ACOUSTICAL ABSORPTIVE PROPERTIES OF MULTI-LAYERED POLYLACTIC ACID, COTTON NONWOVEN BATTS AND NEEDLE-PUNCH FABRICS.

By

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DECLARATION

I declare that the work in the dissertation entitled **'Acoustical Absorptive Properties of Multi-Layered Polylactic Acid, Cotton Nonwoven Batts and Needle-Punch Fabrics'** has been performed by me in the Department of Industrial Design, Ahmadu Bello University, Zaria, under the supervision of Prof. K.A. Bello, Dr. Maiwada and Prof. E.G. Kolawole.

The information derived from the literature has been duly acknowledged in the text and a list of references provided. No part of this dissertation was previously presented for another degree or diploma at any university.

_____	_____	_____
Name of Student	Signature	Date

CERTIFICATION

The dissertation entitled "**Acoustical Absorptive Properties of Multi-layered Polylactic Acid, Cotton Nonwoven Batts and Needle-punch Fabrics"** by **Ogunbowale, Wosilat Omotunde** meets the regulations governing the award of degree of Doctor of Philosophy of Ahmadu Bello University, Zaria and it is approved for its contribution to knowledge and literary presentation.

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DEDICATION

This dissertation is dedicated to the Lord God Almighty, for His grace, mercies, steadfast love and abiding presence in my life and all through the course of this study. And also to everyone who supported me in one way or the other for the successful completion of this study.

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ABSTRACT

This study investigated the absorptive properties of nonwoven cotton and Polylactic acid materials. The nonwoven materials used in this study are batts and fabrics made from 100 percent cotton and 100 percent polylactic acid fibres. These are biodegradable from natural source and are environmentally friendly. The fibres were characterised for their properties by subjecting them to different characterisation tests. Twenty samples were produced from the fibres using the nonwoven processing. Layering was achieved by tacking layers of batts in various sequences of 100%, 75%, 50% and 25% of batts respectively to form blend ratios of the fibres of 800g/m^2 area weights (eight layers). The method used for measuring the acoustical properties of the samples is the impedance tube method whereby; sound absorption coefficient is determined at each of the eleven frequency range in accordance with the ASTM 1050 - 08 standards; which tested five specimens from each sample. Both fibre types achieved good absorption, but the results obtained show that eight (8) layers cotton batts absorbed better than cotton fabric and PLA batts and fabric, since its absorption coefficient is closest to one. The results also show that physical parameters such as; fibre type, size, density, cross section, are significant to level of absorption. These parameters and other variables such as: thickness, resistance, layering order, porosity and air permeability were all investigated and their influence on material absorption is found to be positive and significant. This study suggests that these fibres (cotton and PLA) which are environmentally friendly and cost effective will serve as good alternatives to petroleum based fibres which are currently in use.

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DEFINITION OF OPERATIONAL TERMS

Acoustics – Is the science of sound, including its production, transmission, reception, and effects.

Air conduction: The process by which sound travels to the inner ear via a pathway through the air in the outer ear canal; then utilizing the tympanic membrane and the ossicles.

Ambient noise: The all-encompassing noise associated with a given environment at a specified time, being usually a composite of sound from many sources at many directions, near and far; no particular sound is dominant.

Ambient sound: The all-encompassing sound associated with a given environment at a specified time, being usually a composite of sound from many sources at many directions, near and far including the specific sound source(s) of interest.

Amplitude: The maximum value of a sinusoidal quantity.

Audible sound: Acoustic oscillations that is capable of exciting the sensation of hearing.

Background noise: The total noise from all sources other than a particular sound that is of interest.

Band: A segment of the frequency spectrum.

Bel: A unit of level of which denotes the ratio between two quantities proportional to power; the number of bels corresponding to this ratio is the logarithm to the base 10 of this ratio. [1 bel = 10 decibels (dB)]

Cycle: Of a periodic quantity, the complete sequence of values of a periodic quantity that occurs during a period.

Cycles per second (cps): A unit of frequency, same as hertz (Hz)

Damping: The dissipation of energy in an oscillating system, with either time or distance.

Decay rate: At a given frequency, the time rate at which the sound pressure level in a room decreases. Unit: decibel per second. Unit symbol: dB/s.

Decibel: A unit of level which denotes the ratio between two quantities that are proportional to power; the number of decibels is 10 times the logarithm (to the base 10) of this ratio.

Direct sound: Sound which reaches a given location in a direct line from the source, without any reflection.

Echo: A sound that has been reflected with sufficient magnitude but with a time delay such; as to be distinguishable as a repetition of the direct sound.

Flow resistance: The ratio of the difference of air pressure across a sheet of porous material to the volume of airflow through the sheet. It is measured in pascal second per meter.

Frequency: Is a function of period in time, the number of times that the quantity repeats itself in 1 second (i.e., number of cycles per second). It is measured in hertz.

Infrasonics: The sound of frequency less than 20HZ.

Ldn: The day-night equivalent value of sound level. The day is counted from 6AM to 9PM

(15hrs) and night from 9PM- 6AM (9hrs).

Noise: Noise is unwanted sound.

Octave: The frequency interval between two sounds echoes frequency ratio is two (2).

Pascal: Is a unit of pressure. [1 pascal = 1 Newton per square meter].

Rayl: One rayl equals 1 pascal-second per meter (Pa . s/m).

Receiver: A person (or persons) or equipment which is affected by noise.

Refraction: The phenomenon by which the direction of propagation of a sound wave is changed as a result of a spatial variation in the speed of sound

Resonance: Of a system in forced oscillation, a phenomenon such that any change, however small, in the frequency of excitation results in a decrease in the response of the system.

Sabin: A unit of measure of sound absorption; a measure of the sound absorption of a surface.

Sone: The unit of loudness. One sone is the loudness of a pure tone presented frontally as plane progressive waves of 1000 Hz and a sound pressure level of 40 dB, 20 micropascals (μpa).

Sound: Sound is a form of energy emitted by a vibrating body and on reaching the ear it causes the sensation of hearing through nerves.

Sound absorption: The process of dissipation of sound energy.

Sound absorption coefficient: The fraction of the randomly incident sound power which is absorbed (or otherwise not reflected) by a material.

Tortuosity: Is the ratio between the passageway through the pores and the thickness of the porous material.

Ultrasonics: The sound of frequency more than 20,000 H

ABBREVIATIONS:

A – Total sound absorption

c – Speed of sound

CI - Confidence interval

Batts – Webs of fibres

Bel – 10 decibels

dB - Decibels

dB SPL - decibel(s), sound pressure level.

dBA - Decibel(s), A-weighted

EPA - U.S. Environmental Protection Agency

f - Frequency

hr - Hour(s)

HTL - Hearing threshold level

Hz - Hertz

ISO - International Standards Organization

I – Sound intensity

kHz - Kilohertz

min – Minutes

ms - Millisecond

NIHL - Noise-induced hearing loss

NRR - Noise reduction rating

Pa - Pascal

Pa . s/m - Pascal second per meter.

PEL - Permissible exposure limit

PLA – Poly(lactic) acid fibre

REL - Recommended exposure limit

s - Second(s)

SIC - Standard industrial classification

SPL - Sound pressure level

STS - Standard threshold shift.

CHAPTER 1

INTRODUCTION

In the present age noise is an ever-increasing problem everywhere in the world, especially in the developing countries where Government regulation is not being enforced against public disturbance. Sources of noise are now on the increase and they are steadily growing louder. Noise pollution was once considered an irritating but harmless nuisance, but has now become a major threat to health and well-being. It is a public nuisance, and causes undue distractions, contributes to health problems, stress and eventually can lead to lower productivity. This explains why most people love a quiet environment and are willing to pay for it. In places such as homes, hospitals, offices, hotels, schools and learning environment where one expect to be quiet, are not even exempted from noise pollution in some societies.

Sound is a physical disturbance in a medium (in a gas, liquid, or solid) that the human ear could easily detect. It is a series of longitudinal or compression waves that move through air or other materials which must have mass and elasticity. It travels through matter as a mechanical vibration in a form of wave. Harris (1991) stated that, sound does not travel in a vacuum or in outer space but in a medium. Sound is a mechanical energy which will always find the path of least resistance from the source to the outside world.

In noise control, Conrad (1983) believed that frequency (f) and wavelength (λ) are related because the frequency of a wave is measured as the number of complete cycle. (i.e. back-and-forth vibrations) of a wave particle per unit of time and it is measured in Hertz (Hz).

While the wavelength is the length of the repeating patterns, wave is the distance which a disturbance travels along the medium in one complete wave cycle. The illustration of simple sound wave is shown in Figure 1.1.

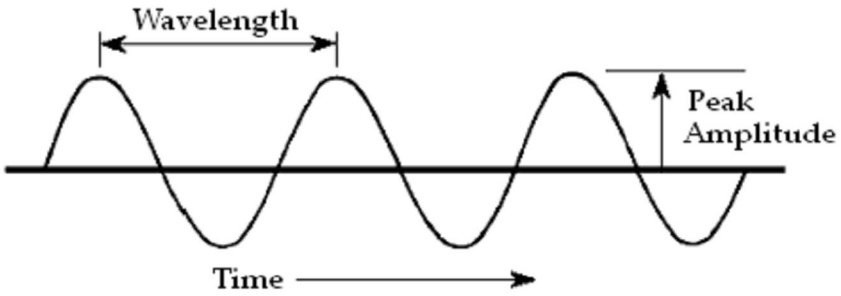


Figure 1.1 Illustration of simple sound wave

$$\text{Wavelength [m]} = \frac{\text{Speed of sound [m/sec]}}{\text{Frequency [Hz]}} \qquad (1.2)$$

Here wave is described in terms of variables like: amplitude, frequency, wavelength, period and intensity. The difference between maxima and minima pressure is referred to as amplitude**.** The term 'period' can be defined as the time required for the completion of one cycle of wave motion (Conrad, 1983). The intensity of a sound wave is defined as the average rate at which sound energy is transmitted through a unit area.

Stacy (1959) defined sound absorption as a measure of the propagation of sound energy falling on a surface, which is not reflected; it is expressed as a coefficient or percentage of the incident energy; which could be 0.5 or 50 percent absorbency. Noise absorbing material absorb sound by dissipating sound wave energy when it passes through, and also convert

some of the energy into heat. Absorption coefficient is the amount of the original energy less the remaining unabsorbed energy; it is the total absorbed energy.

Sound proof and acoustic materials are useful in attenuating, deadening, or controlling sound and noise levels from machinery and other sources for environmental amelioration and regulatory compliance. Sound absorptive or acoustic materials can be either noise reductive or noise absorbent. A noise absorption material suppresses echoes, resonance reverberation and reflection, while noise reduction reduces the energy of sound waves as they pass through. Important specifications for noise reduction and noise absorption products include noise attenuation and noise reduction coefficient. Noise attenuation is the reduction in sound pressure level (SPL) that an acoustic product provides and it is measured in decibels (dB). Noise reduction coefficient (NRC) is the average of an acoustic material's absorption coefficients at a specified set of frequencies, typically 250 Hz, 512Hz, 1024 Hz and 2048 Hz in accordance with the type of tube and acoustic measuring instrument used for tests. Absorption coefficients range between 0 (zero) and 1 (one) and are often evaluated at many frequencies in the audible range in order to create a performance curve for the material throughout the audio spectrum. The understanding of a comprehensive sound phenomenon would lead to an effective noise control.

In sound production, three components are required: a sound source, a medium, and a detector. The sound source is a vibrating body that produces a mechanical movement or sound wave. The medium, such as air, transfers the mechanical wave. The detector, such as an ear, detects the sound wave (Vaughn *et al.*, 2003).

One of the most important design issues today for the building / automotive industries is sound insulation. Textile materials are effective in converting the mechanical motion of the air particles in sound waves into low-grade heat. Almost all materials have some kind of acoustical property. However, materials that absorb a majority of the sound impinging upon them rather than reflecting the sound are termed “acoustical material”. These are materials considered in terms of its acoustical properties, especially materials that are designed to absorb sound.

Sound absorbing materials are attracting much attention as a solution to the ambient noise impact on people’s lives as they have been reported to perform greatly. (Jayaraman, 2005).

Nonwoven fabrics are “sheets or web structures bonded together by entangling fibre or filaments” (INDA, 2009). In a wide range of applications, nonwoven fabrics have been in use as acoustic absorptive materials and are still in use for acoustic ceilings in vehicles, wall claddings and acoustic barriers in buildings. Although, the conventional fibres mostly used are glass-fibres and polyurethane foams; they are neither biodegradable nor recyclable. Nonwoven fabrics are ideal materials for use as acoustical insulation products because they have high total surface. The surface area of the fabric is related to the denier directly and cross-sectional shape of the fibres in the fabric. Smaller deniers yield more fibres per unit weight of the material, higher total fibre surface area and greater possibilities for a sound wave to interact with the fibres in the structure. Another important parameter is the packing density of the fibres in the nonwoven material. More fibres per unit volume at the same fabric thickness yield greater possibilities for sound waves to interact with the fibres. Fabric density also affects the geometry and the volume of the voids in the fabric structure.

1.2 Background of the Study:

The impetus for this study stemmed from the understanding of the effect of noise on the health and wellbeing of a community and the drawbacks associated with some of the existing sound absorbing materials such as; felts made from glass, asbestos, rock, wool and foams. Some of these drawbacks include the fact that the materials are unsuitable for moulding, and at the same time they are not recyclable, difficult to handle and install, dust accumulating and in the case of foams are high in density.

The World Health Organization (WHO), (1992) has documented seven categories of adverse health effects of noise pollution on humans namely; hearing impairment, interference with spoken communication, sleep disturbances, cardiovascular disturbances, and disturbances in mental health; impaired task performance; negative social behaviours and annoyance reactions, (Williams L. and Wilkins, 2007).

The traditional definition of noise is "unwanted or disturbing sound**".** Sound becomes unwanted when it either interferes with normal activities such as sleeping, conversation, or disrupts or diminishes one's quality of life. The air around us is filled with sounds, yet most of us would probably not be aware that we are surrounded by noise. However, for some, the persistent and escalating sources of sound are annoying. This "annoyance" can have major consequences, primarily to one's overall health. Noise pollution is a significant environmental problem in many rapidly urbanizing

communities. This problem is yet to be recognized despite its steady growth in developing countries. It has become obvious that noise is a potential health hazard. It is an imposition upon human comfort, health and quality of life, (Ahmad, 1998).

Noise is a physical pollutant that is difficult to comprehend because the sensitivity of human ear adjusts automatically to the ambient level of sound which causes the increases in the ambient level to go unnoticed. Therefore, noise continues to do the damage silently. Pollution, in general, is a by-product of some essential function or activity. Therefore, it is almost impossible to eliminate the pollutant, but it can be controlled or reduced. In Nigeria today, there is no legal framework upon which noise pollution can be abated. Federal Environmental Protection Agency (FEPA) (1974); in Nigeria only provided daily noise exposure limits for workers in industry (i.e. 90 dB(A) for 8hr exposure, (Oyedepo and Saadu, 2010).

The Nigerian Government and her citizenry appear not to be conscious that the present and future impacts of noise-induced health hazards in their environment. It is typical of places of religious worship calling for prayers and ordering services with the loudest externally mounted megaphone. Top government officials using siren on their vehicles to herald their presence, impatient motorists blaring horn in vehicles, musical shops tuning music loud for advertisement in every part of the community, the upsurge use of electric generating plant with its accompanying noise to augment the erratic power supply; to mention but a few. With this background, it has become imperative to address the issue of noise pollution.

In seeking for solutions for noise pollution, issues with the global warming and the adverse effects of air and water pollution has increased the public awareness about the adverse effects of synthetic materials on the environment. Most of the researches on sound absorption

characteristics of fibrous materials have been devoted to glass fibre mats, foam and other synthetic fibres. Non-woven fabrics offer an environmentally friendly alternative to glass fibre mats due to their lower weights, and production methods with lower impact levels on the environment.

In the acoustical industry, fibreglass has been a common leading material for sound absorption for the past four or five decades, (Tascan, 2005). They are used as ceiling tiles, duct liners, mats and blankets. Attenborough and Ver (2006) stated that; due to issues with health and safety concern, polyester nonwovens are increasingly replacing glass fibre mats. According to Fahy (2001), these materials are used as trimmings on passenger vehicles, and Jayaraman, (2005) reported that they are also used in interior lining for apartments, aircrafts ducts, as enclosures for noisy equipment and as insulations for appliances. In the application sector, the policy measures of European Member States concerning the End-of-Life-Vehicle-Directive (also referred to as 'Scrap' vehicles) lay upon a marked reduction in the use of virgin materials during the manufacturing process and an increase in the amount of recyclable materials recovered during dismantling, (Kandachar and Brouwer, 2002).

In developed countries growing environmental issues, such as the green house effect coupled with the growing awareness of the adverse effects of some synthetic materials on the environment is driving manufacturers to seek more ecologically friendly production materials. Moreover, industries are under pressure of new rules and regulations to effect responsible environmental practices by selecting materials and process technology with minimal adverse impact level on the environment (Hughes, 2004). Whereas, in developing countries lack of proper recycling, careless disposition of worn-out equipment and trash from dilapidated building with harmful substances is becoming a threat to healthy environment and human

health. It is these foregoing reasons that necessitate the search for more environmentally friendly materials being used in this research.

1.3 Statement of the Problem

Noise is an ever-increasing problem everywhere in the world which has made sound insulation one of the most important design issues today for the building and automobile industries. Different activities such as lectures, seminars, meetings now run simultaneously at adjacent rooms to maximize space; these require some noise control measures. In addition, issues with environmental protection are driving industries focus on natural fibrous materials in industrial textile application. Synthetic sound absorbing materials require advanced technology to manufacture, not only that, they are not recyclable and not environmentally friendly. There is a growing public awareness about the adverse effects of synthetic materials on the environment.

The problem of this study therefore, is to provide a better understanding of the effects of some manufacturing processes on nonwovens' noise control performance and also to contribute to the wider adoption of cotton and polylactic acid nonwoven materials as sound absorbers.

1.4 Aim of the Study

The aim of this study is to provide a better understanding of acoustical properties of nonwovens materials by evaluating how effective cotton and PLA nonwoven batts and fabrics are in absorbing sound energy. The study will also seek to understand the various factors that influence the sound absorptive capacity of nonwovens; with particular interest in knowing the effect that fibre type and layering order have on the materials comparing the effectiveness of batts and fabrics as sound absorbing materials.

1.5 The Objectives of the Study

The main objective of this study is to investigate the noise control performance of Cotton and Polylactic acid nonwoven batts and fabrics, but with a view to achieve these other objectives:

1. To explore the feasibility of using natural fibres such as cotton and poly(lactic) acid (PLA) fibres in acoustical applications.
2. Determine the effects of layering arrangements in sound attenuation.
3. To evaluate if nonwoven absorbers can serve as a replacement for petroleum based sound absorbers.
4. To find out other parameters that influences the acoustical ability of fibres.
5. To establish which fibre type absorbs best on exposure to certain frequency level of noise.

1.6 Research Questions:

1. Can natural fibrous textile material be used to absorb sound energy?
2. How can layering structure and fibre type affect the effectiveness of the acoustical absorptive properties of nonwoven batts?
3. Could cotton and PLA be a good replacement of fibreglass mat, foams and other synthetic fibres used for sound absorption?

4. What are the other parameters that influence the acoustical ability of fibres.

5. How can frequency affect the Noise Reduction Coefficient (NRC) of an acoustic absorption material?

1.7 Justification for Study:

One of the most important design issues today for the building / automotive industries is sound insulation. Textile materials are effective in converting the mechanical motion of the air particles in sound waves into low-grade heat. Reducing the undesired or harmful effects of sound is a goal for every sound engineer. The most popular techniques consist in blocking the sound transmission path using porous acoustic material treatments. It has now become a necessity to control noise from its path, since most of the industrial machines, vehicles for high speed transportation, labour saving devices in homes and offices, electricity energy generating sets are all accompanied by noise (Hirabayashi *et al.,* 1991).

This study would only be focusing on the absorption aspect of sound, where sound energy is converted into thermal energy.

The cost of redesigning, developing and retooling is high and may not be easily attainable, the treatment of noise receiver is the least desirable approach since each receiver may have to be treated individually, treatment of the noise path is conceptually the simplest and therefore the most common approach to a localized noise problem. The approach is to place the

material in the path of the noise (mostly between the noise source and the noise receiver) so as to reduce the level of noise at the receiver's end.

It is necessary to treat at least one element in the noise system if we are to reduce the perceived level of the noise. By reducing the noise level at the source or along the path, we would have reduced the noise level at the receiver end. Treating the receiver individually in such a way to minimize the sensitivity to high noise levels is another option; however, this method is seldom put to use.

In Nigeria, the problem of noise pollution is wide spread. Several studies report that noise level in metropolitan cities exceeds specified standard limits. A study by Ugwuanyi *et al*. (2004) conducted in Makurdi, Nigeria found that the noise pollution level in the city was about 3 dB(A) to 10 dB(A) above the recommended upper limit of 82 dB(A). Onuu and Menkiti, (1993) also found that the peak noise level ranges between 86-106 dB(A)

In the 1970s, a series of events related to public health concerns made makers of sound absorbing materials change the main constituents of their products from asbestos-based materials to new synthetic fibres.

More recently, issues related to global warming caused by the emission of greenhouse gases into the atmosphere by industrial manufacture of materials is now changing the acoustical materials market. The production of synthetic materials contributes to the emission of carbon dioxide (mostly from power plants and transportation), methane, and nitrous oxide. Thus, the total set of greenhouse gas emissions caused directly and indirectly by material production affects its carbon content. Moreover, the concept of "green" building materials is commonly in practice in several European countries. In addition, public awareness are concern about the negative effects of pollution has led consumers to favour environmentally friendly materials,

less contaminating processes, and recycled products. Therefore, it is important to increase research on acoustical materials based on renewable resources that can lead to viable alternatives to conventional materials for current and future applications, (Nick, et al. 2005; Asdrubali, 2006).

Recent advances in material science, chemistry, and nanotechnologies are producing significant improvements in the design, production, and performance of acoustical materials. These advances include the use of natural fibres, bio-based polymers, recycled and surplus materials, porous metals, new composites, and smart materials. If natural materials made from cotton and corn kernel are used either as acoustical draperies, divider panels, acoustical screens, acoustical wall or ceiling, the issues of noise pollution and health concern with the use of synthetic materials would be addressed.

1.8 Scope of the Study:

The study covers the fibre characterization, their various properties, and the method employed in the production of the nonwoven batts, and fabrics. The various physical and structural tests carried out on both batt and fabrics are inclusive in this study. Determination of the factors that influence sound absorption, coupled with the effects of fibre type and layering structure on sound absorption at different frequencies for the acoustical tests. All these tests including the Scanning Electron Microscope (SEM) of the fibres were carried out at the College of Textiles and The Nonwovens Cooperative Research Center (NCRC) of the North Carolina State University, Raleigh, U.S.A. In addition, the resultant data generated from the acoustical test was analyzed using the Statistical Analysis System (SAS) program.

CHAPTER 2

Literature Review

This chapter presents a review of the related literature with the intent to obtain broadbase knowledge from renowned authority on the subjects related to acoustics, acoustical absorptive materials, production of non-woven, noise pollution and its effects as well as factors that influence sound absorption, sound measurement and its units.

2.1 Noise

Noise is meaningless sound of greater than usual volume, thus, a loud activity can be referred to as being noisy. However, conversations of other people may be called noise. Noise can also be any unwanted sound such as the noise of dogs barking, neighbours playing loud music, road traffic sounds, chain-saws, or aircraft, spoiling the quietness of the countryside.

The word noise is derived from the Latin term nausea. It has been defined as unwanted sound, a potential hazard to health and communication dumped into the environment with regard to the adverse effect it may have on unwilling ears, (Jaiswal, 2003).

Noise, a by-product of urbanization and industrialization is increasingly recognized as an environmental nuisance that affects human health and well-being, (Mansouri et al. 2006). City noise levels can be investigated in three different ways as traffic and transportation, industrial activities, Sports, marketing and entertainment facilities. In comparison to other pollutants, the control of environmental noise has been hampered by insufficient knowledge of its effects on human and lack of defined criteria. Noise pollution is a significant environmental problem in many rapidly urbanizing areas. This problem is not properly recognized yet despite the fact that it is steadily growing in developing countries.

