ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/IJISRT24AUG1664

Investigating the Sound Absorption Properties of Silk Cotton and Other Sound-Absorbent Materials

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Abstract:- This research investigates the acoustic properties of various materials to mitigate sound transmission and enhance acoustic environments, focusing on silk cotton, cotton wool, chipped foam, and open-cell polyurethane foam. The study evaluates these materials for sound absorption and reduction, considering sound frequency and material density.

Materials were tested for their sound reduction and absorption coefficients, with silk cotton emerging as the most effective across a broad frequency spectrum, particularly below 200 Hz and above 1000 Hz. The research demonstrated that silk cotton, with its high porosity and fine fibre structure, achieved significant sound reduction even at low densities

The findings align with theoretical predictions of resonance frequencies, showing a strong correlation (r^2 = 0.9988 for the sound box and r^2 = 0.9894 for the sound pipe). Sound intensity and sound pressure levels were measured using a sound level meter, and data analysis was conducted using graphing and calculating software. The researcher employed modified laboratory methods to account for loose materials and equipment limitations, validating the use of theoretical equations to estimate sound absorption and reduction properties

The study provides some insights into using fibrous materials like silk cotton for noise reduction and acoustic enhancement. These findings have practical implications for improving sound quality in various environments, such as schools, studios, and public spaces, contributing to noise reduction strategies and enhancing auditory experiences.

Keywords:- *Attenuation, Box Acoustics, Decibel, Impedance Mismatch, Pipe Acoustics, Resonance, Silk Cotton (Kapok), Sound Absorption, Sound Level, Sound Reduction, Sound Transmission.*

I. INTRODUCTION

Sound transmission in the form of speech, music, and other audio-frequency acoustic stimuli is a primary means of communication whereby we transmit and receive auditory information. The human abilities of speech, hearing, and language development depend on sound production, transmission, and reception principles. Music, an integral part of entertainment, education, religion, and other cultural activities, requires careful attention to the mechanism of its production.

With twentieth-century and twenty-first-century technology, auditory information can be transmitted over long distances via cables and modulated electromagnetic waves. Computer hard drives, flash drives, and online technology enable sound recording, storage, and reproduction. High-fidelity sound reproduction depends on the design and construction of loudspeakers used in various devices such as radios, televisions, telephones, headphones, computers, public address systems, and musical instruments.

Sound is a pervasive part of our environment produced by diverse sources. A person who is blind but can hear is more often attuned to the environment than a person who is deaf but can see as a large portion of our sensory stimuli comes from our acoustic environment.

However, high sound levels and poor acoustic qualities can be undesirable and disruptive. Disturbing sounds are mainly due to:

- The noise produced by machinery, ventilation and air ducts, vehicles, voices, loud music systems, and explosions
- Excessive reverberation and resonance in enclosed spaces.

➢ *Excessive Sound Levels and Poor Acoustics can Result In:*

- temporary hearing loss or permanent deafness
- difficulty in conversation
- sleep disturbance
- increase in stress, promoting hypertension and cardiovascular illnesses

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/IJISRT24AUG1664

- decreased worker productivity and increased liability for error
- interference with the studio recording and broadcasting of music and speech

➢ *Excessive Reverberation and Standing Wave Resonance in a Room or Other Enclosure can Result in:*

- less intelligible music and speech
- reduced quality of audio recording, broadcasting, and reception
- low-fidelity sound reproduction in loudspeakers.
  (Yarwood, 1953, p. 289; Diamant, 1986, p. 275; Nathanson & Berg, 2024)

➢ *To Reduce Excessive Sound Levels and Improve Acoustic Qualities, the Following Measures can be Adopted:*

- Use sound absorption materials to line the walls of a room or enclosure to reduce reverberation and resonance and consequently, sound level in the room (unless an anechoic room is being built, reverberation should not be eliminated otherwise the room would sound 'dead')
- Use sound insulation materials in the walls between adjoining enclosures to minimize sound transmission
- Fill an enclosure with sound absorption or sound insulation materials to attenuate resonance and high sound levels.

This research focuses on (3) to determine the sound reduction and sound absorption properties of the materials used to fill an enclosed box and pipe. It is necessary to briefly distinguish three terms:

- Sound absorption - applied to a surface or material lining the walls of an enclosure that absorbs the sound energy and does not reflect it (Souza, 2021). Hence, we speak of the sound absorption properties of a *surface*.
- Sound insulation - applied to a barrier or wall, reducing the transmission of sound from one location to another due to the impedance mismatch between air and the material (Diamant, 1986). We speak of the sound insulation properties of a *barrier*.
- Sound reduction - applied to a filling material's acoustic reduction or attenuation properties that lower the sound level it passes through the material (Mackenzie, 1964).

All materials, whether they are surfaces, barriers, or fillers, exhibit varying degrees of sound absorption, reflection, and transmission properties depending on their nature and placement. For example, concrete is a poor absorber, a good reflector, and a poor transmitter, making it a good sound insulator or sound barrier. Silk cotton, on the other hand, is a good absorber, a poor reflector, and a moderate transmitter, making it useful as a surface sound absorber or a box-filling material. Thus, concrete is a better sound insulator than silk cotton, but silk cotton is a better sound absorber than concrete. However, both materials can be referred to as sound reducers.

A. Objectives of the Research

- Assess the sound absorption and sound reduction properties of the materials: silk cotton, cotton wool, chipped foam, and open-cell polyurethane foam (block foam).
- Explore how variations in sound frequency and material density affect the sound absorption and reduction properties of these materials.
- Show how sound absorbers can be used to attenuate excessive sound levels caused by sound transmission and resonance.
- Determine which materials possess the best sound absorption properties for use in sound reduction and sound insulation applications.

B. Scope of Research

This research primarily investigates the sound reduction (SR) and transmission loss (TL) properties of various sample materials. The methodology involves:

- Determining the baseline acoustic properties of an empty enclosure to establish a control for subsequent experiments.
- Measuring the changes in acoustic properties when the same enclosure is filled with different materials, including adjustments in the density packing of these materials.
- While the primary focus is on SR and TL, efforts are also made to estimate the sound absorption coefficients of the materials used. It should be noted that these values are approximate and intended to supplement the primary SR and TL findings.

The approach aims to evaluate how effectively these materials can attenuate sound, providing a comparative analysis under varied conditions to guide material selection in sound-attenuation applications.

C. Limitations of the Research

- No enclosure, box, or tube is perfectly rigid, which may lead to inevitable sound losses through the enclosure's sides. This compromises the perfect reflection needed for sound to remain entirely within the enclosure, thus reducing the accuracy of the measurements.
- The fibrous materials, especially at very low-density packings, may settle at the bottom of the enclosure during the tests. This settling could result in uneven density distributions, thereby affecting the sound level measurements within the enclosure.
- Due to the lack of more accurate and precise instruments, it was not possible to determine the speed of propagation of sound in the materials to determine how density packing affects this speed. Thus, the materials' acoustic

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/IJISRT24AUG1664

impedance (z) could not be found since $z = \rho v$, where ρ = material density and v = speed of sound in the material.

D. Background

As an educator, the researcher has observed that many schools are noisy and have poor acoustic environments. According to the engineers of an acoustics research laboratory:

"*Controlling a reverberant sound field with sound absorbing materials is often the most practical method of noise control for institutional, industrial, exposition and correctional facilities. Experiments in psychoacoustics and speech intelligibility have shown that long reverberation times make the understanding of speech difficult or impossible. Also as the reverberation time is shortened, the background noise level is reduced as speech intelligibility improves. Improvement in communications has long been recognized as an important feature for most public, commercial and industrial spaces. A good acoustical environment in school classrooms and child care centers is now also recognized as a critical factor in the development of early language skills in very young children*" (IAC Sound Absorption Systems, 2002).

With regards to music, Khroodsma (2005) wrote, *"[H]uman music can improve mood and test scores and reduce blood pressure and pain ... premature infants in intensive care units do better with the right music*" (p. 275).

Therefore, the need for an appropriate acoustic environment in education and child-care settings is evident. Through the use of adequate sound absorbers and sound insulators and better design of classrooms, it is possible to improve their acoustic environment.

Sound-reducing materials also find numerous applications in recording and broadcasting studios, auditoriums, offices, churches, homes, devices such as earplugs, ear defenders/mufflers, sound-reducing helmets, household appliances, and industrial machinery, and generally in situations where noise pollution must be minimised.

In the case of loudspeakers, standing wave resonance due to the dimensions of the box can be problematic as this can affect the quality of sound reproduction. Sound absorbers lining the internal walls or filling the cavity of loudspeaker boxes help dampen standing waves in the boxes and minimize or even eliminate resonance in them, resulting in loudspeakers that have good high-fidelity sound reproduction.

Therefore, to reduce high noise levels, optimize reverberation, and minimize standing wave resonance various sound absorption materials can be used. Very fine fibrous materials make good sound absorbers, for example, silk cotton would be expected to have excellent sound absorption properties. The main characteristic of a good acoustic absorber is that it should provide maximum absorption with minimum thickness. It should also be lightweight, non-toxic, decay-resistant, and humidity-resistant. Silk cotton has these characteristics.

E. Silk Cotton

The silk cotton tree *(Ceiba pentendra)*, also known as the kapok tree, is a deciduous tree native to tropical America but has spread to other tropical regions around the world, notably Asia, Indonesia, and the Pacific Islands. Under ideal growth conditions, as in the Amazon rainforest, this tree can grow more than 200 feet tall with a conspicuously buttressed trunk and widely spreading branches. The fruits are oblong, smooth, and light green pods. While still on the tree, the pods burst open after the leaves have fallen, exposing the cotton-like substance, kapok.

Kapok is lustrous, yellowish brown, fluffy, and very lightweight. The fibres are 0.8 to 3.2 cm long, averaging 1.8 cm, with diameters of 30 to 36 μm. They are moisture- and decay-resistant, quick-drying, resilient, and buoyant and are used in life preservers and other water-safety equipment, as stuffing for pillows, mattresses, and upholstery, as a substitute for absorbent cotton in surgery, and as a sound and heat insulation material. It is highly flammable and cannot be spun into yarn or textiles because it is too brittle and inelastic. Its use has decreased with the development of foam rubber, plastics, and synthetic fibres. (Encyclopedia Britannica, 2024; Jessurun, 2024)

In Guyana, the silk cotton tree is found widely distributed along the coast, with a well-known specimen in the middle of the main road at Mahaicony Village, one in the Beharry compound University Road, Turkeyen, and some growing along the Linden-Soesdyke Highway, to name a few locations (Chin, 2016). The researcher obtained silk cotton from a tree growing west of the University of Guyana's main entrance at Turkeyen.

II. LITERATURE REVIEW: THEORY AND PHYSICAL PRINCIPLES INVOLVED

The first person to do thorough scientific research on sound absorption was the American physicist Wallace Clement Sabine (1868-1919) of Harvard University. His investigations dealt with using sound absorbers to improve the acoustic properties of large rooms such as concert halls and auditoriums. Sabine first measured the reverberation time of an empty hall. He then placed sound absorbers such as cushions on chairs to observe their effect on reverberation and found that this caused a decrease in reverberation time. He found that the sound absorption coefficient is not a specific property of a material but it depends on material thickness, sound frequency, and method of mounting the material (Yarwood, 1953, pp 271-275; Marsh, 2006).

His work is described thus: *"When Harvard opened the Fogg Art Museum in 1895, its auditorium revealed seriously defective acoustics caused by excessive reverberation. Sabine was asked to find a remedy. His discovery that the*

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/IJISRT24AUG1664

product of the reverberation time multiplied by the total absorptivity of the room is proportional to the volume of the room is known as Sabine's law, and a unit of sound-absorbing power, the sabin, was named after him. The first building designed in accordance with principles laid down by Sabine was the Boston Symphony Hall, which opened in 1900 and proved a great acoustical success" (Encyclopedia Britannica, 2024).

A. *Sound Attenuation Problems*

The control of sound in an enclosure may be classified according to the origin of the sound: sound originating inside the enclosure and sound originating outside the enclosure.

In the first case, the inner walls of the enclosure may be lined with sound absorbers to reduce excessive internal sound levels and eliminate undesirable frequencies due to reverberation and resonance. For a large enclosure such as a room, both reverberation and resonance play an important part in determining the room's acoustic qualities. A small enclosure, such as a loudspeaker box, produces resonance mainly due to the box's internal dimensions, and this can be dampened using a sound absorption lining or filling.

In the second case, the problem is to prevent outside sounds from entering the enclosure, which may be an office or home located near an external noise source. This can be done by placing a sound-insulating material such as a heavy concrete wall or a lighter double concrete wall around the enclosure. Trees with dense foliage planted between the room and the noise source also help to reduce sound entering the room by a combination of absorption, reflection, and scattering.

Rooms such as recording and broadcasting studios, auditoriums, and anechoic chambers have to deal with both external and internal noise sources and so have to use an appropriate combination of sound absorbers and sound insulators. In situations where it is impossible to reduce very high sound levels, such as in a noisy factory, machinery, or vehicles, persons have to wear ear defenders or sound-reducing helmets, which are made of composite materials with good absorption and insulation properties to reduce sound intensities.

B. *Sound Intensity and the Sound Level Meter*

Sound intensity is defined as the sound energy per unit time passing through a unit area perpendicular to the direction of travel of the sound waves. It is therefore proportional to sound energy, and its units are W/m^2. The sound level meter does not directly measure sound intensity; rather, it measures sound pressure level in decibels (dB) so that the number of decibels, *n,* is given by

$$n(\text{dB}) = 20\log\left(\frac{P}{P_o}\right) \qquad (1)$$

But since sound intensity is proportional to the square of the sound pressure, the equation can be rewritten as

$$n(\text{dB}) = 10\log\left(\frac{I}{I_o}\right) \qquad (2)$$

where P and I are the sound pressure and sound intensity, respectively being measured, and P_o and I_o refer to the reference standard levels of pressure and intensity, respectively. By convention, $I_o = 10^{-12}$ W/m^2, the threshold level of hearing, which has a 0 dB value. Therefore, the sound meter gives an indirect but exact measurement of sound intensity.

C. *Definitions of Sound Attenuation Coefficients*

Arising from the two-fold classification of sound attenuation problems, there are two basic sound attenuation coefficients:

(1) The absorption coefficient (*s*) of a surface material is defined as the ratio of the absorbed energy to the incident energy (Ford, 1970, p. 113; Yarwood, 1953, p. 274; Diehl, 1973, p. 58; Pierce, 1994, p. 109). For example, Pierce (1994): "On a time-averaged basis, the acoustic energy incident equals the acoustic energy reflected plus the acoustic energy absorbed. The fraction absorbed is the *absorption coefficient*…"

Thus,

$$s = \frac{I_a}{I_i}\text{, where } I_a = \text{absorbed energy and } I_i = \text{incident energy} \quad (3)$$

$$\text{Since } I_i = I_a + I_r\text{, where } I_r = \text{reflected energy} \qquad (4)$$

$$\text{Hence} \qquad s = \frac{I_i - I_r}{I_i} = 1 - \frac{I_r}{I_i} = 1 - r \qquad (5)$$

$$\text{where reflection coefficient,} \qquad r = \frac{I_r}{I_i}.$$

This formula is used when the reflected and incident sound energy can be measured, as done in the standing wave tube technique. A sound meter equipped with a microphone probe measures the sound pressure at maximum and minimum pressure nodes at various points inside the tube, with the sample material at one end and a loudspeaker at the other end. Alternatively, two sound meters can be used to measure maximum and minimum pressure nodes at different points. It can be shown that the sound absorption coefficient is given by

$$s = 1 - \left(\frac{P_1 - P_2}{P_1 + P_2}\right)^2 \qquad (6)$$

Where P_1 = sound pressure at a maximum node and P_2 = sound pressure at a minimum node (Mackenzie, 1964, p. 212).

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/IJISRT24AUG1664

Sound absorption coefficients range from s = 1 for an open window, which is considered to be an ideal absorber (since it allows sound to escape from the room with no reflection, r = 0) for most frequencies, to s = 0.01 at 125 Hz for concrete, a poor absorber. At 4000 Hz, s = 0.03 for concrete; hence, concrete has a reflection coefficient ranging from 0.99 to 0.97, indicating that it is a good reflector and, consequently, a good insulator or sound barrier. The absorption coefficient of a material increases with incident sound frequency and material thickness.

(2) The sound transmission coefficient (t) is defined as the ratio of the sound energy transmitted, I_t, through a barrier material to the incident sound energy, I_i (Randall, 1951, p. 301; Yarwood, 1953, p. 294; Mackenzie, 1964, p. 163). Thus,

$$t = \frac{I_t}{I_i} \tag{7}$$

Like the absorption coefficient, the transmission coefficient is frequency-dependent and thickness-dependent. It ranges from t = 1 for a light curtain at low frequencies to t = 10^{-8} for a heavy wall at high frequencies. It is more convenient to use a logarithmic scale instead of the direct energy ratio for t. So, the **sound reduction factor** (SR), or **transmission loss** (TL), in decibels, is used. This is defined as

$$TL = 10 \log\left(\frac{1}{t}\right) \tag{8}$$

Therefore, $$TL = 10 \log\left(\frac{I_i}{I_t}\right) \tag{9}$$

"Transmission loss is a measure of the effectiveness of a wall, floor, door, or other barrier in restricting the passage of sound. The transmission loss varies with frequency and the loss is usually greater with higher frequencies… The higher the transmission loss of a wall the better it functions as a barrier to the passage of unwanted noise" (Norlite Agg, 2002).

In this method, the sample material is placed in a rigid enclosure with a loudspeaker and a sound meter on one side of the sample and another sound meter on the other side. The first sound meter measures the incident sound intensity and the second sound meter measures the transmitted sound intensity. From the definition of the decibel intensity,

$$I_t = I_o 10^{\frac{I_t(dB)}{10}} \text{ and } I_i = I_o 10^{\frac{I_i(dB)}{10}}$$

Therefore, $$t = \frac{10^{\frac{I_t(dB)}{10}}}{10^{\frac{I_i(dB)}{10}}} = 10^{\frac{I_t(dB) - I_i(dB)}{10}} \tag{10}$$

Also, $$TL = I_i\,(dB) - I_t\,(dB) \tag{11}$$

And $$t = 10^{-\frac{TL}{10}} \tag{12}$$

These last formulas are very useful in getting immediate values for transmission loss and transmission coefficient as obtained by the I_i (dB) and I_t (dB) measurements from the sound meters. It does not matter where the sound meters are placed since the energy on each side of the sample is distributed almost uniformly. (Randall, 1951, p. 301). Figure 1 shows the apparatus arrangement.

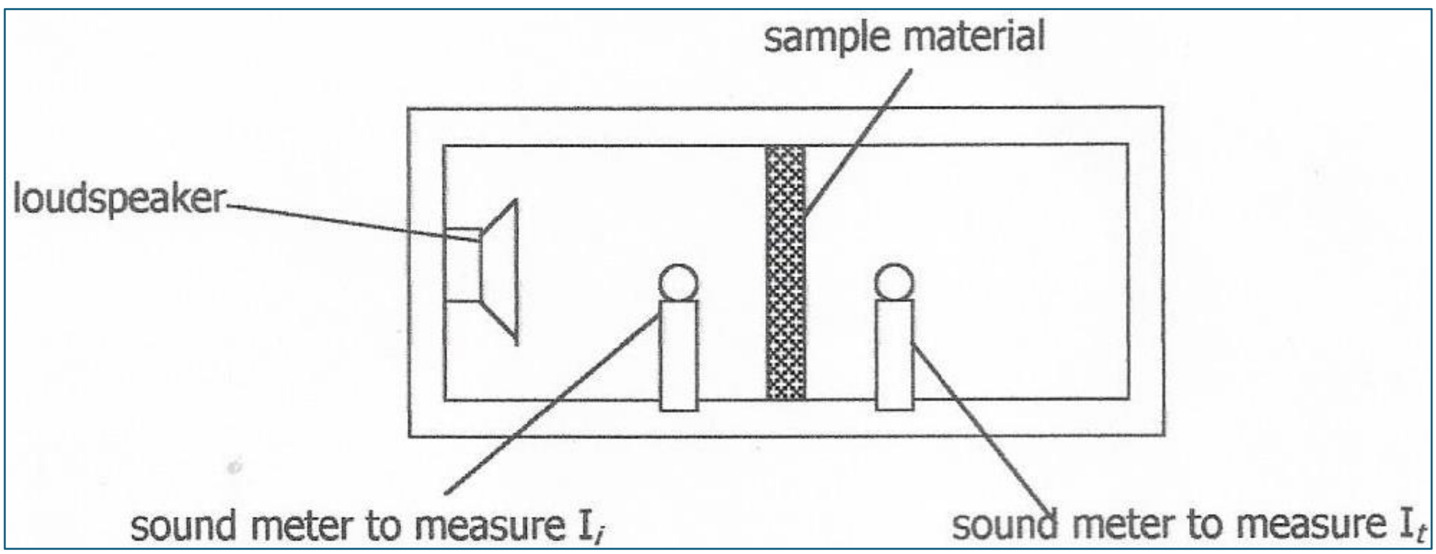

Fig 1: Apparatus Arrangement to Measure Transmission Loss

A modification of this method was used in this research to determine the sound reduction properties of the sample materials. This modification was due to the loose nature of the materials and the availability of only one sound meter. This entailed placing the sample material in an enclosure with a loudspeaker at one end and a sound meter at the other end. The

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/IJISRT24AUG1664

incident intensity is measured when the enclosure is empty, and then the transmitted intensity is measured with the sample material filling the enclosure. In this way, *TL* can quickly be determined. This modification is valid since, in both cases, when the enclosure is empty or filled, the energy is distributed almost uniformly. Provided the enclosure is sufficiently rigid to minimise sound losses through the sides of the enclosure, it will give reasonably accurate results. Figure 2 shows the enclosure arrangement used in the investigation.

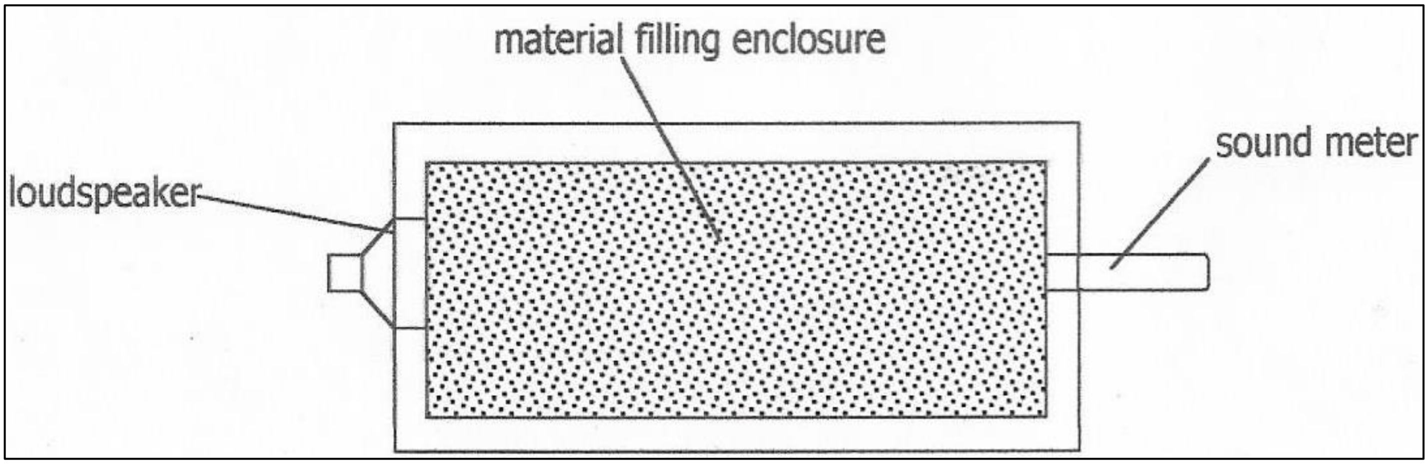

Fig 2: Enclosure Arrangement to Measure Transmission Loss

Hereafter, the term sound reduction factor (SR) will be used in place of transmission loss to indicate the emphasis of the research to determine mainly the general sound attenuation properties of the selected materials. Thus

$$SR = I_i\,(dB) - I_t\,(dB) \tag{13}$$

$$t = 10^{-\frac{SR}{10}} \tag{14}$$

D. *The Absorption, Reflection, and Transmission of Sound*

All materials – surfaces, barriers, and fillers – will absorb, reflect, and transmit sound depending on their nature, placement, and frequency of the incident sound. The classification of a material as an absorber or an insulator depends on the degree of absorption, reflection, and transmission it displays, as shown in Table 1.

