STUDIES ON ACOUSTIC PROPERTIES OF NONWOVEN FABRICS

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Studies on Acoustic Properties of Nonwoven Fabrics

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By

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Declaration

I, Mlando Basel Mvubu, student number 21246243, hereby declare that the thesis for Philosophiae Doctor (PhD) in Textile Science is my own work and that it has not previously been submitted for assessment or completion of any postgraduate qualification to another University or for another qualification. .

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Abstract

This study is divided in to two main parts. The first part deals with the optimization of process parameters of needle-punched nonwoven fabrics for achieving maximum sound absorption by employing a Box-Behnken factorial design. The influence of fibre type, depth of needle penetration and stroke frequency on sound absorption properties were studied. These parameters were varied at three levels during experimental trials. From multiple regression analysis, it was observed that the depth of needle penetration alone was the most dominant factor among the selected parameters, which was followed by the interaction between depth of needle penetration and stroke frequency. Fibre type was the least dominant parameter affecting sound absorption. A maximum sound absorption coefficient of 47% (0.47) was obtained from the selected parameters. The results showed that for a process such as needle-punching, which is influenced by multiple variables, it is important to also study the interactive effects of process parameters for achieving optimum sound absorption.

The second part of the study deals with the effect of type of natural fibre (fineness), and the blending ratio (with PET fibres) on the air permeability of the needle-punched nonwoven fabrics and then it proceeds to study the effect of the air-gap, type of natural fibre (fineness) and blending ratio (with PET fibres) on sound absorption of needle-punched nonwoven fabrics. These parameters are tested individually and their two way interaction (synergy) effect using ANOVA. The air-gap was varied from 0mm to 25mm with 5mm increments, three natural fibre types were used and all were blended with polyester fibres at three blending ratios for each natural fibre type. The *Univariate Tests of Significance* shows that all three parameters have a significant effect on sound absorption together with two two-way interactions, with the exception of the Blend Ratio × Air Gap two-way interaction which was not significant. It was found that the sound absorption improves with the increase in the air-gap size up to 15mm after which sound absorption decreased slightly with the further increase in the air-gap up to 25mm.

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List of abbreviations and symbols

EDANA	European Disposables and Nonwovens Association
INDA	Association of the Nonwoven Fabrics Industry
λ	Wave length
$\boldsymbol{c}$	Speed of sound
$\boldsymbol{f}$	Wave frequency
P	Atmospheric pressure
p_o	Pressure amplitude constant
z	Acoustic impedance
v	Volume velocity
D	Obstacle to sound wave propagation
$\boldsymbol{R}$	Fraction of sound energy which is reflected
dB	Decibels
I	Sound intensity
W	Sound power
SPL or L_p	Sound Pressure Level
α	Sound absorption coefficient
NRC	Noise reduction coefficient
NAC	Noise absorption coefficient
STL	Sound transmission loss
CFC	Chlorofluorocarbon
PVDF	polyvinylidene fluoride
T_g	Glass transition temperature
PET	Polyester

PP	Polypropylene
PLA	Polylactic Acid
PTFE	Polytetrafluoroethylene
R_1	Specific flow resistance
V_a	Volume of the air in the voids
V_m	Total volume of the sample
T_{60}	Reverberation time
H	Transfer function
ASTM	American Society for Testing and Materials
ANOVA	Analysis of Variance
XPS	Extruded polystyrene
OFDA	Optical fibre diameter analysis

1. INTRODUCTION

1.1. Noise

Excessive noise is becoming an increasingly annoying disturbance in society. Increased noise disturbance, particularly in urban areas, is largely due to rise in population density and modern industrialisation. In general, no clear distinction between sound and noise is perceivable. Sound is a sensory perception and its complex pattern is termed as noise, music, speech etc. Noise is thus defined as unwanted sound causing discomfort to human ears [1].

The negative effects of noise on human health and social environment have been studied for a long time since the middle of the 20th Century [2]. Consequently, many methods have been devised to mitigate this problem of noise disturbance. The significance of noise pollution according to the specific effects are: noise-induced hearing impairment; interference with speech communication; disturbance during rest and sleep; adverse effects on psycho-social and mental-health performance; effects on residential behaviour and annoyance; as well as interference in intended activities [2].

Noise can also adversely affect productivity in many environments [3]. For example, noise in the passenger cabin of vehicles, which is generated by tyres, road, traffic, and the engine; interferes with speech, causes driver fatigue, and affects safety [4]. Car owners also usually complain about the noise inside the cabin. Hence, the noise in the passenger compartment not only harms the health and safety of occupants but it also adversely affects the perception on quality of the vehicle [5]. As more electronic communication and entertainment systems are integrated into the vehicle, it is increasingly important to control noise in the passenger compartment.

Main sources of noise include road, rail and air traffic, industries, construction, public works and the neighbourhood. The main sources of indoor noise are ventilation systems (propeller), office machines, home appliances and neighbours. All sound measures consider the frequency of the sound, overall sound pressure level and variations in these levels with respect to time. Sound pressure is a basic measure of the vibrations of air that produces sound.

1.2. Noise Control

The control of noise is as much a matter of awareness as one of action. Many problems arise because noise control is considered only when it occurs rather than in advance as a precautionary measure. Historically, a lot of work in this field has been remedial, solution based, rather than proactive. But experience has led to increasing efforts in the building industry to anticipate and control noise by appropriate design [4].

Given the practicalities of most noisy environments such as industrial plants, together with the cost implications of dealing effectively with noise and its effect on humans (and animals in some instances), the noise control interventions can be arranged in a hierarchical manner like in Figure 1.1. The hierarchy is in a form of an upside down pyramid to demonstrate that the noise control interventions become more expensive the higher you go in the pyramid [6].

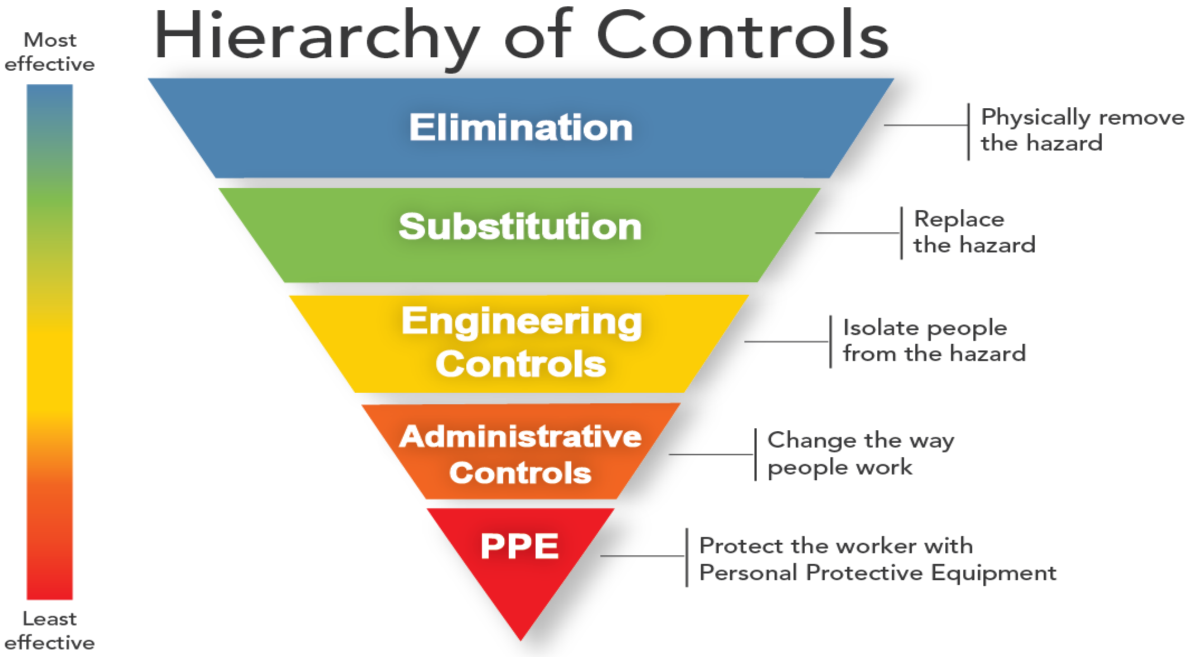

Figure 1.1. The hierarchy of control for noise reduction [6]

A noise system can be divided into three major elements [1]:

- Noise source – The element which disturbs the air.
- Noise path – The medium through which the acoustical energy propagates from one point to another.
- Noise receiver – The person who could potentially complain about the quantity or level of noise as perceived at the same point.

It is necessary to treat at least one of the above mentioned elements in the noise system if the level of the noise perceived by the receiver is to be reduced. Nevertheless, treating more than one element is never ruled out, but it becomes costly.

Noise control at the source may include modification of the source itself such that it emits less noise, or the complete replacement of the source by a quieter source performing the same function or by employing a completely different process. On the other hand, noise control at the receiver may include measures, such as provisions of noise shelters or refuges and/or the use of hearing protection. In controlling the noise path, however, if the noise is airborne, insulation and absorption is used and if the noise is structure-borne, isolation or damping is used [1].

The treatment of the noise path is conceptually the simplest and therefore the most common approach to a localized noise problem; see Figure 1.1 [6]. The treatment of the other two elements, namely, noise receiver and noise source; are more expensive and/or impractical, for example, using hearing protection may not be practical if other processes require normal hearing. The approach is to place the material in the path of the noise (generally between the noise source and the noise receiver) to create a barrier so as to reduce the level of noise at the receiver.

In general, four basic principles are employed to reduce noise [7]: isolation, absorption/ barrier, vibration isolation and vibration damping. The scope of our study here is focused only on sound absorption/barrier phenomenon, where sound energy is converted into thermal energy.

Sound absorption materials reduce airborne sound by converting airborne sound energy into heat energy via frictional mechanism. Generally, the reflection of sound from hard surfaces is reduced and thereby the build-up of reverberant sound in rooms or any other enclosed spaces is reduced [1].

Various types of materials are used for sound absorption; among them are different types of porous media, such as cellular, granular and fibrous porous materials and the nonwoven fabrics fall in this category.

Sound Insulation materials reduce the transmission of airborne sound between spaces. They are used for noise reduction by screens, barriers, partitions and enclosures, as well as for acoustic lagging of ducts and pipes and mechanic panels [1].

Sound Isolation employs resilient materials to reduce the transmission of structure-borne sound or vibration. The principles may be used for many situations including isolation of sound radiating panels from vibrating machine frames, motors, pumps and fans from diesel engine generators and compressors, the isolation of sound from entire rooms etc. [1].

Damping is the process whereby vibrational or structure-borne sound energy is converted to heat, thereby reducing the level of vibration and sound, this is achieved through a resistive frictional process. It is the counterpart to sound absorption, which converts airborne sound energy into heat via frictional process thus reducing the level of air borne sound [2].

1.3. Nonwovens

There are two main processes involved in nonwoven production, namely web formation and web bonding. Three different types of web formation techniques, such as dry-laid, wet-laid, and polymer-laid are generally employed for producing nonwoven fabrics. Dry-laid nonwovens have their roots in classical textiles processes such as spinning and use similar staple fibers as well. The wet-laid process is the adaptation of the paper making process and the polymer-laid originates from polymer extrusion and plastic processing.

The web formation stage in dry-laid nonwovens is carried out by carding and cross lapping or aerodynamically by air laying the fibres on a moving belt. Thereafter, a batt is mechanically bonded by needle punching and /or hydro-entanglement or chemically or thermally using heated air or direct heating by calendaring rollers. Dry-laid nonwovens are the largest segment of the nonwoven production and they are forecasted to grow by 5.3% every year for the next 10 years [8].

Wet-laid nonwovens are produced through a system that is designed to process short fibers suspended in liquid. To distinguish from conventional paper product, a wet-laid nonwoven fabric is classified by EDANA as a nonwoven textile material if more than 50% of its mass is from fibres with a fibre length to diameter ratio greater than 300, or more than 30% fibre content if the material density is less than 0.40g/m^3 [8]. The wet-laid process is not common due to the fact that it is capital intensive and it uses a large volume of water. Therefore, it is employed for highly specialised applications using cellulose fibers to produce technical papers composed of high performance fibres, such as aramids and ceramics.

Polymer laid nonwovens include spunbond, meltblown and flash-spun. Spunbonding is basically characterised by extrusion of synthetic filaments from molten polymer and laying on to a moving conveyor to form a web. This technology is widely used in producing such materials as coverstocks, backings, distribution layers, and leg cuffs. The polymer-laid nonwovens account for 65% of components in hygiene products [8].

As reported in many studies, nonwoven fabrics have been extensively utilised in sound absorption applications. They are well suited for this function due to their bulkiness (high volume-to-mass ratio) and porosity resulting from air cavities [9, 10 and 11]. Moreover, the nonwoven fabrics are cost effective as they are relatively easier to manufacture at high production rates.

Nonwoven fabrics are produced from environmentally friendly processes in comparison to other alternative materials like glass fibres and chip boards. The nonwoven production process is not energy intensive and very minimal use of chemicals is required which may harm the environment [8]. Nonwoven fabrics can also be produced from natural fibres which result in an environmentally friendly product compared to that produced from glass fibres.

Another advantage of nonwoven fabrics over classical woven and knitted fabrics is that it is possible to process a wide variety of fibers with different finenesses and lengths. This makes it possible to use almost all types of natural fibres without lengthy preparatory process as is the case when preparing the fibers for yarn spinning. This also makes it cheaper and quicker to produce nonwoven fabrics from natural fibers as compared to classical textiles which require yarn production and weaving or knitting processes.

However, in some cases the natural fibers are required to be blended with other natural and synthetic fibers, for enhancing thermoformability and strength and to act as carrier fibre during the manufacturing process [12]; synthetic fibers may also be used to increase bulk where necessary. This means that in some cases natural fibers are blended in various proportions with synthetic fibers for achieving synergy in fulfilling specific functions.

1.4. Nonwoven Production Processes

Like most production processes, the type of nonwoven production process to be used is also decided by the required characteristics of the fabric, which in turn determines the choice of fiber(s) and their blending ratio. Next step is to choose the method of web formation together with the bonding method. Then finally it is the choice of finishing, if required by the final product.

Manmade fibers dominate the nonwoven production which accounts for 90% of the output with polypropylene and polyester accounting for 63% and 23%, respectively [8]. However, with the rise in the demand for biodegradable and environmentally friendly products, a steady increase in the use of natural fibers, such as flax, hemp, kenaf, etc. is witnessed. In some instances, synthetic fibers are blended with these natural fibers.

The web formation process is characterised by depositing the fibres or filaments onto a forming surface to form a web or condensed into a web and deposited on the surface of a moving conveyor . In simple terms, web formation involves arranging staple fibers or filaments into a two dimensional web or a three dimensional batt. Their structure and composition strongly influence the structure and characteristics of the final fabric. The arrangement of the fibres in the web governs the isotropy of final fabric properties; however, most nonwoven fabrics are generally anisotropic.

The choice of web bonding method is crucial, as it decides the properties of the fabric, such as strength, porosity, flexibility, density, loftiness and thickness. In some instances, depending on the desired fabric characteristics, more than one bonding method is employed. Needlepunching is the most common bonding method accounting for 35% of the nonwoven output [8]. Hydroentanglement bonding produces comparatively thinner fabrics as compared to needle-punched fabrics but achieve higher tensile strength. Hydroentangled nonwoven fabrics also look similar to woven fabrics, sometimes with similar drape as well.

Chemical bonding is largely employed in combination with another bonding method for applying finishes, such as anti-microbial , anti-static and fire-retardants, but it can be applied for only bonding the web as well. Thermal bonding by heated air produces loftier materials with high thickness and low tensile strength, e.g. duvet inners. Whereas calendaring process applies direct heat under pressure to soften and fuse fibers to bond them without melting.

Various finishing methods are employed in the nonwoven industry and the choice is dictated by the end-use of the fabric. The main types are wet, chemical, lamination, mechanical and surface finishing. Wet finishing includes washing (scouring), coloration (e.g. dying) and printing (pigment applied with binder). As stated above, chemical finishing is sometimes combined with chemical bonding to reduce processing steps.

Chemical finishing methods include padding, coating and spraying. Lamination is used for joining two or more layers of pre-formed nonwoven fabrics or a layer of nonwoven fabric with other materials like films, scrims, and other textile materials, for example, woven fabric. Mechanical finishing includes splitting and winding, perforating and drying. Surface finishing includes singeing (removal of protruding fibers form fabric with heat), shearing, flocking, raising, polishing and softening.

1.5. Nonwovens in Sound Absorption

Needle-punched nonwoven fabrics as sound absorbing media have been studied at length in the past few years. Many parameters affecting their efficacy in sound absorption have also been studied [13-17]. These can be grouped in terms of materials (fiber type and composition), production process and product parameters. Material parameters include fiber dimensions, fiber surface area and fiber blending ratio. Process parameters include depth of needle penetration, stroke frequency, web thickness, density and surface treatments. Product parameters include airflow resistance, porosity, tortuosity and surface impedance [18]. Besides these parameters, other variables influence their efficacy in sound barrier application, for example, layering sequence and the gap between layers (size of the air gap) as factors that have not been widely investigated in sound barrier capabilities of nonwoven fabrics particularly in automotive and building applications.

Mirjalili and Mohammad-Shahi [13] studied the amount of sound absorption in different multi-layered structures made from nonwoven fabrics, these structures in various configurations, including incorporation of the air-gap, were applied for sound absorption, however, these parameters were not optimised. Other researchers have also studied the effect of air-gap on sound absorption properties of nonwovens [14, 19] without optimising or testing synergistic effects with other production parameters.

Applications of nonwoven fabrics for noise control in buildings include wall claddings, acoustic barriers and acoustic ceilings [20], and in passenger vehicles are noise absorbers, dash insulators, engine insulators, carpets, door panels, hood liners etc. [21]. The modern trend in technological advancement is such that one needs to be mindful of the environmental impacts of the materials used. This includes, time of production, time of use and disposal at the end of the service life of the material.

1.6. Nonwovens and the Environment

The recent trend on environmental impact awareness means that producers need to be considerate in terms of mass and volumes of the materials used. Hence, industrialists are increasingly becoming interested in natural or renewable materials as society becomes more aware of the adverse effects of producing and using synthetic non-renewable materials in the eco-system [22].

Natural fibers are renewable and biodegradable, therefore making them an effective choice for the noise absorbing materials particularly for automotive and built environment applications. Recent upsurge in research on the use of recyclable and biodegradable materials in manufactured products has triggered a need for biodegradable nonwovens for nearly forty interior components in automotive production, which include door inner panels, headliners, carpets etc. These components are currently made of traditional materials, such as glass and other synthetic fibers and foams which are difficult to recycle [12].

2. LITERATURE REVIEW

2.1. The Sound Phenomenon

2.1.1. The Nature of Sound

Sound is a result of fluctuations in the pressure of air that is perceived by sensory nerves of the human ear. These fluctuations are in the form of longitudinal wave motions and they can be set up in a number of ways, but usually by some vibrating object [4]. Sound, however, can travel through any medium, including air, liquid and solid, as long as the medium has mass and elasticity [7].

The vibration in a medium produces alternating waves which are relatively dense and sparse in the particles of the medium known as compression and rarefaction, respectively, as shown in Figure 2.1 [24]. The resultant variation to normal ambient pressure is translated by the human ear and it is perceived as sound.

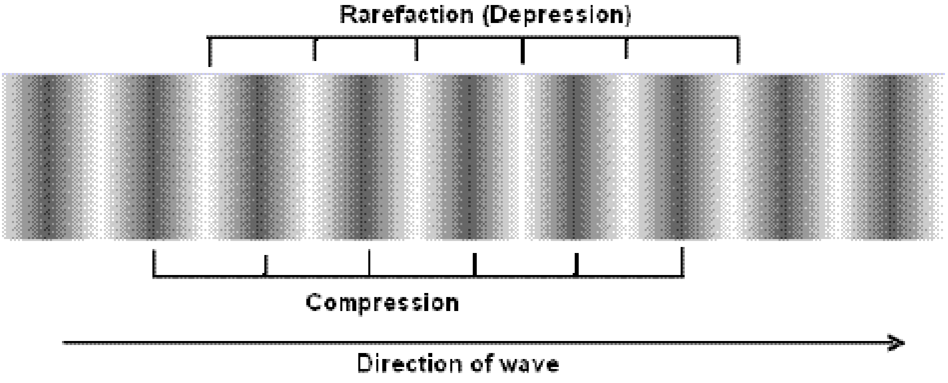

Figure 2.1 Alternative patterns of dense and sparse particles [24]

2.1.2. Properties of Sound

Sound is normally considered to be a wave phenomenon. A sound wave is a longitudinal wave which temporarily displaces the particles of the medium in a direction parallel to energy transport and then the particles return to their original position [25]. A simple sound wave is shown in Figure 2.2 [26] and may be described in terms of variables, namely: amplitude, frequency, wavelength, period and intensity.

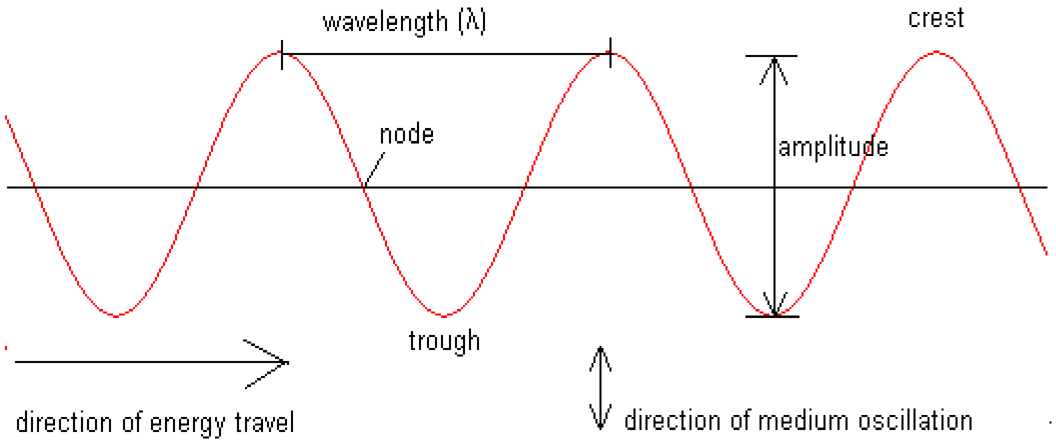

Figure 2.2 Schematics of a sound wave [26]

Amplitude is the difference between maximum and minimum pressure.

Frequency (of a wave) is the number of complete back-and-forth vibrations of a particle of the medium per unit time. A commonly used unit for frequency (f) is the Hertz (abbreviated Hz).

Wavelength (λ) is the distance travelled by a wave along the medium in one complete wave cycle. Since a wave repeats its pattern once every wave cycle, the wavelength is sometimes referred to as the length of the repeating patterns. The term **'period'** can be defined as the time required for the completion of one cycle of wave motion.

Intensity (of a sound wave) is the average rate at which sound energy is transmitted through a unit area.

2.1.3. Sound Mechanics

The **Speed of Sound**, denoted by **c**, is the rate at which sound waves travel. At 20 ^{o}C (68^{o}F) the speed of sound in air is approximately 344 m/s. The temperature of the air (medium) has a significant effect on the speed of sound, the speed increases by about 0.61 m/s for each 1^{o}C increase in temperature of the air [7]. Sound wave travels faster in solids than in air, for example, the speed of sound in a brick is 11 times higher than that in the air.

Therefore, the relationship between the speed of sound c, the wavelength λ and frequency f is given by:

$$c = f\lambda \tag{1}$$

Sound Pressure can be defined by considering a point in the space near the sound source, for example, a speaker [7]. At a point of observation, before the passage of the sound waves, the atmospheric pressure is denoted by **P**. Then when the sound waves pass the point of observation, the additional pressure P (the sound pressure) is given by:

$$\mathbf{P} = p_{o}\,.\sin(2\pi f)t \tag{2}$$

Where, p_o is a constant called the pressure amplitude. The ***sin*** part comes from the fact that the wave motion is described by a ***sin wave*** in a simple harmonic motion [7]. Thus, the total pressure at the point of observation is equal to:

$$P + p = P + p_o . \sin(2\pi f)t \tag{3}$$

The audible range of sound pressure ranges from 20 µPa to 20 Pa. On the other hand, the audible range of sound frequencies varies from 20Hz to 20 000Hz (20 kHz). Acoustic waves with frequencies above the audible range are called ultrasonic waves and those with frequencies below the audible range are called infrasonic waves [1].

From elementary physics we learn that *Power* is a product of the *Force* and the *Velocity* of the particle. Hence the power per unit area in a sound wave equals the product of the excess pressure (force per unit area) and the particle velocity. The maximum power per unit area is the product of the maximum pressure variation $Pmax$ and the maximum velocity [25].

Sound Power from different sound sources varies widely. It varies from 10^{-9} Watts (W) for a whisper of the human voice to 20×10^{-6} W during a conversation and this further increases to about 10^{-3} W on average when shouting. The average sound power of a crawler tractor is about 1 W when in operation and that of a large rocket engine is about 100 MW on average [7].

Audible sound varies from 10^{-12} W/m^2 (a millionth of a millionth per square meter) to 100 W/m^2, which is approaching the pain threshold. Therefore, the sound intensity (I) is a useful quantity as it relates to the sound power of the noise source, and is one of the important factors in determining loudness of the sound [1].

Acoustic Impedance

Acoustic impedance (z) is the ratio of the sound pressure, p, averaged over the surface to the volume velocity, v, as given by Equation 4. The volume velocity is the product of the surface area and acoustic particle velocity.

$$z = p/v \tag{4}$$

Specific acoustic impedance is defined at a point in a sound field, which is a ratio of sound pressure to the acoustic particle velocity; expressed in ($kg.m/s^2$).

Sound Absorption

Sound absorption occurs when sound energy is dissipated from a sound wave and is converted to heat resulting from a frictional process. The normal energy content of a sound wave is usually very small and as such the increase in temperature due to sound absorption is very negligible. Sound absorption can be thought of as a frictional process occurring between vibrating molecules when the sound is transmitted through the medium. Frictional processes occur in vibrating bodies as well, like panels but in these cases the energy loss is referred to as ***damping.*** Sound absorption can occur within the transmitting medium or at the interface with another medium during reflection and scattering. Further discussion on sound absorption will be presented in Section 2.2 on noise control.

Sound Diffraction

Diffraction occurs when the sound wave interacts with a solid object. Like in the case of light, diffraction can be described as the bending of the sound waves around the corner; see illustration in Figure 2.3; however its presence in sound is not readily obvious and can thus remain unnoticed [1, 25]. There are two main considerations in studying or observing diffraction. The first one is to understand what happens when a sound wave meets an obstacle in its path, i.e. to what extent the sound is scattered or bent around or reflected by the object? The second consideration is to understand radiation of the resulting sound waves by the vibrating object. Therefore, sound diffraction is useful in determining:

- the efficacy of noise barriers,
- the directionality of the noise source,
- the directionality of noise receivers, including microphones and human hearing, and
- scattering of sound by objects including sound receivers.

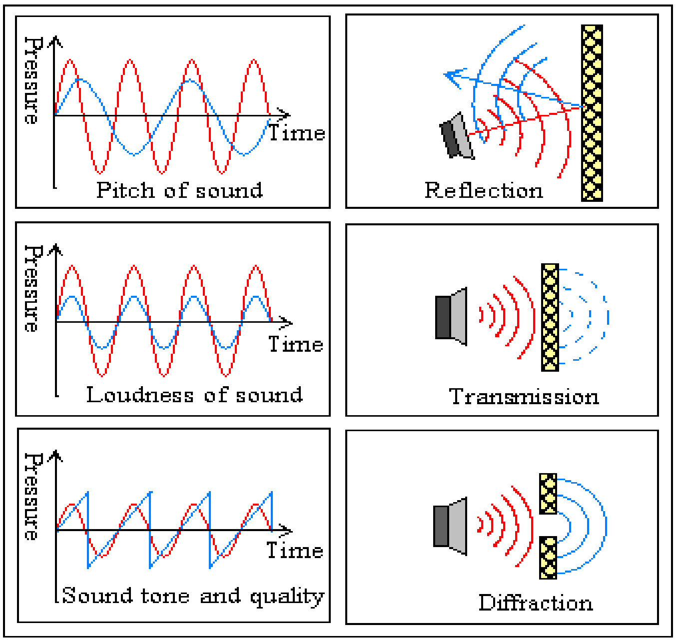

Figure 2.3: Sound pressure in reflection, transmission and diffraction [27]

The main issue in diffraction is the value of the ratio of the size of the obstacle (D) to the wavelength of incident sound, λ. It should be remembered that sound wave lengths vary in the region of 17mm to 11m. If the size of the obstacle (D) is much greater than the wavelength, i.e. D/ λ >> 1 then the objects casts an **acoustic shadow** 'behind' itself (relative to the direction of propagation) [4], as shown in Figure 2.4 below. The regions on this acoustic shadow are effectively shielded from the propagation of sound since some sound waves are reflected from the surface of the object facing the incident sound waves.

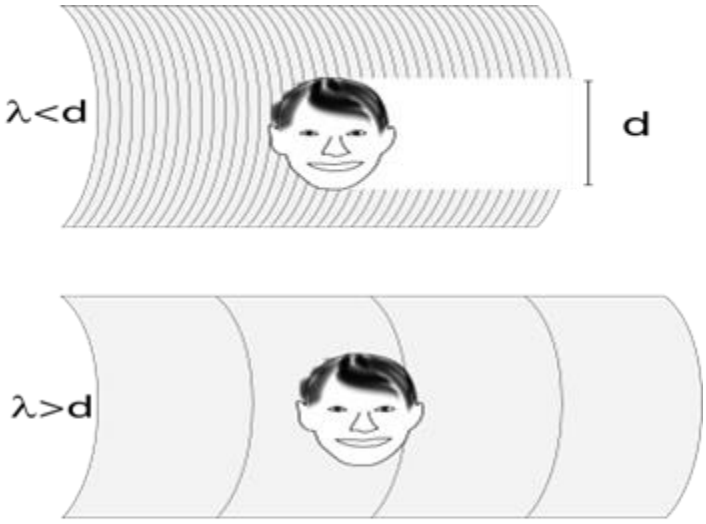

Figure 2.4 Illustration of the Sound (Acoustic) Shadow [44]

If the size of the object is much smaller than the wavelength of the incident sound wave, i.e. D/ λ << 1, then the sound waves are almost completely unaffected by the object. There may be some scattering of the wave but little or no shielding effect, i.e. no acoustic shadow is created [4].

If the size of the object is similar to the wavelength of the incident sound, i.e. $D/\lambda \approx 1$, the interaction between the sound wave and the object is very complex and the theory is covered at length in the study on physics of sound [1, 25].

Sound Reflection

Reflection is actually a special kind of diffraction; see illustration in Figure 2.3 above, when sound waves encounter an object which is relatively larger than the wavelength, and then sound is reflected. If the reflecting surface is flat and smooth then **specular reflection** occurs, i.e. the angle of incidence is equal to the angle of reflection. In the case of a rough surface, the **diffuse reflection** occurs with sound being scattered in all directions [1]. Similar to light waves, a concave surface can cause sound waves to be focused on one point and a convex surface can cause dispersion of sound waves.

When sound waves encounter two consecutive media, sound waves are reflected by the first medium but some sound energy will be transmitted into the second medium, this is called **partial reflection.** The greater the change in specific acoustic impedance, the higher is the fraction of reflected sound energy. For instance, specific impedance values of air and water at room temperature are about 415kg.m/s^2 and 1.5 million kg.m/s^2, respectively. Therefore, given this large difference between the two specific acoustic impedances, it can be expected that most of the sound energy will be reflected at the air-water interface, and only a small proportion will be transmitted [1].

The fraction of sound energy, $\boldsymbol{R}$, which is reflected at an interface between two media with acoustic impedances z_1 and z_2 is given by:

$$R = \left[\frac{(z_1 - z_2)}{(z_1 + z_2)} \right]^2 \qquad (5)$$

In the above example of water and air media, the fraction of sound energy reflected will be 0.998899272, therefore, the fraction which is transmitted is (1- 0.998899272) [1]. In decibels, this means that when a sound wave in air arrives at an interface with water, the level of the sound wave transmitted into the water will be almost 30dB below that in the air; the opposite is true if the direction of the wave travel is reversed.

2.1.4. Sound Levels-The Decibel Scale

The range of sound pressures encountered in addressing noise control is so wide that it is convenient to introduce a quantity termed *sound pressure level* which is proportional to the logarithm of the sound pressure, since the logarithmic scale allows plotting a wide range on a graph [7]. In this case *level* means the logarithm of the ratio of a given quantity to a reference quantity of the same kind. Therefore, the base of the logarithm, the reference quantity and the kind of level must be indicated. The term *level* indicates that a logarithmic scale is being used and the units are expressed in decibels (dB) [25].

The decibel scale is used for comparing and measuring acoustic powers and related quantities, such as sound intensity and sound pressure, so it is necessary to explain the relationship between these two quantities. Although, sound intensity is important as the basis of calculations for many predictions, sound pressure is a more useful quantity in practical terms, and it is always measured using the microphone of the sound level metre

[1]. The intensity of sound (I) at a point is proportional to the square of the sound pressure (p) at that point:

$$I \, \alpha \, p^2 \tag{6}$$

Therefore, if the sound pressure is doubled, the intensity increases four times. Now, in decibel scale, when comparing two sounds, with respective intensities I_1 and $I_{2,}$ it can be said that I_2 is N dB above I_1, where:

$$N = 10 \log (I_2 / I_1) \tag{7}$$

A similar scale may be used to compare the sound power outputs (W_2 and W_1) from two noise sources, i.e.

$$N = 10 \log (W_2 / W_1) \tag{8}$$

Now since sound pressure is related to sound intensity as discussed above, then two sounds with sound pressures p_1 and p_2 may also be compared on the decibel scale [28].

$$N = 10 \log (I_2 / I_1) = 10 \log (p_2 / p_1)^2 = 20 \log (p_2 / p_1) \tag{9}$$

Therefore a 20dB noise reduction, typically achieved by a single glazed window for example, corresponds to a 100 fold reduction in sound intensity, and the 50 dB sound insulation which is typically achieved by a masonry wall means that the wall only transmits one part out of 100 000 parts of incident sound energy.

The decibel scale, which is logarithmic, is convenient because a very large range of audible sound pressure (5 million: 1), which corresponds to an even larger range (25 million: 1) is compressed into a much more manageable range of about 120 dB, for a sample of typical noise levels in decibels, see Figure 2.5. It should be noted that the human response to sound is also logarithmic with each 10-fold increase (i.e. 10dB) in sound intensity being judged, on average, to double the loudness. So, a 100-fold increase, i.e. 20 dB would produce a fourfold increase in loudness and a 1000-fold increase (30 dB) will increase the loudness by a factor of 8 [1].

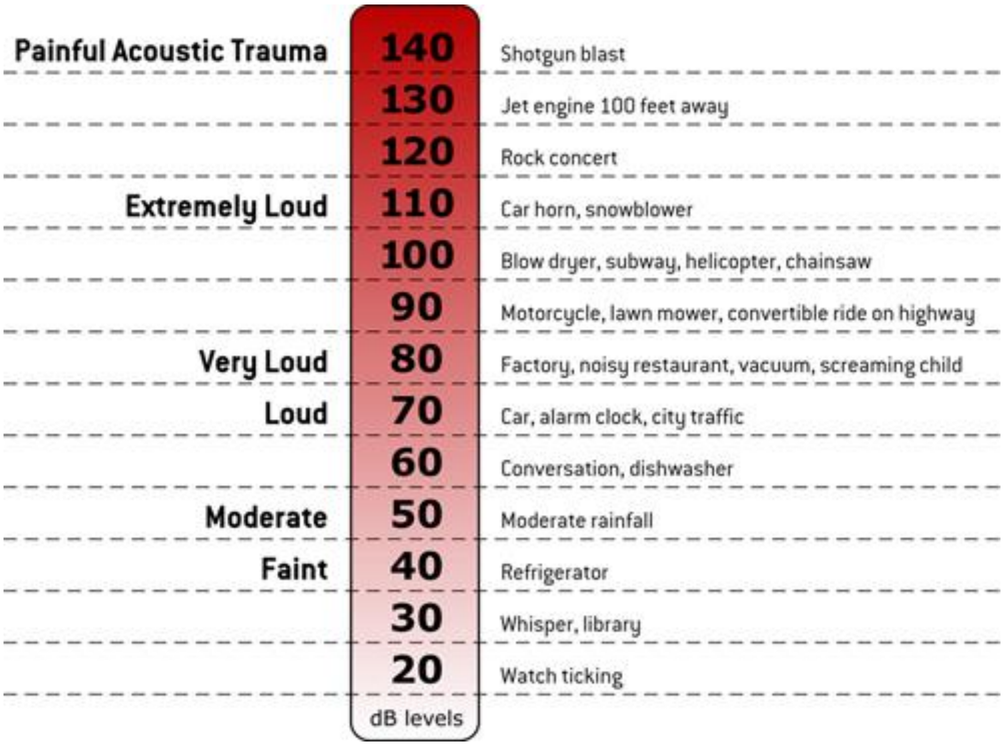

Figure 2.5 Noise comparisons in decibels [29]

When it is said that sound source A is 10 dB noisier than another sound source B, it is a relative use of the decibel scale without assigning an absolute value to either of the two levels. The use of internationally agreed reference levels gives an absolute value to quantities measured on a decibel scale.

The reference value of sound pressure, p_0 , is 2×10^{-6} or 20 micropascals, which represents a threshold for an average young person with normal hearing corresponding to 0 dB. Values measured on a decibel scale relative to this value are called sound pressure levels, and denoted by the symbol SPL or L_p, the reference value, $W_{0,}$ for the sound power level scale (L_w) is 10^{-12} W, and for the sound power level scale (L_I) the reference value (I_0) is 10^{-12} W/m^2 [1].

$$L_p = 20 \log (p/p_0)$$

$$L_I = 10 \log (I/ I_{0)}$$

$$L_w = 10 \log (W/W_0) \tag{10}$$

These scales represent three different physical quantities, i.e. sound pressure, sound power and sound intensity, although they are all measured in dB. It can be understood from the context which one of these three quantities is being referred to, however sometimes it may be necessary to specify them explicitly.

2.2. Noise Control

Various methods for reducing noise in the source-transmission path-receiver model are available; however, treating the transmission path is usually the most viable approach. However, it is not always difficult or unviable to treat the other two elements, i.e. source and receiver. It is important to understand the mechanism of noise generation at the source, i.e. what is it exactly that is making the noise, and the underlying principle at work. By this approach, it is possible to respond with an effective method to reduce the noise. Some simple methods based on common sense relating to general housekeeping also may be employed to reduce noise or its effects. Four standard techniques for reducing noise in the transmission path are employed as already discussed in Section 1.2., i.e., the use of sound absorbing and/or sound insulating materials for reducing airborne sound and the use of vibration isolation and damping for reducing structure borne sound. Sometimes it may be necessary to treat the receiver (of noise) element as well, for example, the use of personal ear protectors, such as ear-plugs and headphones/earmuffs.

