Chapter 2

Literature Review

Sound is one of the important elements of our environment and our day to day life. For human beings, the sound is an inseparable part of life, which is useful to communicate with each other. Similarly, birds, animals, and aquatic animals also use sound for communication with each other. Generally, sounds are of two types, one having a pleasant effect and another is noisy. Harmonic sound like music gives a pleasant effect to a human being. On the other hand, sounds from traffic, heavy industrial machinery, trains, airplanes are unwanted sounds known as noise, gives unpleasant effects to a human being. Day by day noise is increasing public health issues. According to the World Health Organization's "Guidelines for Community Noise". Noise causes adverse health effects like hearing loss, disturbance in the sleep pattern, reduce work efficiency, increase stress, tiredness, cardiovascular problem, adverse social behavior, and psycho physiological problems. Therefore, it is essential to control or reduce noise from traffic, various public places, in factories, offices, and houses. Noise also significantly decreases productivity in various environments. Noise is a byproduct of today's modern engineering era.

In physics, the sound is considered as waves similar to other mechanical waves, which propagates as an audible wave of pressure through various mediums such as a gas, solid, or liquid. Acoustics is known as the science of sound that deals with the propagation of mechanical waves in gases, solids, or liquids. The meaning of sound is "Relating to sound or the sense of hearing." "Acoustic" word is derived from "akoustikos," a Greek word which means ready to hear or hearing. Acoustic is defined as the science of sound that deal with its generation, propagation through various medium, and its psycho psychological effects [5]

The noise must be effectively controlled by designing quite machines and also by the construction of buildings with sound absorbing materials which helps to control noise. Strict rules and regulations imposed by many countries' governments can also be used to control the noise in various places. The use of acoustics textiles material increasing due to an increase in application areas and demand, strict rules and regulations in many countries, as well as technological advancement, concern about the environment, growth in population, and sustainability are some of the reasons for increase acoustic application in different areas. In today's day to day life demand for calm and comfort, further leads to an increase in the demand for sound insulating acoustic materials.

2.1 Noise Generation

In today's modern world, noise pollution has become a severe problem. Noise is produced in the same way as the sound is produced. When an object vibrates, it produces sound waves. The unwanted sound waves not desirable to a human being become noise. An increase in the number of vehicles, different types of construction work, and usage of home appliances lead to generating the noise. Nowadays, increase in transportation facilities like rail, airplane, and usage of heavy industrial machinery in industries is also some of the factors responsible for the noise. In the era of modernization, traffic is one of the main sources of noise, and day by day, it is increased as the number of vehicles is increased. In developed and developing countries like India increased traffic has also become one of the major sources to increase noise pollution [6–9].

Various industries such as textiles, foundries, heavy metal Industries, crushing, and sawmills, in which moving components like belts, gears, motors, fans, and rotors are another major sources of noise pollution. The level of noise in these industries generally depends on the rotating components, equipment, and operation processes such as milling, grinding, drilling, presses, crushing, riveting, etc. Nowadays, the use of household items like television, music systems, grinders, etc. are also responsible for household noise generation. Social events, sports events, dance parties, concerts in open ground, and Garba during Navratri also generated a considerable amount of noise [10]. The use of various defense equipment such as guns, tanks, rockets, explosion, fighter planes, and machine gun generates a lot of noise. Social gatherings, concerts, workshops, parties, clubs, and the use of loudspeakers in open areas are also some of the factors, which produce a substantial amount of noise.

2.2 Effect of Noise

Noise pollution affects the daily activity of the human being. Only in Europe, more than 2.5 lakh people suffered from heart-related diseases, and about fifty thousand people were losing their life due to traffic noise. As per the World Health Organization (WHO), nowadays after air pollution, noise pollution becomes the second major pollution that affects the health of the human being and environment. It leads to create a problem like heart diseases, hearing loss, hypertension, and increase in stress, sleep disturbance, and also affects the performance at work. The effect of noise on human health can be classified as shown below

Physical effect - Permanent hearing loss, and also adversely affect the health of a human being directly.

Physiological effect - Sleep disturbance, high blood pressure, cardiovascular disturbances, and also increase the stress level.

Psychological effect - Reduce the working efficiency of a person, reduce concentration, annoyance, irritation, disturb interpersonal relationships, and also leads to hypertension.

As per the guideline given by the Occupational Safety and Health Administration (OSHA), if a worker exposed to the noise level of 85 decibels (dBA) or higher for 8 hours, shift per day leads to permanent hearing loss. In such a case, the earplug needs to provide for safety. Prolong exposure to 85 dB or higher level of noise leads to an increase in stress level, permanent hearing loss, and increase blood pressure. Continuous exposure to 60 dB or higher sound in the day time and 55 dB during night time can increase the risk of a heart attack. Various noise level and its effect on human health are described in Table 2.1

Table 2.1: Harmful effects of noise level on human health

Noise Level	Effects on Human Health
Up to 30 dB	No effect
30 dB to 60 dB	Prolong exposure to upper range lead to an increase in stress, increase in communication problem, irritation, disturbance in sleep, and an increase in tension, etc.
60 dB to 90 dB	Increase the risk of heart attack, increase blood pressure, leads to hypertension, disturbance in stomach-gall function, cause muscle pain, affect health and also cause a psychological disturbance, etc.
60 dB to 120 dB	Adversely affect human health and permanent hearing loss, etc.
120 dB and Above	Prolong exposure cause painful effects.

2.3 Noise Control

Noise can be controlled at the source or the receiver's end by suppression of unwanted sound. Sound can also be controlled using sound absorbing materials in between the path of sound propagation. The entire noise system can be divided into three elements.

Source of Noise – A starting point where the air molecules get disturbs.

Path of Noise – The medium through which the noise energy propagates from one point to another point.

The receiver of Noise – The person who received the sound energy and able to quantify the level of noise.

To control noise level, it is necessary to control noise at either of three elements of noise, as stated above. Noise level can be reduced by reducing noise at the source or along the path. Reducing the noise level by treating the receiver is another option of noise reduction. Control of noise at the source is not often followed because of its high cost due to redesigning and development. Control of noise by treating individual is again not a preferable approach, because in this individual receiver must be treated. Control of the noise in the path is the simplest way to control noise, and therefore this is the most commonly used approach to reduce the noise level. In the approach generally, the sound absorbing material is placed in between the noise source and noise receiver. The principles of absorption, isolation, damping, and isolation of vibration are used to reduce the noise at the receiver level. To control a noise, a specially engineered textile fabric known as acoustic textiles, can be used for sound absorption.

Control of Noise at Source – Noise at source can be controlled or reduced by proper redesigning of the sound generating source. In case of the machine it can be achieved by proper maintenance of the machine, by using soundproof chambers for the noisy machine, and by using vibration-damping material in construction and foundation of the machine [11].

Control of Noise in the Path – Noise can be controlled or reduced by placing sound absorbing material known as acoustic barriers between the source of noise and receiver. An appropriate design of acoustic barrier must be used [11].

Control of noise at Receiver's End – To reduce the noise at the receiver's end, ear protection aids like earmuffs, earplugs, headphones, noise helmets etc. need to be provided to the receiver [11].

2.4 Basics of Acoustic

Sound moves as a wave in air or other elastic media. The sound is defined as a wave similar to the other mechanical waves in physics. The meaning of acoustics word in Greek word is "to hear". Sound is a hearing sensation that we hear and an essential social sense for a human being to communicate with each other. The science of sound that deals with the propagation of the sound wave in different mediums such as gases, liquid, and solid. Acoustic is also known as "Scientific study of sound". The sound is generated due to the vibration of somethings. This vibration of the body vibrates the surrounding air or liquid or gas medium. These vibrations in the air produce longitudinal waves that travel in the air, and we can hear the sound. In another way, sound wave causes the transfer of energy from source to the medium through which it travels. Its wavelength, amplitude, and frequency characterize a sound wave [12]. When sound wave impinges on the receiver surface, the sound wave can be transmitted, absorbed, diffracted, reflected, and refracted from the surface.

2.4.1 Sound Generation

A sound wave is generated due to the vibration of an object. This vibration of the object vibrates the surrounding air molecules. The vibrating object is responsible for vibrating the air molecules in both directions. Moves in one direction cause compression in air and move in the opposite direction cause expansion or rarefaction of air molecules. This expansion and compression generate a longitudinal wave of sound in the air. Vibrating air molecules move back and forth in the direction parallel to the wave motion. During this back and forth movement of air molecules receiving energy from molecules near to the sound source and passing it to the adjacent molecules far away from the sound source [13]. Sound intensity depends on the vibrating source of the sound, the medium through which it passes, and the receiver. Sound is a mechanical wave that travels through air, liquid, and solid medium, and its speed in the medium depends on the characteristics of air, liquid, and solid medium [5].

2.4.2 Propagation of Sound

Sound is a sequential wave having pressure, propagates through an elastic medium such as solid, liquid, and gases [14]. Sound waves require medium to propagate through it. A sound wave can not travel without any media for it. For example, the sound wave cannot travel through a vacuum. During the propagation, the sound wave can be transmitted, reflected, absorbed, and diffracted by the viscous medium. Following properties of the medium through which the sound wave passing affects the behavior of the sound propagation [14].

- The speed of the sound wave in the medium depends on the relationship between density and pressure. Density and pressure are affected by the temperature of the media.
- The sound further transported due to the motion of the medium itself. e.g., Independent motion of sound through the medium like air get affected by wind.
- The reduction in the amplitude of the sound depends on the viscosity of the medium it passes. Reduction in the amplitude of sound waves in air and water medium is negligible.

The propagation of sound through the medium depends on the temperature, density, pressure, motion of the medium, and viscosity of the medium. Speed of sound wave in dry air at 0°C temperature is 331.29 meters per second and in water 1402.74 meters per second., but if the temperature is 20°C, the speed of sound in the air is 343 meter per second, and in water, it becomes 1481 meter per second.

2.4.2.1 Wavelength and Frequency

As shown in figure 2.1 the displacement of a sound wave with time. In the figure, sound wave displacement function on the Y-axis and time on of the X-axis denoted. A wavelength can be measured between successive peaks or between any two corresponding points on the cycle. The frequency of sound defined as the number of waves generated per second and expressed in hertz (Hz). Sound wave vibrates at a different frequency or many frequencies as they move through the medium. The amplitude of sound defined as the maximum displacement of a peak. While the wavelength defined as the distance between two consecutive peaks [15].

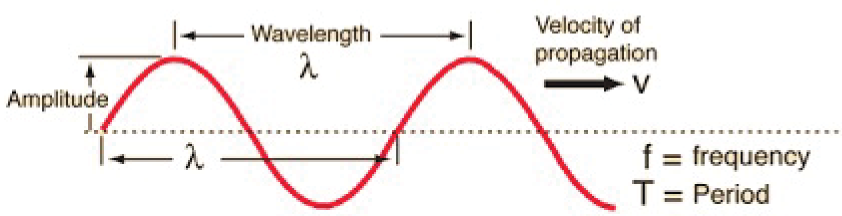


Figure 2.1: Sound wave displacement with time

Following equation 2.1 indicates the relationship between the sound wavelength and frequency:

$$Wavelength = \frac{Speed\ of\ sound\ (m/s)}{Sound\ frequency\ (Hz)} \tag{2.1}$$

Generally, the sound frequency range can be split into sections or bands. These bands usually have a bandwidth of one octave or one-third octave. Each octave band has a centre frequency value, and its value is just double the previous value of centre [16] frequency. The following Table 2.2 indicates the octave bands frequencies [5].

Table 2.2: Octave bands frequencies [10]

Lower band limit (fL) (Hz)	**Centre frequency (fc) (Hz)**	**Upper band limit (fu) (Hz)**
22.4 Hz	31.5 Hz	45 Hz
45	63	90
90	125	180
180	250	355
355	500	710
710	1 kHz	1.4 kHz
1.4 kHz	2	2.8
2.8	4	5.6
5.6	8	11.2
11.2	16	22.4

Source:D.R.Raichel [5]

Kadam et al. [17] mentioned that in octave bands, the centre frequency (f_c) is the geometric mean of lower band limit (f_L) and upper band limit (f_u). The difference between the lower and upper band limits is called bandwidth. Each octave band is divided into three sub-band to obtain a one-third octave band. Each successive frequency is higher by the cube root of 2 than the previous one. The centre frequency for one third octave band ranges from 20 Hz to 20 kHz.

The human ear can not hear all the sound frequencies. Sound audibility to the human ear depends on the sound frequency and intensity. Sound wave having a frequency range of 20 Hz to 20 kHz is an audible sound range for humans [5]. Generally, the frequency of human voice is in the range of 500 Hz to 4000 Hz, and it is the preferable frequency range for a human being [18]. Sound is classified as audible sound, infrasound, ultrasound, and hypersound. The classification of sound based on its frequency is given in the Table 2.3.

2.4.2.2 Intensity of Sound

Sound intensity level, also known as acoustic intensity, is defined as the average rate at which the sound energy is transmitted through a unit area that is perpendicular to the direction of sound waves travel. The intensity of sound can be measured in the SI unit,

Table 2.3: Classification of sound based on the frequency [10]

Sound	**Frequency**
Infrasound	< 20 Hz
Audible Sound	20 Hz - 20 kHz
Ultrasound	> 20 kHz
Hypersound	> 1 GHz

Source:D.R.Raichel [5]

which is the watt per square meter (W/m^2) or watt per square centimeter (W/cm^2) [19].

$$I = p \cdot v \tag{2.2}$$

Where,

I= sound intensity,

p= Sound pressure,

v=Particle velocity

The sound intensity can be measured by auditory equipment independent of a listener's hearing. The sound intensity of one sound can be compared with another sound of the same frequency by using their power ratio. This ratio is denoted as I_0 [20]. The intensity of sound also can be measured by using a standard threshold of hearing intensity I_0 [21], as shown in the equation 2.3:

$$I_0 = 10^{-12}\, watts/m^2 = 10^{-16}\, watts/cm^2 \tag{2.3}$$

If the intensity of one sound is I and Intesity of another sound is I_0, then the sound intensity ration B in bel is

$$B = log_{10}\,[\frac{I}{I_0}] \tag{2.4}$$

Where,

B = bel (Difference in the intensity of sound)

The most commonly used unit is the decibel, which is equal to 0.1 bel [20]. So the relative intensity of sound can be written as shown in below equation 2.5.

$$I(dB) = 10\, log_{10}\, [\frac{I}{I_0}] \tag{2.5}$$

Equation 2.5 Indicate sound intensity in decibels. The ratio of a given sound intensity I to the hearing sound threshold intensity Io gives the value of decibel. In that case, the value of the threshold needs to be considered as 0 decibels (0 dB) [21]. The intensity of sound is related to the surface area of the sound source and sound power.

2.4.2.3 Sound Pressure

The sound pressure starting point is a vibration of somethings in air. This vibration of objects produces sound waves having some pressure, which propagates in all directions in the air [22]. Sound pressure is a force acting on a surface area perpendicular to the direction of the sound wave [23]. Sound pressure is also known as acoustic pressure. The unit of sound pressure is Pascals (Pa). It can also be expressed as N/m^2, which is equal to Pascals. Sound waves with loud sound can produce higher sound pressure, and similarly, a sound wave with quite sound produces less sound pressure. The human ear can hear an extensive range of sound pressure. The quietest sound that the human ear can hear is having sound pressure of 2 X 10^{-5} Pa. This sound pressure is called the threshold of human hearing [22].

2 X 10^{-5} Pa is a standard sound pressure and is equal to 0 decibels. Normally, human ear experience pain at 120 dB to 140 dB, which is known as the pain threshold. The pain threshold may vary from person to person [23]. It is logical to measure the sound pressure on a logarithmic scale. The sound pressure level is measured on a logarithmic scale, which represents the sound pressure relative to a reference pressure [24]. In other words, sound pressure is a measure of sound loudness in terms of decibels. Sound pressure level generally measured using decibels (dB) and can be expressed using the following equation 2.6 [25].

$$L_p = 20\, log10\, [\frac{p}{p_{ref}}] \tag{2.6}$$

where,

L_p = sound pressure level (dB)

p = sound pressure (Pa)

$p_{ref} = 2 \text{ X } 10^{-5}$ - reference sound pressure (Pa)

Typical Subjective Description of Sound Pressure Level

- **0 - 40 dB** : Quiet to very Quiet
- **60 - 80 dB** : Noisy
- **90 - 100 dB** : Very Noisy
- **110 dB and above** : Intolerable

Prolong exposure to the sound pressure level beyond 90 dB may be harmful to human hearing. Table 2.4 shows the different sound source and sound pressure levels along with its subjective evaluation.

Table 2.4: Sound source and sound pressure level

<table>
<tr><th>Sound Pressure Level (dB)</th><th>Typical Source</th><th>Subjective Evaluation</th></tr>
<tr><td>130-140
(Threshold of pain)</td><td>Blasting,</td><td rowspan="4">Extremely noisy
- intolerable</td></tr>
<tr><td rowspan="2">120</td><td>Jet take-off</td></tr>
<tr><td>Firecrackers</td></tr>
<tr><td>110</td><td>Rock concert</td></tr>
<tr><td>100</td><td>Pneumatic hammer</td><td rowspan="4">Very noisy</td></tr>
<tr><td rowspan="3">90</td><td>Heavy truck</td></tr>
<tr><td>Loud shout</td></tr>
<tr><td>Factories</td></tr>
<tr><td>80</td><td>Highway traffic</td><td rowspan="3">Loud</td></tr>
<tr><td rowspan="2">70</td><td>Loud radio or television</td></tr>
<tr><td>Noisy restaurant</td></tr>
<tr><td>60</td><td>Department store</td><td rowspan="3">Moderate to quiet</td></tr>
<tr><td rowspan="2">50</td><td>General office</td></tr>
<tr><td>Quiet street</td></tr>
</table>

Sound Pressure Level (dB)	**Typical Source**	**Subjective Evaluation**
40	Living room	Quiet to very quiet
	Library	
30	Bedroom	
	Country site	
20	Unoccupied recording studio	Almost silent
	Remote underdeveloped area	
< 10 (Threshold of hearing)	Anechoic chamber/ Natural places	Silent

2.4.3 Mechanism of sound interaction with receiving surface

The sound waves impinge on an arbitrary surface, and they may be reflected, transmitted through the surface, or absorbed by the material [10]. These phenomenons are shown in figure 2.2. The amount of energy loss during these reflection, transmission, and absorption depends on the surface characteristics of the material. When sound waves propagate through medium and pass through the receiving material without any loss of in sound frequency is called sound transmission through the material. When sound waves strike on the surface of objects and completely redirected back without altering their characteristics, it is called a reflection of sound waves. The reflection angle of the sound wave is the same as the incidence sound wave angle from the reflecting surface. When the sound waves strike on the surface of the material, and the sound waves are absorbed by the material is called sound absorption. The absorption of sound is measured in terms of energy absorbed by the material and expressed in terms of sound absorption coefficient (α). The absorbed sound may be dissipated or transmitted through the materials that depend on the acoustic properties of the material [26].