Table 1: Acoustic Characteristics of an Absorber and an Insulator Over the Audio-Frequency Range

Material	**Absorption**	**Reflection**	**Transmission**
Insulator Absorber	Poor Good	Good Poor	Low High

Good sound insulators are generally non-porous and dense solids such as concrete, metals, glass, brick, and hardwood. Their insulation properties increase with thickness or by using double walls with an air cavity in between.

Because sound insulators are non-porous, they do not have interconnected air cavities through which sound can be propagated by the vibration of air particles. Instead, sound has to propagate by vibrations of the particles of the materials and therefore, some energy is lost to these particles, which are elastically coupled to one another by absorption. However, internal absorption is only a secondary factor in determining sound insulation properties. The main factor that results in good sound insulation is the impedance mismatch between the surrounding air and the solid, as noted by Berg (2024), *"Mediums in which the speed of sound is different generally have differing acoustic impedances, so that, when a sound wave strikes an interface between the two, it encounters an impedance mismatch. As a result, some of the wave reflects while some is transmitted into the second medium."*

In a similar vein, Randall (1951) stated, *"[I]t is the impedance "mismatch" that accomplishes the desired end...since such an abrupt change in acoustic impedance at the boundary will turn back much of the energy…"* (p. 302).

Air and concrete have acoustic impedances of 415 N m^{-3} s and 9.84 × 10^{6} N m^{-3} s, respectively. The impedance mismatch between these two substances results in much of the sound energy being reflected by concrete and very little being transmitted. Concrete is, therefore, a good sound insulator because of its high reflection and low transmission properties. Other sound insulators have even higher impedances than concrete. (Diamant, 1986, p. 288; Ford, 1970, p. 145). Generally, good insulators are not good absorbers because they are good reflectors.

In contrast to sound insulators, good sound absorbers are generally porous, loose, and light materials such as wool, cotton, foam, asbestos, felt, cloth, cork, and light wood. Depending on their usage, sound absorbers may be

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/IJISRT24AUG1664

flexible or rigid. Like sound insulation, absorption properties generally increase with absorber thickness and sound frequency.

"In the case of porous materials, the energy is dissipated through friction between the material and the moving air within the pores. With soft compressible materials, the energy may be absorbed by internal friction due to the compression, while with board-like materials capable of vibration, it may be dissipated by internal friction arising from the bending of the material" (Yarwood, 1953, p. 280).

"With porous materials such as felt, glass wool, and acoustic plaster, the material contains air in a network of interconnected cavities. When the sound waves set up air vibrations, heat is generated due to friction within the material and the sound wave loses energy (Mackenzie, 1964, p. 151).

The porous nature of sound absorbers is due to the tiny, interconnected air cavities or cells in the material, which allow the vibration of air particles to enter the material. In the material, the sound waves encounter internal friction with the porous material, and so some of the wave energy is converted into heat and absorbed. Also, the sound waves cause the fibres or other elastic absorbent structure of the material to vibrate, dissipating the sound energy in the material as mechanical energy and then heat, resulting in more absorption. Since the sound energy is very small, the amount of heat produced is also minimal.

Materials that have high absorption coefficients usually have soft, porous surfaces. When the sound waves strike these surfaces, air flows in and out of the minute pores in the material because of the pressure changes produced by the sound. Frictional forces convert the sound energy into heat, although the actual amount of energy is small" (Diehl, 1973, p. 138).

"Porous materials supply such attenuation through viscosity and heat conduction effects along the minute ducts. The fibers of such materials themselves move in the presence of a wave, and the resultant internal friction also increases attenuation" (Randall, 1951, p.199).

Sound energy is absorbed when it is converted to heat energy due to the internal viscosity of the material and vibrations of its absorbent structure. Sound absorption of materials is, therefore, due to viscous and vibrational absorption. However, despite the absorption, an appreciable amount of sound energy will be transmitted through the material and exit on the other side. For this reason, good absorbers are generally not good insulators because they are good transmitters.

Consequently, sound control measures often use both sound absorbers and insulators to combine their respective properties to soundproof a room from external sounds and to improve the acoustic qualities of an enclosure concerning internal sounds.

E. Relationships among Absorption, Reflection, and Transmission Coefficients

The definition of the sound absorption coefficient, *s*, as the ratio of absorbed energy, I_a, to incident energy, I_i, assumes that the absorbed energy is all the energy that is *not* reflected, that is, it lumps the absorbed energy that is converted to heat in the material with the transmitted energy that exits the material (Acoustiblok, 2023; Souza, 2021). This assumption is valid for a surface sound absorber lining the internal walls of a recording studio where the idea is to remove excess reverberation and resonance so that whether sound energy is absorbed by the material or transmitted through the material the intention is to remove the excess sound energy from the room. Figure 3 shows the difference between the assumed absorbed energy, I_a, and the absorbed energy converted to heat in the material, I_h.

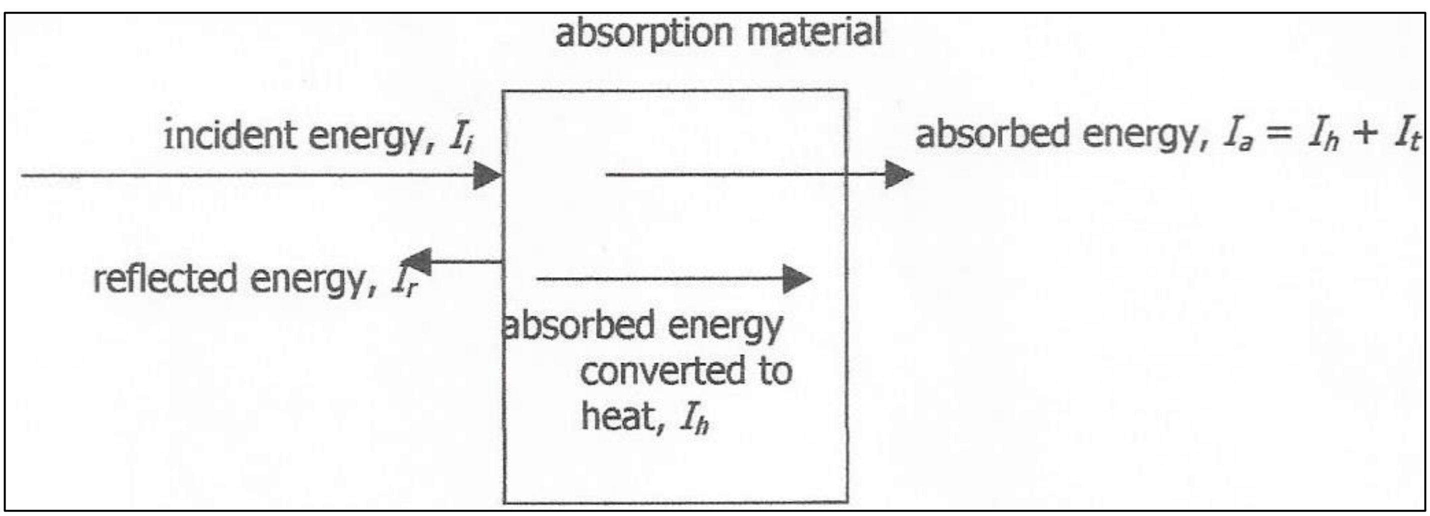

Fig 3: Difference between I_a and I_h

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/IJISRT24AUG1664

This assumption is necessary since it is easier to measure I_i and I_r, than I_a and I_h, and then find the absorption coefficient using Equation 5.

No such assumption is necessary for the transmission coefficient, *t*, since it is relatively easy to measure I_i and I_t. Figure 4 shows the relationship between the four intensities for a sound insulator.

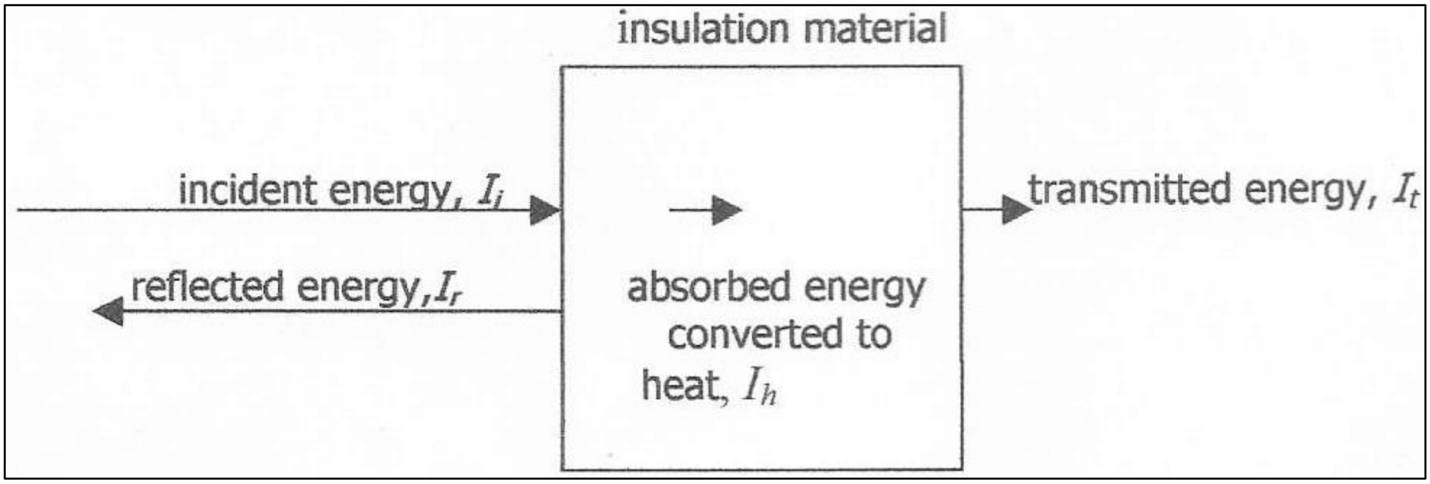

Fig 4: Relationships among the Four Intensities for a Sound Insulator

Therefore, $$I_i = I_r + I_h + I_t \tag{15}$$

Hence, $$1 = \frac{I_r + I_h + I_t}{I_i}$$

Giving, $$1 = r + h + t \tag{16}$$

Where $h = \frac{I_h}{I_i}$.

This relation would also be valid for a sound absorber since it will exhibit some degree of absorption, reflection, and transmission properties. In the case of an enclosure filled with porous material, for example, silk cotton, there would be low reflection, high absorption, and moderate transmission. This relation can be used to give an approximate determination of the sound absorption properties of the sample materials tested in this investigation by assuming negligible reflection, $r \to 0$, so that Equation 16 becomes

$$1 \approx h + t \tag{17}$$

This assumption would only be approximately valid for materials with high sound absorption coefficient, s, and low reflection coefficient, r, for example, loose and porous materials such as silk cotton and cotton wool. It would be invalid for materials with low absorption and high reflection coefficients, such as concrete, because r would be large enough to be significant in Equation 16. Note that h is the fraction of absorbed sound energy converted to heat in the material. This would give an approximate idea of the sound absorption properties of the tested materials.

F. *Resonance in a Pipe Closed at Both Ends*

A loudspeaker fixed to one end of a pipe produces progressive longitudinal sound waves which are reflected when they are incident on the other end of the pipe. The incident and reflected waves interfere constructively and destructively with each other, producing varying sound levels as the sound frequency is increased. Maximum constructive interference occurs when the loudspeaker frequency, called the driving frequency, equals the natural frequency of the pipe, producing a large response called the condition of resonance (Morse & Ingard, 1986, p. 47). When this happens, a reflected compression arrives at the loudspeaker at the precise moment when the loudspeaker is also producing a compression, and a compression is incident on the other end of the pipe precisely when a compression n is reflected. At other points in the pipe incident and reflected rarefactions also combine. The incident and reflected compressions and rarefactions reinforce each other, producing maximum constructive interference, so stationary waves are set up in the pipe. At resonance, the sound level in the pipe rises sharply, and a very loud sound is heard due to the standing waves reinforcing one another.

The natural resonance frequencies of the pipe depend on the effective length of the pipe between the closed ends and the speed of sound in air. These resonance frequencies can be determined from the stationary wave equation for displacement, *y*, of air particles:

$$y = 2y_o \sin\left(\frac{n\pi}{l}x\right) \cos\left(\frac{n\pi v}{l}t + \alpha\right) \tag{18}$$

(Randall, 1951, p. 173)

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/IJISRT24AUG1664

where y_o = maximum displacement; n = 1, 2, 3...(harmonic numbers) ; l = length of pipe; x = distance along pipe from one end; v = speed of sound in air; t = time; α = phase angle.

At the ends of the pipe, $x = 0$ and $x = l$, therefore $y = 0$, showing that the ends of the pipe are displacement *nodes*. Considering the cosine part of the equation, it is known that

$$\omega = 2\pi f = \frac{n\pi v}{l} \tag{19}$$

Therefore,

$$f = \frac{nv}{2l} \tag{20}$$

From the sine part of Equation 18, the wave number k is given by:

$$k = \frac{2\pi}{\lambda} = \frac{n\pi}{l} \tag{21}$$

Therefore,

$$\lambda = \frac{2l}{n} \tag{22}$$

From Equations 20 and 22, the resonance frequencies and wavelengths of the pipe can be determined. The fundamental frequency or first harmonic corresponds to $n = 1$, while the second and third harmonics correspond to $n = 2$ and $n = 3$, respectively. Table 2 shows the first five harmonics, resonance frequencies, and wavelengths for sound produced in the pipe.

Table 2: Harmonics and Resonance Frequencies and Wavelengths in a Closed Pipe

Harmonic (n)	Frequency (f)	Wavelength (λ)
1	v/2l	2l
2	v/l	l
3	3v/2l	2l/3
4	2v/l	l/2
5	5v/2l	2l/5

A pipe closed at both ends is an example of a harmonic resonator because its other harmonics are multiples of the 1st harmonic (fundamental), as seen in Equation 20 and Table 2. Also, the length, l, of the pipe is integral multiples of half-wavelengths at resonance:

$$l = \frac{n\lambda}{2} \tag{23}$$

The sound pressure, p, of the waves is given by the partial differential equation:

$$p = -k\frac{\partial y}{\partial x} \tag{24}$$

(Halliday, et al., 1993, p. 508)

where k = a constant and y = displacement of air particles (Equation 18).

Differentiating Equation 18 with respect to x and putting it into Equation 24 gives the acoustic pressure in the pipe as a function of x and t.

$$p = -2y_o\, k\frac{n\pi}{l}\cos\left(\frac{n\pi}{l}x\right)\cos\left(\frac{n\pi v}{l}t + \alpha\right) \tag{25}$$

Hence, at $x = 0$ and $x = l$, $p = -2y_o\, k\frac{n\pi}{l}\cos\left(\frac{n\pi v}{l}t + \alpha\right)$ that is, a maximum so that the ends of the pipe are pressure *antinodes*. Therefore, the endpoints of the pipe can be called either displacement nodes or pressure antinodes. (Randall, 1951, p. 174).

In between resonances, the sound levels in the pipe drop to lower values than at resonance, as described by The Physics Classroom, (2022): *"At any frequency other than a harmonic frequency, the interference of reflected and incident waves leads to a resulting disturbance of the medium that is irregular and non-repeating."* This happens because the waves interfere more destructively and less constructively as Equation 23 no longer applies as the effective length of the pipe is not integral multiples of half-wavelengths of nonharmonic frequencies.

G. Resonance in a closed rectangular box

Resonance in the box is produced in the same manner as in the pipe; however, whereas the pipe has one mode of vibration along its cylindrical axis, the box has three vibrational modes due to its length, breadth, and height dimensions.

Mackenzie (1964) noted: *"[A] rectangular room can be regarded acoustically as being the same as a closed pipe. The room will resonate if its length is half the wavelength for some frequency present in the sound source. Unlike the pipe, a room can obviously resonate in its other dimensions, behaving like a three-dimensional resonating box. The air in the room can vibrate and resonate in a great many different directions. Normally these are called the 'modes' of a room. First of all, there are the axial modes, the resonances due to each of the axes of the room- length, width, and height. Then there are modes that use two of the axes, for example, the length and the width; these are called the tangential modes. Finally, there are those which use all three dimensions, the so-called oblique modes. All these types will, like the air column, support a fundamental and its harmonics, the lowest fundamental being due to the longest axial dimension"* (pp. 148-149).

Therefore, the axial modes are due to resonances along one of the axes: length, width, or height; the tangential modes are due to resonances along two axes: length and width, length and height, or width and height; and the oblique modes are due to resonances along all three axes. The resonances that occur

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/IJISRT24AUG1664

in a rectangular box are more complex than those occurring in a closed pipe.

Berg, (2024) described the resonances thus: *"An air cavity in the shape of a rectangular box has a sequence of nonharmonic resonances. In such a case, the walls are nodal points, and there are standing waves between two parallel walls and mixed standing waves involving several walls."*

Figures 5, 6, and 7 below show the three types of vibrational modes.

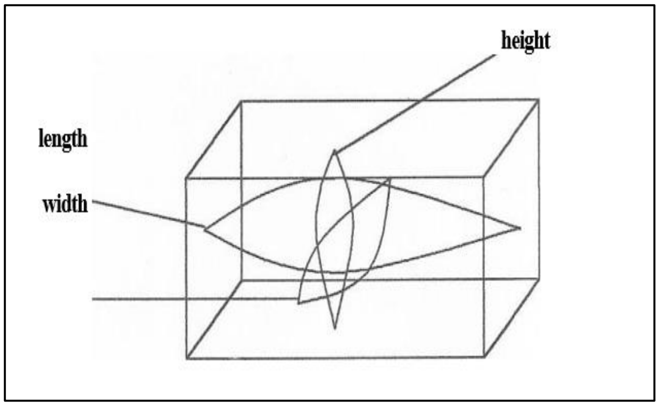

Fig 5: Axial Modes using One of the Axes

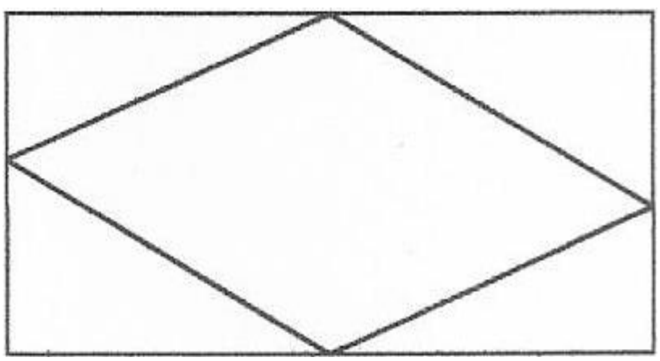

Fig 6: Tangential Modes using Two axes, e.g. Length and Width

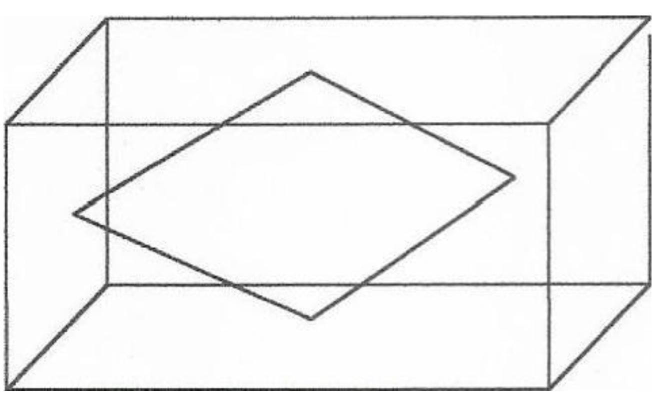

Fig 7: Oblique Modes using all Three Axes

Taking the general case of the oblique modes (Figure 7) where the box resonates using all three axes, the general wave vector equation is given by

$$k^2 = k_x^2 + k_y^2 + k_z^2 \tag{26}$$

where x, y, and z are length, breadth, and height respectively. Applying Equations 21 and 22 to Equation 26 gives:

$$\frac{4\pi^2}{\lambda^2} = \frac{4\pi^2}{\lambda_x^2} + \frac{4\pi^2}{\lambda_y^2} + \frac{4\pi^2}{\lambda_z^2} \tag{27}$$

$$\Rightarrow \quad \frac{1}{\lambda^2} = \frac{1}{\lambda_x^2} + \frac{1}{\lambda_y^2} + \frac{1}{\lambda_z^2} \tag{28}$$

$$\frac{f^2}{v^2} = \frac{n_x^2}{4x^2} + \frac{n_y^2}{4y^2} + \frac{n_z^2}{4z^2} \tag{29}$$

$$\Rightarrow \quad f = \frac{v}{2}\sqrt{\left(\frac{n_x}{x}\right)^2 + \left(\frac{n_y}{y}\right)^2 + \left(\frac{n_z}{z}\right)^2} \tag{30}$$

Equation (30) is the general formula for the resonance frequencies of a rectangular enclosure, room, or box, where n_x, n_y and n_z, are the mode numbers and have integral values. Since the speed of sound, v, in air, and the dimensions of the box are known, the various resonance frequencies can be readily calculated for different combinations of mode numbers. For example, when $n_y = n_z = 0$, and $n_x = 1$, the resonance frequency is

$$f = \frac{v}{2x} \tag{31}$$

This is simply Equation 20, where $n = 1$ and $l = x = \frac{1}{2}\lambda$,and so it gives the fundamental frequency of the box along the length axis. For the fundamental in the length axis, the mode numbers are written x: y: z = 1: 0: 0.

"The second harmonic for the length is the 2: 0: 0 mode; the fundamentals for the width and height are the 0: 1: 0 and 0: 0: 1 modes, respectively. The fundamental for the tangential mode using the length and width is denoted by 1: 1: 0, and the fundamental oblique mode is 1: 1: I" (Mackenzie, 1964, p. 150).

If there are two zeroes for the mode numbers, an axial mode is obtained. If there is one zero, then a tangential mode is produced; if there are no zeroes, then an oblique mode is the result. Equation 30 thus gives the resonance frequencies due to the dimensions of the box, and it also shows that the resonances are nonharmonic, that is, they do not occur at regular intervals as in the closed pipe. A closed rectangular enclosure is, therefore, an example of a nonharmonic resonator.

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The resonance frequencies described by Equation 30 are also found in loudspeaker boxes where they must be damped by sound absorption materials to prevent the loudspeaker from producing too many 'booming' sounds at those particular frequencies. The equation also plays an important role in constructing rooms intended for recording, broadcasting, and other acoustic works so that they will have suitable length, breadth, and height. Rooms can be built with oblique walls to prevent this kind of resonance.