2.2.1. Noise Control at the Source

There are two main considerations of noise sources which must be examined. Firstly, the extent, type and manner of noise emission must be known before any meaningful assessment of its effect can be attempted. Secondly, it is important to know whether it is practical to reduce the noise output at the source without reducing its effectiveness and causing malfunctioning, i.e. easy break-down [1].

Although there are many technical solutions, much can be done to avoid noise problems by good noise control management. Some of the common measures are as follows:

- Avoid making unnecessary noise, for example when leaving machines running even though not required.
- Select the quietest procedure when alternatives exists.
- Arrange regular maintenance of machines and noise control equipment to avoid unnecessary increases in noise levels.
- Educate, inform and train people so that they are aware of the purpose of noise control equipment and how it should be used.

The other approach in dealing with the noise problem at the source is to modify the source itself so as to reduce the noise it emits. In this approach, the main aim is to reduce the noise resulting from vibrating surfaces by controlling the amplitudes of vibrations. The possible solutions here are stiffening or damping the vibrating surfaces, otherwise, other options could be isolation or shielding (acoustic lagging) of moving parts.

Increasing stiffness of the vibrating panel may improve the efficiency of noise, however, the most effective method is to increase its damping rather than to stiffen it particularly for a thin panel. However, for very stiff panels, damping may not be effective since the damping mechanism requires a large amplitude of vibration to convert vibration energy into heat.

If the panel is already very stiff, it is an efficient sound emitter; further stiffening will reduce vibration amplitudes and levels of noise emissions. The best approach for a stiff panel is to isolate them from the surrounding framework so as to prevent the vibration producing forces from reaching the panel, see Figure 2.6 below.

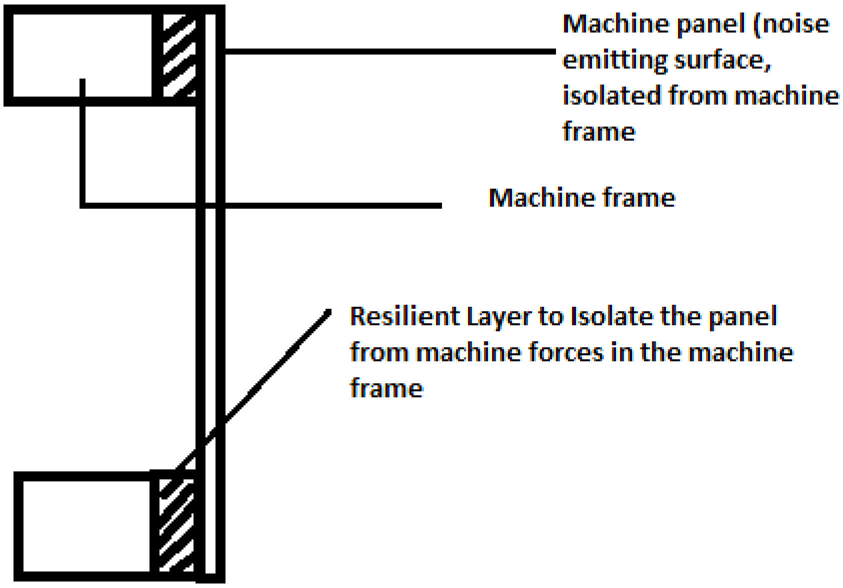

Figure 2.6 Isolation of a stiff panel from a machine frame

The last option is to close shield or cover the panel with an acoustic lagging material positioned very close to the noise emitting surface, as shown in Figure 2.7. The shield consists of a layer of light resilient material attached to a second layer of heavier material; the resilient material may be a synthetic foam or fibrous material such as mineral wool. The shield acts in different ways, such that, depending on the frequency of emitted sound, it acts as a sound insulator, a sound absorber, vibration isolator and a dampener.

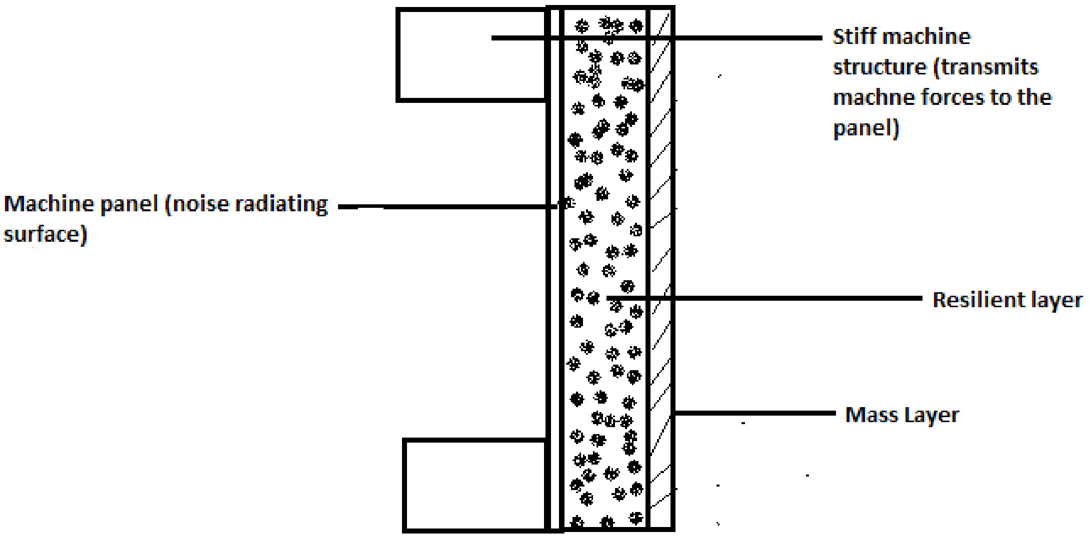

Figure 2.7 Close shielding or acoustic lagging

2.2.2. Control of Noise in Transmission

After the sound has left the source, the next opportunity to minimise the noise is to attenuate it in transmission before it reaches to receiver. The transmission could be either airborne or structure-borne or both, there are methods for treating each transmission type, i.e. sound absorption or insulation for airborne noise or vibration isolation and damping for structure-borne noise.

a. Sound Absorption

It is the property of a material to absorb sound, by converting sound into a small amount of heat energy. When sound waves strike the surface of the material, a fraction of the incident energy is absorbed by conversion to heat. All materials absorb sound to some extent, however, a material is referred to as an acoustic material only if it is able to absorb a large fraction of the acoustic energy which strikes it [7, 25, 28].

The porosity of an acoustic material is the most responsible attribute for the dissipation of sound energy. The pores may be formed by a felted mineral, fiberglass or staple fibres, by interstices between small granules or by a foamed composition in which the solidified bubbles interconnect throughout the material. When a sound wave enters a porous material, the amplitude of vibration of the air molecules is progressively dampened by friction against the surfaces of the fibres or particles forming the porous structure [5].

Another factor affecting sound absorption properties is the thickness of the acoustic material, particularly when dealing with low frequency sounds. A similar factor to this is a case when there is an air space or gap between the acoustic material and the rigid backing. When the thickness of the air-gap is less than a quarter of the wavelength, then the sound absorption at low frequencies decreases with decreasing frequency. The frequency $\boldsymbol{f}$ (Hz) below which the absorption decreases is approximated by:

$$f = \frac{c}{2d} \tag{11}$$

Where, c is the speed of sound and d is the thickness of the air gap. Thus an air-gap of at least 10.2 cm is necessary to maintain a high level of sound absorption particularly at low frequencies [7].

When a beam of incident sound is striking a wall, the sound energy will be reflected back, transmitted through the wall or absorbed within the wall or within an acoustic lining applied to the wall. Let the incident sound intensity be I_i , and the reflected sound intensity, absorbed sound intensity and the transmitted sound intensity are denoted as I_r , I_a and I_t. respectively, then [1]:

$$I_{\mathrm{i}} = I_{\mathrm{r}} + I_{\mathrm{a}} + I_{\mathrm{t}} \tag{12}$$

The fractions of sound that are reflected (r.) and transmitted (t) can then be given by:

$$r = \frac{I_r}{I_i} \tag{13}$$

$$t = \frac{I_t}{I_i} \tag{14}$$

The coefficient of sound absorption is defined differently when compared to coefficients of reflection and sound transmission intensities described above. The absorption coefficient (α) is a fraction of incident sound intensity which is either absorbed or transmitted, i.e. the fraction of incident sound intensity, which is not reflected [1].

$$\alpha = \frac{(I_a + I_t)}{I_i} \tag{15}$$

Which becomes [1]:

$$\alpha = 1 - r \tag{16}$$

The sound absorption co-efficient then varies between 0 and 1, 1 being a perfect absorber and 0 being a perfect reflector, i.e. no absorption.

The noise reduction coefficient, NRC (or NAC) of a material, is a single value expressed as an average of the absorption coefficient of the material at specific frequencies. Noise reduction coefficients are specified for the materials employed in noise control applications. However, at low or very high frequencies, it is better to use the absorption coefficient at that particular frequency for comparing different materials as the use of NRC may become misleading, a material can have a high NRC value but may have low absorption coefficient at low or very high frequencies [7].

It should be noted that sound absorption coefficient varies with variations in sound frequency, incident angle and the type of mounting used. It is necessary to note these parameters when reporting sound absorption coefficients of the material.

There are three main types of sound absorbing materials, namely, porous, panel/membrane and Helmholtz/cavity absorbers. Porous absorbers work over a wide range of sound frequencies, although they are much more effective at high sound frequencies than at low sound frequencies, while the other two types are effective only over a limited range of sound frequency centred around the resonance frequency of the sound absorption material.

b. Sound Insulation

Sound insulation, like sound absorption, is also a method of dealing with airborne noise. When sound waves with varying sound pressures strike the insulation medium then it vibrates, a fraction of the vibrational energy carried by the sound wave is transferred through the medium and causes it to vibrate and thereby sets off the air on the other side to start vibrating and thus transferring sound [7].

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The structural characteristics of the partition such as density and thickness, determine its effectiveness in insulating noise. In many cases the structures of the partitions are complex, they consist of layers of different materials and cavities and thus some of the energy of the sound wave dissipates within the partition and thereby reducing the transfer of sound energy on the other side [7].

Sound Transmission Loss (STL) is the ratio of the sound energy incident on the partition to the transmitted sound energy, expressed in decibels (dB). Therefore, lower the sound energy transmitted higher is the transmission loss.

c. Vibration Isolation

Structure borne noise originates from the vibration of structures, these vibrations can propagate in the structure to various locations with very little attenuation and thereby cause surfaces to vibrate and create airborne noise [7]. Structure-borne noise is caused by forces acting on the structure. These vibrations can be caused by steady state sources, for example, air-conditioners and fans, and impact of sources, such as slamming of doors or dropping of objects [7].

The principle of vibration isolation is simply to reduce the amplitude of vibration of a vibrating system. In order to achieve significant amount of vibration isolation, the value of the vibration frequency, f, should be at least 3 times that of natural frequency, f_0, of free and natural vibrations [1].

A wide range of materials can be used as vibration isolators depending upon the specific frequency range of the vibrating system. For high frequency (25Hz and above) vibrations, where static deflections are very small, typical vibration isolators include cork, cork composites, felts and foamed plastics. These materials derive their elasticity from the air they contain within their internal cavities and they should be used in compressed state.

In the mid-range of vibration frequency (5-35Hz) rubber and elastomer materials in a wide variety of shapes, are used in compressed state for vibration isolation. In the low-range vibration frequency (2-15Hz) where mostly static deflections occur, metal springs are commonly used. The advantage of the metal springs is that they can be designed into various shapes and levels of stiffness and are thus able to withstand heavy loads, however, springs are not suitable for higher frequency vibration systems since the high frequency vibration can travel along the coils of the spring.

d. Damping

Damping is a mechanism occurring between the components in a vibrating system which leads to a conversion of vibrational energy into heat energy and a reduction in the amplitude of vibration. Strictly speaking, every system has some damping mechanism; otherwise there would be perpetual motion or vibration [1].

Hysteretic damping occurs within materials depending on their atomic, molecular and crystal structure, it results from phase changes between stress and strain occurring during vibration. Friction damping occurs because of mechanical contacts between components. Viscous damping occurs if a mass-spring system is fitted with a dashpot where a plunger moves through a viscous fluid (commonly seen in physics and basic mechanics textbooks) [1].

2.2.3. Noise Control at the Receiver

Noise control at the receiver is in fact hearing protection. Generally, this should be the last resort as a method to control noise when the other two approaches (at source and in transmission) have been ineffective or are not practical.

Various types of earmuffs are being used for hearing protection. The main types are: (i) Moulded plastic cups which fit over ears with sound absorbing foam plastic fitted in each cup to minimise vibrations. (ii)Alternatively, flexible plastic cushions are fitted, which enable tight fit of the cups over the ears to minimize leakage of sound around the cups into the ear with adjustable elastic. (iii) Flexible headband which holds the cups in place and helps the cushions to seal around the ear.

For specialised applications, such as in situations with sudden burst of noise, specially developed ear muffs are utilised which allow only low amplitude sound (e.g. from conversation) but prevent transmission of high intensity sound [1].

2.3. Porous Sound absorbing Materials

Porous sound-absorbing materials are capable to absorb a sizable amount of sound energy striking them and reflecting very little sound. Therefore, these materials are very useful for controlling noise. A wide range of sound-absorbing materials exists and their sound absorption properties depend upon sound frequency and composition, thickness and surface finish of the material and method of mounting. However, materials showing a high value of sound absorption coefficient are usually porous [30].

In most cases, sound barriers are confused with sound absorbing materials. Generally, materials providing good sound absorption are poor sound barriers. Unlike barriers and damping materials, the mass of the material has no direct effect on the performance of the sound absorption materials [31].

Porous materials for sound absorption can be classified as cellular, fibrous, or granular according to this is based on their microscopic compositions and configurations. Porous materials are characterized by the fact that their surfaces allow sound waves to enter the materials through a multitude of small holes or openings.

Materials produced from open-celled polyurethane and foams are examples of cellular materials. Fibrous materials consist of a series of tunnel-like openings which are formed by interstices of fibers. Fibrous materials include those made from natural fibres, such as cotton, flax and wool and synthetic fibers such as glass and mineral fibres [32].

The granular porous materials for sound absorption are made up of consolidated granules. These materials consist of relatively rigid, macroscopic granules whose dimensions exceed those of the internal voids. Unconsolidated granular materials consist of loosely packed assemblages of individual granules [30]. Granular sound absorbing materials include some types of asphalt, porous concrete, granular clays, sands, gravel, and soils [33-34]. So the acoustic properties of granular materials are important in controlling sound propagation in outdoor environment [30].

2.3.1. Cellular Porous Sound Absorbing materials

Polyurethane and melamine foams are commonly available cellular porous materials for sound absorption. However, other types of foams have been designed for applications where heat and corrosion resistances are required in addition to sound absorption. Metal foams are relatively new materials which have proven to be suitable for manufacturing lightweight structures, biomedical implants, filters, heat exchangers, sound absorbers and mechanical damping devices [30]. Aluminium foams have traditionally been the most commonly used materials for sound absorption. Metal foams exhibit high stiffness, low weight, good fire resistance and low moisture absorption. Metal foams though relatively more expensive than synthetic foams; they can be recycled after use [30].

Ceramic foams are excellent alternatives to metal foams particularly for high-temperature applications. These foams can be produced in a similar way to polyurethane foams with a network of interconnected open cell walls. They are usually made of silicon-based elements. However, it is also possible to find foams made of other ceramic core elements, such as zirconium, titanium, and boron.

The porosities of ceramic foams range from 80% to 90% and can withstand temperatures above 1500° C. However, new ceramic foams made of aluminium oxide provide higher porosity values of above 94%. Currently, ceramic foams are used extensively in aerospace and industrial applications, such as rocket nozzle components, composite panels, heat shield elements, and acoustic liners in aircraft mufflers [30].

Aerogels are another type of microporous materials used in hi-tech applications [30]. Aerogels are also known as frozen smoke and have been claimed to be the best thermal insulators ever made, about 40 times better than common fiberglass insulation materials. Aerogels are produced by removing the liquid content from gel by a super critical drying process. Aerogel has a monolithic internal structure, which is made-up of a highly porous, extremely lightweight and translucent material in which most of its volume is filled with air [30].

Many different types of raw materials have been used to produce aerogels, but silica aerogels are the most common. Its structure is composed of small spherical silicon dioxide clusters of 3-4 nm in diameter which are interlinked to form chains consisting of a spatial grid with air-filled pores [35]. The typical average size of the pores in aerogel is 30 to 40 nm with porosity value greater than 75% and melting point of 1200° C.

One of the biggest disadvantages of aerogels is that they are very expensive and primarily utilized in high-tech aerospace missions by the National Aeronautics and Space Administration (NASA) in the USA. However, recent research is focused on their use in granular form as sound-absorbing materials, where their mechanical properties lie between that of a gel and a granular material. Experimental results of multilayer sound absorbing panels made of silica aerogels have been presented elsewhere in some published work [36].

2.3.2. Granular Porous Sound Absorbing Materials

Most of the outdoor noise emitted by modern cars and trucks, particularly at medium to high speeds, is attributed to friction between tyres and the roads. The noise level peaks between about 800 and 1,000 Hz, at a somewhat higher frequency in the range of 800 to 1,200 Hz for light and heavy trucks [30].

One way to reduce this noise is to create porous surfaces on the paved roads which can be classified as granular sound-absorbing material. Such porous surfaces offer an advantage by not only reducing noise generated between tyres and the road, but also attenuate it by absorption of sound before it propagates to nearby residential areas. This method is also adopted for noise control in the power plants. Such porous surfaces on the paved roads offer a further advantage of effective rain-water drainage and reduced splashing [37]. The sound absorption of porous surfaces on the paved roads is affected by several geometrical and other parameters of the road pavements, namely:

- Thickness of the porous layer
- Air voids or road surface porosity
- Air flow resistance per unit length
- Tortuosity
- Coarseness of the aggregate mix (small or large aggregates, etc.)

For most common dense asphalt mixes, the air void is about 5%, while for new porous mixes, it varies from about 15 to 30% [37]

2.3.3. Porous Fibrous Materials

Most commercially available porous sound-absorbing materials are fibrous and they are manufactured from continuous filaments or staple fibres to develop pores with air entrapped within them. They are produced in rolls or in slabs with different thermal, acoustic, and mechanical properties. The fibres used can be either natural or synthetic (manmade). Natural fibres can be plant based (e.g. sisal, kenaf, hemp, flax, cotton, wood, etc.), or animal based (e.g. wool, fur felt). Synthetic fibers can be cellulose (viscose, for example), mineral (fiberglass, mineral wool, glass wool, graphite, ceramic, etc.), or polymer (polyester, polypropylene, Kevlar, etc.) based.

Synthetic fibrous materials made from minerals and polymers are the most widely available and therefore they are more common in sound absorption and thermal insulation applications. However, since they are made from high-temperature polymer extrusion and industrial processes based on synthetic chemicals, often from petrochemical sources, they have a significant carbon footprint [30].

In recent years, a steady increase in the use of natural fibers in manufacturing sound absorbing materials is witnessed [38-41]. Natural fibers are essentially completely biodegradable and modern technical developments have made their processing more economical and environmentally friendly. These new manufacturing techniques may result in increased use of natural fibers in producing industrial products at competitive prices. The sound absorption properties of the materials made from natural and synthetic fibres can be similar to those made from mineral fibers [30]. These properties can be modified by pre-treatments such as drying, carbonizing, impregnation, and mineralization. In addition, natural fibers are also safer for human health in comparison to most mineral and synthetic fibers, and they do not need additional precautions in handling.

Materials for thermal insulation and acoustic absorption produced from a blend of kenaf and polyester fibers, treated with a natural fire retardant, are commercially available commercially [41]. Sound absorption materials produced from natural fibers, such as hemp and kenaf can be disposed of easily, and their production involves a low carbon footprint and no chlorofluorocarbon (CFC) emissions, so they can be classified as ecologically green building materials. Therefore, they provide an alternative to building materials produced from harmful chemicals, polymers, and other non-sustainable synthetic materials.

2.3.4. Smart Sound Absorbing Materials

A recent development in the noise control sector is to develop hybrid sound absorbers by combining active noise control mechanisms with passive control methods [30]. Active control technologies appear to be the only effective way to attenuate the low-frequency noise components. Therefore, the hybrid sound absorber can absorb the incident sound over a wide range of frequencies. Figure 2.8 shows the principle of such a device, which combines passive absorbent properties of a porous layer and active control at its rear face, where the controller can be actuated using digital techniques [42-43].

Thin active liners composed of several juxtaposed cells of absorbers for reducing noise in flow ducts have been designed using a piezoelectric actuator as a secondary source (active sound absorption) and wire meshes as porous material (passive sound absorption). Recent research is aimed at producing a broadband (wider range of sound frequency) sound absorber known as smart foam, which is a hybrid active-passive sound-absorbing material [43].

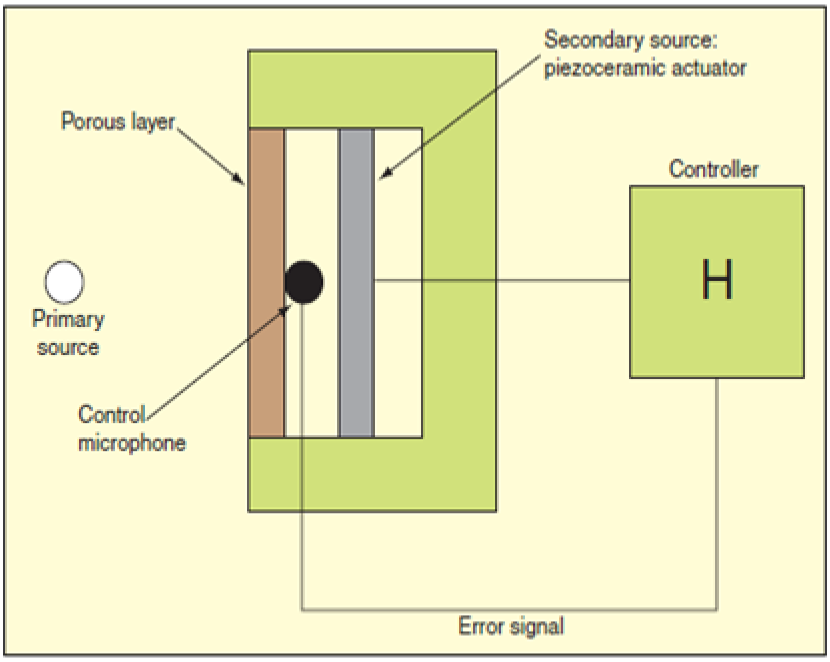

Figure 2.8. Hybrid passive/active absorber cell [30]

This sound absorber is typically made of melamine foam (made of melamine resin, which is a thermoset polymer) with polyvinylidene fluoride (PVDF) piezoelectric-film-embedded actuators. Such composite materials provide high sound absorption properties at middle and high frequencies due to passive properties of the melamine foam, while the low frequency sound absorption is affected by a cancellation mechanism of the active controllers [30].

2.3.5. Nonwoven Fabrics as Sound Absorbers

Nonwoven fabrics, which are porous fibrous materials, are widely employed in noise reduction application. Nonwoven fabrics offer some advantages over cellular and granular sound absorbers (foams and asphalt), such as low production costs and low specific gravity. Nonwoven fabrics produced from natural fibres, in particular, are more environmentally-friendly than conventional polyurethane foams used for sound absorption as the latter are not recyclable and they are produced by environmentally harmful manufacturing processes [18].

Nonwoven fabrics produced from polyester fibres are increasingly replacing glass fiber mats due to health and safety concerns regarding the handling and use of glass fibres [45]. These materials are used in trims of passenger vehicles [12, 46], interior linings for insulations of apartments, aircraft, and ducts, as enclosures for noisy equipment, and as insulations for appliances [47].

2.4. Different Types of Nonwovens

Nonwovens are generally classified by the bonding technique employed to produce the fabric rather than the web formation method; this is largely due to the fact that different bonding techniques can be applied with any particular web formation method. Also, web bonding techniques employed significantly influence the properties of the fabric in comparison to the effect of the web formation methods.

2.4.1. Mechanical Bonding Methods

There are three main types of mechanical bonding methods, namely, needlepunching, stitch bonding and hydro-entanglement.

a. Needlepunching

The needlepunching process will be discussed in detail in section 2.5.

b. Stitch Bonding

In Stitch bonded fabrics the fibres and/or yarns are held together by stitching or knitting-in with additional yarns. In the most common cases, it involves warp knitting of yarns through a fibrous mat [8].

Few stitch bonded fabrics are included in the industry definition of nonwovens since many of them include preformed and ground fabrics. A number of different stitch bonding systems have been developed and commercially available, which include the Maliwatt and Malivlies, Voltex and Malimo [8].

In the Maliwatt system, polyester filament is mainly used as the stitching yarn. The web component varies between 80-95% and area density ranges from 15-3000 g/m^2, with thickness ranging from 0.5 to 20mm [8]. The main applications of the fabrics include soft furnishings, mattress and bed linen, upholstery, insulating materials and linings. The Malivlies system does not involve any filaments and the fabric comprises of fibres only. Bonding achieved by hooking and looping of some of the surface fibres of the web by the stitching needles. Their area weights range between 120 to 1200 g/m^2. The applications of these fabrics include polishing cloths, filter fabrics, medical and hygiene products.

The Malimo system is very similar to weaving; it involves plain overstitching of loose yarn sheets laid on top of one another (weft and warp yarns – featuring different possibilities for modifications). In this system, various weft insertion techniques, depending on envisaged fabric structure and end-uses are employed [8]. The Malimo bonded fabrics are usd in industrial textiles as reinforcements of composite for high-tech applications (fiberglass, carbon, Kevlar), sandwiched nonwovens, geotextiles, insulating materials, laminating substrates, packing textiles, etc.

Voltex fabrics are characteristically lofty due to high piles. Two preformed elements are involved, i.e. a ground fabric and a web which is continuously fed. As no stitching yarn is required in the process, a continuous Voltex system consists of a web forming process followed by a stitch bonding unit. Voltex Fabrics are used in linings, soft toys, imitation furs, shoe uppers and upholstery [8].

c. Hydroentanglement

Hydroentanglement, also known as spunlacing, is a web bonding technology which uses fine, high pressure water jets to cause the entanglement of fibres. These high pressure water jets re-orientate fibers according to the shape of the support screen (sieve belt or perforated drum). This bonding method can be applied to a wide range of web formation methods producing: carded, spunbonded and meltblown , wetlaid and airlaid webs [8].

The first step in the process is to pre-wet the incoming web to eliminate air pockets. The thin collimated water jets pass through the fibrous web and support screen (one hydroentanglement unit). To obtain better bonding efficiency water is extracted through a suction process from the oposite (underneeth) side of the support screen. The water is then purified and returned to the jet manifold for re-use. The structure of the bonded fabric depends on the parameters of the water jets and the structure of the support screen. It is possible (and often used) to have several consequitive hydroentanglement units for better consolidation of the web. The bonded fabric is then dewatered, dried and wound on a roll.

The main parameters influencing the hydroentanglement process are fiber type, web dimensions and process parameters, such as water jets, speed of the web, shape of the sieve belt of perforated drum, quality of water and the drying process. The water jet parameters include water pressure, density and diameter of jets , distribution (spacing between individual jets), and water suction zone. The quality of water is defined by temperature, surface density, viscosity and pH.

The main features of Hydroentangled fabrics include:

- Very good drape (low stiffness) and very soft handle, simmilar to woven fabrics in some cases.
- No chemical or melt binders needed; it is possible to prepare 100 % natural fibers, ideally suitable for sanitary products.
- A wide range of fabric area weights can be produced as well as high density fabrics compared to needlepunch nonwoven fabrics.
- The fabrics produced by hydroentanglement have reletively high tensile strength, in comparison that of needle-punched fabrics of the same area weight.
- Spunlaced fabrics provide more uniform surface in comparison to that of needlepunched fabrics due to higher entanglement of fibres.

Hydroentangled fabrics are used in the medical sector for producing surgical gowns and various wound dressings. Hygiene uses of hydroentangled nonwoven fabrics include sanitary towels, baby and adult diapers and technical applications include filtration, wipes, linings and insulation [8].

2.4.2. Chemical Bonding Methods

Chemical bonding mainly refers to the application of a liquid based bonding agent to the web. There are many ways of applying the chemical binder. It can be applied by impregnating with a foam or saturation, coating or spraying or intermittently, as in print bonding. The physical properties of a chemical bonded fabric are determined by the fibre, polymer, additives and the interaction between them [8].

a. Foam Bonding

Foam bonding is a means of applying a binder at high binder-solids concentration levels. The basic concept employed involves using air as well as water as the binder diluent and carrier media. Foam-bonded nonwovens require less energy in drying, since less water is used. The foam is generated by introducing air into the formulated latex while mechanically agitating the binder solution. Air/latex dilution ratio in the order of 5:25 is normally maintained for various products [8]. With the addition of a stabilizing agent to the binder solution, the foam can resist collapsing during application and curing, and the bonded fabric will exhibit enhanced loft, handle, and resilience.

b. Saturation Bonding

Saturation bonding is used in conjunction with processes that require rapid binder addition, such as card-bond systems, and for applications which require high fabric strength, stiffness, and maximum fibre saturation [8]. Fibre saturation is achieved by totally immersing the web in a binder bath or by flooding the web as it enters between a set of pressure rolls. Excess binder is removed by vacuum or by squeezing between rolls under high pressure. Three variations of saturation bonding exist, i.e. screen, dip/squeeze, and size-press. Screen saturation is used for medium-weight nonwovens, such as interlinings. Dip/squeeze saturation is used for web structures with enough strength to withstand immersion without support, such as spunbonds. Size-press saturation is used in high speed processes, such as wet-laid nonwovens [8].

c. Spray Bonding

In spray bonding, binders are sprayed onto continuously moving webs. Spray bonding is applied for high loft or bulky fabrics, such as fiberfill and wipes made from air-laid pulp. The binder is atomized by air pressure, hydraulic pressure, or centrifugal force. The spraying is applied to the upper surface of the web in fine droplet form through a set of nozzles. Addition of a binder on the other side of the web is accomplished by reversing web direction on a second conveyor and passing the web under a second spraying station [8].

d. Print Bonding

Print bonding applies binder on a specific pattern in only predetermined areas. It is useful for applications that require a part of the area of the fabric to be binder-free, such as wipes and coverstocks. Many lightweight nonwoven fabrics are print bonded. Printing patterns are designed to enhance strength, fluid transport, softness, hand, absorbency, and drape.

2.4.3. Thermal Bonding Methods

Thermal bonding methods use the thermoplastic properties of synthetic fibres to form bonds under controlled heating. In some cases conventional synthetic fibres can be used, but more often a low melt or bi-component fibres are blended during web formation stage to perform thermal bonding subsequently. Several thermal bonding systems are available, namely, powder, through-air and calendar bonding.

a. Powder Bonding

In powder bonding, the adhesive powder of thermoplastic polymers is applied onto webs. Polyesters and polyolefin resins with low glass transition temperature (T_g) and low molecular weight can be used in powder foam as binders. Powder bonded fabrics are typically bulky. The disadvantage of this bonding method lies in difficulties of suitable particle sizes and ranges in comparison to fineness of the fibres in use, and particle distribution during powder application [8].

b. Through-Air Bonding

Through-air bonding technology is ideal for air-permeable products such as thermos-fused nonwovens. In the through-air bonding technology, heated air is circulated in the enclosed chamber through a perforated plenum mounted above the product line in one section of the machine and the other mounted below the product line in the second section. A suction plenum beneath the line (and above the line in second chamber) pulls hot air through the product and the conveyor to facilitate high heat transfer throughout the fabric. Heat transfer is almost instant and thorough along the thickness of the product.

The temperature of the air is set above the melting temperature of the thermoplastic fibres, so that the molten fiber bonds to other fibers and interconnects with them. In the case of bi-component fibers, where the outer layer is of one component with a lower melting point polymers and the inner part made from a different high melting polymer, then only the outer shell of the fiber is molten to bond, thus giving even better stability to the nonwoven. Three main operating parameters, namely the energy distribution, temperature profile, and air velocity in the oven influence the thermal bonding process. Nonwovens made of through-air thermal bonding process find their applications in various fields, such as upholstery padding, mattress protection, thermal and sound insulation, protective and wrapping material [8].

c. Calendar Bonding

Calendar bonding is a process in which a fibrous web containing thermoplastic fibres (could also be powders or films) is passed through a pair of heated rollers pressed against each other. As the web passes through the nip of the rollers, the fibres are both heated and pressed. Three main types of calendar bonding are: area bonding, point bonding and embossing.

In area bonding, the bonding occurs at the surface of the metal roll, heated by conduction from oil circulated through its centre. The composition rolls obtain heat through contact with the heated metal roll. Before the start of a production run, the roll stacks are operated until the composition rolls achieve dynamic heat equilibrium. Pressure is also an important consideration; it is applied simultaneously with the heat. The application of heat causes the thermoplastic fibres to become softer and the applied pressure enhances mechanical bonding by forcing the binder polymer to flow in and around the carrier fibers [8].

Point-bonding calendaring process is mostly used to thermally bond disposable fabrics such as those used in diapers, sanitary products, and medical products. This method involves the use of a two-roll set up consisting of a heated patterned (engraved) metal roll and a smooth or sometimes patterned metal roll as well. Depending upon the application of the fabrics, this second roll may or may not be heated. The heating time is typically very short, in the order of milliseconds. The fabric properties are dependent on the process temperature, pressure between the rolls and contact time [8].

The embossing method is a calendaring process for bonding only in the specific area of the fabric, usually also creating (imprinting) figurines. In this case the area bonding is three dimensional. A "bulky but thin" product can be produced in any aesthetic or functional construction, depending on the figures on the embossing rolls. The calendar roll combination has a ‘male’ patterned heated metal roll and a matching ‘female’ patterned felt-covered roll [8].

d. Ultrasonic Bonding

Thermal radiation has been extensively employed in textile finishing processes, particularly as a drying method. A new application of this is in the production of thermal bonded nonwoven fabrics which requires the inclusion of thermoplastic materials (fibers or powders) in the web to be bonded. Unlike in the other thermal bonding methods where heating is affected by conduction and convection which requires a medium, radiation heating does not require any medium [8].

In ultrasonic bonding, heat energy is transferred by high frequency vibration of the web surface. This happens with short contact time and under limited pressure between the ultrasonic horn and the web at an ultrasonic frequency of about 20 000 Hz. Energy is thus transferred to localised areas in the web to induce thermal bonding as the mechanical energy applied to the fibres is converted into heat. Fabrics produced with Ultrasonic bonding technique are characteristically soft, breathable and strong and they are used in producing laminates, quilts and outdoor jackets [8].

2.5. The Needlepunching Process

A needlepunched nonwoven fabric is made from webs or batts of fibres in which the fibres are deflected upwards or downwards by barbed needles, as shown schematically in Figure 2.9. This needling action interlocks the fibres, and holds the structure together. A three dimensional structure is obtained. This method was originally developed for fibres which could not be felted, such as wool. The barbed needles are clamped on a vertically oscillating board between two plates between which the batt is moving forward.

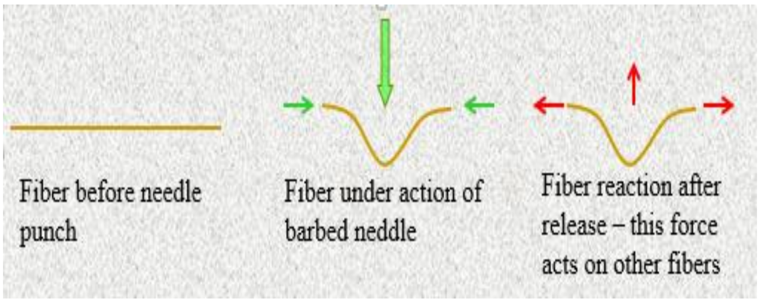

Figure 2.9. Needlepunching action on fibres [48]

The original needlepunched products such as carpet underlay, mattress padding and insulation blankets were made form jute, coir and some waste fibres [8]. The manufacturing process was very dusty until the advent of synthetic fibres, which were relatively clean and easy to process at high production rates.

Needle punching machines are classified as single-board and multi-board. Their configurations and applications vary depending on the end-use of the products. Single board machines are either up-stroking or down-stroking and have one needle beam, as shown in Figure 2.10. Multi board machines can be arranged in different combinations [8] such as:

- Double boards –down stroking
- Double boards – up stroking
- Twin board – two boards up-stroking and down-stroking in the same vertical plane.
- Tandem boards – alternative up and down stroking in two sequential needlepunching zones.
- Four boards or quad-punch – up and down stroking for simultaneous double sided needlepunching with two sets of up and down stroking boards, each set arranged in the same vertical plane.

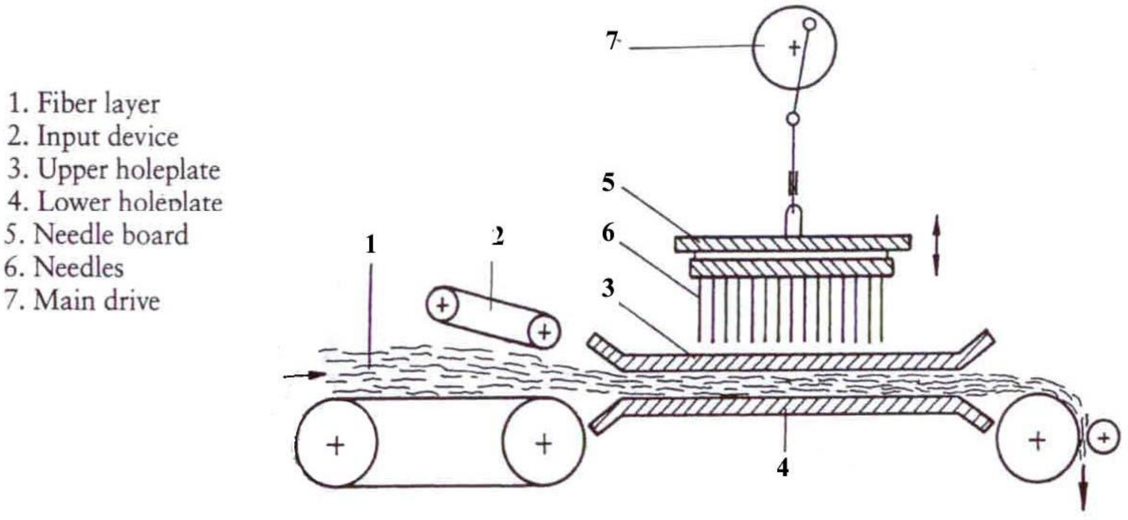

Figure 2.10 Basic parts of a needlepunching machine. [48]

In a basic needlepunching set up like the one described above, and shown in Figure 2.9, the needle loom consists of a heavy metal frame carrying the fixed bed plate and the stripper plate between which a batt is moving forward and vertically reciprocating needle board carrying the needles penetrate in the moving batt to entangle the fibres. Here, significant vibration forces are generated at high speeds which must be absorbed by the sturdy frame.