It is well established now that noise is a potential hazard to health, communication and enjoyment of social life. It is becoming an unjustifiable interference and imposition upon human comfort, health and quality of life, (Ahmad, 1998). Noise as a physical pollutant is not easily recognized, this is because the sensitivity increases in the ambient level go unnoticed. Therefore, noise continues to do the damage silently. In general, pollution is a by-product of some essential function or activity. Therefore, it is almost impossible to eliminate the pollutant, but it can be controlled or reduced. Most of the pollutants can be tolerated only up to a certain level, the level being dependent on the type of the pollutant. When the level of pollution continues to increase, it becomes necessary to know the level above the permissible limit so that their increase can be checked by the introduction of suitable regulations. To know the level of pollution, the pollutant has to be measured. In the case of noise pollution, measurement is essential because of the incapability of our auditory system to recognize slow changes.

2.2 Noise Pollution

According to Miglani, (2011), the present generation and the coming generations have to solve three grave problems, namely; population, poverty, and pollution if they have to survive. Pollution is the most dangerous problem; it is like cancer in which death is sure but slow. Environment pollution is assuming dangerous proportions all through the globe as a result of modern living, industrialization and urbanization.

Broadly speaking, the noise pollution has two sources; industrial and non- industrial. The industrial source includes the noise from various industries and big machines working at a very high speed and high noise intensity. Non- industrial source of noise includes the noise created by transport/vehicular traffic and the neighbourhood noise generated by various activities.

Noise pollution can also be divided in these categories, namely; natural and manmade. Most leading noise sources will fall into these following categories: roads traffic, aircraft, railroads, construction, industry, noise in buildings, and consumer products, (D'Silva, 2009).

The subject of noise pollution is one of the most silent of all forms of pollutions, it is the least spoken about of other forms of pollutions, nevertheless; it is causing as much health issues as the other forms of pollutions do.

2.2.1 Sources of noise

All transportation systems create noise pollution. With residences created adjacent to factories, they experience noise pollution and its adverse effects. Besides transportation noise, noise can come from factory appliances, power generating sets, power tools and audio entertainment systems, (Ogunbowale, 2010).

2.2.2 Measures of noise

Sound is measured in units called decibels. Decibel is the standard for the measurement of noise. The zero on a decibel scale is at the threshold of hearing, the lowest sound pressure that could be heard. As recorded in most literatures, 20 db is a whisper, 40 db the noise in a quiet office. 60 db is normal conversation, 80 db is the level at which sound becomes physically painful and at 120 decibels the ear is in pain and hearing begins to be damaged at 85 decibels. The effects of noise are determined mainly by the duration and level of the noise, but they are also influenced by the frequency. Long-lasting, high-level sounds are the most damaging to hearing and generally the most annoying. High-frequency sounds tend to be more hazardous to hearing and more annoying than low-frequency sounds. The way sounds are distributed in time is also important, in that intermittent sounds appear to be somewhat less damaging to hearing than continuous sounds because of the ear's ability to regenerate during the intervening quiet periods, (Suter, 1991).

On the decibel scale, an increase of 10 means that a sound is 10 times more intense, or powerful. To the ears, it sounds twice as loud. Sources of noise that are able to cause noise induced hearing loss include motorcycles, firecrackers, and small firearms, all emitting sounds from 120 to 150 decibels. Long or repeated exposure to sounds at or above 85 decibels can cause hearing loss. The louder the sound, the shorter the time period before noise induced hearing loss can occur. Sounds of less than 75 decibels, even after long exposure, are unlikely to cause hearing loss, (Miglani, 2008).

2.2.3 Effects of noise pollution

The World Health Organization (WHO), (2007) defines health as "A state of complete physical, mental, and social well-being and not merely the absence of disease or infirmity." This broad definition of health embraces the concept of well-being, and thereby renders noise impacts "health" issues. Noise effects could be broadly categorized into two: auditory (noise-induced hearing/loss) and non-auditory (behavioural and physiological effects). Behavioural effects are those that are associated with activity interference. This includes interference with communication, rest or sleep, and learning; or that produces annoyance. Non-auditory physiological health effects include such things as cardiovascular disease and hypertension, (Miller, 1997).

Noise pollution can take a severe toll on human health on the long run. These effects will not become apparent immediately, but there could be repercussions later on. The following is a list of the kinds of effects noise pollution will have on human health after continuous exposure for months, and even years, (D'Silva, 2009).

Unfortunately a large number of people work in industrial plants, where the noise level found consistently high, and the exposure takes place regularly for about 8-10 hours a day, year after

year, the effects cease to be temporary and even permanent hearing loss, rather than leading to significant adverse physiological effects. Studies on human working in noisy environments have reported an increased incidence of heart disease, accident at work, inefficiency, feeling of annoyance, irritation, speech and work interference, sleep disturbance, cancer, headache, tension, digestive, respiratory, nervous problems and so many psychological effects on human system, (Memom, 2006).

There is fairly consistent evidence that prolonged exposure to noise levels at or above 90 dB(A) cause deafness. The degree of deafness depends upon the length of exposure, as most plants work 8 hours per day for 6 days a week, or 9 hours per day for 5 days a week, with no noise control measures properly adopted. In most of the developing countries, ear protectors are not worn during work, (Memon, 2010). However, noise is more often than not a major problem in terms of quality of human life in specific localities.

2.2.4 Human Health

Noise pollution disturbs our health and behaviour in a number of ways including deafness, causing lack of sleep, irritability, indigestion, heartburn, high blood pressure, ulcers, and heart disease. According to D'Silva, (2009) just one noise explosion from a passing truck drastically alters our endocrinal, neurological, and cardiovascular functions in many individuals. If this is prolonged or frequent, the physiological disturbances become chronic and contribute to mental illness.

2.2.5 Hearing Impairment

Hearing is essential for well-being and safety. Hearing impairment is typically defined as an increase in the threshold of hearing as clinically assessed by audiometry. Impaired hearing may come from the workplace, from the community, and from a variety of other causes (eg,

trauma, ototoxic drugs, infection, and heredity). There is general agreement that exposure to sound levels less than 70 dB does not produce hearing damage, regardless of the duration of exposure, (Berglund Lindvall , 1999). There is also general agreement that exposure for more than 8 hours to sound levels in excess of 85 dB is potentially hazardous, to place this in context, 85 dB is roughly equivalent to the noise of heavy truck traffic on a busy road. With sound levels above 85 dB, damage is related to sound pressure (measured in dB) and to time of exposure. The major cause of hearing loss is occupational exposure, although other sources of noise, particularly recreational noise, may produce significant deficits. Studies suggest that children seem to be more vulnerable than adults to noise induced hearing impairment. (Berglund and Lindvall, 1999).

Noise induced hearing impairment may be accompanied by abnormal loudness perception (loudness recruitment), distortion (paracusis). and tinnitus. Tinnitus may be temporary or may become permanent after prolonged exposure. (Berglund and Lindvall, 1999) The eventual results of hearing losses are loneliness, depression, impaired speech discrimination, impaired school and job performance, limited job opportunities, and a sense of isolation.

2.2.6 Interference with Spoken Communication

The Environmental Protection Agency, (1974); (EPA) in an attempt to protect public health and welfare against the adverse effects of noise, published safe levels of environmental noise that would permit normal communication both in and out of doors.

Noise pollution interferes with the ability to comprehend normal speech and may lead to a number of personal disabilities, handicaps, and behavioural changes. These include problems

with concentration, fatigue, uncertainty, lack of self confidence, irritation, misunderstandings, decreased working capacity, disturbed interpersonal relationships, and stress reactions. Some of these effects may lead to increased accidents, disruption of communication in the classroom, and impaired academic performance [American Academy of Paediatrics', Committee on Environmental Health (2003). Particularly vulnerable groups include children, the elderly, and those not familiar with the spoken language.

2.2.7 Sleep Disturbances

Uninterrupted sleep is known to be a prerequisite for good physiologic and mental functioning in healthy individuals. Environmental noise is one of the major causes of disturbed sleep. When sleep disruption becomes chronic, the results are mood changes, decrements in performance, and other long-term effects on health and well-being. According Suter (1991) much recent research has focused on noise from aircraft, roadways, and trains. It is known, for example, that continuous noise in excess of 30 dB disturbs sleep. For intermittent noise, the probability of being awakened increases with the number of noise events per night.

The primary sleep disturbances are difficulty falling asleep, frequent awakenings, waking too early, and alterations in sleep stages and depth. Apart from various effects on sleep itself, noise during sleep causes increased blood pressure, increased heart rate, increased pulse amplitude, vasoconstriction, and changes in respiration, cardiac arrhythmias, and increased body movement (Hobson, 1989). For each of these, the threshold and response relationships may be different. Some of these effects (waking, for example) diminish with repeated exposure; others, particularly cardiovascular responses, do not. Secondary effects or so-called after effects measured the following day include; fatigue, depressed mood and well-being, and

decreased performance (Carter, 1996). Decreased alertness leading to accidents, injuries, and death has also been attributed to lack of sleep and disrupted circadian rhythms, (Cohen, 1980).

Long-term psychosocial effects have been related to nocturnal noise. Noise annoyance during the night increases total noise annoyance for the following 24 hours. Particularly sensitive groups include the elderly, shift workers, persons vulnerable to physical or mental disorders, and those with sleep disorders.

Other factors that influence the problem of night-time noise include its occurrence in residential areas with low background noise levels and combinations of noise and vibration such as produced by trains or heavy trucks. Low frequency sound is more disturbing, even at very low sound pressure levels; these low frequency components appear to have a significant detrimental effect on health, (Leventhal 2004).

2.2.8 Impaired Task Performance

The effects of noise pollution on cognitive task performance have been well-studied. Noise pollution impairs task performance at school and at work, increases errors, and decreases motivation. Reading attention, problem solving, and memory are most strongly affected by noise. Two types of memory deficits have been identified under experimental conditions: recall of subject content and recall of incidental details. Both are adversely influenced by noise. Deficits in performance can lead to errors and accidents, both of which have health and economic consequences.

Cognitive, language development and reading achievement are diminished in noisy homes, even though the children's schools may be noisier than average (Bronzaft 2000). Cognitive

development is impaired when homes or schools are near sources of noise such as highways and airports. Lee and Fleming, (2002). Noise affects learning, reading, problem solving, motivation, school performance, and social and emotional development. These findings suggest that more attention needs to be paid to the effects of noise on the ability of children to learn and on the nature of the learning environment, both in school and at home. Moreover, there is concern that high and continuous environmental noise may contribute to feelings of helplessness in children. [Evans and Lepore, (1993). Bronzaft (1996)] reported that increased noise levels gives rise to a lack of concentration and accuracy at work, and reduce one's productivity and performance. Difficult tasks can be impaired and instructions or warnings become difficult to be heard and interpreted thus causing accidents.

2.2.9 Disturbances in Mental Health

Noise pollution is not believed to be a cause of mental illness, but it is assumed to accelerate and intensify the development of latent mental disorders. Noise pollution may cause or contribute to the following adverse effects: anxiety, stress, nervousness, nausea, headache, emotional instability, argumentativeness, and sexual impotence, changes in mood, increase in social conflicts, neurosis, hysteria, and psychosis. Population studies had suggested associations between noise and mental-health indicators, such as rating of well-being, symptom profiles, the use of psychoactive drugs and sleeping pills, and mental-hospital admission rates. Children, the elderly, and those with underlying depression may be particularly vulnerable to these effects because they may lack adequate coping mechanisms. Berglund and Lindvall, (1995) discovered that children in noisy environments find the noise annoying and report a diminished quality of life.

Noise levels above 80 dB are associated with both an increase in aggressive behaviour and a decrease in behaviour helpful to others. The news media regularly report violent behaviour arising out of disputes over noise; in many cases these disputes ended in injury or death. The aforementioned effects of noise may help explain some of the dehumanization seen in the modern, congested, and noisy urban environment, (Babisch, 2005).

2.2.10 Noise Control:

Technically, noise control measures can be classified into three groups. The primary methods include modifications of the noise source to reduce noise generation. Secondary solutions concern impeding sound propagation from the source to the human ear, and the third noise control measure is to protect the sound receiver such as use of earplugs, earmuffs, etc. The primary method which may require reconstruction of machines and other noise emitting technical equipments; are generally constrained by non-acoustic factors such as cost and technological requirements (Kuttruff, 2007). Treatment of the noise receiver may not always be a practical solution, as each receiver would have to be treated individually. Therefore, treatment of the noise path is conceptually the simplest and the most common approach in noise reduction. Secondary noise control constitutes enclosure of noise sources, vibration isolation, noise barrier, noise absorption, reactive and dissipative silencing. This work focuses on the absorption phenomenon of sound.

"The process of dissipating sound energy" is known as sound absorption (ASTM C 634). Every sound wave is subject to continuous reduction by certain dissipative processes whether it is propagating through air or porous materials. However, the sound dissipation in propagation through porous materials is much stronger than it is through air (Kuttruff, 2007).

2.3 Acoustics:

Is the interdisciplinary science that deals with the study of all mechanical waves in gases, liquids, and solids including vibration, sound, ultrasound and infrasound, (Bies. and Hansen, 2003).

The Latin synonym is "sonic", after which the term sonic used to be a synonym for acoustics and later a branch of acoustics. (http://books.google.com) After acousticians had extended their studies to frequencies above and below the audible range, it became conventional to identify these frequency ranges as "ultrasonic" and "infrasonic" respectively; while the word "acoustic" refer to the entire frequency range without limit.

The application of acoustics can be seen in almost all aspects of modern society with the most obvious being the audio and noise control industries.

Hearing is one of the most crucial means of survival in the animal world, and speech is one of the most distinctive characteristics of human development and culture. So it is no surprise that the science of acoustics spreads across so many facets of our society; music, medicine, architecture, industrial production, warfare and more. Art, craft, science and technology have provoked one another to advance the whole, as in many other fields of knowledge.

2.3.1 Wave Propagation: Pressure Levels

In fluids such as air and water, sound waves propagate as disturbances in the ambient pressure level. While this disturbance is usually small, it is still noticeable to the human ear. The smallest sound that a person can hear, known as the threshold of hearing, is nine orders of magnitude smaller than the ambient pressure. The loudness of these disturbances is called the sound pressure level (SPL), and is measured on a logarithmic scale in decibels, (Conrad J., 1983)

2.3.2 Transduction in Acoustics

A transducer is a device for converting one form of energy into another. In an acoustical context, this usually means converting sound energy into electrical energy (or vice versa). For nearly all acoustic applications, some type of acoustic transducer is necessary. Acoustic transducers include loudspeakers, microphones, hydrophones and sonar projectors. These devices convert an electric signal to or from a sound pressure wave. The most widely used transduction principles are electromagnetism, electrostatics and piezoelectricity.

2.3.4. Wave Propagation or Frequency:

A sound pressure level is referred to as frequencies by physicists and acoustic engineers, partly because of the way the human ear interpret sound. What are termed the "higher pitched" or "lower pitched" sounds are pressure vibrations having a higher or lower number of cycles per second**.** In a common technique of acoustic measurement, acoustic signals are sampled with time and are presented as octave bands or time frequency plot. The entire spectrum is divided into three sections: audio, ultrasonic, and infrasonic. The audio range falls between 20 Hz and 20,000 Hz. This range is important because the human ear can detect its frequencies. This range has a number of applications including speech communication and music. The ultrasonic range refers to the very high frequencies: 20,000 Hz and higher. This range has shorter wavelengths that allow better resolution in imaging technologies. Medical applications such as ultrasonography and elastography rely on the ultrasonic frequency range. On the other end of the spectrum, the lowest frequencies are the infrasonic range. These frequencies can be used to study geological phenomena such as earthquakes.

(http://www.physics.byu.edu/research/acoustics Sound energy is propagated in alternate pattern of dense and sparse particles as illustrated in figure 2.1 below:

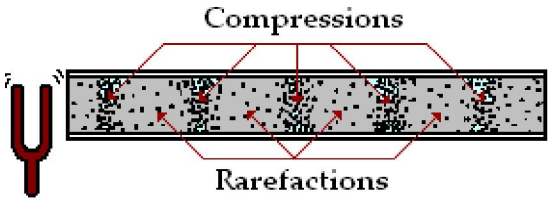


Fig. 2.1: Alternative patterns of dense and sparse particles

The resultant variation to normal ambient pressure is translated by the ear and perceived as sound.

2.4 Sound

Sound is the sensation produced at the ear by very small pressure fluctuations in the air; the fluctuations in the surrounding air constitute a sound field. It is a mechanical vibration transmitted through an elastic medium travelling in air at a speed of approximately 1087 ft. (331 m) per second at sea level (Bies and Hansen (1980). The amplitude of these pressure changes is stated in terms of sound level and the rapidity with which these changes occur is the sound's frequency. Sound level is measured in decibels (abbreviated dB), and sound frequency is stated in terms of cycles per second or Hertz which is abbreviated (Hz). Sound level in decibels is a logarithmic rather than a linear measure of the change in pressure with respect to a reference pressure level. A small increase in decibels can represent a large increase in sound energy. Technically, an increase of 3 dB represents a doubling of sound energy and an increase of 10 dB represents a tenfold increase. The ear however, perceives a 10-dB increase as doubling of loudness, (Harris, 1991).

Another important aspect of sound is the duration and the way it is distributed in time. Continuous sounds have little or no variation in time; varying sounds have differing maximum

levels over a period and intermittent sounds are interspersed with quiet periods while impulsive sounds have the character of being relatively high in sound levels with short durations.

2.4.1 The Sound Pathway

Every day, we experience sound in our environment, such as the sounds from television and radio, household appliances, and traffic. Normally, we hear these sounds at safe levels that do not affect our hearing. However, when we are exposed to harmful noise/sound that are too loud or loud sounds that last a long time sensitive structures in our inner ear can be damaged, causing noise-induced hearing loss (NIHL). These sensitive structures, called hair cells, are small sensory cells that convert sound energy into electrical signals that travel to the brain. Once damaged, our hair cells cannot grow back, (National Institutes of Health, 1990).

Noise induced hearing loss can be caused by a one-time exposure to an intense "impulse" sound, such as an explosion, or by continuous exposure to loud sounds over an extended period of time.

Although being aware of decibel levels is an important factor in protecting one's hearing, distance from the source of the sound and duration of exposure to the sound are equally important. A good rule of thumb is to avoid noises that are "too loud" and "too close" or that last "too long", (National Institutes of Health 1990).

2.4.2 Absorption

As sound travels through any medium, there is some loss due to absorption. Since sound is a regular vibration of the atoms or molecules in a material, some of the kinetic energy of the waveform is lost due to molecular collisions. That sound energy is turned into random heat energy, (Bies and Hansen, 2003).

The absorption of sound mainly results from the dissipation of acoustic energy due to viscosity and heat conductivity of the medium. Attenborough and Ver (2006) cite the friction between the solid body (fibre) of the absorber and the fluid moving in it (air) as the main cause of sound attenuation. Similarly, Cox and D'antonio (2004) refer to the friction due to viscosity of air as the primary cause and thermal conduction as the secondary cause of the sound energy loss. Fahy, (2001) explains the sound absorption phenomena on a molecular level as a combination of viscosity, thermal diffusion and relaxation processes which take place in the boundary layers next to "pore" surfaces.

2.4.3 How Sound Travel

Sound waves can travel through almost anything, but they must travel through something. That something is called a medium, or conductor. Sound waves travel faster through denser (thicker) mediums. Water is denser than air; solids are denser than liquids, etc. They cannot travel as light waves would through completely empty space where there is no air. Light travels faster than sound. Therefore, you can sometimes see something before the sound of it reaches you. Think of thunder as an example: you might see a flash of lightening, but the crash (noise) produced by the lightning bolt (thunder), is not heard for several seconds after the flash of lightening, (Harris, 1991).

2.4.4 How Sound is absorbed

Sound is mechanical energy. The energy displayed by the source is transferred into the medium through which it travels. When the wave, the moving energy comes into contact with a surface, some of the energy is transferred into the surface. The more solid and "less moving" the surface seen on a tiny scale, the less the moving air waves, those compression and

rarefaction waves can transfer energy into the surface. This is what determines how much sound is absorbed when sound hits surfaces. The "softer" the surfaces, the more those pressure waves in air affect the surface and transfer their energy into it.

From studies, it is concluded that not all sound that hits matter is absorbed, some of it is reflected. That means sound bounces off the solid matter the way a tennis ball bounces off a wall. Sound reflected back to its source is an echo as illustrated in figure 2.2 below

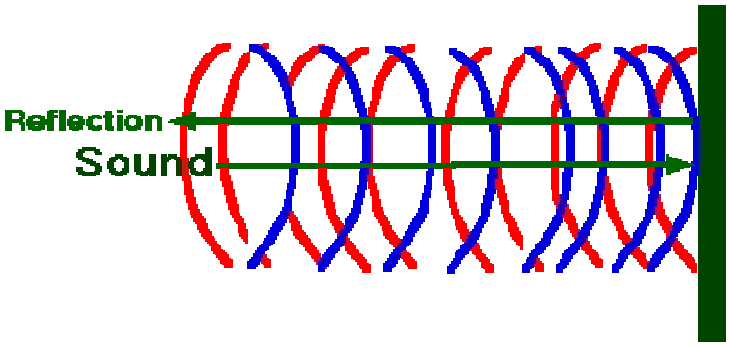


Figure 2.2 Sound absorption and reflection in a medium (Harris, 1991)

When sound strikes soft materials, much of the sound is absorbed. A sound insulator is a material that absorbs most of the energy of sound waves. Once you know how different materials affect sound, you can make it to work.

2.4.5 Acoustic Testing:

Is the process by which acoustic characteristics of materials are determined in terms of absorption, reflection, and impedance; admittance and transmission loss. There are different methods to determine the acoustic properties of materials. These methods involve mainly the exposure of materials to be tested to known sounds fields and

measuring effects; in order to ensure accuracy and repeatability, there is a range of standards covering material testing.

2.4.6 Sound Absorptive Materials

According to Bell, (1994) these are materials that reduce the acoustic energy of a sound wave as the wave passes through it by the way of absorption, and they are commonly used to soften the acoustic environment of a closed volume by reducing the amplitude of the reflected waves.

Absorptive materials are generally resistive in nature, either fibrous, porous or in rather special cases reactive resonators (Bies and Hassen, 2003). Classic examples of resistive materials are nonwovens, fibrous glass, mineral wools, felt and foams. Resonators include hollow core masonry blocks, sintered metal and so on. Most of these products provide some degree of absorption at nearly all frequencies and performance at low frequencies typically increases with increasing material thickness (Bell, 1994).

Fibrous, porous and other kinds of materials have been widely accepted as sound absorptive materials. Literatures from these following authors: Sides et al. (1971); Parikh et al (2001); Shosani and Rosehouse (1991) and Banks-lee. et al. (1992); showed that nonwovens could be considered a prospective candidate for sound absorption.

Some materials absorb sound more than others. Drapes and ceiling tiles are used to absorb unwanted sound and eliminate echoes. Music recording studios use sound absorbing materials on their walls to eliminate any undesired or outside sounds, when recording a song.

2.4.7 Porous sound absorbing materials:

Fabrics, non-woven materials in particular are representative of porous materials. Because these materials are composed of pores whose cavities are connected to one another, open-cell porous materials permit fluidic communication throughout the part.

Sound propagates through an interconnected pore network, which results in sound energy dissipation as found in porous absorbers. These are only effective at mid to high frequency range which is the frequency range which the ear is most sensitive to; hence, where noise control is most necessary, (Cox and D'antonio, 2004).

Porous sound absorbing materials are used for the control of automotive acoustics, room acoustics, industrial noise control, and recording studio acoustics. Sound absorbers are generally used to decrease the undesirable sound reflection from hard, rigid and interior surfaces in order to reduce the reverberant noise levels (Kuttruff, 2007).

Porous absorbers may be classified as cellular, granular, or fibrous materials. Cellular materials include foams from polymers such as polyurethane and increasingly from metals, like aluminium. In order to be an effective absorber, the foam should have an open-pore structure, i.e. pores should be interconnected to allow for air flow from one to the other face of the foam. Although there are concerns about fire hazard and release of toxic combustion by-products, plastic foams are widely used as sound absorbers. Whereas polyurethane foams are the most common type according to Attenborough and Ver, (2006) of plastic foams; metal foams have an advantage over them in terms of mechanical strength (Wright, 2005).

2.5 Factors Influencing Sound Absorption of Nonwoven Materials

Studies on various parameters that influence the sound absorption properties of fibrous materials have been published widely in the literature. A summary of those work are given below.

2.5.1 Fibre Size

Koizumi et al. (2002) reported an increase in sound absorption coefficient with a decrease in fibre diameter. This is because, thin fibres can move more easily than thick fibres on sound waves. Moreover, with fine denier fibres more fibres are required to get equal volume and density which results in a more tortuous path and higher airflow resistance. A study by Lee et al. (2004) concluded that the fine fibre content increases sound absorption coefficient; (NAC) values.

The increase was due to an increase in airflow resistance by means of friction of viscosity through the vibration of the air. A study by Koizumi et al.(2002) also showed that fine denier fibres ranging from 1.5 - 6 denier per filament (dpf) perform better acoustically than coarse denier fibres. Moreover it has been reported by Koizumi et al., (2002) that, micro denier fibres (less than 1 dpf) provide a dramatic increase in acoustical performance.