Another factor that can add further resonance to an enclosure is the mechanical resonance frequency of a sound producer in the room or box, such as a loudspeaker in its box. Any undesirable resonances can be readily removed using the appropriate sound-reducing materials of proper design and construction, carefully considering the acoustic principles involved in any given situation.

III. DESIGN AND METHODOLOGY OF INVESTIGATION

A. Instrument and Apparatus Used

- Power Amplifier
- Moving Coil Loudspeaker
- Oertling Digital Electronic Balance
- Radio Shack Sound Level Meter (50 dB – 126 dB)
- True RMS AC Millivoltmeter Model ACM-102
- Black Star LDO 100 Low Distortion Sine/Square Oscillator (10 – 100,000 Hz)
- Plyboard Box (internal dimensions: 30.5 cm × 15 cm × 15 cm; volume = 6,862.5cm^3)
- PVC Pipe (internal dimensions: radius = 5.5 cm, length 30.5 cm, volume = 2,897 cm^3)

B. Design of Box and Pipe

The sound box, of internal dimensions 30.5 cm × 15 cm × 15 cm, was constructed from 1.25-cm thick plyboard, as shown in Figure 8.

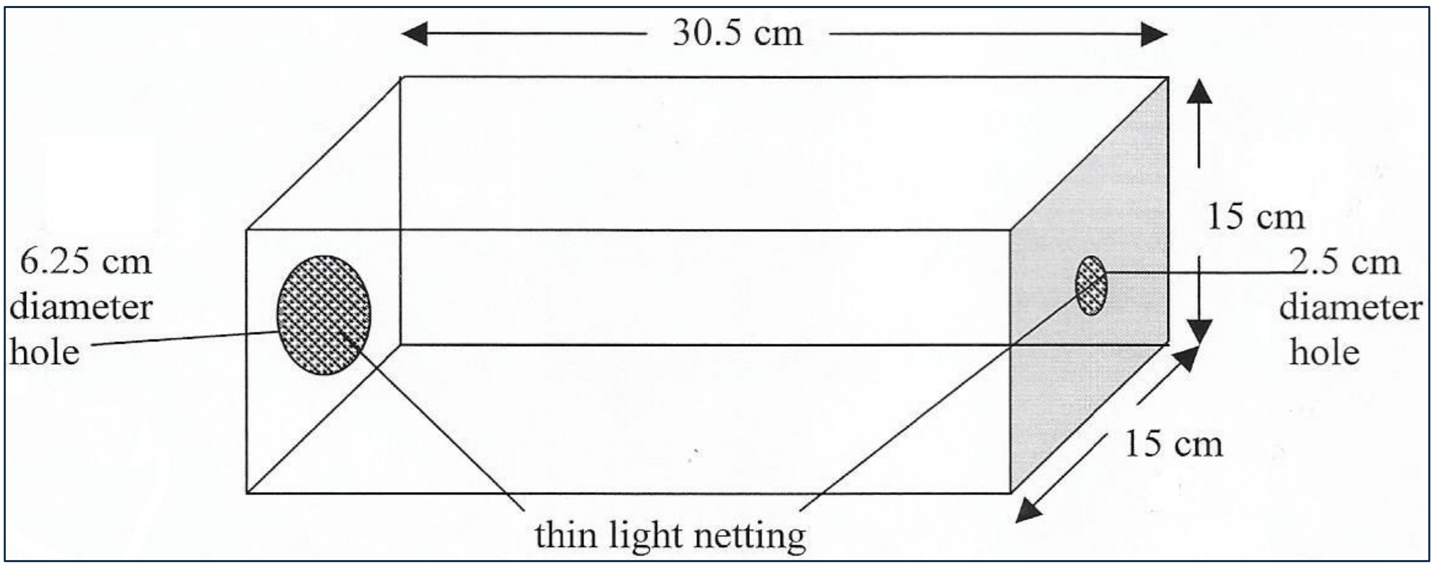

Fig 8: Diagram of Sound Box

The top was covered with a removable lid so that materials could be placed into the box. A thin strip of velvet cloth was affixed to the top edges of the open box to minimise sound losses around the edges when the lid was put on. The lid was then clamped tightly onto the box using screws to prevent vibrations of the lid when the loudspeaker was on. Initially, the lid was held onto the box using rubber bands, but this may have led to unwanted vibrations of the lid against the box, so screws were used to clamp down the lid properly. All previous sound level measurements made were redone and subsequent ones were taken with the clamped lid.

The loudspeaker, which was connected to the amplifier driven by the oscillator, was fitted over the 6.25 cm hole. The sound meter microphone was inserted into the 2.5 cm hole which was lined with a thin velvet cloth to minimize sound losses by providing a snug fit for the microphone. A very thin and light netting was used to cover both holes on the inside of the box to prevent the sound-reducing materials from pressing against the loudspeaker cone and sound meter microphone. The netting was so thin and light that it produced no detectable change in sound levels compared to when there was no netting in place over the holes.

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/IJISRT24AUG1664

The box and sound meter were placed on foam supports to isolate them from the worktable and so minimize the effects of extraneous vibrations originating outside the research laboratory.

The pipe called the sound pipe, was constructed of a 37 cm length PVC pipe with internal dimensions: radius = 5.5 cm and length = 30.5 cm. The ends were closed with 3.25 cm thick wooden caps, one with a 6.25 cm hole for the loudspeaker and the other with a 2.5 cm hole for the sound meter microphone. Figure 9 shows the sound pipe.

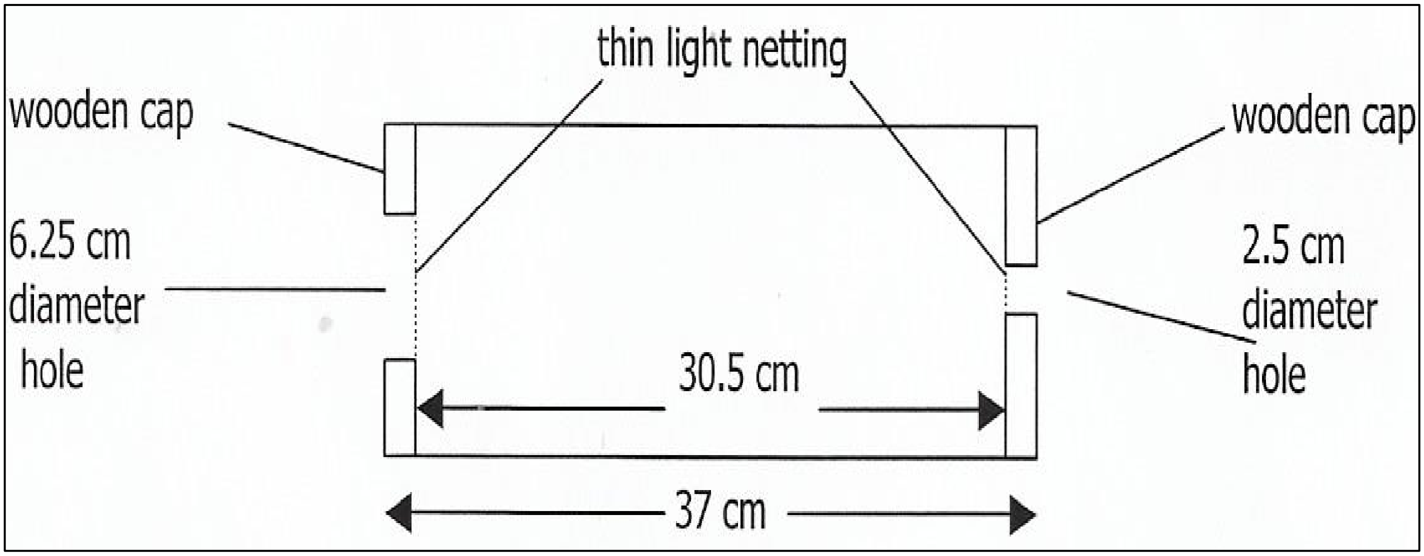

Fig 9: Diagram of Sound Pipe used in the Study

The pipe was set up in the same manner as the loudspeaker. The wooden caps were made to fit snugly into the ends of the pipe. The loudspeaker and cap were removed to place materials into the pipe.

The full laboratory arrangement for measuring sound levels using the box and pipe is shown in Figure 10.

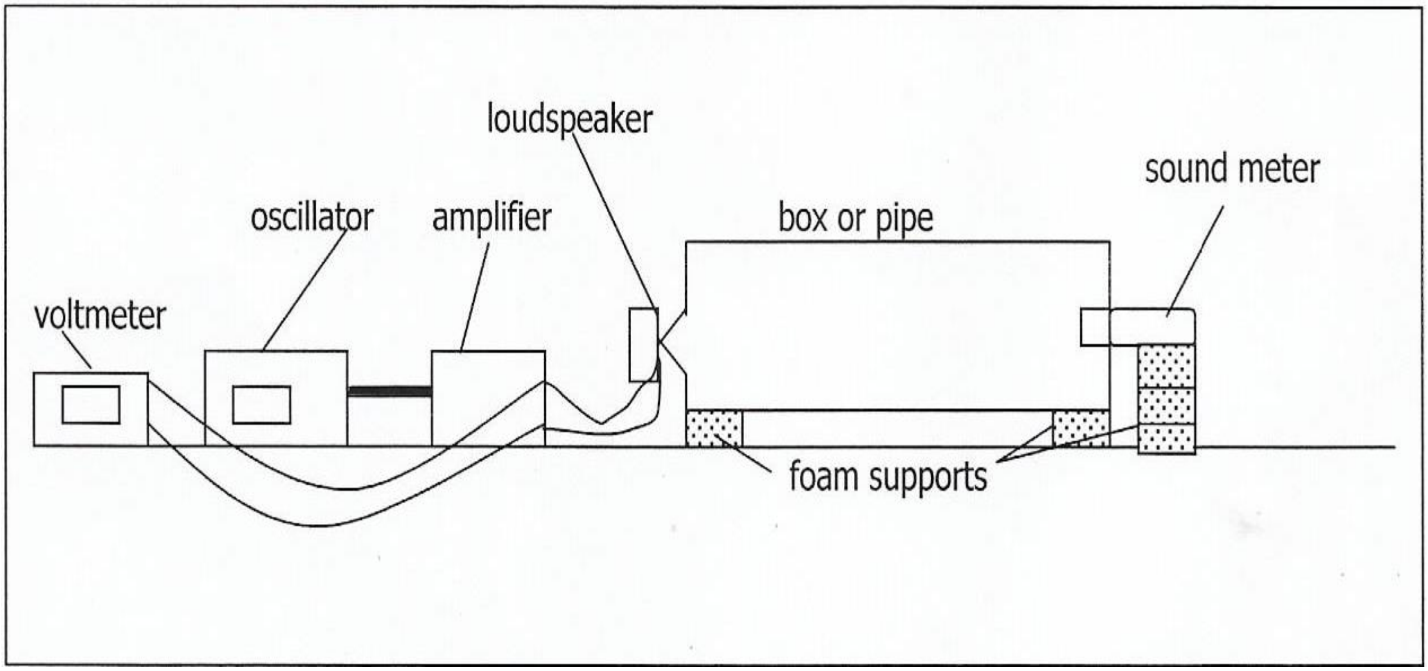

Fig 10: Laboratory Arrangement for Measuring Sound Level

IV. METHODOLOGY

The amplifier output voltage to the loudspeaker was monitored by the AC millivoltmeter and kept constant at 0.34 V. This was necessary to ensure that the power supplied to the loudspeaker was as constant as possible, subject to variations due to the unavoidable rise in impedance of the loudspeaker voice coil as frequency increased.

The acoustic properties of the empty box and pipe were determined by measuring the sound levels in the frequency range 20 Hz to 4000 Hz which is the typical range for human voice and singing and most musical instruments (Blythe, 2017, pp. 377 - 378). Earplugs should be used to protect one's ears as the sound levels would often exceed 80 dB at various audio frequencies.

The box and pipe were filled with the materials at different density packings to investigate (a) the effect of each material and (b) the effect of each material's density packing on sound transmission, absorption, and reduction at the same frequencies recorded for the empty containers.

Because the maximum capacity of the digital electronic balance was 1.5 kg and the box weighed over 2 kg, while the pipe weighed 0.708 kg, different approaches had to be used to find the density packings of materials placed in each one. To find the density packing in the box, the mass of an empty plastic bag was measured, the loose material was weighed in the bag, and then the mass, m, of the material was found. The density packing, p, of the material was calculated using the density formula ρ = m/V, where V = volume of box or pipe. The material was then placed into the box. Silk cotton was an extremely light material to handle and some of its fibres were often lost while placing it into the box. However, the losses were negligible and would not have led to significant errors in density calculations. For the pipe, the material was placed in it, the total mass was measured, and then the mass, m, of the material was found.

Only one density measurement (21.7 mg cm-3) was made for the block foam since it has a rectangular shape (~13 cm × 8 cm × 4 cm), and it would not have been feasible to compress it to greater densities as this would have led to distortions in its rectangular shape. Eighteen blocks of foam plus two smaller ones were placed in the box. However, the block foam was not placed in the pipe as it could not have been accurately cut to the cylindrical shape required for placement in the pipe.

A comparison was made between sound levels when the containers were empty and when they were filled with the materials. Sound levels in the empty containers were taken as incident intensities, Ii , and those in the filled containers were taken as transmitted intensities, It . The sound reduction, SR, and transmission coefficient, t, were calculated using Equations 13 and 14, respectively. The approximate relation Equation 17 was used to calculate the fraction of absorbed sound, h converted into heat by the materials at different frequencies and density packings.

➢ *The Following Graphs were Plotted from the Results Obtained:*

- Frequency versus sound level for the empty and filled containers.
- Frequency versus sound reduction for the different materials.
- Density packing versus sound reduction.
- Frequency versus fraction of absorbed energy converted to heat.
- Density packing versus the fraction of absorbed energy converted to heat.

The results were analysed and compared to determine which materials have good sound reduction properties.

The speed of sound in air, loudspeaker resonance frequency, and relevant physical properties of silk cotton, cotton wool, and foam were determined.

A. *Speed of Sound*

An adaptation of the resonance tube method using a loudspeaker, amplifier, oscillator, and a 0.5 m long glass tube established that the speed of sound in ambient air at 31 °C (T = 304 K) is 348 ms-1. (Tyler, 1981, p. 77). This empirical result is in close agreement with the theoretical value obtained from the formula $v = 331\sqrt{\frac{T}{273}} = 331\sqrt{\frac{304}{273}} = 349 \text{ ms}^{-1}$.

The experimental value of 348 ms-1 was used to calculate the theoretical frequencies at which resonance should occur in the box and pipe.

Most sound level measurements were made at a room temperature of 31°C within a daily range of 29 – 32°C. This range would have resulted in the speed of sound in air varying from 348 – 350 ms-1, thus producing variations in the resonance frequencies of the empty box and pipe. However, the variations observed were so small that they were assumed to be insignificant. In any case, using the sound absorbers removed the resonances in most cases regardless of the temperature.

B. *Loudspeaker Resonance Frequency*

The mechanical resonance frequency of the loudspeaker was found to be 100 Hz using a constant current method. This was done using a large DC resistance of 3.3 kΩ to maintain a constant current of 3.082 mA and measuring the voltage (in mV) across the loudspeaker while the frequency was varied. A graph of frequency versus voltage showed a sharp resonance maximum at 100 Hz. The loudspeaker resonance frequency was also found with the loudspeaker fixed onto the empty box and pipe and a constant voltage of 0.34 V was maintained across the

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loudspeaker. The current passing through the loudspeaker was measured as the frequency was varied. For both enclosures, graphs of frequency versus current showed a sharp resonance minimum at 100 Hz.

C. Physical Properties Of Silk Cotton, Cotton Wool, And Open-Cell Polyurethane Foam

The diameters of silk cotton fibres and cotton wool fibres were determined using the interference fringes air wedge experiment. (Tyler, 1981, p. 66). Both diameters were found to be of the order of 30 μm. By colouring the surface of a block foam to make the cells more visible and counting the number of cells per cm on the surface, it was estimated that the diameter of the cells ranged from 0.5 – 1 mm.

In a simple flotation test, cotton wool sank rapidly in water, while silk cotton floated, and 1 g of it supported a 5 g brass mass in water, showing that silk cotton is very light and buoyant. It also dried quickly when removed from water, while cotton wool took longer to dry. An 8 g block foam initially floated on water but barely floated when it became waterlogged and was able to support a 2 g brass mass in water.

It was necessary to know about these properties of the materials to deduce the effects these properties may have on their sound reduction characteristics as shown by the actual results of the investigations.

The software application Microsoft Excel was used to tabulate and plot the data in graphs and perform calculations mentioned in Section II.

V. RESULTS

Table 3: Acoustics of the Empty Box and with Silk Cotton at various densities

Density/mg cm^{-3}	**Empty**	**10**	**15**	**20**	**25**	**30**	**35**	**40**	**45**	**50**
Frequency/Hz	SL/dB	SL/dB	SL/dB	SL/dB	SL/dB	SL/dB	SL/dB	SL/dB	SL/dB	SL/dB
20	105	103	102	101	98	96	94	91	88	86
40	109	107	107	105	101	97	95	91	87	84
60	112	109	107	104	100	95	92	87	82	79
80	113	111	109	103	97	91	87	83	80	76
100@	113	111	110	99	92	86	83	81	79	75
125	110	109	109	99	77	85	85	83	81	81
140	108	107	108	102	85	76	79	78	74	72
160	106	105	107	104	89	78	78	72	68	52
180	103	103	105	105	95	83	80	72	71	65
200	101	102	103	105	100	87	85	76	75	72
250	100	100	97	97	96	103	97	88	82	87
300	99	99	96	94	97	100	101	86	82	74
380	95	94	90	89	89	95	100	100	97	77
400	95	92	88	87	88	92	99	99	99	81
500	100	88	82	80	80	89	94	98	97	94
560	119	85	80	76	75	86	90	93	94	92
570*	119	85	79	76	75	84	89	92	93	92
600	104	84	78	75	73	75	84	89	92	93
700	91	81	75	70	72	72	82	88	83	93
750	89	80	74	69	70	66	83	86	79	94
800	86	79	72	69	69	69	80	85	75	86
900	86	77	73	72	65	71	69	74	80	79
1000	89	74	69	66	63	69	71	63	83	81
1100	101	71	62	69	66	60	64	76	79	79
1130*	114	73	55	67	67	63	59	75	77	77
1200	93	74	65	64	66	65	61	72	76	79
1350	85	71	65	61	63	65	67	62	69	69
1500	85	69	60	52	51	49	57	59	66	50
1600	90	69	58	50	50	49	49	50	67	61
1690*	112	64	54	51	50	49	49	60	65	53
1700	106	64	55	52	51	49	49	60	64	55
2000	88	62	54	51	49	49	49	49	57	49
2100	94	64	54	50	49	49	49	49	53	54

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2190	105	63	54	50	49	49	49	49	49	54
2200	105	62	54	50	49	49	49	49	49	54
2300	110	60	55	51	52	52	49	51	49	55
2310*	112	60	55	51	52	52	49	49	49	54
2400	99	59	54	55	54	53	55	55	54	53
2490*	111	60	54	52	49	51	49	49	49	53
2500	110	59	54	52	49	52	49	49	49	53
2600	98	59	53	50	49	49	51	49	49	49
2700	102	58	54	51	49	49	49	49	49	49
2760*	109	59	54	51	49	49	49	49	49	49
2800	102	58	54	52	49	49	49	49	49	49
3000	95	56	54	55	51	52	49	50	50	49
3100*	101	55	55	53	53	53	49	51	49	49
3300	84	57	55	52	49	60	54	49	53	49
3500	98	56	55	50	51	49	49	49	49	49
3800	95	59	59	52	49	49	51	49	49	50
3850*	103	59	58	51	51	51	50	52	49	52
3900	94	59	59	53	51	53	49	52	49	53
4000	82	61	61	57	51	56	49	49	49	50

@ Loudspeaker Mechanical Resonance Frequency
* Box Resonance Frequencies

The sound levels tabulated as 49 dB were measured as LO (below the instrument's sensitivity) on the sound meter but were given an arbitrary value of 49 dB so that the graphs would have continuity. A sound level lower than 50 dB would be a hushed conversation.

The data in Table 3 are plotted in the graphs in Figures 11a and 11b: frequency versus sound level. To prevent the graphs from cluttering, only six are shown on the same axes.