The low density batt must be supported by aprons or rollers as it is guided through the gap between the bed plate and the stripper plate (Figure 2.10). The gap between these two plates may be adjusted to control the compression of the batt during needling. After needling, the fabric is transported away from the needling zone by take-up rollers [8].

2.5.1. Web and Batt Formation

Among the three main classifications of web formation, needlepunched fabrics are produced mostly from the dry laid batts, formed by carding and garneting, to a lesser extent. Air laying is also used to produce a web but very seldomly. The continuous filament polymer laid webs can also be needlepunched in some cases [8].

The carding process has many variations in terms of the number of cards used. The cross-lapping may also provide flexibility of laydown and fiber orientation in the machine direction and cross machine directions. Cotton cards are sometimes used to manufacture feminine hygiene products from short staple fibres as well as absorbent products for medical applications. However, the use of short staple or cotton cards in nonwovens is not common because the revolving flats limit the maximum width of the card to 1.5 m and the blending capability of the machine is much lower than that of a card equipped with the worker-stripper rollers commonly used in wool processing [8].

Garnett machines together with a cross-lapping unit are mainly employed to process coarse and waste fibres. Air-laying usually provides more isotropic batts without any defined or distinct layers; these batts are also typically more voluminous than carded batts. The main disadvantage of the air-laying system is the low level of fibre opening by the lickerin mechanism [8].

2.5.2. Needle Design Considerations

Various types of needles are used in the needlepunching process; however, no well-defined rules are set about which type of needle should be used for a particular application. The needles differ in the design of length, thickness, cross-sectional shape and the barb (number, projection, spacing and dimensions). This differentiation in features has an important effect on the needlepunching process and the properties of the final product.

The choice of needles is determined by both the desired final product and the fibers, i.e. the thickness and area weight of the fabric to be produced together with the type and fineness of the fibers to be processed. It is important to match the needle type with the correct fabric, production and fiber parameters to avoid damage to the needles and fiber breakage, which in turn adversely affects fabric strength [8].

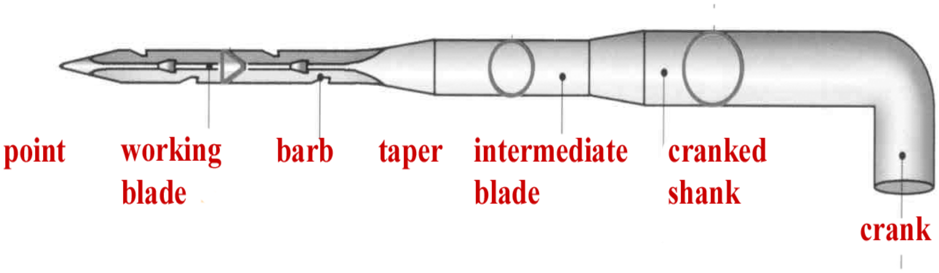

Figure 2.11: Typical Needle Parts [48]

A schematic of a typical felting needle is shown in Figure 2.11 above. It is a double reduction type needle, with a middle or intermediate section which is a transition stage between the diameters of the shank and the blade. There is also another type of needle with a single reduction with no intermediate section. The function of the shank is to hold the needle onto the needle board and the blade is the working part of the needle, it is triangular in cross-section and can vary in diameter. The barbs are formed on the apexes of the blade.

The single reduction type needle is much stiffer than the double reduction type and is suitable for production of thicker fabrics. It is used for punching stiff fibres which include ceramic materials and shoddy fibres where the required needle force is high. Barb spacing is considered in association with the depth of needle penetration. Normaly nine barbs are evenly placed on a blade of 30mm in length in regular needles and other spacings are made for some special applications . Needles with shorter baldes, however, have only six barbs instead of nine, and they are also stiffer and less susceptible to brackages [8].

2.5.3. Fibres for Needlepunching

The needlepunching process is the most versatile amongst different nonwoven bonding methods because of its ability to process a wide variety of fibres. The limit on fiber choice is normally influenced by the type of web formation method. In most operations, carding and cross-lapping machines are used to form webs and subsequently bonded by needlepunching, and to a lesser extent particularly for coarser fibres, garneting is used.

The choice of fibres is dependent on the envisaged characteristics or properties of the fabric to be produced. The cost of the fibres versus the application of the end product should be considered to estimate the cost effectiveness; and the availability of those fibres is also important consideration. Currently, synthetic fibres such as PET and PP are the most widely used fibres in production nonwovens in general and particularly in needle-punching process [49].

PET fibres are suitable for most applications and their costs are comparatively low. PP fibres are largely suitable for manufacturing heavyweight needle-punched fabrics for durable products, such as floorcoverings, geotextiles, filtration media and disposables hygiene products. Viscose fibres are extensively used in medical and hygiene sectors mainly because of its high moisture regain capabilities. Other synthetic fibers such as Polylactic Acid (PLA), nylon and aramid fibres are used mainly in certain specialised applications because they are expensive.

Since the early development of needlepunching technology, nonwoven fabrics were produced from traditional natural fibres like wool and cotton. However, their use in producing nonwoven fabrics has always been limited due to the fact that they are costly for nonwovens in disposable applications, thus adding to the cost factor. The demand therefore, outweighs the supply for these fibres [49]. These factors led to the wide spread adoption of synthetic fibres, in producing nonwovens as they are relatively inexpensive.

Other natural fibres derived from the bast, leaves and fruits of the plant include flax, hemp, jute, sisal, coir, ramie and kenaf, are mainly utilized for certain specialized applications such as geotextiles and paddings [50] largely due to their coarseness and low crimp. Recently, natural fibers like kenaf to produce absorbent nonwovens for cleaning up oil spillage have been reported [50]. Other recent developments on natural fibre based needlepunched nonwovens have been reported for car interiors [12] and as reinforcement in bio-composite applications [51].

Fibre properties directly influence the fabric properties as well as processing performance during fabric production. Processing characteristics, such as web cohesion, fibre breakage, nep formation and web weight uniformity are influenced by fibre diameter, fibre length, tensile properties and crimp.

There are many recently developed fibers whose use in nonwovens has not been widespread due to processing problems particularly during carding. These processing problems include uncontrollable static electricity, low fibre to fibre cohesion and inadequate fibre extension (minimum is 2-5%) leading to fibre breakages and poor yield [8].

The physical properties of the fibres suitable for carding and therefore suitable for needle-punching range from 1-30dtex in fineness and fibre length of 30-100 mm; however this excludes the fibres which require garneting instead of carding [8]. Such a wide range of fibre dimensions therefore requires a variety of needle types, further, also require a variety of roller configuration and layout, settings and the card wire on the carding machine. It would be impossible to process such a wide range of fibre dimensions with one needle type and machine setting. However, fiber blending can be used to minimise the need to change these settings and in some cases carrier fibers are added to help in processing short and stiff fibres.

2.5.4. Applications of Needlepunched Fabrics

A wide range of fibres can be processed on needle-punching technology which results in development of a variety of fabrics suitable for a broad range of applications. These major applications include [5, 8]:

Geosynthetics (Geotextiles)	A fabric used in civil engineering applications, where high tensile strength, deformability and controlled permeability are required. These fabrics are applied in road re-enforcement, sub-soil stabilisation, pond liners and drainage. These fabrics are typically produced by needle-punching of polyester (PET), polyamide (nylon) and polypropylene (PP) fibres.
Filter Media (Liquids and Gases)	The main fabric characteristic for filtration applications are fabric density and permeability. For general applications PET, PP and nylon fibres are used, however, in specialised applications under extreme heat and low pH, for example, other more specialised fibers such as polyacrylonitrile (PAN) and Polytetrafluoroethylene (PTFE) are required. The surface of the fabric may be treated with coatings or calendared to modify the surface structure and thus improving the filtration efficiency of the media.
Synthetic Leather	A densely needled fabric is impregnated with a polyurethane resin to provide a smooth surface without visible needle markings and it achieves a high surface abrasion resistance. Typical production lines may have as many as eight needle looms in sequence from pre-needling to finish needling. The major applications, of this material are in luggage, car interiors and furniture.

Waddings and Paddings	This is one of the highest uses of needlepunched nonwovens by fiber consumption. The major applications are in mattresses, furniture and carpet underlay. Fibres used include that reclaimed from shredded waste clothing, recycled natural and synthetic fibers, jute, sisal, coir and cotton as well as virgin PET and PP.
Automotive Fabrics	These fabrics are applied in decorative trims, seat backings, sound dampers and boot liners. The fabrics are required to have high abrasion resistance, therefore the choice of fibre fineness ranges from 15-18 deniers (16.7 -20dTex). Most widely used fibres are PP and PET, but research to incorporate natural fibres, such as hemp in the production of various automotive nonwoven fabrics is in progress.
Insulation	Both thermal and acoustic insulators are made from needlepunched fabrics. Recycled PET fibres are also used in insulation paddings. In high temperature insulation applications, blown ceramic fibers in a batt form are needle-punched to produce up to 75mm thick insulating media.
Wipes	Heavy duty household and industrial wipes can be produced by needlepunching process. Popular choice of fibres is viscose blended with a thermo-plastic bonding fibres. In pre-moistened wipes, needlepunched nonwoven fabrics are competing with spunlaced fabrics, which have traditionally been used in this sector, because a needlepunched fabric holds larger volumes of moisturiser than that of spunlaced fabric.

2.6. Factors Influencing Sound Absorption of Nonwoven Fabrics

One of the major advantages of nonwoven fabrics is the fact that they can be produced from a wide range of fibres of varying fineness and length. In addition to fibre characteristics, process parameters during the production of the nonwoven fabric also require consideration. These two types of variations (fibre and process) then lead to a variation in fabric parameters. Besides variations in fabric parameters, in-situ variables during applications also influence the efficacy of the nonwovens as sound absorption media.

Therefore, many parameters influence sound absorption capabilities of needle punched nonwoven fabrics. Studies on various parameters influencing the sound absorption properties of fibrous materials have been published widely in the literature [13-17], and they are reviewed briefly in the following sections:

2.6.1. Fibre Parameters

Fibre Type

The effect of fibre type on sound absorption characteristics of nonwoven fabrics is very broad particularly when considering the variation in fineness and length of natural fibres. Fibre type determines the relationship between the fibre size and air flow resistivity [52].

Thilavagathi et al. [12] reported development of natural fiber nonwoven fabrics for acoustic barrier applications in car interiors. They studied sound insulation and other properties of needlepunched nonwoven fabrics produced from natural fibers (banana, bamboo and jute) blended with polypropylene in the frequency range of 100–3200 Hz. They found that nonwoven fabrics produced from a blend of bamboo and polypropylene fibres provided the highest sound absorption coefficient at all levels of sound frequencies. Nick *et al.* [53] compared the sound absorption coefficients of nonwoven fabrics produced from blends of cotton and polypropylene (PP), flax and polypropylene and hemp-polypropylene fibres for automotive applications. They found higher sound absorption coefficients for the nonwoven fabrics produced from cotton and PP blend in comparison to other blends, probably due to better fineness of cotton fibres in comparison to that of flax and hemp fibres.

Fibre Dimensions

An important parameter of a fibre is its diameter. The fiber diameter is directly related to the sound-absorption characteristics of the material. Table 2.1 shows a comparison of the average fiber diameters of several types of industrial fibres as measured on a scanning electron microscope [30]. In general, the diameters of natural fibers are larger than those of synthetic fibers produced by extrusion techniques.

It has been reported that sound absorption coefficient increases with the decrease in fibre diameter [15, 17, 54]. This is attributed to the fact that finer fibres offer higher frictional hindrance than coarser fibres. Finer fibres are required to fill a given volume in comparison to coarser fibres, which results in a more tortuous path and therefore offer higher airflow resistance [55, 56].

Lee et al. [57] concluded that increase in fibre content of fine fibres in nonwoven fabrics increases the noise absorption coefficient (NAC) values, which was attributed to an increase in airflow resistance by means of friction. Koizumi et al. [54] also showed that finer fibers, ranging from 1.5 to 6 denier, provided better acoustic properties in comparison to coarser fibers. Moreover, it has been reported that the use of micro denier fibers provide a dramatic increase in acoustic performance of nonwoven fabrics [54].

Fibre Surface Area

A direct correlation between sound absorption and fibre surface area has been reported [58, 59]. Studies also showed that friction between fibres and air increased with the increase in fibre surface area, thus resulting in higher sound absorption. Moreover, it has been reported that, in the frequency range of 1125 Hz – 5000 Hz, the nonwoven fabrics produced from fibres with serrated cross sections (e.g., Kenaf) absorb more sound than those produced from fibres with round cross-sections [58].

Bo- Young Hur et al. [60] explained that the sound absorption in porous material is a function of the viscosity and pressure of the air in the pores or the friction on the pore walls. Therefore, sound absorption increases with the increase in specific surface area of fibers and with the increase of relative density of the medium and friction of pore walls.

Man-made fibres are available in various cross-sectional shapes, for example; hollow, trilobal, pentalobal and other novel shapes like 4DG fibers. These cross sectional shapes of fibres can add to the improvement in acoustic properties of the medium due to larger surface area in comparison to normal fibres with circular cross-sections [56].

Table 2.1 Average Diameter of Fibres [30]

Origin	Fibrous Material	Diameter µm
Synthetic	Ceramic	2-6
	Mineral Wool (rock & slag)	2 - 10
	Fiber Glass (Continuous Filament)	6 - 13
	Glass Wool	3 - 7
	Graphite	5 - 10
	Basalt	7 - 13
	Polypropylene (PP)	5 - 25
	Polyester (PET)	3 - 15
	Kevlar	12
Natural	Cotton	8 - 33
	Bamboo	14
	Kenaf	21
	Hemp	22
	Wood Fibres	16 - 38
	Flax	19
	Bagasse	20
	Jute	20

2.6.2. Production Process Parameters

Production Method

Among different web formation methods, Jayaraman *et al.* [62] reported higher sound absorption coefficients in air-laid nonwovens compared to that in carded nonwovens irrespective of fibre content. This might be due to higher resistance to flow in the case of air-laid nonwovens in which fibres are relatively randomly oriented, and thus have higher tortuosity, attributed to a higher number of fibre to fibre contact points with smaller pores.

Genis *et al.* [63] found that the sound absorption coefficient of needle-punched polypropylene nonwovens reach its maximum when material density and punching density were 100 kg/m^3 and *28*/ cm^2, respectively.

Thickness

Among different nonwoven web bonding methods, the needlepunching process provide the highest variation in thickness of the materials produced. While thickness can be set initially during web formation, the final adjustments can be achieved during needlepunching, primarily by varying the depth of needle penetration, and to a lesser extent, by varying stroke frequency and needle density on the needle board.

Many studies dealing with the sound absorption properties of the nonwoven materials have reported a direct correlation between the sound absorption coefficient and the thickness of the material [19]. The rule of thumb is that effective sound absorption in a porous absorber is achieved when the material thickness is about one tenth of the wavelength of the incident sound wave [64] and peak sound absorption occurs at a resonant frequency of one-quarter wavelength of the incident sound wave [30]. This requirement of thickness to wavelength ratio renders porous materials inefficient sound absorbers at low frequencies. This ratio is very small at low frequencies as the wavelength of the sound wave may reach values that are in the order of 10 meters [52].

Ibrahim et al [66] reported an increase in sound absorption with the increase in material thickness only at low frequencies. However, at higher frequencies the effect of material thickness on sound absorption becomes insignificant. The maximum value of the sound absorption coefficient moves from high to low frequency range when the material has air spaces within and behind it [54].

Compression

Only a few studies have been published on the effect of fabric compression on sound absorption properties of nonwoven fabrics. Castagnede et al. [68] showed that compression of fibrous web decreases the sound absorption properties, because under compression the various fibres in the web are brought closer to each other without any deformation (without any change in fibre size). However, the compression of a fibrous medium results in a decrease in its thickness and therefore reduction in sound absorption properties.

The study by Castagnede et al.[68] also found variations in other properties occurring during compression, they found that compression resulted in increases in tortuosity and airflow resistivity and a decrease in porosity and thermal characteristic length (shape factor). Despite these changes in physical parameters of the compressed material, the reason for a drop in sound absorption value is mainly attributed to decrease in thickness of the fibrous medium [68].

Levels of compression and its effect on sound absorption require special attention, particularly in the automotive acoustics. The paddings in a seat of a passenger vehicle are subjected to cycles of compression and recovery from load exerted by the occupants. This results in the compression of the porous materials, which in turn results in variation of the thickness of the medium and therefore variation in sound absorption capabilities [47].

Surface Treatments

Most of the time acoustic materials are used inside buildings or vehicle cabins and they have to satisfy certain aesthetic norms. Often when used inside buildings, acoustic materials are coated with paints or some finishes [70]. Therefore, it is necessary to study the effect of these surface coatings on sound absorption behaviour of the material.

It was found that the materials with more open surface are the most adversely affected due to the application of paint. Therefore, Price [71] suggested that a very thin layer of paint coating with a spray gun should be applied over the surface of the material.

The study by Ingard [72] showed that the increase in sound absorption capacity at low frequencies is at the expense of that at higher frequencies. Sometimes, fibrous materials are covered with a film in order to improve the sound absorption properties at low frequencies, which is attributed to the phenomenon of surface vibration of the film [73].

2.6.3. Fabric Parameters

Density

The density of a material is often considered to be an important factor which governs the sound absorption behaviour of that material; however, the cost of an acoustic material is directly related to its density. A study by Koizumi et al. [54] showed increases in sound absorption values with the increase in density of the sample particularly in the middle and higher frequencies (2000Hz and above). The number of fibers increases per unit volume when the apparent density of the material increases; therefore energy loss (of the sound wave) also increases due to increase in surface function, therefore the sound absorption coefficient increases. Moreover, in a presentation by INDA [74] the following effects of fabric density on sound absorption behaviour of nonwoven materials are shown:

- Less dense and more open structure absorbs sound at low frequencies (500 Hz).
- Denser structure performs better at frequencies above 2000 Hz.

Fibre Orientation

Generally, the fibres in a nonwoven fabric are oriented in the machine and cross machine directions as well as parallel to the fabric surface. Thus, nonwoven fabrics are inherently anisotropic and therefore sound propagation within the structure and surface impedance are affected by the orientation of the fibres. Sound waves must enter the material in order to absorb the sound rather than reflect it [45]. Nonwoven fabrics with fibres arranged vertically to the surface, such as needle-punched products, allow sound to enter the material [75].

Composition

Multi-layered materials generally achieve higher sound absorption than the single-layer materials of the same thickness [45]. Ingard [72] reported a significant drop in the critical frequency above which maximum sound absorption is achieved when the fibrous material is composed of several layers of different porosity. The critical frequency is significantly higher for a single layer material of the same total thickness and air flow resistance.

Shoshani [77] reported an increase in the noise absorption capability in the medium frequency range for layered materials made up of a combination of nonwoven and woven fabrics. The highest sound absorption was achieved when the woven fabric was facing the noise source and the effect was more pronounced in low frequency range, i.e. $f < 500$ Hz.

Ingard [72] reported that for frequencies above 150 Hz, the sound absorption was higher when the flow resistivity within the material increased from the surface toward the rigid backing. On the contrary, Jayaraman et al. [62] found that the sound absorption increased when a part of the needlepunched nonwoven composition with higher density was facing the sound source. Ackermann et al. [78] reported that the smoothness and evenness of the surface of the sound absorbing medium facing the sound source reduced frictional losses and thus allowed higher sound absorption.

Airflow Resistance

Specific air flow resistance per unit thickness of the medium is one of the most important parameters that influence the sound absorption characteristics of a nonwoven material. The impedance and propagation constants, which describe the acoustic properties of porous materials, are governed by air flow resistance of the medium [79].

The interlocking of the fibres in nonwoven fabrics provides resistance to acoustic wave motion. Generally, when sound enters a porous material, such as a nonwoven fabric, its amplitude is decreased by friction as the waves pass through the tortuous passages. Thus the acoustic energy is converted into heat [80]. This friction quantity which can be expressed in terms of resistance of the material to airflow is called airflow resistance and is defined in equation given below [81]:

$$R_1 = \frac{\Delta p}{\Delta T u} \tag{17}$$

Where:

R_1 = Specific flow resistance (Rayls/m),

u = Particle velocity through the material (m/sec),

Δp = Sound pressure differential across the thickness of the sample measured in direction of particle velocity (newtons /m^2), and

ΔT = Incremental thickness, (m).

It should be noted that the unit used for the flow resistance is Rayls (N.S/m^3 x10). According to Delany et al. [82], air flow resistance is proportional to the bulk density of the material and fibre dimensions. An increase in fiber packing density of the nonwovens decreases the air permeability with a resultant increase in pressure drop and hence increased air flow resistance [83, 84].

Porosity

Porosity of the material is an important factor which should be taken into consideration while investigating sound absorption mechanism, in particular their quantity (per unit area), size and type. Sound dissipation by friction takes place as the sound wave enters and travels through the porous medium. This means that there should be enough pores on the surface of the medium for the sound to pass through and get dampened. The porosity of a porous material is defined as the ratio of the volume of the voids in the material to its total volume, as expressed mathematically by the following equation [73]:

$$\text{Porosity (H)} = \frac{V_a}{V_m} \tag{19}$$

Where:

V_a = Volume of the air in the voids, and

V_m = Total volume of the sample of the acoustic material being tested.

A nonwoven web designed to achieve high sound absorption coefficient, should have porosity that increases along the propagation of the sound wave [86].

Tortuosity

Tortuosity is defined as the length of the passage through the pores compared to the thickness of the sample. Tortuosity can also be described as the influence of the internal structure of a material to its acoustic properties [87]. Wassilieff [88] describes tortuosity as a measure of how far the pores deviate from the normal or meander within the material. Horoshenkov *et al.* [89] found that tortuosity mainly affected the location of the quarter-wavelength peaks whereas porosity and flow resistivity affect the height and width of the peaks. They also found that the value of tortuosity influenced the sound absorption properties of the porous materials particularly at high frequencies.

Zwikker and Kosten [90] describe the inner structure of porous materials by the term ‘structure factor’. The approximate relation between porosity (Y) and structure factor (K) for homogenous materials made of fibers or granules with interconnecting pores is shown in the figure below [81].

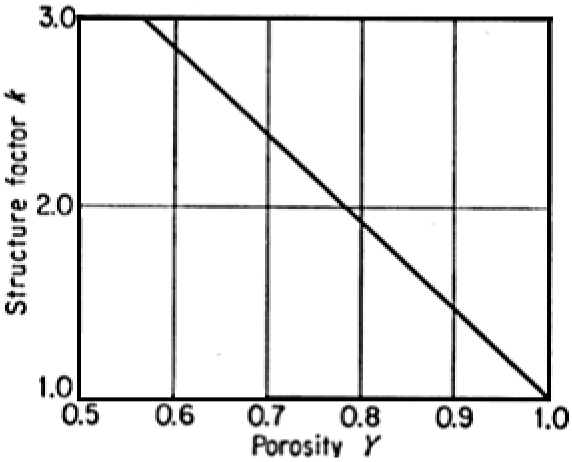

Figure 2.12. Relation between structure factor and porosity [81]

Surface Impedance

The higher the acoustic resistivity of a material the higher is dissipation of the sound energy for a given layer of thickness. At the same time the surface impedance of the layer also increases with the increase in resistivity, thus resulting in a greater reflection of the sound wave on the surface layer and therefore lower absorption capability. Moreover, the whole process is frequency dependent, so that for lower frequency bands the necessary layer thickness increases as resistivity decreases [92].

2.6.4. Other (In-Situ) Parameters

Frequency

It is a well-established fact that porous fibrous materials achieve lower sound absorption particularly in the lower frequency-range [1, 30, 93]. This is due to two main reasons. The first reason is that the maximum energy is dissipated in the region where maximum particle velocity takes place, and the maximum particle velocity is far from the material at low frequencies since wavelengths are longer. This may be prevented by increasing the thickness of the absorbent material or leaving an air gap between the absorbent and the backing. The second reason is that sound waves of shorter wavelengths, with higher frequencies are able to penetrate and dissipate more easily compared to that at longer wavelengths [75].

Placement / Position of Sound Absorption Material

Sound absorption capability of materials also depends on their position and placement. Alton [94] found that if several types of sound absorption material are used, then it was desirable to place some of each type on ends, sides and ceilings of the building so that all three axial modes (longitudinal, transverse and vertical) of sound waves would be influenced.

It has been demonstrated that in a rectangular room, the sound absorbing materials are most effective when placed near the corners and along the edges of room surfaces. In speech studios, some sound absorbents that are effective at higher audio frequencies should be placed on the walls at head (ear) level of the human beings. In fact, the material placed at the lower portions of high walls can be twice more effective than the same material placed elsewhere [94]. Furthermore, it is recommended that untreated surfaces should never face each other within a room.

Air-gap Backing

Mirjalili and Mohammad-Shahi [13] studied the effect of the distance (air gap) between layers of a multi-layered structure of sound insulation media. They found that sound diffraction occurs when a sound wave passes through a multi-layered structure, i.e. a medium alternates between fibre bundles and air (gap). When the material changes the velocity of the sound wave, this change causes the sound absorption coefficient of the multi-layered structures to be different from that of the homogenous multi-layered structures. In fact, a part of the sound energy within different materials is reflected. As is known, the sound waves are transferred by air molecules, therefore, the distance between layers or the gaps between them in the multi-layered structures can improve the sound insulation.

Seddeq et al, [19] also found similar results when studying the sound absorption of nonwoven fabrics produced from recycled natural fibers blended with synthetic fibers and backed by air-gaps ranging from 1cm to 4 cm together with a perforated plate placed in front of the nonwoven sample (plate-sample-air gap). Air gap behind the material increases normal incidence sound absorption coefficient (NAC) substantially in the low frequency range [47].

2.6.5. Secondary Factors

There are some other factors not related to acoustic performance that may affect their usefulness as sound absorption media, these include aesthetic, structural and safety considerations [7]. Furthermore, material selection for acoustic applications may be affected by factors, such as those concerning exposure to solvents, vibrations, corrosion, and regulatory restrictions, such as load bearing materials in food and drug areas, firebreak requirements, ducts, shafts etc. [59].

Apart from all the parameters mentioned above, the efficacy of sound absorption materials is dependent on the frequency of the sound to be absorbed. Generally, the sound absorption increases with the increase in sound wave frequency. Thus, in real world applications, sound absorption materials are chosen according to the prevailing spectrum of sound wave frequency being emitted. For example, in automotive noise control, thinner materials that are capable of absorbing sound at high frequencies are employed in headliners. At the same time, thicker materials capable of absorbing sound at lower frequencies are used for door panels and carpet backings [98]. Thus, it is essential to know the range of sound wave frequencies required to be controlled in order to utilize sound absorption materials more effectively.

2.7. Methods of Testing Sound Absorption of Materials

The basic principle of measuring sound absorption in a material is to find the difference between the incident and reflected sound which then provides a value quantifying the absorbed sound energy. There are three standardised methods for measuring sound absorption properties of materials [99]:

- The reverberation chamber method (ISO -354:2003/ ASTM C423) [100].
- Impedance tube measurement using the standing wave ratio method (ISO-10534-1:2001 / ASTM C384) [101].
- Impedance tube measurement using the transfer function method (ISO 10534-2: 2001 / ASTM 1050-98) [102].

2.7.1. The Reverberation Chamber Method

This method is based on the concept of measuring reverberation time (T_{60}) which is defined as the time required for the decay of steady sound pressure level in an enclosed space by 60 dB, measured from the moment the sound source is switched off [1].

The definition of reverberation time is simple but the actual measurement is not well defined [103]. The task is to find how the room responds to an impulse. The most common method uses a loudspeaker as a sound source, a microphone, and a computer with software which controls and analyses the acquired data. Methods vary in terms of sound source and measurement signal. All the methods aim to produce an impulse response from which the value of the T_{60} can be calculated.

Sound absorption is then calculated using the difference in measured reverberation times between the T_{60} of an empty room and T_{60} of the same room with the absorption material in place. The sound absorption coefficient is calculated from [100]

$$\alpha_S = \frac{A_T}{S} \tag{20}$$

Where A_T is the equivelent sound absorption area of the test specimen and S is the area covered by the test specimen.

2.7.2. Impedance Tube Measurement Using The Standing Wave Ratio Method

In this method, the sound field inside a tube is measured [101]. A sample material is placed at one end of a straight, rigid and smooth tube and a loud speaker is placed at the other end of the tube. Microphones are attached in such a way that they can be moved inside along the length of the tube. The loud speaker produces a static sound field inside the tube, which is then measured and analysed. The sound absorption coefficient is measured for normal (perpendicular to the sample) incident sound wave only.

Impedance is a function of frequency; a frequency response is a ratio between sound pressure and particle velocity as given in Equation (22) below. This method measures the response of one frequency at a time. Figure 2.13 illustrates the acoustic phenomena in a tube where the loudspeaker produces a plane sound wave, p_i , which together with the reflected wave , p_r , produces a standing wave, p as given by:

$$p = p_i + p_r \, . \tag{21}$$

$$\mathbf{Z}_n(f) = \frac{\mathbf{P}(f)}{\mathbf{U}(f)}, \tag{22}$$

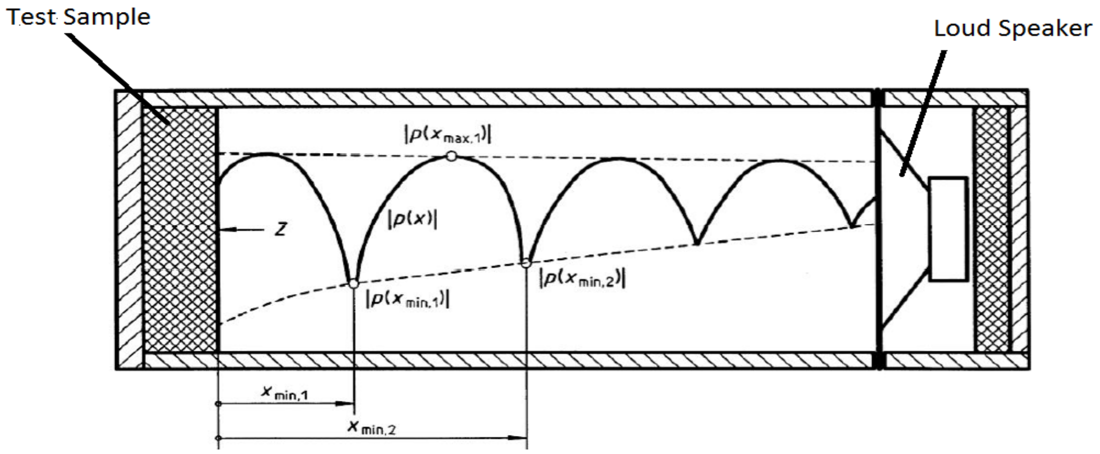

Figure 2.13. Standing wave method [101]

The principle of measurement is to estimate the maxima and the minima, $|p(x_{\max})|$ and $|p(x_{\min})|$, respectively, and their distance from the sample material, from which, acoustic absorption can be calculated. Additionally, the distance from the reference point which is the surface of the tested sample to the first pressure minimum, x_{min}1and its wavelength, λ_0 , is also measured in order to find out the reflection factor, *r,* of the material.

A maximum pressure occurs when p_i and p_r are out of phase. The ratio of standing wave is [106]:

$$s = \frac{|p(\max)|}{|p(\min)|}, \tag{23}$$

which can be written as:

$$s = \frac{1 + |r|}{1 - |r|}, \tag{24}$$

and

$$|r| = \frac{s - 1}{s + 1}, \tag{25}$$

and the acoustic absorption, α , of the material can be calculated using the absolute value of the reflection factor, r, in the equation below [106]:

$$\alpha = 1-|r|^2 \tag{26}$$

2.7.3. Impedance Tube Measurement Using The Transfer Function Method

The main difference between the transfer function method and the standing wave ratio method is the measurement of the acoustic phenomena occurring inside the tube [107]. The standing wave ratio method uses one frequency at a time whereas the transfer function method can measure the whole frequency band at once.

Like in the standing wave ratio method, the sample is placed at one end of the tube and the speaker on the other end and the microphones placed inside the tube to measure the occurring acoustic phenomena. In this method [102], the complex transfer function, $H_{12,}$ as given in equation (27) between the two microphone points is measured in order to calculate the acoustic descriptors similar to that in the standing wave ratio method.

The microphones can be attached to the edges of the tube, as shown by labels 1 and 2 and by a label 3 in figure 2.14 below a is the test sample. The microphone used in this measurement must be an identical pair.

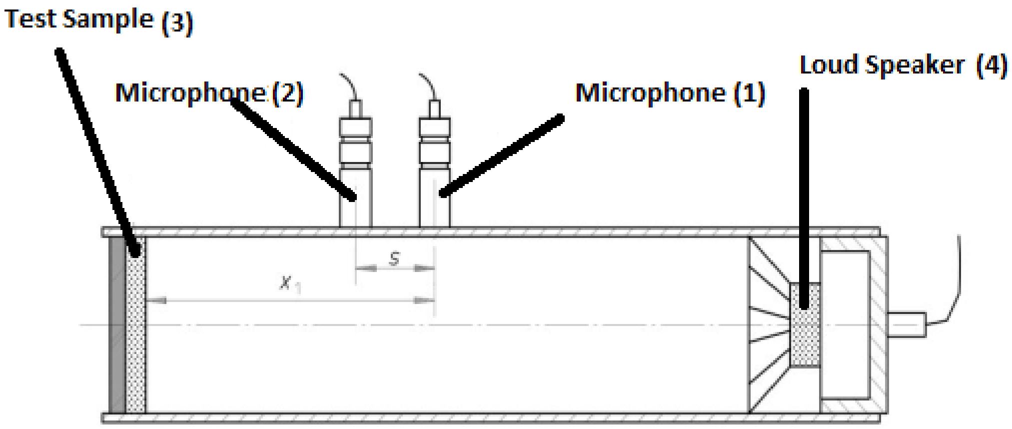

Figure 2.14: The transfer function method using two microphones [102]

The transfer function between the microphones is given by [102]:

$$H_{12} = \frac{S_{12}}{S_{11}} \tag{27}$$

Where $\mathbf{S}_{12}$ is the cross spectrum between the two microphones and $\mathbf{S}_{11}$ is the autospectrum of the first microphone. The reflection factor can be calculated from the measured transfer function as given by [102]:

$$r = \frac{H_{12} - H_I}{H_R - H_{12}} e^{2jk_0 x_1} \tag{29}$$

Where $\mathbf{H}_I$ is the transfer function for the incident wave alone and $\mathbf{H}_R$ is the transfer function for the reflected signal alone. $\mathbf{H}_I$ and $\mathbf{H}_R$ are measured between two microphone positions, x_1 is the distance between the test sample and the first microphone and k_0 is the wave number, which is defined as:

$$k_0 = \frac{2\pi f}{c_0} \tag{30}$$

Acoustic absorption is then calculated using:

$$\alpha = 1 - |\mathbf{r}|^2 \tag{31}$$

2.8. Problem Statement

High levels of noise emission are one of the major health hazards affecting the quality of human life. The significance of noise pollution according to the specific effects are: noise-induced hearing impairment; interference in speech communication; disturbance in rest and sleep; adverse effects on psycho-social and mental-health performance; effects on residential behaviour and annoyance; as well as interference in intended activities.

There are three main ways to mitigate noise pollution. It can be treated at the source, the medium or at the receiver. Amongst these, controlling the noise by placing a sound absorption/barrier medium between the source and the receiver is the most practical approach. One of the methods to mitigate the propagation of noise and its adverse effects is to use a sound barrier medium. Needle punched nonwoven fabrics are widely used for this function as they are porous and therefore act as good sound absorption media.

The nonwoven fabrics for sound absorption are usually produced from polyester (PET) and/ or polypropylene (PP) fibers, but in recent years, developments in introducing some natural fibers such as flax, bamboo and jute have been reported [12]. But this is still in early stage of development and the research is still required. One of the main motivations for using natural fibre to produce “greener” material to replace existing synthetic fiber based materials which are environmentally unfriendly and not biodegradable.

Most of the published research reports in this field are focused on studying the effect of needlepunched nonwoven parameters on sound absorption behaviour. Most of these parameters have been studied individually for different fibre types and their blends; however, not much focus has been directed to investigate the synergistic and interactive effects of these parameters. Therefore, this study is aimed at bridging this gap in the body of knowledge on sound absorption behaviour of nonwoven fabrics by optimizing some of the governing parameters of needlepunching process. This work will also study the effect of an air gap backing on the needle punched nonwoven fabrics in sound absorption. This study is aimed at assessing the potential of nonwoven fabrics produced from natural fibres for sound absorption application.

2.8.1. Motivation

Needle punched nonwoven fabrics are relatively simple and cost effective to produce; they can be also produced from a wide variety of fibres. Nonwoven production lines operate at high production rates and these materials are utilized in a wide range of applications in various fields including sound absorption and heat insulation. In view of this, it is expected that with more research and development efforts, environmentally friendly natural fibre based needlepunched fabrics can be also extensively applied in sound absorption.

The outcome of this study will assist in determining optimum process parameters for the natural fibres and their blends for producing needlepunched nonwoven fabrics for sound absorption applications. The findings from the effects of the air-gap tests will assist in incorporating the air-gap in sound insulating structures, thereby saving material and processing costs.

2.9. Objective of the Research

The main objectives of this research work are:

- To study the effects of nonwoven fabric production parameters on sound absorption properties of needle punched nonwoven fabrics with a view to establish optimized conditions for processing parameters. This will include the use of different natural fibres and their blends with PET with the purpose of producing “green materials”.

- To study the effect of air-gap backing on sound absorption capability of needlepunched nonwoven fabrics and to optimize the size of the air-gap to achieve maximum sound absorption. The nonwoven fabrics and the air-gap will be further backed by a commercial roof ceiling material made from extruded polystyrene. So, all three components, i.e. nonwoven fabric specimen, air gap and polystyrene sample will be tested as one unit-specimen, with the air-gap being varied to achieve best results.

2.10. Research Methodology

To achieve the objectives stated above, the following methodology will be adopted. The first part of the research will be directed to production of needlepunched nonwoven fabrics from 50:50 blends of natural fibres and polyester (PET), i.e. agave-PET, flax-PET and hemp-PET. These fabrics will be produced by varying the depth of needle penetration and stroke frequency of the needle loom. The Box-Behnken factorial experimental design resulting in the production of 15 different samples will be adopted to study the effects of governing parameters, i.e. fibre type, depth of needle penetration and stroke frequency during needlepunching.

The samples will then be tested for physical properties such as area weight and thickness, according to the ASTM D 3776-96 and (EDANA) -WSP 120.6 (05) testing standards, respectively. The main test on sound absorption properties will be carried out according to

ASTM E 1050-98. After obtaining the sound absorption results, response surface plots will be drawn to ascertain the optimum parameters for the production of needlepunched nonwoven fabrics for sound absorption applications.

The second part of the study will also be on the production of the needle punched nonwovens produced from blends of wool-PET, hemp-PET agave-PET. The blend ratio will be varied, i.e. for all three blends; some samples will be produced with 30:70 blends of natural fibres and PET and others will be produced with 50:50 blends of natural fibres and PET. All the other production parameters such as, stroke frequency, speed of conveyor belts and area weigh will be held constant and not varied. An attempt will also be made to keep the sample thickness as similar as possible for all the fabrics to exclude the influence of variation in thickness on sound absorption.