2.4.3.1 Sound Absorption

The sound absorption is the loss of sound waves energy when the sound waves interact with the absorbent material and not reflected back [27]. Sound absorbent material absorbed the sound wave energy and reduced its intensity. Sound absorption property of material

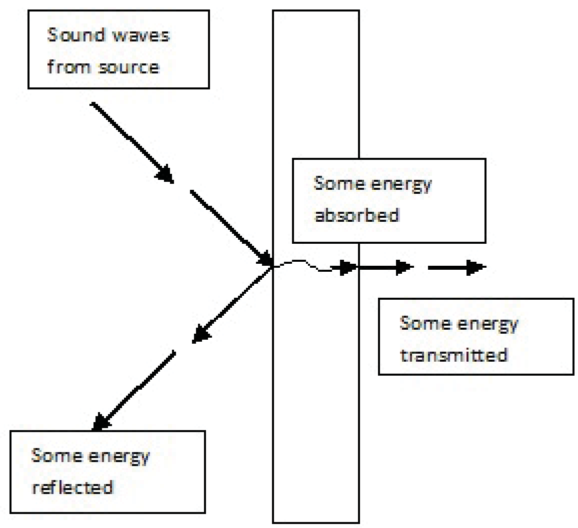


Figure 2.2: Sound interaction with receiving surface

is helpful to create a suitable acoustic environment by absorbing the sound wave energy and reduce the noise level from the surrounding environment [27].

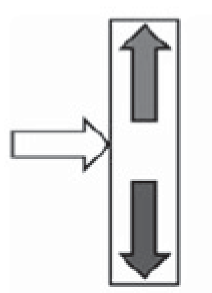


Figure 2.3: Sound absorption

As shown in figure 2.3 sound absorbing material dissipates the sound wave energy and minimizes its reflection from the surface. Sound wave absorption occurred when the used acoustic material absorbed the emitted sound energy. It is like water absorbed by the sponge [10]. There are various types of sound absorption material available. Generally, the sound absorption material is porous or resonant type. Fibrous materials and open-cell foam are examples of porous absorbents. When sound waves impinge on these materials, they convert the sound energy into heat energy [10]. The resonant type absorbents are membrane absorbers consists of a solid plate with a tight air space behind it, and here mechanical or acoustic oscillation system is used [27].

The sound absorption property of the material is measured in terms of the sound absorption coefficient, which indicates the amount of energy absorbed by the material. The sound absorption coefficient (α) is well-defined as the ratio of energy absorbed by the material to the incident energy on the material surface [10]. Sound absorption value depends on the frequency of the incident sound waves. Sound absorption is an important phenomenon for absorbent material to judge its acoustic performance.

2.4.3.1.1 Sound absorption mechanism of fibrous materials .

Acoustic porous materials have more than 90% porosity and allow sound to easily enter into the material called porous [28]. Common materials used for acoustic applications are fibre and open-cell foam. When sound waves strike on the fiber or open-cell foam, the kinetic energy of the sound waves is converted into heat energy. This energy conversion process is known as sound absorption. The sound is dissipated into the porous acoustic material due to its conversion into heat. Porous material can absorb sound due to this energy conversion process. When sound enters into the porous materials with pressure, the pressure of sound creates an oscillation of air molecules surrounding it inside the porous material. The air molecules oscillate inside the porous material according to the wave frequency. This oscillation of air molecules/ sound waves causes frictional losses. Sound waves lose their momentum due to the contraction and expansion phenomenon of sound waves inside the porous material. Contraction and expansion of sound waves occur due to the changes in the direction of sound waves, as a result of this, air molecules undergo periodic relaxation and compression inside the porous material. In low-frequency range, heat conversion takes place isothermally, due to the high heat conductivity and large surface to volume ratio of fibre [29], and at high frequency, compression takes place adiabatically. This leads to cause a change in temperature. Sound energy loss due to the heat exchange between this isothermal and adiabatic compression [29]. Sound energy loss is up to 40% of sound attenuation if the sound propagates parallel to the plane of fiber [29]. The main reasons for acoustic energy loss, when sound is passing through the sound absorbing acoustics materials, are as follows.

- Momentum loss of sound wave
- Frictional loss

- Temperature change

The more fibrous material gives better sound absorption, while denser materials are less absorptive. The sound absorption of the material also depends on the frequency of incident sound waves. It is found that low-frequency sounds are very difficult to absorb due to its long wavelength. At the same time, low-frequency sounds are less harmful to humans in comparison to high-frequency sound [30].

Aso et al. [31] mentioned in their study that generally, there are three types of absorption characteristics of fibrous materials. The first type of mechanism of absorption characteristics of fibrous materials, the sound absorption is very less at low frequency, but at high pitched tones, sound absorption is quite considerable. When the sound waves strike on a fibrous assembly, the air molecules in the fine space of fibrous assembly vibrates due to the sound pressure. Energy is taken out from sound waves, to overcome the friction resistance between the fibre and vibrating air. The relative motion of fibre and air converts sound wave energy into heat by air viscosity. This type of absorbing mechanism is known as viscosity resistance type absorption. In the second type of mechanism for sound absorption by the fibrous assembly, a peak value got at a low frequency, and the sound absorption coefficient values increase with an increase in a frequency value at a high-frequency range. This type of absorption is known as fibrous resonance. Fibrous resonance differs from the viscosity resistance type by airtight material, such as a pulp broad or plywood, placed at some distance from a solid wall. The peak at low-frequency sound waves is presumed because of the resonance of the sample. The sound absorption coefficient value increase with an increase in frequency value at a high-frequency range is peculiar to a fibre assembly. The third type of absorption mechanism is behaved somewhere in between the first type and second type mechanisms [32]. The third type of mechanism shows resonance absorption without a peak because the absorption coefficient is higher than viscose resistance at a higher frequency range than the resonance frequency [31].

2.4.3.1.2 Sound Absorbing coefficient .

The absorbing coefficient mathematically presented as follows [32]:

$$\alpha = 1 - \frac{I_R}{I_I} = \frac{|P_i|^2 - |P_r|^2}{|P_i|^2} = 1 - |R|^2 = 1 - (\frac{n-1}{n+1})^2 = \frac{4n}{(1+n)^2} \tag{2.7}$$

$$n = \frac{P_{max}}{P_{min}} = \frac{V_{max}}{V_{min}} \tag{2.8}$$

Where,

α = Sound absorption coefficient

I_I = One-sided intensity of the incident Sound

I_R = One-sided intensity of the reflected Sound

P_i = Pressure of incident sound wave

P_r = Pressure of reflected sound wave

R = Reflectance factor

n = Standing wave ratio

P_{max} = Maximum value of sound wave pressure

P_{min} = Minimum value of sound wave pressure

V_{max} = Maximum value of Voltage corresponding to maximum pressure

V_{min} = Minimum value of voltage corresponding to minimum pressure

Equation 2.7, can be used to measure the sound absorption coefficient. Generally, the value of the sound absorption coefficient of a material varies from 0 to 1. Sound absorption coefficient value 0 indicates no sound absorption, and 1 value indicates 100% sound absorption by the material. There are several standard testing methods available to measure the sound absorption coefficient. One of the simplest and more commonly used methods is a plane wave impedance tube with two microphones. This method is more popular because of its added advantages like a very small size sample is required for testing and also less time-consuming. In the acoustic material testing section, this method is discussed in detail. In this research work, customized impedance tubes are developed with 100 mm, and 30 mm diameter and testing were done according to ISO 10534-2 test method.

2.4.3.2 Sound Transmission

As shown in figure 2.4, when the sound waves propagate through the medium and pass through the material without any loss in the frequency is called sound transmission through the material [10]. One should note that, in this process of sound transmission, the generated sound pass through the material without being absorbed or reflected by the material.

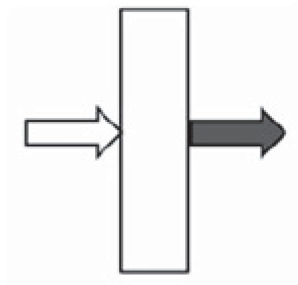


Figure 2.4: Sound transmission

2.4.3.3 Sound Reflection

As sown in figure 2.5, when a sound wave strikes on any hard or smooth surface and reflected without altering their characteristics is called the reflection of sound. During the reflection of sound, there is no loss in terms of frequency and energy. The angle of reflected sound waves is the same as the angle of incidence sound waves incidence from the reflecting plane, which means both angles are equal [5]. There are lots of usages of the reflected sound waves. The echo (reflected sound wave) produced from the reflective surface can be used to measure the depth of water from sea level [10]. Raichel DR [5] said that the reflection phenomenon could be used for the measurement/ identification of geological composition at the bottom of the ocean and inside the earth's crust [15]. One of the simple examples of sound wave reflection is the Echo of sound.

2.4.3.4 Sound Refraction

As shown in the figure.2.6, when the sound wave passes through the material and bends away from the path of wave (deviate from its normal path) is called sound refraction. The refraction of sound depends on the speed of sound, wind direction, the direction of sound propagation, angle of the incident sound wave, temperature, and relative humidity of the surrounded atmosphere [10]. This sound refraction phenomenon also affects the speed and wavelength of the sound wave.

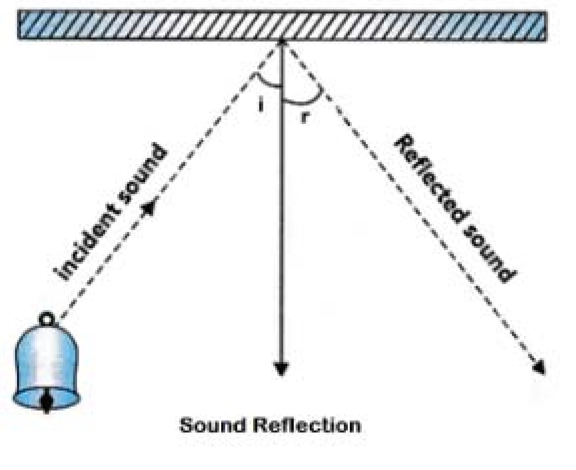


Figure 2.5: Sound reflection

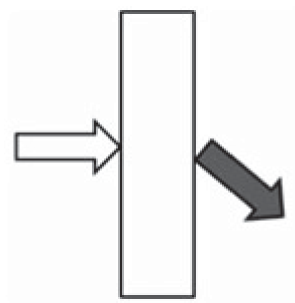


Figure 2.6: Sound refraction

2.4.3.5 Sound Diffraction

As shown in figure 2.7, when sound waves strike on the surface of the material and reflected back with the change in the direction of the sound waves from the top surface known as the diffraction of sound waves. The sound with low frequencies tends to diffract easily than the sound wave with high frequencies [10]. Sound diffraction is reduced as the sound source comes closer to the surface. We can hear the sound of another person speaking to us from the adjacent room is a simple example of sound diffraction.

2.5 Acoustic Textiles Materials

Sound absorbing materials are very useful to absorb unwanted noise. Sound absorbing materials reduce or eliminate the noise by absorbing it from the surrounding atmosphere

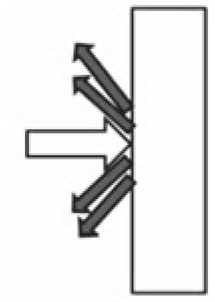


Figure 2.7: Sound diffraction

[10]. Noise has a harmful effect on human health. Sound absorbing materials play a vital role in reducing it and also helpful to create a pleasant environment for a human being. Sound absorbing material absorbs the unwanted noise, which impinges on the surface of it. The materials, which can reduce or absorb most of the sound energy impinge on it, is called sound absorbing material [10]. When a sound wave enters into the absorbing material, oscillated air molecules, along with sound waves, come into the frictional contact with the fibre. Frictional contact of a sound wave with fibre cause energy loss of sound and helping in reducing noise.

The noise can be controlled by putting sound absorbing material either of these three places

- Near to sound source
- Between sound source and receiver
- Near to receiver

The selection of the material for sound absorption depends on its application and the sound frequency. Sound absorbing materials like open-cell foam, porous, and panel can be used for different sound absorbing applications [33]. Porous materials are the ideal for sound absorbing because it consists of high porosity which helps the sound to enter into the structure and effective reduction of sound wave energy due to the frictional loss into the structure. Fibrous materials like textiles due to its porous structure are used for the acoustic application. Textile materials used for various acoustic applications are woven, knitted, or nonwoven. Nonwoven is one of the best sound absorbing materials due to its highly porous structure and added economic advantages. Some time to improve the aesthetic value of nonwoven material used in combination with a woven or knitted textile structure.

To produce these Acoustic textile materials generally, both natural and synthetics fibers are used. Textile based acoustic materials are used either in the form of panel absorber or porous absorber [33]. Some time to improve the performance of the material, some value added chemical treatment also given to the textile material. Acoustics properties of the sound absorber are measured either in terms of sound transmission loss (STL) or Sound/Noise absorption coefficient (NAC). Generally, NAC (Noise Absorption Coefficient) value is used to measure the acoustic properties of textile materials, and to measure the acoustic properties of flat surface material like panel or metal plates STL (Sound transmission loss) is used.

2.5.1 Raw Materials

Fibre is the basic raw material for any textile product. The fibres which have inherent sound absorbing properties are used in producing sound absorbing textile material. Natural and synthetics both fibres are widely used to produce sound absorbing material. All natural fibre has some inbuilt variation in terms of its length, fineness, cross-section as the growth of fibre depends on the climatic condition, which does not remain ideal for all time. In the case of synthetic fibres it is possible to produce as per required length, fineness, and cross-section having required surface area. Natural fibres, like kapok and Estabragh(Milkweed) obtained from the tree and plant, respectively, are freely available. They are the best and cheapest alternative of currently used non-eco-friendly material. These natural fibres do not have any harmful effect on the environment because they are biodegradable.

2.5.1.1 Synthetic Fibre

Synthetic fibers alone or in blend with natural fibers are used to produce the sound absorbing material. Some time synthetic fibers are also blended with recycled material like shoddy to produced acoustic materials. Some of the synthetics fiber used for acoustic applications are polypropylene, polyester, viscose, glass and bi-component fibre, etc.

While selecting the fiber for particular application fiber properties, which affect the performance of the acoustic material, are also need to consider. The fiber properties which affect the acoustic material performance are fiber fineness, length, tenacity, and uniformity. One of the most important fiber properties affecting the acoustic performance of the material is fiber diameter, which relates to its fineness. Synthetics fiber has certain advantages as compared to natural fiber in terms of more uniform diameter, less various along the fiber length, and good mechanical properties. Fibre having a finer and more uniform diameter, it is easy to control the acoustic properties of the textile materials.

The use of synthetics fibers either alone or in blend with natural fibers has a specific advantage as compare to the natural fiber.

Advantages of synthetic fibers

- Higher tenacity
- Less variability in fiber properties
- High durability
- Low cost
- Good mechanical properties

Disadvantages of Synthetic fiber

- Majority of the synthetics fibers are non-biodegradable, leads to an increase in pollution.
- High carbon emission.
- Fiber like glass creates a problem of skin irritation.
- Some fiber has an adverse effect on a human being.
- Mineral fibers like rockwool and fiberglass are harmful to human health.

Various researchers [34–36] studied the effect of fineness and cross-sectional shape of thermoplastics synthetic fibre on sound absorption properties. They found that finer fibres give better sound absorption properties. The use of finer fibre in nonwoven fabric leads to giving better sound absorption due to an increase in surface area and tortuosity.

Tascan M and Vaugha EA [37] investigated the effect of various fibre shape on sound absorption properties. They produced five different needles punched nonwoven fabrics with different fibre shapes (Trilobal 4DG and Round) and two different fineness of fibre (3 denier, 15 denier). They found that nonwoven fabric produced with trilobal and 4DG fibres gives better sound absorption properties than the round shape fibre. 4DG fibre has deep grooves that provide a higher fibre surface area. 4DG fibre has an octalobal cross-sectional shape. They also mentioned that as fabric density affected the sound insulation behavior of nonwoven fabric. Both total surface area and fabric density positively affect the sound insulation properties of nonwoven fabrics.

2.5.1.2 Natural Fibre

Uses of natural fiber in the field of acoustics application has increased drastically, as the synthetic fibers are harmful to the environment. Most of the synthetic fibers are non-biodegradable, and now in many country rules and regulations related to environmental pollution are very stringent. Natural fiber has enormous potential to replace synthetic fibers in the field of acoustic textile. Lots of research works are going on natural fiber to find out the best alternate of synthetic fibers. So many researchers studied the acoustics properties of different natural fiber and came up with favorable results. They studied the acoustic properties of natural fiber like kenaf, hemp, agave, flax, jute, bamboo, coir, and wool for acoustic application [10, 38]. The problem with the natural fiber is its inherent variations in physical properties of fibre like length, fineness or diameter and cross-section. At the same time, due to some favorable properties like the low elongation of jute, coir, hemp, and flax fibers are more suitable for acoustic applications. The use of natural fibre for acoustic applications have certain advantages and disadvantages over synthetic fiber.

Advantages of natural fibers:

- Sustainable and Biodegradable
- No harmful effect on the environment
- No side effects on human being and safer
- Reduced carbon emission

Disadvantages of natural fibers:

- Less strength compare to synthetic fiber
- Inbuilt variation present in the fiber
- Less durable and flammable
- Cost of fiber

Natural fibers are harmless to the environment than synthetic fibers due to its biodegradable nature. Natural fibre functional properties can be enhanced by blending with synthetic fiber or by giving various chemical treatments like coating, carbonization, flame retardant finish, or impregnation. Base on the application area, natural fibre required different functional properties. For example, the natural fibre used in the automotive, aerospace, and building industries require moisture and fire resistance properties. These properties can be imparted by giving fire resistance or a retardant and moisture-resistant finish to the natural fibre.

Hollow fibres are possessed hollow lumen in them. This hollow structure helps to enhance the sound absorption properties of hollow fibre. Natural fibre, like kapok and Estabragh (milkweed), is natural hollow fibre. Both Kapok fibres and Estabragh fibres have enormous potential to be used as sound absorbing material due to its inherent hollow structure [39,40]. Natural fibres such as hemp, coir, flax, jute, kenaf, ramie, husk, cotton, banana, bamboo, wool, etc. can also have the potential to be used as raw material for the acoustic application.

Xiang et al. [41] evaluated the sound absorption properties of natural kapok fibre. They prepared different Kapok fibre samples by varying fibre length, thickness, bulk density, and orientation of fibre. The acoustic properties of prepared samples were measured using an impedance tube test. They found that the kapok fibre has excellent acoustic damping performance due to its natural hollow structure. They also stated that the sound absorption coefficient of kapok fibrous assemblies is significantly affected by the bulk density, thickness, and arrangement of kapok fibre but less dependent on the fibre length.

Hassani et al. [40] studied the noise reduction coefficient of estabragh/polypropylene blended fibres nonwoven. They also studied, the effects of blend ratio, punch density, and areal density (g/m^2) on the acoustic properties of nonwoven samples. They found that the noise absorption behavior of samples increases as the proportion of Estabragh fibres in the blend is increased. Their results also indicate that samples subjected to more severe needling operation exhibit higher values of NRC. They also stated in their findings that the areal density of samples directly affects acoustical performance.

Oldham J et al. [42] studied the sustainable acoustic absorbers from the biomass. The author studied the sound absorption properties of sisal, ramie, cotton, wool, jute, and flax fibers at 500 Hz frequency. They concluded that sustainable absorber could be produced by the combination of natural fibres with the whole reed, which have very effective sound absorption properties for a wide range of frequency.