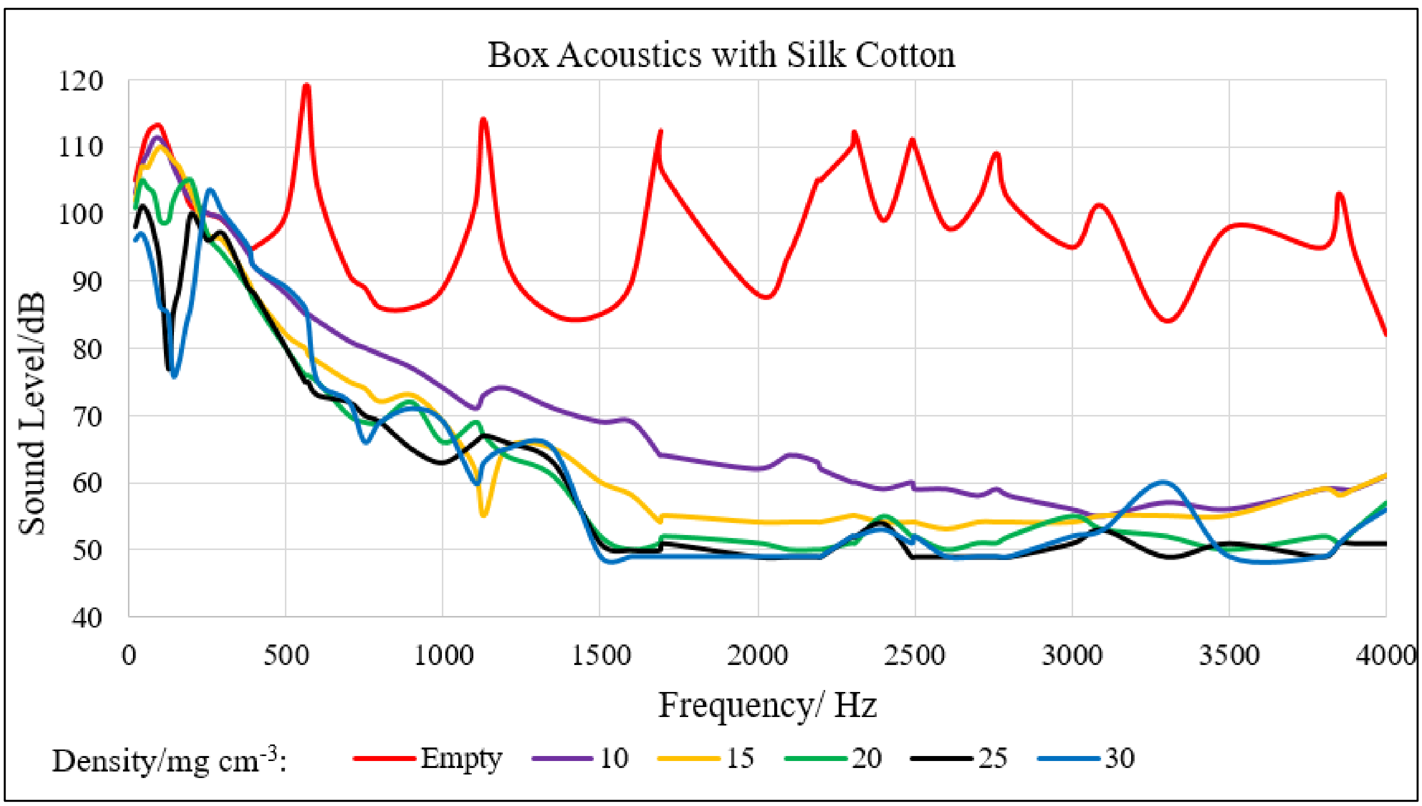

Fig 11a: Graph Showing Box Acoustics with Silk Cotton

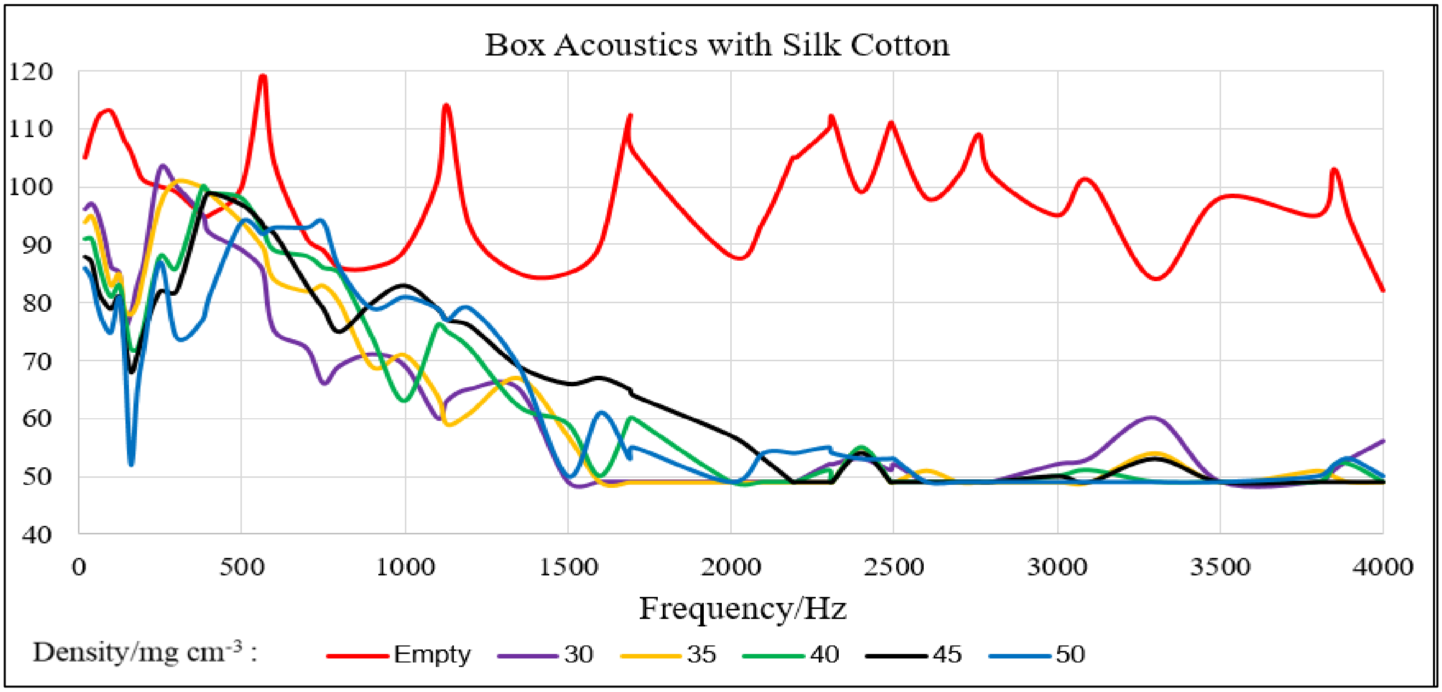

Fig 11b: Graph Showing Box Acoustics with Silk Cotton

Table 4: Sound Reduction in the Box with Silk Cotton at Various Density Packings

Density/mg cm^{-3}	**10**	**15**	**20**	**25**	**30**	**35**	**40**	**45**	**50**
***f*/Hz**	**SR/dB**	**SR/dB**	**SR/dB**	**SR/dB**	**SR/dB**	**SR/dB**	**SR/dB**	**SR/dB**	**SR/dB**
20	2	3	4	7	9	11	14	17	19
40	2	2	4	8	12	14	18	22	25
60	3	5	8	12	17	20	25	30	33
80	2	4	10	16	22	26	30	33	37
100	2	3	14	21	27	30	32	34	38
125	1	1	11	33	25	25	27	29	29
140	1	0	6	23	32	29	30	34	36
160	1	-1	2	17	28	28	34	38	54
180	0	-2	-2	8	20	23	31	32	38
200	-1	-2	-4	1	14	16	25	26	29
250	0	3	3	4	-3	3	12	18	13
300	0	3	5	2	-1	-2	13	17	25
380	1	5	6	6	0	-5	-5	-2	18
400	3	7	8	7	3	-4	-4	-4	14
500	12	18	20	20	11	6	2	3	6
560	34	39	43	44	33	29	26	25	27
570	34	40	43	44	35	30	27	26	27
600	20	26	29	31	29	20	15	12	11
700	10	16	21	19	19	9	3	8	-2
750	9	15	20	19	23	6	3	10	-5
800	7	14	17	17	17	6	1	11	0
900	9	13	14	21	15	17	12	6	7
1000	15	20	23	26	20	18	26	6	8
1100	30	39	32	35	41	37	25	22	22
1130	41	59	47	47	51	55	39	37	37
1200	19	28	29	27	28	32	21	17	14
1350	14	20	24	22	20	18	23	16	16
1500	16	25	33	34	36	28	26	19	35

1600	21	32	40	40	41	41	40	23	29
1690	48	58	61	62	63	63	52	47	59
1700	42	51	54	55	57	57	46	42	51
2000	26	34	37	39	39	39	39	31	39
2100	30	40	44	45	45	45	45	41	40
2190	42	51	55	56	56	56	56	56	51
2200	43	51	55	56	56	56	56	56	51
2300	50	55	59	58	58	61	59	61	55
2310	52	57	61	60	60	63	63	63	58
2400	40	45	44	45	46	44	44	45	46
2490	51	57	59	62	60	62	62	62	58
2500	51	56	58	61	58	61	61	61	57
2600	39	45	48	49	49	47	49	49	49
2700	44	48	51	53	53	53	53	53	53
2760	50	55	58	60	60	60	60	60	60
2800	44	48	50	53	53	53	53	53	53
3000	39	41	40	44	43	46	45	45	46
3100	46	46	48	48	48	52	50	52	52
3300	27	29	32	35	24	30	35	31	35
3500	42	43	48	47	49	49	49	49	49
3800	36	36	43	46	46	44	46	46	45
3850	44	45	52	52	52	53	51	54	51
3900	35	35	41	43	41	45	42	45	41
4000	21	21	25	31	26	33	33	33	32

Since most sound reduction problems occur in the frequency range 20 – 4000 Hz (the typical range for human voice, singing, and most musical instruments), sound reduction and sound absorption analysis was focused in this range. Sound reduction (SR) was calculated using the relation Equation 13:

$$SR = I_i\,(dB) - I_t\,(dB)$$

where incident sound level, I_i = sound level in the empty box and transmitted sound level, I_i = sound level in the material-filled box at the various frequencies and density packings. The data in Table 4 are plotted in Figures 12a and 12b: frequency versus SR and Figures 12c and 12d: density versus SR for selected frequencies, including the resonance frequencies.

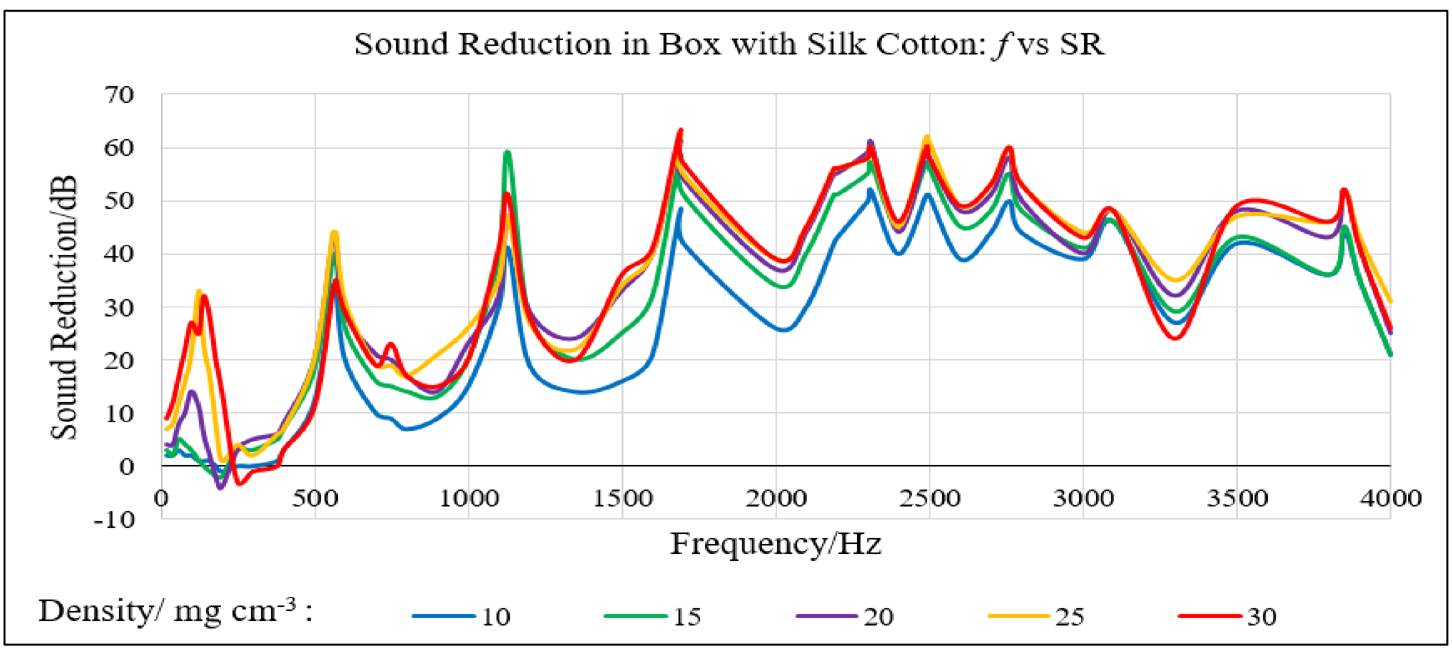

Fig 12a: Graph Showing Sound Reduction in Box with Silk Cotton: f vs SR

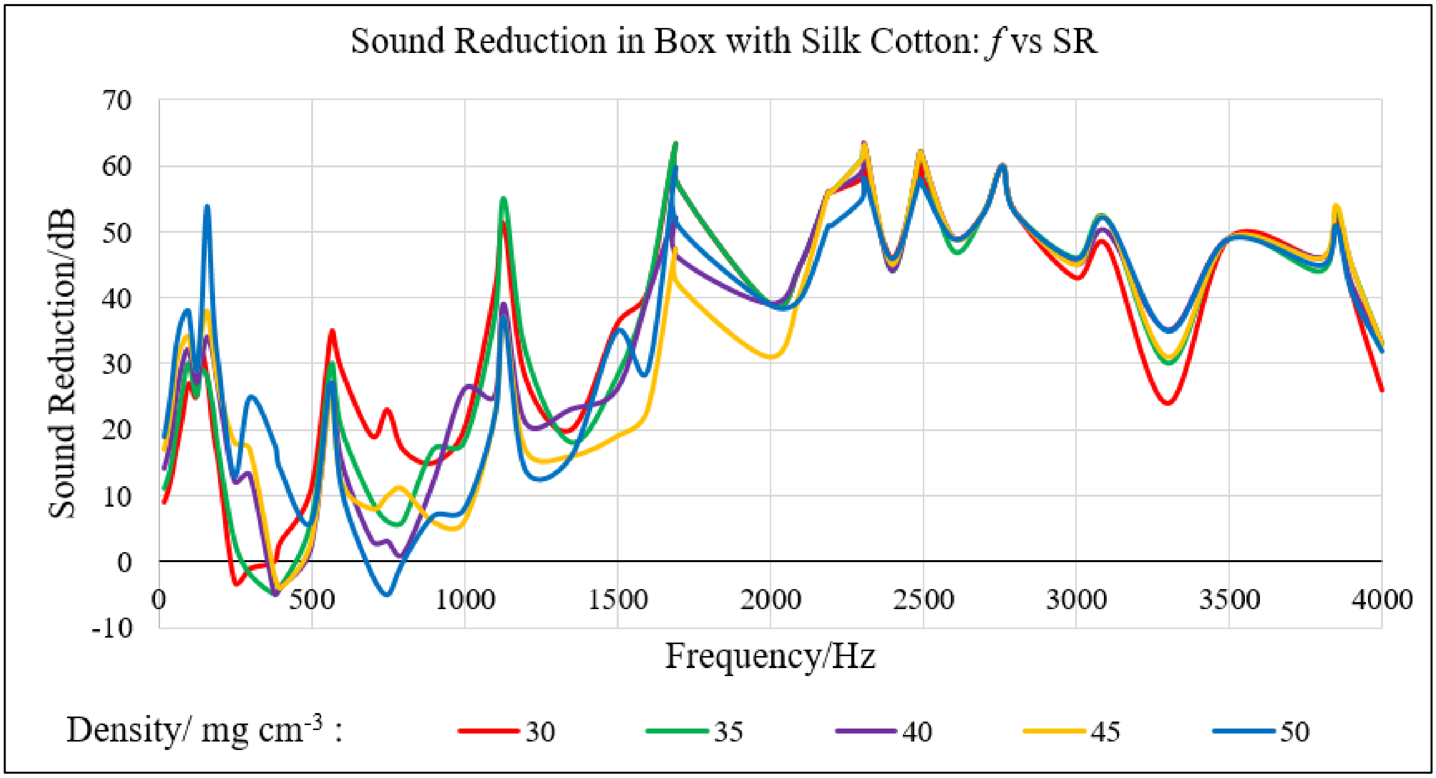

Fig 12b: Graph Showing Sound Reduction in Box with Silk Cotton: f vs SR

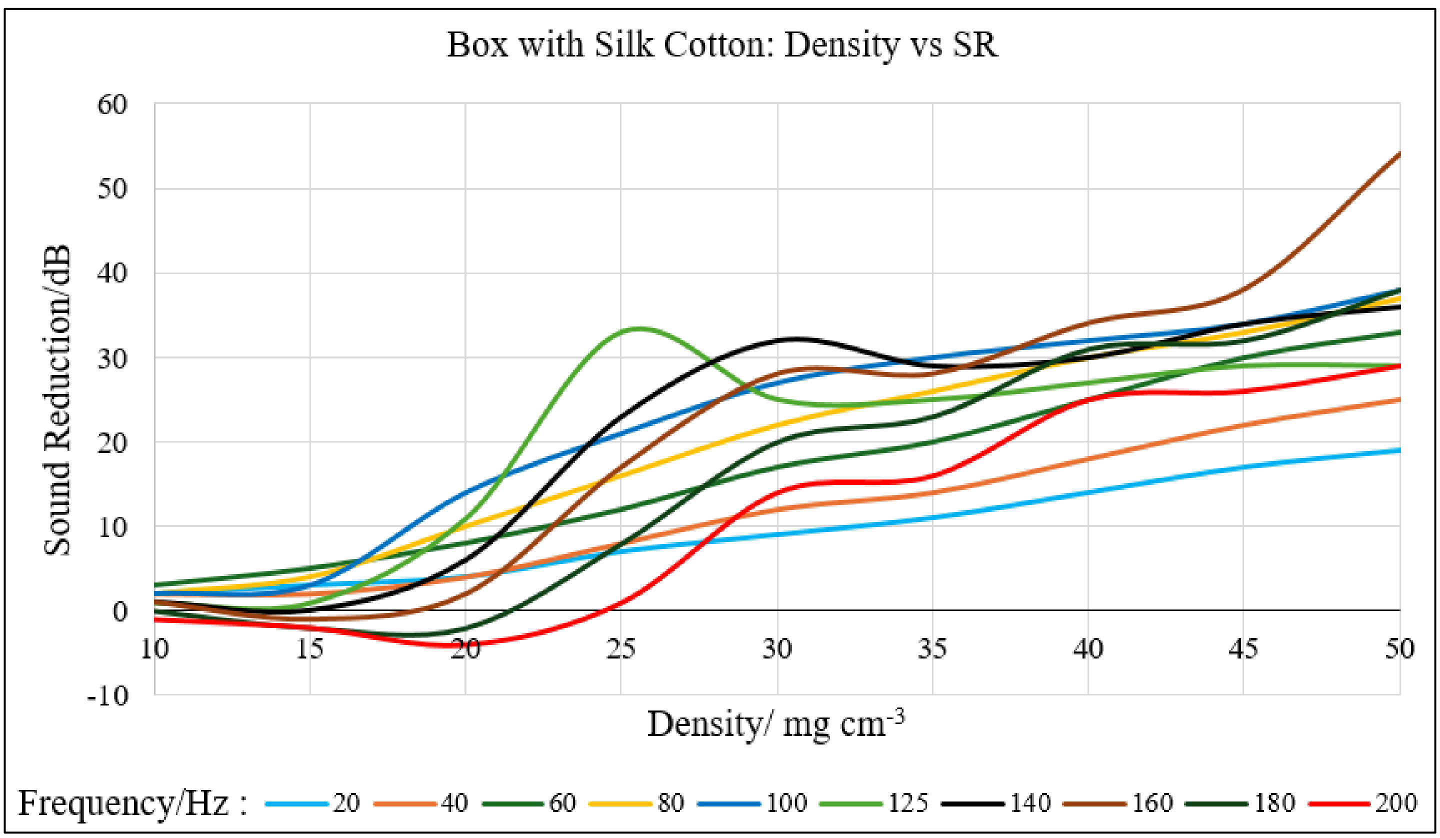

Fig 12c: Graph Showing Sound Reduction in Box with Silk Cotton: Density vs SR

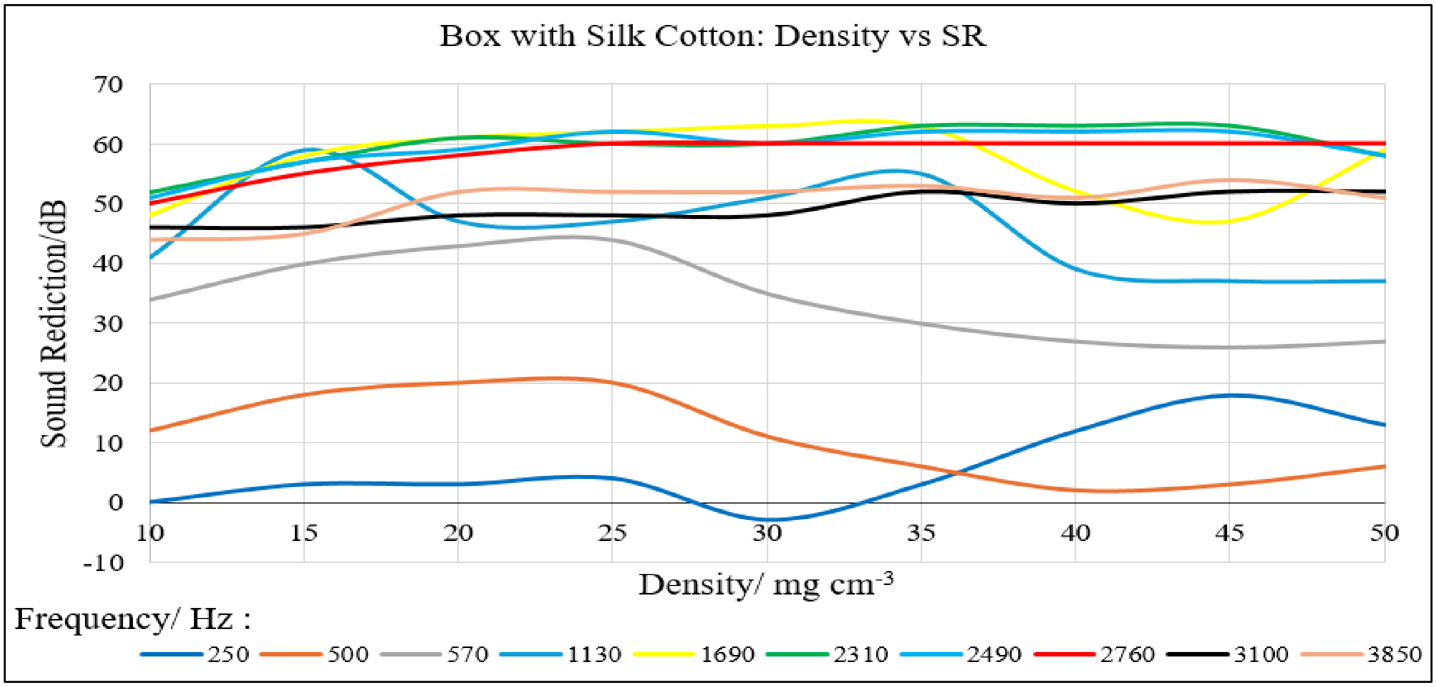

Fig 12d: Graph Showing Sound Reduction in Box with Silk Cotton: Density vs SR

Table 5: Fraction of Absorbed Energy Converted into Heat, h, in the Box with Silk Cotton

Density/mg cm-3	10	15	20	25	30	35	40	45	50
Frequency/Hz	**h**	**h**	**h**	**h**	**h**	**h**	**h**	**h**	**h**
20	0.369	0.499	0.602	0.800	0.874	0.921	0.960	0.980	0.987
40	0.369	0.369	0.602	0.842	0.937	0.960	0.984	0.994	0.997
60	0.499	0.684	0.842	0.937	0.980	0.990	0.997	0.999	0.999
80	0.369	0.602	0.900	0.975	0.994	0.997	0.999	0.999	1.000
100	0.369	0.499	0.960	0.992	0.998	0.999	0.999	1.000	1.000
125	0.206	0.206	0.921	0.999	0.997	0.997	0.998	0.999	0.999
140	0.206	0.000	0.749	0.995	0.999	0.999	0.999	1.000	1.000
160	0.206	-0.259	0.369	0.980	0.998	0.998	1.000	1.000	1.000
180	0.000	-0.585	-0.585	0.842	0.990	0.995	0.999	0.999	1.000
200	-0.259	-0.585	-1.512	0.206	0.960	0.975	0.997	0.997	0.999
250	0.000	0.499	0.499	0.602	-0.995	0.499	0.937	0.984	0.950
300	0.000	0.499	0.684	0.369	-0.259	-0.585	0.950	0.980	0.997
380	0.206	0.684	0.749	0.749	0.000	-2.162	-2.162	-0.585	0.984
400	0.499	0.800	0.842	0.800	0.499	-1.512	-1.512	-1.512	0.960
500	0.937	0.984	0.990	0.990	0.921	0.749	0.369	0.499	0.749
560	1.000	1.000	1.000	1.000	0.999	0.999	0.997	0.997	0.998
570	1.000	1.000	1.000	1.000	1.000	0.999	0.998	0.997	0.998
600	0.990	0.997	0.999	0.999	0.999	0.990	0.968	0.937	0.921
700	0.900	0.975	0.992	0.987	0.987	0.874	0.499	0.842	-0.585
750	0.874	0.968	0.990	0.987	0.995	0.749	0.499	0.900	-2.162
800	0.800	0.960	0.980	0.980	0.980	0.749	0.206	0.921	0.000
900	0.874	0.950	0.960	0.992	0.968	0.980	0.937	0.749	0.800
1000	0.968	0.990	0.995	0.997	0.990	0.984	0.997	0.749	0.842
1100	0.999	1.000	0.999	1.000	1.000	1.000	0.997	0.994	0.994
1130	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
1200	0.987	0.998	0.999	0.998	0.998	0.999	0.992	0.980	0.960
1350	0.960	0.990	0.996	0.994	0.990	0.984	0.995	0.975	0.975 1.000

1500	0.975	0.997	0.999	1.000	1.000	0.998	0.997	0.987	1.000
1600	0.992	0.999	1.000	1.000	1.000	1.000	1.000	0.995	0.999
1690	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
1700	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
2000	0.997	1.000	1.000	1.000	1.000	1.000	1.000	0.999	1.000
2100	0.999	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
2190	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
2200	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
2300	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
2310	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
2400	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
2490	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
2500	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
2600	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
2700	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
2760	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
2800	1.000	1.000	1.000	1.000.	1.000	1.000	1.000	1.000	1.000
3000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
3100	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
3300	0.998	0.999	0.999	1.000	0.996	0.999	1.000	0.999	1.000
3500	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
3800	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
3850	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
3900	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
4000	0.992	0.992	0.997	0.999	0.997	0.999	0.999	0.999	0.999

The fraction of absorbed sound energy converted into heat, h, was calculated using Equation 14: $t = 10^{-SR/10}$ and the approximate relation Equation 17: $1 \approx h + t$. Thus, giving

$$h \approx 1 - 10^{-SR/10}$$

The data in Table 5 are plotted in the graphs in Figures 13a and 13b for frequency versus h and in Figures 13c and 13d for density versus h for selected frequencies, including the resonance frequencies. Graphs in Figures 13a and 13b are plotted up to 2000 Hz as $h = 1$ for higher frequencies, so the graphs are flat lines after that.