In total, six samples will be produced, i.e. 2 blend ratios for all 3 natural fibres blended with PET. The produced samples will be tested for thickness and area weight. In the main test of sound absorption, each specimen will be mounted together with a backing of polystyrene sample used to make ceiling boards with an air gap between them. The air gap will be varied from 0mm (nonwoven and polystyrene touching) up to 25mm in 5mm increments for each of the six samples under study. A three-way ANOVA will be carried out which includes two-way interactions of the output data to test the parametric effect on sound absorption.

3. EXPERIMENTAL DESIGN AND METHODS

The experimental work was divided into two parts. The first part dealt with the optimization of material variables such as fibre type and needle-punching process parameters, namely, depth of needle penetration and stroke frequency in producing nonwoven fabrics for sound absorption application. Preliminary trials were carried out to establish the ranges within which selected variables would be varied for an optimization study. Subsequently, optimisation of these selected process parameters was attempted.

The second part focused on the application of the developed nonwoven fabrics for sound absorption application in the building industry. The objective was to study the synergistic effect of the nonwoven fabric parameters (i.e. fibre type and blend ratio) and air-gap on sound absorption capabilities. The air-gap, which was varied, was maintained between the nonwoven specimen and the commercial ceiling insulation material made from extruded polystyrene (XPS) used as a backing layer. Furthermore, the aim of the study was to ascertain the factors playing the most dominant role in sound absorption properties in the developed samples.

3.1. Preliminaries

Part A – Optimisation of Production Parameters

The aim of this work was to establish the domain of governing parameters of the needlepunched nonwoven fabrics, such as fibre type (agave, flax and hemp each blended with polyester fibres), stroke frequency and depth of needle penetration on sound absorption properties. It was necessary to establish the minimum and maximum values of the depth of needle penetration and stroke frequency, as well as to determine the optimum blending ratio of natural and PET fibres.

Blending

Different blending ratios, namely; 20:80%, 30:70%, 50:50%, 70:30% and 100:0% of natural fibres to polyester fibres (by weight), were selected. The preliminary results for fabrics produced from 100% natural fibres and those blended with high natural fibre content (higher than PET fibres) showed that sound absorption coefficients of the resultant nonwoven fabrics were very low in the frequency range of 50-5700Hz. All the samples produced from 100% natural fibres achieved sound absorption coefficients that were below 0.2 (20%) and those produced from 70% natural fibres and 30% PET fibres achieved sound absorption coefficients below 0.25 (25%) in the frequency range of 50 -5700Hz.

On the other hand, blends with a high content of PET fibres showed high sound absorption coefficients, ranging between 0.45 (45%) and 0.65 (65%), in the same sound frequency range. However, with the aim to produce nonwoven fabrics that can be classified as natural fibre based materials, it was felt that a 50:50% blend of natural and PET fibres would be ideal in terms of desired performance properties and processing these fibres without significant fibre damage. Hence, further work was carried out only on 50:50% blends of each of the three natural selected and PET fibres.

Depth of Needle Penetration

Initially, depths of needle penetration of 6 mm, 8 mm and 10 mm were chosen. However, these depths of needle penetration produced fabrics with nearly the same thicknesses, mostly ranging between 2.4 mm and 3.2 mm. This implied that the chosen variation in the depths of needle penetration of only 2mm was inadequate to produce nonwoven fabrics with different thickness values. Therefore, depths of needle penetrations of 4 mm, 7 mm and 10 mm were selected while keeping in mind the desirable structural integrity of the final fabric samples.

Stroke Frequency

Initially, levels of stroke frequency were set at 240/min, 255/min and 270/min, however, as observed in the case of depths of needle penetration, these settings were also found to produce nonwoven fabrics with insufficient variations compared to what was desired. Therefore, the settings for stroke frequency were changed to 250/min, 300/min and 350/min, and necessary precautions were taken to avoid or minimise damage to natural fibres.

Part B – Application of Nonwoven Fabrics with Variable Air Gap and Extruded Polystyrene Sheet (XPS) Backing

The main aim of this work was to study the effect of the air-gap and XPS backing on sound absorption coefficients of the needlepunched fabrics. It was necessary to vary the air-gaps between the nonwoven fabric specimen and the XPS sheet as well as other production parameters to study their simultaneous effects on sound absorption coefficients.

Fibre Choice and Blending Ratios in Nonwoven Fabrics

As discussed in Part A above, fibres were chosen such that they vary in their physical properties. It was also decided to produce nonwoven fabrics from three blending ratios, namely, 30:70%, 50:50% and 70:30% (natural fibre to PET). Furthermore, it was anticipated that there would be variation in the thickness of nonwoven fabrics resulting from variations in blend ratios and fibre types (fineness) which would influence sound absorption properties. Therefore, it was decided that variation in thickness of the nonwoven samples should be controlled and maintained between 7 mm and 8 mm.

Materials Tested

In the context of the work carried out in Part A; it was necessary to use similar needlepunched fabrics in this part of the study, for effective comparison. Moreover, for the sake of practical relevance of this study, it should incorporate a commercially available sound absorption material because nonwoven fabrics used for sound absorption in buildings are normally used along with other materials as backing. Therefore, it was decided that needlepunched fabrics backed by an XPS sheet at different air-gaps will be tested as a unit.

Air Gap Size

The air-gaps between the nonwoven fabrics and the XPS sheet were initially varied from 0 to 8mm in increments of 2 mm. It was observed that sound absorption increased with an increase in air-gap. However, the observed change in sound absorption was too little to draw any meaningful conclusions from the data obtained. Therefore, the increment was then increased from 2 mm to 5 mm, and the air-gap was varied from 0 mm to 25 mm.

3.2. Optimization of Process Parameters of Needle-punched Nonwovens for Sound Absorption Application.

The aim of this part of work was to study the individual and interactive effects of the needle-punching process parameters in order to achieve maximum sound absorption properties in the nonwoven fabrics. The Box-Behnken response surface design with three variables varied at three levels (-1, 0, +1) was selected for the experimental work.

3.2.1. Box-Behnken –Response Surface Design

There are two types of response surface designs, namely, Central Composite designs and the Box-Behnken design, the latter was used in his study. A response surface design is a set of advanced techniques to design experiments which can help to better understand and optimize the responses (effect being tested). Response surface design methodology is often used to enhance the models after determining important factors from the factorial design. This is pursued especially when an apparent nonlinear (curved) relationship between the factors (independent variables) and the effect (dependent variable) exist [108-110].

Box-Behnken design usually requires fewer design points in comparison to the central composite design; therefore it is less expensive and less laborious to run with the same number of factors. Box-Behnken design usually considers 3 levels per factor, unlike the central composite design which can have up to 5 levels. Also, unlike the central composite design, the Box-Behnken design never includes experiment runs where all factors are at their extreme setting, such as all at the lowest levels [108, 110].

Box-Behnken designs require at least three factors. Figure 3.1 shows a three-factor Box-Behnken design. Points on the diagram represent 12 experimental conditions and 3 control conditions so that in total 15 sets of experiment are required.

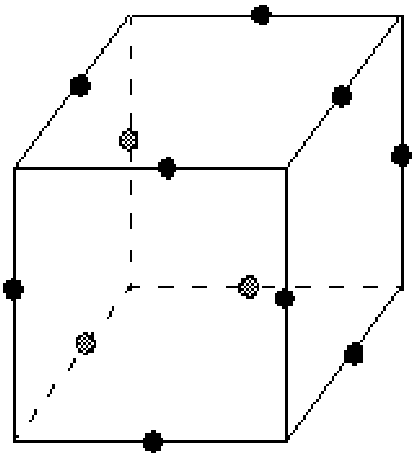

Figure 3.1Three factor Box-Behnken design [110]

3.2.2. Materials

The needle punched nonwoven fabrics were produced and tested for various properties. These fabrics were produced from 50:50% blends of three natural fibres, namely, agave, flax and hemp, each one blended with polyester (PET), i.e. each mat was produced from a 50-50% blend of PET and one of the three natural fibers. The flax fibres were sourced from growers in the Britz area in the North West Province of South Africa and agave fibres were sourced from growers in the Graff Reinet area in the Eastern Cape Province of South Africa. Hemp fibres were imported from France.

The selection criteria for fibres were mainly influenced by their availability and suitability for being processed into nonwoven fabrics. The length and fineness of the fibres with

CV% values are shown in Table 3.1 below. The plant based natural fibres (agave, flax and hemp) were measured for lengths and fineness. Length was measured by sampling 5 bundles from each lot, and then from each bundle 5 fibres were measure by a measuring tape for length making it a total of 25 fibres measured for each fibre type, a mean and CV% were then calculated and reported. The fibre fineness was measured via the optical fibre diameter analysis (**OFDA)** method, which measures the fibre micronaire from which fineness in ***dTex*** can be calculated, five readings were done for each fibre type from which the mean and CV% were calculated and reported. For wool fibres, length and diameter were measured on OFDA as well. All the fibres were measured after conditioning for 24 hours in a standard testing laboratory atmosphere maintained at 21^{o}C ± 2^{o}C and 65% ± 2% RH [111].

Table 3.1 Fibre length and fineness with percentage CV in brackets

Fibre	Length(mm)	Fineness(dtex)
Agave	95 (22%)	16.8 (16%)
Flax	62 (49%)	10.2 (87%)
Hemp	60 (49%)	12.5 (92%)
Coring Waste Wool	22 (25%)	20.7 µm (28.5%) (diameter)
PET	60	6.6

3.2.3. Fabric Production

3.2.3.1.Fibre Preparation

The most important fibre characteristics are fibre diameter or fineness and fibre length. Other fibre parameters are for specific niche applications, depending on a specific function envisaged. "Textile character" or usability of fibres can be determined by factors such as mechanical properties and desired technical functions.

All the natural fibres were received after scutching in a long tow form, this means that further processing on a cottoniser was required to obtain short-staple fibres for processing on a nonwoven carding machine, see Figure 3.2. The natural fibres were cottonised in-house by a 2-pass process in a pre-opener and cottoniser on the Temafa natural fibre preparation line. The function of the opener is to unbundle the fibres from the scutched bundles into individual strands and the cottoniser, in turn, shortens the fibre strands into staple fibres suitable for processing on a nonwoven carding machine.

After the natural fibers were cottonised to a desired staple form, 50:50% (by mass) blends of natural and polyester fibres were manually prepared before feeding to the carding machine.

Figure 3.2. Scutched flax (L) and cottonised flax (R).

3.2.3.2. Fibre Processing

Each fibre blend was carded twice to ensure homogeneous blending of the fibres since the fibres were manually mixed without processing in a fibre mixer. The blended fibres were fed to the carding machine via a chute equipped with sensors to control the feeding rate which ensures uniformity of the fibrous web.

The production of needle-punched nonwoven fabric comprised of three main processes, i.e. roller carding, followed by cross-lapping and needle-punching. As it has already been indicated, the main carding, i.e. web formation process, occurs during the second pass on the carding machine, as the first pass is used only to improve blending of the natural and PET fibres.

The carding machine used in this study is equipped with a main cylinder of 800mm in diameter and 600mm wide (working width) covered by universal card clothing. The main cylinder is the heart of a carding machine and it distributes the fibres during the process. On its upper side, the main cylinder is partly surrounded by a series of pairs of “worker” and “stripper” rollers which accomplish the dual function of carding and mixing (blending). The doffer stripper rollers condense and remove the fibres in a form of a continuous web [8]. The carding machine settings during the second pass are shown in Table 3.2. The density of the web produced is influenced by the rate of feeding of the fibres into the card, i.e. the higher the rate of feeding the denser is the fibre web produced.

The carding machine produces a web of desired area weight which is then carried by a conveyor belt to a cross-lapping unit whose function is to layer up the web in a cross-machine direction to form a batt of desired thickness and density. The speed of the conveyor belt (from the cross lapper to the needle-puncher), which transports the batt at a right angle to the direction of carding (see Figure 3.3), also contributes in determining the thickness of the batt during cross-lapping.

Table 3.2 Machine settings during the second pass carding and needle punching

Parameter	**Settings**		
	Hemp	Flax	Agave
Card Feeding Speed (m/min)	0.80	0.80	0.80
Vertical Lap Output Speed (m/min)	0.70	0.70	0.75
Incline Conveyor Speed (m/min)	0.70	0.70	0.75
Puncher Infeed Apron Speed (m/min)	0.75	0.75	0.80
Puncher Infeed Rollers Speed (m/min)	0.75	0.75	0.80
Needle Depth (mm)	0.00	0.00	0.00
Stroke Frequency (1 / min)	200	200	200

The planned nominal area weight of all the samples was 1000g/m^2, so with the difference in natural fibre size (fineness) and density, the settings of the take-off speed and feed rate on the carding machine were adjusted accordingly for each natural fibre type blended with PET fibres to ensure that all the samples were produced with the similar area weight. A batt with nominal area weight of 500 g/m^2 was produced and two layers of the same were combined to produce the fabrics with a nominal area weight of 1000 g/m^2. This was necessary to prevent needle damage caused by needling very thick batts. Given the variation in natural fibre properties, the actual area weights of the fabrics produced were ranging between 950 g/m^2 to 1100 g/m^2, nevertheless, attempts were made to keep the area weight of the fabrics as close to nominal weight as practically possible.

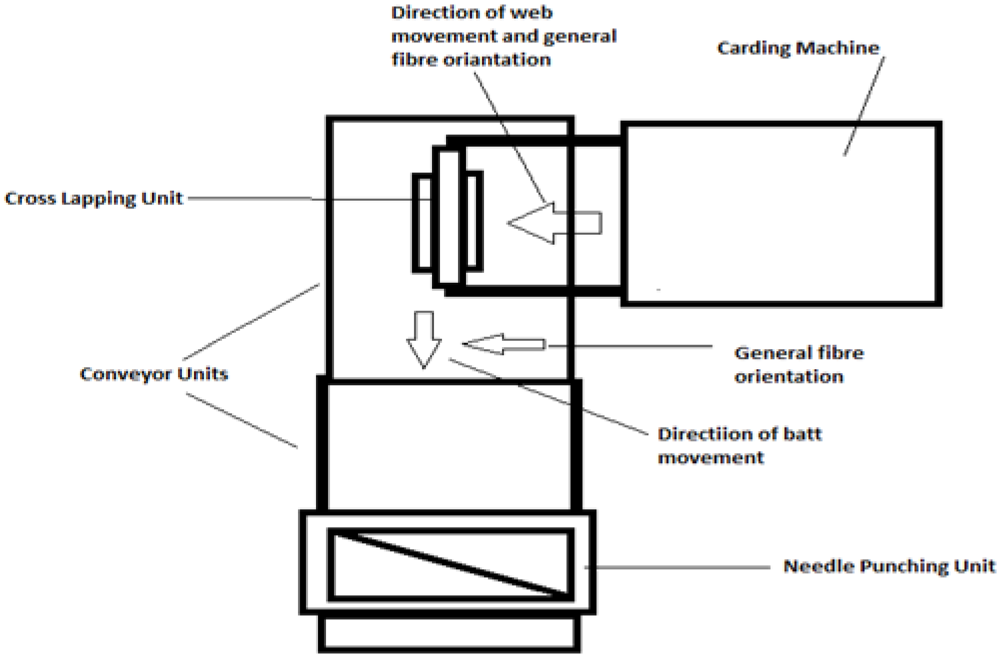

Figure 3.3: Schematics showing carding and cross-lapping processes.

The batt was then transported on a conveyor belt to the needlepunching machine for the first of the two passes. For each fabric blend type, a lightly needled fabric with an area weight ranging between 450 to 550 g/m^2 was produced. During the first pass the depth of needle penetration and stroke frequency were set at 0 mm and 200/min respectively and they were kept the same for all blends types produced.

Thereafter, two layers of these lightly needle-punched fabrics were combined during the second pass in the needlepunching machine in accordance with the experimental design, shown in Table 3.3, to produce the nonwoven fabrics with the nominal area weight of 1000g/m^2

Table 3.3: Coded levels of fibre blends and needle-punching process parameters during the second pass on needle-punching machine

		Code Levels	
Variables	**-1**	**0**	**1**
Fibers	Hemp-PET	Flax-PET	Agave-PET
Needle Depth (mm)	4	7	10
Stroke Frequency (1/min)	250	300	350

3.2.3.3. Needle Punching

During the second pass of needle-punching, the speed of the machine was maintained constant at 2 m/min and all other needle-punching parameters were maintained as shown in Table 3.3. The parameters were varied according the Box-Behnken factorial design explained in Section 3.2.1, with three independent variables varied at three levels (-1, 0, +1). As such, the depths of needle penetration were set at 4 mm, 7 mm and 10 mm, and the stroke frequencies were set at 250/min, 300/min and 350/min. The third parameter tested being the type of natural fibre used, i.e. three different blends of agave and PET fibres, three different blends of flax and PET fibres and three different blends of hemp and PET fibres in 50:50% proportion by weight. In addition, three identical fabrics produced from blends of flax and PET fibres corresponding to the three control conditions were produced. Therefore, a total of 15 samples were produced as per the experimental design explained in Section 3.2.1.

A Dilo needle-punching machine, Model: D1-LOOM OD-11 6, with two needle boards, operating only in a top-down needling mode, was utilised in this study. The dimensions of the boards are 600 mm × 200 mm with about 3000 needles mounted on each one of them and the needle-puncher has a collective working length of 1000 mm (1m) from the infeed rollers to the output rollers, and working width of 600 mm (0.6 m), hence the samples produced were also limited to the 600 mm in width. The maximum possible stroke frequency is 1200/min, with both the stitching board and stripper plate being perforated and manually adjustable heights. A fabric sample of about 2 meters long was produced for each set of variables.

3.2.4. Fabric Characterisation

All fabrics were conditioned for 24 hours in a laboratory maintained at standard atmospheric conditions according to the ASTM D1776-96 standard [117] before any testing.

3.2.4.1.Fabric Area Weight (Mass per Unit Area)

In order to verify the targeted nominal area weight of the fabric, the ASTM D 3776-96 method was followed [119]. Five square specimens (20 cm × 20 cm) were cut at random places from the nonwoven fabric sample and weighed individually on an electronic balance, to the nearest 0.01g; the average weight of the five specimens was calculated in grams per square meter (g/m^2).

3.2.4.2.Fabric Thickness

The specimens used in measuring area weight were also used to test fabric thickness according to the European Disposables and Nonwovens Association (EDANA) -WSP 120.6 (05) method [120]. A digital thickness gauge (Mitutoyo, Model- ID-C112XB) consisting of a metal disc weighing 170g and 50mm in diameter was utilised to measure thickness of the fabrics under a constant pressure of 1 KPa. An average of five readings was calculated for each sample from which a mean value was calculated and reported.

3.2.4.3.Sound Absorption

In this work, the impedance tube method was used to determine the sound absorption coefficient of the needle-punched nonwoven fabrics [118]. In particular, the impedance tube measurement which follows the transfer function method (ISO-10534-2:2001 / ASTM E 1050-10) was employed, and the equipment consists of a tube, two microphones and a digital frequency analysing system. Five circular specimens with a diameter of 34.9 mm were cut from each fabric and tested and the average values were reported. LMS acoustic testing instrument as shown in Figure 3.4 was used in this study and the specimen were tested in the frequency range of 50-5700Hz [122].

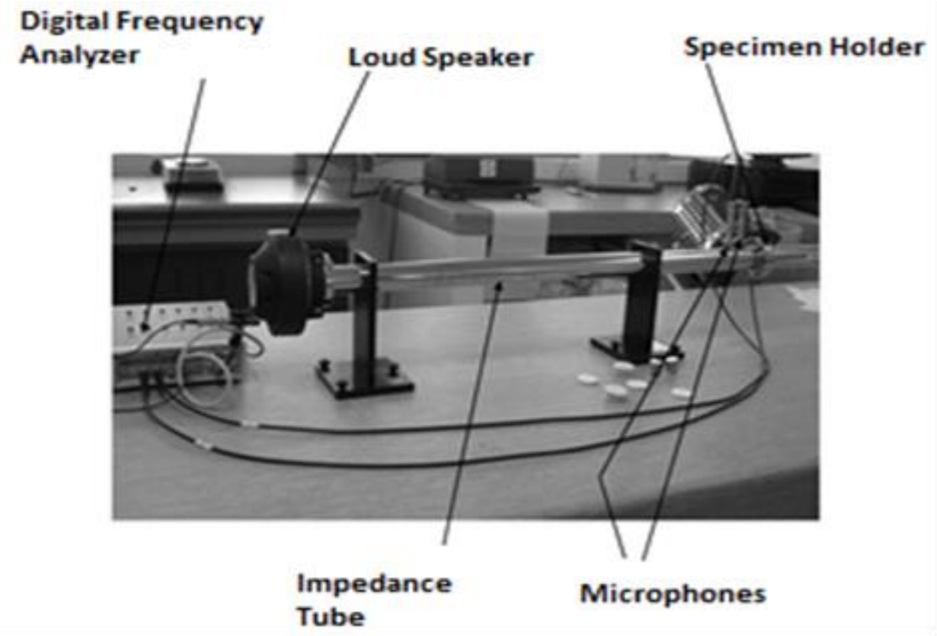

Figure 3.4: LMS sound absorption measurement set up. [118]

3.3. Effects of Air-gap Size, Fibre Type and Blend Ratio on Sound Absorption Coefficients of Needle-Punched Nonwoven Fabrics

3.3.1. Materials

As was the case in Section 3.2, needle-punched nonwoven fabrics produced from blends of natural and polyester fibres were tested for sound absorption application in the building industry. These samples were tested in combination with a varying air-gap and a backing of a commercial ceiling material made from extruded polystyrene (XPS), as shown schematically in Figure 3.5. The natural fibres selected for this study were agave (Americana), hemp and waste cored wool.

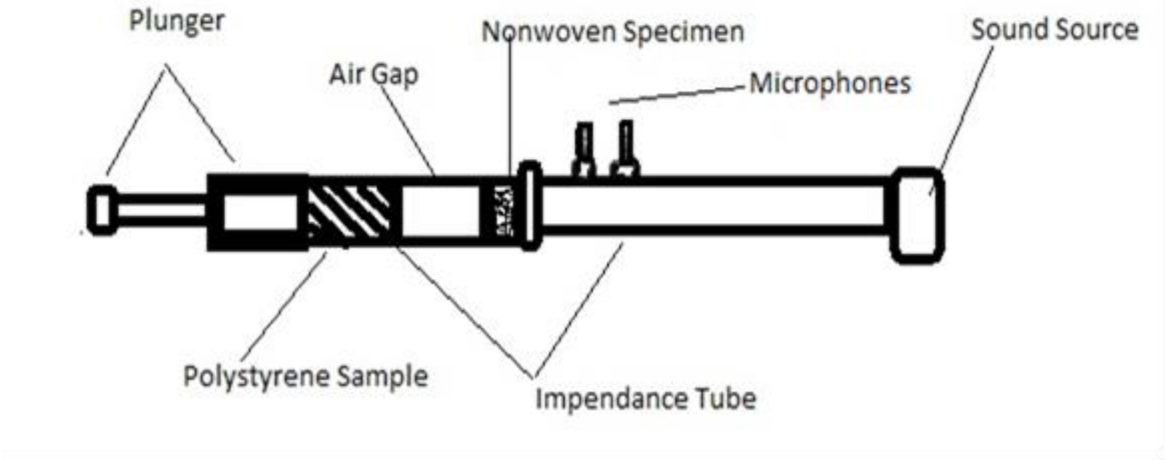

Figure 3.5. Schematic of the set-up inside the impedance tube

These fibres were selected by considering their physical properties, i.e. agave is coarser than hemp and wool, and agave is not known to possess good sound absorption properties whereas wool is known to be a good sound absorber and hemp fibres are finer than agave fibres. The same PET, hemp and agave fibers were utilised as discussed in Section 3.2. The waste wool was obtained from subsistence farmers in the Lundini area of the Eastern Cape Province of South Africa. The fibre properties are shown in Table 3.1.

3.3.2. Fabric Production

3.3.2.1.Fibre Preparation

Fibre preparation was carried out in the similar way as discussed in Section 3.2, with hemp fibres being substituted by wool fibres. Wool fibres in this study were received clean and ready for blending, the other fibres were sourced and prepared as discussed in Section 3.2.

3.3.2.2.Fibre Processing

The same procedure for fibre processing was carried out in this study as discussed in Section 3.2. In this the experiment, three different sets of machine settings were employed to produce samples from three different blending ratios as shown in Table 3.4. Also, the machine settings were adjusted such that all the samples produced would have an initial nominal area weight of about 500 g/m^2 irrespective of variation in the fineness of natural fibres. Thereafter, two layers of individual fabrics of 500 g/m^2 were combined during the second pass through the needle-puncher to produce final fabrics with a nominal area weight of about 1000 g/m^2.

Table 3.4 Machine settings for the first-pass needle-punching of the fabrics

Parameter	**Settings**								
	Wool-PET			**Hemp-PET**			**Agave-PET**		
	30-70	**50-50**	**70-30**	**30-70**	**50-50**	**70-30**	**30-70**	**50-50**	**70-30**
Card Feeding (m/min)	0.65	0.70	0.75	0.80	0.75	0.70	0.80	0.75	0.70
Output from Vertical Lap (m/min)	0.95	0.65	0.85	0.70	0.75	0.65	0.75	0.75	0.80
Incline Conveyor (m/min)	0.95	0.65	0.85	0.70	0.75	0.65	0.75	0.75	0.80
Puncher Infeed Apron (m/min)	1.00	0.70	0.90	0.75	0.80	0.70	0.80	0.80	0.85
Puncher Infeed Rollers (m/min)	1.00	0.70	0.90	0.75	0.80	0.70	0.80	0.80	0.85
Needle Depth (mm)	3	3	3	3	3	3	3	3	3
Stroke Frequency (1 / min)	200	200	200	200	200	200	200	200	200

3.3.2.3.Needle-punching.

Unlike in Section 3.2, the effect of depth of needle penetration was neglected as a variable in this part of experimental work; because the aim of this study was to ensure that the thicknesses of the samples were as uniform as possible. Therefore, depths of needle penetrations were varied according to fibre fineness and blend ratio to achieve targeted nominal thickness ranging from 7 to 8 mm. This was particularly necessary for the fabrics produced from blends containing agave fibres, which were notably thicker in the first trial. All parameters that were to be tested are shown in Table 3.5 below, the specimens and the polystyrene ceiling material are shown in Figure 3.6.

Table 3.5 Tested Parameters and Their Variations

Parameters	**Variations**					
Air Gap Size (mm)	0	5	10	15	20	25
Fiber type (blended with PET)	Waste Wool-PET	Hemp-PET	Agave-PET			
Blend Ratio (Natural Fiber-PET)	30% -70%	50% -50%	70%-30%			

Figure 3.6: Specimens from samples produced

3.3.3. Fabric Characterisation

The area weight and thickness of the samples were tested in the same manner as discussed in Section 3.2.

3.3.3.1. Air Permeability/ Air Flow Resistance

The air permeability of each of the nonwoven fabrics was tested using a WIRA Air Permeameter according to the ASTM D7371-04 standard [121], using a pressure differential of 1.25 cm of water. Atmospheric air was drawn through the test specimen by means of a suction pump. The rate of flow was controlled by means of the pass and series valves. The rate of flow was adjusted until the required pressure drop across the specimen was indicated on the gauge, graduated from 0 to 25cm water head. When the required pressure drop of 1.25cm of water was attained and the indicator of the gauge was steady, the rate of flow of air was noted and recorded. Five circular specimens from each sample were tested and the mean air flow per second was calculated. The air permeability of the fabrics was expressed in cubic centimetres per second (cm^3/s) at 1.25 cm of water.

3.3.3.2.Testing For Sound Absorption

The sound absorption properties of each nonwoven sample backed by a 40 mm thick extruded polystyrene sheet and a varying air gap between them were measured. The air-gap was varied from 0 mm to 25 mm, in increment of 5 mm, as shown in Figure 3.7 below. A digital vernier calliper was used to measure the air-gap size. The extruded polystyrene sheet was placed in the sample holder of the impendence tube, then the required air-gap was adjusted in such a way that the nonwoven sample would always fit in the front end of the sample holder and the adjustable plunger at the rear end of the sample holder was used to adjust the position of the polystyrene sheet to create the required air-gap between the polystyrene sheet and the nonwoven sample. The rest of the sound absorption set up was the same as explained in Section 3.2 above.

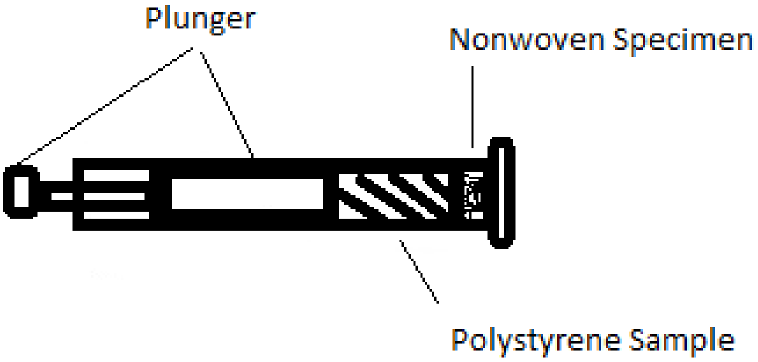

Figure 3.7a: Testing set-up with air gap of 0 mm (no air gap).with nonwoven specimen in contact with the polystyrene sheet specimen.

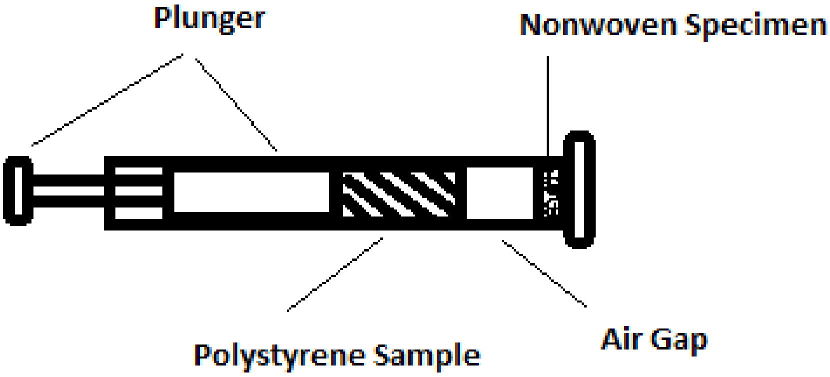

Figure 3.7b: Testing set-up with a variable air gap between the nonwoven specimen and the polystyrene sheet specimen.

4. RESULTS AND DISCUSSION

This chapter reports detailed analysis of the results obtained from the experimental work conducted in two distinct parts. The results and analysis are separated and discussed in three sections. The first section reports preliminary results obtained for establishing suitable ranges of the chosen variables for the optimization study. The second section deals with the results on optimization of production parameters in producing needlepunched nonwoven fabrics for sound absorption application. The third section reports the results on application of the needlepunched nonwoven fabrics backed by extruded polystyrene (XPS) sheet with varying air gaps in between the fabric and the XPS sheet. The objective of this study was to achieve maximum possible sound absorption coefficients.

4.1. Preliminary Results

The sound absorption coefficients and sample thicknesses of the nonwoven fabrics are shown in Tables 4.1. (a-d). In general, both fabric thickness and sound absorption coefficients increased with an increase in PET fibre content within a blend for the fabrics under study.

As shown in Table 4.1(a), the sound absorption coefficients of the nonwoven fabrics produced from 100% natural fibres were generally lower than those for all the fabrics produced from natural fibre blends. This was largely due to the fact that natural fibres are generally coarse and have low crimp, which minimises the level of tortuosity, thus offering minimum resistance to air-flow within the fabric. Therefore, the sound absorption coefficients were lower in the fabrics containing a high amount of natural fibres, which is attributed to minimised frictional hindrance.

Table 4.1 (a): Average sound absorption coefficient (50-5700 Hz) and thickness of nonwoven fabrics produced from 100% natural fibres at different process variables.

Variables			**Sound Absorption**	**Fabric Thickness**
X (Fibre Type)	Y Depth of Needles Penetration (mm)	Z Stroke Frequency (1/min)	**α**	mm
Hemp	6	255	0.20	5.40
Agave	6	255	0.23	8.38
Hemp	10	255	0.23	5.19
Agave	10	255	0.21	7.60
Hemp	8	240	0.18	5.28
Agave	8	240	0.24	8.13
Hemp	8	270	0.17	4.97
Agave	8	270	0.21	7.33
Flax	6	240	0.21	5.55
Flax	10	240	0.27	6.83
Flax	6	270	0.38	8.30
Flax	10	270	0.23	5.98
Hemp	8	255	0.21	5.41
Hemp	8	255	0.20	4.81
Hemp	8	255	0.21	4.88

Thus, as PET fibres are relatively finer, their addition in the blend addresses the problem by increasing the bulkiness of the structure resulting from increased thickness at the same area weight, thereby, maximising frictional hindrances. This character of the PET fibres implies that more (PET) fibres are required per unit volume to match with the weight of the natural fibres, which results in more fibre surface area per unit volume as well.

The finer PET fibres are also responsible for increased tortuosity and resultant increase in resistance to airflow which, in turn, increases the sound absorption coefficient of the fabric. It was observed that the sound absorption coefficient of the nonwoven fabrics improved with the addition of 30% PET fibres in a blend with the natural fibres (Table 4.1 (b)).

Table 4.1. (b): Average sound absorption coefficient (50-5700 Hz) and thickness of nonwoven fabrics produced from a blend of 70% natural and 30% pet fibres at different production variables.

Variables			Sound Absorption	Fabric Thickness
X (Fibre Type)	Y Depth of Needles Penetration (mm)	Z Stroke Frequency (1/min)	α	mm
Hemp	6	255	0.24	5.14
Agave	6	255	0.26	7.87
Hemp	10	255	0.27	5.01
Agave	10	255	0.25	7.22
Hemp	8	240	0.21	5.02
Agave	8	240	0.28	7.67
Hemp	8	270	0.20	4.27
Agave	8	270	0.25	7.10
Flax	6	240	0.26	5.27
Flax	10	240	0.30	6.48
Flax	6	270	0.42	7.98
Flax	10	270	0.27	5.72
Hemp	8	255	0.24	5.24
Hemp	8	255	0.22	4.87
Hemp	8	255	0.24	5.04

From Table 4.1 (c-d), it can be noticed that further increase in PET fibre content in the blends, generally resulted in further increase in sound absorption coefficient of the fabrics under study.

Initially, the depth of needle penetration was varied in a step of 2 mm, which implied that a difference of only 4 mm was set between the minimum and maximum depths of needle penetration of 6mm and 10mm as shown in Tables 4.1 (a) and 4.1 (b) above. This resulted in modest variations in the thickness of the fabrics amongst the fabrics produced. Therefore, a larger variation of 3mm in depth of needle penetration was then tried, and set at 4mm, 7mm and 10mm, with the difference between the minimum and maximum being

Table 4.1. (c): Average sound absorption coefficient (50-5700Hz) and thickness of nonwoven fabrics produced from a blend of 30% natural and 70% pet fibres at different process variables.

Variables			**Sound Absorption Coefficient**	**Fabric Thickness**
X (Fibre Type)	Y Depth of Needles Penetration (mm)	Z Stroke Frequency (1/min)	**α**	mm
Hemp	4	300	0.58	9.56
Wool	4	300	0.54	9.68
Hemp	10	300	0.30	5.86
Wool	10	300	0.42	7.77
Hemp	7	200	0.48	8.84
Wool	7	200	0.56	10.41
Hemp	7	400	0.39	7.25
Wool	7	400	0.43	8.33
Agave	4	300	0.51	10.40
Agave	10	300	0.35	10.40
Agave	7	200	0.45	9.16
Agave	7	400	0.41	8.23
Hemp	7	300	0.41	7.42
Hemp	7	300	0.41	7.74
Hemp	7	300	0.40	8.51

6mm, this is 50% higher than the previous difference of 4mm. This change resulted in achieving higher variations in the thickness of the fabrics as shown in Table 4.1 (c) and 4.1 (d). For the purpose of this study, the depths of needle penetration were chosen to ensure perceptible variations in the physical characteristics of the fabrics, such as thickness and density together with other fabric characteristics, namely, pore size and its distribution.

The difference in stroke frequency was also revised in order to achieve higher variations in the physical properties of the fabrics produced. Wider variations in the physical properties of the fabrics were necessary to bring about more variation in sound absorption properties. To achieve this, the stroke frequency was revised from 240/min, 255/min and 270/min, to 200/min, 300/min and 400/min. This was later adjusted to 250/min, 300/min and 350/min

Table 4.1. (d): Average sound absorption coefficient (50-5700 Hz) and thickness of nonwoven fabrics produced from a blend of 20% natural and 80% pet fibres at different process variables.

Variables			**Sound Absorption Coefficient**	**Fabric Thickness**
X (Fibre Type)	Y Depth of Needles Penetration (mm)	Z Stroke Frequency (1/min)	**α**	mm
Hemp	4	300	0.49	8.99
Agave	4	300	0.66	12.43
Hemp	10	300	0.35	6.61
Agave	10	300	0.30	6.28
Hemp	7	250	0.45	8.57
Agave	7	250	0.52	7.86
Hemp	7	350	0.48	8.53
Agave	7	350	0.56	10.31
Flax	4	300	0.54	9.61
Flax	10	300	0.36	6.27
Flax	7	250	0.41	7.72
Flax	7	350	0.46	8.12
Hemp	7	300	0.41	7.47
Hemp	7	300	0.42	7.51
Hemp	7	300	0.40	7.75

after concerns about possible fibre damage at high stroke frequencies due to needle breakages were noticed since the production speed was also relatively slow.

After experimenting with different blend ratios, stroke frequencies and depths of needle penetration, a choice of settings was established for the study reported in Section 4.2. The blending ratio of 50:50 (natural fibre: PET fibre) was chosen as a good balance between the need for thermoformability and bulkiness in the fabric by adding PET fibres and maintaining the desired bio-based character by using natural fibres to reduce the carbon footprint of the final products [10].

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4.2. Optimization of Needlepunching Process Parameters For Sound Absorption Applications

After the nonwoven fabrics were produced, the area weight was measured to ensure that this chosen independent variable was held as uniform (minimum variation) as possible among the samples produced for this study. Therefore, it was necessary to eliminate any samples with unacceptable variations (outside the 900-1100 g/m^2) in nominal area weight of 1000 g/m^2 and those samples were reproduced. The area weight is an important parameter as it affects density and thickness of the needlepunched nonwoven fabrics. Thickness is a major factor which influences sound absorption properties of the nonwoven fabrics, particularly at low sound frequencies [75, 19]. Density of the fabrics plays an indirect role in determining the tortuosity and air voids (porosity) within the material, which influences sound absorption coefficient as discussed in Section 2.6.