Mvubu et al. [38] studied the process parameters optimization of needle-punched non-wovens for sound absorption application. The authors evaluated the acoustic properties of the needle punched non woven fabric produced by blending agave, flax, and hemp fibres with PET fibre in the ratio of 50:50. They found that when multiple factors are considered for its effect on the acoustic properties of the material, fibre type is least significant in determining the sound absorption coefficient. The maximum sound absorption value 0.47 is achieved for selected parameters.

In another study, the acoustic properties of natural fibre nonwovens fabric developed using natural fibre like bamboo, banana, and jute fibres for car interiors to reduce noise were studied [43]. They developed nonwoven fabric by blending bamboo, banana, and jute fibres with polypropylene in equal proportion (50/50 blends) and studied their acoustic properties using the impedance tube test method. They found out that bamboo/polypropylene nonwoven samples give the highest sound absorption coefficient value than banana/polypropylene and jute/polypropylene samples in the frequency range of 100 to 1600 Hz. They also stated that bamboo/polypropylene nonwoven has good thermal insulating properties than banana/polypropylene and jute/polypropylene samples.

Sedeeq et al. [44] investigated the sound absorption properties of recycled fibrous materials made of natural fibres, synthetic fibres, and agricultural lignocellulosic fibres. They developed nonwoven samples of polyester/cotton/wool, polypropylene/cotton/wool, cotton/polyester blends 70/30, 80/20, and 50/50, respectively, and 100% jute fibre sample. The sound absorption coefficient of samples measured using impedance tube test methods. They found that sound absorption coefficient values are lower or equal to 0.06 at low frequencies (100 - 400 Hz), and polyester/cotton/wool samples give the highest value 0.67 at high frequency (2000 - 6300 HZ). They concluded that recycled fibrous materials due to its low cost, lightweight and biodegradable nature could be used as raw material for acoustic materials.

Patnaik et al. [45] analyzed the sound insulation properties of nonwoven fabrics developed using waste wool and recycled polyester fibres for building applications. They used waste wool obtained from sheep's generally nurture for meat purpose, is not for apparel application due to its shorter length. They developed two nonwoven samples using coring wool (CW) and dorper wool (DW), Name coring wool, and dorper wool derived from the sheep bread. They also produce one sample using 100% recycled fibres and another two samples by blending coring wool and dorper wool with recycled polyester in the ratio of 50:50. The sound absorption coefficient of all developed samples was measured using an impedance tube as per ASTM E 1050-10. They found that all samples show the lower value of the sound absorption coefficient in the frequency range from 50 – 1000 Hz and the value of the sound absorption coefficient increased with an increasing frequency range from 1000 – 2000 Hz to 2000 – 5700 Hz. They also reported that all samples show good acoustic properties in the frequency range from 50 - 5700 Hz.

Manning and Panneton [46] investigated the acoustic properties of post-consumer and post-industrial recycled fibres know as shoddy. They developed shoddy based absorbers consist of 32% polyester, 28% cotton, 18% acrylic, 6% polypropylene, 5% nylon, 8% wool and 3% other fibre. They produced three nonwoven samples using mechanical, thermal, and resin bonding methods. They found that there was no much difference in the sound absorption coefficient value of samples in the frequency range of 0 - 4000 Hz. Sound absorption value 0.2 was obtained for all shoddy samples at low frequency.

Parikh et al. [47] investigated the sound absorption properties of natural fibre nonwoven floor covering systems for the automotive interior. They produced needle punched nonwoven samples using natural fibres like jute, kenaf, flax, and cotton waste by blending each fibre with polypropylene and polyester fibres in the blend ratio 35:35:30. They also produced samples using polyester/ polyester/polypropylene in the blend ratio of 70:30. They evaluated all samples for acoustic properties using an impedance tube as per the ASTM E 1050 test method. The sound absorption value of developed samples also measured in combination with either polyurethane foam (PU) or cotton nonwoven underpad. The sound absorption coefficient of all samples was measured in the frequency range of 100 to 3200 Hz. They found that sound absorption coefficient values for nonwoven samples without underpad were in the range of 0.54 to 0.81 at 3200 Hz frequency. These results indicate that all the samples show good acoustic properties. When all these samples tested with cotton or polyurethane (PU) underpads, their sound absorption coefficient values were increased. The highest sound absorption coefficient value 1.0 was achieved for kenaf fibre nonwoven samples with polyurethane underpads at 3200 Hz frequency. They said that natural fiber-based nonwoven samples with underpad could be used for effective noise reduction in the automobile.

Lee and Joo [48] evaluated the sound absorption properties of fibrous materials produced using recycled polyester. They produced thermal bonded nonwoven samples using low melting polyester fibre. One group of samples were produced using 40% low melting polyester fibres of 6 denier and 42 mm length by blending with 60% regular PET of 38 mm length and different fineness. Four different samples were produced by blending 40% low melt polyester as one component with 60% regular PET as another component in proportion: 60% regular PET (2 denier), 20% PET (1.25 denier) and 40% PET (2 denier), 40% PET (1.25 denier) and 20% PET (2 denier), and 60% PET (1.25 denier). Authors also produced another group of samples by varying carded web angles by 0^o, 35^o, 45^o, and 90^o degree. Acoustic properties of all samples measured using an impedance tube. They found that as the fineness of fibre increased, the sound absorption coefficient value also increased. An increase in the carded web angle leads to an increase in the sound absorption value at all frequency levels, but the difference of sound absorption coefficient value between samples was insignificant.

ALRahman et al. [49] carried out an experimental study to evaluate the acoustic properties of natural fibre to develop green micro porous acoustic material. They used date palm fibre and coconut coir fibre to develop a green acoustic product. Samples were produced by varying the thickness and density of the materials. Samples with two thickness of 20 mm and 40 mm and different density were produced. Acoustic properties of green materials measured using impedance tube test methods. They found that fibre size plays a vital role to improve the sound absorption properties of the material, decreasing in the size of fibre gives higher sound absorption. As the thickness of natural fibre material increases, the sound absorption property of material increased at low frequencies. The date palm fibre gives good sound absorption properties at low and high frequencies, while the coconut coir fibre gives good acoustic properties at low to medium frequency range. They finally concluded that both date palm and coconut coir fibre have the potential to replace the non-eco-friendly material and can be used as green acoustic material.

Natural fibres materials are a valid alternative to traditional synthetic materials in the fields of acoustic treatments and energy saving.

2.5.2 Porous Materials

Porous material usually shows high sound absorption, and that's why it is more commonly used as sound absorbing material. Porous materials are solid and consist of cavities, cracks, and channels into them [50]. Porous materials are the ideal for sound absorbing because it consists of high porosity which helps the sound to enter into the structure and effective reduction of sound wave energy due to the frictional loss into the structure. When an incident sound waves impinging on the porous material, the air molecules inside the pore of material and at the surface of the material are forced to vibrate due to sound wave pressure. The vibration of air molecules leads to convert sound energy into heat due to the frictional loss between sound and porous materials [51, 52]. Generally, the porous materials are two types, open-cell foam, and fibrous material. Fibrous materials are composed of textile material that traps air inside the structure. Fibrous materials like textiles due to its porous structure are used for the acoustic application. Natural fibre, synthetic fibres, and blends of synthetic and natural fibre are used as textile fibrous porous material. Recently, the use of natural fibre in the field of acoustic textile material gained much more attention because they are biodegradable, eco friendly, and more economical. Sound absorption is less in solid and denser material; thus, the porous material like textiles is more widely used as compared to the solid panels.

The porous material efficiently traps the air into them due to its complex structure [50]. The pore size and porosity of the porous material significantly affect the performance of porous acoustic material. More than 90% porosity of porous material allows the incident sound wave to enter the porous material easily. The acoustic wave energy of the incident sound wave, which entered into the porous material, is dissipated because of thermal and viscous effects. These thermal and viscous effects of porous materials depend on the pore size. Small pore size leads to an increase in the attenuation of sound per unit distance, but a small pore size also creates problems for sound waves to enter the porous structure. The larger pore size reduced the acoustic attenuation per unit distance, but it is easy for the sound wave to entre the porous structure. The airflow resistivity of the porous structure depends on the porosity and pore size of the material. Pore size and porosity of porous materials affect the airflow resistivity of the material, which plays a vital role

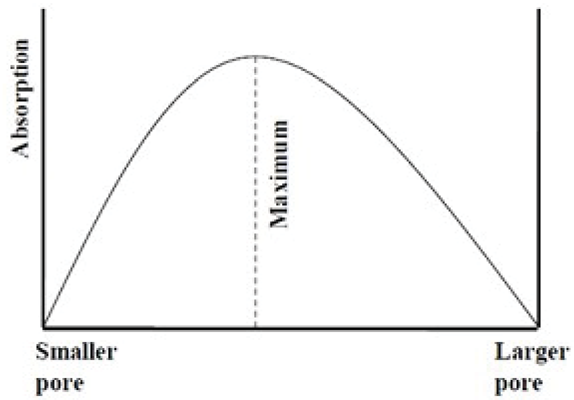


Figure 2.8: Sound absorption in a porous material [50]

in getting optimal results of sound absorption. Figure 2.8 shows the airflow resistivity at which the maximum acoustic absorption achieved for a wide range of frequency [50].

As shown in figure 2.9 porous absorber materials are generally three types, fibrous material, cellular material, and granular materials [51]. The porous fibrous material produced using natural fibres, synthetic fibres, and their blends. Cellular porous materials are made of foam and open-celled PU. Foam is the best example of cellular materials. Soil, concrete, clay, and asphalts are examples of granular materials. Textile fibrous materials are most commonly used as commercial porous sound absorbing material. Textile porous materials are produced by using one of the fabric formation technique such as weaving, knitting, nonwoven or composite. Needle punched nonwoven materials are generally used as a fibrous porous material for sound absorption due to its techno economical advantages. The porous material depending on their thickness, further can be categorized as bulk materials and sheet materials [53]. The sheet material thickness is much smaller in comparison to sound wavelength, and the thickness of the bulk material is much larger in comparison to sound wavelength. The acoustic properties of sheet materials depend on the mass per unit area and viscous effects. While the acoustic properties of bulk materials depend on the density of the material and thermal and viscous effects. In the case of nonwoven fabric inter fibre porosity, and in case of for woven and knitted fabric inter fibre and intra yarn/fibre porosity contribute to the porosity of the textile fibrous materials.

The porous materials have different properties than the sound barriers. Generally, the barriers are solid and heavy compare to the porous material; they work on sound

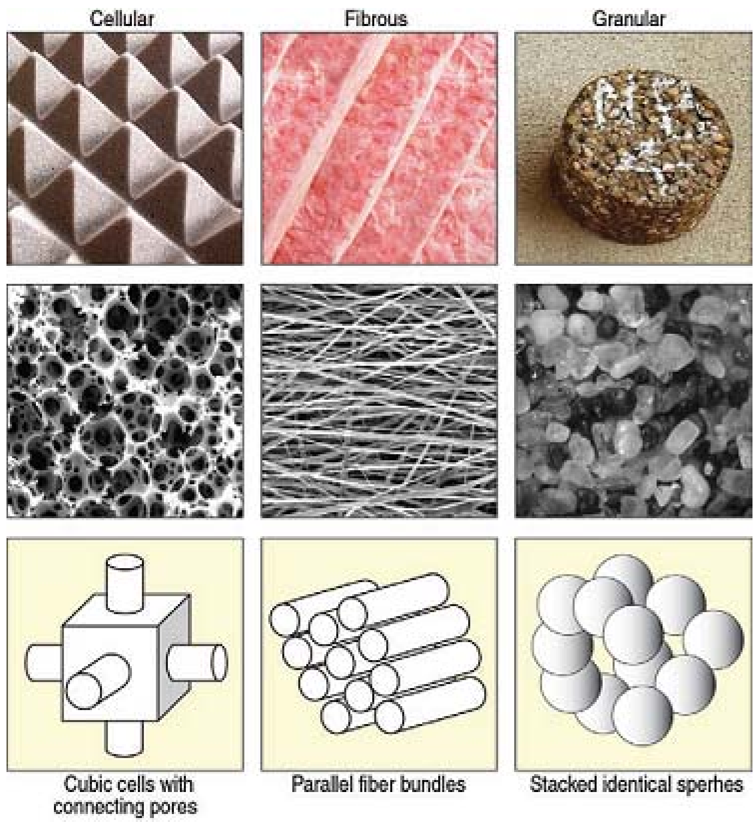


Figure 2.9: Porous absorbing materials [51]

transmission loss while the porous material absorbs the sound energy. Some time good sound absorber may give a poor performance as a barrier. In the case of the sound barrier, the mass of the material has a direct relation with sound absorption performance. While sound absorbers do not show any direct relation between the mass of material and sound absorption performance [54], to reduce the noise level in enclosed places, sound absorbers can be used in combination with the barrier. Here the porous sound absorbing material allows the sound to pass through it, while the sound barrier converts the sound energy into the heat energy. The greater is the distance from the wall; the better is the sound absorption at low frequency.

The textile materials like drapery, carpet, under carpet insulator, dash insulator, ceiling insulator, and the door panel are the most commonly used fibrous sound absorbers. Among all these, carpets play a vital role in sound absorption. The acoustic properties of carpet depend on its thickness, construction, type of backing material, characteristics of the pile, underlay, and weight. Pile characteristics depend on its structure, density, height, air gap, and type of fibre used [[55, 56]]. The acoustic properties of the carpet also get affected by the type of pile cut or loop pile, type of backing material like coated or uncoated and thickness of the pad.

Yang and Yu [57] investigated the acoustic absorbing behaviors of several nonwoven fabric. They produced different six nonwoven fabric by varying fundamental structural parameters like thickness, mass per unit area, and porosity. They studied the acoustic properties of nonwoven samples by using the impedance tube test method. They found that the sound absorption coefficient value of nonwoven fabric increased with an increase in thickness and mass per unit area of nonwoven fabric. The maximum sound absorption coefficient value 0.963 obtained for glass fibre nonwoven fabric at frequency range 800 to 6200 Hz.

The sound absorption characteristics of porous sintered fibre metal were studied by Bo and Training [58]. The porous metal materials possess multifunctional properties. They have the properties of porous material like filtration, noise absorption, and energy absorption and also have the properties of metal material like ductability, conductivity, high specific stiffness, and heat transfer. These kinds of metal porous materials can be used in extreme conditions.

Kucuk and korkmaz [59] investigated the effects of physical parameters on sound absorption properties of nonwoven fabric produced by using different fibres combination.

They produced eight different nonwoven composites, including different fibre types mixed with different ratios and combined by different bonding methods like thermal bonding, water-jet bonding, and needle punching method. The thermally-bonded nonwoven samples were produced by using 70% wool and 30% bicomponent polyester, 70% cotton and 30% polyester, 70% acrylic/cotton/polyester and 30% polypropylene, and 90% polyester and 10% low melt polyester. The thickness of the produced samples was in the range of 2.47 mm to 35.38 mm, and mass per unit area was in the range of 55 g/m^2 to 2900 g/m^2. The water jet bonded nonwoven samples were produced using 100% polyester, and 100% meta-aramid fibre. The mass per unit area and thickness of produced samples were in the range of 100 g/m^2 to 900 g/m^2, and 0.51 mm to 7.34 mm, respectively. They found that thermally bonded nonwoven fabric with wool and bicomponent polyester shows very good sound absorption properties in the middle to the high-frequency range. The thermally-bonded nonwoven samples with 70% cotton and 30% polyester show the best sound absorption properties than other samples and give the highest sound absorption coefficient value 0.96 at 3000 Hz frequency. Needle punching or water jet bonded samples do not show any significant effect on the sound absorption properties of the material. They also stated that nonwoven samples produced by using microfiber with high thickness and low areal weight give a better acoustic performance.

2.5.3 Nano Materials

The nanomaterial is the smallest engineered structure with a small pore size and a higher specific surface area. Properties of nano material show their potential to produce advanced noise absorbing material. The obtained nanofiber by electrospinning has notable characteristics such as a high surface area to volume ratio, good pore inter connectivity, high porosity, and the ability to incorporate active components on a nanoscale. These features make nanofiber layers have different properties in comparison with conventional material like glass wool and felts used for sound absorption. These unique characteristics of nanomaterial and recent development in the area of nanotechnology make the nanomaterial more suitable to use for the acoustic application. The nanomaterial provides improved acoustic properties in comparison to conventional material without increasing the weight and size of material [60]. Nanofiber can improve the acoustic properties of the product by increasing the sound absorption coefficient, reducing the material thickness, and low weight due to its higher surface area to volume ratio.

Work [61] indicates that if the nanomaterial used in between the high loft and scrim, as shown in figure 2.10 gives a dramatic improvement in the acoustic performance of a traditional sound absorption material, as shown in graph 2.11.

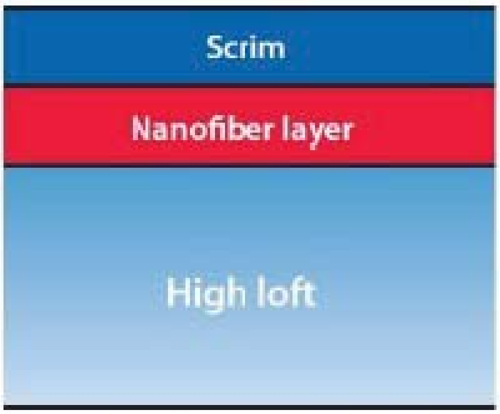


Figure 2.10: Representative construction

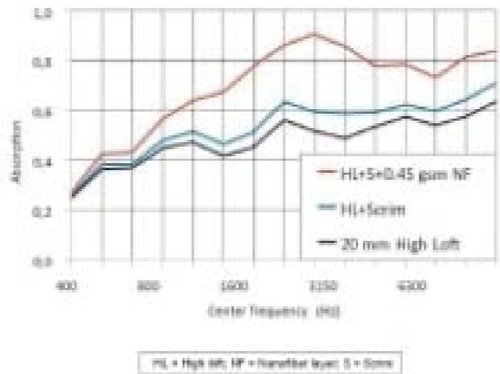


Figure 2.11: Measurements of acoustics absorption with usage of different materials

Nanospider^{TM} technology developed by Elmarco company allows nanofibers to be produced on an industrial scale for a number of applications. Nanospider^{TM} is developed with a free liquid surface electrospinning process and a high voltage.

AcousticWeb^{TM} as shown in figure 2.12 is a new patented material with unique absorption properties. It can absorb sounds across a wide range of frequencies, particularly standing out in the absorption of low frequency sound below 1000 Hz.

The nanofibrous layer behaves like a membrane which vibrates at low frequencies due to their nano dimensions of the inter-fiber areas. The nanofibrous membrane starts to vibrate and, in case of resonance, reach its maximum amplitude when the sound waves strike on to their surface. Fibrous underlay material ensures the adequate suppressing of the resonant membrane so that most of the sound energy accumulated in the resonator is transferred into the heat energy. Individual elements are accumulated into one resonant system by laying these elements on each other. Carded web layer with recycled cotton staple fibre along with PES flame retarding modification having fibre fineness in the range of 3.3 – 6.7 dtex used to produce web and then nanofibers layers are electrostatically spun on a carded web with PVA having to mean diameter 350 nm and areal weight in the range 0.2-0.8 g/m^2.