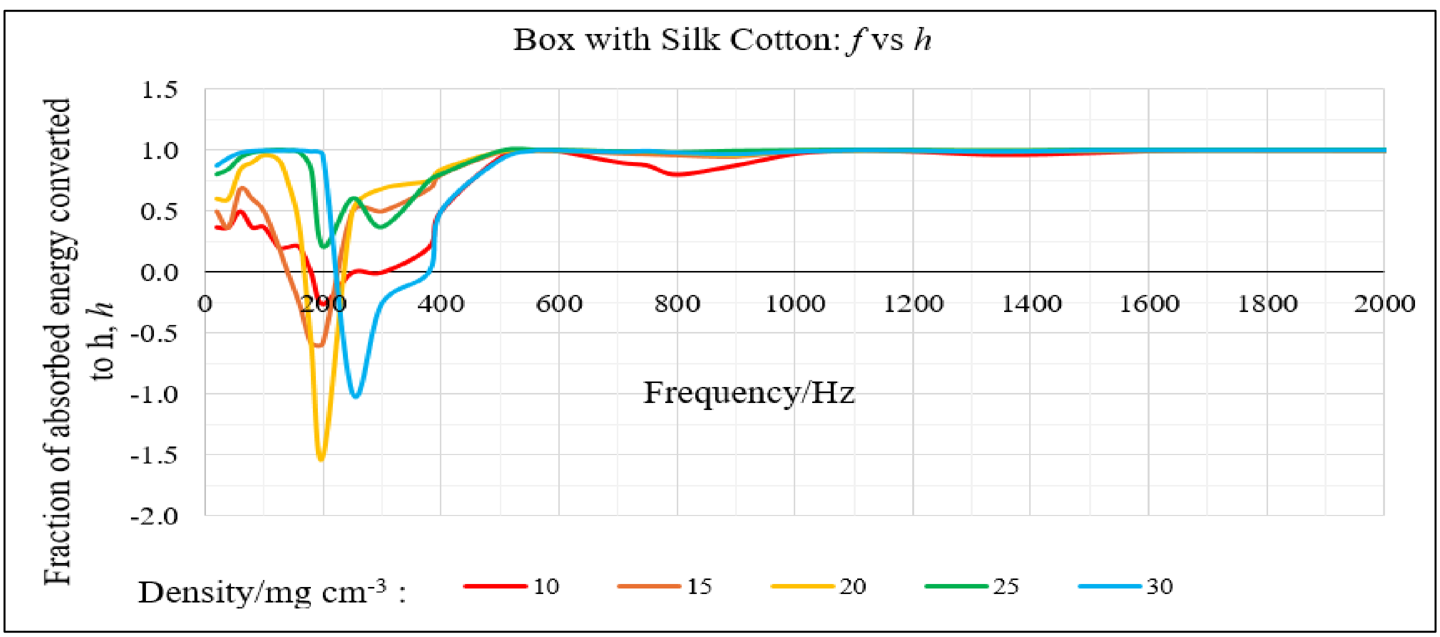

Fig 13a: Graph Showing Box with Silk Cotton: f vs h

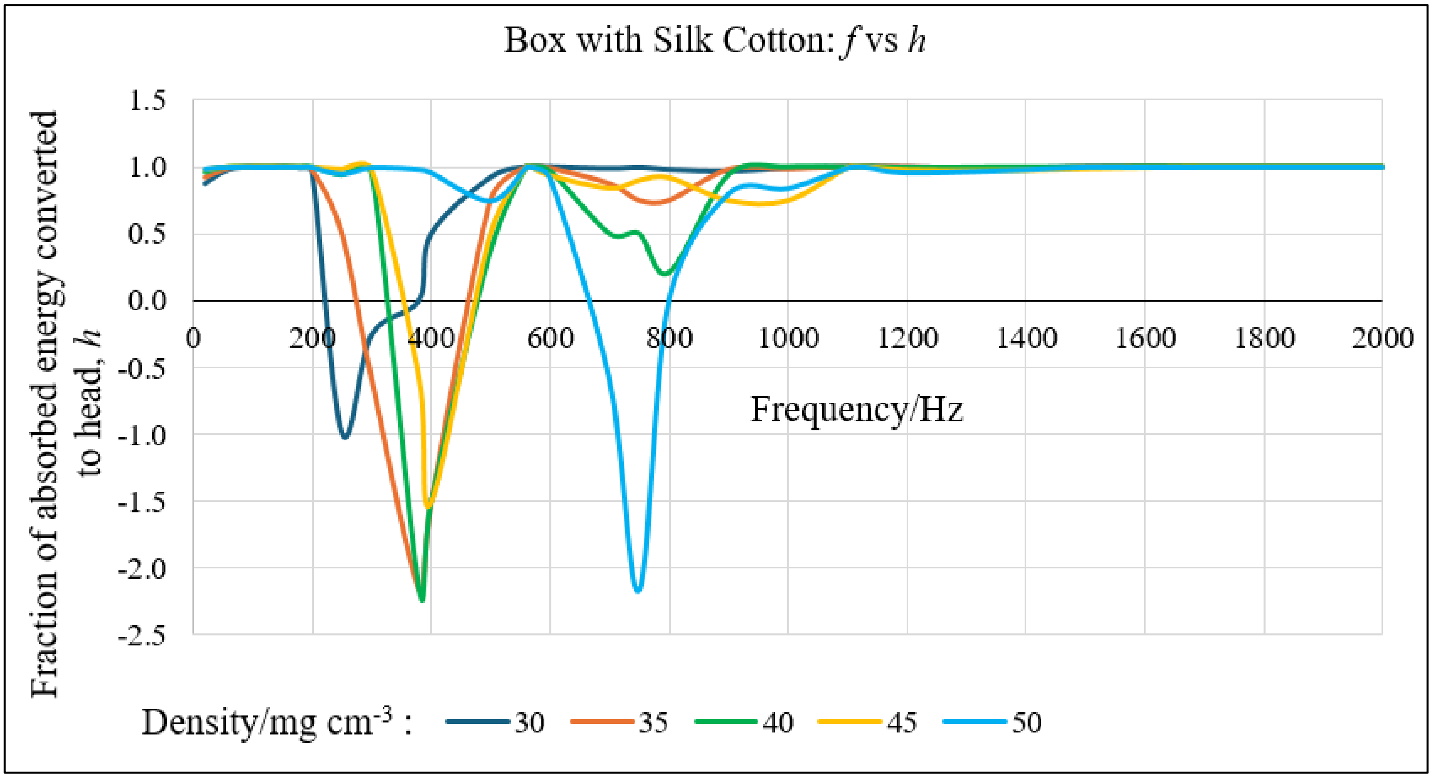

Fig 3b: Graph Showing Box with Silk Cotton: f vs h

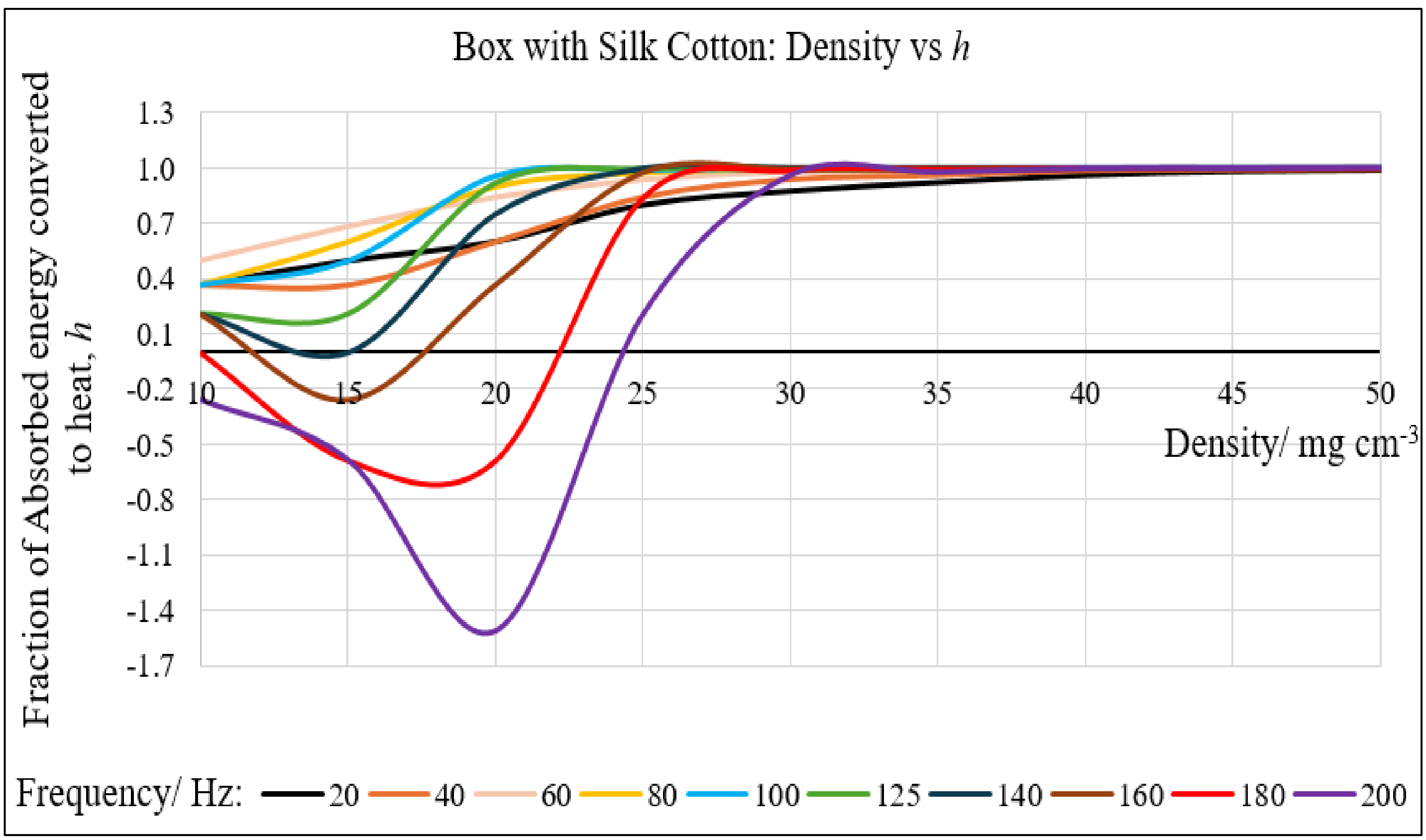

Fig 13c: Graph Showing Box with Silk Cotton: Density vs h

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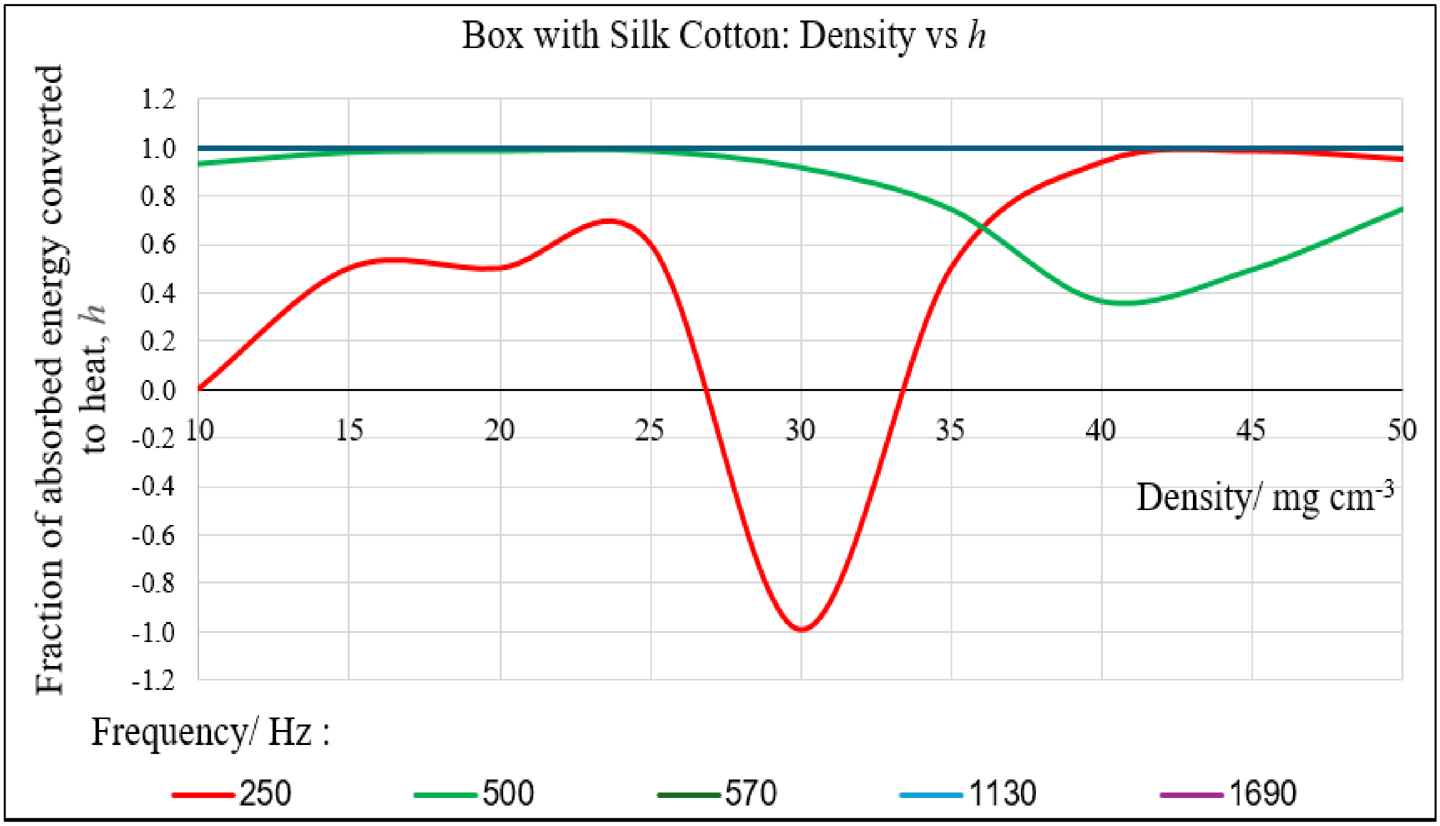

Fig 13d: Graph Showing Box with Silk Cotton: Density vs h

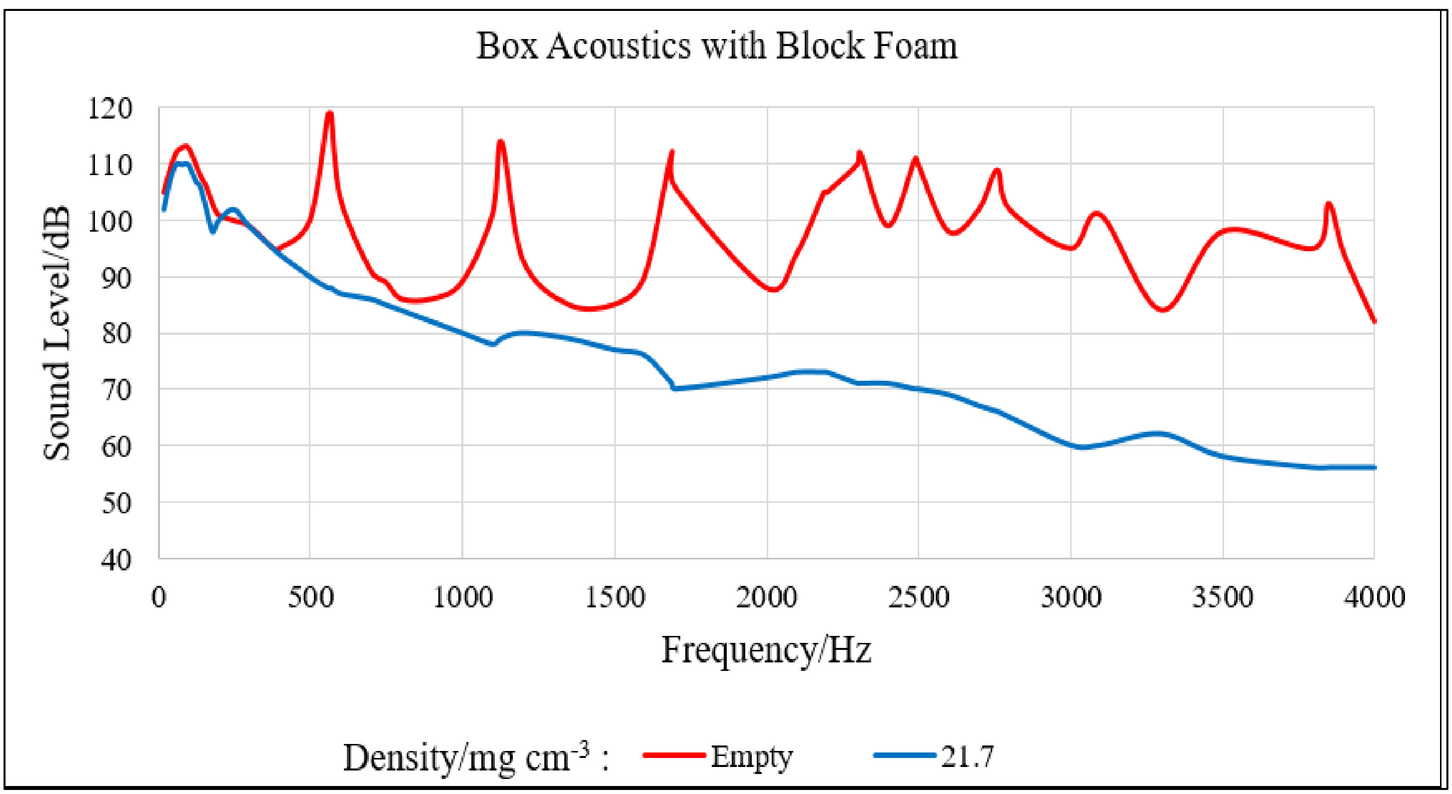

Fig 14a: Box Acoustics with Block Foam (density 21.7 mg cm^{-3})