2.5.2 Fibre Surface Area

Previous work done by Kyoichi et al., (1999) indicated a direct correlation between sound absorption and fibre surface area. Their study explained the fact that friction between fibres and air increases with fibre surface area resulting in a higher sound absorption. Moreover it has been said that, in the frequency range 1125 Hz – 5000 Hz, fibres with serrated cross sections (e.g., Kenaf) absorb more sound compared to ones with round cross sectional area. Hur *et. al,* (2000), further explained that the sound absorption in porous material is due to the

viscosity of air pressure in the pores or the friction of pore wall. Therefore, sound absorption increases with specific surface area of fibre with increase of relative density and friction of pore wall.

Man-made fibres are available in various cross sectional shapes for instance: hollow, trilobal, pentalobal and other novel shapes like 4DG fibres. These cross sectional shapes can add acoustical value by providing more surface area than normal round shaped fibres.

2.5.3 Airflow Resistance

One of the most important qualities that influence the sound absorbing characteristics of a nonwoven material is the specific flow resistance per unit thickness of the material. The characteristic impedance and propagation constant, which describes the acoustical properties of porous materials, are governed to a great extent by flow resistance of the material (Ren and Jacobson, 1999). Fibres interlocking in nonwovens are the frictional elements that provide resistance to acoustic wave motion. In general, when sound enters these materials, its amplitude is decreased by friction as the waves try to move through the tortuous passages. Thus the acoustic energy is converted into heat (Conrad, 1983). This friction quantity which can be expressed by resistance of the material to airflow is called airflow resistance and is defined in equation (2.1) as:

$$R_1 = \frac{\Delta p}{\Delta T u} \; mks\; Rayls/m \qquad (2.1)$$

where: R_1 = Specific flow resistance, mks Rayls/m^2

u = Particle velocity through sample, m/sec

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

ΔT = Incremental thickness, m^2

Note: The unit that is generally used for the flow resistance is Rayls ($N.S/m^3$ x10). According to Delany et al (1970) flow resistance is proportional to the material bulk density and fibre size. Fibre packing density decreases the air permeability with a resultant increase in pressure drop and hence flow resistance [(Bies and Hansen, 1980), (Imam and Asano, 1982)].

Based upon the airflow test, ASTM D-1564 (1971), flow resistance R of the sample is obtained from the following equation.

$$R = Pvl \qquad (2.2)$$

where: P = Static pressure differential between both faces of the sample, dyn/cm^2

(10-1 Pa)

v = Air velocity, cm/s

l = Thickness of sample, cm

The airflow resistance per unit thickness of a porous material is proportional to the coefficient of shear viscosity of the fluid (air) involved and inversely proportional to the square of the characteristic pore size of the material. For a fibrous material with a given porosity, this means that the flow resistance per unit thickness is inversely proportional to the square of the fibre diameter (Ingard, 1994).

2.5.4 Porosity

Number, size and type of pores are the important factors that one should consider while studying sound absorption mechanism in porous materials. To allow sound dissipation by friction, the sound wave has to enter the porous material. This means, there should be enough pores on the surface of the material for the sound to pass through and get dampened. The porosity of a porous material is defined as the ratio of the volume of the voids in the material to its total volume.

$$Porosity\ (H) = \frac{V_a}{V_m} \qquad (2.3)$$

where: *Va* = Volume of the air in the voids

Vm = Total volume of the sample of the acoustical material being tested. Shoshani *et. al.,* (2003) stated that, in designing a nonwoven web to have a high sound absorption coefficient, porosity should increase along the propagation of the sound wave.

2.5.5 Tortuosity

Tortuosity is a measure of the elongation of the passage way through the pores, compared to the thickness of the sample. According to Knapen *et al.* (2003), tortuosity describes the influence of the internal structure of a material on its acoustical properties. Wassilieff (1996) describes tortuosity as a measure of how far the pores deviate from the normal, or meander about the material. It was stated by Horoshenkov *et al.* (2001) that, tortuosity mainly affects the location of the quarter-wavelength peaks, whereas porosity and flow resistivity affect the height and width of the peaks. It has also been said by the value of tortuosity determines the high frequency behaviour of sound absorbing porous materials.

Along with tortuosity, the inner structure of porous materials has been described by the term 'structure factor' by Beranek, (1992) has given the approximate relation between porosity (*Y*)

and structure factor (*K*) for homogenous materials made of fibres or granules with interconnecting pores.

2.5.6 Thickness

The thicker the material, the higher is the sound absorption; resistance to flow is achieved through the depth of the material. Generally, when the thickness of the material matches one tenth wavelengths of the incidence sound, effective sound absorption is achieved. At a resonance frequency of one-quarter wavelength of the incidence sound, peak sound absorption occurs, (Yilmaz *et al*., 2008).

The rule of thumb rule that has been followed is the effective sound absorption of a porous absorber is achieved when the material thickness is about one tenth of the wavelength of the incident sound, (Coates and Kierzkowski, 2002) Peak absorption occurs at a resonance frequency of one-quarter wavelength of the incident sound ignoring compliance effect (Hirabayashi *et.al.,* 1991).

A study by Ibrahim *et al.* (1978) showed the increase of sound absorption only at low frequencies, as the material gets thicker. However, at higher frequencies thickness has insignificant effect on sound absorption. When there is air space inside and behind the material, the maximum value of the sound absorption coefficient moves from the high to the low frequency range (Koizumi *et al.* 2002)

2.5.7 Density

Density of a material is often considered to be the important factor that governs the sound absorption behaviour of the material. At the same time, cost of an acoustical material is directly related to its density. A study by Koizumi et al. (2002) showed the increase of sound absorption value in the middle and higher frequency as the density of the sample increased. The number of fibres increases per unit area when the apparent density is large. Energy loss increases as the surface friction increases, thus the sound absorption coefficient increases.

Moreover, a presentation by (www.inda,org/automotiveinteriorshow/innotherm) has showed the following effect of density on sound absorption behaviour of nonwoven fibrous materials.

Less dense and more open structure absorbs sound of low frequencies (500 Hz), denser structure performs better for frequencies above 2000 Hz.

2.6 Mechanism of Sound Absorption in Fibrous Materials

The most important mechanism of sound in porous materials is due to viscosity and to some extent, heat conduction. As materials generally are either porous structure of rigid or flexible form in which the pore size is small, typically in order of a few thousands of an inch.

Many authors have explained this dissipation of acoustic energy to heat. Fridolin *et al*. (1992) describe the mechanism of sound dissipation as: when sound enters porous materials, owing to sound pressure, air molecules oscillate in the interstices of the porous material with the frequency of the exciting sound wave. This oscillation results in frictional losses. A change in the flow direction of sound waves, together with expansion and contraction phenomenon of flow through irregular pores, results in a loss of momentum.

Owing to exciting of sound, air molecules in the pores which undergo periodic compression and relaxation. These results in change of temperature due to length of time, large surface to volume ratios and high heat conductivity of fibres, heat exchange takes place isothermally at low frequencies. At the same time in the high frequency region compression takes place adiabatically. In the frequency region between these isothermal and adiabatic compression, the heat exchange results in loss of sound energy. This loss is high in fibrous materials if the sound propagates parallel to the plane of fibres and may account up to 40% sound attenuation. So, altogether the reasons for the acoustic energy loss when sound passes through sound absorbing materials are due to: frictional losses, momentum losses and temperature fluctuations. And these are all microscopic and physical material parameters of porous material that can be readily measured.

2.7 Sound absorption coefficient

Sound absorption coefficient is a simple way of defining the sound absorption behavior of a surface. It is the ratio of the energy absorbed by the sound absorber to the incident sound energy. Normal and random sound absorption coefficients are the two commonly-used types, (Cox and D'antonio, 2004).

Normal-incidence sound absorption coefficient, αn, is the fraction of the perpendicular incident sound power absorbed by a surface at a specified frequency or otherwise not reflected according to ASTM C 634 08a Standard Terminology Relating to Building and Environmental Acoustics. Random-incidence sound absorption coefficient, α, with the unit of metric sabin/m^2, is the measure of the random-incidence sound absorptive property of a

material in a specified frequency band determined by the sound decay/reverberation time, (ASTM C 634 08a; Attenborough and Ver, 2006).

Normal-incidence sound absorption coefficient may be measured according to ASTM E 1050-08 Standard Test Method for Impedance and Absorption of Acoustical Materials Using "A Tube, Two Microphones and A Digital Frequency Analysis", as shown in Fig.2.3. Random-incidence sound absorption coefficient may be measured according to ASTM C 423 – 08a Standard Test Method for Sound Absorption and Sound Absorption Coefficients by the Reverberation Room Method.

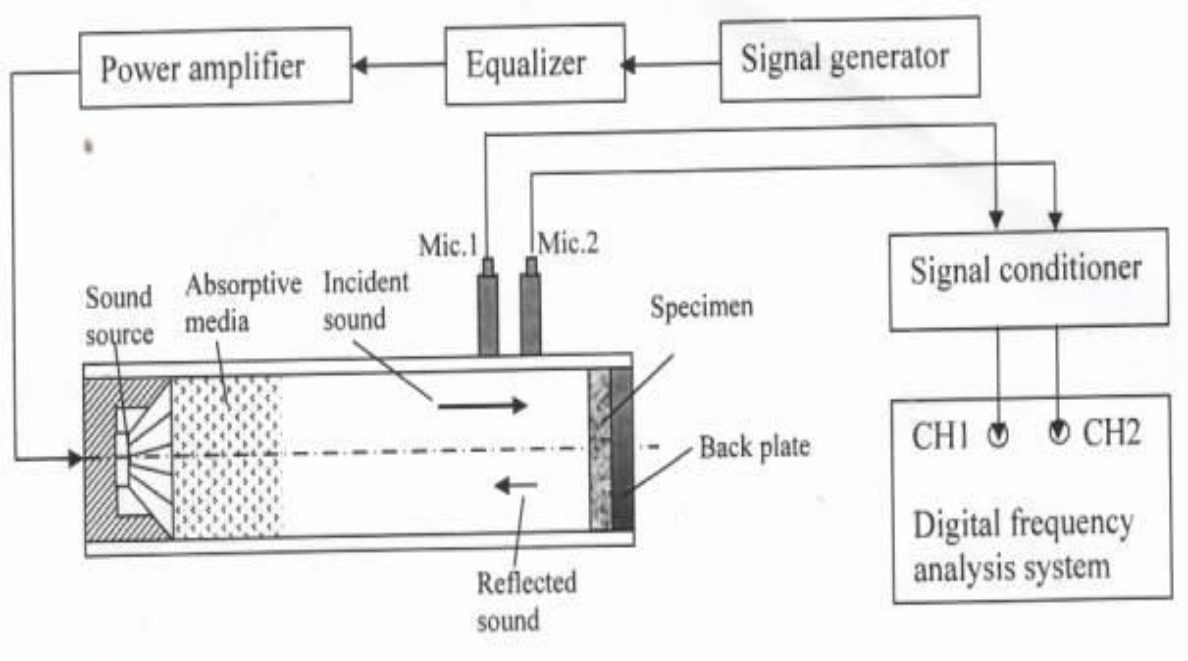


Fig. 2.3: Schematic diagram of acoustical material testing system. ***This is adapted from ASTM E 1050-08 and Bruel & Kjaer, (2009)***

Normal-incidence sound absorption coefficient, αn, which is the ratio of the absorbed or otherwise not reflected energy to the incident energy of plane waves propagating

perpendicular to the surface of the absorber, is adopted in the present research. *αn* can range from 0 (no absorption) to 1 (total absorption). The formulation below defines *αn*:

2.8 Calculations for Sound Absorption Coefficients

The sound absorption coefficient indicates how much of the sound is absorbed in the actual material. The absorption coefficient can be expressed as:

$$\alpha = {}^{I_a}/_{I_i} \qquad .(2.4)$$

where

I_a = sound intensity absorbed (W/m^2)

I_i = incident sound intensity (W/m^2)

2.8.1 Mean Absorption Coefficient

The mean absorption coefficient for the room can be expressed as:

$$a_m = {}^{A}/_{S} \qquad (2.5)$$

where

a_m = mean absorption coefficient

A = the absorption of the room (m^2 Sabine)

S = total surface in the room (m^2)

A room acoustic characteristic can be calculated with the formulas above, or estimated for typical rooms.

2.8.2 Total Room Sound Absorption

The total sound absorption in a room can be expressed as:

$$A = S_1\alpha_1 + S_2\alpha_2 + S_n\alpha_n = \sum S_i\alpha_i \qquad (2.6)$$

where :

A = the absorption of the room (m^2 Sabine)

S_n = area of the actual surface (m^2)

α_n = absorption coefficient of the actual surface include porosity, flow resistance and weight. (www.EngineeringToolBox)

2.9 Nonwovens

By definition; nonwoven is a manufactured sheet, web or batt of directionally or randomly orientated fibres, bonded by friction, and/or cohesion and/or adhesion, excluding paper and products which are woven, knitted, tufted, stitch-bonded incorporating binding yarns or filaments, or felted by wet-milling, whether or not additionally needled. The fibres may be of natural or man-made origin. ISO 9092:1988 – Textiles – Nonwovens.

Nonwovens are engineered fabrics made from fibres and polymers. They are manufactured by high-speed, low-cost process, large volume and lower cost than the traditional processes. Nonwovens are in many applications already, but most are still hidden and we do not see them, (Banks-lee., 2010).

These properties are often combined to create fabrics suited for specific jobs, while achieving a good balance between product use-life and cost. They can mimic the appearance, texture and strength of a woven fabric and can be as bulky as the thickest padding. In combination with other materials they provide a spectrum of products with diverse properties, (www.technicaltextile.net)

2.9.1 Nonwoven Fabrics

The Association of Nonwoven Fabrics Industry (INDA) (2008) defines nonwoven fabrics as sheet or web structures bonded together by entangling fibre or filaments (and by perforating films) mechanically, thermally or chemically. They are flat, porous sheets that are made directly from separate fibres or from molten plastic or plastic film. They are not made by weaving or knitting and do not require converting the fibres to yarn (http://www.inda.org/category/nwn_index.html).

Nonwoven fabrics which are fibrous porous materials have an important use in noise reduction. Nonwovens have some advantages over cellular absorbers i.e. foams; such as low production costs and low specific gravity. Nonwovens can also be friendlier to the environment than conventional sound absorbers of polyurethane foams, which are unable to be recycled and have environmentally damaging manufacturing methods (Yilmaz *et al*. 2009).

Fibreglass has been a leading sound-absorbing material for the last four or five decades, as ceiling tiles, duct liners, mats, and blankets from fibreglass have been the commonly used in the acoustical industry (Tascan, 2005). Polyester nonwovens are increasingly replacing glassfibre mats where there are health and safety concerns (Attenborough and Ver, 2006). These materials are used as passenger vehicle trims Fahy, (2001), interior lining for apartments, aircraft ducts, as enclosures for noisy equipment, and as insulations for appliances, (Jayaraman, 2005).

As stated by Shoshani and Yakubov, (1999). Noise control applications of nonwoven fabrics include wall claddings, acoustic barriers and acoustic ceilings, passenger vehicle, noise absorbers, and various others.

2.9.2 Structures of Nonwoven

As stated by Tescan, (2005) rigid materials because of their high-density, high cost and are also heavy; they cannot be used for sound insulation for the automotive and building industries. Nonwoven materials are more suitable for these industries, and they can also absorb sound in order to decrease sound pollution in the environment. Therefore, nonwoven materials are one of the most important materials for sound insulation and absorption applications material.

The structure of nonwovens only has fibres and voids that are filled by air. Voids that are covered by fibres are called pores in nonwoven structures and their geometry is very important, especially for the absorption properties of nonwovens.

2.9.3 Production of nonwovens

There are two major steps in nonwoven production, namely, web forming and web bonding. Web forming involves the conversion of staple fibres or filaments into a two-dimensional (web) or three-dimensional (batt) fibrous structure. Web formation has a crucial role in the determination of the fibre orientation in the final product.



Fig. 2.4: A perspective view of 3D virtual carded/hydroentangled web. ***(Jaganathan et al, 2008b).***

The lack of sufficient frictional forces in the formed web has to be compensated for by the second step which is web bonding. Web bonding has an important effect on the mechanical properties, porosity, flexibility, and density of the resultant nonwoven fabric (Wilson, 2007). There are three ways of bonding:

- Chemical bonding (use of binders)

- Thermal bonding (calendering, through-air blowing, or ultra-sonic impact)

- Mechanical bonding (needling, stitching, water-jet entangling), (Massenaux, 2003).

These properties are often combined to create fabrics suited for specific jobs, while achieving a good balance between product use-life and cost. They can mimic the appearance, texture and strength of a woven fabric and can be as bulky as the thickest paddings. In combination with other materials they provide a spectrum of products with diverse properties.

Nonwoven manufacture starts by the arrangement of fibres in a sheet or web. The fibres can be staple fibres packed in bales, or filaments extruded from molten polymer granules. Four basic methods are used to form a web and nonwovens are usually referred to by one of these methods:

- Drylaid
- Spunmelt
- Wetlaid
- Other techniques

2.9.4 Drylaid

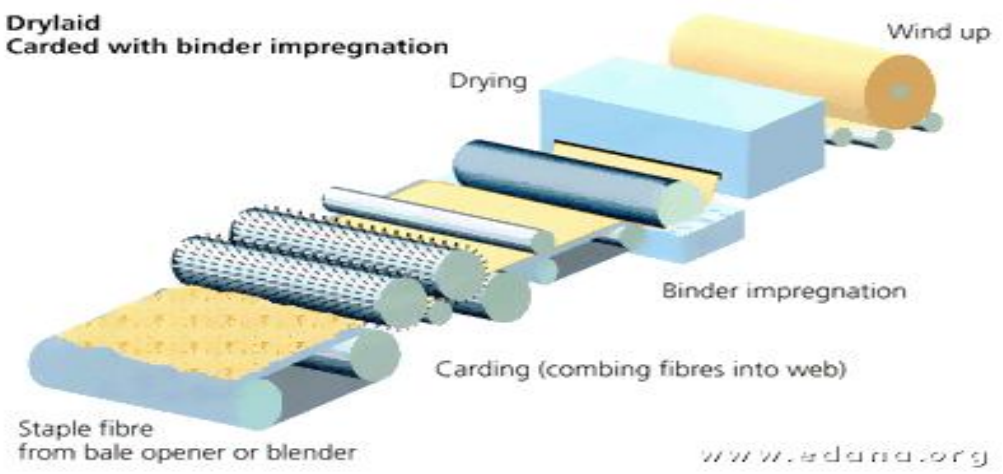


Fig.2. 5: Carding machine with binder impregnation.

There are two methods of drylaying:

- carding
- airlaying

2.9.5 Carding

Carding is a mechanical process which starts with the opening of bales of fibres which are blended and conveyed to the next stage by air transport. They are then combed into a web by a carding machine, which is a rotating drum or series of drums covered in fine teeth. The precise configuration of cards will depend on the fabric weight and fibre orientation required. The web can be parallel-laid, where most of the fibres are laid in the direction of the web travel, or they can be random-laid. Typical parallel-laid carded webs result in good tensile strength, low elongation and low tear strength in the machine direction and the reverse in the cross direction. Relative speeds and web composition can be varied to produce a wide range of fabrics with different properties.

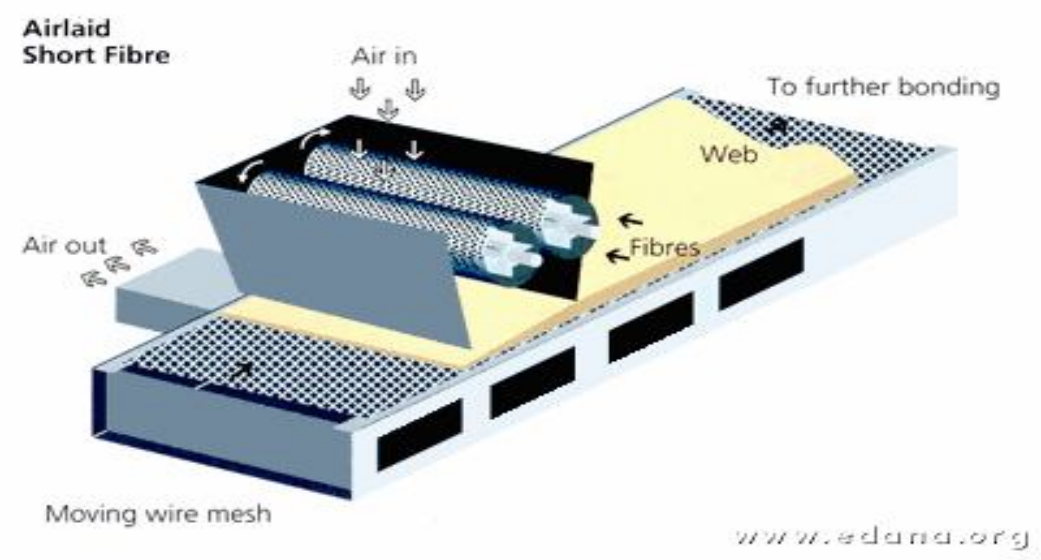


Fig. 2.6: Airlaying machine

In airlaying, the fibres, which can be very short, are fed into an air stream and from there to a moving belt or perforated drum, where they form a randomly oriented web.

Airlaying involves uniformly dispersing individualised fibres in an airstream and leading this air-fibre mixture towards a permeable screen or conveyor where the air is separated and the fibres are randomly deposited in the form of a web.

Compared with carded webs, airlaid webs have a lower density, a greater softness and an absence of laminar structure. Airlaid webs offer great versatility in terms of the fibres and fibre blends that can be used.

Airlaying, like other technologies has certain benefits and limitations, among these benefits are:

- Isotropic web properties

- Three-dimensional structure if the basis weight is above about 50 g/m2 producing voluminous, high-loft structures with a very low density
- Compatibility with a wide variety of generic fibre types including natural and synthetic polymer fibres, ceramics, metals including steel, carbon, melamine, aramids and other high-performance fibres.

The main limitations are:

- Fabric uniformity is highly dependent on fibre opening and individualisation prior to web forming.
- Air flow irregularity adjacent to the walls of the conduit leads to variability across the web structure
- Fibre entanglement in the airstream can lead to web faults.

Depending on fibre type and fineness, airlaying is claimed to be more efficient than carding in the production of webs greater than 150–200 g/m2, where production rates of 250 kg/h/m can be achieved, (www.technicaltextile.net).

2.9.6 Spunmelt

Spunmelt is a generic term describing the manufacturing of nonwoven webs directly from thermoplastic polymers.

It encompasses 2 processes and the combination of both.

- Spunlaid
- Meltblown

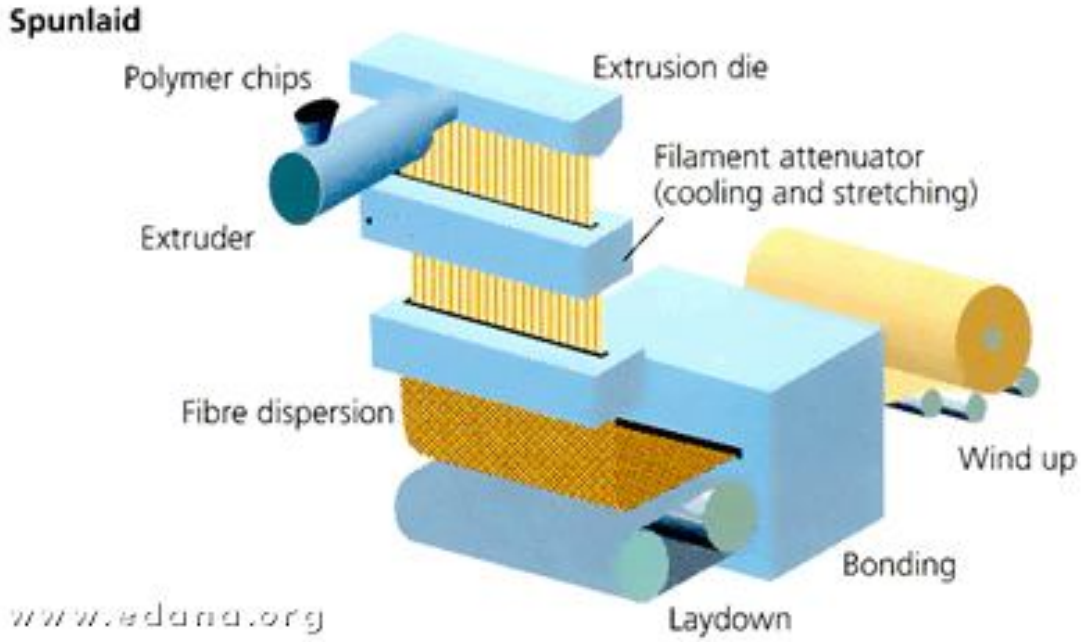


Fig.2.7: Spunlaying machine for spinning polymer chips *(www.edana.org)*

In this process polymer granules are melted and molten polymer is extruded through spinnerets. The continuous filaments are cooled and deposited on to a conveyor to form a uniform web. Some remaining temperature can cause filaments to adhere to one another, but this cannot be regarded as the principal method of bonding. The spunlaid process (also known as spunbonded) has the advantage of giving nonwovens greater strength, but raw material flexibility is more restricted, (www.technicaltextile.net).

