrical properties were prepared according to the findings of previous works. Regarding the results, we can conclude that the amount of NAC in multi-layer structures made from nonwoven layers produced by needle punching depends on the number of layers i.e. the thickness of the multi-layer structures.

As observed from this work, at all frequencies the NAC of the structures without a space between the layers increases with an increase in the number of layers of up to three; however, when the number of layers in the structure is increased to four, this characteristic decreases significantly. However, there is an exception - the three layer structure at 1600 Hz.

Comparing the performance of the multi-layer structures with different distances between the layers, it may be mentioned that in the multi-layer structures with a low distance between the layers (5 mm), increasing the layers has a positive effect on the NAC. As can be seen, the three layer multi-layer structure with a 5 mm distance between the layers performed better than the multi-layer structure with two layers with the same distance between them.

Meanwhile, if the distance between the layers in the two layer structures is increased, for instance to 15 mm, the NAC of the multi-layer structure also improves. In other words the NAC of the two layer structure with a 15 mm distance between the layers has better performance in comparison with the three layer structure with a similar distance between its layers.

In the future, the results relevant to other structure configurations will be presented in part - II.

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