4.2.1. Effect of Thickness, Fibre Type, Depth of Needle Penetration and Stroke Frequency on Sound Absorption

Table 4.2.1 shows the coded and actual values of the parameters used to produce each fabric together with values of average fabric thickness and average sound absorption coefficients measured in the frequency range of 50-5700 Hz. These values of thickness and sound absorption coefficients were compared to corresponding values of a commercial needle-punched fabric produced by *Feltex Trim*.

Since the area weight of 1000 g/m^2 was maintained as uniform as practically possible for all the samples in this study, other production parameters were varied according to the experimental design explained in Section 3.2. It followed that the thickness of the produced fabrics would also vary due to its dependence on these production parameters. Therefore, given the importance of material thickness already explained, it is important to analyze and discuss the patterns in fabric thickness variation.

Table 4.2.1 Average sound absorption coefficient (50-5700 Hz) and thickness of nonwoven fabrics produced with different experimental variables.

Run Number	Sample ID	Levels			Actual Values			Sound Absorption Coefficients	Thickness (mm)
		X	Y	Z	X	Y	Z	α	
1	1 Hemp	-1	-1	0	Hemp	4	300	**0.44**	**7.497**
2	2 Agave	1	-1	0	Agave	4	300	**0.40**	**9.091**
3	3 Hemp	-1	1	0	Hemp	10	300	**0.38**	**6.144**
4	4 Agave	1	1	0	Agave	10	300	**0.33**	**6.670**
5	5 Hemp	-1	0	-1	Hemp	7	250	**0.35**	**6.876**
6	6 Agave	1	0	-1	Agave	7	250	**0.35**	**8.316**
7	7 Hemp	-1	0	1	Hemp	7	350	**0.33**	**6.325**
8	8 Agave	1	0	1	Agave	7	350	**0.31**	**7.453**
9	9 Flax	0	-1	-1	Flax	4	250	**0.42**	**8.088**
10	10 Flax	0	1	-1	Flax	10	250	**0.45**	**7.139**
11	11 Flax	0	-1	1	Flax	4	350	**0.45**	**7.924**
12	12 Flax	0	1	1	Flax	10	350	**0.33**	**6.127**
13	13 Flax	0	0	0	Flax	7	300	**0.32**	**5.970**
14	14 Flax	0	0	0	Flax	7	300	**0.31**	**5.945**
15	15 Flax	0	0	0	Flax	7	300	**0.34**	**5.829**
X	Commercial Sample							**0.28**	**7.550**

At a first glance of Table 4.2.1 above, it is somewhat difficult to notice any trends or patterns about the effect of fabric thickness on sound absorption coefficients which is largely because of the fact that process parameters are not the same for all the samples produced according to the experimental design used in this study. The next step was to analyze the data on thickness and sound absorption individually, each one as a function of the tested variables.

On a closer and careful observations of Table 4.2.1, it can be observed that the fabrics produced from a blend of agave and PET fibres, with a mean thickness of 7.883mm, were generally thicker than those produced from other blends, see also Figure 4.2.1.; this is largely due to the fact that agave fibres are relatively coarser than hemp and flax fibres. On the other hand, it can be seen that the fabrics produced from a blend of hemp and PET fibres, and the fabrics produced from a blend of flax and PET fibres showed mean fabric thickness of 6.711 mm and 6.717 mm, respectively.

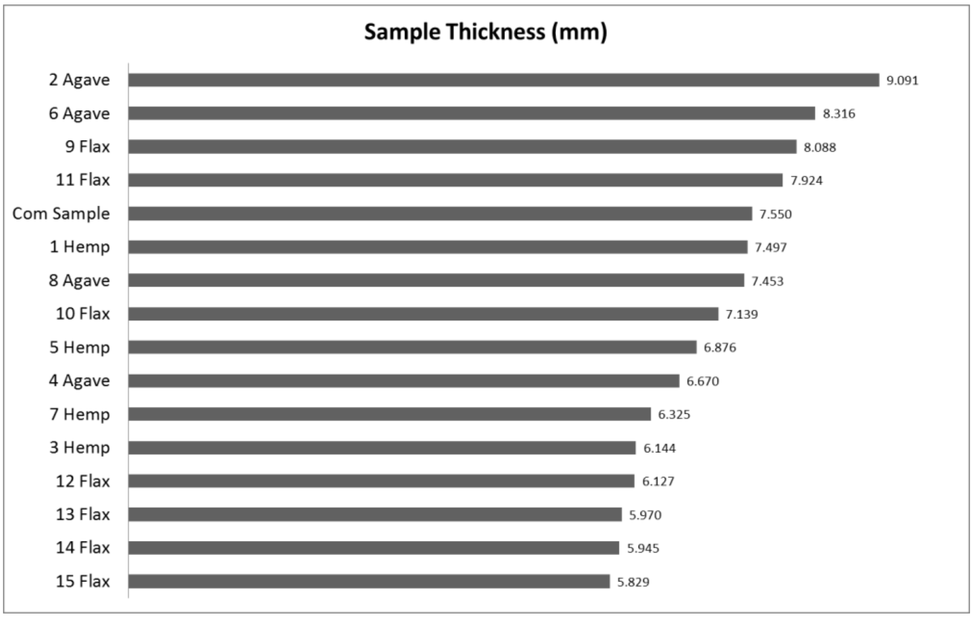


Figure 4.2.1 Comparison of thicknesses of nonwoven fabrics (run number and fiber type)

While thickness was set initially during web formation, the final adjustment can be achieved during needlepunching, primarily by varying the depth of needle penetration. Depth of needle penetration is the most influencing factor which influences thickness of the fabric during needlepunching. Three settings of depth of needle penetration were chosen deliberately in this work to bring about variations in the thicknesses of the samples as explained in Section 3.1. The fabrics produced with the lowest depth of needle penetration are generally expected to be thicker than those produced with the highest depth of needle penetration. From Table 4.2.1 and Figure 4.2.1 it is observed that the fabrics produced from agave and flax fibres with depth of needle penetration of 4mm tended to be in the majority of the top third of the thickest fabrics.

Stroke frequency is not generally a major factor influencing the thickness of the needlepunched nonwoven fabrics. However, since the stroke frequency, the number of needles per width (cm) and production speed, together determine **"***punch density***"**, stroke frequency may indirectly influence the thickness of the fabrics [8]. A careful observation of Table 4.2.1 shows that when comparing the fabrics produced from the same fibres and same depth of needle penetration but different stroke frequencies, those produced at a lower stroke frequency were generally thicker. As shown in Table 4.2.1 this can be observed by comparing the samples 5Hemp vs 7Hemp both produced at 7mm depth of needle penetration with 250/min vs 350/min stroke frequency, 6Agave vs 8Agave produced at 7mm depth of needle penetration and 250/min vs 350/min stroke frequency and 10Flax vs 12Flax produced at 10mm depth of needle penetration and 250/min vs 350/min stroke frequency. The fabrics produced at 250/min stroke frequency were generally thicker than those produced at 350/min stroke frequency. This can be attributed to the fact that at high stroke frequency the fabric experiences higher number of needle punching strokes per unit area in given time and thus achieve more compact fabric [116].

It may be concluded that all the three parameters studied here influence the fabric thickness, so, they also influence sound absorption coefficients of the fabrics because sound absorption is directly related to the fabric thickness. As explained in Section 2.6.2, fabric thickness is a main influencing factor particularly at low sound frequencies in comparison to high sound frequencies [66]. This is due to the fact that sound absorption of a porous material is effective when the material thickness is about one tenth of the wavelength of the incident sound wave [64].

This relationship between thickness and sound absorption implies that, in general, high sound absorption coefficient is achieved when the fabric thickness is higher. However, as observed from Figure 4.2.2, this was not the case for all the fabrics which implies that other fabric characteristics may be affecting sound absorption properties. It should also be quickly pointed out that the parameters studied here do not determine or affect fabric thickness alone, there are other parameters which affect thickness that were not part of this study.

As shown in Figure 4.2.2, all experimental fabrics achieved relatively better sound absorption coefficient than that of the commercial sample ($\alpha = 0.28$). The commercial reference sample is a needlepunched nonwoven fabric which consists of a mixture of polyester (PET) and recycled shoddy fibres with an area weight of about 1000 g/m^2 and a thickness of about 7.55mm; which is used in automotive carpets for acoustic insulation by the majority of South African automotive manufacturers.

In Figure 4.2.2, the comparison of sound absorption coefficients by sample type shows that it is difficult to conclusively explain any general trend or pattern relating to any one of the parameters studied here.

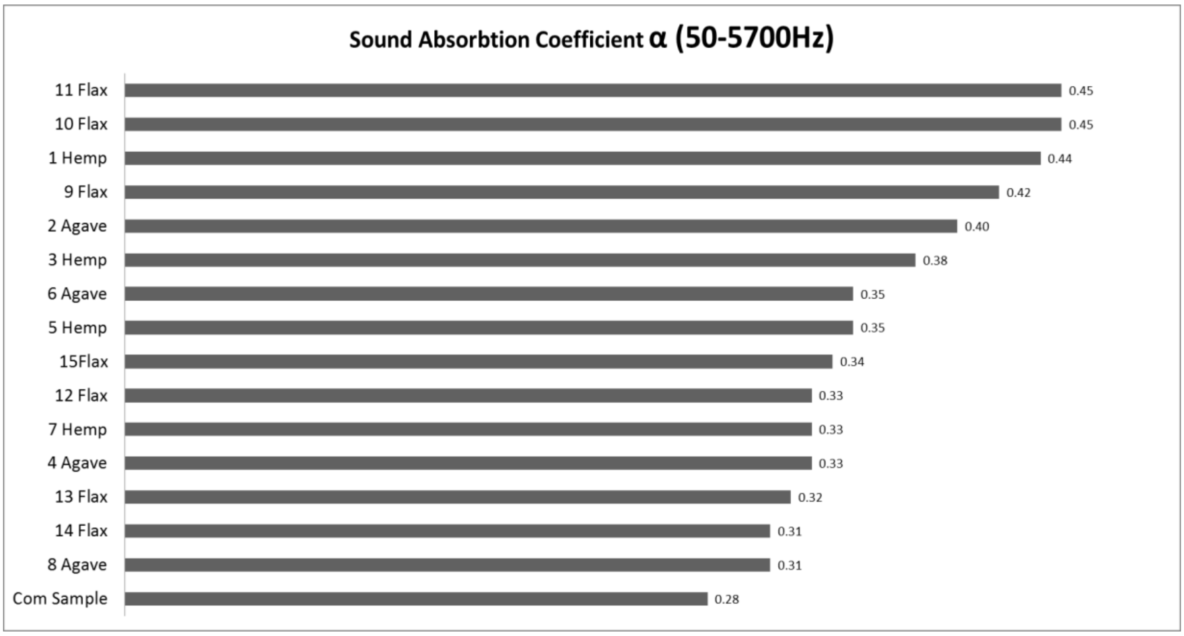
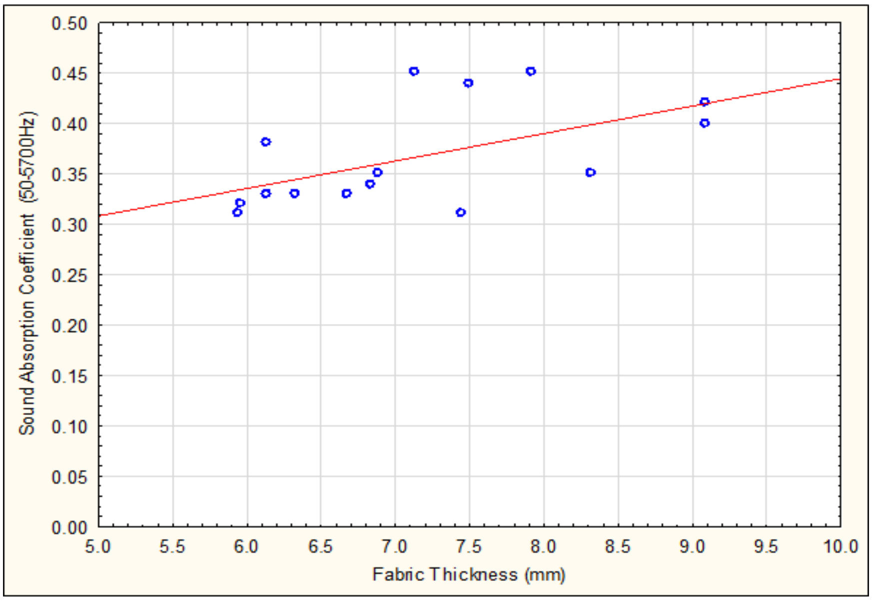


Figure 4.2.2. Comparison of measured sound absorption coefficients (run number and fiber type)

The three parameters studied here also influence other fabric characteristics, such as porosity, compression, fabric density and tortuosity which may be intricately interlinked with thickness. Therefore, it is necessary to analyse simultaneous effects of all these parameters particularly in context to determining sound absorption properties of the nonwoven fabrics.

It is important to estimate the correlation between the thickness of the material and sound absorption coefficient to verify their inter-dependence as shown in Figure 4.2.3. Generally, the correlation coefficient between fabric thickness and sound absorption coefficient is expected to be high. However, the relatively low value of r = 0.56 (Pearson correlating coefficient) obtained here may be due to simultaneous effects of other fabric characteristics on sound absorption over and above fabric thickness. However, the significance probability, p-value = 0.030 (95% confidence interval), still shows that thickness is a significant factor for sound absorption.



r = 0.56 (Pearson correlation coefficient)
P = 0.030 (Significant at 5% level)

Figure 4.2.3. The correlation coefficient between fabric thickness and sound absorption coefficient (50-5700Hz)

Other fabric characteristics like porosity and tortuosity are determined by the type of natural fibres (level of fineness) and their contents in a blend in the fabric. The fabrics produced by blending coarse fibres, for example, agave will be more porous with less air resistance because of a wide difference in the diameters of agave and PET fibres which means that there will be less fibre hindrance per unit volume. Therefore, these fabrics will absorb less sound energy for a given fabric thickness compared to those fabrics produced from blends of flax-PET and hemp-PET fibres, since they are relatively finer than agave fibres.

The fabrics produced from a blend of flax-PET fibres will therefore have more fibres per unit volume which implies that the fabrics are denser with less porosity, more air resistance and higher tortuosity [17]. This is why these fabrics achieve better sound absorption coefficient than those fabrics produced from a blend of agave-PET fibres.

Fabric density and fabric compression are directly linked to the depth of needle penetration, stroke frequency and fabric area weight. The number of fibres per unit volume increases when the apparent fabric density increases; therefore, energy loss (of the sound wave) increases due to the increase in surface friction, which results in a better value of the sound absorption coefficient.

The compression of the nonwoven fabrics also results in variation in other fabric properties such as increased tortuosity and air flow resistivity and decreased porosity. Despite these changes in physical parameters of the compressed material, the reason for a drop in sound absorption value is mainly attributed to the decrease in thickness of the fibrous medium [68].

Now, given that the area weight was not varied in this work, variation in fabric thickness also resulted in variation in fabric density, i.e. the denser fabrics (more fibres per unit volume) were also comparatively thinner than the other fabrics. Therefore, comparing sound absorption as a function of fabric density and compression individually was difficult due to the fact that thickness of the fabric is a major factor in determining sound absorption properties.

4.2.1.1. The Synergistic Effect of the Tested Parameters on Sound Absorption Coefficient –The Rationale for Optimization

A conclusion that can be drawn from the analysis in Section 4.2.1 above is that all the fabric characteristics influencing sound absorption properties of the needlepunched fabrics discussed in Section 2.6 are dependent upon more than one parameter, be it process parameters or fibre parameters. Therefore, it is apparent that some of the effects of varying natural fibre type (which is effectively a variation in physical dimension of the fibres and surface area) are the same as the effects of varying depth of needle penetration and stroke frequency. In other words, the effects of varying these parameters are interlinked for all the parameters.

Therefore, it can be generally argued that the production parameters interactively influence the properties and functionality of the needlepunched nonwoven fabrics. This is also the case with fabric characteristics, such as thickness and density, which influence the sound absorption coefficient of the fabric. It is, therefore, important to analyse individual and interactive effects of these parameters on sound absorption coefficients.

The interactive effects of the process parameters may be analyzed by a systematic optimization study. Therefore, by multiple regression analysis, coefficients of parameters (fiber type, depth of needle penetration and stroke frequency) and significance probability (P-value) were calculated, as shown in Table 4.2.2. The statistical significance of probability, P-value at 95% confidence interval was determined; if it is less than 0.05 then the effect of the parameter on sound absorption is significant and vice versa.

From Table 4.2.2, it is observed that all the selected parameters showed significant effect on measured sound absorption since all the P-values were less than 0.05. As evident from the table, the depth of needle penetration played the most dominant role among all the selected parameters. This was expected as the depth of needle penetration is the main determinant of fabric thickness and it has already been explained that the fabric thickness has the most dominant effect on sound absorption ability of a porous material [12].

Table 4.2.2. ANOVA for the three parameters and their interactions, probability (*P*-value) and correlation coefficient.

Term	**Coefficient**		**P-value**
Constant	C	31.923	0.000
Fibre Type	X	-1.375	0.028
Needle Depth	Y	-2.75	0.001
Stroke Frequency	Z	-1.875	0.006
Fibre Type * Fibre Type	X^2	-	**0.156**
Needle Depth*Needle Depth	Y^2	7.135	0.000
Stroke Frequency*Stroke Frequency	Z^2	1.885	0.037
Fibre Type * Needle Depth	XY	-	**0.097**
Needle Depth * Stroke Frequency	YZ	-3.75	0.001
Stroke Frequency*Fibre Type	ZX	-	**0.171**
Coefficients of determination	R^2	0.96	

The interaction between depth of needle penetration and stroke frequency showed the second most dominant effect on sound absorption coefficients. The effects of interactions between stroke frequency and fibre type and between fibre type and depth of needle penetration on sound absorption coefficients were not significant as they all had high P-values. Again, as it has already been discussed, depth of needle penetration together with stroke frequency, directly affect fabric thickness, and so also influence fabric density, porosity and air resistivity. Therefore, it is expected that the interactive effect between depth of needle penetration and stroke frequency should have high contribution in determining sound absorption capabilities of the fabric.

The variation in fibre type played the least dominant role in determining sound absorption properties. This could be because of the fact that the differences (variation) in mean fibre fineness between different natural fibres were not enough to cause highly variable effects on sound absorption coefficients of the fabrics. Also, the fact that all the blends were made from 50% PET and 50% natural fibres means that half of the fibres in each fabric were PET, with uniform fibre characteristics. Ultimately, this means that the effect of fibre type (fineness) on sound absorption will be minimized. For evaluating a complete picture on the role of different parameters and their interaction effects on sound absorption coefficients, a response surface methodology was employed.

The response surface equation for sound absorption is given by:

$$\alpha = C_0 + C_1 X + C_2 Y + C_3 Z + C_{22} Y^2 + C_{33} Z^2 + C_{23} YZ \qquad (32)$$

Where α is the coefficient of sound absorption and C is the coefficient of a particular variable, after substituting relevant values, we obtain the following equation with coefficient of determination, $\mathbf{R^2}$, value of 0.96.

$$\alpha = 31.923 - 1.375X - 2.75Y - 1.875Z + 7.135Y^2 + 1.885Z^2 - 3.75YZ \qquad (33)$$

4.2.2. Effect of Selected Parameters on Sound Absorption Coefficients and Process Optimization

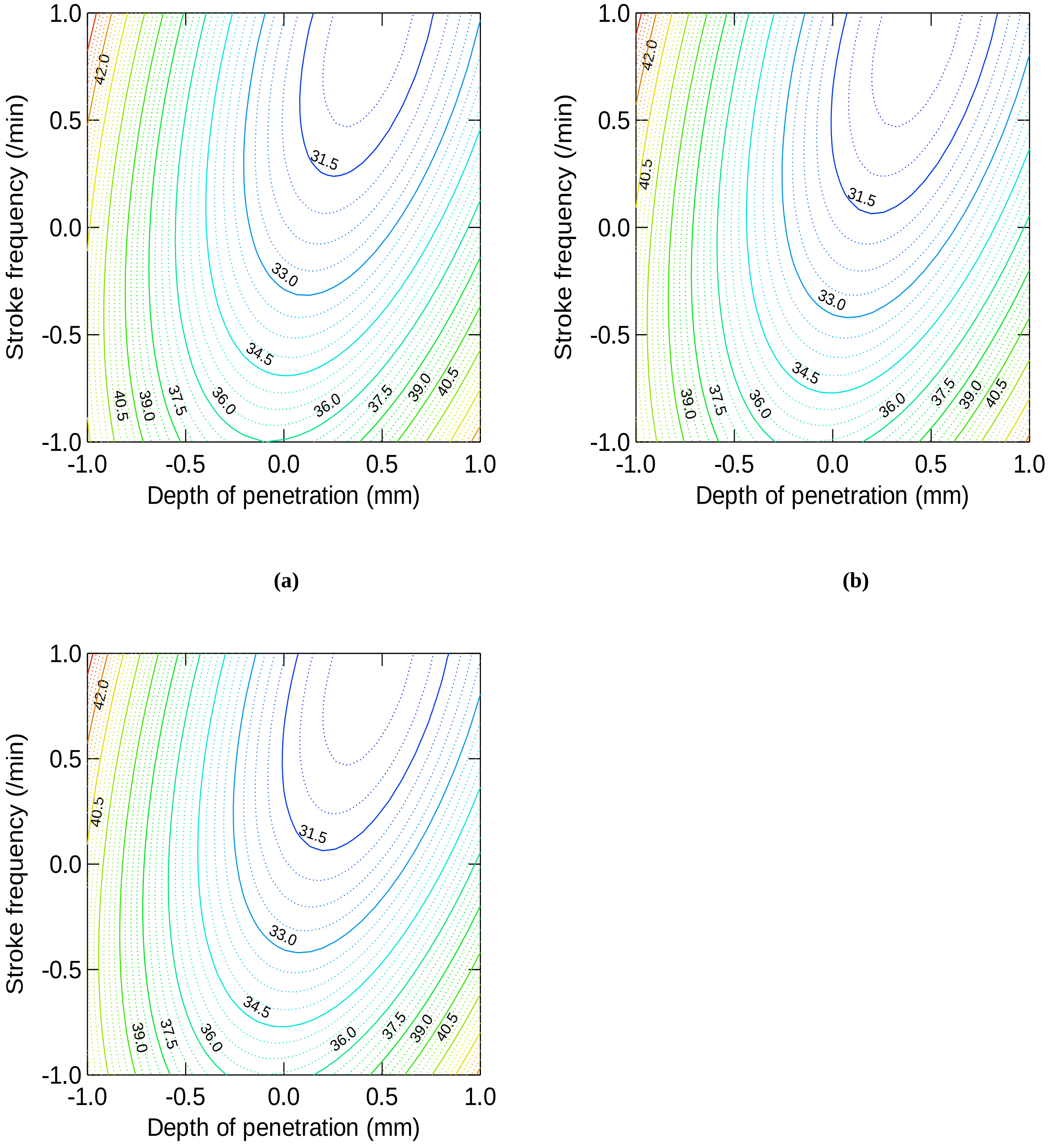
The response surfaces of sound absorption coefficients (50-5700Hz) as a function of different levels of selected parameters and optimized regions are discussed in this section. The different cases have been evaluated based on statistical significance and dominance of the selected parameters in achieving maximum possible sound absorption coefficients as shown above in Table 4.2.2.

4.2.2.1. Effect of Depth of Needle Penetration's and Stroke Frequency on Sound Absorption coefficients for Different Fiber Types

From Table 4.2.2, it is observed that depth of needle penetration showed the most dominant effect followed by the interaction between depth of needle penetration and stroke frequency. Figure 4.2.4 shows the response surface plots of interaction effect between different levels of depth of needle penetration and stroke frequency for different fibre types (hemp, flax and agave) on sound absorption coefficients.

For the fabrics produced from a blend of 50% hemp and 50% PET fibres, an interaction effect between depth of needle penetration and stroke frequency on sound absorption coefficient at different levels is shown in Figure 4.2.4 (a). The values of percentage sound absorption coefficient at -1 level (4mm), 0 levels (7mm) and +1 level (10mm) of depth of needle penetration were 41%, 36% and 42%, respectively. It can be observed that with the increase in depth of needle penetration from -1 level (4mm) to 0 level (7mm), the percentage sound absorption coefficient decreased by 12%, however, it increased by 17% when depth of needle penetration is increased from 0 level (7mm) to +1 level (10mm).

This trend remains the same for the fabrics produced from the other two natural fibres, i.e. flax and agave as shown in Figures 3b and 3c respectively. For the fabrics produced from



(a)

(b)

(c)

Figure 4.2.4. Contour plots showing interaction effects between depth of needle penetration and stroke frequency on sound absorption coefficients of fabrics produced from different natural fibres: (a) Hemp, (b) Flax and (c) Agave.

a blend of flax and PET fibres, the values of percentage sound absorption coefficients at -1 level (4mm), 0 level (7mm) and +1 level(10mm) of depth of needle penetration were 41.5%, 35.5% and 43%, respectively. For the fabric produced from agave and PET fibres, the values of percentage sound absorption coefficients at -1 level (4mm), 0 level (7mm) and +1 level (10mm) of depth of needle penetration were 42%, 35.5% and 45%, respectively. Sound absorption coefficients decreased when the depth of needle penetration increased from 4mm to 7mm but it increased when the depth of needle penetration was increased from 7mm to 10mm.

This could be attributed to fabric thickness playing a major role between -1 level (4mm) and 0 level (7mm) of depth of needle penetration, i.e. with the increase in depth of needle penetration the fabric thickness decreased which led to the decrease in sound absorption coefficient [10,11]. On the other hand, between 0 level (7mm) and +1 level (10mm) of depth of needle penetration, when the density of the fabric is increased due to the decrease in thickness (same area weight), the sound absorption coefficient was increased, which is consistent with the results reported by Koizumi et al [54].

Furthermore, as the fabric structure becomes more compact, the average pore size decreases but with more pores in any given unit volume, therefore, hindrances to the passage of sound also increase with the increase in frictional resistance. In other words, the fabric structure becomes more tortuous; thereby sound absorption coefficients also increase due to energy losses resulted from conversion of sound energy to heat energy [89].

The values of percentage sound absorption at -1 level (250/min), 0 level (300/min) and +1 level (350/min) of stroke frequency were 41%, 41% and 43.5%, respectively for hemp fibre, as shown in Figure 4.2.4 (a). With the increase in stroke frequency from -1 level (250/min) to 0 level (300/min), no change in sound absorption coefficients was observed and when stroke frequency increased from 0 level (300/min) to +1 level (350/min) only a modest increase of 6% was observed.

The trend is similar for the other two fibres, where between -1 level (250/min) and 0 level (300/min) of stroke frequency, change in sound absorption coefficient was marginal and then a modest increase between 0 level (300/min) and +1 level (350/min) of stroke frequency (or a slight decrease of 3.5% and 5% for flax and agave fibres, respectively).

This general trend is similar to that observed above in the case of depth of needle penetration. This also confirms that the effects of depth of needle penetration and stroke frequency are interlinked in determining the resultant fabric structure as evident from the P-values of 0.001 and 0.006, respectively shown in Table 4.2.2 above, where the effect of interaction between depth of needle penetration and stroke frequency on sound absorption coefficients was statistically significant. Furthermore, the levels of stroke frequency selected in the present set of experiment may not be high enough to cause significant variations in sound absorption coefficient.

Maximum percentage sound absorption coefficient of 45% (0.45) was achieved for fabrics produced from flax fibres at -1 level (4mm) of depth of needle penetration and +1 level (350/min) of stroke frequency which corresponds to experimental trial run 11, see Table 4.2.1.

4.2.2.2. Effect of Fibre Type and Depth of Needle Penetration on Sound Absorption Coefficients at Different Values of Stroke Frequency

The second case of the interaction effect is that of different fibre types and different levels of depth of needle penetration on sound absorption coefficient (50-5700Hz) at different levels of stroke frequency, namely, 250, 300 and 350/min.

The response surface plots of fiber type and depth of needle penetration at a stroke frequency of 250/min is shown in Figure 4.2.5.(a). The values of percentage sound absorption coefficient at -1, 0, +1 levels of fibre types (hemp, flax and agave) were 43%, 42% and 40.5%, respectively. For the fabrics produced from a blend of hemp and PET fibres and those produced from a blend of flax and PET fibres, a smaller difference (2.3%) in percentage sound absorption coefficient was observed as compared to that for the fabrics produced from a blend of agave and PET fibres where the differences with respect to the fabrics produced from a blend of hemp and PET fibres and those produced from a blend of flax and PET fibres were 6% and 3.6%, respectively.

At the stroke frequency of 300/min, the percentage sound absorption coefficient values for the fabrics produced from a blend of hemp and PET fibres, those produced from a blend of flax and PET fibres and those produced from a blend of agave and PET fibres were 43%, 42% and 40% (0.43, 0.42 and 0.40), respectively. The differences in percentage sound absorption coefficient values between the fabrics produced from a blend of hemp and PET fibres and those produced from a blend of flax and PET fibres and between the fabrics produced from a blend of flax and PET fibres and those produced from a blend of agave and PET fibres were only 2% and 7.5%, respectively.

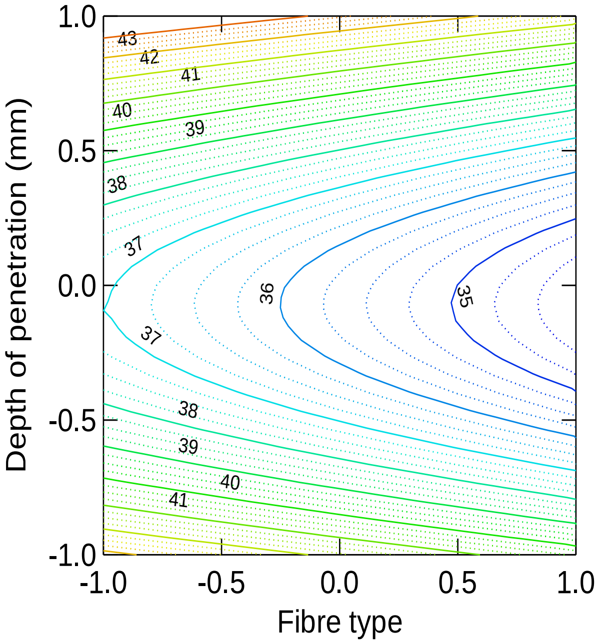


Figure 4.2.5 (a)

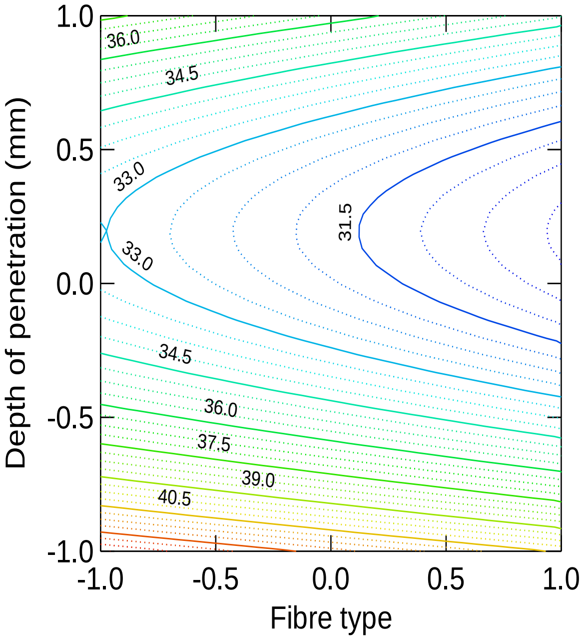


Figure 4.2.5 (b)

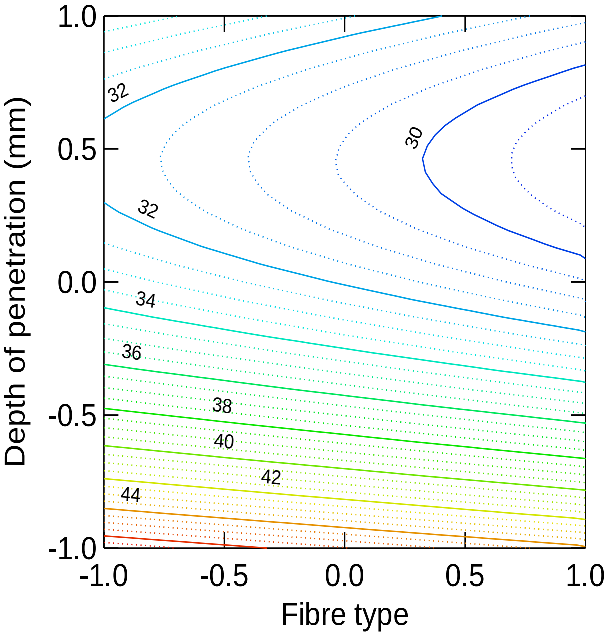


Figure 4.2.5 (c)

Figure 4.2.5. Contour plots showing interaction effects between different fibres and depth of needle penetration on sound absorption coefficients of fabrics produced at variable stroke frequencies: (a) 250/min, (b) 300/min and (c) 350/min.

At the stroke frequency of 350/min, the percentage sound absorption coefficients of the fabrics produced from a blend of hemp and PET fibres, those produced from a blend of flax and PET fibres and those produced from a blend of agave and PET fibres were 47%, 45.5% and 44%, respectively. Like in the other two stroke frequencies, the differences in percentage sound absorption coefficients of the fabrics were very minimal, only 3% between the fabrics produced from a blend of hemp and PET fibres and the fabrics produced from a blend of flax and PET fibres, only 3% between the fabrics produced from a blend of flax and PET and those produced from a blend of agave and PET fibres and 6% between the fabrics produced from a blend of hemp and PET fibres and those produced from a blend of agave and PET fibres.

Overall, the trend is the same for all three settings of stroke frequency studied, i.e. sound absorption coefficients vary marginally among different fibre blends and particularly the variations were even smaller between the fabrics produced from a blend of flax and PET fibres and those produced from a blend of hemp and PET fibres. This can be due to the fact that fibre fineness values of flax and hemp fibers are lower as compared to that of agave fibres which are much coarser than the other two fibres. Yilmaz et al. [15] and Tascan and Vaughn [17] showed that nonwoven fabrics made from finer fibres absorb sound better than those made from coarser fibres. This is due to the difference in the number of fibres per unit volume in the fabric structure, where the use of finer fibres results in more fibres per volume and vice-versa.

At a constant stroke frequency of 250/min the increase in depth of needle penetration from -1 (4mm) to 0 level (7mm), percentage sound absorption coefficient decreased from 43% to 37%, which accounts for 14% decrease, but as the depth of needle penetration increased from 0 level (7mm) to +1 level (10mm), percentage sound absorption coefficient increased again from 37% to 45%, which accounts for 22% increase, this trend is similar to that observed in Section 4.2.2.1 above.

At a stroke frequency of 300/min, with the increase in depth of needle penetration from -1 level (4mm) to 0 level (7mm), the percentage sound absorption coefficients decreased from 45.5% to 33.5% which is about 26% decrease. When the depth of needle penetration was further increased from 0 level (7mm) to +1 level (10mm), the percentage sound absorption coefficients increased from 33.5% to 37.5%, which is about a 12% increase. This trend is the same as observed in the case of 250/min stroke frequency and discussed in Section 4.2.2.1 above.

In the last case, at a stroke frequency of 350/min, when the depth of needle penetration was increased from -1 level (4mm) to 0 level (7mm), the percentage sound absorption coefficients decreased from 46.5% to 33.5%, which is about 28% decrease. When the depth of needle penetration was further increased from 0 level (7mm) to +1 level (10mm), the percentage sound absorption coefficients increased slightly from 33.5% to 34%, which is about 1.5% increase. Although, this is the smallest increase when compared to the corresponding change in depth of needle penetration and stroke frequencies, the trend is still the same.

The combined influence of fibre type (fineness), depth of needle penetration and stroke frequency showed that -1 level of fibre type (hemp), -1 level of depth of needle penetration (4mm) and +1 level of stroke frequency (350/min) provided the fabrics with highest percentage sound absorption coefficient of 47% (0.47). However, no fabric was produced with these exact parameters according to the Box-Behnken experimental design used in this study, see Table 4.2.1.

4.2.2.3. Effects of Stroke Frequency and Fibre Type on Sound Absorption Coefficients at Different Depths of Needle Penetrations

The last case is to study the interactive effects between different levels of stroke frequency and fibre types (fineness) on sound absorption coefficient of the fabrics at different levels of depth of needle penetration, as shown in Figure 4.2.6. The stroke frequency was the second most dominating individual parameter after depth of needle penetration and the fibre type was the least dominant and the interaction between stroke frequency and fibre type was not significant as it is absent in Table 4.2.2. But for evaluating a complete response surface design, this effect needs to be analysed further.

The interaction effect between different levels of stroke frequency and fiber types at depth of needle penetration of 4 mm is shown in Figure 4.2.6(a). At -1 level (250/min), 0 level (300/min) and +1 level (350/min) of stroke frequency, the percentage sound absorption coefficients of the fabrics were 43%, 42% and 40%, respectively.

When the stroke frequency is increased from -1 level (250/min) to 0 level (300/min), about 2% decrease in percentage sound absorption coefficient of the fabric was observed and a further 5% decrease as the stroke frequency increased from 0 level (300/min) to +1 level (350/min) which accounts to an overall decrease of 7% in percentage sound absorption coefficient as the stroke frequency increased from -1 level (250/min) to +1 level (to 350/min).