Co-extrusion of second components is used in several spunlaid processes, usually to provide extra properties or bonding capabilities.

2.9.7 Meltblown

In meltblown web formation, low viscosity polymers are extruded into a high velocity airstream on leaving the spinneret. This scatters the melt, solidifies it and breaks it up into a fibrous web.

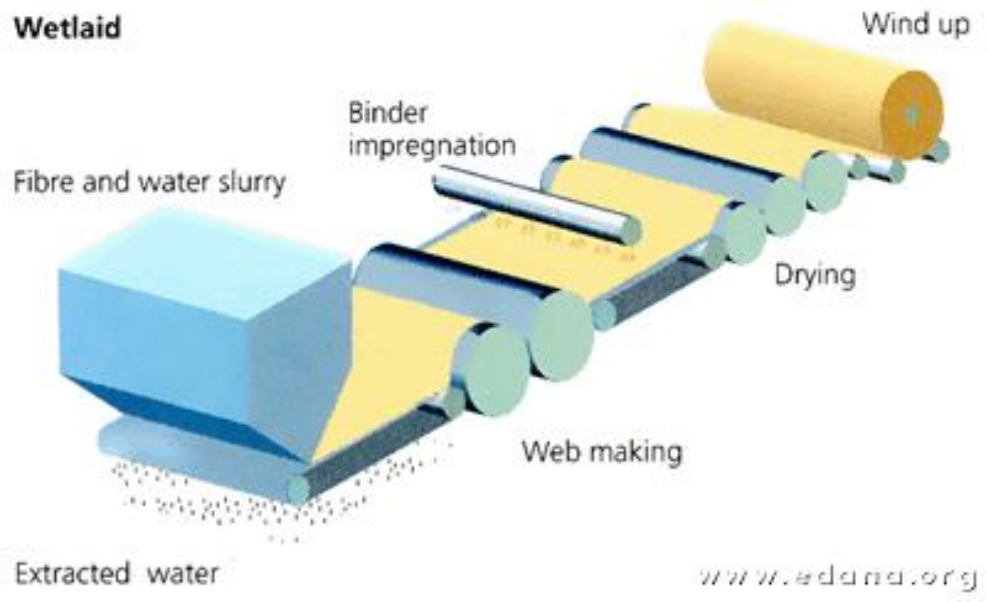


Fig. 2.8: Wetlaying machine; drains water from slurry to form a web *(www.edana.org)*

The principle of wetlaying is similar to paper manufacturing. The difference lies in the amount of synthetic fibres present in a wetlaid nonwoven. Dilute slurry of water and fibres is deposited on a moving wire screen and drained to form a web. The web is further dewatered, consolidated, by pressing between rollers, and dried. Impregnation with binders is often included in a later stage of the process. The strength of the random oriented web is rather similar in all directions in the plane of the fabric. A wide range of natural, mineral, synthetic and man-made fibres of varying lengths can be used, (**www.edana.org)**

2.9.8 Other techniques:

This includes a group of specialised technologies, in which the fibre production, web structure and bonding usually occur at the same time and in the same place. Flash spun webs are made by dissolving a polymer in a suitable solvent and then spraying it into a vessel held at reduced pressure. The solvent evaporates, or flashes off, leaving a cloud of fibres, which are collected and bonded. Other variants of in situ web forming techniques include different methods of fibrillation such as electrostatic spinning. Processes are emerging where two or more web forming techniques are used in tandem. The spunlaid/meltblown process is an example, where one or more meltblown webs and spunlaid webs are combined, (www.technicaltextile.net).

2.9.9 Needlepunch Technology

The process of needlepunching, also known as needle felting was originally developed to produce mechanically bonded nonwoven fabrics from fibres that could not be felted like wool. The fibres are mechanically entangled to produce a fabric by reciprocating barbed needles (felting needles) through a moving batt of fibres in a needleloom.

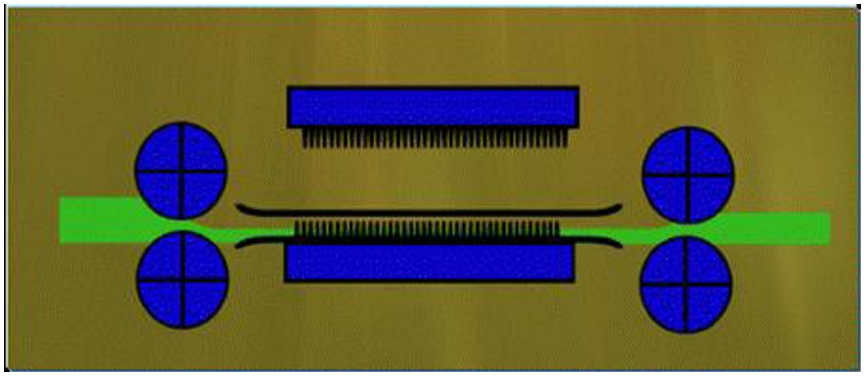


Fig.2.9: Moving fibres in-between up and down barbed needle boards.

Typical applications for this type of technology are geosynthetics, filtration media, synthetic leather, waddings and paddings, floor coverings, automotive fabrics, insulation fabrics, blankets, wipes, roofing etc.

The applications of needlepunched fabrics are extensive and extend into many niche product areas including, for example, medical wound dressings composite breather felts, capillary mattings for horticulture, fire barriers and ballistic-impact-resistant fabrics, (www.technicaltextile.net).

2.9.10 Needle-Punching:

Needlepunch is the process of producing fabrics by the method of using triangle needles to averagely punch the fibre webs to make the fibres directly tangle each other together instead of using the traditional weaving process. This controls the density, intensity, and function of the fabrics; by needle density, needle depth, needle number, and other physical elements. No water, air, heat and chemicals are needed at all. It is a kind of pure physical and mechanical bonding method, which saves energy and does not cause pollution.

Materials produced by the needle punch bonding method are of 3 dimensions' (3D) effect, with excellent flexibility and accessible to extension for processing. Furthermore; it provides good pore arrangement which is not available in other traditional fabrics. The same needlepunch equipment can be used for different types of fibres, including artificial fibre, synthetic fibre, recycled fibre, inorganic fibre, and metal fibre. The scope of raw materials that can be used is wide and the products that can be produced are almost limitlessly diversified. In order to satisfy individual industrial requirement, the fabrics can be made into various materials for their special functions. The range of application for needle punch product is very extensive; it can be used for care products, industrial products, hi-tech aviation, Industrial products, and national defence industrial products.

2.8.11 Needlepunch Process Description

a) Opening and mixing:

Bales of fibres are open-up to individualise fibres. In processing different types, fibres are blended in the correct proportions by means of openers. The fibres are opened and dispersed for the preparation of carding process.

b) Feeding

The fibres are blown from the opening machine which supply a predetermined Quantity to Cards by electric auto scale controlled system.

c) Carding

The fibres fed into the carding machine are snared by the wire of rotating cylinder and fibres are aligned in an essential parallel direction. A web or net is formed on card; and are removed from the card by doffer to the cross lapper.

d) Crosslapping

Fibre webs are layered to increase the fabric's cross directional strength, thickness, weight, width and improve uniformity.

e) Web Feeding

Layered web can be adjusted to meet the standards of any specifications and delivered to needle punching machine by means of Web Feeder.

f) Pre-needling

The layered web is fed through a series of needle punching machines, the pre-needle punching is to interlace the various layers each other with lower needle density. It is a preliminary 3D intertwining to entangle the fibres to impact strength.

g) First Double Side Needle Punching

The layered web is delivered by means of conveyor belt and rollers to; first part of the double side needle punching loom. Then the operation will make the web become a nonwoven fabric of medium density.

h) Second Double Side Finish Needle Punching

The applications of geotextile and filtration need high tensile and high entanglement nonwoven fabric. Special fibres have been developed to permit the conversion of web into soft, fine finish fabric to be high density structure.

i) Calender

After the fabric has been sufficiently interlaced by the double side needle punching; it can then be fed through the calenders to further compress it, depending on the end product desired.

Needle punched cotton provides highly efficient filter media based on the irregular fibre shape and absorption properties. Increased tenacity in the wet condition can be an important advantage for cotton filters. To build strength, scrim materials can be used as in bed blankets and industrial fabrics. Needles of 36-42 gauges have been found appropriate for the production of cotton needle punched nonwovens. For very heavy fabrics, needle gauge 32 could be used and for finer fabrics needle gauge of 40-42 are being used.

2.10 Natural and Renewable Fibres

It is reported in the Textile World (2010) that; in consideration for the increasing demand for more environmentally sustainable products and processes, natural and biobased fibres are good choices for certain nonwoven products. This is because they are biodegradable and compostable as well as being products of renewable resources.

Although, available as agricultural resources in many countries; natural fibres exhibit mechanical properties comparable to those of synthetic fibres. They are biodegradable and are from a renewable resource. Secondly, natural fibres have a potential in cost and weight reduction, which are combinations that have currently attracted the manufacturers' attention. (Mat.Res. Soc. Symp. Proc. 2002).

Natural fibres have very low toxicity and their production processes contribute to protect the environment. They are easy to manipulate without any protection device and they do not release loose fibres or dust even when subjected to an extended mechanical stress, such natural materials are cotton and polylactic acid fibres.

Borneman, (2008) stated that; "as sustainability and the green movement surge ahead, cotton will continue to craft an argument for greener crop production". When compared to synthetic fibres commonly used either as a whole or in composite, natural fibres have greater advantages that make them attractive to the manufacturers. In addition to being environmentally safe natural fibres require low energy to process during production since they are organic material that does not pose hazard to health during handling. They are available

and cheap in most parts of the world; moreover, giving their hollow tubular nature they exhibit good properties for acoustical absorption and thermal insulation.

Natural fibres such as cotton, kenaf, hemp, flax and jute have greater advantages over synthetic or petroleum-based materials. These could be classified into the following categories: environmental, economical, biological, light in weight and usefulness, (Golbabaie, 2006).

The advantages of natural fibres have currently attracted the manufacturers' attention. These benefits can be classified into the following categories:

1) Environmental Aspects: Plant fibres are renewable resources. They need low energy requirements during production. Furthermore, natural fibres show carbon dioxide neutrality and their disposal can be done by composting.

2) Biological Aspects: They are natural organic products. There is no dermal issue for their handling compared to glass fibres and do not pose a bio-hazard upon disposal.

3) Production Aspects: Natural fibres are non-abrasive and exhibit great formability.

4) Component Weight Issues: Natural fibres are light weight (less than half the density of glass fibres).

5) Financial Aspects: Natural fibres are very cheap in comparison to glass fibres.

6) General Aspects: Natural fibres show safer crash behaviour in tests (i.e., no splintering). They are also available on a worldwide basis. In addition, they exhibit good thermal insulating and acoustic properties due to their hollow tubular structures, (Golbabaie 2006).

2.10.1 Cotton Fibre:

Is a vegetable fibre obtained from the mature capsule of the cotton plant, a shrub of about 40cm in height. Cotton fibre is an economical natural fibre derived from cotton the seed hair. It could be used for making fabrics, padding, and for manufacturing artificial fibres and cellulose, (infogroup/ORC).

Today cotton is the most used textile fibre in the world. Its current market share is 56 percent for all fibres used for apparel and home furnishings and sold in the U.S., (Cotton_Incorporated, 2011).

Cotton nonwovens are recyclable and could be re-used or disposed of by natural degradation conditions. Cotton is a readily renewable resource with long-term supply assurance. Extensive research work is improving bleached fibre quality and quantity. Nonwoven industries are producing various types of nonwovens with different manufacturing techniques for better production. Cotton share of the textile fibre market has been steadily increasing and will continue to increase as cotton-containing items is preferred by the consumers as reported in, (http://www.cottoninc.com).

Another contribution is attributed to nonwoven textiles and personal care items; it is generally recognized that most consumers prefer cotton personal care items to those containing synthetic fibres. As stated by Shaw (1998), in 1998, the total World Textile fibre consumption was approximately 45 million tons and out of this total, cotton represented approximately 20 million tons.

The character and attributes of cotton are difficult to be determined because it is in part connected with the origin, variety and maturity. But at the end, cotton of good character is that whose fibres are the most strong and robust, this would help to resist traction and breakage, would make fibre homogenous and uniform, thereby producing minimal losses during production. When fibres have a complete physical and structural/chemical constitution, it gives the cotton fibre mass notable solidity and compactness, smoothness and silkiness.

2.10.2 Cotton in Non-woven:

Cotton is the most important apparel fibre throughout the world. It is a fibre that was used fairly extensively during the early developmental period of the Nonwovens business primarily because; the emerging dry-laid producers came from the textile industry and had an intimate knowledge of cotton and its processing characteristics. Cotton Fibres; (http://www.nonwovens.com/facts/technology/fibers/cotton.html)

It was in the early part of 20th Century that a few cotton mills in the US wanted to find ways to upgrade the waste cotton fibres into saleable products. The first method used was bonding the short cotton fibres (fibre waste) with latex and resin. These products were used mainly as industrial wipes. After World War II products like draperies, tablecloths, napkins and wiping towels were developed. It was realized that woven fabrics have better properties than nonwovens therefore; the approach was to claim the market where superior qualities of woven or knit fabrics were not essential but where qualities better than those of paper were needed. As the quality requirements for nonwoven fabrics increased and particularly as the need for white, clean fabric emerged; the use of raw cotton became unacceptable and was abandoned by the industry except for a few isolated product areas.

Within the last decade, bleached cotton fibre suitable for processing on conventional nonwoven equipment has become available and has substantially increased interest in this fibre. This is particularly true in medical and healthcare applications, wiping and wiper markets, as well as some apparel markets. The raw cotton consists of about 96% cellulose and 4% of waxes, pectin and other pertinacious and plant material. These minor constituents that must be removed in the scouring and bleaching process to give the soft, clean, white, absorbent fibre that is satisfactory for the nonwovens industry after the application of appropriate finishing oil.

The fibre length of cotton is important, particularly as regards to its processing ability; longer staple cotton is satisfactory for nonwoven production. The fibre has excellent absorbency and feels comfortable against the skin. It has good strength both wet and dry, and has moderate dimensional stability and elastic recovery. However, the resilience of cotton is relatively low, unless it is cross-linked by a chemical treatment.

In nonwoven applications, the purity and absorbency of bleached cotton are utilized in the growing medical and healthcare applications. The spun lace process usually produces such fabrics. For similar reasons, cotton spun lace fabrics are well accepted in personal and related wipes, (Kamath 2004).

2.10.3 Polylactic Acid Fibre:

PLA is a sustainable alternative to petrochemical-derived products, since the lactides from which it is ultimately produced can be derived from the fermentation of agricultural by-products such as corn starch.

Corn fibres are fibre made from PLA (PolyLactic Acid). Polylactic acid is made from corn. Corn fibre products look and feels just like the regular polyester fibre, but they are 100% biodegradable and compostable. Corn is a renewable resource which makes corn fibre more

sustainable than regular polyester fibre made from petroleum. (biodegradable fibre, corn fibre, PLA fibre, PLA yarn, PLA non-woven manufacturer).

Polylactic acid (PLA) and its composites were primarily used for medical applications due to comparatively high cost and inadequate availability. But with the beginning of commercial scale production and reduction in cost, polylactic acid is now being used both as fibre and matrix for various composite applications. Oksman et al. (2003) used PLA as matrix material for reinforcing enzyme retted flax fibres in the form of roving and characterized the composites for mechanical properties, (Oksman, 2004).

2.10.4 Evaluation of Potentials of PLA Fibre and Application

Natural fibres are available in large quantities and in different parts of the world. Besides the technological data hitherto presented, the designers of industrial products need to be aware of the following aspects as well whenever such a new material with promise is presented:

- Economical aspects
- Legislation
- Ecological aspects

2.10.5 Economic Aspects

Cost effectiveness is an important consideration for the designer in the competition between materials. Great attention is given to product performance and profitability when substituting new materials for old ones. The two factors, Economy and Ecology often are being strong and opposing forces, the third factor Technology is often being looked for to come up with satisfying solutions, with Legislation as a supporting and intermediating factor, (Kandachar and

Brouwer, 2002). In addition, the field of materials is one of the major disciplines attracting attention of environmentalists, stressing designers' responsibility towards environment.

2.10 Modeling of Sound Absorption in Nonwoven Fabrics

The optimal design of acoustic nonwovens needs a theoretical model with the power of predicting the noise absorption coefficient provided the thickness, porosity, fibre content, and other intrinsic characteristics are known (Shoshani and Yakubov, 1999). Most of the models which have been found to be useful for predicting acoustical properties of absorptive materials fall in one of two categories: theoretical microstructural and empirical phenomenological models. Furthermore, transfer matrix modeling is a very powerful technique which is often applied to porous materials. It can be applied to single or multiple layer absorbers (Cox and D'antonio, 2004).

2.11 End-of-Life

End-of-life (EOL) is a term used with respect to a retailed product, indicating that the product is in the end of its product lifetime. With hardware products, the term has come to incorporate the disposal and recycle-ability of an article. Many hardware products are now engineered with end of life in mind. The industry is now interested in manufacturing products which are biodegradable and are easy to recycle. When using natural or renewable materials, the environment should be protected without compromising industrial development (Olesen and Plackett, 1999).

Advancement in technology and increase knowledge on material, process and technology has enhanced the choice of materials and processes; it is of great importance now to balance the development of advanced materials with responsible environmental practices. The use of sustainable fibrous materials is becoming widely acceptable in various applications as alternatives to synthetic fibres therefore; increase attention has been turned to natural fibres

in order to explore the combination of their acoustic and thermal performances with a low impact on the environment and on human health. The use of natural materials in manufacturing is to reduce the green-house effects by establishing a carbon dioxide cycle that is almost close. In addition, the energy demand required for the fabrication of a nonwoven fabric from natural fibres comprising cultivation, harvest, and fibre dissociation only amounts to approximately 30–40% required for the production of a glass as reported by (ICA, 2007).

CHAPTER 3

MATERIALS AND METHODS

3.1 Research Design

This research is an experimental research and it is intended to assess the noise insulation properties of polylactic acid fibres made from corn kernel and cotton fibres which are both natural fibrous materials derived from plant source.

The final testing and analysis is a core component of this research, since it is related to the effectiveness of the material as a sound suppressor, which could indicate the usefulness of the indigenous fibres as potential building materials. Several parameters were used for the evaluation of these fibres before and after the production processes as discussed under various subheadings.

3.2 Methodology

In this study, the effect of fibre type and layering structure on the acoustical absorptive properties of cotton, PLA batts and fabrics were evaluated. This was done by assembling layers of PLA and cotton batts in varying order of 100, 50-50, 25-75, and 75-25 percentages to establish the acoustical properties of various layering order at different frequencies. 100 percent cotton and 100 percent PLA fabrics were produced, by using the needle-punch technology. All the samples were tested for their acoustical absorptive characteristics.

Samples produced were evaluated for some physical properties and several parameters were used in their evaluation; such as the airflow resistance, the fibre strength, the fibre orientation, porosity, linear density and thickness, which are all factors that influence sound absorption of

the materials used. These factors usually have a positive effect of increasing the sound absorptive characteristics of the fibrous material.

3.3 Experimental Details

The purpose of this study is to evaluate the sound absorptive capacity of cotton and PLA nonwoven; this is of prime importance due to the issue of environmental protection and the focus of industries on the use of natural fibrous materials in textile application.

The experiment was designed to produce PLA, cotton batts and fabrics. It also carried out various investigations to characterize the fibres used before they were processed into batts and fabrics. The batts and fabrics were also tested in order to establish their characteristics, which was discussed in the later part of this write up.

The experiment was designed to evaluate the properties of both the front and back of a sample, where the assembly of batts resulted in different fibre type for the front and back of sample fabric for airflow resistivity and sound absorption. Seventeen (17) fabric samples were produced for analysis in this study. Six (6) fabric samples were assembled with single fibre type and eleven (11) fabric samples were assembled by varying the order of assembling layers of PLA and cotton batts. Three (3) out of the eleven (11) samples have the front surfaces assembled with different fibre type from the back surface. Two fabric samples were produced by the needle punch technology each with 12mm needle penetration. A total of 13 samples were made by assembling four (4) layers of 200 g/m^2 batts together using 15 mm depth tacking with 2 boards top and bottom having 4 needles within a square centimeter on the Asselin 169-DF Rotary Tacker.

3.4 Materials and Method

Polylatic acid (PLA) fibre, synthesized from corn starch was supplied to North Carolina State University by Fibre Innovation Technology, Johnson City, Tennesse, USA and the second fibre; Ultra – Clean 100% cotton fibre which was supplied by the Cotton Corporation, Raleigh.

Before the production, the following physical tests were carried out to ascertain some physical characteristics of the fibre such as the diameter, length, tenacity, nep content, short fibre content, energy to break; all at 70 degrees Fahrenheit and 65% Relative humidity .conditioned laboratory. Ultra-clean cotton fibre characteristics were identified with the Uster Afis MultiData Module Version 4.00 Sample Analyzer while the Polylactic Acid fibre was analysed with the Textexhno H. Stein 41066 Mlnchengladbach–Vibromat- Me both at the North Carolina State University, College of Textiles Testing Laboratory.

3.5 Characterising Cotton Fibre:

An Uster Afis MultiData Module Version 4.00 Sample Analyzer was used for determining the characteristics of cotton. Approximately 9000 cotton fibres of 0.2gms was weighed and stretched out, the stretched fibres were rolled and slightly twisted into a sliver. The Uster Afis was calibrated and the details of the fibre such as the type of sample to be identified, operator/identifier and purpose for the test were imputed into the system before the analysis. The Uster was set on general channel which does a general analysis of the sample character. The sliver was introduced into the front orifice; which was drawn into the machine by air suction and the test was completed within about 5minutes. A cumulated results and the summary of histogram on length by weight, fibre diameter, nep count per gram, short fibre content, and weight per gram were printed out on individual result sheet.

3.6: Characterising Polylactic Acid Fibre:

For the purpose of characterising PLA fibre, two different machines were utilised; the Instron strength tester and the Textechno H. Stein 41066 Vibromate Me respectively.

3.6.1: Fineness Tester

On the Vibromat Me; the fineness of the fibre was tested by using some pre-tensioning weights inorder to ascertain the average tension to which the fibre can be subjected. An average weight of 700mg was suitable for the tensioning of individual fibre and a pincer was used to place the sample in the analysing unit of the machine, which run for a few seconds and displayed the results on system screen. 10 specimens were tested and the statistics of the result was computed and an average was presented as minimum and maximum fineness in denier. For the test, the oscillation method was used; this induced an automatic excitement in the optical/electronic amplitude detection of the machine.

3.6.2: Q-test

The tenacity of polylactic acid fibre was determined by carrying out a Q-test according to (GRAB- ASTM_D3822 msm) Standard Test Method for Tensile Properties of Single Textile Fibres on an Instron Strength Tester. After setting the parameters for the grip pressure and the jaw face size at laboratory condition of 70 degrees Fahrenheit and 65% relative humidity, twelve (12) specimens of the fibre samples were measured at a crosshead speed of 15 mm/min., Gauge length 25.4mm and 25 N load cell. At the completion of the test, a print out

of the computed detailed results was obtained. The results was analysed by the computer attached to the Instron, the mean value for the 12 specimens was recorded with a corresponding graph of the tearing force of fibre.



Plate I: PLA fibre is being mounted on an Instron for analysis.

3.7 Production of Nonwovens

3.7.1 Fibre Opening:

The fibres supplied in dense press-packed bales were opened in order to form a homogeneous web of individualized fibres. Fibre opening was carried out in a Truetzschler Opener. All fibre webs were produced in single-fibre web form.

3.7.2 Fine opening

In the processes for making a nonwoven web, the fibres were opened and blended using opening machines. This is normally followed by carding or air-lay processing forming a uniform web. The web can be provided with integrity and strength by bonding it using mechanical, chemical or thermal bonding methods.