Nanospider AcousticWeb^{TM} is getting a higher value of the alpha coefficient, especially standing out in the absorption of low frequencies below 2000 Hz refer figure 2.13.

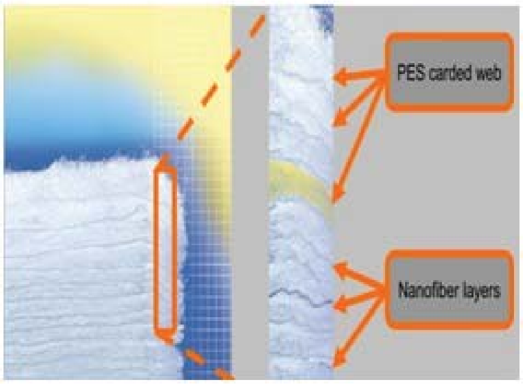


Figure 2.12: Nanospider Acoustic Web^{TM}

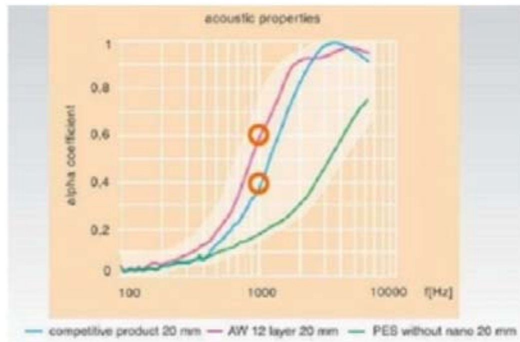


Figure 2.13: Alpha coefficient

Trematerra et al. [62] investigated the acoustic properties of nanofibers coated porous materials. The needle free electrospinning technique was use to produce nanofiber from NY6 (Nylon). The layer of nanofibers having a thickness of 10 microns and nanofibres diameter 150 – 200 nm were glued on the surface of different types of porous materials [60] made of kenaf, glass wool, polyester and felt with different thickness of porous materials. The acoustic properties of prepared samples were measured using impedance tube test methods in the frequency range of 200 Hz to 6300 Hz. The obtained sound absorption coefficient value of porous material with nanofibers layers was compared with the results of porous material without nanofibers layer. From the obtained results, it is clear that the porous materials made of kenaf, glass wool, foam, or polyester coated with nanofibers show better sound absorption coefficient value in the medium to low frequency range than the porous material without nanofibers coating.

Shuichi Akasaka, Takashisa, and Shigeo Asai [63] developed the sound absorption material with a silica nanofiber sheet and evaluated its sound absorption properties. They produced nonwoven laminate with silica nanofiber by varying fibre diameter from few nanometers to hundreds of nanometers and evaluated the effect of fibre diameter on the sound absorption properties. They found that as the fibre diameter decrease, the flow resistivity increased because of the increase in the surface area of the fibre. The laminates SF1, SF2, and SF3 made of thinner silica fiber show the high sound absorption due to low stiffness and higher flow resistivity of fiber.

Oldrich [64], studied the nanofibers technology for different applications like air and liquid filters, wound dressings, tissue engineering, surface modifications, and sound absorptive materials. They applied the nono fibrous layers of different areal densities on the basic fibrous material, as shown in figure 2.14, and testing was carried out for noise coefficient value. Results were obtained as shown in the figure 2.15.

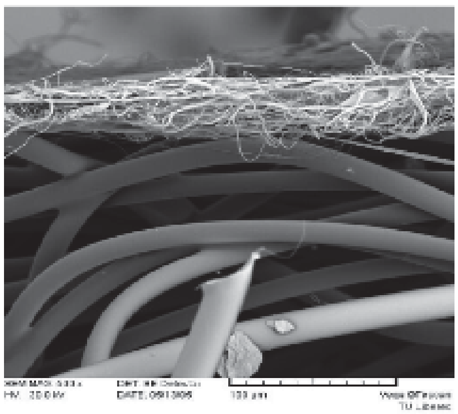


Figure 2.14: Nanofibrous layer is applied by the electro spinning

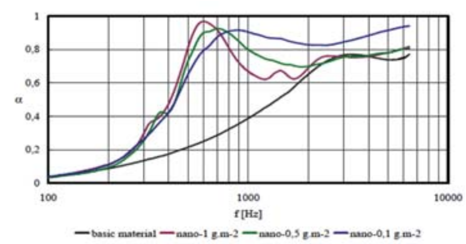


Figure 2.15: NAC of nanofibrous layers of different areal densities

Mohrova [65], investigated the different PVA nanofibrous membrane for their acoustic application. They produced a thin nanofibrous layer using electrospinning technology. To change the structure of the nanofibrous membrane, water vapor was applied for 10 to 12 seconds on the surface of the nanolayer. The average diameter of the produced nanofiber was 280 ± 80 nm, with an areal weight of nanoweb 17 ± 1 g/m^2. The sound absorption coefficient value of the produced samples was measured using a two-microphone impedance tube. They found that the sound absorption properties of materials get influenced by the nanofibrous thin membrane. The absorption properties of the material also affected by the inner friction in the polymer layer and a possible movement of nanofiber in structure. As the water vapor time increased, the irregularity in the nanofiber web was increased, which results in increasing the sound absorption coefficient up to 2800 Hz. The sound absorption coefficient values in the range of 0.15 to 0.18 obtained for water vapor time 30, 90, and 120 seconds in the low frequency range 100 to 1000 Hz.

The sound absorption properties of multi-layered nanofibres produced using an electrostatic technique from melt spin polyamide fibres and compare its acoustic properties with the microfiber [66]. The areal weight of the nanofibre layer was 30 g/m^2, and the diameter of nanofibre was 800 nm. To get the areal density of microfibers material, Several layers of the nanofibre web are plied together, so that the nanofibers material can be compared with microfibre fabrics. Nanofibre fabric having 6-18 nanofibre layers produced with area weight varied in the range of 180-540 g/m^2. The results indicate that the NAC value of nanofibre fabric higher than the knitted microfiber fabric, which means the sound absorption properties of nanofibre fabrics was higher than microfiber fabric in the frequency range from 1000 to 4000 Hz. They also found that with increasing the number of nanofiber layers, the sound absorption coefficient values also increased because of the large surface area of the nanofiber fabrics.

Md Ayub, Anthony C. Zander [67], in their research work, studied the acoustic properties of carbon nanotube (CNT) arrays and compared with conventional porous material. The acoustic properties of vertically aligned carbon nanotube (CNT) arrays was measured using an impedance tube. The results indicate that the 3 mm forest of vertically arranged CNT arrays gives as much as 10% sound absorption capability in the frequency range of 125 Hz to 4 kHz and enhanced acoustic absorption performance compares to conventional porous material of equivalent mass and thickness. The comparison between CNT and conventional porous materials showed that CNT absorber with lower thickness and mass could give the same or higher sound absorption coefficient values than conventional porous material. The authors' finally concluded that the carbon nanotube gives favorable sound absorption ability, which indicates that the carbon nanotube has a huge potential to replace the conventional porous material as an acoustic absorber.

Alba et al. [68] investigated the sound absorption properties of nanofibres in a combination of polyester wool fabrics and also studied the effect of nanofibers by placing the nanofibers combined with polyester wool fabric under the drilled panels. The acoustic properties of developed samples were measured using the sound absorption coefficient in reverberant chambers according to ISO 354:2004 and impedance tube according to ISO 10534-2:2002 test methods. They found that samples with nanofibers layers on polyester wool show sound absorption increased in the frequency range of 125 - 3150 Hz. The maximum sound absorption coefficient values with nanofibre layer polyester wool were 0.40 compare to polyester wool without nanofibre, which was 0.20 at 500 Hz. The highest NAC value was 0.92 obtained with nanofibre polyester wool at 1600 HZ. The author also studied the sound-absorbing properties of the drilled panel without polyester wool, drilled panel with polyester wool, drilled panel with nanofiber on the surface of polyester wool, and drilled panel with mineral wool. It was found that the sound absorption coefficient values about 0.95 were obtained for drilled panel with polyester wool having a nanofibre layer at a frequency range from 125-1000 Hz. No significant change was observed in the NAC values of the different samples at high-frequency range 1000-5000 Hz.

R. Gayathri [69] investigated the acoustic properties of polyurethane foam modified using nano clay, nano silica, and crumb rubber fillers. In this study, they developed a new polyurethane foam-based porous composites materials. The new composite materials were synthesized in the presence of nano clay, nano-silica, and crumb rubber fillers using situ foam rising polymerization of diisocyanate and polyol. The sound absorption properties of samples were studied by varying the concentration of fillers up to 2%. The acoustic properties of samples were measured using an impedance tube test. The highest sound absorption coefficient value 0.8 obtained at 1.4% weight concentration of all the fillers in the lower frequency range from 100 to 200 Hz.

The effects of applying polyurethane (PU) and polyacrylonitrile (PAN) nanofibers within polyester and wool nonwoven layers on soundproofing behavior were studied by Amir Rabbi [70]. The sound transmission loss and sound absorption properties of polyester and wool nonwoven samples increase with the use of nanofibers on nonwoven fabric surface in medium to lower frequency range. They also found that increases in the weight per unit area and a number of nanofibers layers results in increasing the sound transmission loss. The highest sound transmission loss was observed with samples having PAN nanofiber layers because of the higher elasticity and air permeability of the PU nanofiber layer in comparison to PAN nanofiber layers.

The acoustic properties of electrospun nanofibers producing using polyvinyl chloride (PVC) were studied by Asmutulu et al. [71]. In this study, the PVC nanofibers having a diameter in the range of 500 nm to 900 nm were produced. Sound absorption coefficient values of samples measured using impedance tube test methods. The obtained results were compared with melamine foam results. The sound absorption properties of samples tested with 0.5 g, 1 g, and 1.5 g of polyvinyl chloride (PVC) nanofibers compared with melamine samples having a weight of 2 to 4 g. they found that the sound absorption value of PVC nanofibers samples was higher than melamine foam in the frequency range of 2000 Hz to 6200 Hz, but there was no significant difference in the sound absorption coefficient values observed in the low frequency range from 50 Hz to 1000 Hz. They concluded that the micro and nanofibers material could be used as sound absorbing material to control the interior noise level of the aircraft.

From the various research work; It can be said that the adding of nanolayers within the nonwoven fabric results in an increase in the sound absorption properties of the material and gives high sound absorption coefficient value. Some of the disadvantages of using nanomaterials are the high production cost, solvent recovery problem, required high voltage, handling problem, and poor mechanical strength of the nanoweb.

The important property of nanofibrous materials is that they show excellent acoustic properties in the low-frequency range of sound waves, where most of the conventional material is less effective or fail. It can be said that nanomaterials have a considerable potential to be used as acoustic material in the various acoustic application.

2.5.4 Composites

Composite material generally used in building and civil works due to their acoustic insulation properties. The increasing importance of eco-friendly materials has resulted in increased use of natural fibre composite in various applications. Natural fibres like kapok, estabragh (milkweed), kenaf, flax, coir, jute, hemp, and bamboo due to their added advantages of low cost, good mechanical properties, lower density, eco-friendly nature, biodegradable and most importantly potential for acoustic application make them perfect raw material to be used in composite materials used for sound insulation [72]. Natural fibre composite material has been traditionally used to control the noise in the cabin of the car. Recently, natural fibre also used in bicycle frames and tennis rackets to improve the damping characteristics of carbon or carbon nanotube fibre reinforced composite materials.

The available commercial sound absorptive materials utilized in outdoor and indoor applications are classed as granular, cellular (tubular), and fibrous, as shown in figure 2.16. Fibrous materials are either natural or synthetic. The acoustic panels manufactured from natural fibers are less hazardous to human health and more eco-friendly than those fabricated from conventional synthetic fibers [51, 73]. Therefore, a growing concern for human health and questions of safety has encouraged manufacturers and engineers to find alternative materials from natural fibers as a replacement for synthetic fibers.

So many researchers are doing research to produce fibre composites material in a combination of rubber and plastics based granular material. The flow resistivity and bulk

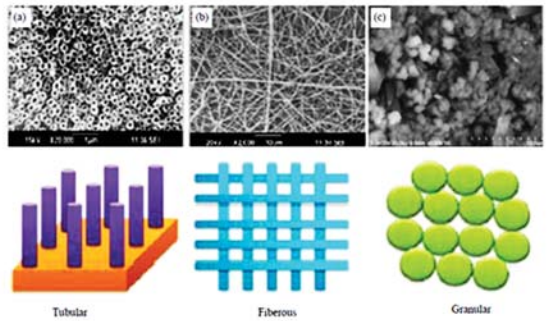


Figure 2.16: Scanning electron microscope image and schematic representation of porous absorber

density of the composite increase, when the fibre material is used in granular materials like rubber. The increase in the flow resistivity and bulk density of materials results in improving the sound absorption properties at low frequency. Other factors like chemical concentration, fiber-grain composition ratio, fiber size, and grain size might also play a vital role in improving sound absorption at low frequency. Some researchers studied the natural fibre and rubber granular to develop the sustainable, eco-friendly natural fibre composite material, which is known as fibrogranular composite. These fibrogranular composites increase the acoustic performance of composite material used for indoor and outdoor applications.

Natural fibre composites become more popular as an alternative of synthetic fibre for acoustic applications because of their properties like lightweight, low cost, biodegradable, non-hazardous, and ecofriendly nature. The natural fibers with environmental and economic advantages, and required physical and mechanical properties, make them suitable to be used in high-performance composites [73]. Many natural fibres like kapok, milkweed, kenaf, flax, jute, coir, sisal, hemp, and bamboo can be used for producing sustainable acoustic materials in place of synthetic material such as fiberglass, mineral wool, and glass wool. The synthetic fibre composite gives better sound absorption properties due to their thinner diameter and other properties, but at the same time, they are harmful to the environment [73].

According to Joshi et al. [74] recently, natural fiber-reinforced resin/polymer composites gets a lot of attention due to their unique properties like low cost, lightweight, abundant, biodegradable, and eco-friendly nature. Generally, the natural fibre composite materials are cheaper and environmentally superior to glass fiber reinforced composites.

However, some properties of natural fibre composites like poor moisture resistance, low interfacial adhesion, and the low antifungus make them less popular in comparison to synthetic-based composites.

Researchers are working on these issues and trying to overcome these deficiencies by giving chemical treatment to the natural fibre before used in composite production. Convention polymer-based composite is not recyclable. However, Natural fibre reinforced composites can be recycled, while the natural fibre composites have other benefits such as less costly and safer. Several researchers investigated the composite material for acoustic applications [75–77]. A lot of research works already carried out, and presently also so many researchers are studying natural fibre composite, which is beyond the scope of the present study.

2.6 Factors Influencing Acoustic Performance of Sound Absorptive Materials

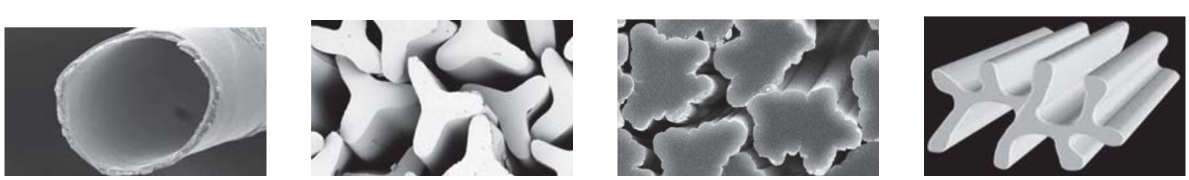
Sound absorption of any material can be maximized by using various physical effects like heat exchanges, viscous along the boundaries, mechanical vibration, magnetic and electrical damping. Many factors such as fibre type, fibre fineness, the shape of fibre, density, porosity, thickness, compression, and tortuosity affect the absorption properties of textile materials. All these factors indirectly affect the sound absorption coefficient of any textile materials.

2.6.1 Fibre Diameter

Nick et al. [78] observed that the sound absorption coefficient increased as the fibre diameter decreased. The use of finer fibre would result in high flow resistivity because the flow resistivity is inversely proportional to the squared fibre diameter. Furthermore, finer fibre leads to an increase in the acoustic performance of the material due to viscous friction through air vibration [73]. Kuzumi et al. [79] mentioned that the decrease in the fibre diameter leads to an increase in the sound absorption coefficient because more fibre is required to reach the same volume density at the same thickness. Hence, this results in more tortuous friction through air vibration. Fine denier fibres ranging from 1.5 to 6 denier per filament give better acoustic results than coarse fibers, and the use of microfibre provides a dramatic increase in acoustical properties of the material. ALRahman et al. [49] stated that a decrease in the fibre size of microporous materials, such as palm and coir fibre provide higher acoustic absorption. Koizumi et al. [79] observed that as the diameter of bamboo fibre decreased, the sound absorption coefficient of bamboo fibre material increased. Moreover, as the diameter of the fibre decreased, the number of fibre per volume is increased results in increasing surface friction, which lead to an increase in higher thermal dissipation per volume of material and hence, directly affecting the sound absorbing ability of acoustic material.

2.6.2 Fibre Cross-sectional Shapes

There is a direct relationship between the fibre surface area and the sound absorption properties of the material. The study explained the fact that friction between fibres and air increase with fibre surface area resulting in higher sound absorption. In frequency range, 1125 Hz to 5000 Hz, fibre with serrated cross-sections (kenaf) absorb more sound compared to fibre with a round cross-section. The porous material gives better sound absorption properties, due to the viscosity of air pressure in the pores or the friction of the pore wall. Therefore, sound absorption increases with a specific surface area of fibre with an increase of relative density and friction of the pore wall. Manmade fibres are available in various cross-sectional shapes. For instance: hollow, trilobal, pentalobal, and other novel shapes like 4DG fibres have cross-sections with several deep grooves that run along the length of the fibre. The various cross-sectional shapes of fibres shown in figure 2.17.



(i)-Hollow (ii)-Trilobal (iii)-Multilobal (iv)-4DG

Figure 2.17: Different cross sectional shapes of fibres

2.6.3 Density

The density of a material is often considered to be an important factor that governs the sound absorption behavior of the material [80]. The density of a material indicates the mass concentration of the material, which is measured as mass per unit volume. In the case of porous material, the bulk density plays an important role in the acoustic absorption of the material. Koizumi et al. [79] observed that as the density of the sample increased, the sound absorption value of material in the middle and higher frequency range increased. The number of fibers per unit area increases as the fibre density increase leads to an increase in the energy loss due to an increase in the surface friction and leads to an increase in the sound absorption coefficient. Moreover, the sound absorption behavior of nonwoven fibrous materials also get affected by the density and shows the following effects.

- Low frequencies sound easily absorbs by the less dense and more open structure.
- Sound having frequencies more than 2000 Hz absorbs by the denser structure.