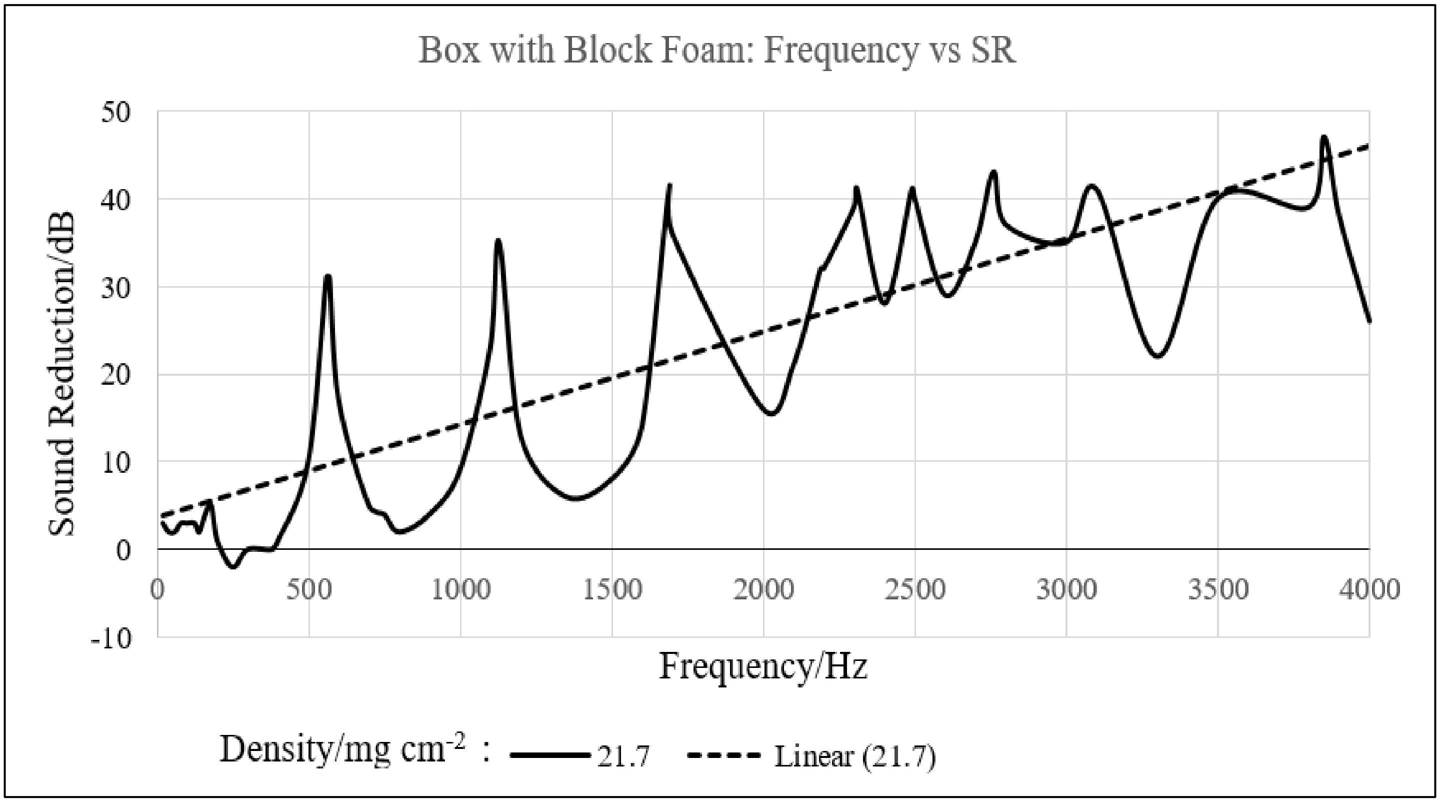

Fig 14b: Graph Showing Sound Reduction in Box with Block Foam: Frequency vs SR

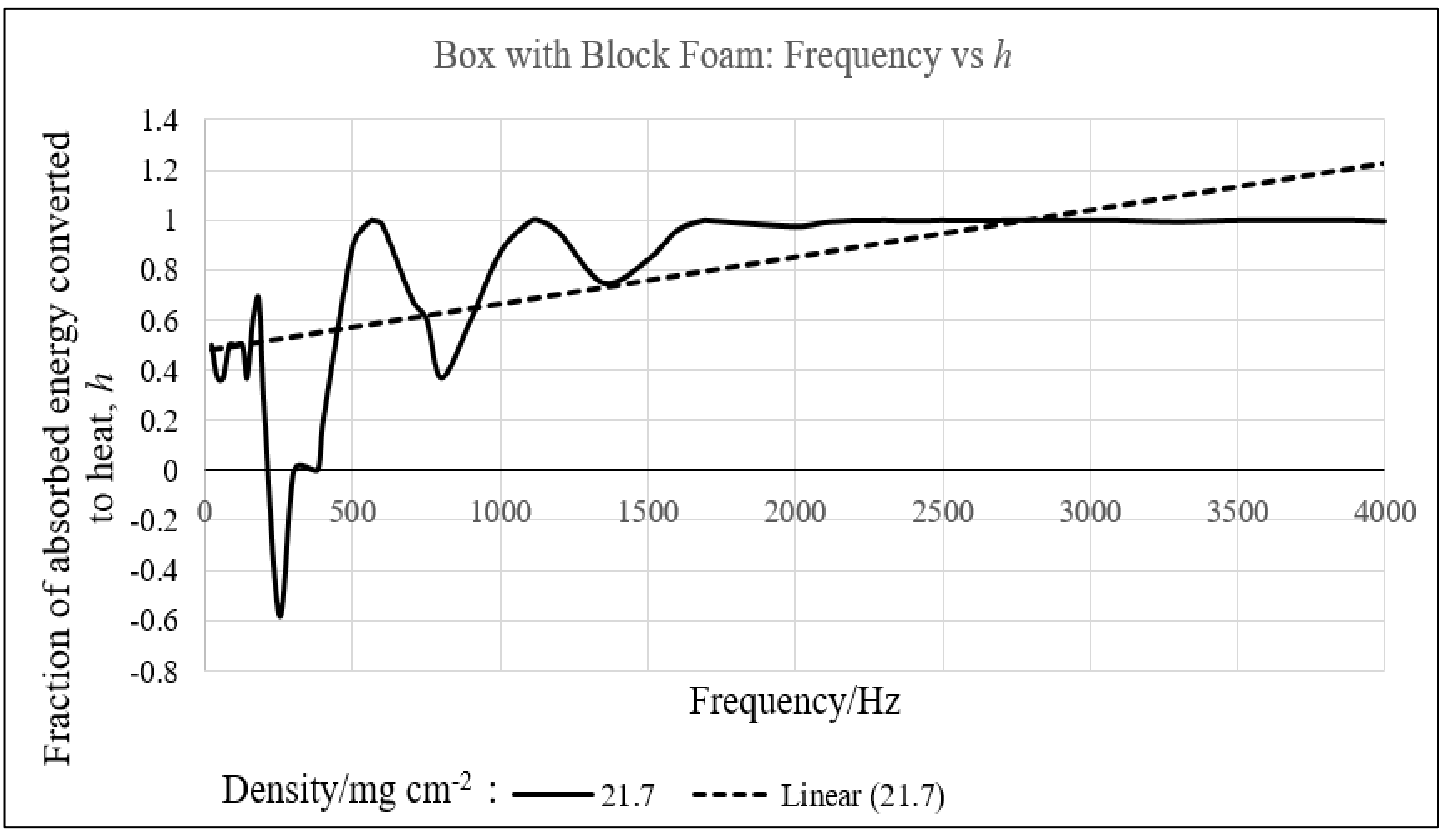

Fig 14c: Graph Showing Box with Block Foam: Frequency vs h

ISSN No:-2456-2165
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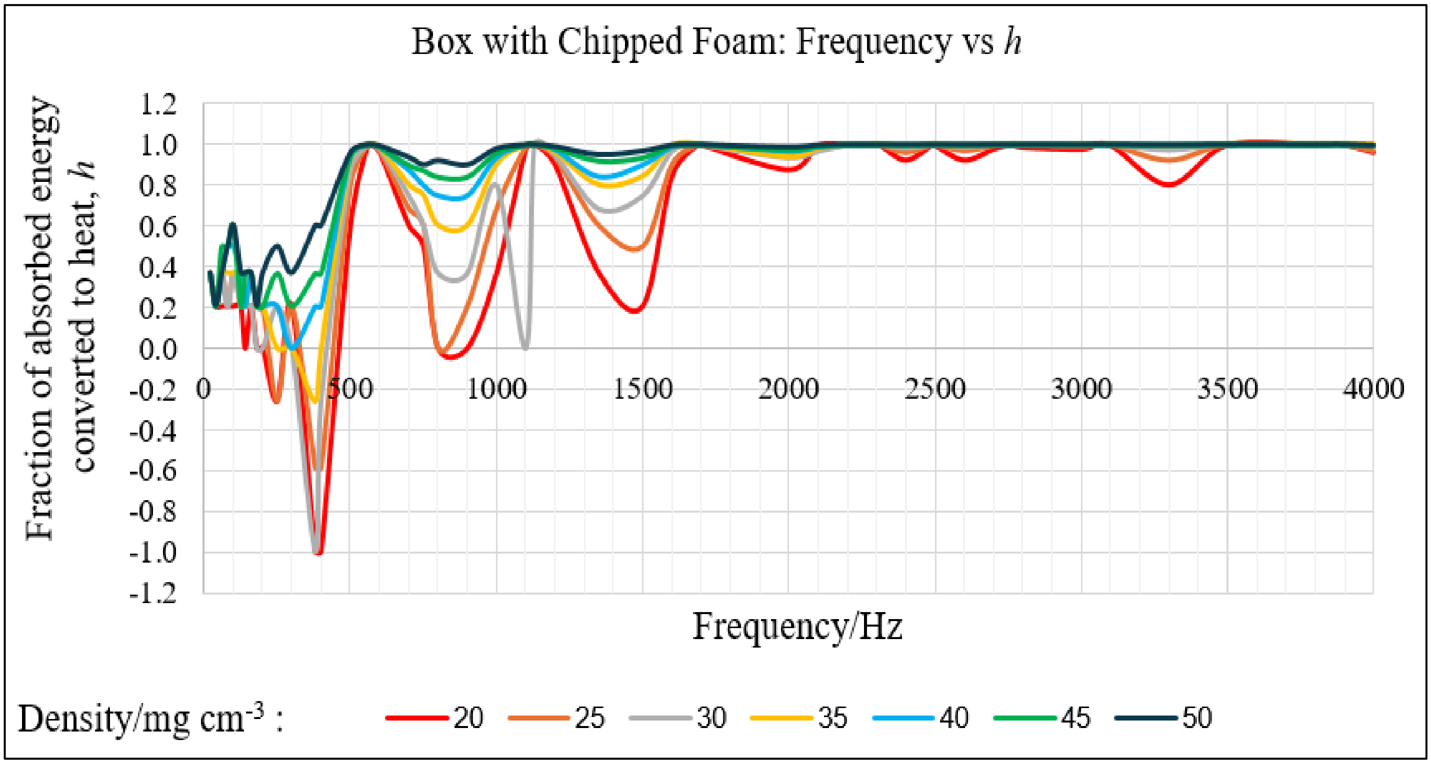

Fig 15: Graph Showing Box with Chipped Foam: Frequency vs h

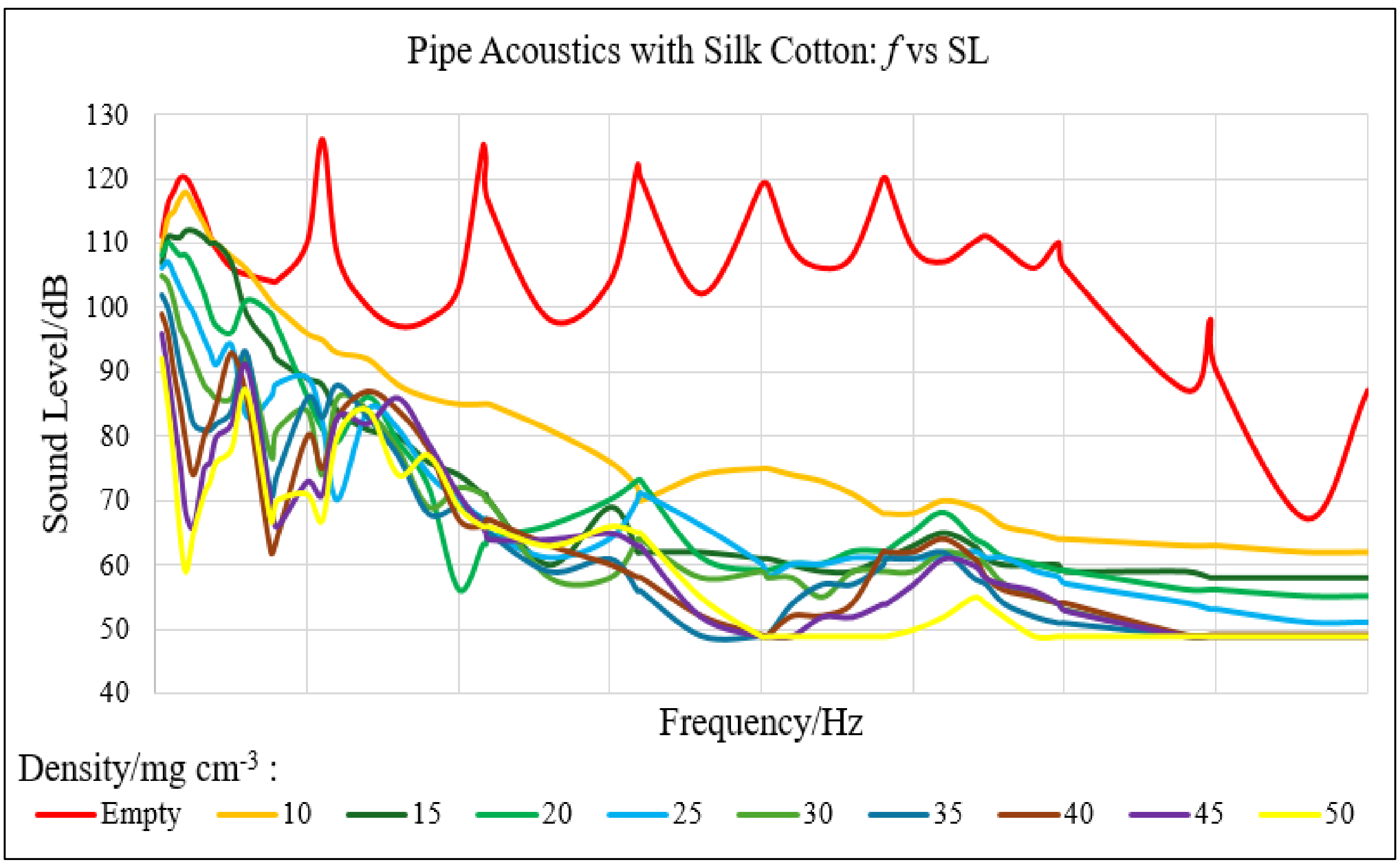

Fig 16a: Graph Showing Pipe Acoustics with Silk Cotton

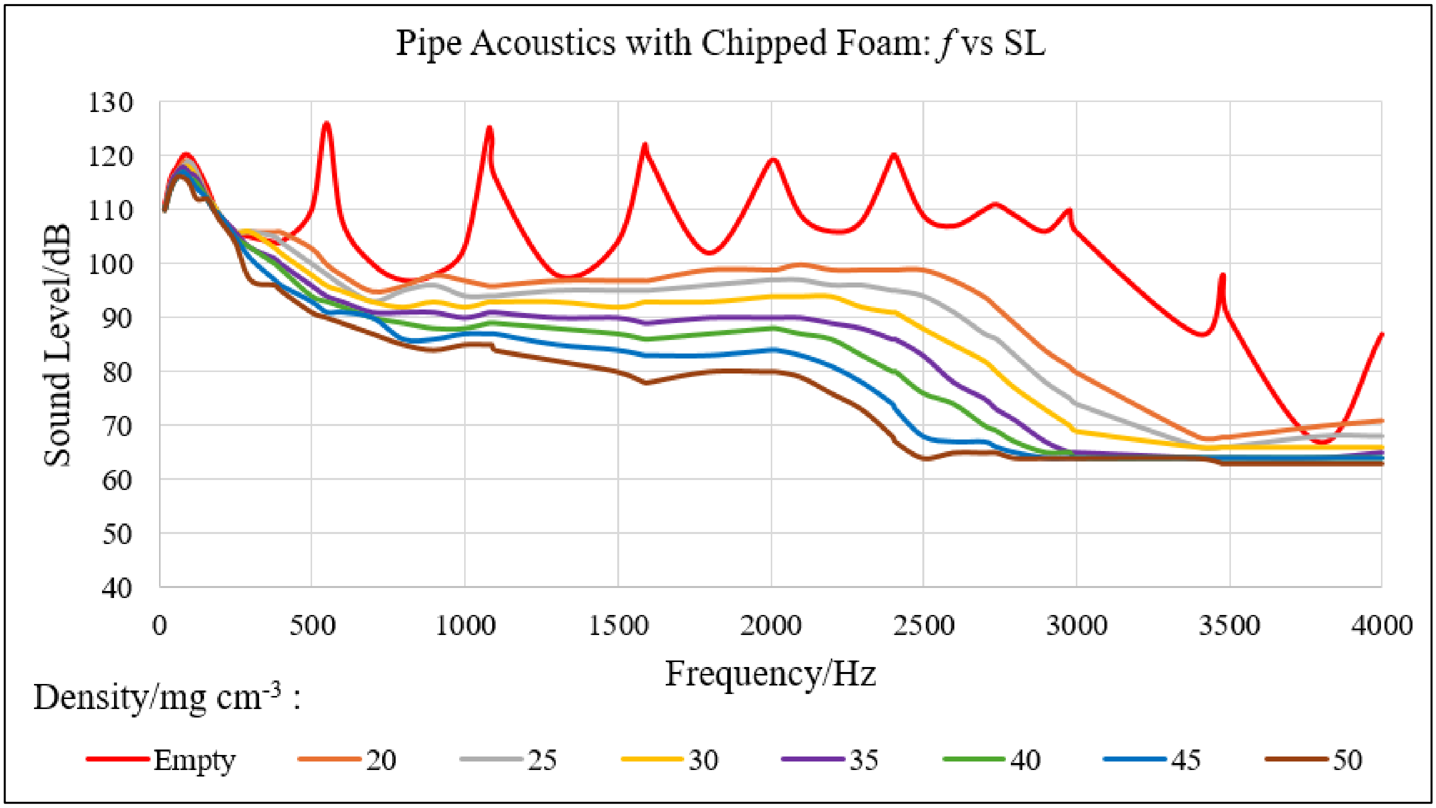

Fig 16b: Graph Showing Pipe Acoustics with Chipped Foam

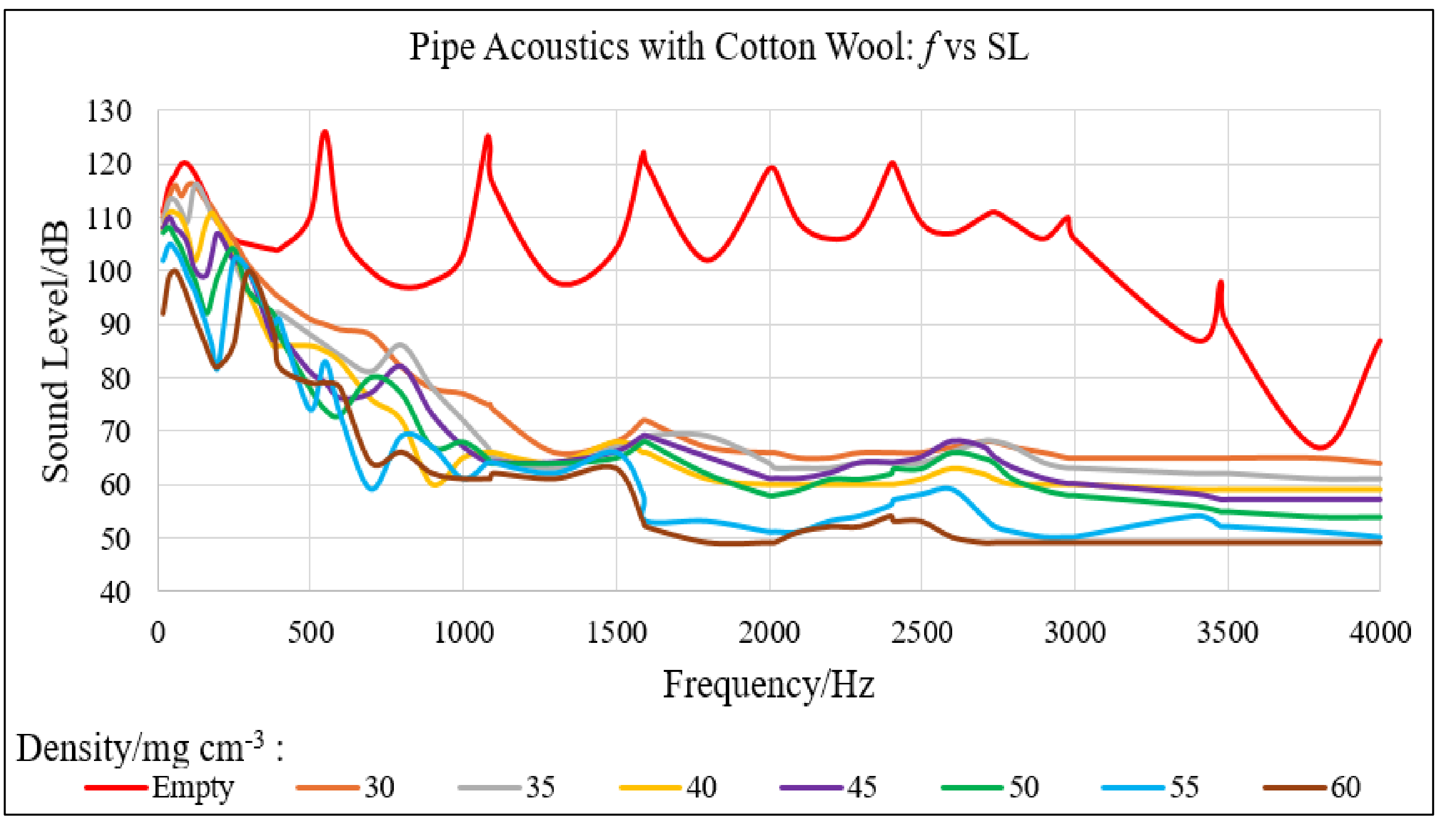

Fig 16c: Graph showing Pipe Acoustics with Cotton Wool

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➢ *Graphical Comparison of the Box Acoustics of Silk Cotton (SC), Chipped Foam (CF), Block Foam (BF) and Cotton Wool (CW)*