The fibres were further opened in the BXM opener, and were transported by air to the feed box of the fine opener. The fine opener consists of two opening rolls, one evener roll and a cylinder roll all of which are wound with metallic clothing. The opener reduced the tuft size by using the principle of carding. The reduced tufts were then transferred to the cylinder roller which eventually conveyed them into the air stream and unto the web-former.

3.8 Web Formation

3.8.1 Carding

The main objective of carding is to separate small tufts into individual fibres, to begin the process of parallelization and to deliver the fibres in the form of a web. The principle of carding is the mechanical action in which the fibres are held by one surface while the other surface combs the fibres causing individual fibre separation. In the middle is a large rotating metallic cylinder covered with card clothing. The card clothing is comprised of needles, wires, or fine metallic teeth embedded in a heavy cloth or in a metallic foundation. The cylinder is partly

surrounded by an endless belt of a large number of narrow, cast iron flats positioned along the top of the cylinder. The top of the cylinder may be covered by alternating rollers and stripper rolls in a roller-top card, (Street, 1981) and (Banks-Lee, 2010).



Plate II: Truetzschler DK-903 flat top card used for this research

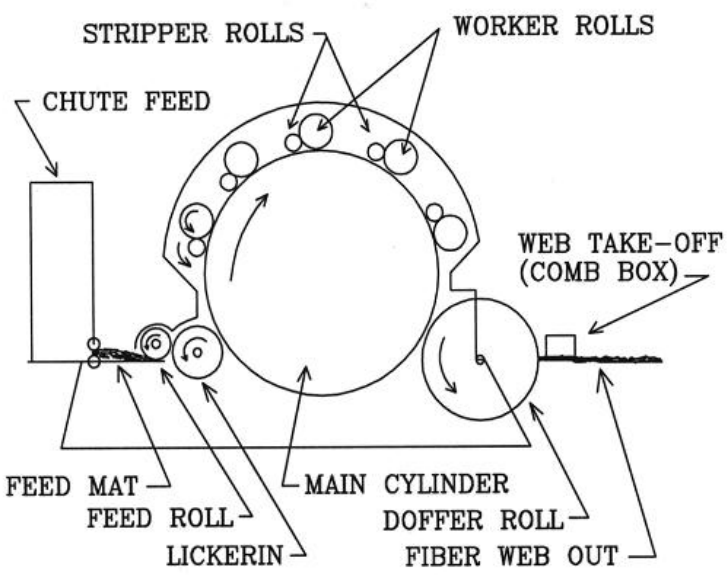


Fig. 3.1: Basic diagram of a card and its parts



Plate III: NSC Asselin Nonwoven Machine used for the Research.

The fibres are fed by a chute or hopper and condensed into the form of a lap or batting. This is initially opened into small tufts by a licker-in, which feeds the fibres to the cylinder. The needles of the two opposing surfaces of the cylinder and flats or the rollers are inclined in opposite directions and move at different speeds. The main cylinder moves faster than the flats and, due to the opposing needles and difference in speeds, the fibre clumps are pulled and teased apart. In the roller-top card the separation occurs between the worker roller and the cylinder. The stripping roller strips the larger tufts and deposits them back on the cylinder. The fibres are aligned in the machine direction and form a coherent web below the surface of the needles of the main cylinder. The web is doffed from the surface of cylinder by a doffer roller and deposited on a moving belt, (Street, 1981) and (Banks-lee, 2010).

3.9 Air-laying:

Fibre webs were produced using the air laying process. In this process; fibres are fed into an air stream and then transferred to a moving belt or perforated drum, where they formed a

randomly oriented web. The major operation set-up parameters used are Opener, Roller Top Card, Crosslapper and pre-needling.

Polylactic Acid fibres and Ultra-clean Cotton fibres were converted into three-dimensional fibrous structure batts and Nonwoven fabrics with the Truetzschler Tuft Feeder Scanfeed Machine at the Short Staple Fibre Laboratory of the North Carolina State University. The air laying was carried out with a target aerial weight of 200 g/m^2.

The bale was opened and blown using a Fine Opener 2; and transported to Fan 2. The Doffer was set for 23.8 meters per minute; the workers were set for 15, 12 and 10 RPM; the cylinder was set for 224 RPM; while the feed roll was 4.1 RPM, and the main convey was set to run for 24 metres per minute. With the above specifications, homogenous samples of 100% cotton batts of 200 grams per meter square (g/m^2) were produced along side with 100% PLA batts of 200 grams per metre square (g/m^2).



Plate IV: Airlaying of Fibres on Asselin "Profile 415-FD"

3.10. Pre-needle Punching

After the air laying, pre-needling was carried out with the NSC Asselin Pre-needler. The layered web was fed through a series of needle punching machines, the pre-needle punching was interlaced by various layers each other with lower needle density. It is a preliminary 3D intertwining to entangle the fibres to impact strength.



Plate V: Web formation on Asselin 169 DF

3.11 Needle-punching

The mechanical method of bonding, which is tacking and needle-punch were used to impact sufficient frictional force to the web. Barbed needles, mounted on a board, punched fibres into the web and then were withdrawn leaving the fibres entangled. The needles were spaced in a non-aligned arrangement and were designed to release the fibre as the needle board is

withdrawn. The barbed needle used for the samples were 940ga conical needle of 15x16x40x3-.5 M222G 53027.

The sample was needle-punched using on the NSC Asselin needle-punch loom set at a 100 cm/min speed, 100-cm width 15mm needle at 4 needles in a square centimetre, with 2 boards at the top and two boards at the bottom with the pitch set for 228 strokes/cm, 175 c/cm$_2$ penetration density, 3 mm penetration depth.



Plate VI: Needle-punch in Progress on the Asselin A.50-RL Needle Loom

3.12 Web Tacking

Prior to bonding, stacks of four layers were formed from webs of the two different fibre types used in the study. The webs were layered in various sequencing as shown in the layering arrangement in Table 3.1 below**.** Layers of webs were tacked together using 15mm needle at 4

needles in a square centimetre, with 2 boards at the top and two boards at the bottom with the pitch set for 12mm depth penetration This manner of sequencing provided allowance for the types of evaluation designed to be carried out in this study.

Plate VII: Web Tacking in Progress on the Asselin 169-DF Rotary Tacker.

TABLE 3.1.

Layering Arrangement of Batts:

50/50 COTTON/PLA:

SAMPLE (1)	SAMPLE (2)	SAMPLE (3)	SAMPLE (4)	SAMPLE (5)
PLA	PLA	COTTON	PLA	COTTON
PLA	PLA	PLA	PLA	COTTON
PLA	COTTON	COTTON	COTTON	PLA
PLA	COTTON	PLA	COTTON	PLA
COTTON	PLA	COTTON	COTTON	PLA
COTTON	PLA	PLA	COTTON	PLA
COTTON	COTTON	COTTON	PLA	COTTON
COTTON	COTTON	PLA	PLA	COTTON

75/25 PLA/COTTON:

SAMPLE (6)	**SAMPLE (7)**	**SAMPLE (8)**
PLA	COTTON	PLA
PLA	PLA	PLA
PLA	PLA	COTTON
COTTON	PLA	PLA
COTTON	PLA	PLA
PLA	PLA	COTTON
PLA	PLA	PLA
PLA	COTTON	PLA

75/25 COTTON/PLA

SAMPLE (9)	**SAMPLE (10)**	**SAMPLE (11)**
COTTON	PLA	COTTON
COTTON	COTTON	COTTON
COTTON	COTTON	PLA
PLA	COTTON	COTTON
PLA	COTTON	COTTON
COTTON	COTTON	PLA
COTTON	COTTON	COTTON
COTTON	PLA	COTTON

100g/m^2 EACH LAYER.

PLA 100g/m^2 X (2) = **SAMPLE 12**
COTTON 100g/m^2 X (2) = **SAMPLE 13**
NEEDLE-PUNCH COTTON FABRIC = **SAMPLE 14**
PLA 100g/m^2 X (8) LAYERS BATT = **SAMPLE 15**
COTTON 100g/m^2 X (8) LAYERS BATT= **SAMPLE 16**
NEEDLE-PUNCH PLA FABRIC = **SAMPLE 17**

After the batts were produced, the above layering orders were used in tacking them together on the scanfeed needle-punch machine. This was done in-order to achieve the desired effect of having cotton/polylactic sandwich; which resulted into an assembly 800g/m^2 batts.

Taked Webs

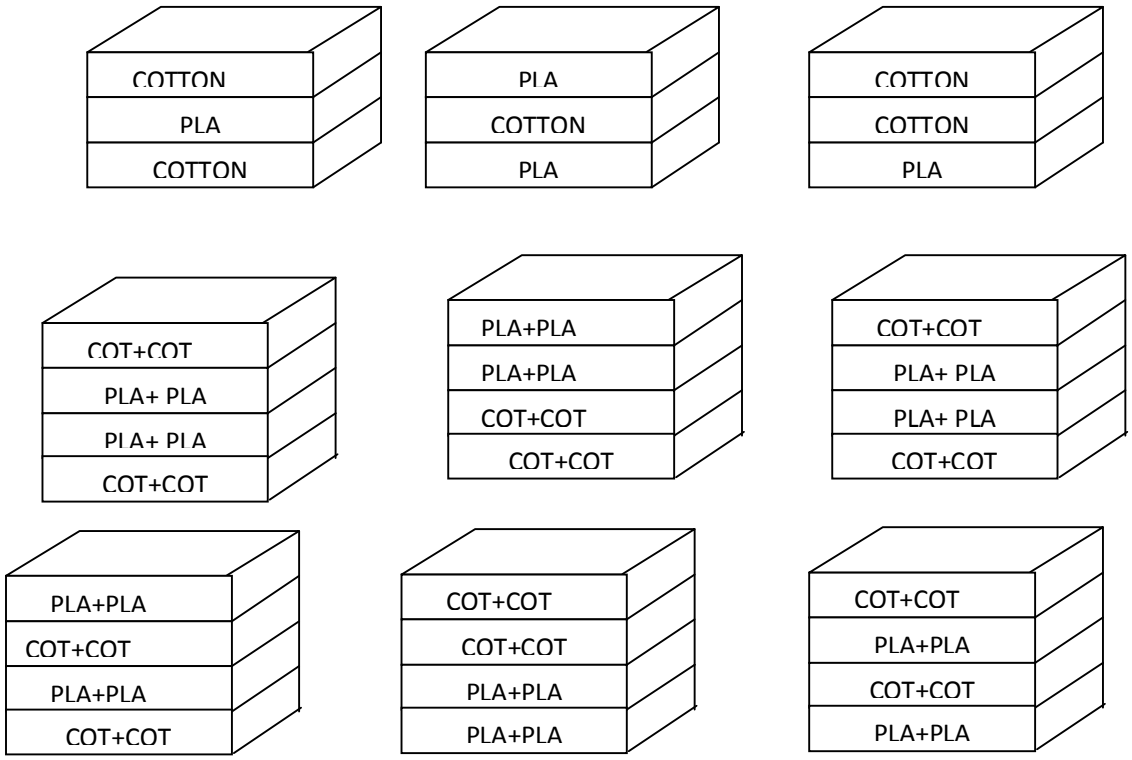


Fig. 3.2: Schematic diagram of web arrangement in order of fibre content and layering sequence.

Prior to the characterization processes samples were exposed to conditioning of 20^{o}C and 65% relative humidity for at least 24 hours. All tests were carried out according to the procedures and specification of the American Standard Test Method (ASTM).



Plate VIII: about to remove fabric from the cloth roller of NSC Asselin Nonwoven Machine



Plate IX: Samples ready for further processing.

3.13.0 CHARACTERISATION OF BATTS AND FABRICS

3.13 Scanning Electron Microscope Image of Fibres

The SEM is an instrument that produces a largely magnified image by using electrons instead of light to form an image. A beam of electrons is produced at the top of the microscope by an electron gun. The electron beam follows a vertical path through the microscope, which is held within a vacuum. The beam travels through electromagnetic fields and lenses, which focus the beam down toward the sample. The 4Pi EDS/Digital Imaging system was used to acquire SEM digital images and line scans.

3.13.1 Procedure for Measuring SEM of Samples

The imaging of samples was carried out by cutting tiny specimen from each sample, and then a gummy tape was stuck unto the sample holder before mounting the specimen, precautions was taken to ensure that the specimen was properly glued to the holder so as to avoid it been blown into the sample chamber which could damage the electron column due to high air pressure. The sample holders were arranged on a sample holders' rack which was placed in the sample chamber. The SEM instrument was set to run, the electromagnetic beam aid the microscope to focus the sample which could be magnified as desired. Images of samples were magnified by 220 x 1000 magnifications, then details on the sample identification, the identifier, magnification units and other relevant information were imputed before the image was saved for references as displayed on Plates Xa and Xb.

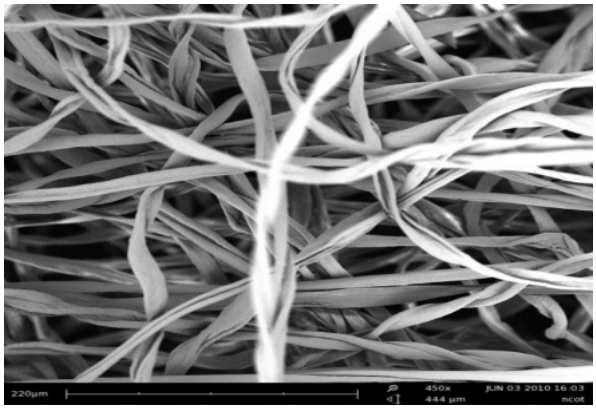


Plate Xa: Scanning Electron Microscope image of Cotton Fibre at 220 x 1000**magnification.**

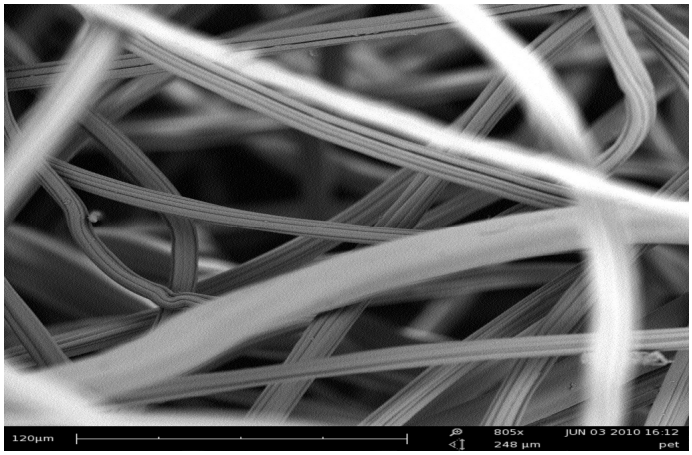


Plate Xb: Scanning Electron Microscope (SEM) of PLA nonwoven fabric at 220 x 1000 **magnification.**

PLA fibres used in this research have a hollow structure, only the connected pores are included in porosity in acoustics. Taking the high aspect ratio of the void, and the probability of fibre bending, and fibre orienting in directions other than parallel to air flow, the voids in PLA are unconnected pores; and are not included in porosity. Thus, PLA fibres are assumed to act like solid fibres in terms of air resistivity.

3.14 Fibre Orientation Distribution

The fibre orientation distribution function; (ODF) of the samples was evaluated with an image analysis technique; whereby the optical image of the sample is scanned. The technique was developed by the Nonwoven Cooperative Research Center, (NCRC) at North Carolina State University, Raleigh, USA.

Fibres in nonwoven fabrics have some level of orientation in machine - or cross-direction and parallel to fabric surface. Thus, nonwoven fabrics are inherently anisotropic and the propagation constant, *k*, and surface impedance, *z1*, changes according to the direction the

sound waves propagate. Sound waves must be permitted to enter the material in order for the material to be able to absorb the sound rather than reflect it.

Fibre orientation plays an important role in defining appearance, performance, and processability of the nonwoven materials. Uniformity of the webs is mainly dependent on the orientation of the fibres. The nonwovens are expected to have a uniform mass distribution for better performance and aesthetics. In nonwovens, fibre orientation is an important factor because it directly influences the properties of the material and the way in which fibres are deposited on top of each other. The nonwoven could be oriented towards the machine direction, the cross direction or it could be randomly laid. In this study all the samples tested tends to be aligned to the angle of machine direction.

The angular deviation as the maximum fibre alignment angle from the machine direction can be termed as the fibre alignment angle. In the case of no deviation, the ratio between the fibre oriented in the machine (MD) and cross machine (CD) direction has been termed the MD/CD ratio and has been used as a measure of fibre alignment.

3.14.1 Procedure for Evaluating Fibre Orientation Distribution:

Fibre orientation of sample batts and fabrics was evaluated by using the Optical Image Fourier Transformer to analyse the direction of fibres. This was done by placing the samples under the magnifying lenses of the Fourier, the machine was set to be on optical and then the lens was adjusted to give light of various degrees of intensity on the image of the sample been analysed. Details samples were imputed into the attached system and the visual display monitor presented first the image and then the statistics for the image.

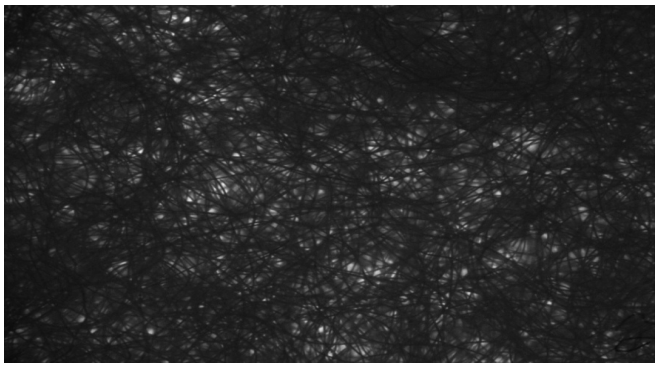


Plate XIa: Fibre orientation distribution image of PLA fibre batt

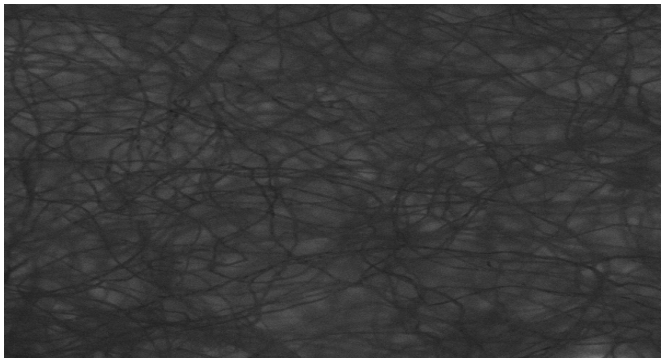


Plate XIb: Fibre orientation distribution image of cotton fibre batt

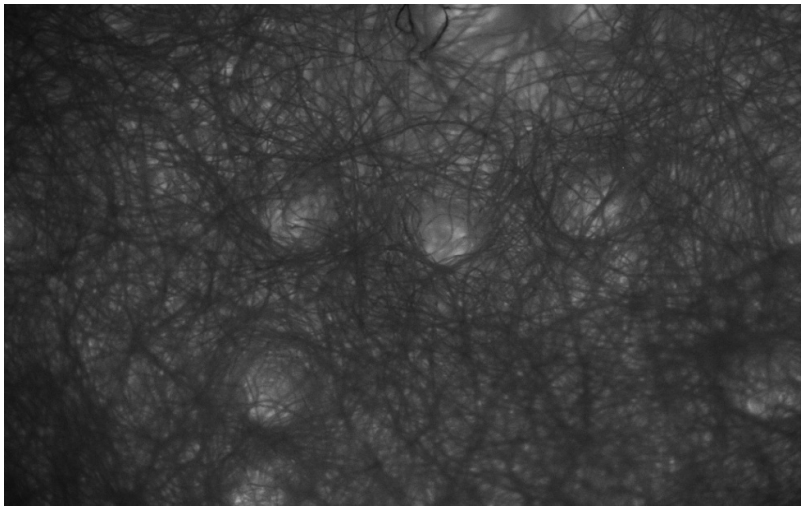


Plate XIc: Fibre orientation distribution image of cotton needlepunch fibre

Spatial frequencies in a non-woven image are related to the orientation of the fibres; fibres were shown in black on a white background. Nonwoven samples are inherently anisotropic as fibres do not lie in random directions but with some level of orientation in machine as shown in the results of the analysis.

3.15 Density

The ASTM D 1577-07 Standard Test Methods for Linear Density of Textile Fibres was used to determine the average linear density of fibres. Average linear densities of the fibres were obtained by fibre diameter measurement gauge on the scanning electron microscope image. A Hitachi S-3200N Scanning Electron Microscope and the Analytical Instrumentation Facility of NCSU was used. The 4Pi EDS/Digital Imaging system was used to acquire SEM digital images and line scans. Density of a material is often considered one of the important factors that govern the sound absorption behaviour of the material.

3.16 Fabric mass per unit area

The Mettler Toledo Precision Weighing (AG 245) balance was used to measure the Mass per unit area values of batts and fabrics. In accordance with the ASTM D 3776-07 Standard Test Methods for measuring Mass per Unit Area (Weight) of Fabrics. Five samples with a minimum diameter of 8.89 cm (3.5”) were cut at random and are weighed grams. The average of the weights of 5 specimens was then taken; this is a necessary precaution because of the uneven nature of nonwoven.

3.17 Thickness

The thickness of the samples were tested determined using the AMES thickness gauge with pressure level 4.14 kPa according to ASTM D 5729-97 Standard Test Method for Measuring the Thickness of Nonwoven Fabrics. Five specimens were randomly cut and measured from each sample. For precaution against the un-uniform nature of nonwoven, the average of the thickness from 5 specimens was taken from each sample.



Plate XII: AMES thickness gauge.

3.18 Airflow resistance

The air flow resistance of the samples were evaluated according to ASTM D 737-04 Standard Test Method for Air Permeability of Textile Fabrics. The Frazier air permeability tester (Frazier Precision Instrument Company Inc.), was used to test five specimens of each sample. The Frazier Differential Pressure Air Permeability Instrument gives the rate of flow of air in cubic feet per square foot of sample area per minute, the *Frazier Number*, at a differential pressure of 0.5 inches of water, (Frazier, 2009). These units have been converted to air flow resistivity, *r0*, in Pa·s·m-2, where *l* is the thickness of the fabric in meters.



Plate XIII: The Frazier Differential Pressure Air Permeability Testing Instrument.

3.18.1 Procedures for measuring air-permeability:

The rates of air flow of the samples were measured in cubic feet, per square foot of fabric per minute at 30" mercury, 70^{o}F, and 65% relative humidity. The power switch of the Fraizer was turned on, the handles for sample fixation was released and lifted. The sample was spread over air orifice and the handle was clamped to hold the specimen down tightly. The machine flow nozzles were selected for 2.75 inches test area, when the sample is run on a correct flow nozzle; the differential pressure reads from right hand vertical manometer. A value obtained from the manometer is multiplied by the orifice diameters which are calibrated in millimetres, and the correct air-permeability is obtained. 10 specimens are tested from each sample in accordance with the ASTM D 737-04 Standard Test Method for Air Permeability of Textile Fabrics of the Frazier air permeability tester.

3.19 Porosity

The porosity of textiles is defined as a void part of the textile's full volume. The full textile's volume is usually occupied by a fibres, air and water. The part of the volume that is occupied by fibres is constant and the portion of the volume that is occupied by water may vary considerably.

For instance, there is no water in the absolutely dry flat textile, and in the absolutely wet condition, air is replaced by water, but in dry textile material the moving air or wind can penetrate the pores.

The porosity can be described by the pore distribution, the average pore size / average pore diameter and the number.

Porosity, *h*, has a major effect in acoustical properties as it takes place as a direct coefficient in fundamental wave equations. Porosity values of five specimens of all nonwoven samples were calculated using the equation below:

Porosity, *H*, of the nonwoven samples were calculated using equation below:

$$h = 1 - \frac{\rho fabric}{\rho fibre} \qquad (3.1)$$

where: *fabric* ρ = Fabric Density, g/cc

fibre ρ = Fibre Density, g/cc

Where h is porosity, pw is density of fabric; pf is the density of the fibre.

Although the capillary flow analysis was also carried out in-order to determine the tortousity factor, the mean flow pore pressure and the mean flow pore diameter of the fabric, but it could only be used polylactic acid fibre fabric did not absorb the denatured alcohol fluid used for wetting the material in preparation for the test.

3.19.1 Procedures for Measuring Porosity and Tortousity.

The PMI capillary flow porometer machine was switched on. Fabric sample which was cut to size of the test was saturated with denatured alcohol fluid. A fully wetted sample was placed in the sample chamber and the chamber was closed. Gas was then allowed to flow into the chamber behind the sample. When the pressure reaches a point that can overcome the capillary action of the fluid within the largest pore, the bubble point has been found. After determination of the bubble point, the pressure was increased and the flow was measured until all pores were empty, and the sample was considered dry. Gas pressure and flow rates through the dry sample were also measured. The attached system and the visual display monitor presented the result which was printed.