Berardi et al. [81], investigated the effect of density on the sound absorption coefficient of natural fibre and found that the sound absorption coefficient of kenaf fibre increased in the mid- and high-frequency range as the density increased. It was found that for a glass-fiber material, there is relatively little difference in the sound absorption coefficient as the density increased. Bies et al. [82]studied an upward trend in the airflow resistivity as the bulk density increased in materials, such as fibreglass, rock wool, and gypsum Insulwool. This is the result of sound waves dissipating more energy due to the increase of surface friction, which leads to an increase in the sound absorption performance of the material [73]. Therefore, it can be said that as the density increases, the sound absorption coefficient shifts to the higher frequency range. It should be noted that for very low-density fibrous materials, the fibres are spaced far from each other; hence, the ability for the material to attenuate acoustic energy suffers. On the other hand, materials with very high densities suffer due to high surface reflection and low acoustic penetration.

2.6.4 Thickness

Textile material thickness is one of the most important parameters affecting the sound absorption properties of textile materials. Numerous studies carried out on sound absorption of textile properties have concluded that thickness of material has a direct relationship with sound absorption, particularly in the low frequency range. Michael Coates and Marek Kierzkowski [83] stated in his study that the effective sound absorption of textile material is achieved when the material thickness is about one-tenth of the wavelength of the incident sound wave. This implies that for sound absorption at the low frequency required thicker material due to its long wavelength. Timothy at el [84] mentioned that the highest sound absorption occurs at a resonant frequency of one-quarter wavelength of the incidence sound. Thick material showed higher sound absorption only at low frequencies of sound waves. However, at a higher frequency range, thick material hardly affects the sound absorption.

2.6.5 Porosity

Porosity defines as the amount of space or void present in the structure. porosity is expressed as the ratio of the amount of void present in the structure to the total volume of the sample [85], Equation 2.9 defines porosity.

$$Porosity(\o) = \frac{V_a}{V_m} \tag{2.9}$$

Where,

V_a = Air volume in the voids,

V_m = Total volume of the acoustic sample being tested

One should consider the properties of the porous material like size, type of pore, and a number of pores while studying the acoustic properties of porous materials. The first and foremost requirement of the porous material is that they should allow the sound wave to enter into them to dissipate the sound energy by friction. This means the porous material should have enough pore on the surface to allow sound to pass through and dampened inside the structure.

In the present study, the porosity of the nonwoven fabric is calculated from the measured fabric thickness, fabric GSM, and fibre density using the following equation 2.10.

$$P_V = \frac{V_{pore}}{V_{web}} = \frac{(V_{web} - V_{fib})}{V_{web}} = 1 - \frac{V_{fib}}{V_{web}} = 1 - \frac{\rho_{web}}{\rho_{fib}} = 1 - \frac{M_{web}}{D_{web} \cdot \rho_{fib} \cdot 1000} \tag{2.10}$$

Where,

P_V = Porosity

V_{pore} = volume of air space ($V_{web} - V_{fib}$)

V_{web} = Volume of fabric (l x b x h)

V_{fib} = Volume of fibre ($\pi/4xd_2xl$) x n

V_{fib}/V_{web} = Fibre packing density

ρ_{web} = Fabric volume mass or Fabric density (g/cc)

ρ_{fib} = Fibre volume mass or fibre density (g/cc)

M_{web} = Web mass (g/m^2)

D_{web} = Web thickness in mm

For a material to be classified as porous, it must be permeable, thus attaining some level of porosity, since porosity allows sound waves to enter and pass through the porous medium, hence allowing sound dissipation by air friction. The value of porosity for porous materials ranges between 0 and 1, and for polymer foams and fibrous sound absorbing materials, it is in the range, $0.95 < Ø < 0.99$ [86]. Fouladi et al. [87] investigated natural fibres: coir, corn, sugarcane, and grass, and showed that the sound absorption coefficient increased as the porosity decreased.

Yilmaz et al. [88] studied the effects of porosity, fibre fineness, and layering sequence on the sound absorption performance of needle punched nonwoven fabrics. Their results indicated that airflow resistivity increased with a decrease in fibre diameter and porosity. Shoshani et al. [89] mentioned that to increase the sound absorption coefficient at a high-frequency level, and care should be taken in designing a nonwoven web. The nonwoven web should be designed in such a way the porosity of nonwoven increase along the propagation of the sound wave. According to Hakamada et al. [90], the sound absorption coefficient of porous material increased as the porosity increased. Jin et al. [91], found that there is a gradual increase in the sound absorption coefficient of aluminium foams with a rise in porosity. The decrease in porosity resulted from the doubling of the sample thickness, which explains why the sound absorption coefficient increased.

2.6.6 Tortuosity

Tortuosity is a measure of the sinuosity and interconnectivity of void space in a porous structure. Generally, tortuosity indicates the diffusion in porous media such as fibrous structures. According to Knapen et al. [92], tortuosity describes the influence of the internal structure of a porous material on the acoustic behavior of the material. Tortuosity is a measure of how far the pores deviate from the normal or meander about the material. The tortuosity, of a porous material, is a dimensionless structural parameter that shows the influence of the internal pore structure on the macroscopic velocity of fluid flow through a porous material [93]. Hence, the influence of tortuosity on the internal structure of porous material has a direct impact on the airflow resistivity and thus directly influences the sound absorption of the porous material. Tortuosity is also a parameter that takes into account the non-uniform distribution of pores per unit section throughout the thickness of the poroelastic material [86]. Bil'ová is of the view that tortuosity is responsible for the difference between the speed of sound through air and the speed of sound through a rigid porous material at very high frequencies [94].

Horoshenkov et al. [95] reported that the location of the quarter wavelength peak mainly gets affected by the tortuosity, while the height and width of the peaks get affected by the porosity and flow resistivity. They also stated that the behavior of sound absorbing porous material at high frequencies depends on the value of tortuosity. Zwiker and Koster first applied the term for the inertial interaction between the solid and fluid phases of a porous material, resulting from the deflection of fluid flow by the pore walls [96].

According to Mamtaz, the more tortuous the material, the greater the sound absorption [73]. This is most likely true up to a critical density where the material surface impedance increases to a point where the incident sound waves can no longer penetrate the absorber's surface. This occurs because the density must increase as the tortuosity per unit volume increases.

2.6.7 Airflow Resistance

Airflow resistance is one of the most important qualities that influence the sound absorbing properties of fibrous material. The airflow resistance is the specific flow resistance per unit thickness of the fibrous material. The acoustic absorption of a material is greatly influenced by the airflow resistance. The woven and nonwoven structure of textile material provides resistance to the passage of air, which is intrinsic properties of the textile material. The acoustical properties of porous materials depend on the propagation constant and characteristic of impedance, which influences by flow resistance of the material [97].

According to del Rey et al. [98], airflow resistance is directly related to the capacity of a material to absorb sound energy. As the airflow resistivity is increased, so is the dissipation, and for a given thickness as well as for low-frequency bands, the necessary absorber thickness increases as the airflow resistance decreases [99].

The airflow resistance is measured in terms of the resistance provided by the material thickness. When sound enters into the nonwoven materials, the fibres interlocking in nonwoven materials provide the frictional resistance to the sound wave by acting as frictional elements. As the sound wave passes through the tortuous passages in the nonwoven materials, its amplitude is decreased due to friction, which converts the acoustic energy into the heat [100]. This friction quantity can be expressed by the resistance of the material to airflow, is called airflow resistance and is defined in the following equation 2.11 as per ASTM D-1564-1971:

$$R = \frac{P}{v \cdot l} \tag{2.11}$$

Where,

R = flow resistance of the sample,

P = Static pressure differential between face and back of the sample, dyn/cm^2,

v = Velocity of air, cm/s

l = Sample thickness, cm

For the porous material, the airflow resistance per unit thickness is directly proportional to the shear viscosity coefficient of the fluid (air) involved and inversely proportional to the square of the characteristic pore size of the material [80]. This means, for the given porosity of the material, the airflow resistance per unit thickness of the porous material is inversely proportional to the square of the fibre diameter. It has also been observed that airflow resistance affects the width of the quarter-wavelength sound absorption peaks [95]. When a porous material is backed by an air gap, the particle velocity reaches a maximum at the quarter-wavelength of the lowest frequency of interest and therefore increases the sound absorption [101].

These absorption peaks are present at odd multiples of the quarter-wavelength [102]. According to Bies et al. [82], It is interesting to note that if a fibrous material is characterized by fairly uniform fibre diameter, and the binder used does not play a significant role, the flow resistivity may be predicted using knowledge of the fibre diameter and the materials bulk density. This statement is significant that the viscous dissipation of sound energy is a complex phenomenon [103].

Kino et al. [104], using a similar relationship to the Bies model, showed that the flow resistivity of melamine foam could be estimated using only the bulk density and an equivalent diameter based on the hexagonal open cell structure of the melamine foam. It should also be noted that the airflow resistivity stays constant at varying absorber thicknesses, as long as the density stays constant, as reported by Ramis et al. [105].

2.6.8 Surface Impedance

Surface impedance is also known as the specific boundary impedance of acoustic material. The term specific boundary impedance is defined as a ratio of the acoustic surface pressure to the normal velocity of the fluid at the surface with positive direction into the boundary. According to Allard et al. [85], the surface impedance of a material depends on the angle of incidence, if the pores are interconnected, resulting from the interference between waves inside the material. Simón et al. [99] reported that it is desirable to have the surface impedance of the absorbing material as close as practically possible to the wave impedance of the air. It is also desirable to increase the airflow resistance progressively in the direction of the propagating sound wave.

For a given thickness of the material layer, if the dissipation is higher than the acoustic resistivity of the material is higher. As the airflow resistivity increases the surface impedance also increases, which leads to an increase in the higher reflection of a sound wave from the surface and shows lower absorption capability. The sound absorption process also depends on the sound wave frequency, that why the thickness of the material needs to be increased to absorb the low frequency sound wave due to decreases in the resistivity at low frequency [106].

Hence, the larger the difference in the characteristic impedance between the two media, the more energy is reflected off the surface of the absorber [107]. Hence, the harder and denser a surface is, the more it will reflect acoustic energy. This is not desirable in terms of porous absorbers since porous absorbers are meant to absorb and attenuate incident acoustic energy and not to reflect it.

2.6.9 Compression

Textile structures used for acoustic absorption are compressible, which can change the sound absorption property. When the textile structure or porous material is compressed, the porosity and thickness values decrease, but the density increases. Large structure density results in large flow resistivity of the structures if the other parameters of the structure remain the same. With a large flow resistivity, the characteristic impedance and propagation constant of the structure might vary from those in the medium significantly, and this results in low sound absorption of the structure

Very few research publications are available regarding the effect of compression on the sound absorption behavior of the material. Bernard Castagnede et al. [108] observed that compression of fibrous mats decreases the sound absorption properties. This compression results in a decrease in thickness. More remarkably, they also found that compression also leads to create other physical changes in the material. Compression increases the airflow resistivity and tortuosity, and at the same time, decreases the thermal characteristics and porosity of the material. In the case of automotive acoustics materials, compression plays a vital role and is significantly affected by the sound absorption properties of the material.

Fouladi et al. [109] also reported that compression affects the physical parameters of porous materials affecting porosity, tortuosity, flow resistivity, and the two characteristics, viscous and thermal. Compression tests done on polyester fibre showed a drop in the absorption coefficient when the fibrous mat experienced a compression [110]. Nor et al. [111], shown that coir fibre, at a higher compression rate, indicated an acoustic absorption greater than when the absorber was uncompressed. This unexpected effect may be due to an increase in density and airflow resistivity of the fibrous material due to the increased compression rate.

Though compression does not necessarily result in small sound absorption, usually, compression increases sound absorption in the low frequency range at the cost of reducing sound absorption in the high-frequency range.

2.6.10 Air Gap (Position of Sound Absorptive)

The performance of the sound absorptive material is dependent on their relative position. The sound absorption of the acoustic material depends on the position and placement of the sound absorbing material. Placing a porous material at a distance from a rigid surface, thus creating an air gap between the porous materials and rigid surface, has the effect of moving the maximum value of sound absorption coefficient from a high to a low-frequency range [79].

Fatima et al. [112], reported that an increase in the noise reduction coefficient (NRC), of TD5 grade jute fibre, was observed, as the air gap distance increased. The creation of an air gap increases the sound absorption coefficient in the mid- and high-frequency range [80]. This happens because when there is an air cavity behind a material, the material acts as a frequency-dependent membrane of a certain mass, and the inside air cavity acts analogously to a mechanical spring [113].

Fouladi et al. [109] mentioned that tests done on coir fibre showed that an increase in the air gap had a positive effect on the low-frequency sound absorption coefficient. But it was also noticed that the medium- and high-frequency sound absorption coefficients were reduced by moving the peaks to lower frequencies. The reason for this behavior is due to an increase in the absorber's impedance, which moves the acoustical resonance to lower frequencies and improves the absorption in that range. This gives the designer an additional degree of freedom in the design and implementation of sound absorbing materials into a system.

Alton Everest [102], reported that it is important to select the best position of the acoustic material to get the best sound absorption. The performance of the sound absorption material is improved if it is placed along edges of rectangular rooms surface and corners. In speech studios, the sound absorptive materials most effective at higher frequencies are placed at the head height on the wall. The acoustic material placed at the lower portion of the walls gives better acoustic performance than the material placed at somewhere else [102]. Furthermore, it is recommended that untreated surfaces should never face each other.

2.7 Performance of Sound Absorbing Materials

The acoustic performance of fibrous and porous material is determined by measuring the sound reflection coefficient, sound absorption coefficient, sound transmission loss, normal reduction coefficient, acoustic impedance, and propagation constant of sound. There are various methods available to measure these acoustics parameters. Generally, in all these methods, the materials are exposed to the known sound fields, and their effects on the sound field are measured. The performance of the sound absorbing materials is determined by using the sound absorption coefficient (α) value [95]. The sound absorption coefficient can be measured by using the acoustic energy absorbed by the material upon incidence sound energy. The sound absorption value of the material varies from 0 to 1. If the material absorbs 60% of the incident sound energy, then the sound absorption coefficient of that material is 0.60. here, the sound absorption coefficient value 1 means, material absorbed all the incident sound waves energy strike on to their surface, and 0 means no energy is absorbed. The value of the sound absorption coefficient also gets affected by the sound wave frequency and by the angle of incident sound wave impinging on the surface of the materials. As per the various literature, the standards frequencies value that used to measure the sound absorption coefficient is 125, 250, 500. 1000 and 2000 Hz [114]. Other important parameters that are needed to take into consideration for studying the sound absorption properties of materials are:

1. Sound reflection coefficient: It can be determined as the ratio between the total reflected sound intensity to the total incident sound intensity.
2. Acoustic impedance: It can be determined by the ratio of sound wave pressure action on the surface of the material to the associated particle velocity normal to the surface.

To compare the sound absorbing properties of different materials, the noise reduction coefficient (NRC) generally used. NRC is the average value usually measured at 250, 500, 1000, and 2000 Hz frequencies and mentioned to the nearest multiple of 0.05. It is used to indicate the sound absorption property of a material by a single number index. The NRC value indicates how well the material surface absorbs the incident sound [115].

2.8 Assessment Methods for Sound Absorption Performance

Sound pollution is the third major pollution in today's era of continuing technological development. The use of more powerful machinery and an increase in a number of vehicles has led to increase in the noise pollution. Its effect on the environment and human health is a matter of concern. Looking at the importance of this, so many students, researcher, and academician of textiles have shown their interest in this field. Measurement of an acoustic coefficient is important to determine the acoustic properties of textile materials. The sound absorption coefficient indicates the amount of incident sound absorbed by a material. To measure the sound absorption coefficient, first sound waves are generated using sound source and transmitted through medium towards the samples. There are two methods generally used for measuring the normal incident sound absorption coefficient for small samples using the sound absorption coefficient. One is the standing wave ratio standardized in ISO 10534-1, and the other is the transfer-function method standardized in ISO 10534-2 [116, 117].

The methods using standing wave ratio is well established, but slow, so it is substituted with transfer-function methods due to its quick and accurate results. There are various methods available to calculate the absorption coefficient using a tube [118]. Jeong and Chang [119] presented an optimization method to improve reproducibility using flow resistivity methods. Gibiat and Laloe [120] proposed a two microphone three calibration method. In this method, the impedance of unknown devices calculated using the impedance of three known devices and the transfer function measured to find out the sound absorption coefficient.

Cho and Nelson [121], proposed improved multiple methods to measure transfer function value. They also calculated acoustic impedance from transfer function with a different combination of the microphone using least square curve fitting and optimizing the response of microphone position. Garai and Pompoli [122] gave an echo impulse technique to measure the sound absorption coefficient, which requires further processing of results to get accurate results. The sound absorption coefficient measured using a wide range of frequencies, and these methods introduce some error in the measurement setup. They suggested various procedures to minimize these errors. Abom [123] investigated that space between two microphones should be minimized to reduce errors due to pressure at the microphone. They also stated the errors were minimized by decreasing the tube length, having a non-reflective source end, and keeping the microphone as close as possible. Impedance tube testing available at few places in India, and the cost of the commercially available instrument is not affordable. In the present study, a customized impedance tube designed and constructed to measure the sound absorption coefficient as per ISO 10534-2 [117].

2.8.1 Theory and Measurement of Sound Absorption

There are two standard methods used to measure the sound absorption coefficient for small samples: one using a standing wave ratio [116], and the other is the transfer function method [117]. This method is considered that there is only a plane incident and reflected waves propagating along the tube axis in the testing tube. The incident plane sinusoidal standing wave is generated by a loudspeaker placed at one end of the tube, at the other end of the tube sample mounted, and it is backed with a hard reflective end.

2.8.1.1 Method Using Standing Wave Ratio

This method is considered that there is only a plane incident and reflected waves propagating along the tube axis in the testing tube. The incident plane sinusoidal standing wave is generated by a loudspeaker placed at one end of the tube, at the other end of the tube sample mounted, and it is backed with a hard reflective end. Following equation used for the measurement in the 1/3 octave frequency band. The standing wave ratio is defined by using the equation 2.12:

$$S = \frac{|P_{MAX}|}{|P_{MIN}|} \tag{2.12}$$

The reflection factor can be defined as given in equation 2.13:

$$|r| = \frac{S-1}{S+1} \tag{2.13}$$

Yielding the sound absorption coefficient α for plane waves using equation 2.14:

$$\alpha = 1 - |r|^2 \tag{2.14}$$

Where,
S = standard wave ratio
P_{MAX} = maximum values of sound wave pressure
P_{MIN} = minimum values of sound wave pressure
r = reflection factor
α = Sound absorption coefficient

2.8.1.2 Transfer Function Method

To measure the sound absorption coefficient using the transfer function method an impedance tube is used. On one end of the impedance tube speaker is mounted to generate the sound, and on the other end, a test sample is mounted. Plane waves of sound are generated in the tube by sound source emitting random or pseudo-random sequence, and pressure is measured at two locations close to the sample. The sound absorption coefficient is determined using a complex acoustic transfer function of the two microphones. The working frequency range depends on the diameter of the tube and the space between the two microphones. The normal incidence reflection factor can be calculated using the equation 2.15.

$$r = |r|e^{j\phi_r} = r_r + jr_i = \frac{H_{12} - H_I}{H_R - H_{12}} e^{2jk_0x_1} \tag{2.15}$$

Where,

r = Reflection factor of normal incidence;

r_r = Real component

r_i = Imaginary component

x_1 = Distance between the sample and to its nearest microphone;

j = Square root of minus one

k_0 = Wave number = 2πf/c (m^{-1}) = ω/c; where c is speed of sound

ϕr = Phase angle of the normal incidence reflection factor

H_{12} = Transfer function from microphone one to two, defined by the complex ratio $P_2/P_1 = S_{12}$ / S_{21}

H_R and H_I = Real and imaginary part of H_{12}

The sound absorption coefficient can be calculated using equation 2.16,

$$\alpha = 1 - |r|^2 = 1 - {r_r}^2 - {r_i}^2 \tag{2.16}$$

Where,

α = Sound absorption coefficient;

r_r = Real Component,

r_i = Imaginary Component

Below Figure. 4.1 indicate the symmetrical diagram of impedance tube.