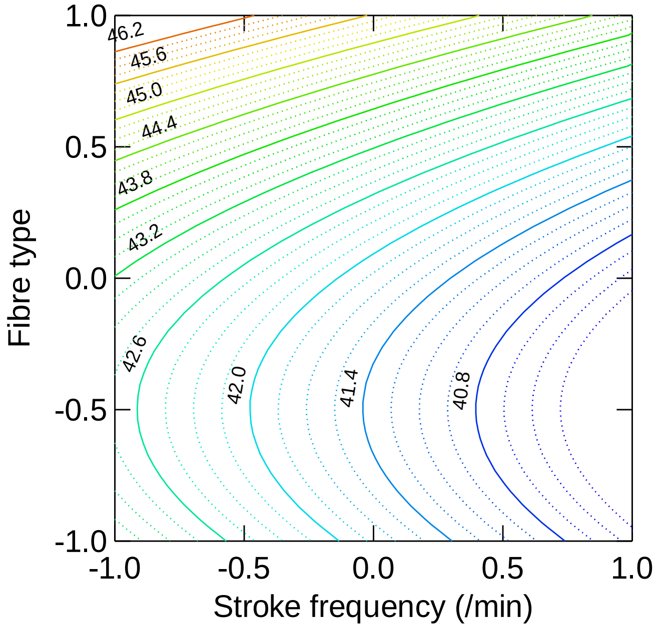


Figure 4.2.6.(a)

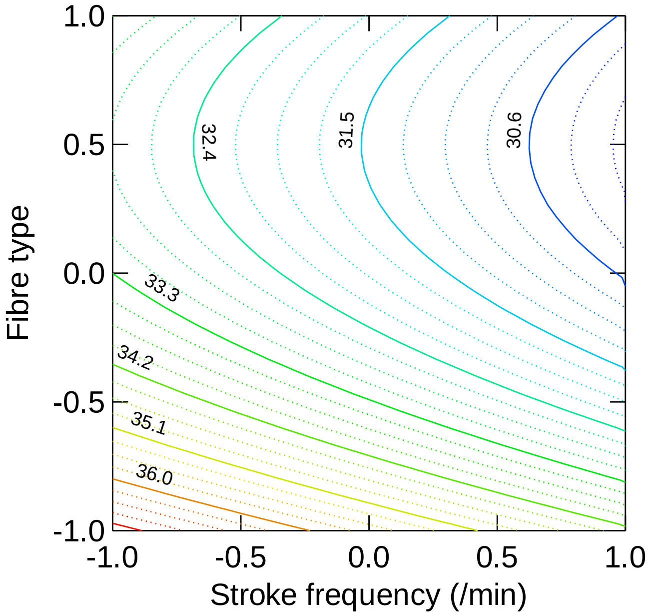


Figure 4.2.6 (b)

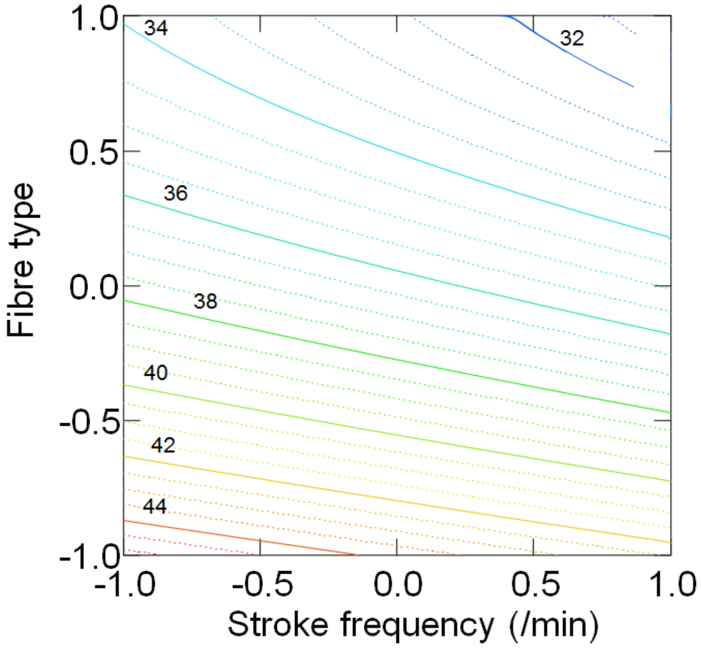


Figure 4.2.6 (c)

Figure 4.2.6. Contour plots showing interaction effects between stroke frequency and fibre type on sound absorption coefficients of the fabrics at variable depth of needle penetrations: (a) 4mm, (b) 7mm and (c) 10mm.

At a depth of needle penetration of 7 mm the percentage sound absorption coefficients of the fabrics produced at -1 level (250/min), 0 level (300/min) and +1 level (350/min) of stroke frequency were 37%, 35.5% and 34.5%, respectively. This means that with the increase in stroke frequency from 250/min to 300/min, the percentage sound absorption coefficients decreased by 4% and when the stroke frequency increased further from 300/min to 350/min the sound absorption coefficient decreased by 3% with overall decrease of about 7%.

At the depth of needle penetration of 10 mm, percentage sound absorption coefficients at -1 level (250/min), 0 level (300/min) and +1 level (350/min) of stroke frequency were 45%, 43.5% and 42.5%, respectively. Here, the percentage sound absorption coefficients decreased by 3% with the increase in stroke frequency from 250/min to 300/min, after which it decreased by 2% with the increase in stroke frequency to 350/min, which accounts to an overall decrease of 5 %.

The inverse relationship between stroke frequency and sound absorption coefficients may be described by the fact that higher stroke frequency results in decrease in fabric thickness, however, not enough to allow sufficient increase in fabric density to affect sound absorption coefficient as discussed in the previous section. Also, the pore sizes may not have changed so much to cause drastic changes in sound absorption coefficients.

At a depth of needle penetration of 4mm, with the change in fiber type, from hemp flax, and agave, the percentage sound absorption coefficients of the fabrics were 43%, 43% and 47%, respectively. The percentage sound absorption coefficients of the fabrics produced from blends of flax and PET fibres and those produced from hemp and PET fibres were similar but about 9% higher in the case of fabrics produced from agave fibres. However, at a depth of needle penetration of 7 mm, the percentage sound absorption coefficient of the fabrics produced from blends of agave and PET fibres was 33% which is similar to that of fabrics produced from blends of flax and PET fibres but lower than that produced from hemp fibres (37%), which is higher by about 12%. At a depth of needle penetration of 10 mm, for the fabrics produced from a blend of hemp and PET fibres, a blend of flax and PET fibres and a blend of agave and PET fibres, the percentage sound absorption coefficients were 45%, 37.5% and 34% , respectively.

The fabrics produced from a blend of agave and PET fibres performed better at lower depths of needle penetration than the fabrics produced from blends of the other two natural fibres with PET fibres because of the coarseness of agave fibres, which resulted in a bulky nonwoven. The fabrics produced from hemp and PET fibres performed better than those produced from blends of the other two natural fibres with PET fibres at a higher depth of needle penetration because a relatively compact fabric structure was produced. In this case, a combined influence of fibre type and stroke frequency showed the maximum percentage sound absorption coefficient of 47% (0.47) for the fabrics produced from agave fibres at 4mm depth of needle penetration and 250/min stroke frequency. However, no fabric was produced with these exact parameters according to the Box-Behnken experimental design used in this study, see Table 4.2.1.

4.2.2.4.Effect of the Optimized Parameters on Fabric Characteristics.

After the process of optimizing the three parameters from the response surface plots of three different two way interactions, furthermore, it was necessary to analyse the implications of the effects of these optimized parameters on fabric characteristics. As it can be seen from the analysis in the previous Sections 4.2.2.1 to 4.2.2.3, the highest percentage sound absorption coefficient of 47% (0.47) was obtained in two different response surface plots.

In the interaction between fibre type and depth of needle penetration at different values of stroke frequency, the percentage sound absorption coefficient of 47% (0.47) was obtained at -1 level of fiber type (hemp), -1 level of depth of needle penetration (4mm) and +1 level of stroke frequency (350/min). While for the interaction between stroke frequency and fiber type at different depths of needle penetration, the percentage sound absorption coefficient of 47% (0.47) was obtained at +1 level of fibre type (agave), -1 level of depth of needle penetration (4mm) and -1 level of stroke frequency (250/min).

Both these samples were not produced as part of this work, see Table 4.2.1. Also, the effect of interaction between stroke frequency and fibre type on sound absorption coefficients was not significant according to the high P-values (95% confidence interval) in Table 4.2.2. Therefore, only the maximum percentage sound absorption coefficient of 47% (0.47) for the interaction between fibre type and depth of needle penetration will be considered here as well as the second highest percentage sound absorption coefficient of 45% (0.45) achieved among the fabric samples actually produced (experimental run 11, Table 4.2.1) from flax fibres at -1 level (4min) of depth of needle penetration and +1 level (350/min) obtained on the interaction effect between depth of needle penetration and stroke frequency.

According to the optimization exercise reported above, the optimized depth of needle penetration is 4 mm, which is the minimum setting in this study. Given that the main fabric characteristic, namely, thickness, is affected by the depth of needle penetration, a thicker fabric with less density is produced in comparison to that at higher depth of needle penetration.

It has already been stated, thicker fabrics achieve better sound absorption coefficients at low sound frequencies. Also, it has been discussed that an increase in fabric density increased the sound absorption coefficients particularly in the middle and higher sound frequencies [54]. Therefore, the converse is true; a less dense fabric would not achieve higher sound absorbing at middle to high sound frequencies. Therefore, in context to these two attributes of the fabrics, namely, thickness and fabric density, the fabrics produced with the optimized parameters are suitable for sound absorption application at low sound frequencies.

The optimum fibre type is hemp fibre, which is finer than agave fibre but slightly coarser than flax fibre. It must also be noted that out of the three tested parameters, fibre type was the least significant parameter with the P-value of 0.028 in comparison to 0.001 and 0.006 for depth of needle penetration and stroke frequency, respectively, as shown in Table 4.2.2.

4.3. Effects of Air-gap, Fibre Type and Blend Ratio on Sound Absorption Performance of Needle-Punched Nonwoven Fabrics

4.3.1. Air Permeability

As explained in Section 2.6.3, air flow resistivity is one of the main factors which influence the sound absorption capabilities of a nonwoven fabric. Air flow resistivity is dependent on air permeability of the material which, in turn, is influenced by other factors such as fibre fineness (type) and blending ratio. Air permeability values of all the nonwoven fabrics produced are shown in Table 4.3.1 and Figure 4.3.1 below.

Table 4.3.1 : Air permeability values of the tested fabrics

Fibre Blend	**Air Permeability ($ml/s/cm^2/125Pa$)**
Wool 30:70 PET	**19.41**
Wool 50: 50 PET	**19.56**
Wool 70: 30PET	**22.68**
Flax 30: 70 PET	**20.03**
Flax 50: 50 PET	**22.06**
Flax 70: 30 PET	**24.14**
Agave 30: 70 PET	**31.37**
Agave 50: 50 PET	**38.56**
Agave 70: 30 PET	**43.79**

From Figure 4.3.1, it can be observed that, in general, the fabrics produced from agave and PET fibres were the most air permeable. Also the air permeability of the fabrics increased with the increase in natural fibre content in the blend.

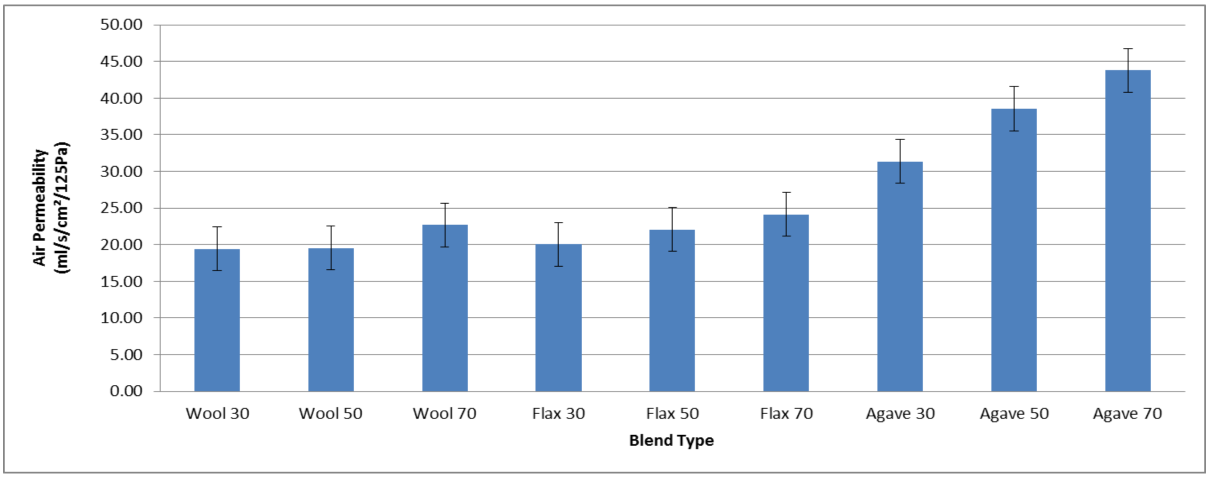


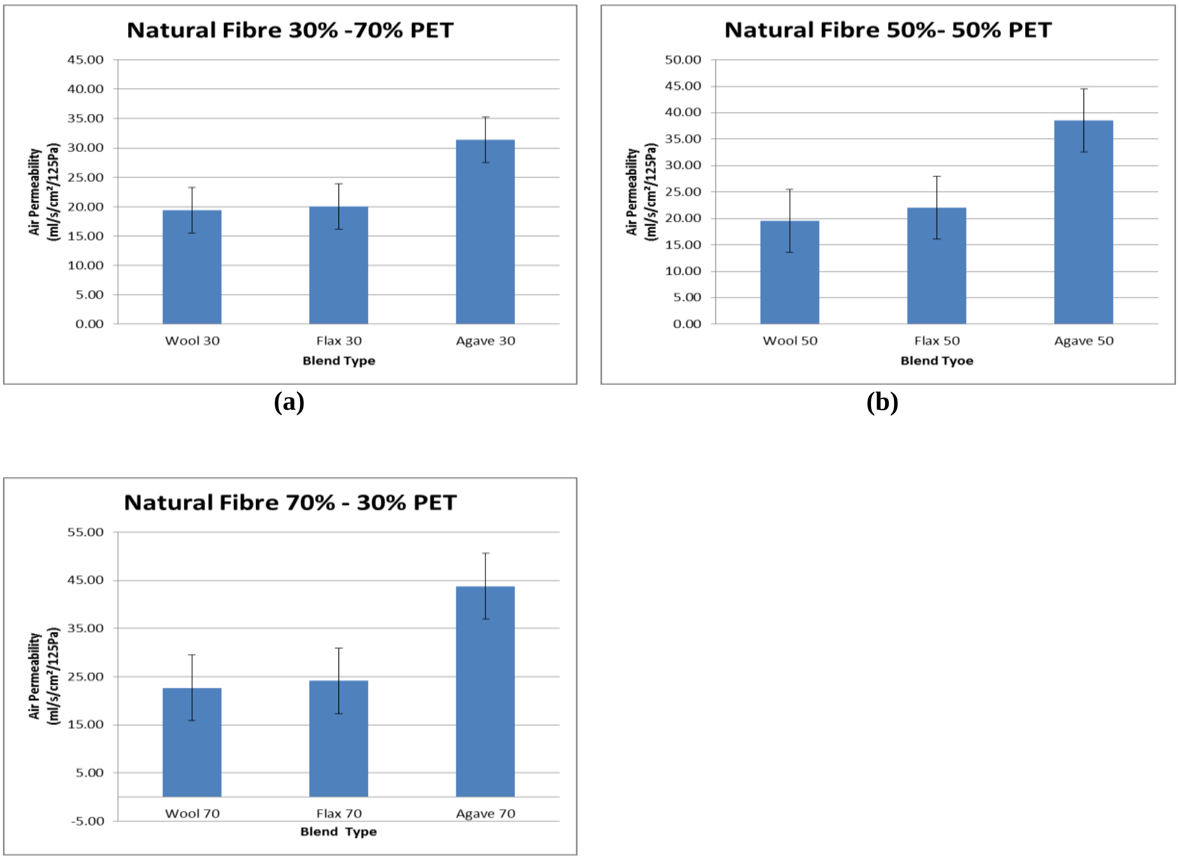
Figure 4.3.1. Air permeability of the nonwoven fabrics

Both these observed trends can be attributed to the fact that the natural fibres are coarser than PET fibres and agave fibres were the coarsest of the three natural fibres used. So, the fabrics containing higher amounts of natural fibres than PET fibres, would have bigger pores compared to those containing lesser amounts of natural fibres than PET fibres, this is attributed to relative disparity in fibre fineness, thus resulting in higher air permeability, which is consistent with the observation of Nick et al [53].

A more in-depth investigation started with studying the effects of fibre fineness (type) on air permeability values of the fabrics produced from the three natural fibres blended with PET fibres for a given blending ratio. The second part of the investigation will be to study the effect of blending ratio on air permeability by studying air permeability values of the fabrics produced at different blending ratios of PET fibres and a particular natural fibre.

4.3.1.1.Effect of Fibre Fineness (Type) on Air Permeability

Comparisons of air permeability values of the samples produced from three different natural fibres blended with PET fibres at three blending ratios are shown in Figure 4.3.2. The effect of fibre fineness on air permeability of the fabrics is studied by comparing the air permeability of the fabrics produced at the same blending ratio.



(a)

(b)

(c)

Figure 4.3.2 Comparison of air permeability of fabrics produced from: (a) 30:70 % blend of natural and PET fibres, (b)) 50:50 % blend of natural and PET fibres and (c)) 70:30 % blend of natural and PET fibre

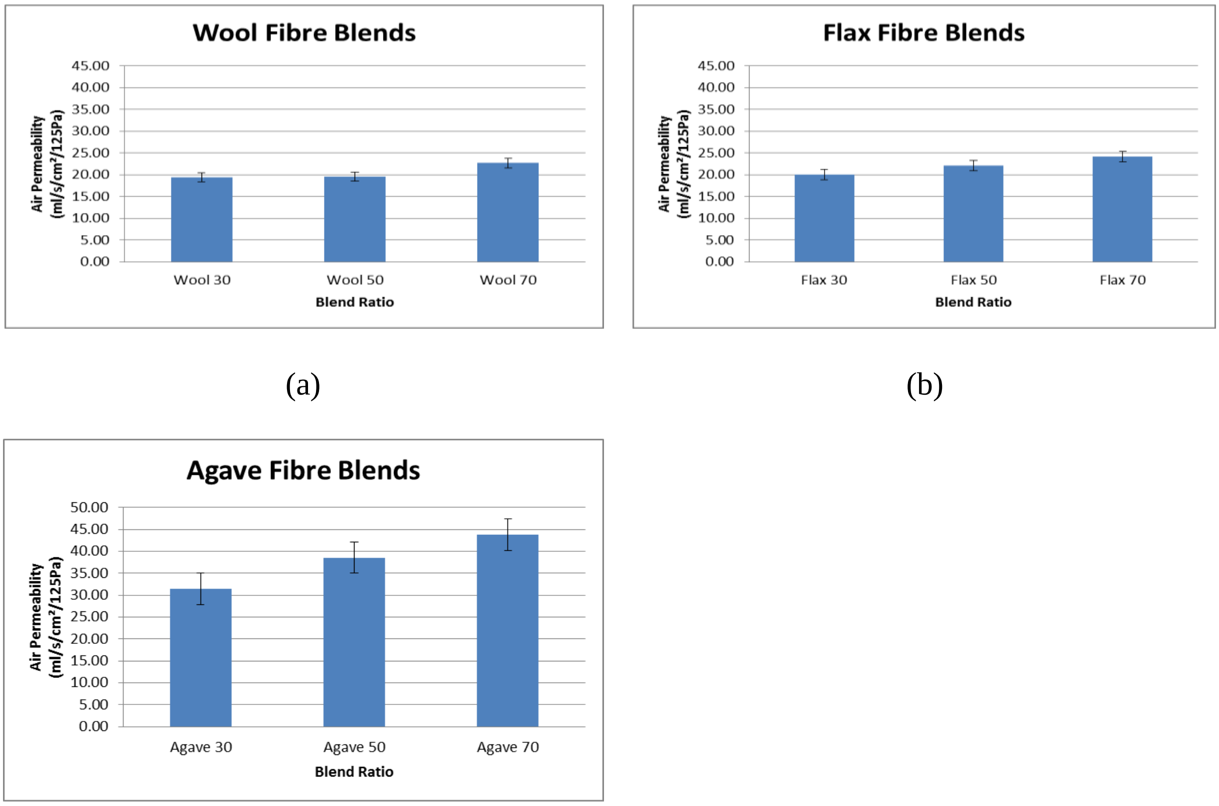
It can be observed that amongst all the fabrics in all three blend ratios, the fabrics produced from a blend of agave and PET fibres achieved the highest air permeability, followed in general, by fabrics produced from blends of flax and PET fibres. Fabrics produced from blends of wool and PET fibres generally had the least air permeability. In all the blends containing 70% natural fibres, the difference in air permeability values between the fabrics produced from agave and PET fibres and the one produced from flax and PET fibres is about 45%, while the difference between the fabrics produced from agave and PET fibres and the one produced from wool and PET fibres is about 48%. Yet the difference in air permeability between the fabrics produced from flax and PET fibres and the one produced from wool and PET fibres is 6%. A similar comparison exists in the fabrics produced from the other two blend ratios as well.

This trend can be attributed to the fact that agave fibres are considerably coarser than PET fibres, more so than wool and flax fibres. This disparity in fibre fineness results in higher porosity in the fabrics produced from agave fibres and thus they are more air permeable than the fabrics produced from wool and flax fibres. This observation of a direct link between fibre fineness and air permeability is consistent with the results reported by Cox and D'antonio [52].

4.3.1.2.Effect of the Blending Ratio on Air Permeability

As shown in Figure 4.3.3, the effect of blending ratio on air permeability is studied by comparing air permeability results of the fabrics produced from the blends of three different natural fibres, each one blended with PET fibres at three blending ratios.

From Figure 4.3.3, it can be seen that for a given natural fibre; air permeability of the fabrics is directly proportional to the amount of natural fibre content in a blend with PET fibres, i.e. air permeability increases with the increase in natural fibre content. This follows from the fact that finer fibres, in this case PET fibres, will be packed such that there is more fibres per unit volume in comparison to coarser fibres, which results in a more tortuous path and therefore hindrance to air permeability [55-56]. Thus, the air permeability is lower for the fabrics containing 70% PET fibres than that for the fabrics containing 30% PET fibres.



(a) (b)

(c)

Figure 4.3.3 Comparison of Air Permeability of Fabrics Produced at Different Blending Ratios of: (a) Wool (b) Flax, (c) Agave and PET Fibres

The rate of change in air permeability with respect to change in natural fibre content in the blend is markedly different for the three different natural fibres. It is minimal for the fabrics produced from a blend of wool and PET fibres and more defined in the fabrics produced from a blend of agave and PET fibres. About 1% increment in air permeability was noticed as the wool fibre content in the blend increased from 30% to 50% and about 16% increment in air permeability as the wool fibre content increased from 50% to 70%. Overall, as the wool fibre content in the fabrics increased from 30% to 70%, the air permeability of the fabric increased by 17%.

As the flax fibre content in the blend increased from 30% to 50% the resultant increase in air permeability of the fabric was 10% and with further increase in flax fibre content from 50% to 70% the air permeability increased by 9.5%. Overall, as the flax fibre content increased from 30% to 70%, air permeability of the fabric increased by 21%. In the case of fabrics produced from a blend of agave and PET fibres, it can be seen that when the agave fibre content increased from 30% to 50%, the air permeability increased by 23% and with further increase of the agave fibre content from 50% to 70%, the air permeability of the fabric increased by 13.5%. So overall, as the agave fibre content increased from 30% to 70%, the air permeability of the fabric increased by 40%.

In summary, with the increase in natural fibre content from 30% to 70%, the air permeability of the blended fabrics increased by 17%, 21% and 40%, for the fabrics produced from wool and PET fibres, flax and PET fibres and agave and PET fibres, respectively. These observations together with those reported in Section 4.3.1.1 above showed that while both fibre type (fineness) and blending ratio affected air permeability of the fabric, the effect of fibre type was the most pronounced. The biggest change in air permeability with the change in natural fibre content was observed in the fabrics produced from a blend of agave and PET fibres, more so than the change in air permeability observed by changing the blending ratios for blends of wool and PET fibres and blends of flax and PET fibres.

4.3.1.3. Statistical Analysis of the Effect of Fibre Fineness and Blending Ratio on Air Permeability

The data on air permeability of the produced samples was statistically analysed using Statistica II software on MS Excel to establish the significance of fibre type and blending ratio. The statistical significance of probability, P-value at 95% confidence interval was tested as shown in Table 4.3.2.

Table 4.3.2. ANOVA for fibre type and blend ratio as parameters affecting air permeability.

	SS	Deg. of Freedom	MS	F	P
Intercept	6486.39	1	6486.39	939.3556	0.0000
Fibre Type	554.1992	2	277.0996	40.12942	0.0023
Blend ratio	65.3858	2	32.6929	4.734569	0.0882
Error	27.62059	4	6.905148		

From Table 4.3.2, it can be observed that the P-value for fibre type is below the 0.05 threshold, meaning that the influence of fibre type is significant. The P-value of the blend ratio on the other hand is greater than the 0.05 threshold which means that the effect of blending ratio is insignificant at the 95% confidence interval; see further discussion on Table 4.3.4 below.

The Tukey HSD Tests and the corresponding least square plots were produced for both the parameters to further analyse the internal variation within each parameter. The values in the top row of Table 4.3.3 are the least square mean values for air permeability corresponding to a particular parameter, i.e. fibre type.

The P-values in the middle of the Tukey HSD Test Table indicate whether these mean values in the first row of the table are significantly different from each other, if the value is less than 0.05 then the two mean values of air permeability are significantly different from each other, and vice versa. These P-values also correspond to the positioning of the confidence interval bars on the graph relative to each other, if the confidence interval bars overlap then it means that the mean air permeability values are not significantly different form each other and if there is no overlap then it means that the mean air permeability values are significantly different from each other.

A Tukey HSD Test Table for the effect of fibre type on air permeability is shown in Table 4.3.3 and the corresponding least square plot in Figure 4.3.4. It can be observed that the P-value of the comparison of the mean air permeability value of the fabrics produced from a blend of agave and PET fibres and that of the fabrics produced from a blend of wool and PET fibres is 0.003 and the P-value of the comparison of the mean air permeability value of the fabrics produced from a blend of agave and PET fibres and that of the fabrics produced from a blend of flax and PET fibres is 0.0041. Both these P-values are less than 0.05 and thus indicate that the difference is significant. However, when comparing the mean air permeability value of the fabrics produced from a blend of wool and PET fibres with the mean air permeability value of the fabrics produced from a blend of flax and PET fibres, the P-value of 0.7703 (above 0.05) indicates that the two mean air permeability values are not significantly different from each other.

Table 4.3.3. Tukey HSD Test for Fibre Type

Fibre Type	**Mean Air Permeability**		
	20.551	**22.078**	**37.908**
Wool			
Flax	0.7703		
Agave	**0.0030**	**0.0041**	

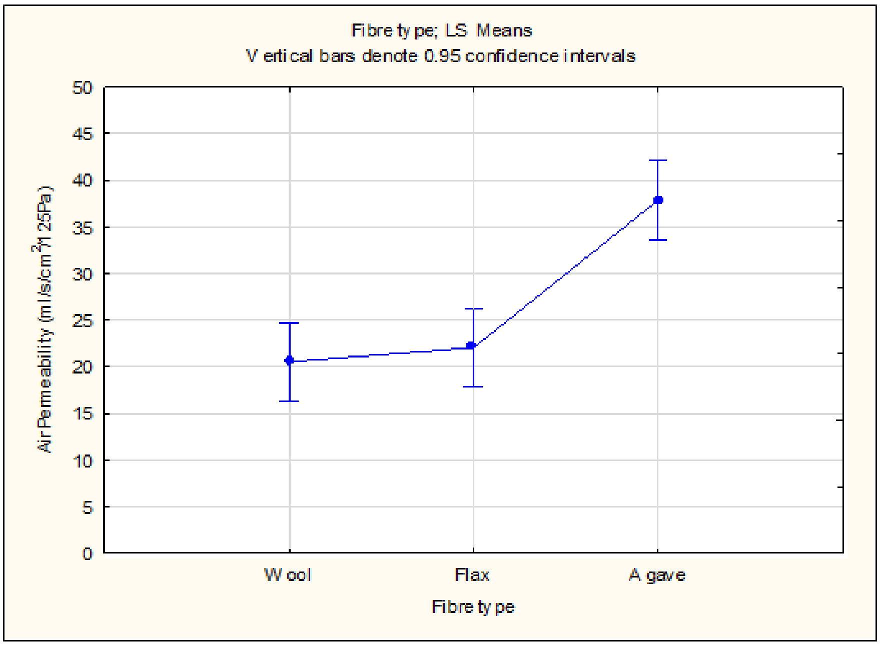


Figure 4.3.4. Least Square Mean values of the effect of fibre type on air permeability.

It can be observed from the least square plot in Figure 4.3.4 that the air permeability of the fabrics produced from a blend of agave and PET fibres is the highest which is in agreement with Figure 4.3.2. The mean air permeability values of the fabrics produced from a blend of flax and PET fibres and those produced from a blend of wool and PET fibres have overlapping confidence intervals and therefore not significantly different from each other.

In comparing the mean values of air permeability from Table 4.3.3, it can be observed that the air permeability of the fabrics produced from the blends of agave and PET fibres are 72% higher than that of the fabrics produced from a blend of flax and PET fibres and it is 84% higher than that of the fabrics produced from a blend of wool and PET fibre. While the difference between the mean air permeability of the fabrics produced from flax fibre blends and wool fibre blends is only about 7.5 %.

For analysing the effect of fibre blending ratio on air permeability the Tukey HSD test was conducted and the results are shown in Figure 4.3.4. The P-values indicate that all the mean air permeability values are not significantly different from each other at the 95% confidence interval as all the values are above 0.05. This is in agreement with Table 4.3.2, where the effect of blending ratio on air permeability was not significant at the 95% confidence interval.

Table 4.3.4. Tukey HSD Test for blending ratio

Ratio	**Mean Air Permeability**		
	23.606	**26.728**	**30.205**
30_70			
50_50	***0.4001***		
70_30	***0.0778***	***0.3379***	

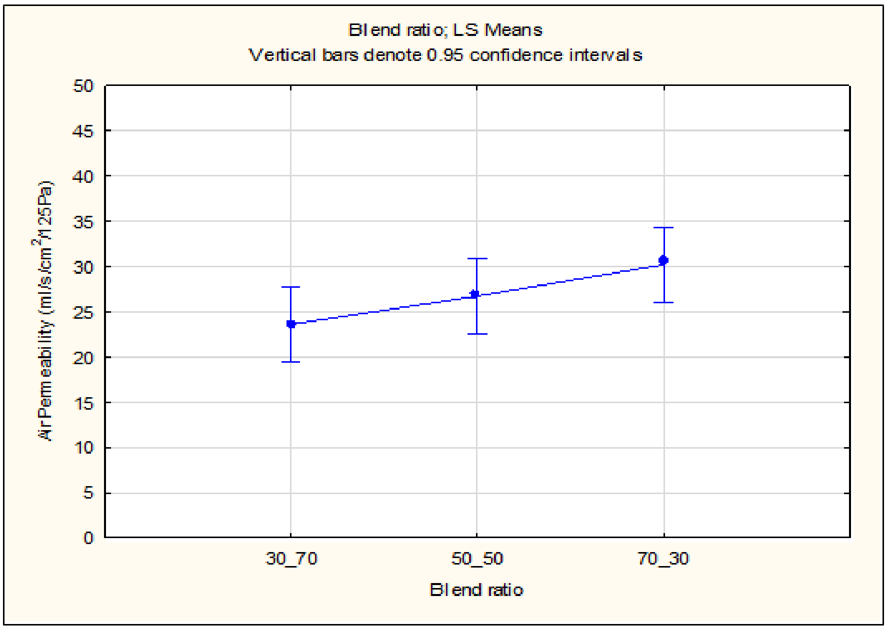


Figure 4.3.5. Least Square Mean values of air permeability vs blend ratio

The overlap of the confidence interval bars is evident in Figure 4.3.5 which indicates statistically insignificant difference in the three mean air permeability values. This observation also confirmed that the effect of blending ratio on air permeability was not significant as shown by P-value in Table 4.3.2. However, on a closer inspection of the results, since the P-value is still small (< 0.10), the effect is significant at the 90% confidence level. In the Tukey Test results shown in Table 4.3.4, it shows that the difference in air permeability values between the 30%-70% blend ratio (mean air permeability=23.6 ml/s/cm^2/125Pa) and the 70%-30% blend ratio (mean air permeability=30.2 ml/s/cm^2/125Pa), although statistically insignificant at the 95% confidence level, it is still significant at the 90% confidence level (P = 0.0778).

The least square plot in Figure 4.3.5 showing the effect of blending ratios on air permeability is also in agreement with Figure 4.3.3 showing that air permeability is directly proportional to natural fibre content for a particular natural fibre type, i.e. with the increase in natural fibre content in a blend, from 30% to 70%, the air permeability of the fabric also increases.

4.3.2. Sound Absorption

In this section the effect of each parameter, namely, fibre type (fineness), blend ratio and air gap on sound absorption coefficients is described, and it is followed by a statistical analysis of the overall results by ANOVA.

The average sound absorption coefficients in the frequency range of 50-5700 Hz for each fabric produced from blending natural fibres with PET fibres backed by a varying air gaps and an XPS sheet were evaluated as shown in Table 4.3.5 and Figure 4.3.6. The fabrics produced from wool and PET fibres, in general, showed better sound absorption coefficients than the other fabrics. Amongst the three different fabric blends, the fabrics produced from agave and PET fibres showed the lowest sound absorption coefficients. This was expected because wool fibre is known for its good sound absorption properties due to fibre surface morphology characterized by scales [38]. These scales play a major role in absorbing sound as they increase fibre surface area and thus create higher hindrance to the sound wave.

Agave fibres on the other hand is thick with poor crimp which means that fibre surface area per unit volume is relatively lesser in the fabrics produced from a blend of agave and PET fibres and the porosity is generally higher and therefore air permeability of the fabrics is higher as discussed in Section 4.3.1.

The fabrics produced from different blend ratios of flax and PET fibres generally showed the second highest sound absorption coefficients due to the fact that the flax fibres were relatively finer than agave fibres so the fabrics produced from a blend of flax and PET fibres have more fibre surface area per unit volume compared to those produced from a blend of agave and PET fibres and thus have less air permeability and are more tortuous.

Table 4.3.5. Sound absorption coefficients of nonwoven fabrics backed by an XPS sheet at varying air-gaps and different fibre types

Natural Fibre Type	Air Gap Size (mm)	Sound Absorption Coefficients (α) At 50-5700 Hz		
		30:70 % Natural Fibre: PET Fibres	50:50 % Natural Fibre: PET Fibres	70:30 % Natural Fibre: PET Fibres
Waste Wool	0	0.46	0.46	0.47
	5	0.62	0.61	0.63
	10	0.75	0.75	0.76
	15	0.77	0.77	0.78
	20	0.78	0.77	0.78
	25	0.77	0.76	0.76
Flax	0	0.44	0.44	0.47
	5	0.63	0.64	0.60
	10	0.73	0.73	0.72
	15	0.77	0.76	0.74
	20	0.77	0.75	0.74
	25	0.76	0.74	0.73
Agave	0	0.44	0.45	0.42
	5	0.61	0.57	0.52
	10	0.71	0.69	0.62
	15	0.72	0.71	0.64
	20	0.71	0.71	0.65
	25	0.69	0.67	0.62

In general, the fabrics produced from a blend of 30:70% natural and PET fibres achieved higher sound absorption coefficients than those produced from a blend of 50:50% natural and PET fibres, while the sound absorption coefficients of the fabrics produced from a blend of 70:30% natural and PET fibres were generally the lowest with an exception for the fabrics produced from a blend of wool and PET fibres in which the sound absorption coefficients increased with the increase in wool fibre content. This can be attributed to the fact that the fabrics produced from higher PET fibre content than natural fibres have higher surface area per unit volume due to fineness of the PET fibres [75].

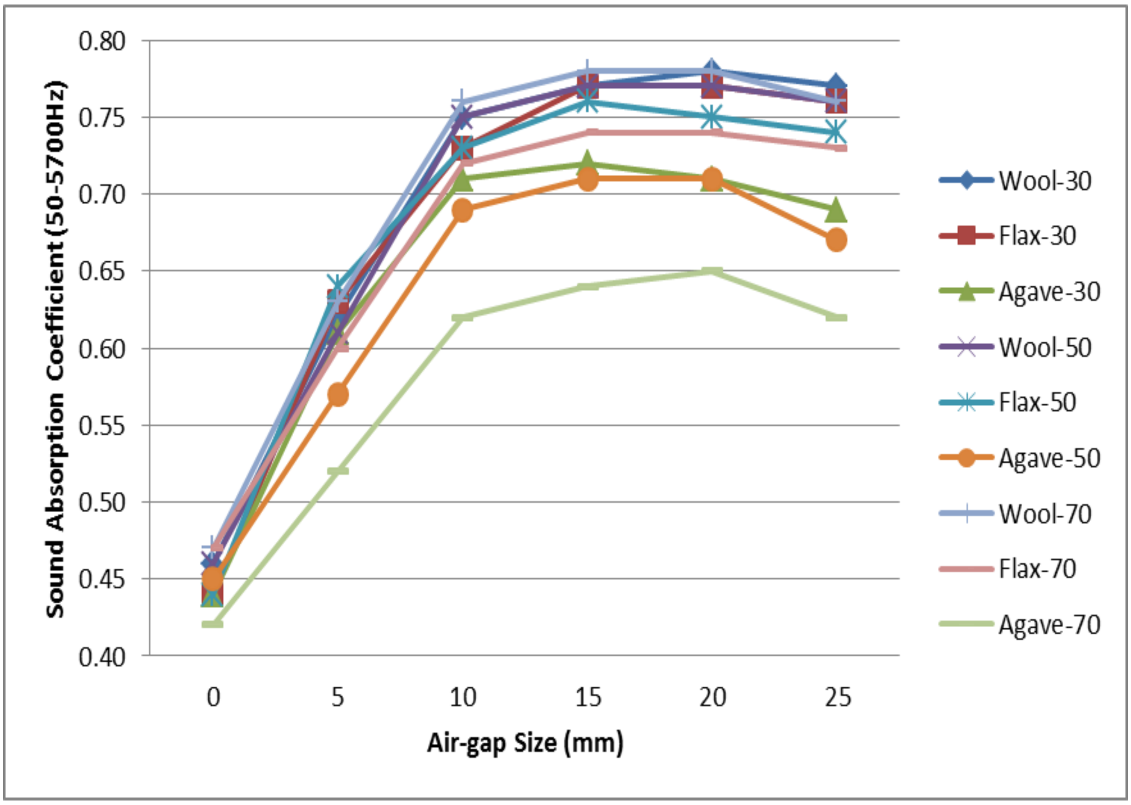


Figure 4.3.6. Sound absorption coefficient curves of the fabrics produced.

The fabrics produced from a blend of wool and PET fibres were different because, other than fibre fineness, the surface of wool fibres with their characteristic scales is an important consideration. So, a very little change in the sound absorption coefficient was observed regardless of fibre blending ratios, in fact, the sound absorption coefficients the increase in wool fibre content in the fabric.