Plate XIV: PMI Capillary Flow Porometer Machine.

3.20 Sound Absorption Test

The impedance tube method that determines the Normal Incidence parameters with measurements based on the two-microphone transfer-function was used in this study. This

method uses very small test sample that gives fast and accurate measurements of frequency range from: 500Hz – 6.4 kHz, and other parameters such as; sound absorption coefficient, reflection coefficient, acoustic impedance, acoustic admittance and transmission loss coin efficient.

Normal-incidence sound absorption coefficient (NAC) was measured according to ASTM E 1050-08 Standard Test Method for Impedance and Absorption of Acoustical Materials; using a tube, Two Microphones and A Digital Frequency Analysis.

The samples for acoustic tests were prepared by using a 29 mm diameter circular die punch to cut all samples to 29mm diameter, which fits the small sample tube used for the test.

Five specimens were taken from each sample in accordance with the test standard. Normal-incidence sound absorption coefficient, *αn*, which is the ratio of the absorbed or otherwise not reflected energy to the incident energy of plane waves propagating perpendicular to the surface of the absorber, is adopted in the present research. In acoustic measurement; *αn* can range from zero (0) (i.e. no absorption) to one (1) (total absorption).



Plate XV: Bruel & Kjaer two-microphone impedance tube type 4206 (2009).

The empirical models discussed in this section are based on the measurements made on the Two Microphone Impedance Tube used to determine the normal incidence sound absorption coefficient, NAC.

The impedance tube is a hollow cylinder with a sound source at one end and a test sample holder at the other. Microphone ports are mounted at two locations along the wall of the tube as shown in Figs. 3.7 and 3.8 above. For data acquisition and processing, a two-channel digital frequency analysis system is used. The signal processing equipment includes two matched microphones, two identical analog signal conditioners and a two-channel Fast Fourier Transform (FFT) analyzer. An individual channel of the analyzer is connected to the signal from each microphone system. A desktop computer is used for determining the acoustic absorption coefficient from the measured transfer function data (ASTM E 1050-80).

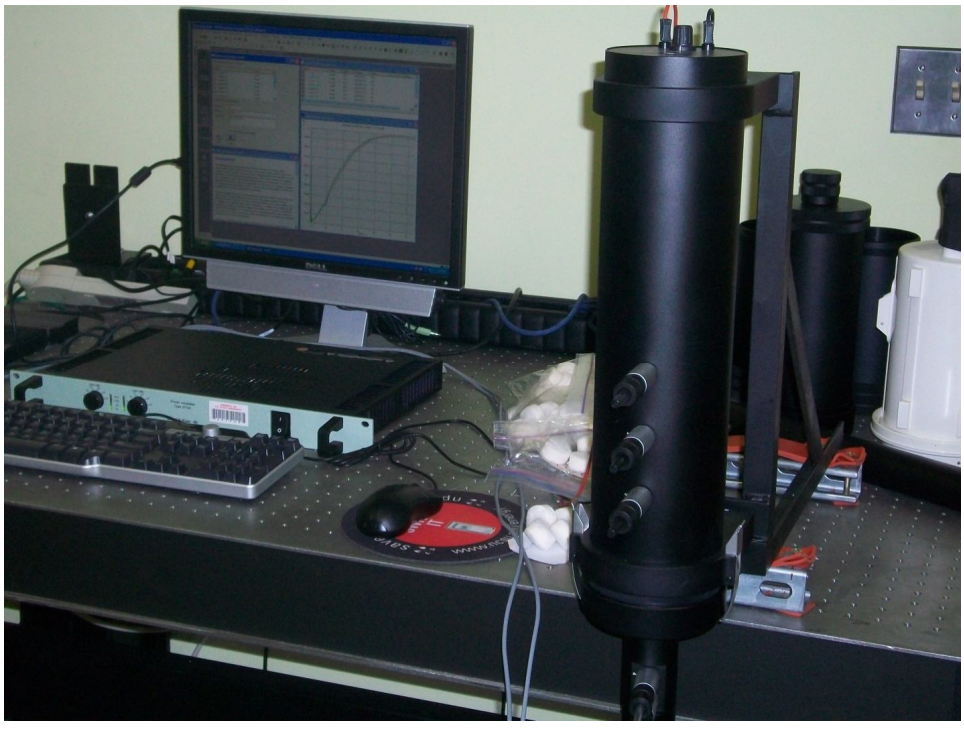


Plate XVI: Acoustic material tester used for the Research. (Courtesy; NCRC Lab Raleigh)

The test method used in this research provides a much faster measurement technique with accurate results.

A broad band signal from a noise source and plane waves are generated in the tube which forms a stationary sound wave pattern in the tube. The sound wave pattern which include the incident sound and the fraction of the sound that has been reflected back from the backing plate and not absorbed by the test specimen. The stationary sound wave pattern in the tube is decomposed into forward-travelling (incident) and backward travelling (reflected) components by measuring sound pressures simultaneously at two spaced locations in the tube's side wall.

3.21 Normal Incidence Sound Absorption Coefficient

The effectiveness of the samples in absorbing sound energy was investigated; beginning with single-fibre web and fabric materials, followed by the investigation on the effect of layer sequencing of web. The Digital Frequency Analysis of the two-microphone transfer-function presented each specimen's result by frequency range. The frequency ranges from 500Hz – 6.4

kHz, and results for parameters such as; sound absorption coefficient, reflection coefficient, acoustic impedance, acoustic admittance and transmission loss coefficient were displayed.

Five specimens were tested from each sample batt and fabrics, for each frequency range, the summation of the data generated were averaged. The average data sets along with results from other relevant tests were imported into the SAS statistical data analysis software for processing and analysis.

3.22 Statistical Analysis

Statistical models that would be appropriate for the analysis of data generated from the tests were formulated on the basis of the desired evaluation to be done. In order to test the correctness of the model and the accuracy of the values of the acquired data, the predicted versus the observed model was used as a trial analysis.

3.23 Procedures for Processing Data Acquired:

The Statistical Analysis System; SAS was used to analyse the data acquired from the different tests conducted. Many models were developed in order to ascertain the model that would give the best result when used.

The general linear models (GLM Procedure); Duncan's Multiple Range Test and t-test (LSD); and the ANOVA were all test before adopting general linear, the Pearson Correlation Coefficients and the backward regression models, this decision is as a result of the unequal replication of test carried out. Statistical test results and the graph curves were also used to determine and compare the effectiveness of the materials in absorbing sound.

As NAC values of each specimen were measured repeatedly at different sound frequencies, a repeated-measures model has been adopted. Repeated measures methodology is mostly used in the area of human psychology (Littell, 2006). Each specimen has been taken as a subject, which is measured repeatedly for different frequencies. The covariance structure was assumed a heterogeneous symmetry compound. Mixed model is used because it is a procedure widely used for longitudinal data analyses; whereby repeated measurements are analysed in agreement with (Liu et al, 2007).

CHAPTER 4

4.0 RESULTS AND DISCUSSION

This chapter presents results and discussion of the data obtained from all tests carried out. Other results and graphs are available in the Appendix of this write up.

4.1: Cotton Fibre Characterisation:

On the Uster Afis MultiData Module Version 4.00 Sample Analyzer ultra-clean cotton fibres' characteristics were identified. The results on Table 4.1 present the analysis.

Table 4.1 Analysis for Ultra-Clean Cotton Fibres

Sample Type	Rep Times	Fibre no	Diameter µm	Weight /gram	Length in	Density g/m^3	Nep Count Content %	Short Fib /gram
U/C cot	1	3000	16.0	0.414	0.70	1.56	196	12.3
U/C cot	2	3000	16.0	0.419	0.71	1.56	200	11.5
U/C cot	3	3000	16.0	0.422	0.69	1.56	218	12.2
Mean	=		16.0	0.416	0.69	1.56	205	12.0

Table 4.1 presents the results for the analysis of ultra-clean cotton used for this study. It can be seen from this result that cotton fibre diameter is 16 microns which is a fine diameter; fibre fineness enhances the sound absorptive ability of materials. This is because, thin fibres can move more easily than thick fibres on sound waves and with fine denier fibres more fibres are required to fill the voids and give an appreciable density which results in a more tortuous path and higher airflow resistance. Therefore, fine fibre content increases the sound absorptive ability of nonwoven material.

The density of cotton fibre is 1.56 which is very high and good for acoustic insulation. Materials with high density perform better in absorbing sound in mid and high frequency ranges, whereas less dense material result in open structures which absorb sound at lower frequencies. The number of fibres increases per unit area when the apparent density is large. Energy loss increases as the surface friction increases, thus the sound absorption coefficient increases when the density of material is high.

4.1.1 Polylactic Acid Fibre Characterisation:

Polylactic Acid fibre was analysed with the Textexhno H. Stein 41066 Mlnchengladbach–Vibromat-Me which is used to test for fibre fineness. The summary of the results is presented in Table 4.2.

Table 4.2 Fibre Fineness Results for PLA

Pre-tensioning weight: 700mg

Statistics Fineness	-N- tests	Average (den)	Minimum (den)	Maximum (den)	Confidence %
	10	6.684	6.120	7.544	95

Table 4.2; shows that ten (10) strands of fibres were tested individually and ten (10) different results with slight disparities were obtained. The minimum being 6.120 denier, while the maximum is 7.544 denier and the average is 6.684 denier. There is 95% confidence of the accuracy of the results obtained. Length of fibre was given as 63.6mm or 2.60 inches by Fibre Innovation Technology, Johnson City, Tennessee U.S.A, which is the source. For fair comparison with cotton, denier was converted to micronaire. Since 2.824 micron is equal to one denier; therefore, 6.684 x 2.824 = 18.875.

With this result, it can be concluded that Polylactic Acid Fibre is not as fine as the cotton fibre. Fine fibre denier ranges between 1.5 - 6 denier per filament (dpf); and they perform better acoustically than coarse denier ones.

For the tenacity of the PLA fibre a Q-Test for strength test was carried out on the Instron and the results is summarised in Table 4.3.

Table 4.3: PLA Tensile Test

Type of Test = Straight Test Lab Conditions = 70F, 65% Relative Humidity

No of Specimen 12	%Strn @ Pk Ld %	Elong @ Break mm	%Strn @ Break %	Energy to Break g*mm	Fibre Modulus gf/denier	Fibre Tenacity gf/denier	Fibre Toughness gf/denier
Mean	30.68	7.86	30.93	61.05	39.46	1.87	0.36
Std. Dev	16.97	4.28	16.83	51.64	13.57	0.74	0.30

The summary of tenacity test in Table 4.3 shows that polylactic acid fibre is a strong fibre since the average tenacity is 1.87 gf/denier, while the fibre toughness is

0.36gf/denier and the fibre modulus is 39.46gf/dnier. PLA is a compostable fibre from a renewable source; it is durable in most application and does not degrade just because it is wet due to its tenacity which is higher than natural fibres.

4.2 Capillary Flow Analysis:

The material's pore is described as the unit of measure typically associated with pore size values in micrometers (which is commonly referred to as microns), whereby 1 micron equals 1 X 10E-6 meters (3.93 X 10E-5 inches). For reference, a human hair is approximately 25 microns in diameter.

The PMI Capillary Flow Porometer was used to analyse the needle-punch cotton, needle-punch PLA and cotton batt samples only. The machine could not test PLA batt because the denatured alcohol fluid was running off and draining out from the PLA sample instead of soaking the sample; therefore, PLA batt which is sample twelve (12) in Table 3.7 was not tested on the machine; but was rather calculated.

Porosity, *H*, of polylactic acid fibre batt (PLA) was calculated using the equation below:

$$h = 1 - \frac{\rho fabric}{\rho fibre} \qquad (4.1)$$

where: *fabric* ρ = Fabric Density, g/cc

fibre ρ = Fibre Density, g/cc

Where h is porosity, pw is density of fabric; pf is the density of the fibre.

Density of PLA fabric = 377 = 2.96

Density of PLA fibre = 0.127

Therefore, the porosity of PLA needle-punch fabric is 2.96.

Denier and cross-sectional shape of the fibres in the fabric is directly related to the tortuous path. Smaller deniers yield more fibres per unit weight of the material and greater possibilities for a sound wave to interact with the fibres in the structure. Fabric density also affects the geometry and the volume of the voids in the fabric structure.

Also the packing density of the fibres in the non-woven material would determine the fibres per unit volume of the fabric and its tortous pathway.

Table 4.4.1: Capillary Flow of Needle-punch PLA.

PARAMETER	MICRONS	PSI
Tortuosity =	0.715	
Smallest Detected Pore Diameter (At 98.51% Cff) =	14.634	
Mean Flow Pressure		0.282
Mean Flow Pore Diameter =	29.539	
Largest Detected Pore Diameter =	71.824	
Standard Deviation Of Average Pore Diameter =	17.824	
Bubble Point Pressure =		0.116
Bubble Point Pore Diameter =	71.810	
Maximum Pore Size Distribution =	47.480	

Diameter At Maximum Pore Size Distribution	23.239
Tortuosity Factor =	Wet Up/Dry Up.

Table 4.4.2: Capillary Flow Result of Cotton Batt:

PARAMETER	MICRONS	PSI
Tortuosity =	0.715	
Smallest Detected Pore Diameter (At 98.22% Cff) =	7.758	
Mean Flow Pressure		0.241
Mean Flow Pore Diameter =	34.556	
Largest Detected Pore Diameter =	90.939	
Standard Deviation of Average Pore Diameter =	22.733	
Bubble Point Pressure =		0.092
Bubble Point Pore Diameter =	90.939	
Maximum Pore Size Distribution =	11.706	
Diameter At Maximum Pore Size Distribution	10.469	
Tortuosity Factor =	Wet Up/Dry Up.	

Table 4.4.3: Capillary Flow of Needle-punch Cotton:

PARAMETER	MICRONS	PSI
Tortuosity =	0.715	
Smallest Detected Pore Diameter (At 100% Cff) =	10.6075	
Mean Flow Pore Diameter =	32.1718	
Mean Flow Pressure =		0.259
Standard Deviation of Average Pore Diameter =	17.5888	
Bubble Point Pressure =		0.119
Bubble Point Pore Diameter =	69.8211	

Maximum Pore Size Distribution =	106.8016
Diameter At Maximum Pore Size Distribution	10.6075
Tortuosity Factor =	Wet Up/Dry Up.

Fibrous nonwoven materials are considered to be capillary porous bodies because they consist of a number of capillaries (which are channels of small diameter).

As can be seen in equation 4.1, the porosity of a material (batts or fabric) is a function of the density of the fibre from which it is made. Tables 4.4.1, 4.4.2 and 4.4.3 are summaries of Capillary Flow results in which pore factors of the samples were analysed.

In equation 4.1; where the porousity of polylactic acid batts is equal to 2.96. For fair comparison the value is converted to microns which is now = 2.96g/cc = 2.960g/cm therefore, the porousity of PLA is 2.96g/cc = 29.6 x 10^{-14}kg/μ^3.

For the Capillary Flow Porometer test, the volume of the liquid drained or absorbed between two successive capillary pressures is the fractional void volume of the pores. Usually, the pore sizes are equivalent to the capillary radius corresponding to the capilliary pressure.

4.3 Fibre Orientation Distribution

Fibre orientation plays an important role in defining appearance, performance, and processability of the nonwoven materials. Uniformity of the webs is mainly dependent on the orientation of the fibres. The nonwovens are expected to have a uniform mass distribution for better performance and aesthetics. In nonwovens, fibre orientation is an important factor because it directly influences the properties of the material and the way fibres are deposited. The nonwoven could be oriented towards the machine direction, the cross direction or it could be randomly laid. In this study all the samples tested tends to be anisotropic. They are anisotropy because fibres fell at various areas in the angle of machine direction. In the angles of distribution, machine direction is equal to minus one (-1); random laying is equal to zero (0), while cross direction is equal to one (1). Table 4.4.4 is a summary for the results of the fibre orientation test carried out on the samples. The Fourier Transformation Imaging analysis was used for the evaluation of fibres.

Table 4.5: Fibre Orientation Distribution

Needle-punch Cotton fabric

FFT orientation statistics for image C:\Cot NP 1.Ffo

Domin. Angle	Std. Dev	Mahine Cosine Squared Anisotropy	Cosine Squared Anisotropy
72.997	5.180	-0.063	-0.076

PLA Batts

FFT orientation statistics for image C:\PLA 2.Ffo

Domin. Angle	Std. Dev	Machine Cosine Squared Anisotropy	Cosine Squared Anisotropy
112.342	5.313	-0.015	-0.020

Cotton Batts

FFT orientation statistics for image C:\cotton 2.Ffo

Domin. Angle	Std. Dev	Machine Cosine Squared Anisotropy	Cosine Squared Anisotropy
112.418	5.124	-0.083	-0.118

Needle-punch PLA

FFT orientation statistics for image C:\PLA 5.Ffo

Domin. Angle	Std. Dev	Machine Cosine Squared Anisotropy	Cosine Squared Anisotropy
28.742	5.363	0.004	-0.007

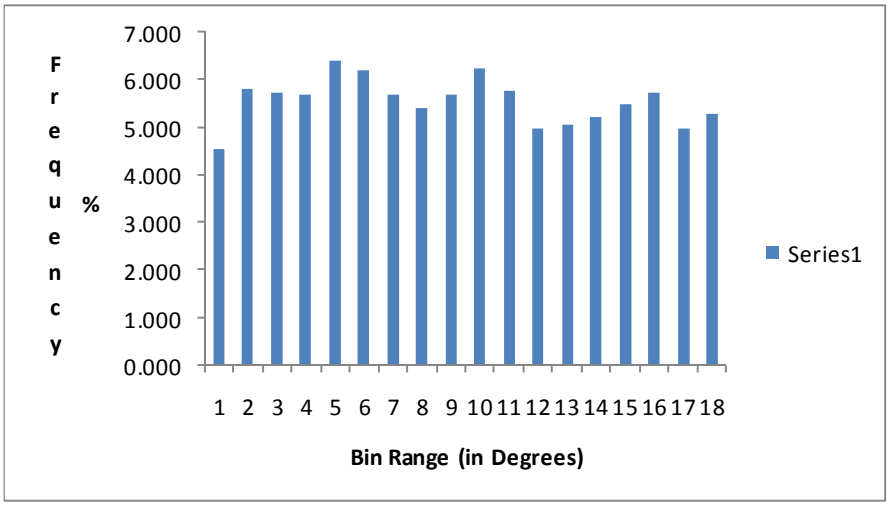


Fig. 4. 1: Fibre Orientation of Needle-punched Cotton showing alignment in Machine Direction

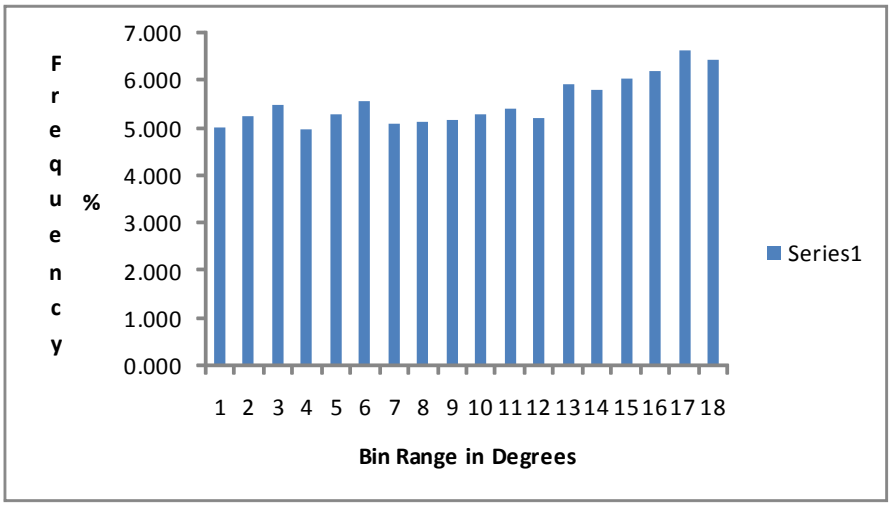


Fig.4.2: Fibre Orientation of Cotton Batt showing alignment in Machine Direction

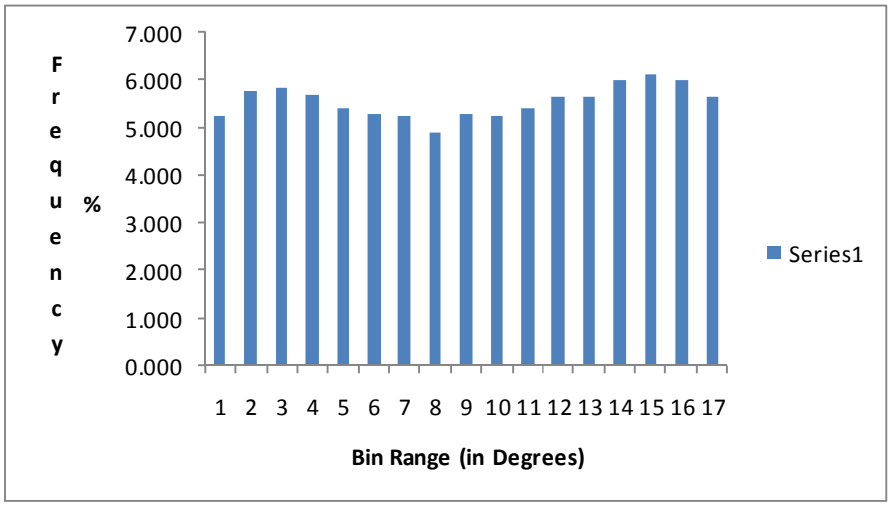


Fig. 4.3: PLA Batt showing alignment in the angle of Machine Direction

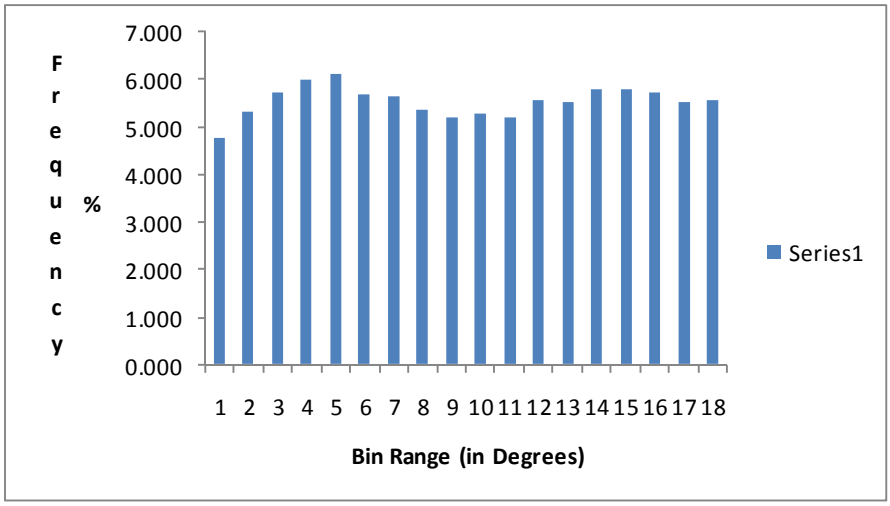


Fig. 4.4: Needle-punch PLA showing alignment in the angle of Machine Direction

The fibre orientation distribution function results obtained for the samples tested in this study aligned in the machine direction. As can be seen in Table 4.5 that both the machine cosine squared and the cosine squared are all minus one (-1) and anisotropy in the materials tested; this signifies strength of material especially in the machine direction. The cosine squared anisotropy ratio, H_t, varied from -0.038 to -0.14, indicating slightly higher frequency of fibres oriented in the machine direction which is of great importance in nonwoven material. All the samples tested exhibited an angle of orientation that are between the sample axis and the loading direction; which is machine direction (MD).

4.4 Airflow Resistivity

Airflow resistivity indicates how absorptive a material is by evaluating how much air can pass through the material at a given volumetric flow rate. Airflow resistivity was measured according to ASTM test method C 522 "Standard Test Method for Airflow Resistance of Acoustical Materials." Fibrous insulations have varying degrees of resistivity that are largely dependant on the density of the material. The absorption of energy from a sound wave mainly depends on the airflow resistivity of the material. If the resistivity is too high, the sound wave is reflected and only a minor part is absorbed. If the resistivity is too low, the sound wave can pass through the material without being absorbed.

Air Resistivity; where the Dependent Variable: Resist

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	219	0.46982441	0.00214532	Infty	<.0001
Error	880	0.00000000	0.00000000		
Corrected Total	1099	0.46982441			

R-Square	Coeff Var	Root MSE	Resist Mean
1.000000	0	0	0.050539

4.5 Airflow Permeability

Air permeability is the rate of air flow passing perpendicularly through a known area of the material under a prescribed air pressure differential.