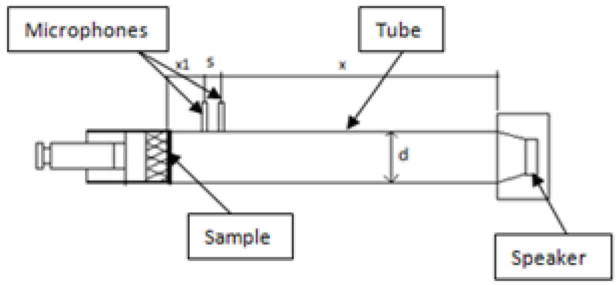


Figure 2.18: Schematic diagram of the impedance tube

Where,

x_1 = Distance between a sample and its nearest microphone;

S = Distance between two microphones;

x = Distance between a sound source and first microphone;

d = Diameter of the impedance tube.

2.9 Application of Sound Absorbers

Acoustical material plays a vital role in controlling room acoustics, industrial noise control, studio acoustics, and automotive acoustics in acoustic engineering. Generally, the sound absorptive materials are used to neutralize the unwanted sound reflection by the rigid, hard, and interior surfaces of the material, which leads to reduce the reverberant noise levels [114,124]. They can be used as interior lining for automotive, aircraft, apartments, ducts, enclosures for noise equipment, and insulation for appliances [92,125]. The characteristics of the aural environment are getting affected by the sound absorptive material used to control the response of artistic performance spaces to transient and steady. It also affects the clarity of speech and the quality musical sound [126]. Sometimes the composite products such as sound absorption material in combinations with sound barriers can be use to produced sound absorptive curtain assemblies. The sound spectra of the sound source are the starting point in controlling the noise problem. Therefore, selection of type of material, the dimension of the sound absorbing material according to the frequency of the sound to be controlled is very important.

2.10 Kapok Fibre

Unconventional natural, sustainable materials are quite often a valid alternative to traditional synthetic material used in acoustic applications because the production of these materials generally has a lower environmental impact than traditional synthetic materials. Naturally, hollow fibre such as kapok and milkweed has a huge potential to be used for sound absorption, which shown similar sound absorption properties to the rock or glass wool. In the last few years, industries are trying to produce eco-friendly or "green" material products due to increased environmental awareness. This leads to the need to explore environmentally friendly, sustainable materials to find out the new resources of unconventional fibres instead of using the petroleum-based synthetic fibres.

Kapok fibre is obtained from the seed hairs of the bombax tree, which is commonly known as the cotton tree (Ceiba pentandra) [127]. In India, particularly in Gujarat state, it is known as a ”Simal” tree. It is sometimes known as silk-cotton or kapok. Kapok fiber is a seed hair cellulosic fiber. Kapok fiber is a natural hollow fibre and also possesses the other features like it has a thin cell wall, large lumen, low density, and hydrophobic–oleophilic properties. Kapok can be considered a sustainable fibre because it leaves no carbon footprint behind. Kapok fibre also has numerous properties such as silky soft and dry to the touch, as well as anti-moth, anti-mite, and insulation properties comparable to down, and one has a useful, sustainable fibre. One should keep in mind that, due to decreasing in natural resources like cultivation land, there is always tuff to decide to go for food or fibre as day by day demand for food is increasing because of an increase in the population. The natural fibres such as cotton being resource-intensive to process and petroleum-based fibres such as polyester, acrylic, nylon, and spandex are not environmentally friendly. It is high time to look for sustainable fibre such as kapok or milkweed as an alternative when producing yarns and fabrics. Kapok fibre is one of the natural cellulosic fibres which grow on the bombax or kapok tree. Kapok fibres are extracted from the seedpod (as shown in figure 2.20) of the kapok tree (as shown in figure 2.19).

The kapok tree is grown mainly in mainland Indonesia, middle America, and Asia. Kapok is also known as silk cotton or Java cotton, and the kapok can grow to an average of 20 meters and an old tree up to 60 meters height in wet tropical regions [127], with growing up to 4 meters per year, and eventually reaching a height of 50 to 60 meters.

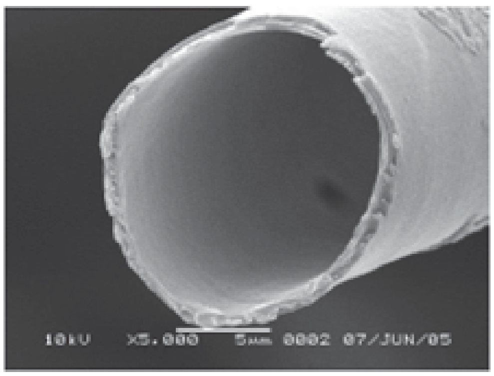
Figure 2.19: Kapok tree

Figure 2.20: Kapok seedpods

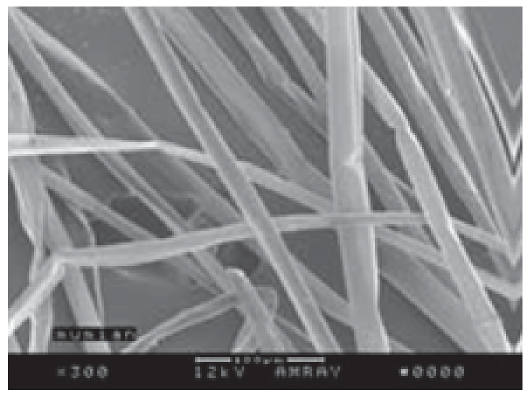
The Kapok tree is a deciduous tree, grows up to 50 to 60 meters, and it has capsular fruits, which can be picked and opened by hand [128]. The kapok fibers of the fruits are not treated with chemicals and allow to dry in air. Kapok fibres are natural biodegradable fibres. Kapok fibres also have natural anti-bacterial and anti-microbial properties, and therefore moths, mites, and other microorganisms cannot infest the kapok fibre products. The Indian kapok fibres obtained from the simal cotton tree (Bombax malabarica) are more brownish-yellow in colour and less resilient. It absorbs only 10 to 15 times water by its own weight when immersed in the water. Kapok trees are members of hibiscus or mallow, a family of Malvaceae. In Brazil and West Indies, tree cotton or bombax cotton is produced, which belongs to the cotton itself. The kapok genus name is *Ceiba*, and *Ceiba* is a genus of trees in the family Malvaceae. The word *Ceiba* is derived from a Carib word used for a dugout boat.

2.10.1 Physical Characteristics of Kapok Fibre

Kapok fibre is cellulosic fibre with soft silky handal, but different from the other cellulosic fibres. Kapok fibre is a natural hollow fibre [129]. Kapok as natural fibre shows the lowest specific mass and the highest hollowness than any microchemical fiber, which are desirable properties of fibre to be used for functional textiles. Kapok fibre having microtubules natural fine tube structure with hollowness up to 97%. The one end of kapok fibre which is a bulbous shape is tightly closed, and the other end of the kapok, which is a taper to one point, is also closed [130]. Cotton fibre as a single cell fibre looks like twisted ribbons, which is known as convolutions. While in the case of the kapok fibre no convolutions are available. The cross-sectional shape and longitudinal SEM micrographs of kapok fibre are as shown in figure 2.21. The cross-section view of kapok fibre shows that kapok fibre has a wide-open lumen in it, and the longitudinal view of kapok fibre shows that kapok fibre has a smooth cylindrical surface. Kapok fibre has a higher specific surface area due to its unique natural hollow structure. These unique structures of kapok fibre provide it an outstanding moisture transfer property, better thermal insulation property, and better acoustics property, and make kapok an ideal eco-friendly natural fibre with unique functional properties.



(a)-Kapok fibre's cross section



(b)-Kapok fibre's surface

Figure 2.21: SEM of Kapok fibre

However, during the harvesting of kapok fibre, the pods are either collected when they fall or cut down from the tree, then broken with a hammer and open [131]. The fibre and seed removed from the pod by hand. To separate the seed from the fibre, are stirred in a basked so that the seeds fall down to the bottom of the basket and leave the fibres free from seed. The seed can be further processed to get oil for making soap, and the residue is used as cattle feed and fertilizer.

Kapok is a natural cellulosic fibre which is found in several regions of the world, and it was once used for technical application only rather than apparel purpose.

Kapok is a resilient, buoyant, moisture-resistant, and quick-drying fibre [131]. Kapok fibre having both cellulose, a carbohydrate and lignin, a woody plant substance. The spinning of kapok fibre is very difficult due to its brittleness and inelastic properties. Kapok is very light fibre, and its weighs is only one-eighth of the cotton fibre. Kapok can support 30 times its own weight in water, due to this property kapok has been used in water safety equipment and also used in the life-saving jacket. Some results indicate that after 30 days of water immersion, the kapok loss 10 percent, means losing its Buoyancy slowly. Kapok is used as filling material in pillows, mattresses, and upholstery because of its thermal insulation and resilience properties. Kapok is also used as a substitute for absorbent cotton in surgery. Kapok is highly flammable. The importance of kapok fibre gradually decreased because of the development of foam rubber, plastics, and synthetic fibres.

The natural hollow kapok fibre has a length around 25 $\pm$ 5 mm, internal diameter around 7.25 $\pm$ 4 μm, and the external radius around 8.25 $\pm$ 4 μm [128,132]. Kapok fibres contain 64% cellulose, 13% lignin, and 23% pentosan. They also contain cutin wax on its surface, which makes them water repellent, anyhow they are generally composed of cellulose.

According to Lim et al. [133], Individual kapok fibres are 0.8 to 3.2 cm long, with an average length of 1.8 cm, diameters of 30 to 36 micrometers, and has a specific density of 0.29 g/cm^3. Kapok fibre can not be easily processed on the modern spinning line because of poor inter fibre cohesion. The poor inter fibre cohesion is a result of the low volume weight, short length, and smooth surface of the kapok fibers.

As shown in the figure 2.22 & 2.23 the longitudinal and cross-section shape of the kapok fibre wall is different than the cotton fibre [130,134]. The cell of the kapok fibre is divided into five layers or walls, such as outer skin, primary wall, secondary wall, tertiary wall, and inner skin, and generally, denoted as S, W1, W2, W3 and IS respectively. The outer layers are working as protective layers. Layer 'S' is working as protective layer for the fibre which is a thin layer of about 40 to 70 nm thickness. A primary wall W1 is thicker than outer skin S, but thinner than secondary wall W2 and tertiary wall W3, having an average thickness of about 200 nm. The thickness of a primary wall varies from 160 to 240 nm. The thickness of the secondary and the tertiary wall is the same, and its value is around 500 nm. The inner skin 'IS' is easily identified in cross-section due to its uneven and very thin thickness. The average thickness of the inner skin of kapok fibre is around 30 nm. Apart from these five layers, additional two transition layers L1 and L2 also observed between W1 and W2.

Kapok fibre contains high levels of acetyl groups, about 13.0 %. The cell wall of kapok plants contains about 1 to 2 % of acetyl groups, which is attached to the non-cellulosic polysaccharides. Kapok fibre is superhydrophobic fibre and does not get wet with water easily when immersing in water [135].

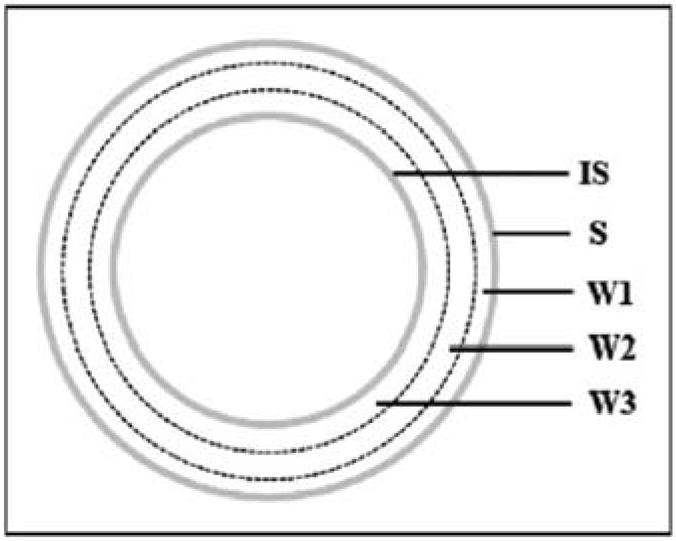


Figure 2.22: Diagram of the lateral cell wall structure of kapok fibre

The SEM images of kapok fibre as shown in the figure 2.21: SEM (a) show a homogenous circular cross-section with a wide air-filled lumen having a wall thickness of about 1 to 2 μm. The thickness of the homogenous hollow wall is about 0.8 to 1.0 μm, which makes it difficult to water to penetrate. The kapok fibre lumen occupied around 64% of the average area, and even after harsh mechanical treatment, it does not collapse. Kapok fibre can be easily open and cleaned by hand as it contains low trash and foreign contaminant because of these kapok fibre production required less energy [129].

The Fourier-transform infrared spectroscopy (FTIR) of kapok showed intense broadband 3364.96 cm^{-1} related to OH strong stretch, due to intermolecular hydrogen bonding. For C-H strong stretch, the band value of 2917.46 cm^{-1} and for C-O double bond strong stretch peak value 1739.87 cm^{-1} was obtained. The C-H bonding due to the presence of the acetyl group gives a peak value was of 1374.34. Similarly, the weak stretching and bonding of O-H and C-H give peaks values of 1244 and 1057, respectively [129].

2.10.2 Physical Properties of Kapok Fibre

According to the various research studies, it was found that the average breaking elongation and breaking strength of kapok fibre are in the range of 1.83 – 4.23 % and 1.4 – 1.7 CN, respectively. Kapok fibre has the tenacity and initial modulus similar to the cotton fibre, but it has a lower tensile elongation in comparison to cotton fibre. Kapok fibre due

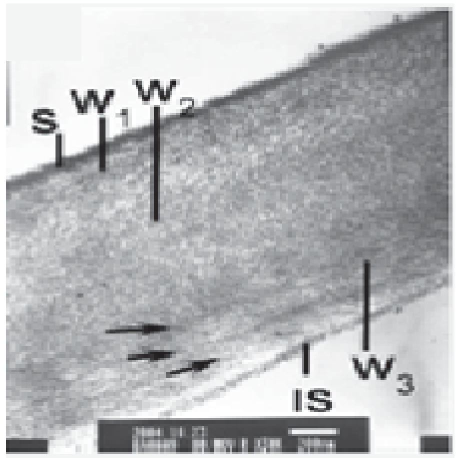


Figure 2.23: Transmission electron microscope (TEM) image of kapok fibre

to its softness and fineness easily fragile [130]. In comparison to cotton fibre Kapok fibres 8 times lighter by volume. Kapok fibre also shows good resistance to alkalis and does not get affected by alkali.

Appearance - kapok fibres are lustrous, silky-soft, yellowish brown and made of a mix of lignin and cellulose.

Fineness - 0.4 – 0.7 denier

Tenacity - 1.4 – 1.74 gram/denier

Elongation at Break - 1.8 – 4.23

Xu et al. [136] reported that the bending rigidity of single kapok fibre in comparison to cotton and some hollow synthetic fibres is lower, but its relative bending rigidity is much higher. As reported, the calculated bending rigidity of a single kapok fibre from obtained values are found to be 0.823×10^{-5} cN$\cdot cm^2$, whereas its relative bending rigidity is 21.06×10^{-4} cN$\cdot cm^2 \cdot tex^{-2}$. The compression resilience test of kapok fibre performed using the Kawabata Evaluation System (KES) is shows that compressional resilience of dry kapok fibrous assemblies is better than that of wet kapok fibrous assemblies [137]. The mercerization process of kapok/cotton blended yarns influences the mechanical properties of the yarn. The NaOH concentration during the mercerization process increases from 180 to 250 g/l, leads to an increase in the strength of kapok/cotton blended yarns, and decreases the elongation at breaking. When the NaOH concentration further increases up to 280 g/l, the strength of kapok/cotton blended yarns dramatically drops and elongation at break increase with an increase in kapok fibre content [138]. Physical properties of different natural fibres are given in Table 2.5

Table 2.5: Physical properties of natural fibers [129]

Sr. No.	Fibre	Fineness Denier	Tenacity g/den	Relative weight	Elongation at Break	Fibre color range
1	Cotton	2	2.5	200	8	Cream white
2	Kapok	0.4-0.7	1.4-1.74	-	1.8-4.23	Ivory white to camel brown
3	Jute	20	3	167	1.5	Creamy white to grey brown
4	Flax	5	5	100	1.5	Bleached white to grayish brown
5	Hemp	6	4	125	2	Light brown to grayish brown
6	Ramie	5	5	100	4	Bleached white to grayish brown
7	Sisal	290	4	125	3	Creamy white to yellowish brown
8	Pineapple	27	41.4	-	2.4	-
9	Murva	60	5.8	-	1.4	-
10	Abaca	190	5	100	3	Creamy white to dark brown
11	Henequen	370	3	167	5	Creamy white to yellowish brown
12	Istle	360	2.5	200	5	Nearly white to light reddish yellow

To enhance the inherent properties or alter the surface characteristics of kapok fibre is usually pretreated by using following methods

1. Physical treatment: ultrasonic or radiation treatment is given to remove the surface

impurities and improve the interfacial properties of the fibre.

2. Chemical treatment: alkali, acid, solvent, oxidation, or acetyl treatment given to improve or modify the inherent properties of the fibre.

So, in general, kapok fiber is white or pale yellow in colour and also lightweight, lustrous, brittle, elastic. Kapok is a single-cell cylindrical fibre having a bulbous base. It is naturally hollow fibre with the air-filled lumen. Kapok fibre is fragile due to its fineness and softness. The kapok fibre is very difficult to process on the modern spinning line due to the smoothness of its outer surface. some of the properties of kapok fibre listed in Table 2.6.

Table 2.6: Average physical properties of kapok fibre

Average physical properties of kapok fibre	
Linear density	0.64 dtex
Diameter	20.5 μm
Length	20 mm
Moisture regain	10 %

2.10.3 Absorbency

Kapok is hydrophobic/oleophilic fibre that could be attributed to its waxy surface. However, the presence of large lumen provides excellent oil absorbency and retention properties to the fibre [133]. The surface tension and surface energy are the two main factors on which the absorbency of material depends. The less amount of hydroxyl group present in the kapok fibre wall makes it hydrophobic. The value of the surface tension of water and oil is 72 dynes/cm and 30–35 dynes/cm, respectively. The absorption takes place in the material if the surface tension is nullified by the surface energy of the material, but in case of kapok fibre presence of lumen makes it oil absorbent, while its low surface energy makes it hydrophilic. The absorption capability of kapok fibre assemblies depends on the packing density [139]. With better packing density of the material leads to increase and decrease the absorption levels vice versa. The absorbing and retaining of fluid depends on the properties such as cohesion and capillary action. After one hour of dipping, the retentivity value of the material is very high and loses about 8 to 12 % of absorbed oil.