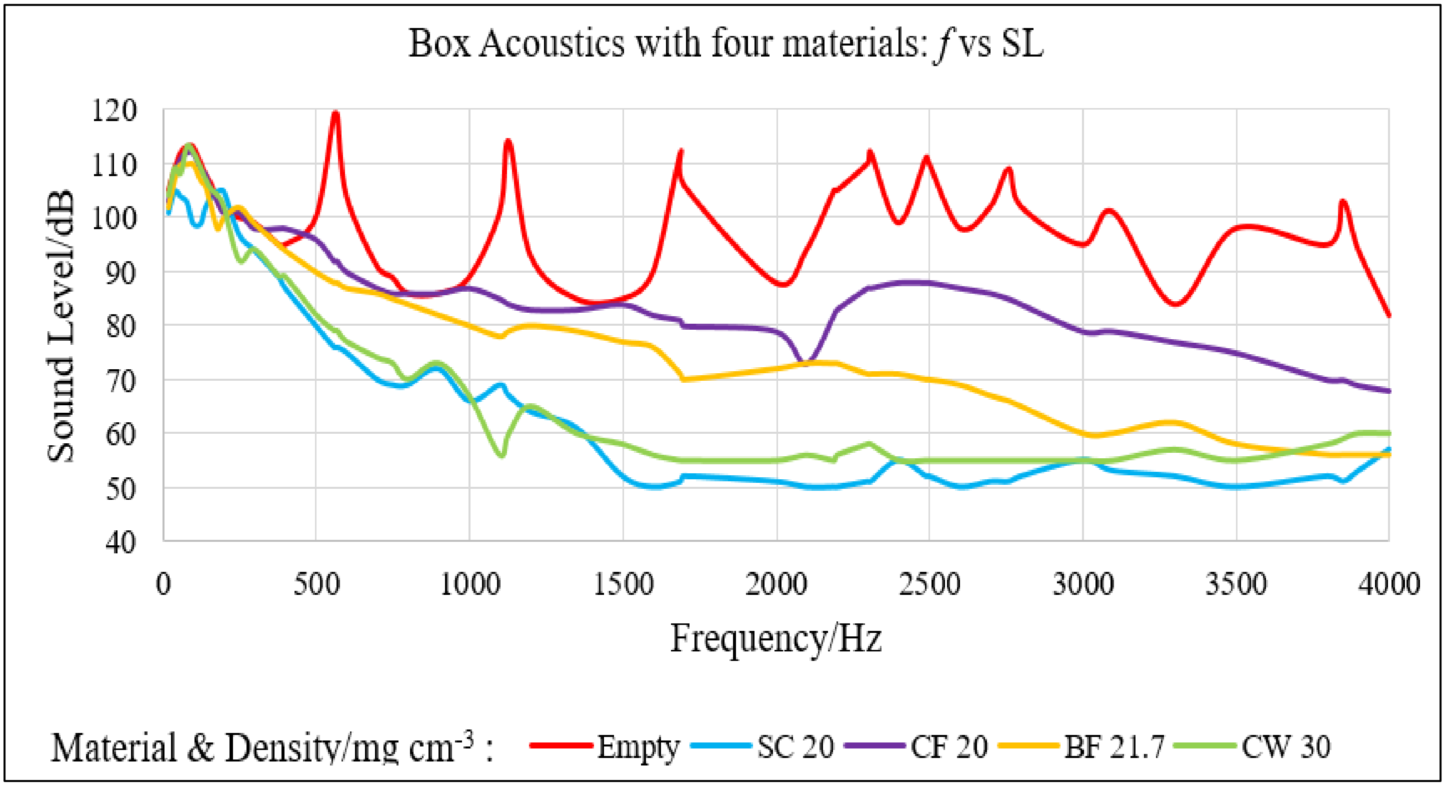

Fig 17a: Graph Showing Box Acoustics with Four Materials

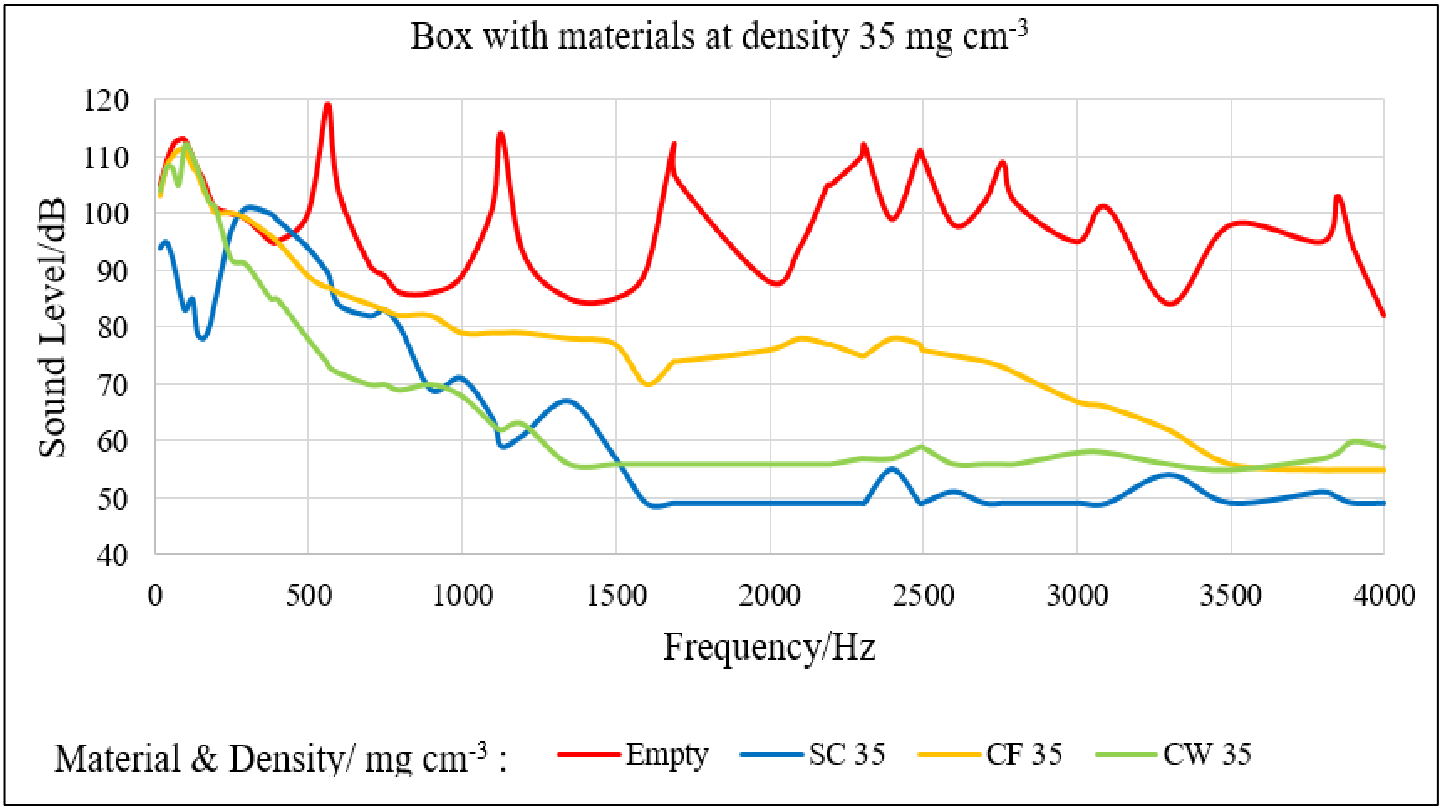

Fig 17b: Graph Showing Box Acoustics with Materials at Density 35 mg cm^{-3}

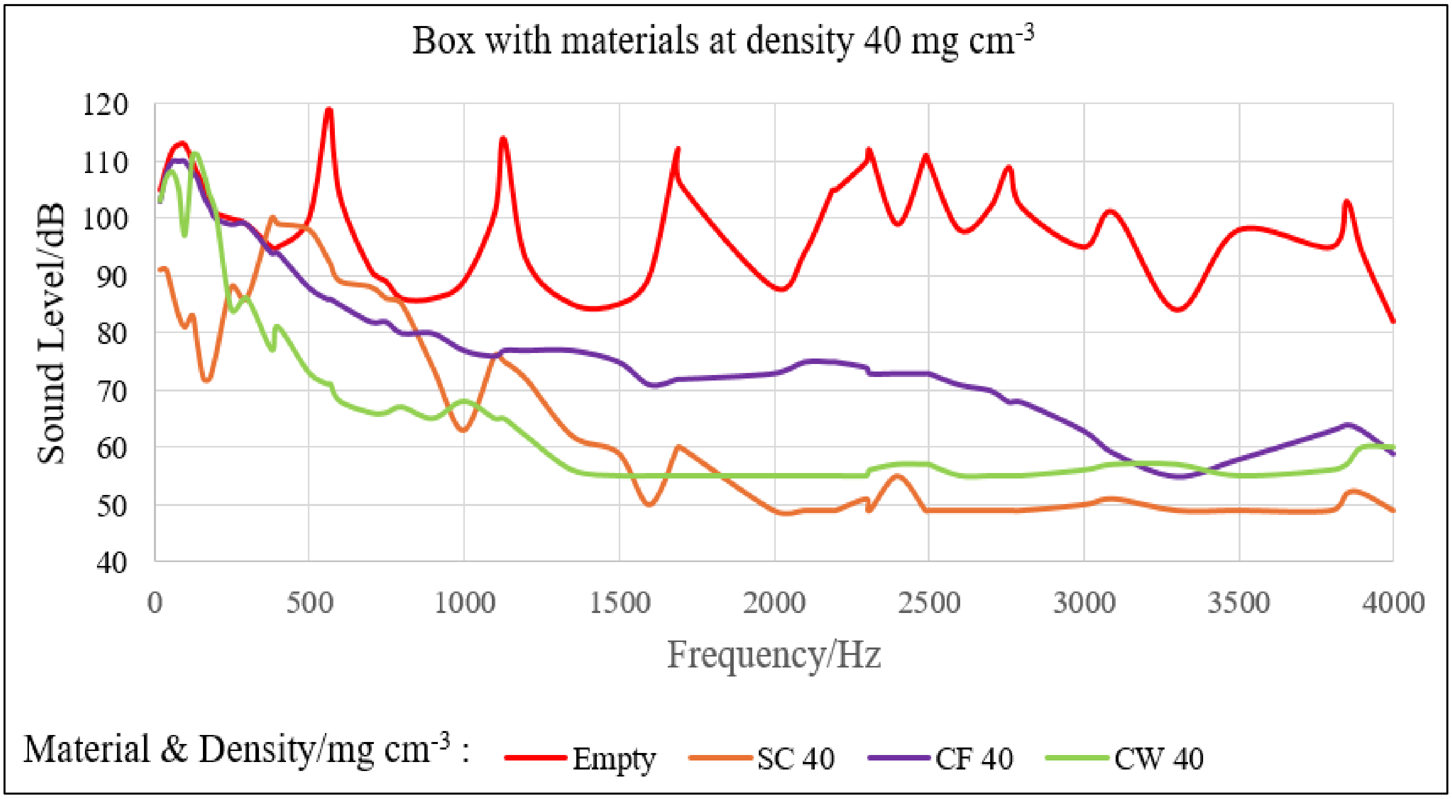

Fig 17c: Graph Showing Box Acoustics with Materials with Density 40 mg cm^{-3}

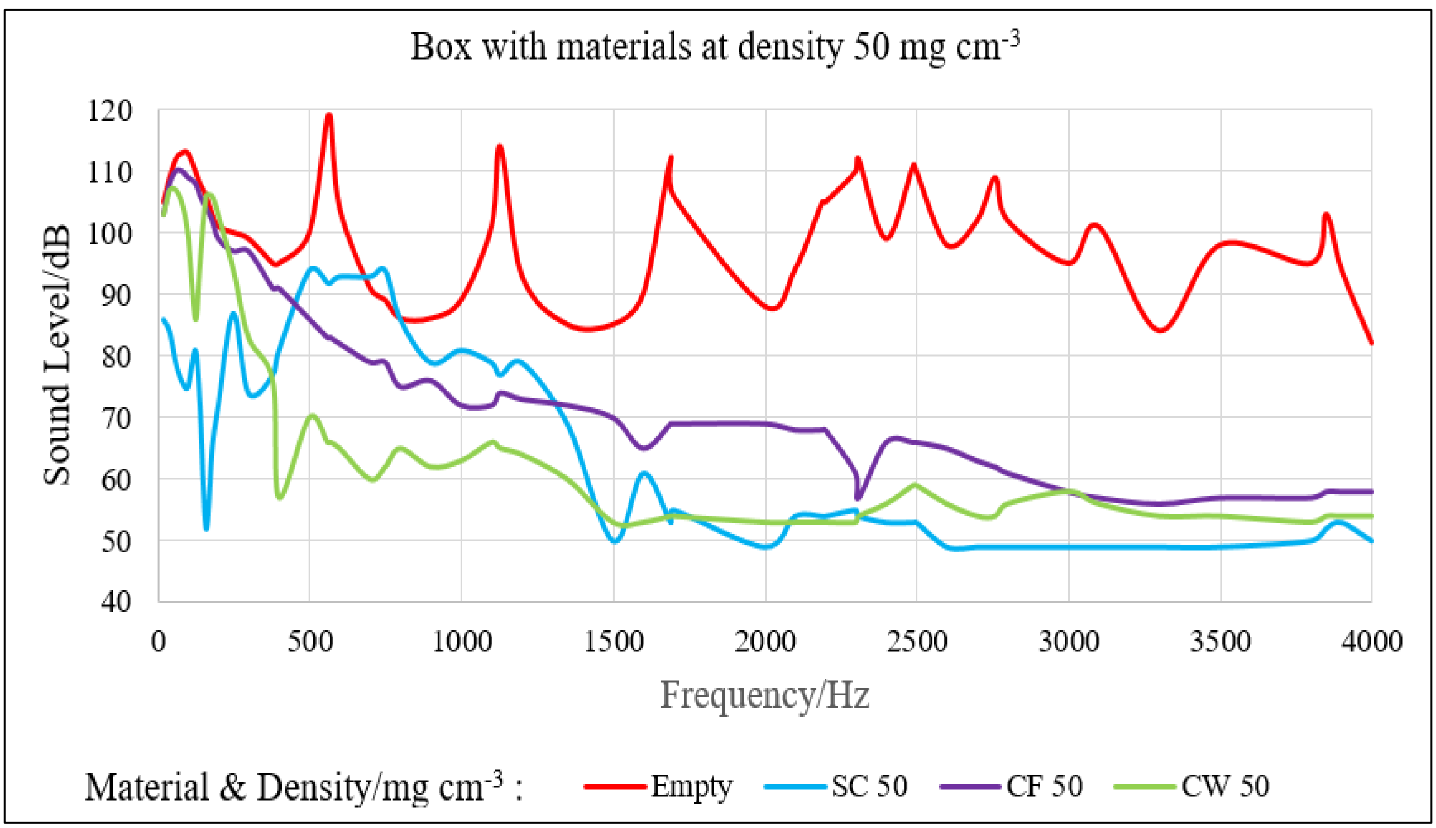

Fig 17d: Graph Showing Box Acoustics with Materials at Density 50 mg cm^{-3}

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➢ *Graphical Comparison of the Sound Reduction Properties of the Materials in the Box*

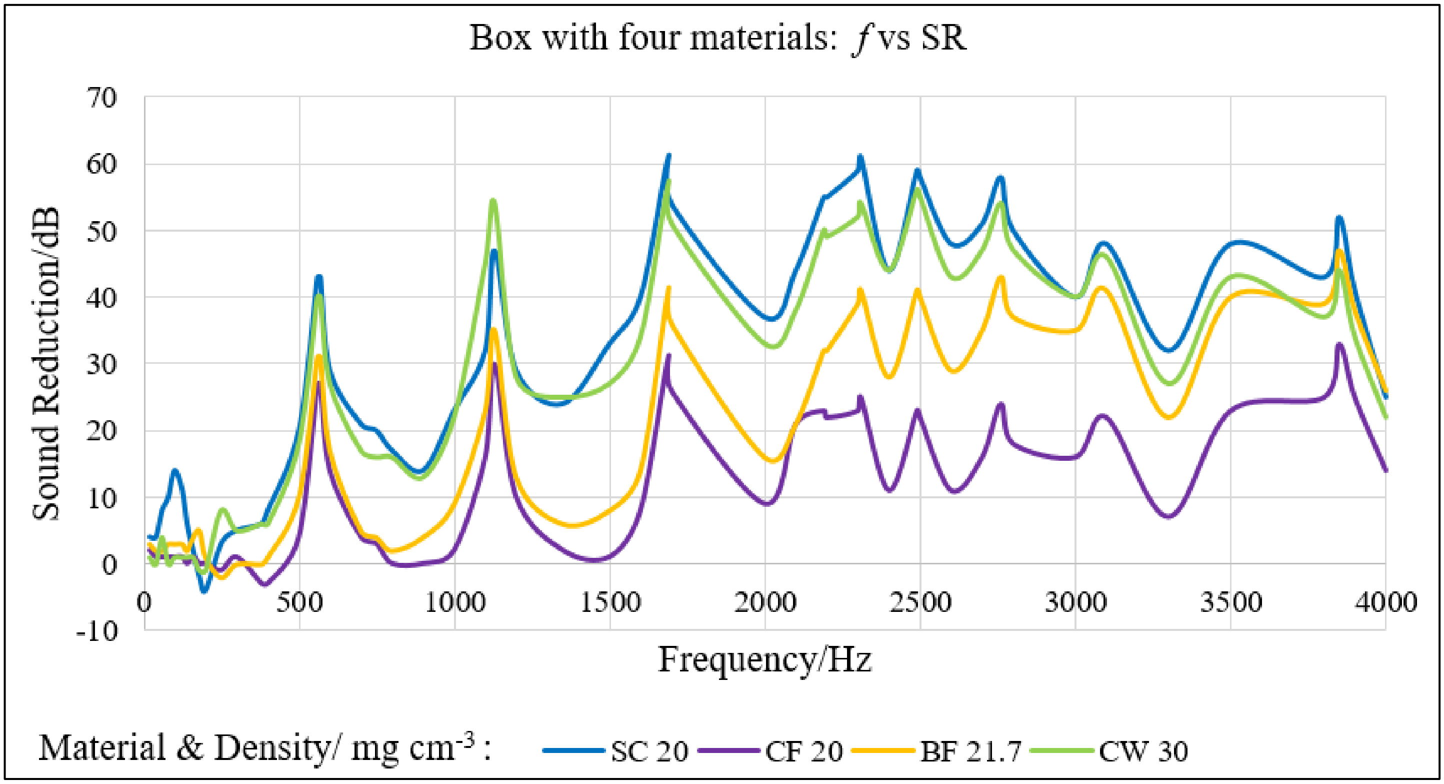

Fig 18a: Graph showing Sound Reduction in Box with Four Materials: Frequency vs SR

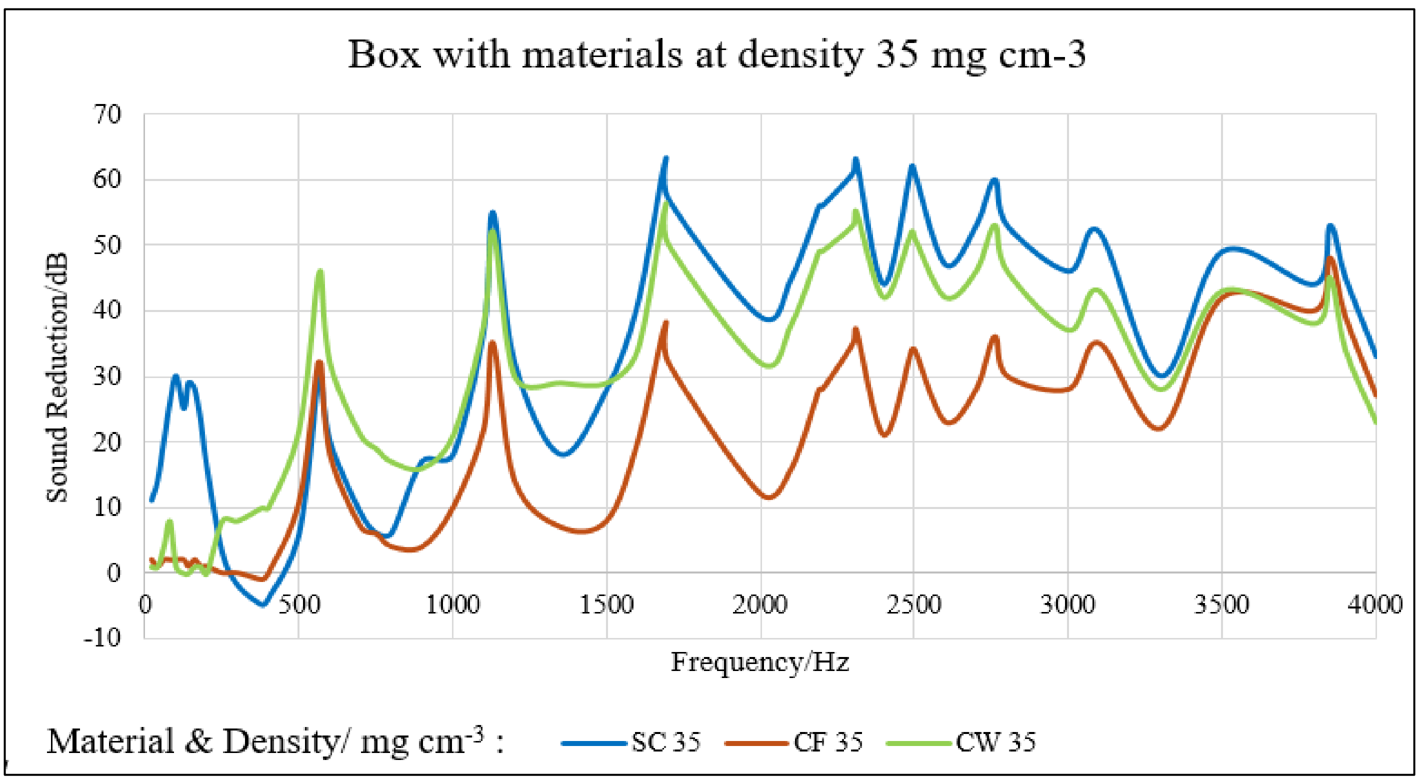

Fig 18b: Graph Showing Sound Reduction in Box with Materials at Density 35 mg cm^{-3}

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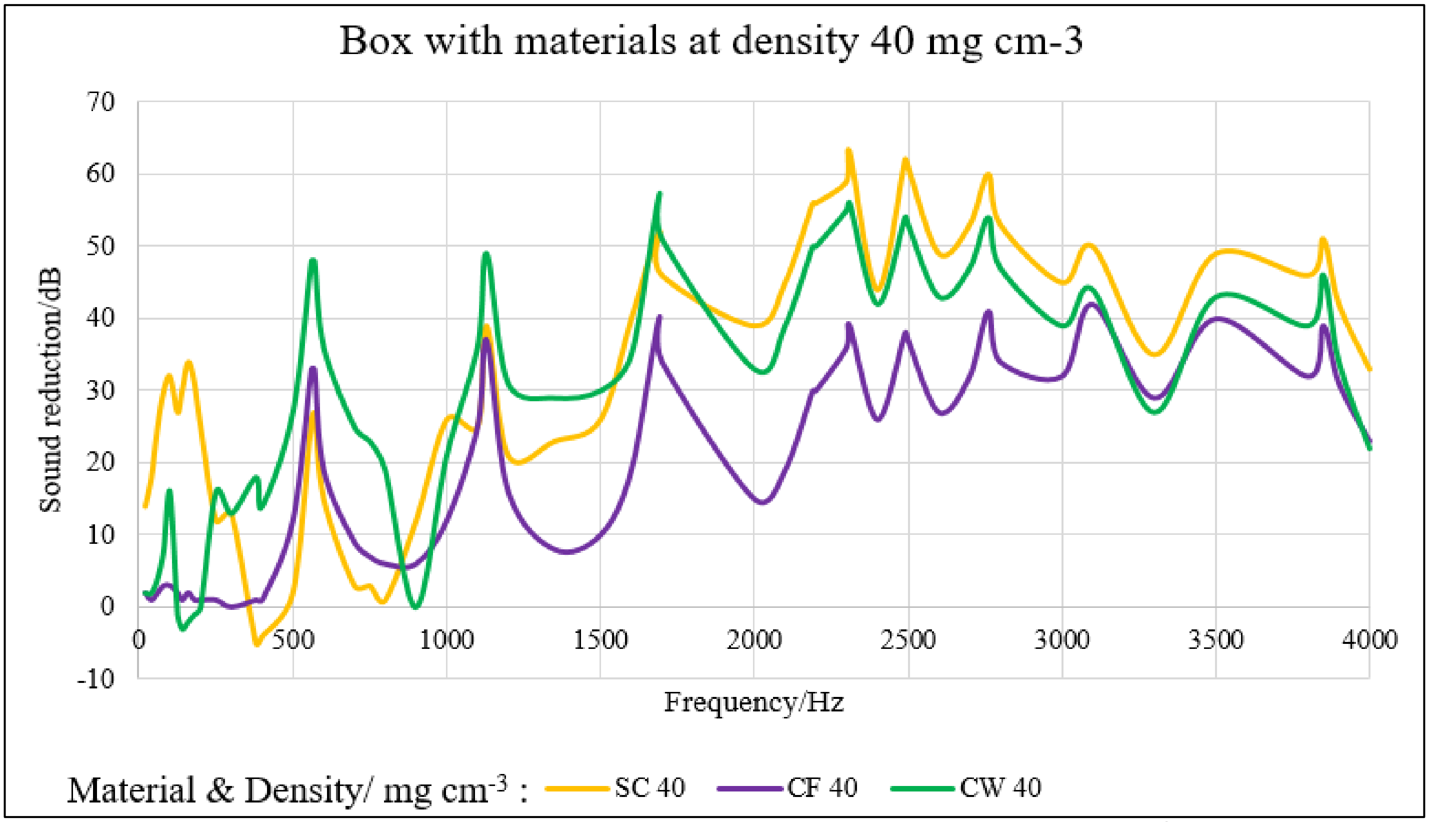

Fig 18c: Graph Showing Sound Reduction Box with Materials at Density 40 mg cm^{-3}

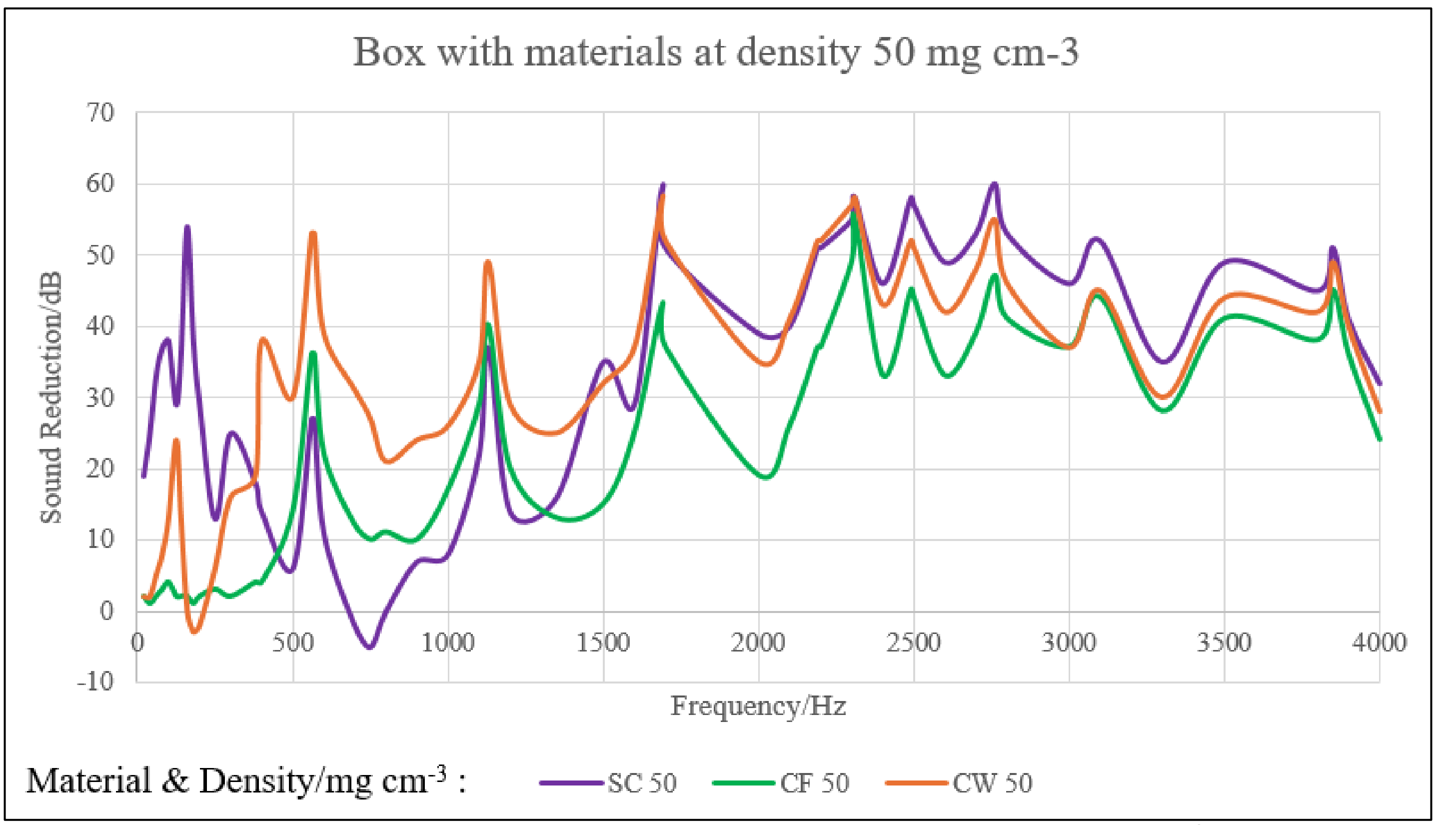

Fig 18d: Graph showing Sound Reduction in Box with materials at density 50 mg cm^{-3}

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/IJISRT24AUG1664

➢ *Processing of Tables and Plotting of Graphs*

Table 3 and its related graphs in Figures 11a and 11b give an overview of the results obtained for the acoustic properties of the empty box and the effects of various densities of silk cotton placed in the box. Also, from Table 3, the other tables for sound reduction and absorbed energy were derived, and the related graphs were plotted using Microsoft Excel. To save space, tables for the effects of the other materials: block foam, chipped foam, and cotton wool, are excluded; however, the relevant graphs are included. For the pipe and its filling materials, only graphs of sound level against frequency are included (Figures 16a, 16b & 16c); sound reduction and h were not found for the pipe. This was because the box was the main emphasis, while the pipe was used for comparison only since it has one mode of vibration, whereas the box has three different vibrational modes.