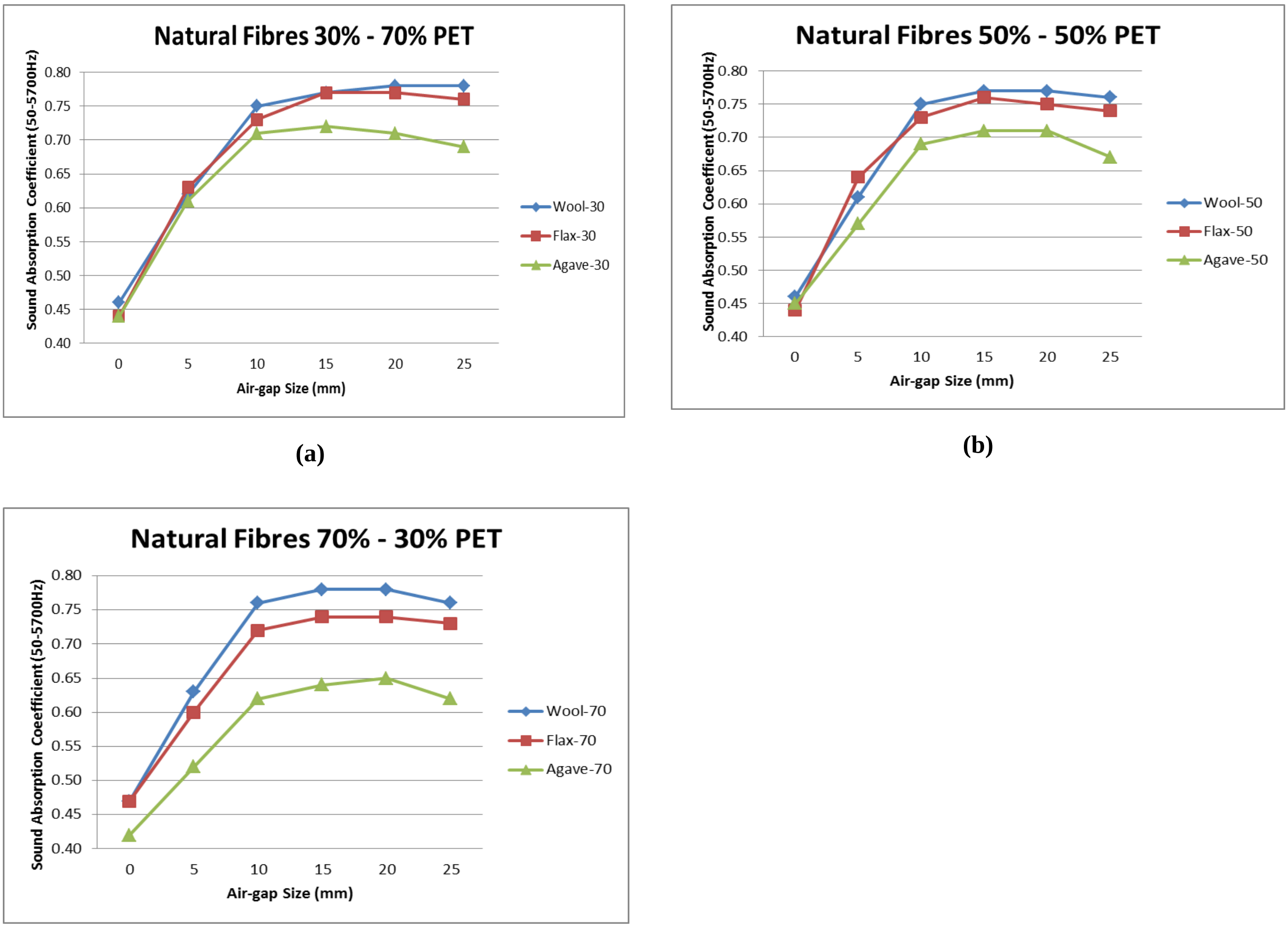
When the air-gap was increased from 0 mm to 25 mm it could be noticed that the sound absorption coefficient also increased but reached its maximum at about 15 mm air-gap after which it reduced again with the increase in air-gap from 15 mm to 25 mm**.** This phenomenon is due to the fact that higher air gap behind the nonwoven fabrics can absorb the sound energy of longer wavelengths at middle to low sound frequencies. This is due to

sound diffraction which happens when a sound wave passes through the nonwoven layer and air medium before striking the backing medium (XPS sheet) in this study [4,12].
So by increasing the air gap, the sound energy at long wavelengths (low frequency) can be absorbed. A similar effect is attained by increasing fabric thickness which can improve the sound absorption coefficients at low, middle and high sound frequencies due to increase in sound energy losses [12].

4.3.2.1.Effect of Fibre Type (Fineness) on Sound Absorption Coefficients

A comparison of sound absorption coefficients of the fabrics produced from three different natural fibres blended with PET fibres at three blending ratios is shown in Figure 4.3.7. The effect of fibre fineness on sound absorption coefficients of these fabrics is studied by comparing the fabrics produced from three natural fibres at the same blending ratio.

It can be observed that, in general, the trend of sound absorption coefficients is the same for all the blending ratios. Generally, the fabrics produced from a blend of wool and PET fibres showed the highest sound absorption coefficients followed by the fabrics produced from a blend of flax and PET fibres and the least for the fabrics produced from a blend of agave and PET fibres.



(a)

(b)

(c)

Figure 4.3.7 Comparison of sound absorption coefficients of fabrics by fibre type.

On a closer look to Figure 4.3.7, it can be observed that the differences in sound absorption coefficients of the fabrics among the blend ratios increased with an increase in natural fibre content in a particular blend. In other words, as shown in Figure 4.3.7 (a), the differences in sound absorption coefficients are minimum for the fabrics produced from a blend of 30:70% natural: PET fibres and increase to maximum for the fabrics produced from a blend of 70:30% natural: PET fibres as shown in Figure 4.3.7 (c).

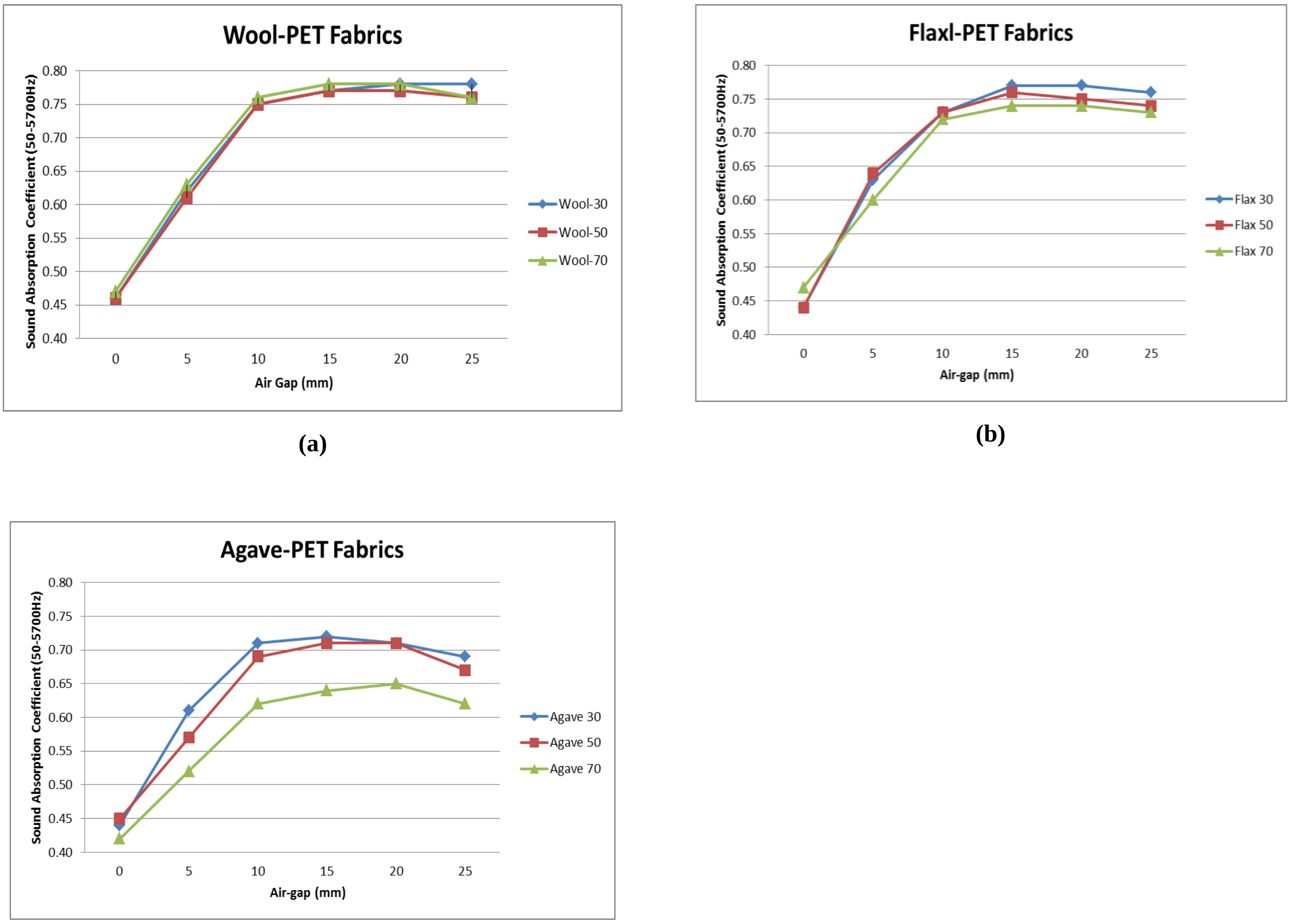
As stated earlier, and as shown in Figure 4.3.7 (a), in the fabrics containing more PET fibres (70%), the sound absorption coefficients are mainly influenced by the fineness of

PET fibres, due to the packing of higher number of fibres per unit volume. The natural fibres only start affecting the sound absorption coefficients of the respective fabrics when its content is increased from 30% to 50% and then to 70%, as the difference in the natural fibre fineness and morphology begin to influence the sound absorption capability of the fabric.

4.3.2.2.Effect of Blending Ratio on Sound Absorption Coefficients.

A comparison of sound absorption coefficients of the fabrics produced from three different natural fibres blended with PET fibres at three blending ratios is shown below in Figure 4.3.8. The effect of blending ratio on sound absorption coefficients is studied by comparing them for the fabrics made from the same natural fibre at three different blending ratios.

As shown in Figure 4.3.8, the sound absorption coefficients of the fabric generally decreased with the increase in natural fibre content, which is similar to the observation reported in the previous section. The change in the blend ratio has almost no effect on wool fibre blends as all three curves almost lay on top of each other as shown in Figure 4.3.8 (a). The change in sound absorption coefficients due to flax fibre content is also minimal in comparison to that for agave fibre content; this is largely due to the fact that the mean diameter of the flax fibres is lower than that of agave fibres, but closer to that of PET fibres.



(a)

(b)

(c)

Figure 4.3.8 Comparison of sound absorption coefficients of the fabrics by blending ratios

Among different fabrics produced at different blending ratios of agave and PET fibres, as shown in Figure 4.3.8 (c), the fabrics produced from 70%-30% blend achieved the least sound absorption coefficients, because agave fibre is comparatively more thicker (coarser) than PET fibres, therefore, when agave fibre content is increased to 70%, the fabric becomes the most porous and the least tortuous.

4.3.2.3.Effect of Air-gaps on Sound Absorption Coefficients

The effect of air-gap on sound absorption coefficients of the nonwoven fabrics was studied by comparing the sound absorption profiles of the same fabric at different air gaps, as shown in Figure 4.3.9, For the purpose of this comparison, only 50:50% blends of natural: PET fibres were selected.

As it can be seen in Figure 4.3.9 (a-c), the trend of sound absorption coefficients is the same for all three blend ratios. As the air gap increases, the sound absorption coefficients also increase. Further to that, the peaks of the profiles, i.e. maximum sound absorption coefficients, tend to “shift” to the left towards lower frequencies with the increase in air-gap.

The increase in the air gap between the fabrics and XPS moves the resonance frequencies, i.e. peak sound absorption, to lower frequency ranges and thus results in lower sound absorption coefficients at higher frequencies [7] as shown in Figure 4.3.9 and thereby reduction in sound diffraction effect. Another observation that accompanies this effect, as shown in Table 4.3.5, is that the sound absorption coefficient generally attains maximum value at an air gap of 15 mm after which it decreases slightly with further increase in air gap from 15 mm to 25 mm.

Also, according to Attenborough and Ver [45], the highest value of sound absorption coefficient occurs when the distance (air-gap in this case) between the medium and the wall is odd multiples of a quarter-wavelength for the particular sound frequency. This is due to the fact that a phase difference of 180^o occurs between the incident and the reflected waves and destructive interference of the sound wave takes place.

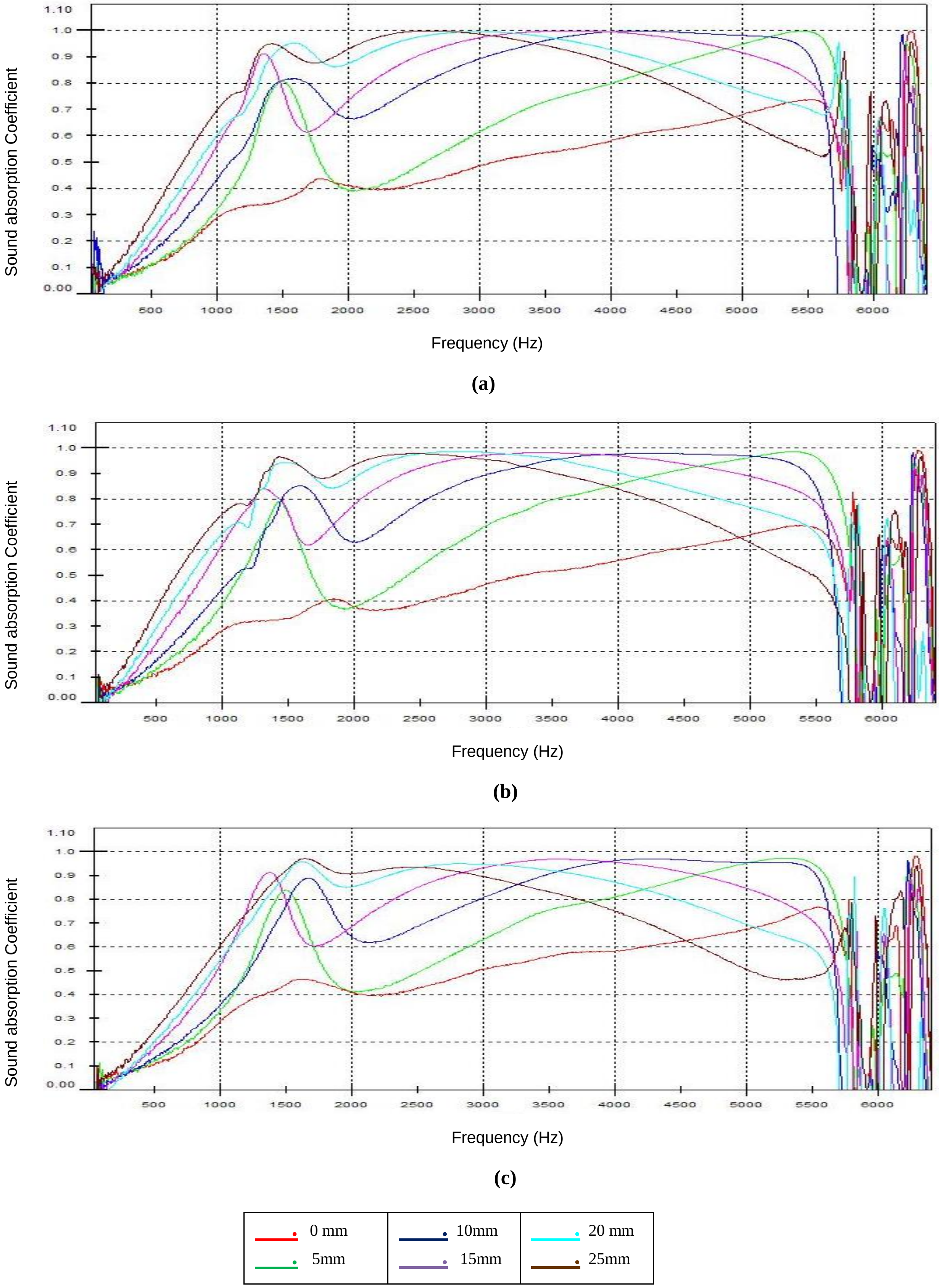


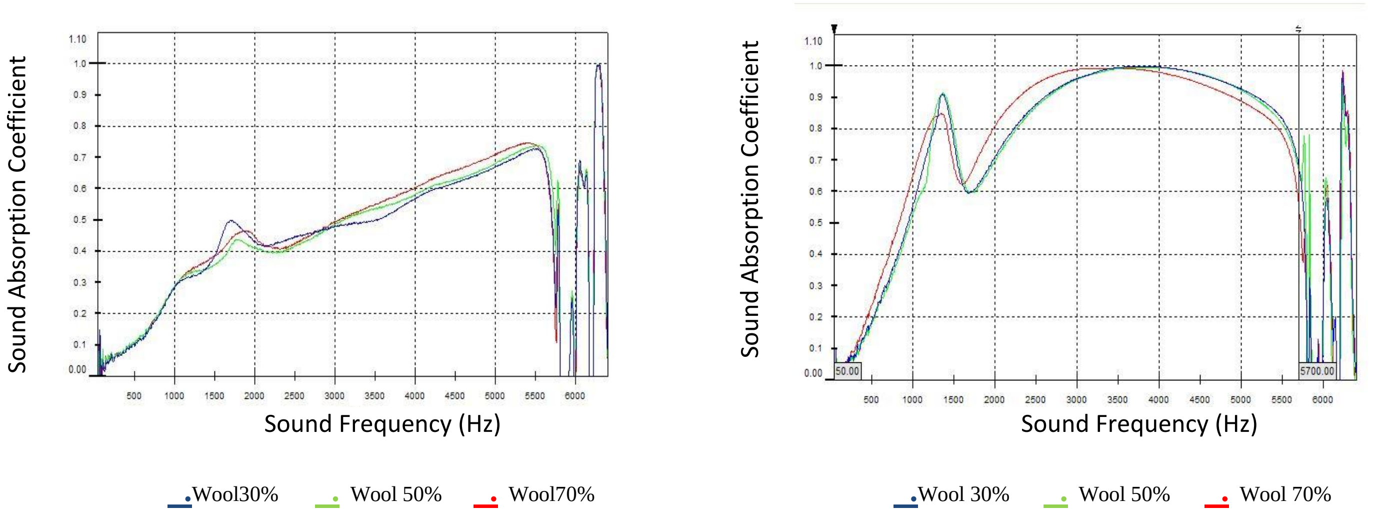
Figure 4.3.9 Sound absorption coefficients of 50:50 blends of (a) wool-PET, (b) flax-PET and (c) agave-PET at different air-gaps measured in the sound frequency range of 50-5700 Hz

Conversely, when the air gap is an even multiple of a quarter-wavelength of the incident sound wave (and thus a multiple of half-wavelengths as well), it becomes totally ineffective as the incident and reflected waves are in phase, i.e. constructive sound wave interference takes place [45]. Therefore, sound absorption coefficient decreased slightly when the air-gap was increased from 15mm to 25mm. This could be due to the change in air-gap from being odd multiples of quarter-wavelengths at about 15mm air-gap (maximum sound absorption) to being multiples of half-wavelengths as the air-gap increased to 25mm.

So by increasing the air gap, the sound energy at long wavelengths (low frequency) can be absorbed. A similar effect can be obtained by increasing sample thickness, which can improve the sound absorption coefficients at low, middle and high frequencies due to increased losses in sound energy losses [13].

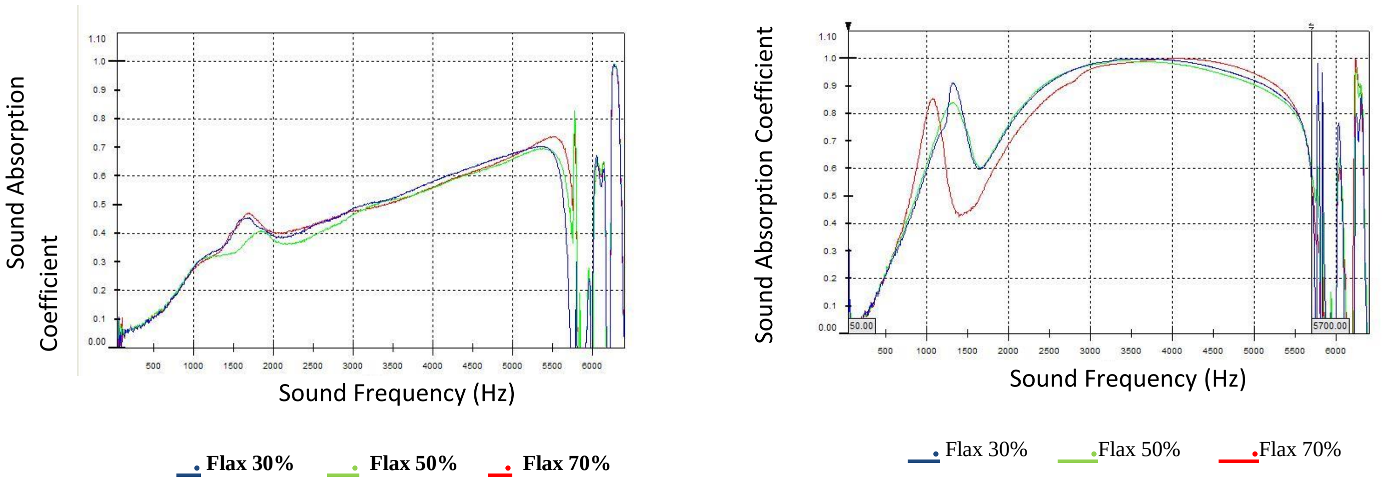
Furthermore, the effect of constant air-gap on sound absorption coefficients of the fabrics produced with different blending ratios was evaluated as shown in Figure 4.3.10 and then the third case was studied to evaluate the sound absorption coefficients of the fabrics produced from different natural fibres at the same air-gap as shown in Figure 4.3.11.

Figure 4.3.10 shows the sound absorption coefficient profiles at the same air-gap (0mm and 15mm) for the three blending ratios of each of the natural fibres used in this section. In both the air-gaps, the differences in sound absorption coefficients among the fabrics produced from blends of wool and PET fibres and among the fabrics produced from blends of flax and PET fibres were minimal as evident from closely lying profiles in Figures



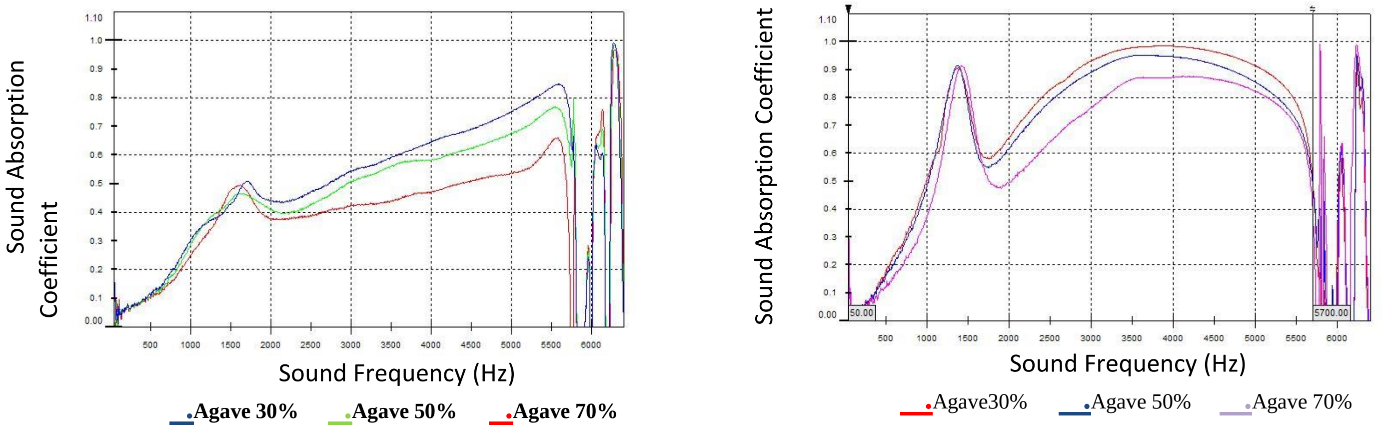
(a) Wool /PET Fibres – 0mm Air Gap

(b) Wool /PET Fibres – 15mm Air Gap



(c) Flax /PET Fibres – 0mm Air Gap

(d) Flax/PET Fibres – 15mm Air Gap



(e) Agave/PET Fibres – 0mm Air Gap

(f) Agave/PET Fibres – 15mm Air Gap

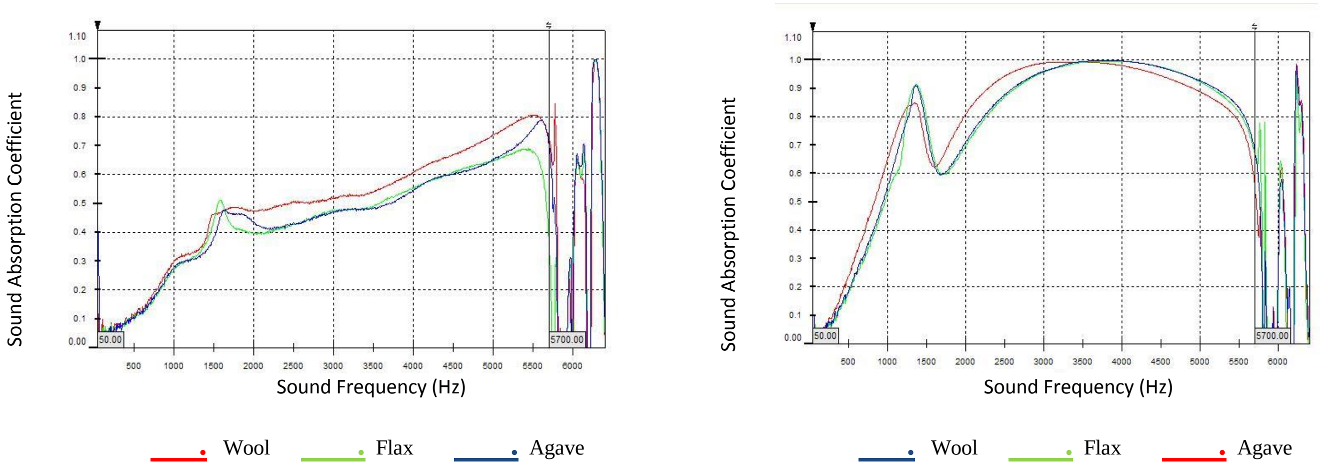
Figure 4.3.10. Sound absorption coefficients (50-5700Hz) at air gap of 0mm (Left) and 15mm (Right) for different blending ratios of the same natural fibre type

4.3.10 (a) to (d), while the differences in sound absorption coefficients among the fabrics produced from blends of agave and PET fibres were more pronounced as seen from the profiles in Figures 4.3.10 (e) to (f). This trend is in agreement with the trend observed in Figure 4.3.8.

As stated in Section 4.3.2.2, the differences in variation of the sound absorption coefficients among the fabrics produced from three different natural fibres were due to relative coarseness of agave fibres compared to PET fibres, whereas the differences in fineness between wool and flax fibres with respect to PET fibres were relatively smaller. The airgap, and its variation, has no effect in this observed trend as it remains the same for all air gaps including 0mm (no air-gap).

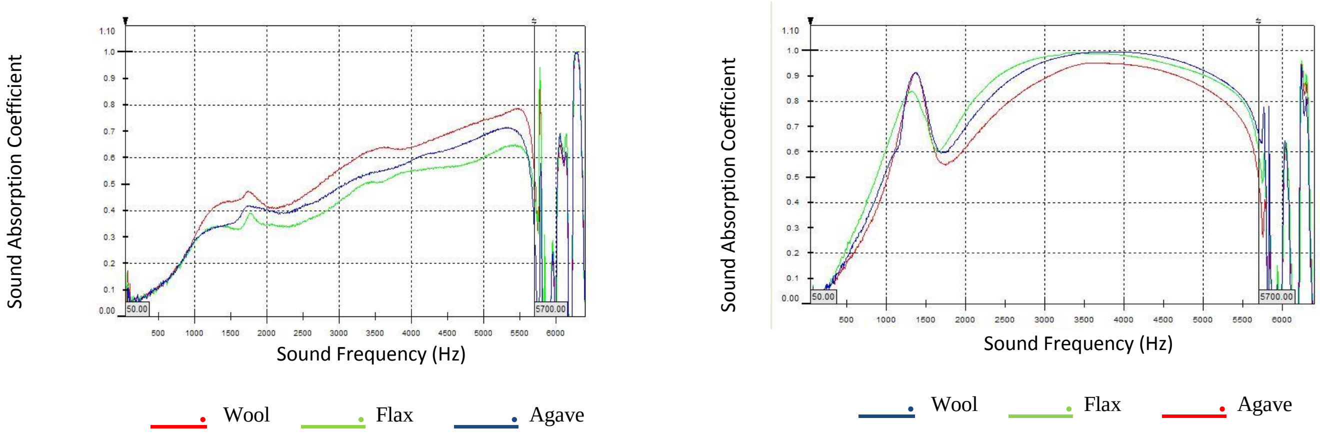
Figure 4.3.11 shows the sound absorption coefficient profiles of the fabrics produced from blends of the three different natural fibres and PET fibres at the same air gap (0mm and 15mm). The trend in sound absorption coefficients is similar to that observed in Figure 4.3.7 of Section 4.3.2.1. The fabrics produced from blends of wool and PET fibres generally achieve the highest sound absorption coefficients, followed by the fabrics produced from blends of flax and PET fibres, and the least for the fabrics produced from blends of agave and PET fibre.

Generally, these trends remain the same for both the air gaps of 0mm and 15mm, therefore it may be concluded that the air-gap and its variation have no effect on sound absorption coefficients. Rather, it is mostly influenced by the differences in fibre fineness of the natural fibres used, together with the special surface morphology of the wool fibres which



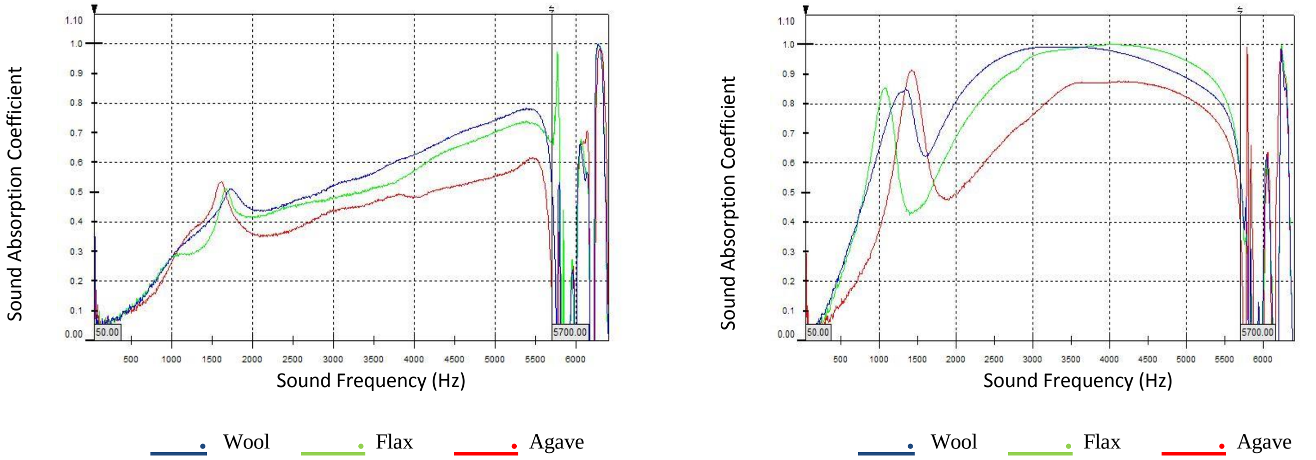
(a) 30% Natural Fibre/70% PET – 0mm Air Gap

(b) 30% Natural Fibre/70% PET – 15mm Air Gap



(c) 50% Natural Fibre/50% PET – 0mm Air Gap

(d) 50% Natural Fibre/50% PET – 15mm Air Gap



(a) 70% Natural Fibre/30% PET – 0mm Air Gap

(f) 70% Natural Fibre/30% PET – 15mm Air Gap

Figure 4.3.11. Sound absorption coefficients at 0mm and 15mm air gaps for different natural fibre types at the same blending ratio

makes them more effective for sound absorption. This is further confirmed by the fact that the difference in sound absorption coefficients of the fabrics among different blends studied increases with an increase in natural fibre content in the respective blends. A similar observation was also drawn from Figure 4.3.7 in Section 4.3.2.1.

4.3.2.4. Statistical Analysis of the Effect of Fibre Type (fineness), Blending Ratio and Air-gap on Sound Absorption Coefficients

A three-way ANOVA was carried out which included three two-way interactions of the output data in Table 4.3.5. The statistical significance of probability, P-value at 95% confidence interval was tested as shown Table 4.3.6, if it is less than 0.05 then the parameter has significant effect on sound absorption coefficients and vice versa.

Table 4.3.6 Univariate test of significance for sound absorption

Variable	**Sum of Squares (SS)**	**Degree of Freedom**	**Mean Square (MS)**	**Fischer Index (F)**	**Probability Value (P)**
Intercepts	23.681	1	23.681	218594.46	0.0000
Fibre Type	0.052	2	0.026	238.82	0.0000
Blend Ratio	0.007	2	0.003	30.92	0.0000
Air Gap	0.606	5	0.121	1118.07	0.0000
Fibre Type × Blend	0.010	4	0.003	23.51	0.0000
Fibre Type × Air Gap	0.007	10	0.001	6.55	0.0002
Blend × Air Gap	**0.002**	**10**	**0.000**	**2.04**	**0.0837**
Error	0.002	20	0.000		

From Table 4.3.6, it is observed that all the parameters as well as two two-way interactions showed significant effects on measured sound absorption coefficients. The only two-way interaction effect that failed to achieve significant effect on sound absorption coefficient at 95% confidence interval was between **Blend Ratio and Air Gap**, however, the P-value is low enough to achieve significance at 90% confidence interval.

The Tukey HSD tests and their corresponding least square plots were produced for all the parameters to further analyse internal variations within each parameter, to assess the two-way interactions, to elaborate the effects of the variables on sound absorption coefficient and to compare them with each other.

Table 4.3.7 Tukey HSD Test for Fibre Type

Fiber Type	**Mean Sound Absorption**		
	0.69	**0.68**	**0.62**
Wool			
Flax	0.0006		
Agave	0.0001	0.0001	

The P-values in Table 4.3.7 show that all the values of mean sound absorption coefficients are significantly different from each other since they are all below 0.05. Figure 4.3.12 shows a comparison of mean sound absorption coefficients of the three natural fibre blends, it shows that the fabrics produced from wool and PET fibres achieved the best sound absorption coefficient followed by the fabrics produced from flax and PET fibres. The fabrics produced from agave and PET fibres achieved considerably lower sound absorption coefficient in comparison to the fabrics produced from blends of other two natural fibres.

The mean sound absorption coefficients of the fabrics produced from blends of agave and PET fibres are about 11% and 9.5% below the fabrics produced from blends of wool and PET fibres and blends of flax and PET fibres, respectively, yet the difference between the sound absorption coefficients of the fabrics produced from blends of wool and PET fibres and those produced from blends of flax and PET fibres is only 1.5%. The reasons for this difference in the performance of the fabrics produced from the three different natural fibres have already been discussed at length in the previous sections. Also, it is already well known that the use of finer fibres in the nonwoven fabrics achieve better sound absorption in comparison to coarser fibres [75].

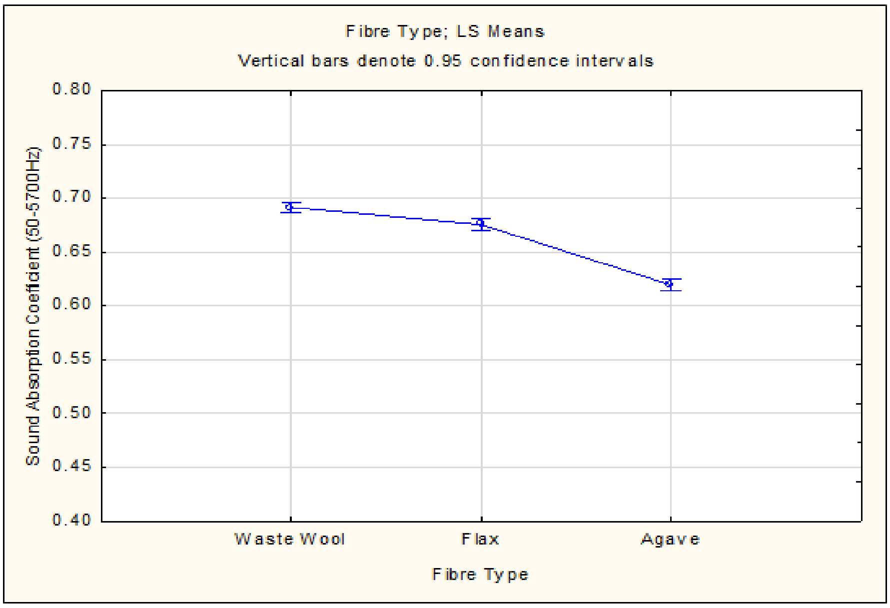


Figure 4.3.12 Least square mean values of sound absorption vs fibre type for the three blending ratios.

A Tukey Test for blending ratios of all the fabrics tested is shown in Table 4.3.8 together with the corresponding least square mean plot in Figure 4.3.13. Looking at the P-values, it can be seen that the mean values of the sound absorption coefficients for 30:70 and 50:50 % blending ratios are not significantly different as the P-value of 0.065 is slightly above 0.05. However, the mean sound absorption coefficient values of 30:70 and 70:30% as well the mean sound absorption coefficients values of 50:50 and 70:30 % show significant differences as their P-values are well below 0.05.

Table 4.3.8 Tukey HSD Test for Blending Ratio

Blending Ratio	**Mean Sound Absorption**		
	0.674	**0.667**	**0.647**
30:70			
50:50	***0.0648***		
70:30	0.0001	0.0002	

Figure 4.3.13 shows a comparison of the three blending ratios in terms of sound absorption coefficients for all the fabrics tested, it is clear that the fabrics produced from a blend of 30:70% natural and PET fibres achieved the best sound absorption coefficient. The fabrics produced from 70% natural fibres in a blend showed the least value of mean sound absorption coefficient, because of higher number of coarser (compared to PET fibres) natural fibres, wool is an exception here as already been pointed out earlier and described in detail in Section 4.3.2.1 The reasons for the difference in the effect of the blending ratios on sound absorption coefficients have already been explained in Section 4.3.3.2.