Result for Air Permeability Where the Dependent Variable: Thickness

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	219	0.01605734	0.00007332	Infty	<.0001
Error	880	0.00000000	0.00000000		
Corrected Total	1099	0.01605734			

R-Square	Coeff Var	Root MSE	Thickness Mean
1.000000	0	0	0.011835

Air flow was measured in (cubic feet per square feet of sample per minute) or (feet per minute) or (CFM). The formula for calculating airflow the results of the tested samples can be expressed as follows:

Airflow = - 394.591(int) -1041.482 (rst) +4332.556(po) -11313.93(t) +0.099(wt)

$\mathbf{R^2}$ = 84.8% . . . . . (4.2)

Where (int) is intercept, which is a constant and the value of airflow; when other variables are 0. (rst) is airflow resistivity, (po) is porosity, (t) is thickness and (wt) is weight.

In this analysis, the value of $\mathbf{R^2}$ for airflow is 84.8% which means that all variables used in this model are significant.

4.6: Sound Absorption Tests

Regression analysis is commonly used in statistical analysis for predicting dependent variable value at a given independent variable level in some fields of studies. The models or functions are in the forms of simple and multiple linear regressions. They also include the polynomial and non-linear models. This is used to test for accuracy of results whereby data set from the

observed experiment is imported into the statistical analysis software (SAS); and commands for procedures are given. Usually, it is analysed to produce sets of values such as: the predicted, the observed and the residual. For further evaluation, the value of the residual considered and a graph for the predicted and the observed is plotted. In this trial analysis; the predicted is expected to be very close or parallel to the observed values in an ideal experiment.

Results obtained are presented in Tables 4.6 and 4.7 which were used to test for accuracy of the model used for the analysis as shown in Tables 4.6 and 4.7 and graphically represented in Figs. 4.6 and 4.7 respectively.

Table 4.6: Sample 1.1 Trial Model

Frequencies (Hz)	**500**	**630**	**800**	**1000**	**1250**	**1600**	**2000**	**2500**	**3150**	**4000**	**5000**
Observed	0.159	0.207	0.249	0.385	0.504	0.626	0.751	0.866	0.952	0.992	0.991
Predicted	0.292	0.315	0.345	0.381	0.435	0.487	0.557	0.646	0.761	0.910	1.087

Table 4.7: NAC for sample 2.1 Trial Model

Frequency (Hz)	500	630	800	1000	1250	1600	2000	2500	3150	4000	5000
observed	0.095	0.126	0.153	0.213	0.3	0.39	0.5	0.63	0.774	0.895	0.967

predicted	0.244	0.267	0.297	0.332	0.376	0.438	0.508	0.597	0.712	0.862	1.038

Residual values for 1.1

-148l	-0.118	-0.108	-0.037	0.036	0.097	0.160	0.188	0.173	0.075	-0.092

Residual values for 2.1

-0.149	-0.141	-0.144	-0.119	-0.076	-0.048	-0.008	0.0331	0.062	0.033	-0.071

From the results shown in Table 4.6, the predicted is close to the observed values therefore, it is deduced that the data generated by the two-microphone transfer-function was accurate as illustrated in the Figures 4.6 and 4.7 respectfully.

The residual values from the entire trial model are insignificant as can be seen in Table 4.6; Residual value for sample 1.1 and 2.1 respectively.

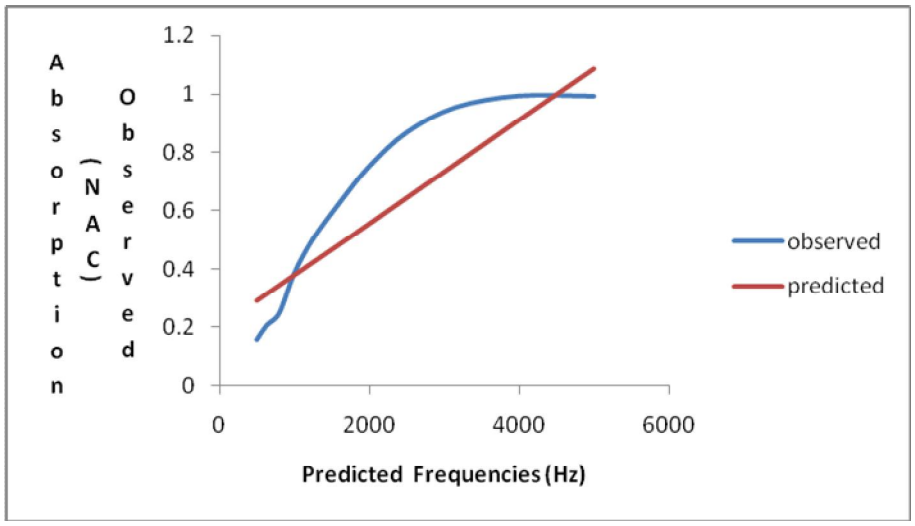


Fig.4.5: Observed versus predicted absorption curve of Sample 1.1

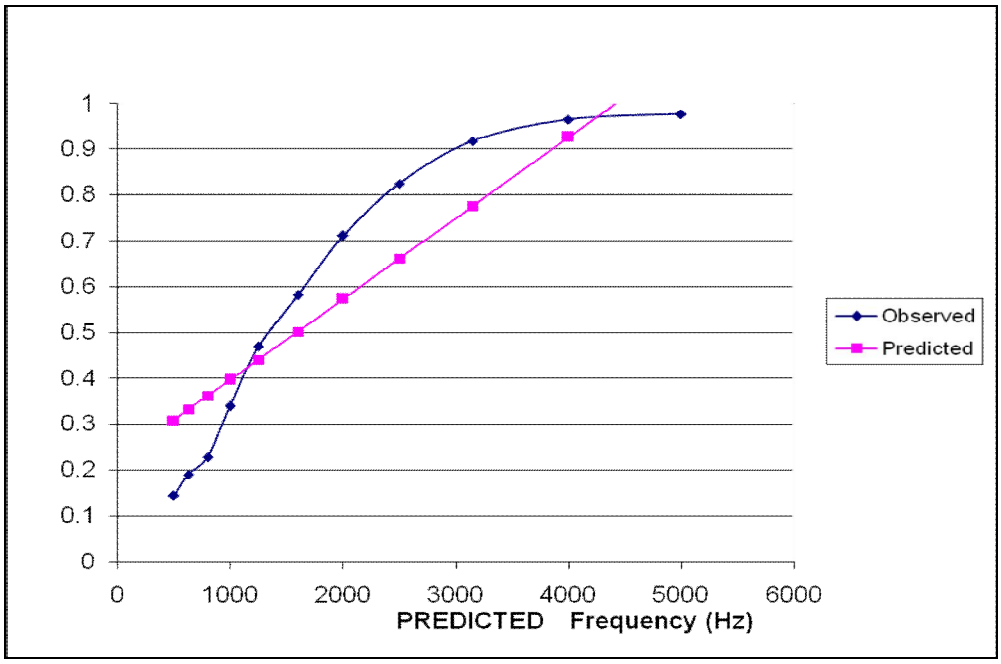


Fig. 4.6: Observed versus predicted absorption curve of sample 2.1

In the graph plotted in figure 4.6 although, absorption was predicted to begin at about 0.28 at the frequency range of 500Hz and stop at range 4500Hz whereas; the observed began at 0.17 and stopped at the range of 5000Hz with total absorption of one (1) on both curves at the frequency range of 4000Hz . From this analysis, it is obvious that there is closeness therefore; it could be assume that this model (GLM) is excellent for analysing the results acquired from the sound absorption test. The residual of values between the observed and the predicted was minimal.

The same explanation for Figure 4.6 above goes for Figure 4.7 and other crop of values from samples which were tried but, not presented as figures 4.6 and 4.7 serves as representation.

Dependent Variable: Absorb

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	219	112.9536275	0.5157700	364.54	<.0001
Error	880	1.2450648	0.0014148		
Corrected Total	1099	114.1986923			

R-Square	Coeff Var	Root MSE	Absorb Mean
0.989097	7.883600	0.037614	0.477123

In the above analysis where absorption is the dependent variable, the R-Square value is 0.989

Table 4.8: Normal Incidence Sound Absorption Coefficient; (NAC) results presenting the R-Square and mean values.

The GLM Procedure

Class Level Information

Class	Levels	Values
Fabric	20	1.1 1.2 2.1 2.2 3.1 3.2 4.1 5.1 6.1 7.1 8.1 9.1 10.1 11.1 12.1 13.1 14.1 15.1 16.1 17.1
Freq	11	500 630 800 1000 1250 1600 2000 2500 3150 4000 5000
Number of Observations Read	1100	
Number of Observations Used	1100	

The GLM Procedure

Dependent Variable: Absorb

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	219	112.3156	0.512857	239.67	<.0001
Error	880	1.883085	0.00214		
Corrected Total	1099	114.1987			

R-Square	Coeff Var	Root MSE	Absorb Mean
0.98351	9.695351	0.088759	0.790123

Source	DF	Type I SS	Mean Square	F Value	Pr > F
Fabric	19	29.23773	1.538828	719.12	<.0001
Freq	10	74.78499	7.478499	3494.84	<.0001
Fabric*Freq	190	8.292883	0.043647	20.4	<.0001

Source	DF	Type III SS	Mean Square	F Value	Pr > F

Fabric	19	29.2002	1.536853	718.2	<.0001
Freq	10	74.79633	7.479633	3495.37	<.0001
Fabric*Freq	190	8.292883	0.743647	20.4	<.0001

Since sound absorption (*α)*, ranges from zero (0) (i.e. no absorption) to one (1) (total absorption), R-square values which are closest to one (1) are taken as excellent absorption. Results show that the R-square values of all parameters having great influence on the sound absorption ability of the samples gave resultant value closer to one (1).

Also the general linear model (GLM) was used to determine the batts and fabric which absorbs best in order of efficiency. The analysis of other parameters that influence sound absorption of acoustic materials was carried out using the procedural general linear model. The Pearson Correlation Coefficients model was equally used to determine the relationship and strength of variables in the analysis.

As presented in Table 4.8; a total of 20 samples were evaluated for each of the eleven frequency range used. Five specimens were tested from each sample at all the frequency ranges. Averages for data generated from the sound absorption tests, the air-permeability,

weights, porosity, thickness, fibre density and fibre diameter tests were all imported into the statistical analysis software (SAS). The general linear model (GLM) was adopted for the analysis. In this model absorption is the dependent variable and the total number of observations read was 1100, with the results of 0.984 (R-Square), 9.695 (Coefficient Variance) and (Absorption mean) 0.790 values.

The R-Square value of 0.983 at this level is considered good for experimental textile data, since there is a relative variability in the raw materials used. Moreover; complete absorption is one (1) for normal incidence sound absorption coefficient in acoustic material. Therefore, an R-square value of 0.984 is an excellent absorption, so it could be concluded that the material test performed excellently in absorbing sound.

Table 4.9a: Samples Level of sound absorption from the highest to the least and other Variables and their influence on Absorption

SAMPLE		DESCRIPTION	ABSORB	RESIST	POROSITY	WEIGHT	MASS	FIBDEN	FIBDIA	FABDEN	B/RATIO	AIRFLOW	LAYERS
		Sample I.D	**dB**	**(Pa·s/m^2)**	**% void**	**g/m^2**	**(mm)**	**kg.m-^{3}**		**g/cc**	**%**	**ray1/m**	**(No x 200g/m^2)**
no.	**S/L**								**µm**				
Cd	**S/L**												
16	1	COT-BATT (Layered)	0.790164	0.00005	0.964257	884	0.018	0.00127	0.019	48611.11	100	28.84	8
1.a	2	CCCCPPPP	0.603364	0.00007	0.951489	891	0.01349	0.001315	0.0175	65974.8	0.5	47.88	8
5	3	CCPPPPCC	0.583909	0.00005	0.950228	894.67	0.0137	0.001315	0.0175	65449.64	0.5	50.59	8
10	4	PCCCCCCP	0.575727	0.00005	0.949969	890	0.0133	0.001338	0.01675	66942.11	0.75	35.43273	8
11	5	CCPCCPCC	0.575327	0.00005	0.950155	864	0.01296	0.001338	0.01675	66692.13	0.75	38.55455	8
3.b	6	PCPCPCPC	0.566673	0.00005	0.954699	835	0.014	0.001315	0.0175	59571.43	0.5	50.64	8
7	7	CPPPPPPC	0.565855	0.00004	0.950196	917	0.01424	0.001293	0.01825	64396.07	0.25	66.6	8
9	8	CCCPPCCC	0.560127	0.00006	0.949854	782.33	0.01166	0.001338	0.01675	67095.2	0.75	48.55364	8
3.a	9	CPCPCPCP	0.546506	0.00004	0.954699	835	0.014	0.001315	0.0175	59571.43	0.5	50.82455	8
8	10	PPCPPCPP	0.533491	0.00004	0.954116	859.67	0.01449	0.001293	0.01825	59327.81	0.25	63.715	8
1.b	11	PPPPCCCC	0.509073	0.00004	0.951489	891	0.01349	0.001315	0.0175	65974.8	0.5	45.45	8

15	12	PLA-BATT (Layered)	0.489636	0.00007	0.956513	850	0.014	0.00127	0.019	59142.86	100	133.62	8
6	13	PPPCCPPP	0.489018	0.00007	0.955443	753	0.01307	0.001293	0.01825	57612.85	0.25	58.32364	8
4	14	PPCCCCPP	0.479945	0.00008	0.949895	761	0.01155	0.001315	0.0175	65887.45	0.5	25.14	8
2.a	15	CCPPCCPP	0.469724	0.00001	0.948472	889	0.01311	0.001315	0.0175	67810.83	0.5	62.6	8
2.b	16	PPCCPPCC	0.456173	0.00003	0.948472	835	0.01311	0.001315	0.0175	67810.83	0.5	62.74	8
13	17	COT-BATT (Single)	0.288616	0.00004	0.962059	258	0.005	0.00136	0.016	51600	100	133.58	1
12	18	PLA –BATT (Single)	0.202562	0.00002	0.970323	203	0.005386	0.0127	0.019	37690.31	100	238.48	1
17	19	PLA-Fabric	0.129106	0.00011	0.937664	380	0.0048	0.001315	0.0175	79166.67	100	79.49	1
14	20	COT-Fabric	0.127458	0.00004	0.94403	255	0.00335	0.00136	0.016	76119.4	100	91.59	1

Table 4.9b: Averages of Properties for Cotton and PLA Batts and Fabrics.

SAMPLE CODE	LAYERS	FABRIC STRUCTURE	ABSORB	RESIST	POROSITY	WEIGHT	THICKNESS	B/RATIO	AIRFLOW
	No. x 200g/m^2			**(Pa·s/m^2**					
		Sample ID	**dB**	**(Pa.s/m^2**	**% void**	**g/m^2**	**(mm)**	**%**	**rayl/m**
1.1	8	CCCCPPPP	0.60336-B	0.00007-K	0.951489-H	891-D	0.01349-F	0.5	47.88-J
1.2	8	PPPPCCCC	0.509073-G	0.00004-E	0.951489-H	891-D	0.01349-F	0.5	45.45-K
2.1	8	CCPPCCPP	0.469724-IJ	0.00001-J	0.948472-O	889-F	0.01311-H	0.5	62.6-G
2.2	8	PPCCPPCC	0.456173-J	0.00003-I	0.948472-O	835-J	0.01311-H	0.5	62.74-G
3.1	8	CPCPCPCP	0.546506-FE	0.00004-H	0.954699-F	835-J	0.014-D	0.5	50.82455-I
3.2	8	PCPCPCPC	0.566673-D	0.00005-G	0.954699-F	835-J	0.014-D	0.5	50.64-I
4.1	8	PPCCCCPP	0.479945-HI	0.00008-L	0.949895-M	761-L	0.01155-L	0.5	25.14-O
5.1	8	CCPPPPCC	0.583909-C	0.00005-F	0.950228-I	894.67-C	0.0137-E	0.5	50.59-I
6.1	8	PPPCCPPP	0.489018-H	0.00007-O	0.955443-E	753-M	0.01307-I	0.25	58.32364-H
7.1	8	CPPPPPPC	0.565855-D	0.00004-M	0.950196-J	917-B	0.01424-C	0.25	66.6-E
8.1	8	PPCPPCPP	0.533491-F	0.00004-P	0.954116-G	859.67-H	0.01449-B	0.25	63.715-F
9.1	8	CCCPPCCC	0.560127-E	0.00006-D	0.949854-N	782.33-K	0.01166-K	0.75	48.55364-J
10.1	8	PCCCCCCP	0.575727-DC	0.00005-C	0.949969-L	890-E	0.0133-G	0.75	35.43273-M

11.1	8	CCPCCPCC	0.575327-CD	0.00005-B	0.950155-K	864-G	0.01296-J	0.75	38.55455-L
12.1	1	PLA –BATT (Single)	0.202562-L	0.00002-T	0.970323-A	203-Q	0.005386-M	100	238.48-A
13.1	1	COT-BATT (Single)	0.288616-K	0.00004-R	0.962059-C	258-O	0.005-N	100	133.58-B
14.1	1	COT-Fabric	0.127458-M	0.00004-Q	0.94403-P	255-P	0.00335-P	100	91.59-C
15.1	8	PLA-BATT (Layered)	0.489636-H	0.00007-S	0.956513-D	850-I	0.014-D	100	133.62-B
16.1	8	COT-BATT (Layered)	0.790164-A	0.00005-A	0.964257-B	884-A	0.018-A	100	28.84-N
17.1	1	PLA-Fabric	0.129106-M	0.00011-N	0.937664-Q	380-N	0.0048-O	100	79.49-D

Foot note: ** Averages followed with different letters (ABC); are significantly different at 5% level of confidence.

** Letters attached to figures by hyphens are the grades of ranking for level of absorbency of samples.

** All values are average of 55 specimens

KEY:

Sample no. means sample layering arrangement as in Table 3.1 (Chapter 3)

S/L Means sample level on the absorption table as presented in Table 4.3**.**

Sample I.D = Sample description by composition/form, where C = Cotton and P = PLA

C represents a layer of cotton batt of 200g/m^2

P represents a layer of **PLA** batt of 200g/m^2

PLA-batt^L means 100% PLA batt 800g/m^2

Cot Batt^L means 100% Cotton batt of 800g/m^2

Cot-batt^S means 100% cotton batt of 200g/m^2

PLA-batt^S means 100% PLA batt of 200g/m^2

N/P Cot means Needlepunch cotton fabric

N/P PLA means Needlepunch PLA fabric

Absorb means absorption value of samples

Mass means the Thickness of samples.

Fibden means the density of fibre

Fabden means the density of fabric

Fibdia means fibre diameter

B/Ratio means the percentage of each fibre in web-laying

Sample arrangement in order best to least absorption; /relationship with other parameters

Table 4.8 displays the absorption characteristics of the seventeen (17) samples used with the addition of 3-flips; (i.e samples having one side of it surface different from the other) due to layering order of different fibre type; alongside with other variables and their influence on the samples. Making a total of twenty (20) samples used in this research. Data sets acquired from test procedures carried out in accordance with the American Standards Test Method for each parameter was processed for analysis in the order of the highest to the least in sound absorption and in interaction with other variable of great influence on absorption.

Although five (5) specimens were tested from each sample for sound absorption test, other tests required ten (10) and others twelve (12) as stipulated by various test procedures.

The results in Table 4.8; is the presentation of results on sound absorption of all the samples and variables with respect to their influence on sound absorption. The first sample on the table is sample (16) which is cotton batts of 800g/m^2. The sample exhibited an excellent absorption capacity of 0.790 dB and the variable with great influence is porosity which is 0.952. Porosity is the amount, size and types of voids in the sample which in turn dictates the air-flow resistivity of the sample. This inter-relationship explains the reason why in the analysis the same values are obtained for these two variables. Of course the fibre type (cotton) is characterised with fine fibre diameter. The amount, size and type of pores in a porous material are a function of the fibre size and type. Pores are important factors in sound absorption mechanism. For sound dissipation by friction, sound wave has to enter the porous material. Fibre interlocking in nonwovens is the frictional elements that provide resistance to acoustic wave motion and it greatly depends on fibre size. When sound enters the material, its amplitude is decreased by friction as the waves try to move through the tortuous passages and as a result, the acoustic energy is converted into heat.

It could be observed from the results in Table 4.8 that sample (16) which is cotton batts, absorb sound better than needle-punched cotton fabrics. It is also observed that cotton batts and fabric absorb sound better than ploylactic acid batts and fabric as can be seen in Table 4.8 where cotton batts exhibited the absorption mean is 0.790; whereas PLA batts exhibited absorption value of 0.489 which placed it on level (12) in the sample level in Table 4.8, where cotton batts is placed on the first level. Although polylactic acid batts exhibited good absorption in 50 - 50 layering sequence with cotton as demonstrated by samples 1.a, 5, and 3.a in Table 4.8.

In addition to the exhibition of high absorption by cotton, it is observed that the airflow resistivity and porosity of cotton are very good, and these are parameters which influence sound absorption positively. In Table 4.8 these variable were also presented as it relates to their contribution to absorption coefficient of various samples, it can be observed that porosity, fibre type, frequency of absorption, airflow, layering order and thickness are all significant at 99% confidence.

Table 4.10 NAC for samples 15 and 16

	Frequency Range (Hz)										
sample ID	**500**	**630**	**800**	**1000**	**1250**	**1600**	**2000**	**2500**	**3150**	**4000**	**5000**
100% COT*	0.059	0.078	0.101	0.131	0.176	0.230	0.292	0.368	0.460	0.580	0.699
100% PLA*	0.062	0.076	0.090	0.109	0.135	0.162	0.195	0.238	0.291	0.380	0.489

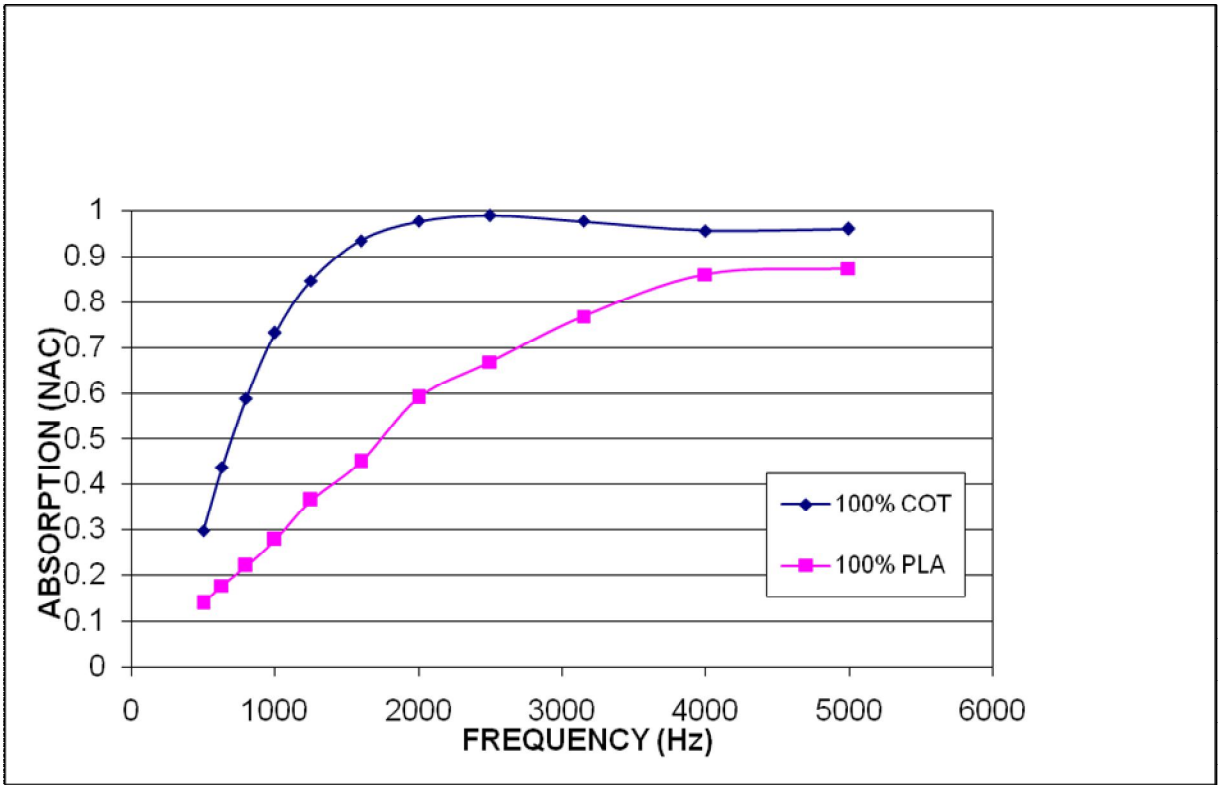


Figure 4.7: The absorption curve of 100% cotton versus 100% PLA batts.