Sound reduction (SR) was calculated using Equation 13, and the fraction of absorbed energy converted to heat (h) was determined using Equation 14 and the approximate Equation 17. An example is illustrated here. From Table 3, consider the sound levels in the empty box and the box filled with silk cotton at a density of 25 mg cm^{-3} at the first box resonance frequency of 570 Hz. In the empty box at this frequency, SL = 119 dB, and in the box filled with silk cotton of the given density, SL = 75 dB. From Equation 13:

$$SR = I_i\,(\text{dB}) - I_t\,(\text{dB})$$

where SL in empty box = I_i (dB) = 119 dB and SL in filled box =I_t (dB) = 75 dB. The sound reduction due to the silk cotton is therefore SR = 44 dB. The transmission coefficient, t, is given by Equation 14:

$$t = 10^{-\frac{SR}{10}}$$

$$\Rightarrow t = 10^{-4.4} = 4 \times 10^{-5}$$

This dimensionless quantity is the fraction of the incident energy that has been transmitted through the silk cotton in the box according to Equation 7:

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

where I_i and I_t are direct energy values and *not* decibels as in Equation 13. In terms of direct sound intensity values, I_i and I_t can be found using Equation 2:

$$n(\text{dB}) = 10 \log\left(\frac{I}{I_o}\right)$$

Therefore, I = 0.794 Wm^{-2} and I_t = 3.16 × 10^{-5} Wm$^{-2,}$ and the values for t and SR are as given above. The sound has been reduced by a factor of 10$^{4.4}$ = 25,119. The approximate relation Equation 17: 1≈ $h + t$ is then used to determine the fraction of absorbed energy converted to heat. Hence, h = 1 – 4 × 10^{-5} = 0.99996. For a relatively low SR = 2 dB, t = 0.631 and h = 0.369. In this manner, all the necessary calculations for the four materials at the different frequencies and density packings were carried out.

VI. DISCUSSION AND EVALUATION OF THE RESULTS

A. *Resonance*

The resonance frequencies of the box are given in Results Table 3, and they are compared with the theoretical resonance frequencies obtained using Equation 30, which, using the internal dimensions of the box: 0.305 m × 0.15 m × 0.15 m and the speed of sound in air = 348 m s^{-1} at 31°C, becomes:

$$f = 174\sqrt{\left(\frac{n_x}{0.305}\right)^2 + \left(\frac{n_y}{0.15}\right)^2 + \left(\frac{n_z}{0.15}\right)^2}$$

Table 6 below was obtained using trial and error to determine which mode numbers would give experimental resonance frequencies as close as possible to the theoretical ones.

Table 6: Resonance Modes and Resonance Frequencies

MODES					
***n*₁** → n_1	n_2	n_3	**Resonance/No.**	**Theoretical Resonance Frequency/Hz**	**Actual Resonance Frequency/Hz**
1	0	0	1	570	570
2	0	0	2	1141	1130
3	0	0	3	1711	1690
0	2	0	4	2320	2310
4	1	0	5	2560	2490
4	1	1	6	2810	2760
5	0	1	7	3079	3100
6	1	1	8	3796	3850

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/IJISRT24AUG1664

There was an initial resonance at 100 Hz, but this was due to the loudspeaker's mechanical resonance frequency, which was experimentally verified to be 100 Hz. The loudspeaker resonance had a lower sound level than the resonances due to the dimensions of the box.

The first three resonances, shown clearly in the graphs in Figures 11a and 11b, are caused by the first, second, and third harmonics for the length with mode numbers as given in the table above. These resonances are, therefore, set up along the axial mode of length. The fourth resonance is due to the second harmonic (n_y = 2) for either the width or the height of the box since they are equal, and this is also an axial mode of either width or height. At higher resonances, other vibrational modes begin to predominate.

A graph of actual resonance against theoretical resonance is nearly a straight line as in Figure 19 below. It yields a correlation coefficient, r^2 = 0.9988, indicating a close correlation between the experimental and theoretical resonances for the frequency range used. The box resonance equation is, therefore, a fairly accurate predictor of the resonance frequencies of a rectangular enclosure. (Richardson, 1962, p. 268).

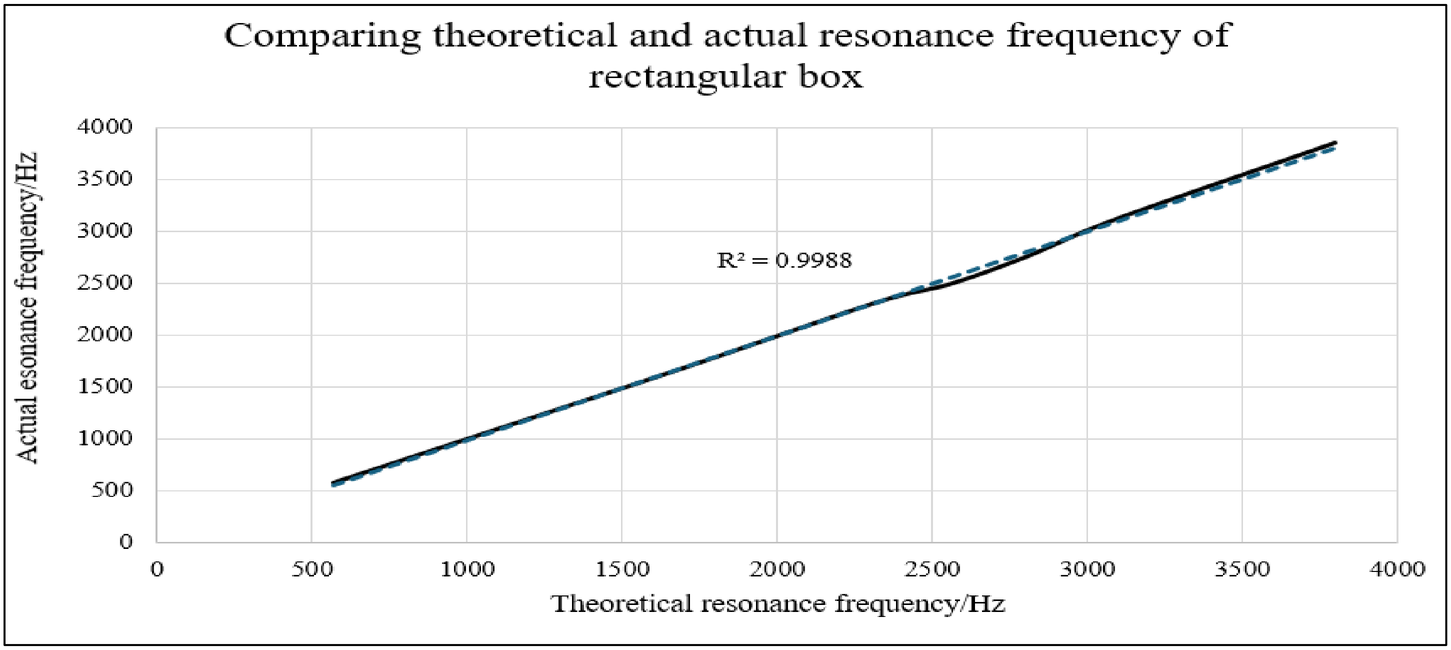

Fig 19: Graph of Theoretical Resonance Frequency vs Actual Resonance Frequency for Box

For the pipe, the theoretical resonances were calculated using Equation 20, which using v = 348 m s^{-1} and x = 0.316 m, becomes f = 550.6 n. Table 7 below compares the theoretical resonances with the experimental ones obtained for the empty pipe.

Table 7: Theoretical and Experimental Resonance for Pipe

Resonance/ Harmonics No.	**Theoretical Resonance Frequency/Hz**	**Actual Resonance Frequency/Hz**
1	551	550
2	1101	1080
3	1652	1590
4	2203	2020
5	2753	2410
6	3304	2740
7	3854	2980
8	4405	3480

The correlation coefficient for the two quantities is r^2 = 0.9894, and the corresponding graph in Figure 20 below yields a gentle curve. The straight line is the trend line.

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/IJISRT24AUG1664

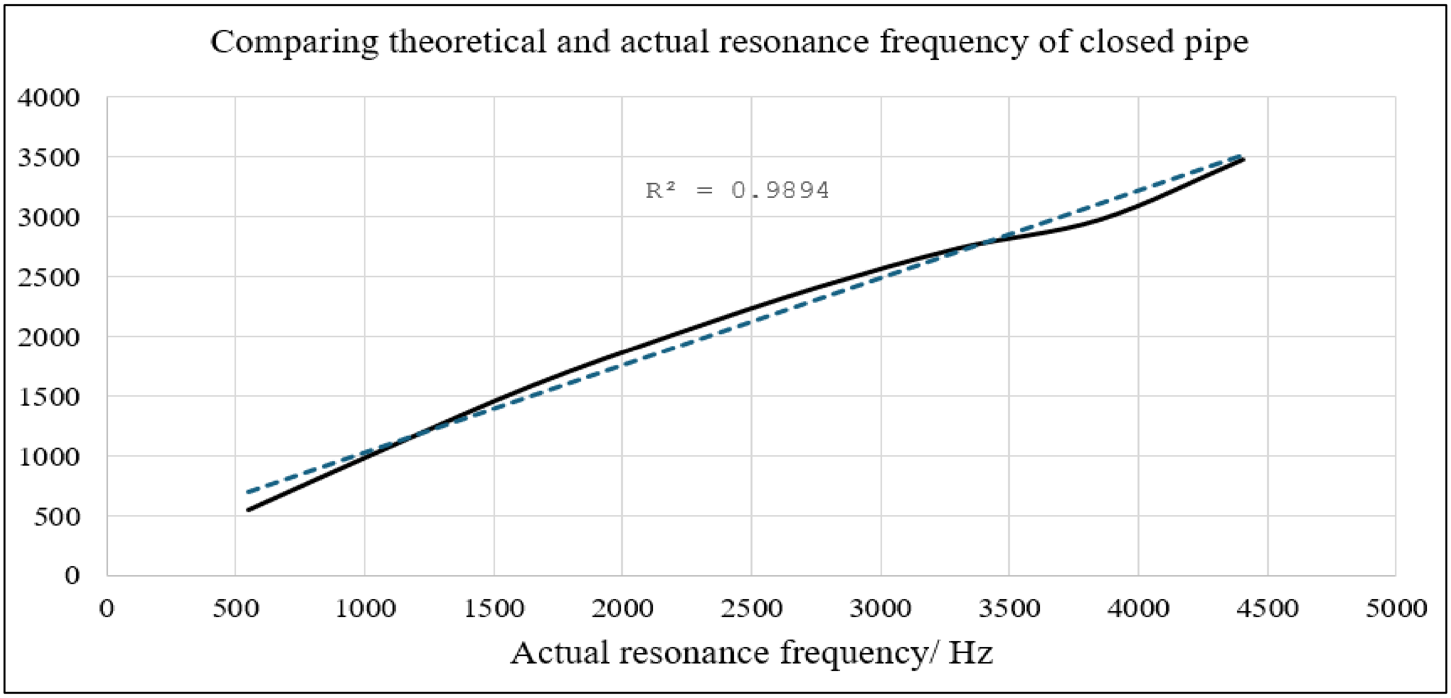

Fig 20: Graph of Theoretical Resonance Frequency Vs Actual Resonance Frequency for Pipe

For the pipe, its internal length of 0.305 m was not used in Equation 20; instead, an *effective* length of 0.316 m was used, which gave a closer agreement with the experimental resonance frequencies. This was most likely because the wooden caps on either end were each 3.25 cm thick and this may have increased the effective internal length of the pipe by 1.1 cm. The loudspeaker resonance frequency of 100 Hz was also observed in the empty pipe.

B. Effect of the Sound-reducing Materials on Resonance

The resonances in the empty box and pipe were significantly reduced or even eliminated when they were filled with the materials at various density packings. In the case of silk cotton, the lightest density of 10 mg cm^{-3} was able to dampen the resonances in both the box and pipe as seen in the graphs in Figure 11a and Figure 16a.

The block foam (open-cell polyurethane foam), which was used only in the box at single density packing of 21.7 mg cm^{-3}, had a good damping effect on resonance as seen in the graph in Figure 14a. Also, for the block foam, the graphs in Figures 14b and 14c show general trend lines which indicate that sound reduction and the fraction of absorbed energy converted to heat increase with frequency.

The sharp peaks in all the frequency versus *SR* graphs are caused by the sharp rise in sound reduction at resonances, that is, the general shape of the *f* vs *SR* graphs is similar to the shape of the *f* vs sound level graphs for the empty enclosures.

However, the material that has the most effective reduction of resonance, especially at frequencies below 200 Hz and above 1000 Hz, is silk cotton. This is evident from Figures 17a to 17d and Figures 18a to 18d. In portions of the graphs, cotton wool surpasses the sound reduction of silk cotton, but in general, silk cotton is a better sound absorber than cotton wool.

C. Sound Reduction Properties of Materials

At frequencies above 2000 Hz, silk cotton is unsurpassed by the other materials. This may be because silk cotton is highly porous as it is composed of extremely fine and light fibres whose diameter is of the order 30 µm and they would vibrate easily with high-frequency sounds, thus absorbing some of the sound energy. Sound energy would also be attenuated by viscous or frictional absorption as the air particles in the material vibrate longitudinally and come into contact with the large surface area of the packed fibres. Cotton wool fibres have a similar diameter, but they are much heavier than silk cotton fibres and, as such would respond less readily to high-frequency vibrations. According to Yarwood (1953), "*In general, porous materials absorb best at high frequencies ...*" (p. 281).

Graphs in Figures 18a – 18d also indicate that silk cotton has good sound reduction properties at frequencies below 200 Hz, with sound reduction peaks being evident around 100 Hz, which is the resonance frequency of the loudspeaker. This is seen in the graphs in Figures 17a to 17d, where there are large dips in sound levels at frequencies 100 – 200 Hz. At this same frequency range, the other materials do not show any significant sound reduction, except for

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/IJISRT24AUG1664

cotton wool, which shows dips in sound level and peaks in sound reduction at densities of 40, 45, and 50 mg cm^{-3}. (Figures 17c & 17d and 18c & 18d). According to Ford (1970), *"Materials which are both flexible and truly porous provide viscous and vibrational absorption. At high frequencies, the viscous absorption predominates while at low frequencies flexibility may supply absorption peaks* (p. 126)." So, the low-frequency absorption of silk cotton may be due to the flexibility of its fibres that respond readily to low-frequency sounds and absorb some of the energy, while its high-frequency absorption may be due to viscous absorption.

D. Negative Values in Sound Reduction and Fraction of Absorbed Energy Converted to Heat

During the experiments, occasional negative values in sound reduction and the fraction of absorbed energy converted to heat were observed. These are seen in the graphs in Figures 12a to 12d and Figures 13a to 13d from frequencies 160 – 750 Hz. These negative values are not physically meaningful and indicate potential issues in the experimental setup. Several factors could contribute to these anomalies:

- Equipment Calibration: Despite regular calibration, minor deviations in the sensitivity of the sound level meter could lead to inaccuracies.
- Environmental Noise: The experiments were conducted in a laboratory environment that, while controlled, was not completely free from external noise interference.
- Material Packing Density: The packing of materials may not have been perfectly uniform. Variations in material distribution could lead to inconsistencies in sound level measurements.

Despite these challenges, the overall trends observed in the data align with established acoustic theories, and the general conclusions regarding the effectiveness of silk cotton and other materials as sound absorbers remain valid.

E. Frequency and Density Dependence of Sound Reduction and Absorption

All the graphs indicate that generally, as frequency increases, sound level decreases and sound reduction increases, indicating that acoustic absorption due to the material increases with frequency. This is seen from the graphs of frequency versus h and frequency versus SR.

The relevant graphs also indicate that, generally, the acoustic absorption of each material increases with its density packing over the frequencies used, especially at higher frequencies. The graphs of density versus h and density versus SR show this general trend. In the case of silk cotton, the graphs in Figures 12c & 12d and Figures 13c & 13d indicate that this material has an optimum density packing for good acoustic absorption at about 30 – 35 mg cm^{-3} for most frequencies between 20 – 4000 Hz. Packing the silk cotton into the box or pipe to higher densities becomes more difficult. This is because of its high resilience and resistance to further compression. There was some difficulty in filling the enclosures to the final silk cotton density of 50 mg cm^{-3}. However, using silk cotton as a sound absorber would not require such a high-density packing. The lowest silk cotton packing density, 10 mg cm^{-3}, achieved considerable sound absorption.

F. The Approximate Relation: $1 \approx h + t$

The approximate Equation 17: $1 \approx h + t$ to construct the frequency versus h graphs and density versus h graphs has been validated to an extent as it indicated that the tested materials were good sound absorbers. For silk cotton at most densities, $h \to 0$ for frequencies below 200 Hz and above 1000 Hz, indicating good acoustic absorption. (Figures 13a and 13b). For chipped foam, h varies widely with frequency and density and only reaches a constant value of $h \approx 1$ at 3500 Hz. At no frequency below 500 Hz does h for chipped foam reach a value of 1 (Figure 15). For block foam, which was only tested in the box at one density (21.7 mg cm^{-3}), h reaches a constant value of ~1 at a frequency of 1700 Hz. (Figure 14c). For cotton wool, $h \approx 1$ at frequencies below 200 Hz and above 1000 Hz, and in this regard, is similar to silk cotton, but this is not true for all the tested densities of cotton wool. The lightest density possible for cotton wool is 30 mg cm^{-3}, while for silk cotton, the lightest possible density is 10 mg cm^{-3}. In this manner, one can use less silk cotton than cotton wool and still achieve comparable acoustic absorption.

However, a caveat is necessary in concluding this section. Equation 17 assumes that the reflection coefficient, r, is negligible. However, like transmission coefficient, t, and sound absorption coefficient, s, the reflection coefficient is also frequency-dependent and may vary considerably with frequency. This would invalidate Equation 17. Therefore, the results for h obtained in this investigation must be treated with some degree of caution and not be taken as the final word. Further investigation using more accurate and precise instruments to measure reflected sound energy would help to clarify this point. Nevertheless, the values for h give a good estimate of the acoustics absorption properties of the tested materials.

VII. CONCLUSION

A. Key Findings

➢ *Effect of Sound-Reducing Materials*

- The addition of sound-reducing materials significantly dampened or eliminated resonances in both the box and the pipe.
- **Silk Cotton:** Proved to be the most effective material for sound absorption, especially below 200 Hz and above 1000

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/IJISRT24AUG1664

Hz. Silk cotton's high porosity and fine fibre structure contributed to its superior absorption properties.

- **Block Foam:** Demonstrated good damping effects in the box at a single density, with an increase in sound reduction correlating with frequency.
- **Cotton Wool:** Showed effectiveness in reducing sound, especially at higher densities, but generally was less effective than silk cotton.

➢ *Material Properties and Frequency Dependence:*

- Silk cotton's high-frequency absorption was attributed to viscous absorption due to its fine, light fibres. Its low-frequency absorption was attributed to the flexibility of its fibres.
- Cotton wool had a similar fibre diameter but was heavier, which made it less responsive to high-frequency vibrations compared to silk cotton.

➢ *Frequency and Density Relationships:*

- Sound reduction generally increased with frequency, and acoustic absorption improved with higher material density.
- Silk cotton showed an optimum density range of 30 – 35 mg cm^{-3} for effective absorption across most frequencies.
- Higher packing densities for silk cotton were challenging to achieve due to its resilience, but even at lower densities, significant sound absorption was observed.

B. Recommendations

These materials, especially silk cotton, can be used in loudspeakers to improve their fidelity of sound reproduction by eliminating undesirable resonance. Silk cotton can also be used as a suitable filling material in ear mufflers. It can also be combined with other sound absorbers to enhance their sound attenuation properties as in sound-reducing helmets and sound-proofing walls.

Although silk cotton is not cultivated commercially in Guyana, the knowledge gained from this investigation can be disseminated so that interested and able persons can explore its potential benefits and consider small-scale or experimental cultivation to assess its viability and economic potential.

C. Areas for Future Research

Work remains to investigate the acoustic absorption properties of local materials obtained from plant fibres and suitable discarded materials. Such materials can be recycled for acoustic purposes, reducing wastage and, at the same time, improving the acoustics of some local situations.

More work can be done to determine the sound reflection properties of the materials. This would require a sound meter equipped with a telescopic microphone probe that can be inserted into an enclosure and the sound pressure and sound intensity variations inside the enclosure be measured.

Future acoustic researchers may devote their energies to determining the speed of sound in different materials to find their acoustic impedance using the appropriate instruments and techniques. Further data analysis should reveal other significant details of the acoustic absorption properties of the selected materials at different frequencies and density packings.

ACKNOWLEDGMENTS

The author thanks the University of Guyana, Turkeyen, and Berbice Campuses for providing the laboratory facilities and the necessary academic, library, and technical support.

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