The retentivity values decreased by 27 to 30 % on repeated usage in the fourth cycle. Increasing the thickness of oil layers in the feed stream leads to an increase in the oil recovery rate [140]. Figure 2.24 indicate the absorbency of kapok fibre.

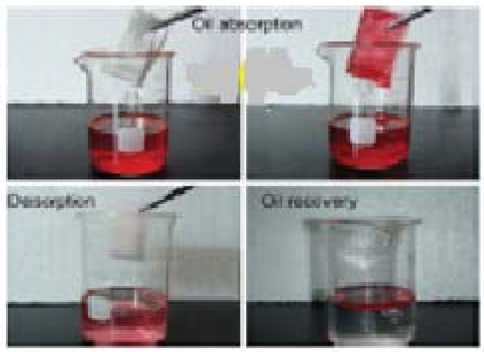


Figure 2.24: Absorbency of kapok fibre [129]

2.10.4 Sound Absorption

Kapok fibres have better sound absorption properties due to its natural hollow structure. The hollow structure of the fibres increases the surface area of the fibre, which influences the acoustic performance of kapok fibre. The thickness, bulkiness, and arrangement of fibres directly affect the sound absorption properties of the materials, but the influence of fibre length on the sound absorption properties is very less [41].

2.10.5 Compressibility of the Kapok Fibre

The compressive behavior of the kapok fibre is not great even though it has a hollow structure, and this is due to its high crystallinity. Kapok fibre is brittle in nature and tends to break out easily. Kapok fibre generally gets back to its original shape after compression. When fibre assembly has given the wet treatment without pressure, 90% of the fibre get back to its original shape, but in the case of wet treatment with pressure, 80% of fibre crushed. The loss of hollow structure and inter fibre space of fibre assemblies is very less when dry pressure treatment is given, which means fibre assemblies shapes less affected by the dry pressure treatment compare to wet pressure treatment [137].

2.10.6 Thermal Behavior of Kapok

Heat transfer is taking place either by means conduction, convection, or radiation. Out of these, the conductivity is the most important mechanism of heat transfer inside the fibre assemblies. The heat insulation performance of fibres assemblies is governed by the combined effect of conduction and convection. The trapped air or immobile air conductivity coefficient (W/m°K) plays a major role in the thermal behavior of fibre. Fibrous material structure and its properties also play an important role in deciding its thermal behavior. The heat retention properties of kapok fibre are much better than the other fibres, due to the static trapped air in the large lumen of kapok fibre. The kapok conductivity values vary between 0.03 and 0.04 W/m°K for density values 5 to 40 kg/m^3. The average diffusivity values of the kapok fibre (17.1x10^{-7} m^2/s) indicate that kapok fibre has excellent heat insulation properties [141].

2.10.7 Spinnability

Kapok fibre is known for its silky-soft feel, lightweight, fineness, smoothest surface, highest hollowness, and warm nature. In the early years. In olden days, the kapok fibres are considered as not suitable fibre for textile applications, due to its short length, brittleness, smooth surface make it a fragile. The short length and smooth surface also provide the low inter fibre cohesion, and low elasticity of the fibre makes it difficult to spin solely. This limitation restricts the use of kapok fibre in textile apparel and other applications. Nowadays, it is possible to spin the kapok fibre blended with cotton fibre. It was observed that with an increase in the kapok fibre proportion in the blends, the tenacity and evenness of yarn is decreased, but the extensibility of the yarn increased. It is found that for improving the spinning performance, kapok fibre can be blended with cotton fibre, but its proportion in the blend should not increase beyond 50 %. Otherwise, it going affect the spinning and weaving process performance [142,143]. Also, the total cost of production of the yarns decreases significantly with increase kapok fibre content in the blends. Kapok fibre in blends with other fibre can be used to produce thermal insulating materials, fast oil-absorbing material, fast moisture conductive material, and sound absorption material.

2.10.8 Weavability

The weaving of kapok fibre is not possible due to its smooth surface, which provides less cohesive force and leads to gives slippage between the fibres. In order to improve the wearability of kapok fibre, the surface of the fibre needs to modify either by giving chemical treatment or plasma treatment to the fibre. The cohesive force can also be improved by blending the kapok fibres with other cellulosic fibres like cotton, hemp, flax, jute, or other fibres.

2.10.9 Chemical Composition of Kapok

Kapok is single-cell natural cellulose fibre and contain 64% cellulose, 13% lignin and 23% pentose [144]. Hori et at. [135] mentioned that kapok fibre contain cellulose (35% dry fibre), xylan (22%), and lignin (21.5%). Kapok fibre is inherently free from pesticides and mold due to the presence of a large amount of wax and lignin and bitterness. The main components of kapok fiber are cellulose, lignin, and xylan [145, 146]. The outer cell wall layer contains less lignin and more of the minor polysaccharides mannan and galactan and more proteins than the main part. The surface characteristics of kapok fibre get influenced by the high mineral content. In comparison to normal plan cell walls, the kapok fibre has a high ratio of syringyl / guaiacyl units with a high level of acetyl groups 13.0 % [147]. The specific density of kapok fibre is 0.30 g/cm^3, the birefringence is 0.017, and the crystallization degree is 35.90% [130]. The crystallinity of kapok fibre is lower than the cotton fibre and also shows well-resolved spectrum of cellulose I [147].

Cellulose: Cellulose with an organic compound ($C_6H_{10}O_5$)n, is the superabundant organic polymer on the earth. Kapok is polysaccharide having a linear chain of several 100 to 10000 β (1 $\rightarrow$ 4) linked D-glucose. The degree of polymerization varies in the range of 200 to 10000, but its degree of polymerization that depends on the purification and isolation process is around 3000. Polysaccharides in a generic term known as hemicellulose. The degree of polymerization of hemicellulose is around 100, which is generally found in vegetable fibre other than cellulose. Cellulose is an important component of the primary walls of any green plant. The carboxymethyl cellulose and methylcellulose is an example of water-soluble binders and adhesives, which is produced by using cellulose. These binders and adhesives are used in wallpaper paste. Kapok fibre contains less amount of hydroxyl group, which makes it hydrophobic.

Lignin: Lignin or lignin is found in the secondary cell walls of the plants. Lignin is derived from the wood and has a complex chemical compound ($C_9H_{10}O_2$, $C_{10}H_{12}O_3$, $C_{11}H_{14}O_4$). Lignin plays a vital role in water conduction in stems of the plants. Lignin is hydrophobic, whereas the hemicellulose components of the plant wall are hydrophilic in nature and allow water to pass through. The crosslinking between the lignin and the hemicellulose creates resistance for water absorption into the cell wall.

Xylan: Xylans is hemicellulose made from the units of a pentose sugar (xylose). Xylans are always present as cellulose in the plant cell walls. Similar to cellulose, Xyland also contains the β-D-xylose units linked. In green algae and macrophytic siphonous genera, xylan is found in cell walls, in which it replaces cellulose. Similarly, in some red algae, the inner fibrillar cell wall layer is replaced by xylans. The chemical composition of different natural fibres is given in Table 2.7

Table 2.7: Chemical composition of different natural fibres [129]

Sr. No.	**Fibre**	**Cellulose %**	**Hemi Cellulose %**	**Pectin %**	**Lignin %**	**Extrac -tives %**	**Moisture %**
1	Cotton	94	2	2	-	2	8
2	Kapok	35-65	23	23	13	-	0
3	Flax	71.2	18.5	2	2.2	6	9
4	Hemp	74.3	17.9	0.9	3.7	31	8.8
5	Ramie	76.2	14.5	2.1	0.7	6.4	-
6	Jute	71.5	13.3	0.2	13.1	1.8	9.9
7	Sisal	73.2	13.3	0.9	11	1.6	6.2
8	Pineapple	69.5-71.5	-	1.0-2.0	4.4-4.7	5.2	6.1
9	Murva	70.1	-	-	12.9	-	9.1
10	Furcraea	80	-	-	18	2	7.6

2.10.10 Dyeability of Kapok Fibre

Kapok is a hydrophobic fibre, which does not allow the water-based dye molecules to penetrate for dyeing. The wax layers on the surface of the kapok fibre also create a problem in the dyeing of fibre. To make the kapok fibre dyeable, its surface has to be modified by giving chemical or plasma treatment. Kapok fibre low rate of dyeing performance can be improved by using anionic dye such as reactive dye. For dyeing a kapok fibre, certain steps need to follow. First, some pre-treatment is given to the kapok fibre to modify its surface characteristics and to get whiteness and then for mordant dyeing of kapok fibre, complex rare earth mordant added into the dye bath of pretreated kapok fibre. For printing and dyeing of kapok fibres dye of fibre, rare earth elements ions, and other compounds of sulfonic acid group, hydroxyl group, azo groups etc. are used.

2.10.11 Effect of Microorganisms

Nilsson and Björdal [148] found that the ordinary cellulolytic bacteria is not attacked to the kapok because of its high lignin content, and therefore, the kapok fibre have better antibacterial property [149]. Liu et al. [150] studied antibacterial, anti-mite, and anti-moth properties of kapok battings. The results of the antibacterial test show that kapok batting has both bactericidal and bacteriostatic effects on the Escherichia coli, but did not have these effects on the staphylococcus aureus. The results of the anti-moth test show that the kapok loses less weight in comparison to the reference sample, the damage grade of the surface batting obtained is 2A. The anti-mite test results show that the kapok has good anti-mite property because its mite expelling rate is 87.54%.

2.10.12 Advantages

- Lightweight
- Hydrophobic and the good buoyancy effect
- Comfortable
- Thermal insulator
- Biodegradable

2.10.13 Disadvantages

- Fibres are break easily and fragile

- Less inter fibre cohesive force
- Fibres are easily flown into the air due to its lightweight
- Causes the lungs Irritation
- Highly inflammable

In the last 30 years, the usage of kapok fibres reduced due to the development of various types of polyester fibre, which provide good competition to the kapok fibre. But the recent development in technology helps kapok fibre to overcome its drawbacks. Nowadays, it is possible to spin a kapok fibre by blending with cotton fibres. So further advancement is required to explore the various usages of kapok fibres.

2.10.14 Applications of Kapok fibres

Kapok fibre finds its usage in life-saving equipment, as a stuffing, especially for life preservers, upholstery, bedding, thermal insulating material and to produce sound insulating materials [128]. Kapok fibre is used in producing the lifebuoys, waistcoats, belts and other naval life-saving equipment, due to its characteristics such as buoyancy, hydrophobic nature, free from water logging problem, and good weight-bearing capacity. The buoyancy of kapok fibre is 3 times greater than the reindeer hair and 5 times greater than the cork; that why the kapok is used in replacement of cork wherever more moisture resistance, lightness, and floating power is required. During the second world war, the kapok fibre was used for filling floats of army assault bridges, for lining aviation suits and for insulating the tanks [130]. Kapok fibre also used in floatation vest and in building as insulation material due to its hollow structure [128].

- Kapok fibre due to its soft silky, smooth and slippery surface, and its brittleness consider as unsuitable for apparel application.
- Refined kapok seed oil can be used for the same purpose as the refined cottonseed oil is used.
- Kapok wood is very soft and lightweight, so it is used for making canoes, toys, and matches.

- Kapok is the best suitable material to separate the oil from the water in case of spilling of oil in seawater because of its higher oil absorbency property.
- Kapok fibre due to its hollow structure able to have trapped air inside the large lumen, which gives a good buoyant property, so that kapok fibre is used in producing the buoyancy suit / anti drowning suits.
- Kapok fibre also suitable material for oil and air filtration because of its air-filled structure.
- Kapok fibre hollow structure allows the combustion to penetrate deep inside the structure, due to that flame travel quickly inside the material, which makes it unsuitable for apparel wears.
- Kapok apparel fabric can be produced by using knitting or weaving technology in blends with cotton fibres.

Today the environment pollution becomes a big issue, and the manmade fibre used in the various application are not eco friendly, so considering this fact the natural fibre has huge opportunity to replace the existing man-made fibres. One such fibre is kapok fibre. In present research work, kapok fibre has been studied to analyze the acoustic absorption to explore its end uses in the field of acoustic. Kapok fibre is a natural hollow fibre, which is provides higher surface area to sound wave to interact and convert sound energy into heat. So that Kapok fibre has huge potential to be used for sound absorption.

2.11 Estabragh Fibre

The most viable way towards eco-friendly noise absorptive material is the use of natural fibers/fabrics as acoustics material. The existing sound absorption materials are generally made of synthetic materials, which are not bio-degradable. This is where natural fibers find relevance due to their intrinsic properties such as low weight, low cost, mechanical strength, renewable and biodegradable nature making them an attractive choice for acoustic applications [84, 151]. Hence in this research work, Natural fiber fabrics developed to study acoustic properties of naturally hollow fiber estabragh for technical uses. A Persian name Estabragh is used here for milkweed fibre.

Milkweed (In the Persian language known Estabragh) are categorized as versatile substitutive fibers with numerous unique properties, which are mainly attributed to their hollowness structures. The presence of a hollow channel along the fiber length is responsible for their lightweight, good insulation and acoustic properties. Due to the unique structure Estabragh (milkweed) fibre have huge potential to be used for acoustic application. After looking into its properties, this fibre is selected for present study. Here *a Persian name Estabragh of milkweed fibre is used*, in India; it is also known as Mudar.

Moreover, many studies focused on developing natural fibres as a raw material has been done and reported, such a palm, kenaf, coconut coir, and many others that have the potential to be used as raw material for acoustic application [49, 152]. The industrial tea-leaf-fibre waste material also has sound absorption properties at high frequencies [153]. These show that natural fibres have a high potential to be used as raw materials of sound absorbing materials. Milkweed fibre has not found its industrial application until now [154]. Sakthivel and Anydia [155] believed that the milkweed spin-ability on a large production scale would eventually make them a new remarkable agricultural product and could be developed as the alternative crops for conventionally used fibres such as cotton.

Milkweed fibres (Asclepias syriaca), also called the "Vegetable Silk," have similar appearance with Rux fibres (Caleotropis gigantea), which could be extracted from a native plant of South Asia, Thailand [156, 157]. Milkweed fibres, illustrated in figure 2.25. Milkweed fibres could be extracted either from the seedpod or from the plant's stem. Also, a white milk sap extracted from the plant's stem has numerous medical applications, especially for pain, asthma, bronchitis, dyspepsia, leprosy, tumor, and some other gastrointestinal diseases [158]. Milkweed fibres are also used as raw material for the paper industries in some regions.

Milkweed fibres are cellulosic seed fibres growing on single cells in a large seed of the plant. This fibre is lightweight due to a hollow structure with thin walls compared to its diameter. Milkweed fibre is useful in the application where good insulation, buoyancy, and sound absorption properties are required, due to its hollow structure. Milkweed belongs to the genus Calotropis of the family of Asclepiadaceae. Its botanical name is Calatropis gigantea, and the common name is milkweed (or Mudar) fibre. These fibres mainly found in the tropical region of the world. Found especially in the drier parts of central and south America, Asia, and South Africa, although these newly known fibres are widely distributed over most regions of the world.

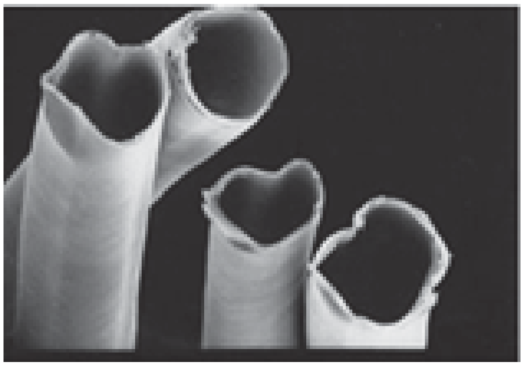
Figure 2.25: Estabragh / Milkweed Fibre

The base of the region in which the milkweed plant has grown, different native nickname could be attributed to the fibres including Swallow Wort, Dead Sea Apple, Milkweed (commonly used), Desert Wick, Mudar (Indian name), Estabragh (Persian name), Rubber Bush, etc. Since the widely grown milkweed plant possesses such high adaption with different soil conditions, it could almost be found in every continental region from sandy and arid (hot and dry) to moist and swampy (temperate and humid) [158]. So, the high adaptability and weed-like nature of the Milkweed plants made them cost-effective and easy-cultivable.

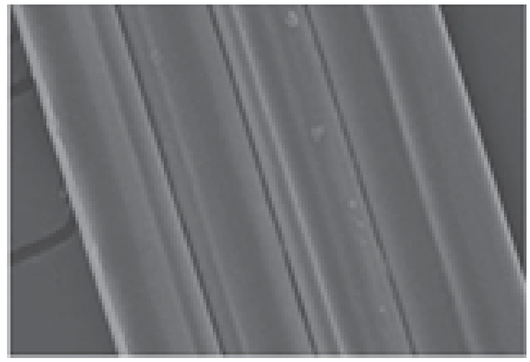
Milkweed fibre first utilized for textile fabric production in Thailand (Called Rux fibre) [159]. During the second world war, the United States utilized milkweed fibre in life jackets production. In the 1980s, milkweed fibre used in nonwoven applications as a new natural cellulosic fibre. Many researchers have studied the possibilities of using milkweed fibre as an alternative natural resource.

Generally, fibres are available in wastelands and by the roadside, often on black cotton soil. The fibres are grown in seedpod, and then during the second stage of growing follicle opens up. Generally, the seed is flat, oval, oblong, and is crowned by the fruit of hairs. The pods need to be picked when they are green and still unopened. They are spilled, and the green husk pulled back, which uncovers the inside. The milkweed fibres can be separated from the attached seed by hand. When the attached seed is rubbed lightly against the palm of the hand, they fall off readily from the fibers.

2.11.1 Appearance and Physical Properties of Milkweed fibre



(i)-Milkweed fibre Cross-section



(ii)-Milkweed fibre surface

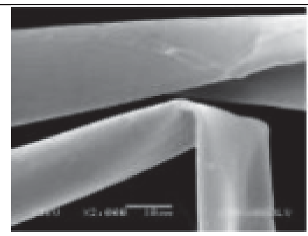
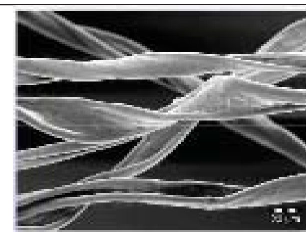
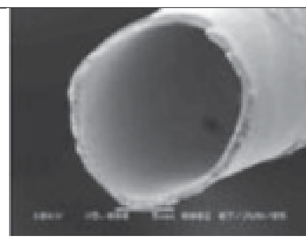
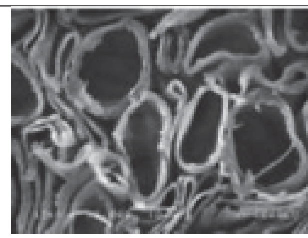
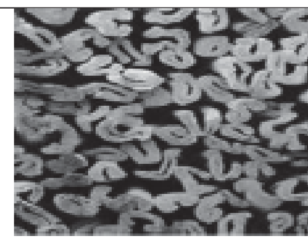
Figure 2.26: SEM of Milkweed fibre

Similar to the cotton fibre, milkweed is single-cell fibres, but there is no convolution along the fibre length. As shown in figure 2.26., milkweed fibres are naturally hollow fibres. Due to this unique structure, milkweed fibres are lightweight and possess good insulation properties. Milkweed fibre has a smooth surface and also has low sustainability against the external loads leads to create difficulties during the spinning process of the fibres. The milkweed fibre is thin-walled fibre with three regions, including the inner wall, the micro-fibrils in the middle, and the outer wall [160]. Fibre's wall thickness strongly affects the hollowness percentage of the milkweed fibres which subsequently influence their acoustic and insulation properties. JF. Drean et al. [161] investigated the wall thickness of milkweed fibre and found that the mean value of fibre's wall thickness is about 1.27 μm.