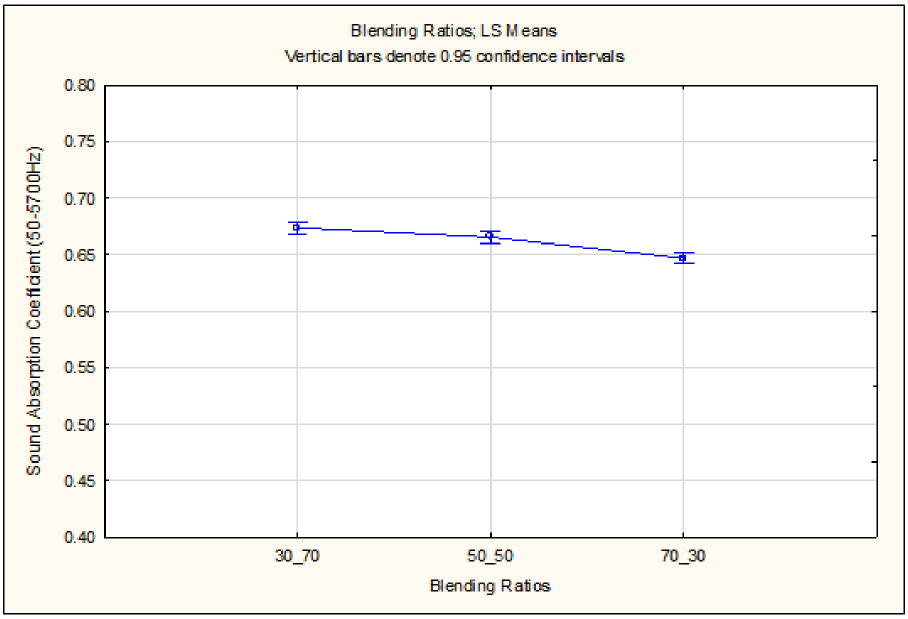


Figure 4.3.13 Least square mean values of sound absorption vs blending ratio for all the fabrics tested

The Tukey Test for the effect of air gap on sound absorption in Table 4.3.9 shows that the values of sound absorption coefficients are mostly significantly different from each other as most of the P-values are below 0.05. The only mean sound absorption coefficient comparisons that were not significantly different are those of the air gap of 10 mm that was not significantly different to that at 25 mm and the mean sound absorption coefficient at 15 mm air gap was not significantly different to that at 20 mm air gap. This was due to the trend of the sound absorption coefficient reaching a maximum at about 15mm and then slightly declining as the air gap is increased further to 25mm, thus there was an overlap in the confidence interval bars.

Table 4.3.9 Tukey HSD Test for Air Gap Size

Air Gap Size	**Mean Sound Absorption**					
	0.45	**0.60**	**0.72**	**0.74**	**0.74**	**0.72**
0						
5	0.0001					
10	0.0001	0.0001				
15	0.0001	0.0001	0.0025			
20	0.0001	0.0001	0.0025	***1.0000***		
25	0.0001	0.0001	***0.9405***	0.0182	0.0182	

Figure 4.3.14 shows the comparison of various air gaps for all the fabrics tested. As already discussed in Section 4.3.2.3 it can be seen that the sound absorption coefficient increases with an increase in air gap from 0 mm to 15mm, after which it decreases with further increase in airgap up to 25mm. It can also be seen that a marginal difference in sound absorption coefficients occurs when the air gap is increased from 15mm to 25mm. Also, as it is shown by the P-values in the Tukey test, the confidence interval bar at an air gap of 10 mm overlaps with that at an air gap of 25 mm and the confidence interval bar of an air gap of 15 mm overlaps with that of at an air-gap of 20 mm.

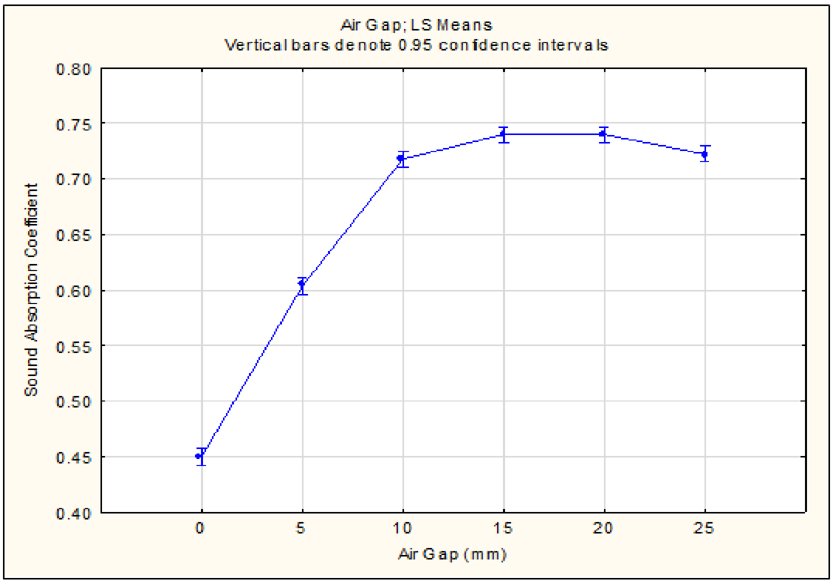


Figure 4.3.14 Least square mean values of sound absorption vs air gap size (mm) for all the fabrics tested

The Tukey Test for the effect of the interaction between fibre type and blend ratio on sound absorption coefficient is shown in Table 4.3.10. Generally, it can be observed that the values of mean sound absorption coefficients of the fabrics produced from a blend of wool and PET fibres are not significantly different from each other and also not different from mean sound absorption coefficients of fabrics produced from a blend of flax and PET fibres, as shown with bold values in Table 4.3.10.

Figure 4.3.15 shows a comparison of blend ratios and fiber types. As already seen in Figures 4.3.12 and 4.3.13 above, the fabrics produced from a blend of wool and PET fibres and those produced from a blend of 30:70% natural and PET fibres, in general, achieve superior sound absorption properties. The exceptional case of wool fibre blends can be seen here as the plot (in blue) does not follow the same trend as the other two. As the natural fibre content in the blend increases, the sound absorption coefficients decrease. However, the sound absorption coefficient marginally decreases when the wool fibre content in a blend is increased from 30% to 50% after which it increases again with the increase in wool fibre content to 70%.

Table 4.3.10 Tukey HSD Test for Fibre Type × Blend Ratio

Fiber Type	Blending Ratio	Mean Sound Absorption								
		0.69	0.69	0.70	0.68	0.68	0.67	0.65	0.63	0.58
Wool	**30_70**									
Wool	**50_50**	***0.9943***								
Wool	**70_30**	***0.9943***	***0.7600***							
Flax	**30_70**	***0.8902***	***0.9997***	***0.4310***						
Flax	**50_50**	***0.2903***	***0.7600***	***0.0655***	***0.9659***					
Flax	**70_30**	0.0115	***0.0655***	0.0020	***0.1845***	***0.7600***				
Agave	**30_70**	0.0002	0.0002	0.0002	0.0003	0.0020	***0.0655***			
Agave	**50_50**	0.0002	0.0002	0.0002	0.0002	0.0002	0.0007	***0.4310***		
Agave	**70_30**	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	

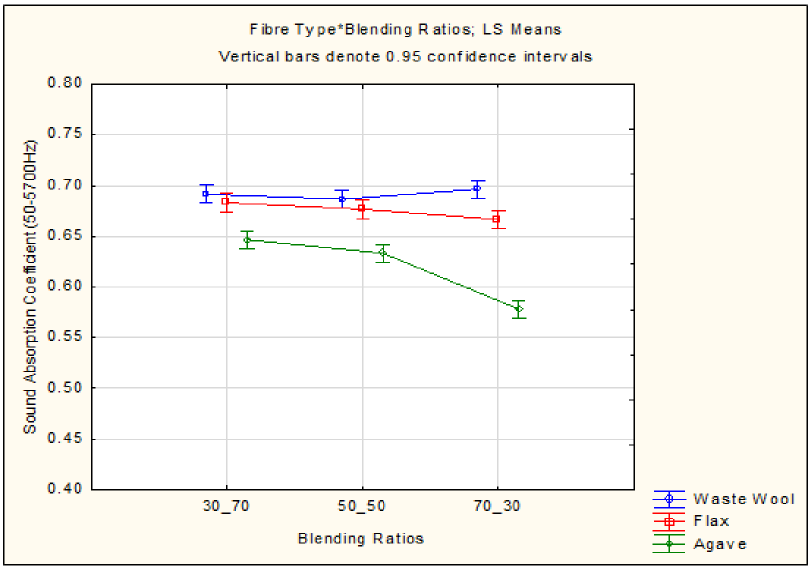


Figure 4.3.15 Least square mean values of sound absorption vs fibre type × blend ratio for different fibre types

It can also be noticed that there is a considerable overlap in the confidence interval bars for the fabrics produced from blends of wool and PET fibres and those produced from blends of flax and PET fibres; this corresponds to P-values in Table 4.3.10 which shows that the mean sound absorption coefficients for fabrics produced from blends of wool and PET fibres are not significantly different from each other and from the mean sound absorption coefficients of the fabrics produced from blends of flax and PET fibres.

Furthermore, the differences in sound absorption coefficients by fibre types and blend ratio become more pronounced in the case of fabrics produced from 50:50 % and 70:30% blend of natural and PET fibres, this can be noticed from the mean sound absorption coefficients which are further apart in the fabrics produced from these two blend ratios but closer in the fabrics produced from a blend of 30:70% natural and PET fibres.

The Tukey Test for the effect of the interaction between fibre type and air gap on sound absorption coefficients as shown in Table 4.3.11 indicates that the mean sound absorption coefficients of the fabrics produced from blends of wool and PET fibres and those produced from blends of flax and PET fibres at air gaps of 15 to 25mm were mostly not significantly different from each other as the P-values are above 0.05, while the mean sound absorption coefficients for the fabrics produced from blends of agave and PET fibres are mostly significantly different from each other and from the mean sound absorption coefficients of the fabrics produced from blends of wool and PET fibres and those produced from blends of flax and PET fibres.

From Figure 4.3.16, it can be observed that the trend is similar for all three blends of natural and PET fibres. The fabrics produced from blends of wool and PET fibres achieved the highest sound absorption coefficients and the fabrics produced from agave and PET fibres achieved the least sound absorption coefficients. Also, the sound absorption coefficient increased with the increase in air gap until 15mm, after which it remained constant with further increase in air gap from 15 to 25mm. Furthermore, the overlaps in confidence interval bars for the fabrics produced from blends of wool and PET fibres and fabrics produced from blends of flax and PET fibres correspond to the high P-values given in Table 4.3.11.

Table 4.3.11 Tukey HSD Test for Fibre Type × Air Gap Size

Fiber Type	Air Gap	Mean Sound Absorption																	
		0.46	**0.62**	**0.75**	**0.77**	**0.78**	**0.76**	**0.45**	**0.62**	**0.73**	**0.76**	**0.75**	**0.74**	**0.44**	**0.57**	**0.67**	**0.69**	**0.69**	**0.66**
Wool	**0**																		
Wool	**5**	0.0002																	
Wool	**10**	0.0002	0.0002																
Wool	**15**	0.0002	0.0002	***0.6434***															
Wool	**20**	0.0002	0.0002	***0.4104***	***1.0000***														
Wool	**25**	0.0002	0.0002	***0.9983***	***0.9983***	***0.9711***													
Flax	**0**	***0.9711***	0.0002	0.0002	0.0002	0.0002	0.0002												
Flax	**5**	0.0002	***1.0000***	0.0002	0.0002	0.0002	0.0002	0.0002											
Flax	**10**	0.0002	0.0002	***0.2288***	0.0022	0.0010	0.0248	0.0002	0.0002										
Flax	**15**	0.0002	0.0002	***1.0000***	***0.8561***	***0.6434***	***1.0000***	0.0002	0.0002	***0.1156***									
Flax	**20**	0.0002	0.0002	***1.0000***	***0.6434***	***0.4104***	***0.9983***	0.0002	0.0002	***0.2288***	***1.0000***								
Flax	**25**	0.0002	0.0002	***0.9983***	***0.1156***	***0.0547***	***0.6434***	0.0002	0.0002	***0.8561***	***0.9711***	***0.9983***							
Agave	**0**	***0.2288***	0.0002	0.0002	0.0002	0.0002	0.0002	***0.9711***	0.0002	0.0002	0.0002	0.0002	0.0002						
Agave	**5**	0.0002	0.0005	0.0002	0.0002	0.0002	0.0002	0.0002	0.0003	0.0002	0.0002	0.0002	0.0002	0.0002					
Agave	**10**	0.0002	0.0005	0.0002	0.0002	0.0002	0.0002	0.0002	0.0010	0.0005	0.0002	0.0002	0.0002	0.0002	0.0002				
Agave	**15**	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0248	0.0002	0.0002	0.0005	0.0002	0.0002	***0.8561***			
Agave	**20**	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0248	0.0002	0.0002	0.0005	0.0002	0.0002	***0.8561***	***1.0000***		
Agave	**25**	0.0002	0.0110	0.0002	0.0002	0.0002	0.0002	0.0002	0.0248	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	***0.9711***	***0.1156***	***0.1156***	

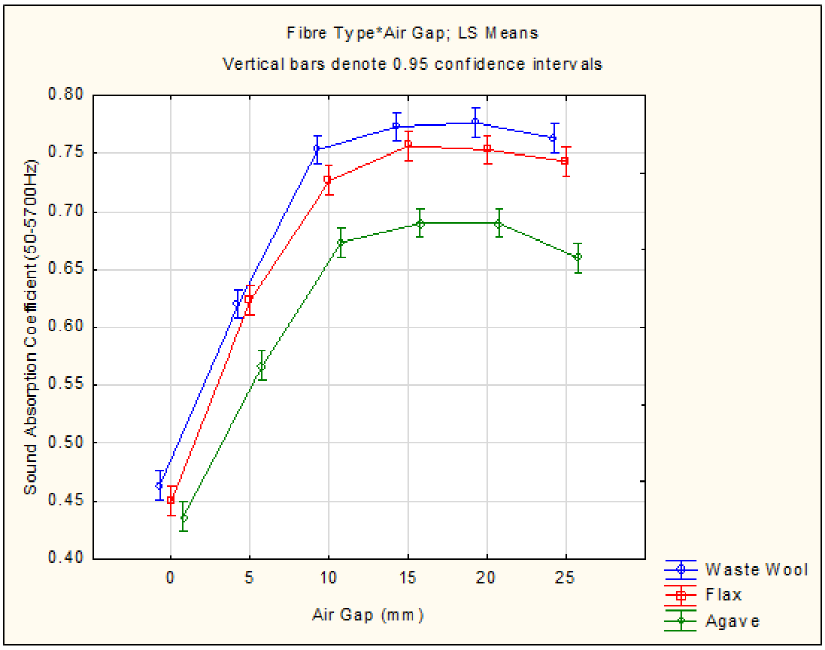


Figure 4.3.16 Least square mean values of sound absorption vs the interaction of fibre type and air gap for different fibre types

Table 4.3.12 shows the Tukey Test for the effect of interaction between blending ratio and air gap on sound absorption coefficients. It is noticeable that in this Tukey Test table many P-values above 0.05 when compared to the Tukey Tests of the other two two-way interactions shown in Tables 4.3.10 and 4.3.11. This implies that a greater number of mean sound absorption coefficient values are not significantly different in this case. Also, the effect of this two way interaction is not significant at 95% confidence interval (P-value = 0.0837), however, this value is still low enough to show significance at 90% confidence interval.

Table 4.3.12 Tukey HSD Test for Blending Ratio × Air Gap Size

Fiber Type	**Air Gap**	**Mean Sound Absorption**																	
		0.45	**0.62**	**0.73**	**0.75**	**0.75**	**0.74**	**0.45**	**0.61**	**0.72**	**0.75**	**0.74**	**0.72**	**0.45**	**0.58**	**0.70**	**0.72**	**0.72**	**0.70**
30_70	**0**																		
30_70	**5**	0.0002																	
30_70	**10**	0.0002	0.0002																
30_70	**15**	0.0002	0.0002	***0.4104***															
30_70	**20**	0.0002	0.0002	***0.4104***	***1.0000***														
30_70	**25**	0.0002	0.0002	***0.9983***	***0.9711***	***0.9711***													
50_50	**0**	***1.0000***	0.0002	0.0002	0.0002	0.0002	0.0002												
50_50	**5**	0.0002	***0.9711***	0.0002	0.0002	0.0002	0.0002	0.0002											
50_50	**10**	0.0002	0.0002	***1.0000***	***0.1156***	***0.1156***	***0.8561***	0.0002	0.0002										
50_50	**15**	0.0002	0.0002	***0.8561***	***1.0000***	***1.0000***	***1.0000***	0.0002	0.0002	***0.4104***									
50_50	**20**	0.0002	0.0002	***0.9711***	***0.9983***	***0.9983***	***1.0000***	0.0002	0.0002	***0.6434***	***1.0000***								
50_50	**25**	0.0002	0.0002	***1.0000***	***0.1156***	***0.1156***	***0.8561***	0.0002	0.0002	***1.0000***	***0.4104***	***0.6434***							
70_30	**0**	***1.0000***	0.0002	0.0002	0.0002	0.0002	0.0002	***1.0000***	0.0002	0.0002	0.0002	0.0002	0.0002						
70_30	**5**	0.0002	0.0248	0.0002	0.0002	0.0002	0.0002	0.0002	***0.4104***	0.0002	0.0002	0.0002	0.0002	0.0002					
70_30	**10**	0.0002	0.0002	***0.1156***	0.0005	0.0005	0.0110	0.0002	0.0002	***0.4104***	0.0022	0.0048	***0.4104***	0.0002	0.0002				
70_30	**15**	0.0002	0.0002	***0.9983***	***0.0547***	***0.0547***	***0.6434***	0.0002	0.0002	***1.0000***	***0.2288***	***0.4104***	***1.0000***	0.0002	0.0002	***0.6434***			
70_30	**20**	0.0002	0.0002	***1.0000***	***0.1156***	***0.1156***	***0.8561***	0.0002	0.0002	***1.0000***	***0.4104***	***0.6434***	***1.0000***	0.0002	0.0002	***0.4104***	***1.0000***		
70_30	**25**	0.0002	0.0002	***0.2288***	0.0010	0.0010	0.0248	0.0002	0.0002	***0.6434***	0.0048	0.0110	***0.6434***	0.0002	0.0002	***1.0000***	***0.8561***	***0.6434***	

The Least Square plot in Figure 4.3.17 shows that the trends in sound absorption coefficients with the change in air gap size remains the same for all three blending ratios. In general, the highest sound absorption coefficients are achieved in the fabrics produced from the blends containing 70% PET fibres in the fabrics, followed by the fabrics containing 50% PET fibres and the lowest for the blend containing 30% PET fibres. These observations are in agreement with those discussed earlier in this section.

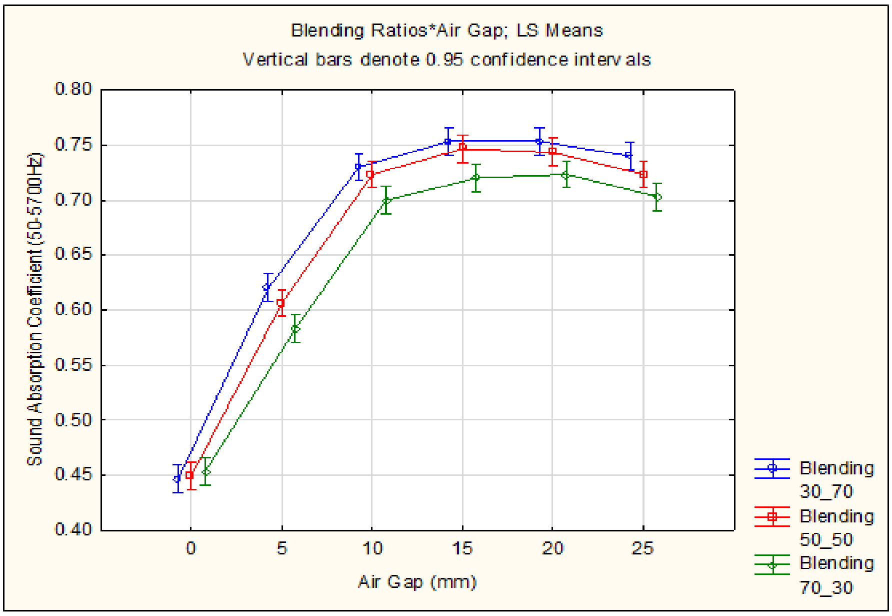


Figure 4.3.17 Least Square mean values of sound absorption vs blending ratio × air gap size for different fibre types

4.4. Evaluation and Selection of Parameters for Sound Absorption Application

The evaluation and selection of suitable parameters and machine settings for the fabrics produced for sound absorption application and tested with varying air gap and XPS backing was mainly based on their ability to absorb sound. However, some other factors should also be considered to arrive at a final decision. Besides the ability to absorb sound, other factors which include; availability of raw materials, cost-effectiveness and manufacturing efficiency, adaptability and environmental friendliness should also be considered.

Sound Absorption Ability

From the results on measurement of sound absorption coefficients, it was noticed that the fabrics produced from blends of wool and PET fibres achieved superior sound absorption performance. It was also seen that the differences in the sound absorption coefficients among the three different blend ratios were marginal and not enough to conclusively choose one blend ratio over the other as the best choice. This can be substantiated by the fact that the means of sound absorption coefficients of the fabrics for the three blend ratios of wool and PET fibres were almost identical, i.e. 0.69, 0.69 and 0.70 for 30:70%, 50:50% and 70:30% blends of wool and PET fibres, respectively. Therefore, the final selection should be based on other factors, outlined in the previous section, besides sound absorption coefficients.

The Availability of Raw Materials

The input and raw materials required to produce this type of units are the XPS board and four different fibre types. The XPS boards are already commercially available. PET fibres with various physical properties are widely available in the market. The same is the case with flax fibres which are also commercially grown and available in South Africa. Therefore, the question of availability mainly affects waste wool fibres and agave fibres, as they are not widely available and used commercially.

The problem with waste wool fibre is that while it is a by-product of commercial wool fibre processing, currently no formal method of collecting and packaging exists with subsistence farmers, however, some wool washers in the Eastern Cape Province (South Africa) have reported availability of coring wool waste in substantial quantities (excluding the waste from other wool types).

The situation is similar for agave fibres, there are some local initiatives to develop agave cultivation, however, no formal commercial entity exists currently to cultivate, process and grade agave fibres. However, a big potential for sufficient supply exists as more alternative uses of agave fibres are being developed and thus demand for the fibres would be expected to increase the supply (cultivation and processing).

Adaptability

The materials produced are better suited for application in the construction sector, mainly because the whole system consisting of nonwoven fabrics backed by XPS at varying air gaps limits the options for application due to space requirements. Therefore, the main considerations, among the characteristics of the produced material, are their adaptability in real life applications, dimensions and handling. The main criterion here is total thickness of the system, to fit well with the other building materials in-situ.

The thickness of the nonwoven fabrics, optimum air-gap size and thickness of XPS was 7-8 mm, 15 mm and 40mm, respectively. Therefore, the total thickness of the unit is about 63mm. This is still thinner than the average dry-wall partition thickness of 90-190mm currently prevalent in the building sector. Also, this sound absorption unit is ideally suited for internal wall partitioning especially as a pre-fabricated panel for dry-wall partitioning. However, the means of fixing the air gap between the nonwoven fabric and XPS may still pose a challenge.

Cost-effectiveness and Manufacturing Efficiency

As it has already been discussed, the most practical mode of application of these sound absorption units is in the form of pre-fabricated panels for internal room partitioning. Therefore, the costs of the fibres are major input costs in the production of such pre-fabricated boards as the XPS is already used commercially for ceiling and wall partitioning applications. See Table 4.3.12 below for the prices of fibres used in this work.

Table 4.3.12 Prices of the fibres used.

Fibre Type	Price (ZAR/kg)
PET	16.10
Waste Wool	0.50 - 8
Flax	5-8
Agave	8-10

Other costs are associated with the production of nonwoven fabrics and assembling prefabricated panels. These costs will then inform the comparison of the total cost of the pre-fabricated panels with other types of panels used in room partitioning with or without sound absorption ability. The question of manufacturing efficiency of this prefabricated panel only lies in the stage of forming the panel as nonwoven fabric production is an established technology. The main determining factor here would be the finishing materials (face of the wall panel) and the means of fixing the air-gap.

Environmental_Friendliness

All the nonwoven fabrics produced contain natural fibres blended in different proportions with PET fibres. PET fibres are synthetic and not bio-degradable and they are extruded from energy intensive processes. Therefore, the PET fibres are not considered environmentally friendly green material. Wool fibres are from animal origin and are biodegradable; however, the washing of wool may consume a lot of energy and water but still it is regarded as a green material. Flax and agave fibres are from plant origin and are bio-degradable. However, irrigation water and pesticides are the main considerations during cultivation, and the mechanical processing of the fibres consumes energy which should be accounted in the life cycle analysis of the final product.

Summary

When considering all the factors evaluated above, it is clear that some of them are applicable to all products regardless of the natural fibre used. Among the factors that are dependent on fibre choice, it is clear that the fabrics produced from a blend of 70:30% Wool: PET fibres are the most desirable since they achieved the highest sound absorption coefficients. The fabrics also have high natural fibre content to promote better biodegradability and thus can be considered environmentally friendly “green material”. Waste wool fibres are also the cheapest among the fibres used in this work and promoting their use in such value-added products will benefit subsistent farmers in rural areas.

5. SUMMARY AND CONCLUSIONS

Needle-punched nonwoven fabrics are widely used in sound absorption application because of their porous structure. Traditionally, these needle-punched nonwoven fabrics have been mainly produced from synthetic fibres, such as PET and PP. The review of literature carried out in this work showed a gradual shift in attempts to introduce natural fibres particularly in the products used in sound absorption applications. Also, many studies have been carried out to study the effects of production parameters on the sound absorption properties of the needle-punched nonwoven fabrics but very little work has been carried out to optimize and study the synergistic effects of these parameters.

The major objectives of this work included studying the effects of some important production parameters on sound absorption properties of the needle-punched nonwoven fabrics, and then to optimize the variables to achieve the best functionality of the final product. The fabrics were produced by blending natural fibres such as agave, hemp and flax fibres with PET fibres. Furthermore, the effect of the production parameters on air permeability of the needle-punched fabrics was studied. In the last part of this work, the effect of air gap between needlepunched nonwoven fabric and extruded polystyrene sheet (XPS) backing material was studied. The effect of varying air gap together with the effect of varying some major production parameters on sound absorption coefficient was studied.

5.1. Optimization of Needlepunching Process Parameters For Sound Absorption Applications

The optimization of process parameters was carried out on the fabrics produced from a blend of 50% PET and 50% of natural fibres (agave, flax and hemp). The needle-punching parameters, such as *depth of needle penetration*, *stroke frequency* and *natural fibre type* were optimized. The nominal area weight of 1000g/m^2 was kept as uniform as possible for all the samples produced to eliminate the effect of variation in area weight. The Box-Behnken experimental design was employed to optimize the parameters under study.

The thickness of the fabric and sound absorption coefficients were evaluated for all samples. Fabric thickness is dependent on production parameters, such as depth of needle penetration, area weight, and to a lesser extent on fibre type (fineness). Fabric thickness also has a major effect on sound absorption properties of the fabric, therefore, it was necessary to measure and analyse it.

The results showed that the samples produced from a blend of agave and PET fibres, with a mean thickness of 7.88 mm, were generally thicker than the other fabrics, this is largely because of the fact that agave fibres are coarser than hemp and flax fibres. On the other hand it can be seen that the fabrics produced from a blend of hemp and PET fibres, with a mean thickness of 6.37 mm, were generally the thinnest of the three blend types, with fabrics produced from a blend of flax and PET fibres showing a mean thickness of 7.32 mm.

The fabrics produced with the lowest depth of needle penetration are generally expected to be thicker than those produced with the highest depth of needle penetration. The results showed that the fabrics produced with the lowest depth of needle penetration of 4 mm, were amongst the top third (ranked by thickness) among all the fabrics produced in this study. While the fabrics produced with depth of needle penetration of 10 mm were generally thinner.

Generally, stroke frequency is not considered to be a major factor influencing the thickness of the needlepunched nonwoven fabrics. However, since the stroke frequency is used to determine **"***punch density***",** stroke frequency may be considered as an indirect determinant of sample thickness. The results showed that when comparing the fabrics produced from the same fibres and at the same depth of needle penetration but different stroke frequencies, those produced at a lower stroke frequency were generally thicker.

Thus, it may be concluded that all the three parameters studied here influence the fabric thickness and fabric density. So, these tested parameters affect sound absorption of the fabrics through fabric thickness and fabric density, in other words, the parameters affect fabric thickness and fabric density directly and, in turn, affect sound absorption properties of the fabric.

It was important to determine the correlation between fabric thickness and the sound absorption coefficient. The *Pearson correlation coefficient,* **r = 0.56**, was obtained. Generally, the correlation coefficient between fabric thickness and sound absorption is expected to be higher, however this relatively lower value might be due to simultaneous effects of other fabric characteristics on sound absorption over and above fabric thickness.

However, the significance probability, p-value = 0.030 (95% confidence) still implied that thickness of the fabric was a significant factor in determining sound absorption coefficient in this study.

A conclusion drawn from the analysis of the results on sound absorption coefficient for individual parameters was that all the fabric characteristics influencing sound absorption properties of the needlepunched nonwoven fabrics discussed in Section 2.6, were dependent upon more than one parameter, namely process parameters or fibre properties.

Therefore, it was necessary to study the synergistic/interactive effects of these parameters. Thus, by multiple regression analysis, coefficients of parameters (fiber type, depth of needle penetration and stroke frequency) and significance probability (P-value) were calculated. The statistical significance of probability, P-value at 95% confidence interval was tested. The results revealed that effects of all the selected parameters were statistically significant on measured sound absorption coefficients. For evaluating a complete picture on the role of different parameters and their interaction effects on sound absorption, a response surface methodology based on Box- Behnken experimental design was employed.

The response surface plots of sound absorption coefficients at different levels of selected parameters and optimized regions were studied and discussed. The different cases were considered as per the statistical significance and dominance of the selected parameters in achieving maximum possible value of sound absorption coefficient.

The analysis of the three different two-way interaction response surface showed that the highest sound absorption coefficient attained was 47% (0.47) and it was found in two different cases. In the interaction between fibre type and depth of needle penetration at different values of stroke frequency, the sound absorption coefficient of 47% (0.47) was obtained for the fabric produced from hemp and PET fibres, produced at 4mm depth of needle penetration and 350/min stroke frequency. While for the interaction between stroke frequency and fiber type at different depths of needle penetrations, the sound absorption coefficient of 47% (0.47) was obtained for the fabrics produced from agave and PET fibres, produced at 4mm depth of needle penetration and 250/min stroke frequency. Also, the interaction of stroke frequency and fibre type did not show a significant effect on sound absorption coefficient as the P-value was above 0.05 at 95% confidence interval level. Therefore, only maximum sound absorption coefficient of 47% (0.47) in the interaction of fibre type and depth of needle penetration was considered.

In the optimized parameters, the depth of needle penetration is required to be 4mm, which is the minimum setting in this study. Given that thickness is affected by the depth of needle penetration, a minimum setting produced a thicker fabric with less density in comparison to that produced at higher depths of needle penetration. The optimum fibre type was found to be hemp, which is finer than agave but slightly coarser than flax. It must also be noted that, of the three tested parameters, fibre type was the least significant according to results obtained by multiple regression analysis. Therefore, fibre type would be regarded as less important factor, as compared to depth of needle penetration and stroke frequency.

The possible application of these developed materials was discuissed extensively in Section 4.2.2.4.

5.2. Effects of Air-gap Size, Fiber Type and Blend Ratio on Sound Absorption Performance of Needle-Punched Nonwoven Fabrics

Air Permeability

Air flow resistance is one of the main factors influencing sound absorption capabilities of the nonwoven fabric. Air flow resistivity is a function of air permeability of the material, which in turn, is influenced by factors, such as fibre fineness (type) and blending ratio. It was observed that overall; the fabrics produced from agave and PET fibres were the most air permeable. It can also be observed that the air permeability increased with the increase in the natural fibre content in a blend.

A more in-depth investigation on air permeability started with the effect of fibre type (fineness) by observing the air permeability of the fabrics produced from three different natural fibres blended with PET for a given blending ratio. Then further investigation was conducted to assess the effect of blending ratio on air permeability at different blend ratios of natural fibres (with PET) for a particular natural fibre.

The effect of fibre fineness on air permeability was studied by comparing the air permeability of the fabrics at the same blending ratio produced from the three different natural fibres, each blended with PET fibres. It was observed that the fabrics produced from blends of agave and PET fibres achieved the highest air permeability, while the fabrics produced from blends of wool and PET fibres were the least air permeable. This trend is attributed to the fact that agave fibres are considerably coarser than PET fibres, more so than wool and flax fibres. This disparity in fibre fineness results in more porous fabrics from a blend of agave and PET fibres and thus more air permeable than the fabrics produced from blends of wool and PET fibres and flax and PET fibres. This points to a direct link between fibre fineness and air permeability.

The effect of blending ratio on air permeability is studied by comparing the air permeability of the fabrics made from the same natural fibre at three different blending ratios. It was observed that for a given natural fibre; air permeability of the fabrics is directly proportional to the amount of natural fibres blended with PET fibres, i.e. air permeability increases with an increase in natural fibre content. This is attributed to the diminishing component of finer fibres, in this case PET fibres, which tend to occupy more fibres per unit volume in comparison to coarser fibres, thus resulting in a more tortuous path and higher hindrance to air passage through the medium.

The rate of change in air permeability with the change in the natural fibre content in the blend was markedly different for the three natural fibres studied. It was minimal for wool-PET blend and more defined in agave-PET blend. It was found that while both fibre type (fineness) and blending ratio affected air permeability, however, the effect of fibre type was the most pronounced. This was further confirmed by the ANOVA results and the least square plots.

Sound Absorption

The effect of each parameter, namely, fibre type (size), blending ratio and air gap on sound absorption coefficient were studied, subsequently; a statistical analysis of the overall results using ANOVA was carried out. The fabrics produced from a blend of wool and PET fibres, in general, showed better sound absorption coefficients than the other fabrics, with the fabrics produced from a blend of agave and PET fibres achieved the lowest sound absorption coefficients of the three fibre blends. This was expected because wool fibres are known to have good sound absorption properties due to scales on the fibre surface.

In general, the fabrics produced from a blend of 30:70% natural: PET fibres showed higher sound absorption coefficients than the fabrics produced from 50:50% natural: PET fibres, while the sound absorption coefficients of the fabrics produced from a blend of 70: 30% natural: PET fibres were generally the lowest with an exception for fabrics produced from a blend of wool and PET fibres.

When the air-gap was increased from 0mm to 25mm the sound absorption coefficients also increased but reached its maximum at 15mm air-gap after which it slightly decreased again with further increase in air-gap from 15mm to 25mm**.** This phenomenon is attributed to the fact that higher air gap behind the sample can absorb the sound energy of longer wavelengths particularly at middle and low sound frequencies. This is due to sound diffraction, which happens when a sound wave passes through the nonwoven layer, enters the new medium (air) and passes into the third medium (Extruded Polystyrene sheet in this study) .

The effect of fibre fineness on sound absorption coefficients of the fabrics was studied by comparing the fabrics produced from three different natural fibres at the same blending ratio. It was observed that the trends in sound absorption coefficients are generally the same for all blending ratios. Generally, the fabrics produced from a blend of wool and PET fibres achieve the highest sound absorption coefficients, followed by those fabrics produced from blends of flax and PET fibres and the fabrics produced from blends of agave and PET fibres showing the lowest sound absorption coefficient. It was also observed that the difference in sound absorption coefficients of the fabrics among the natural fibre blends increased with the increase in natural fibre content in respective blends of natural and PET fibres, i.e. for the blends of 30:70% natural: PET fibres the difference in sound absorption coefficient among the three blends is minimal, then it increases to maximum among the fabrics produced form blends of 70: 30% natural and PET fibres.

The effect of blending ratio was studied by comparing the sound absorption coefficients of the fabrics produced from the same natural fibres at three blending ratios. Again, it was observed that the sound absorption coefficients of the fabric generally decreased with an increase in natural fibre content. The change in blend ratio was found to have very little effect on sound absorption, especially for wool fibre blends. The change in sound absorption coefficients due to flax fibre content was also minimal when compared to agave fibre content. The fabrics produced from a blend of 70:30% agave and PET fibres achieved the lowest values of sound absorption coefficients.

The effect of air-gap size on sound absorption coefficients of the nonwoven fabrics was studied by comparing the sound absorption profiles of the same fabric at different air gaps. The trend for the effect of sound absorption was found to be the same for all three natural fibre blends, i.e. as the air gap was increased the sound absorption coefficients also increased. Furthermore, with the increase in air-gap, the peaks of the sound absorption coefficient profiles at maximum sound absorption tend to shift to the left (towards lower sound frequencies).

It was observed that the sound absorption coefficients generally reach maximum at an air-gap of 15 mm, after which it decreases slightly with an increase in air gap from 15mm to 25mm. This general decrease in sound absorption coefficient is caused by the shifting of resonance frequencies (peak absorption) towards lower frequencies with the increase in air-gap beyond 15 mm. Also, according to Attenborough and Ver [45], the highest sound absorption coefficient occurs when the distance (air-gap in this case) between the sound absorber and the wall is in odd multiples of a quarter-wavelength for the particular sound frequency. This is due to the fact that the incident wave and the reflected wave will have a phase difference of 180^o, i.e. destructive sound wave interference will occur. Conversely, when the air-gap is a multiple of a half-wavelength (even multiples of quarter-wavelengths), the air-gap becomes totally ineffective as the incident and the reflected waves will be in phase, i.e. constructive sound wave interference will occur, in this study it happens, when the air-gap is increased from 15mm to 25mm.

So, by increasing the air gap, the sound energy at long wavelengths (low frequency) can be absorbed. A similar effect obtained by the increase in sample thickness which can improve the sound absorption coefficients at low, middle and high frequencies due to the increase in sound energy losses. All these results were further processed by ANOVA and the least square plots were in agreement with these observations.

The possible application of these developed materials was discussed extensively in Section 4.4.

5.3. Recommendations for Future Work

1. Optimized Production Parameters: Only three parameters were optimized in this study, namely fibre type (fineness), depth of needle penetration and stroke frequency. More work is required to study and optimise other parameters such as production speed and stroke frequency so that the outcome can be more than just academic interest and it can be translated into industrial practice.

2. Types of Fibres: The type of fibres used in this study may not have required variations, particularly since flax and hemp fibres are very similar in characteristics. In a future study, an attempt should be made to use different fibres with larger variation in fibre properties.. Also, the sound absorption coefficients of the same fibre type but at different levels of cottonization / fibre preparation can also be studied to analyse the real cost benefit of using highly cottonised natural fibres.

3. Study other fabrics characteristics in conjunction with the air-gap size: Only the effects of fibre type (fineness) and blending ratio were studied in this section of work. Other parameters, such as fabric thickness, density and pore size and its distribution can also be included. Other parameters may also be optimised at an air-gap size of 15mm which was found to be an optimum air gap in this study.

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Appendix

This study resulted into published manuscripts and manuscripts in preparation for publication.

Published Manuscripts

Mvubu M., Patnaik A., Anandjiwala R.D. (2015). Process Parameters Optimization of Needle-punched Nonwovens for Sound Absorption Application. Journal of Engineered Fibres and Fabrics, 10 (4), 47-54.

- **On Line**

Patnaik A., **Mvubu M.,** Muniyasamy S., Botha A., Anandjiwala R.D. (2015). Thermal and sound insulation materials from waste wool and recycled polyester fibers and their biodegradation studies. Energy and Buildings (Elsevier), 92, 161–169.

- **On Line**

Manuscript in Preparation

Mvubu M., Patnaik A., Anandjiwala R.D. Effects of Air-gap, Fiber Type and Blending Ratio on Sound Absorption Performance of Needle-Punched Nonwovens