Milkweed fibre morphology is generally affected by environmental conditions. Different properties of the milkweed fibre in comparison to cotton and kapok fibre given in Table 2.8.

Table 2.8: Comparison of properties of milkweed, kapok and cotton fibres

	Milkweed	**Kapok**	**Cotton**
Plant Family	Asclepiadaceae	Malvaceae	Malvaceae
Genus	Asclepias	Ceiba	Gossypium

	Milkweed	**Kapok**	**Cotton**
Longitudinal appearance	Smooth, Single-cell, Cylindrically shaped, without any convolution, large lumen.	Smooth, Single-cell, cylindrically shaped, without any convolution, large lumen.	Flat and ribbon like with convolutions, thick wall, and small lumen
			
Cross-section	Oval to Round	Oval to Round	Bean shaped, Elliptical
			
Diameter (µm)	20-50	20-43	12-45
Linear density (tex)	0.11	0.064	0.12-0.18
Length (mm)	20-30	10-24	25-60
Strength (cN/tex)	16-25	8-15	25-40
Elongation (%)	1.5-3.0	1.5-3.0	5-10
Moisture regain (%)	10.5-10.9	10-10.73	7-8

	Milkweed	**Kapok**	**Cotton**
Density (g/cm3)	Wall density 1.4 Considering lumen 0.27, Wall thickness 1.4 µm (0.9)	Wall density -1.5 Considering lumen -0.384, Wall thickness 1-2 µm (0.29)	1.54
Chemical composition	Cellulose -55% Hemicellulose -24% Lignin -18% extractables -3%	Cellulose -35-50% Hemicellulose -22 45% Lignin -15 22% Wax -2 3% Proteins -2.1%	Cellulose -80-90% Water -6-8% Wax & fats 0.51% Proteins 0-1.5% Pectins 4-6% Ash -1-1. 8%
Crystallinity (%)	32-39	38-40	72-75
Degree of polymerization	4000	3300	9000-15000
Application	Padding and tuffing of upholstery, cushions, mats, life-saving belts, soundproofing, electrical insulation, oil spill clean up	Padding and stuffing of upholstery, cushions, mats, life-saving belts, soundproofing electrical insulation, oil spill clean up	Clothing, bedding, towels, and furnishings.

2.11.2 Physical Characteristics of Milkweed Fibre

The physical characteristics of the fibres are mainly affected by the morphology and structural characteristics such as shape, size, and chemical composition of the cellulose molecules as well as molecules aggregation either in the crystalline form or in the amorphous region. Some of the physical characteristics of the milkweed fibres are as below.

Uniformity ratio milkweed fibre: The physical characteristics of the milkweed fibre are significantly different from the cotton fibres. Uniformity ratio is one of the most important physical properties to give an idea about the fibres length distribution. Table 2.9 indicates the finding of various researchers about the different lengths of milkweed fibre in comparison with the cotton fibres. It can be concluded that shorter fibre length of milkweed leads to their lower uniformity ratio than cotton.

Table 2.9: Uniformity ratio of milkweed fibres Vs. cotton

Fiber Length	**Milkweeds**			**Cotton**
	Common Milkweed (US)	**Mudar**	**Rux (Southeast Asia)**	
2.5% span length (mm)	26.7	27.9	30.7	26.7
50% span length (mm)	11.2	13.6	12.7	13.9
Uniformity ratio (%)	42	48.7	41.4	52.1

Aspect ratio of milkweed fibre: The aspect ratio is the ratio of fibre length to its width, which indicates the flexibility of the fibre. Karthik and Murugan [162] said that the percentage of short fibres within the milkweed fiber bundles is 10.2%, while for cotton fibre it is only 4.3%. Ashori and Bahreini [163], stated that the average aspect ratio of milkweed stem fibre is 76% higher than that of the seed fibres.

Density and Fineness of milkweed fibre: Milkweed fibres due to their thin-walled hollow structure have a lower density than other natural cellulosic fibres [163, 164]. Sakthivel et al. [165] determining the seedpod type fibre density, using a laboratory density gradient column with a mixture of xylene 0.866 g/cc and carbon tetrachloride 1.592 g/cc utilized. They found that the milkweed fibre density is about 0.97 g/cm^3 .

Reddy and Yang [166] stated that the presence of a shorter and narrow width single wall is considered as the main reason for the coarse milkweed fibres as compared to cotton. The seedpod milkweed fibres fineness is about 0.944 μg/cm or 94.4 mtex which is lower than the cotton fibre fineness of about 1.417 μg/cm or 141.7 mtex [165].

2.11.3 Mechanical Properties of Milkweed Fibre

The milkweed plant growth is affected by the surrounding environment condition, which leads to affect the chemical and mechanical properties of the milkweed fibre. The milkweed fibre strength is 20.5 g/tex, which is lower than the cotton fibre strength 24.2 g/tex [167, 168]. Reddy and Yang [166] stated that ultra-thin single wall and the lower crystallinity percentage of milkweed are mainly responsible for their lower strength compare to other cellulosic fibres. Louis and Andrews [167] found that the elongation percentage of the milkweed fibre is almost 86% lower than the cotton fibre. Table 2.10 provides the mechanical properties of milkweed fibre (Mudar fibre) compare to some natural and synthetic fibres [163].

Table 2.10: Mechanical properties of milkweed fibre

Fibres	**Tensile Strength (MPa)**	**Young Modulus (GPa)**	**Elongation at break (%)**
Milkweed (Stem Extracted fibre)	381	9.2	2.1
Milkweed (Seed Extracted fibre)	296	8.2	1.6
Common natural fibres			
Cotton	287-800	5.5-12.6	7.0-8.0
Jute	393-773	26.5	1.5-1.8
Flax	345-1035	27.6	2.7-3.2
Hemp	690	70	1.6
Sisal	511-635	9.4-22.0	2.0-2.5
Synthetic fibres			
E-glass	2000-3500	70	2.5
Aramid	3000-3150	63.0-67.0	3.3-3.7
Carbon	4000	230.0-240.0	1.4-1.8

2.11.4 Chemical Composition of Milkweed Fibre

Milkweed fibre is a lingo-cellulosic fibre, composed of different components, mainly cellulose, lignin, wax, and ash. The main chemical composition of the milkweed seed extracted fibres in comparison with cotton and kenaf given in Table 2.11.

Table 2.11: Chemical composition of Milkweed fibre

Chemical Composition	Milkweed (%)	Cotton (%)	Kenaf (%)
Cellulose (crystal)	55	85.0-90.0	79.0-83.0
Hemicellulose	24	-	-
Lignin	18	0.7-1.6	14.0-17.0
Ash	1.0-2.0	0.8-2.0	2.2-6.0
Wax	1.0-2.0	0.5	-

Knudsen [164] investigated the chemical composition of common milkweed fibres and found that milkweed fibre has 55% cellulose, 24% hemicellulose, 18% lignin, and 3% extractable. He also stated that the milkweed seed fibre has a potential application as a super absorbent, thermal insulation, fluid carrier, bulking, bonding, and tactile-changing fibre.

According to Campbell [169], the environmental conditions might strongly affect the chemical compositions and mechanical performance of Milkweed fibres. Hemicellulose is one of the main components of the milkweed fibres, and it is a natural polymer mainly participated in forming the branch skeleton of amorphous structure [170]. On the other hand, the higher content of holocellulose gives higher fibre strength, due to higher crystallinity.

Reddy & Yang [166] have analyzed the characterization of cellulose fibre from common milkweed stems in terms of their composition, structure, and properties. The results showed that the fibre obtained from the milkweed stem has about 75% cellulose, higher than the milkweed floss but lower than that in cotton and linen. The milkweed stem fibres have low crystallinity when compared with cotton and linen with the strength similar to cotton and higher elongation than that of linen. Overall, the milkweed stem fibres have properties required for high value textile, composites, and other industrial applications.

Timell & Snyder [171] have studied the molecular properties of common milkweed

-cellulose content and found that the cellulose fraction is entirely composed of anhydro-glucose and the hemicellulose portion of anhydro-oxylose units. In addition to the original material, it also contained minor amounts of arabinose and uronic acid residues. They also found that the milkweed fibre had a rather interesting composition, apparently comprising only two main constituents, namely, an exceedingly high molecular weight cellulose part and a probably low molecular weight hemicellulose portion, the latter consisting chiefly of xylan. The lower degree of polymerization limit was 2500, and the upper was 8000. Despite the presence of high degree of polymerization of cellulose, the fibre has low strength due to the high content of xylan.

2.11.5 Chemical Properties of Milkweed Fibre

Sakthivel et al. [165] studied the fibre solubility with different mineral acids and strong alkalis at both hot and cold conditions. They find out that milkweed fibre strongly affected by the sulfuric acid similar to the cotton fibre. Milkweed fibres do not have any damages while treating with volatile organic acids such as acetic acid and formic acid. Milkweed fibre treated with a strong alkali, its color changes and also deteriorate their mechanical performance in terms of tensile strength and stiffness.

2.11.6 Moisture Property of Milkweed Fibres

According to various literature, the milkweed fibres have higher moisture regain and moisture content compared to the cotton [162, 171]. The higher absorbency of milkweed fibres is mainly attributed to the presence of a hollow channel along the fibre length. Thus, a nonwoven fabric made of milkweed fibres could provide high moisture absorbancy [165, 167]. Moisture content value of seedpod milkweed fibre is 10%, and moisture regain is about 11.1 [165]. The presence of air pockets trapped within the hollow channel of milkweed fibres made them suitable for thermal insulators.

2.11.7 Thermal Stability of Milkweed Fibres

Gu et al. [172] have studied the thermal analysis of milkweed. The result showed that pyrolytic decomposition of the three chemical constituents, such as acetic acid, formic acid, and methanol of milkweed occurs without any apparent synergistic interaction. The combustion of milkweed has produced CO_2 and H_2O, but the removal of the waxy coating from the fibres results in increased susceptibility to combustion.

Further, they stated that the fibre undergoes three reactions after moisture loss: 1) An exothermal reaction associated with the major weight loss, 58% between 100 and 300°C. 2) rapid combustion between 300 and 450°C resulting in loss of most of the remaining sample mass (38% and 32%, respectively) and 3) a small weight loss recorded at temperatures between 450 and 600°C (0.8% and 0.6%). It could be stated that the cellulose content of milkweed fibres has higher stability against thermal degradation than the hemicellulose and lignin [172].

2.11.8 Application of Milkweed Fibres

The fibers extracted from the Milkweed plant's stems or seedpods have been identified prehistorically and utilized as the textile raw materials, especially in different regions of the United States and southern Canada. These fibers are also used for food and medical applications. Because of their hydrophobic nature and hollow structure, Milkweed fibers are employed as the raw material in life jacket manufacturing during the second world war [164, 173]. Later, lots of interest in using the Milkweed fibers in non-woven applications, apparel manufacturing, and technical textiles are rapidly expanded. Milkweed fibre has the potential to be used for the acoustic application because its unique hollow structure provides a higher surface area, which helps in sound absorption.

2.12 Response Surface Methodology – Central Composite Design (RSM-CCD)

Response surface methodology (RSM) is a mathematical and statistical technique. A response surface design method is a set of advanced design of experiments (DOE) techniques that help in better understanding and optimize response. The first step in any design of the experiment is to identify the different factors that affect the response. Once the important factors have been identified, the next step is to find out the set of conditions for the process variable that results in the best process performance. Methodologies that help the experimenter to achieve the goal of optimum response is known as response surface methods. Response surface methods are exclusively used to study the relationship between the response and the factors affecting the response. In Response surface methods (RSM), the Regression models are used for the analysis of the response, because here the focus is on the type of the relationship between the response and the factors.

The objective of this method is to optimize the response and useful for analysis and modelling, where the response of interest is prejudiced by several variables. The RSM method was developed in 1950 and used in the chemical industry. In the last 20 years, the Response surface method has found its application in various industries like machining, metal cutting, semiconductors, and electronics manufacturing, metal cutting and joining process industry, etc. Now, a days' Response surface methodology also included in many software as a standard feature for designs of experiment and optimization techniques. Suppose the humidity in the spinning unite is denotes as (x_1) and the end breakage rate on ring frame by (x_2), the maximum production (y) of spinning units is a function of levels of humidity and end breakage rate, can be represented as below equation 2.17.

$$y = f(x_1 + x_2) + \varepsilon \tag{2.17}$$

Where,

ε = Error in response y

If the expected value of the response is E(y) = $f(x_1, x_2)$, then the response surface method can be represented by the following equation 2.18 and is known as response surface. The response surface can be presented by figure 2.27. Here, E(y) is plotted versus the level x_1 and x_2. The response is plotted as a surface plot in three-dimensional space. For the better visualize the shape of a response surface often plot as contours as shown in the figure 2.28. In the contour plot, the line of constant responses is drawn in the x_1 and x_2 plane. Each contour relates to a particular height of the response surface. The contour graph is useful to analyze the level of x_1, x_2 that results in deviations in the shape or height of the response surface.

$$E(y) = f(x_1 + x_2) \tag{2.18}$$

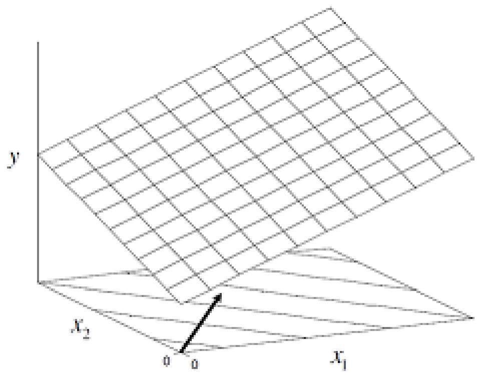


Figure 2.27: A three-dimensional response surface

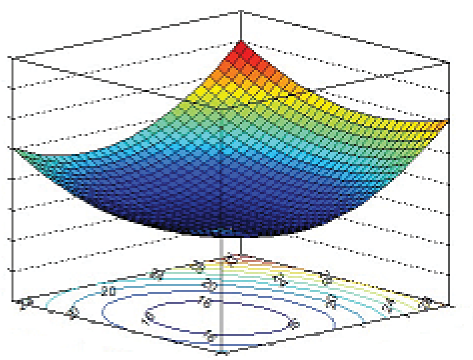


Figure 2.28: A Contour plot of the three-dimensional response surface

The relationship between the response and the independent variable is unknown in Response surface methodology. So that the first step in RSM is to find out the suitable approximation for the true relationship between response and independent variable. Generally, a low order polynomial in some regions of the independent variables is employed. In such a case, the approximating function of the first-order model by linear function can be represented by an equation 2.19. The second-order model, as shown in equation 2.20 needs to be used if there is a curvature in the system. In RSM, any one or both models are used. It gives a more true functional relationship for relatively small regions than the entire space of the independent variables.

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_1 + \ldots + \beta_i x_k + \varepsilon \quad (2.19)$$

$$y = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k} \beta_{ii} {x_i}^2 + \sum_{i<} \sum_{j=2}^{k} \beta_{ij} x_i x_j + \varepsilon \tag{2.20}$$

To estimate the value of $\beta's$ using equation 2.19 and 2.20, a method of least square is used to find the value of parameters with minimizing the sum of squares of the model error. The RSM analysis is done in terms of the fitted surface. If the fitted surface is an adequate approximation of the true response function, then the analysis of the fitted surface can be able to give approximately equivalent to analysis of the actual system. Response surface methodology is a sequential procedure. When a point on response surface is far away from the optimum, one can see a little curvature in the contour and the first-order model will be appropriate, once the region at the optimum value has been found a second-order model needs to be employed, and analysis may be performed to locate the optimum. The objective of response surface methodology is to determine the optimum operating conditions for the system or to determine a region of the factor space in which operating specifications are satisfied.

There are two types of response surface designs:

1. Central Composite designs

2. Box-Behnken designs

2.12.0.1 Central Composite Design

Central Composite designs can befit a full quadratic model. This design of experiment techniques is used for planning the sequential experimentation because CCD designs also include the information from a correctly planned factorial experiment [174]. A Box-Wilson Central Composite Design, commonly called 'Central composite designs are a factorial or fractional factorial design with center points, factorial points, and axial points. The central composite design is frequently used for building a second-order polynomial for the response variable in response surface methodology without using full factorial design. In this method, experiments must have at least three levels in each factor, to calculate the coefficients of a polynomial with quadratic terms. If the distance from the center of the design space to a factorial point is ± 1 unit for each factor, the distance from the center of the design space to a star point is $|\alpha| > 1$. A central composite design always contains twice as many star points as there are factors in the design. The star points represent new extreme values (low and high) for each factor in the design. The central composite design is the most commonly used response surface designed experiment. Central composite design can be used to [174]:

- Estimate the first- and second-order terms efficiently.
- By using the value of centre and axial points of a previously done factorial design, a model of the response variable with curvature can be created.

Central composite designs are often built on previous factorial experiments by adding axial and center points. Therefore this method is very useful in planning the sequential experiments.

2.12.0.2 Box-Behnken Design [174]

Box-Behnken design has less design points in comparison to central composite designs. Therefore, this design is comparatively cost-effective for the same number of factors. However, this design is not suitable for sequential experiments. This method is capable of estimating the first and second-order coefficient, but the information from a correctly planned factorial experiment could not be included. The central composite design has up to 5 levels per factor, whereas the Box-Behnken designs have only 3 levels per factor. Box-Behnken design has an added advantage that all design points fall in a safe operating zone, as it does not include the axial points. Box Behnken designs do not set all factors at a higher level at the same time [174].

In the present study, all the samples are developed using Response surface Methodology – Central Composite Design (RSM-CCD).

The literature survey carried out for research indicates that very little information is available on the acoustic properties of milkweed and kapok fibre fabric along with various process parameters and physical properties of fabric that influence the sound absorption properties of the acoustic material. A systematic study is carried out in the present study with the primary aim to evaluate the acoustic properties of unconventional natural fibres like kapok and milkweed fibres fabric developed for acoustic applications. The effect of various process parameters and physical properties of fabric on the sound absorption property of kapok and estabragh (milkweed) fibre nonwoven fabric also evaluated.

The next chapter deals with the design of experiments and their planning.