The normal incidence sound absorption coefficient (NAC) curve in Figure 4.7 displays the importance of fibre type and size in sound absorption of a material. The two (2) samples; 100% cotton and 100% polylactic acid (PLA) of 800g/$m^{2;}$ having their weights normalised, with test methods and other condition being the same; exhibited different absorption capabilities.

The NAC curve in Fig.4.7 displays absorption of samples 15 and 16; which are 100% cotton and 100% PLA batts respectively at various frequencies.

The polylactic acid fibre (PLA) demonstrated a constant absorption at a lower frequency and got to its highest capacity at 4000Hz. The peak absorption in the mid-frequency range was at 0.7 and 3000Hz; whereas cotton maintained a constant absorption, had a total absorption at 2000Hz and maintained a constant flow all through.

The R-square value for the most absorbent sample (sample no.16) which is 100% cotton batts is 0.983, the absorption mean is 0.790 and the sum of square is 0.887. Other parameters with great influence on the sound absorptive capacity of this sample are: airflow resistivity = 0.964 and porosity = 0.884.

Although samples were produced with the aerial weight of 200 g/m^2 before they were tacked and all samples are eight (8) layers except for the singles layer batts and the needle-punched samples but it was necessary to normalize all their weights for fair evaluation of samples due to lack of uniformity of non-woven materials. During airlaying it is usual for more fibre to fall or concentrates at a particular point than it does other thereby creating fabrics that are not uniform since fibre are not uniformly distributed. When weights are normalized, samples are assumed to be of equal thickness and weight for fair comparison of their acoustic character.

The statistical model of normal incidence sound absorption coefficient (NAC) is expressed in Equation 1:

NAC = .000177 (*fq*.) - .00114 (*af*) + 308394 (*rst*) + 12.62643 (*po*) + .000764 (*wt*) – 18.1349 (*t*) + .025848 (*%c*) -12.21778 (*int*) . . . . . equation (3)

Where (*fq*) = frequency, (*af*) airflow, (*rst*) resistance, (*po*) porosity (*wt*) weight, (*t*) thickness (*%c*) percentage of cotton and (*int*) intercept.

This is used where absorption is the dependent variable as could be seen in the general linear method (GLM) procedure in Table 4.10 which is the presentation of estimate of sample parameters on absorption.

The differences in the absorption rates of the samples made from PLA and that of cotton could be attributed to the fibre type and size as already mentioned. PLA used in this research have a hollow structure and it is crystalline in nature, whereas cotton is multifabrillar (i.e is spirally structured and tends to be amorphous with some crystalline regions in the middle as presented in Figs.3.3a, 3.3b and in Plate XII of chapter 4 respectfully).

The nature of fibre is important here, because only the connected pores are included in porosity where acoustics is concerned. When we take the high aspect ratio of the void and the probability of fibre bending, interactions and fibre orientation in directions other than parallel to air flow, the voids in PLA are assumed to be unconnected pores and not included in porosity. This is so because PLA is assumed to act like solid fibre which does not enhance fibre bending and opening of void in tortousity. On the other hand, the cotton fibre can be viewed as a microscopic physical sponge with a complex porous structure. This internal structure

makes cotton fibres accessible to liquids and vapours. The capillary action of the fibrils pulls liquid or air in, where it is held in the pores between the fibrils. Therefore, the wickability and unique absorbing capacity of cotton fibre is attributed to this structure.

The cellulose chains within cotton fibres tend to be held in place by hydrogen bonding. These hydrogen bonds occur between the hydroxyl groups of adjacent molecules and are most prevalent between the parallel, closely packed molecules in the crystalline areas of the fibre.

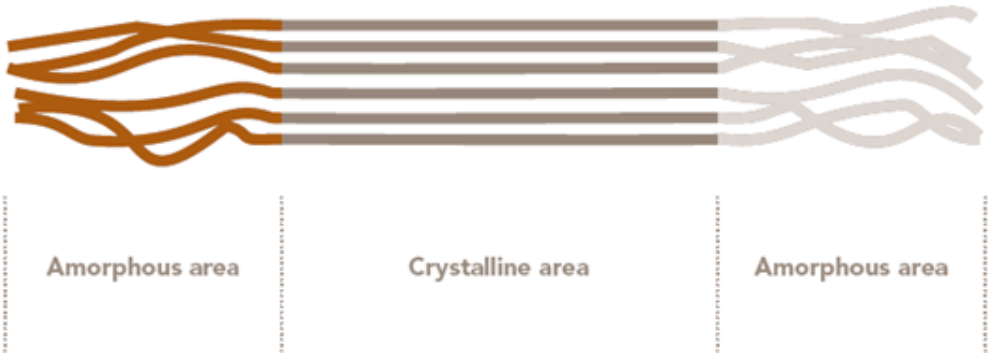


Plate XVII: Amorphous and crystalline Areas of Cotton Polymers

It is observed that both cotton and PLA are good in sound wave absorption, but where cotton sample is laid close to PLA sample; cotton dominates the absorption. This is evidence from this study that samples with the same layering order but with different fibre type facing the microphone during acoustical measurement. Whenever cotton samples faces the microphone, the sample exhibits a high value of absorption; this is in agreement with the observations by Ogunbowale et. al, (2010). This could be accounted for by the primary cell wall in cotton structure which is a thin cell wall made of network of fine fibrils (small strands of cellulose). This makes for a well-organized system of continuous and very fine capillaries. It is well known that fine capillaries rob liquids/gas from coarse capillaries. The fine surface capillaries of each cotton fibre contribute greatly to cotton's absorbency.

In this study it has also been observed that acoustical sample tend to have lower variation in the regions where minimum or maximum absorption takes place. This is demonstrated in the nonwoven PLA and cotton batts used in this study are very fluffy and lofty and contain a considerable amount of pores. Although it was observed in the needled samples that the differences in absorbency is not so much. This might be attributable to higher flow resistivity of airlaid nonwovens because of relatively random placement, and thus, higher tortuousity, higher number of pores with smaller sizes, higher number of fibre to fibre contact points, and gradient in porosity due to gravity.

From this research, it could be said that, fibres with smaller diameter give higher sound absorption coefficient. Thin fibres would move more easily than thick fibres in interacting with sound waves. Moreover, it could be said from the results obtained that with fine denier fibres more fibres are required to produce a material of an equal volume of density with coarser ones. This results in a more tortuous path and higher airflow resistance through friction of viscosity through the vibration of the air.

Table 4.11: GLM result presenting estimate of sample parameters on absorption

The GLM Procedure

Dependent Variable: Absorb

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	7	96.57588	13.79655	864.92	<.0001
Error	1091	17.40276	0.015951		
Corrected Total	1098	113.9786			

R-Square	Coeff Var	Root MSE	Absorb Mean
0.847316	26.49447	0.126298	0.476696

Source	DF	Type I SS	Mean Square	F Value	Pr > F
Freq	1	68.34887	68.34887	4284.87	<.0001
Airflow	1	11.59949	11.59949	727.19	<.0001
Resist	1	2.648608	2.648608	166.04	<.0001
Porosity	1	8.404482	8.404482	526.89	<.0001
Weight	1	5.489761	5.489761	344.16	<.0001
Thickness	1	0.067644	0.067644	4.24	0.0397
percentcotton	1	0.017029	0.017029	1.07	0.3017

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Freq	1	68.18409	68.18409	4274.54	<.0001
Airflow	1	0.354878	0.354878	22.25	<.0001
Resist	1	0.008085	0.008085	0.51	0.4767

Porosity	1	1.104859	1.104859	69.26	<.0001
Weight	1	0.450587	0.450587	28.25	<.0001
Thickness	1	0.060715	0.060715	3.81	0.0513
percentcotton	1	0.017029	0.017029	1.07	0.3017

Parameter	**Estimate**	**Standard Error**	**t Value**	**Pr > |t|**
Intercept	**-12.2178**	1.422279	-8.59	<.0001
Freq	**0.000177**	2.7E-06	65.38	<.0001
Airflow	**-0.00114**	0.000242	-4.72	<.0001
Resist	**0.308394**	0.433173	0.71	0.4767
Porosity	**12.62643**	1.517133	8.32	<.0001
Weight	**0.000764**	0.000144	5.31	<.0001
Thickness	**-18.1349**	9.295328	-1.95	0.0513
percentcotton	**0.025848**	0.025017	1.03	0.3017

In order to evaluate the effects of certain parameters on the sound absorption performances of the samples a GLM procedure was run to get the estimate of their influence on the materials and the results are presented in Table 4.11.

Weight of batts and fabrics were normalized for the purpose of analysis; samples were assumed to be of equal thickness and weight for a fair comparison of acoustic character, where the ability of samples in absorbing sound was compared.

Frequency was found to have the highest mean square value indicating that maximum proportion of the variation in the response is explained by the variation in the frequency. In nonwovens maximum energy is dissipated in the region where maximum particle velocity take place and this in most cases occur toward the mid-frequencies. Also, in agreement with Tascan (2005), shorter wavelengths (higher frequencies) are able to

penetrate into the porous material and be dissipated more easily compared to that of longer wavelengths. Nonwoven absorbers have low sound absorption in the lower frequency-range as observed by Ogunbowale et al., 2010).

As frequency increases, the wavelength decreases and the thickness of the sound absorber can cover a bigger fraction of a wavelength. During the propagation of sound, excited air molecules in the pores undergo periodic compression and relaxation. The thermal state is said to be under isothermal conditions, while the higher frequencies is said to be under the adiabatic conditions. This is because low frequency propagation is controlled by viscosity whereas high frequency is controlled by inertia.

Table 4.12 Samples with 50/50% Cotton/ PLA at Various Frequencies

	Frequency (Hz										
Sample ID	**500**	**600**	**800**	**1000**	**1250**	**1600**	**2000**	**2500**	**3100**	**4000**	**5000**
ccccpppp	0.153	0.198	0.264	0.376	0.493	0.617	0.746	0.859	0.949	0.991	0.992
ppppcccc	0.111	0.146	0.181	0.258	0.350	0.461	0.586	0.723	0.856	0.942	0.839
ccppccpp	0.099	0.131	0.160	0.223	0.311	0.404	0.515	0.646	0.801	0.905	0.971
ppccppcc	0.096	0.128	0.163	0.210	0.243	0.379	0.564	0.620	0.766	0.886	0.962

cpcpcpcp	0.142	0.188	0.226	0.326	0.436	0.552	0.627	0.810	0.921	0.986	0.995
pcpcpcpc	0.136	0.173	0.231	0.326	0.432	0.550	0.678	0.810	0.920	0.980	0.996
Ppcccpp	0.109	0.143	0.171	0.234	0.325	0.417	0.530	0.662	0.805	0.911	0.973
Ccpppcc	0.148	0.197	0.243	0.345	0.458	0.577	0.707	0.835	0.939	0.987	0.988

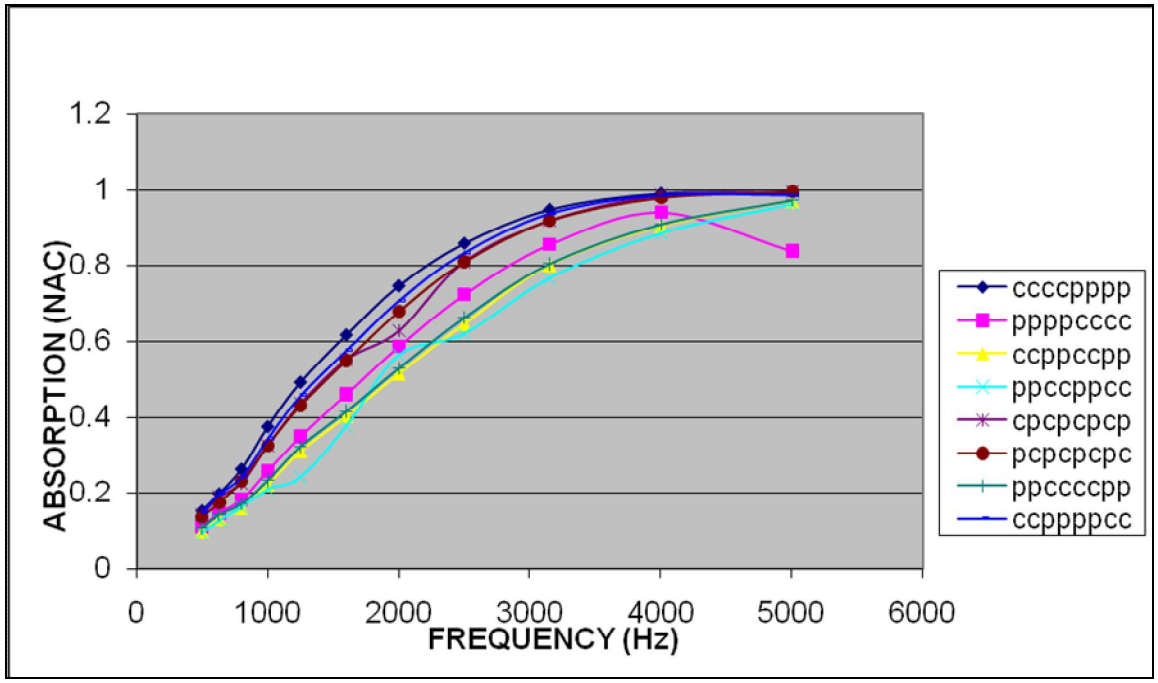


Fig. 4.8: The NAC curves of samples with 50/50% Cotton/PLA layering order

Table 4.12 is the result for the 50/50% cotton and polylactic acid fibre layering sequences, which are samples 1, 2, 3, 4, and 5 in Table 3.1 (of chapter 3) which presented layering arrangement of batts.

It can also be seen in the highest to least absorption details presented in table 4.8; samples with 50% cotton and 50% polylactic acid batts layering orders came next to 100% cotton in absorption capabilities with values of 0.603. The layering arrangements are such that all 50% cotton was tacked next to cotton as in sample 1^{a} or 25% cotton in the front facing the microphone tacked next to 50% PLA in the middle and 25% cotton tacked at the back as in sample 5; all in Table 4.12. Other layering arrangements are such with thin interface of PLA as in sample 3^{b}, where a layer of 12.25% PLA was tacked next to a layer (12.25%) of cotton all through. In all of these arrangements the two fibre types interact as composites and performed excellently in absorption, except in orders where all the 50% or 25% PLA is facing the microphone. The poor performance of samples having these arrangements can be attributed to the hollow structure coupled with the crystalline nature of PLA which may act as a solid fibre with no much tortuous path. This is because sound dissipation is caused by friction and when sound waves enters into a porous material and interacts within the connected pores, it losses energy. Fibre interlocking in nonwovens is the frictional elements that provide resistance to acoustic wave motion which is greatly dependent on fibre size that is coarse in PLA and does not allow for easy interface into the next region which is cotton. Where cotton faces the microphone; the reverse becomes the case because when sound enters the material, its amplitude is decreased by friction as the waves try to move through the tortuous passages. Although each sample exhibited excellent absorption it is interesting to note that the performance of each sample differs according to the layering sequence, the type and level of interface in-between layers.

Table 4.13 Comparison of samples with 50/50 cotton/PLA

	Frequency Range (Hz)										
SampleID	**500**	**630**	**800**	**1000**	**1250**	**1600**	**2000**	**2500**	**3150**	**4000**	**5000**
Ccccpppp	0.153	0.198	0.264	0.376	0.493	0.617	0.746	0.859	0.949	0.991	0.992
Ccppppcc	0.148	0.197	0.243	0.345	0.458	0.577	0.707	0.839	0.939	0.987	0.988
Cpcpcpcp	0.142	0.188	0.226	0.326	0.436	0.552	0.628	0.811	0.921	0.986	0.995
Ppcccpp	0.109	0.143	0.171	0.234	0.324	0.419	0.530	0.663	0.805	0.911	0.973
Ppccppcc	0.096	0.128	0.163	0.210	0.243	0.379	0.564	0.620	0.766	0.886	0.962

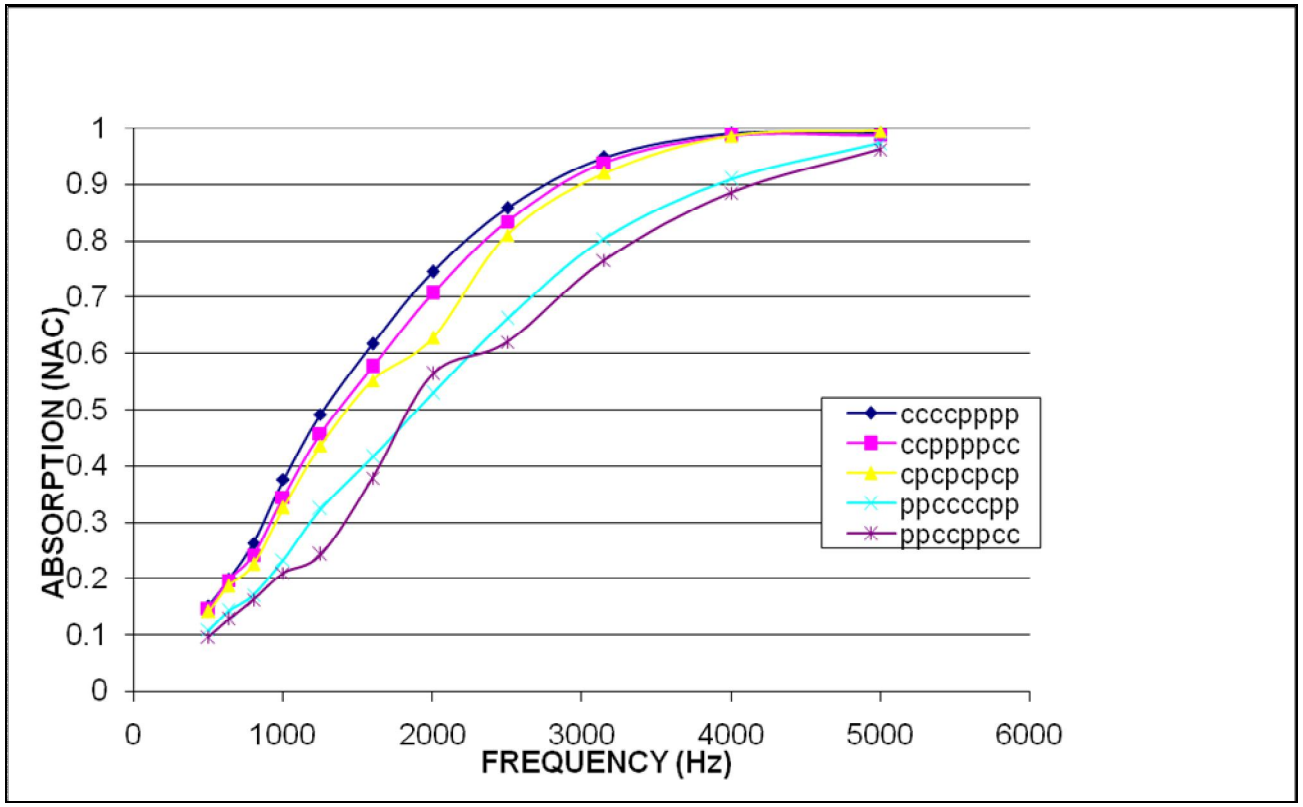


Figure 4.9: The NAC curves of layering arrangement of 50 /50% Cotton/ PLA layering sequence

Fig. 4.9 is also a display of 50/50% layering arrangements; in this order, cotton dominates absorption when it faces the microphone or where the interface with PLA is not much. Since the tacking is only fibre entanglement as sound interacts in the pores. Multi-layer absorbers achieve higher sound absorption than the mono-layer absorbers with the same thickness. From the results in Figs. 4.9., 4.10 and 4.11; it could be deduced that cotton tends to demonstrate greater absorptive strength especially wherever it is facing the microphone. In these figs., the two samples with layers of PLA facing the microphone have least absorption although, test method, conditions and other parameters are equal. The sample with four layers of cotton facing the microphone absorbed best, followed by the sample with two layers of cotton and next to it is the sample with a single layer of cotton facing the microphone. It is observed that the absorption flow rate in last two samples with two PLA facing the microphone is not constant; this can be attributed to the structure of PLA which would not allow for easy migration of sound.

Table 4.14: Comparing Effects of Interface where double PLA is facing the microphone in 50/50% layering order

Sample ID	Frequency (Hz)										
	500	630	800	1000	1250	1600	2000	2500	3150	4000	5000
Cpcpcpcp	0.142	0.188	0.226	0.326	0.436	0.552	0.628	0.811	0.921	0.986	0.995
Pcpcpcpc	0.136	0.173	0.231	0.326	0.432	0.550	0.678	0.810	0.920	0.980	0.996
Ppccppcc	0.097	0.128	0.163	0.210	0.243	0.379	0.564	0.620	0.766	0.886	0.962
Ccppccpp	0.099	0.131	0.160	0.223	0.311	0.404	0.515	0.646	0.801	0.905	0.971

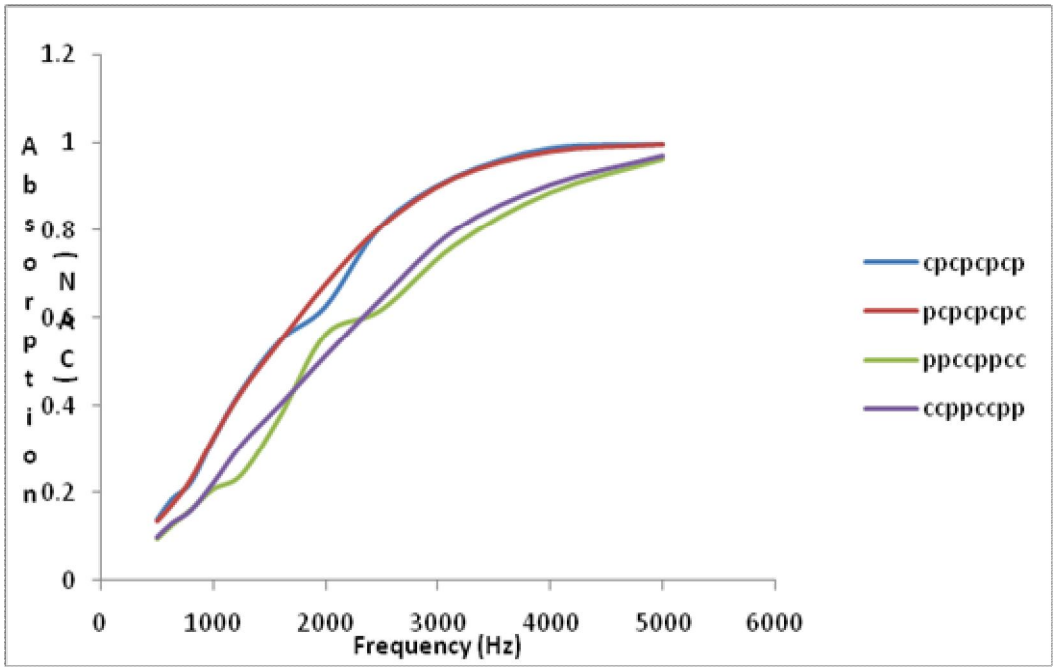


Fig. 4.10: NAC curve of 50/50% layering order where the interface is more.

It is observed in the results in Table 4.14 and NAC curve in Fig. 4.10 that in layering arrangements where the interface is less, sound wave can flow easily at a relatively constant frequency as the case is with the first two samples plotted on the graph which are samples 3^a and 3^b (flip of same sample) respectively. But in the third sample on the graph with a double layer of PLA facing the microphone, sound would propagate at lower frequency, since the wavelength is longer therefore; thickness rather than fibre size is the determining factor at this level. But where there is an interface of cotton, which resulted into a change in wave propagation and sound absorption especially in the region of mid and high frequency. In this sample, it can be seen that there was an easy propagation at lower frequency and at 2000Hz absorption rose to 0.58 owing to double layer of cotton (25%) interface before the next double layer of PLA (25%) interface.

Table 4.15 NAC of the flip of samples 1 and 2 in 50/50% layering order

Sample ID	Frequency (Hz) 500	630	800	1000	1250	1600	2000	2500	3150	4000	5000
ccccpppp	0.153	0.198	0.264	0.376	0.493	0.617	0.746	0.859	0.949	0.991	0.991
ppppcccc	0.111	0.146	0.181	0.258	0.350	0.461	0.586	0.723	0.856	0.942	0.839
ccpppccc	0.148	0.197	0.242	0.345	0.458	0.576	0.707	0.835	0.939	0.987	0.988
ppcccccp	0.109	0.143	0.171	0.234	0.324	0.417	0.530	0.663	0.805	0.911	0.973

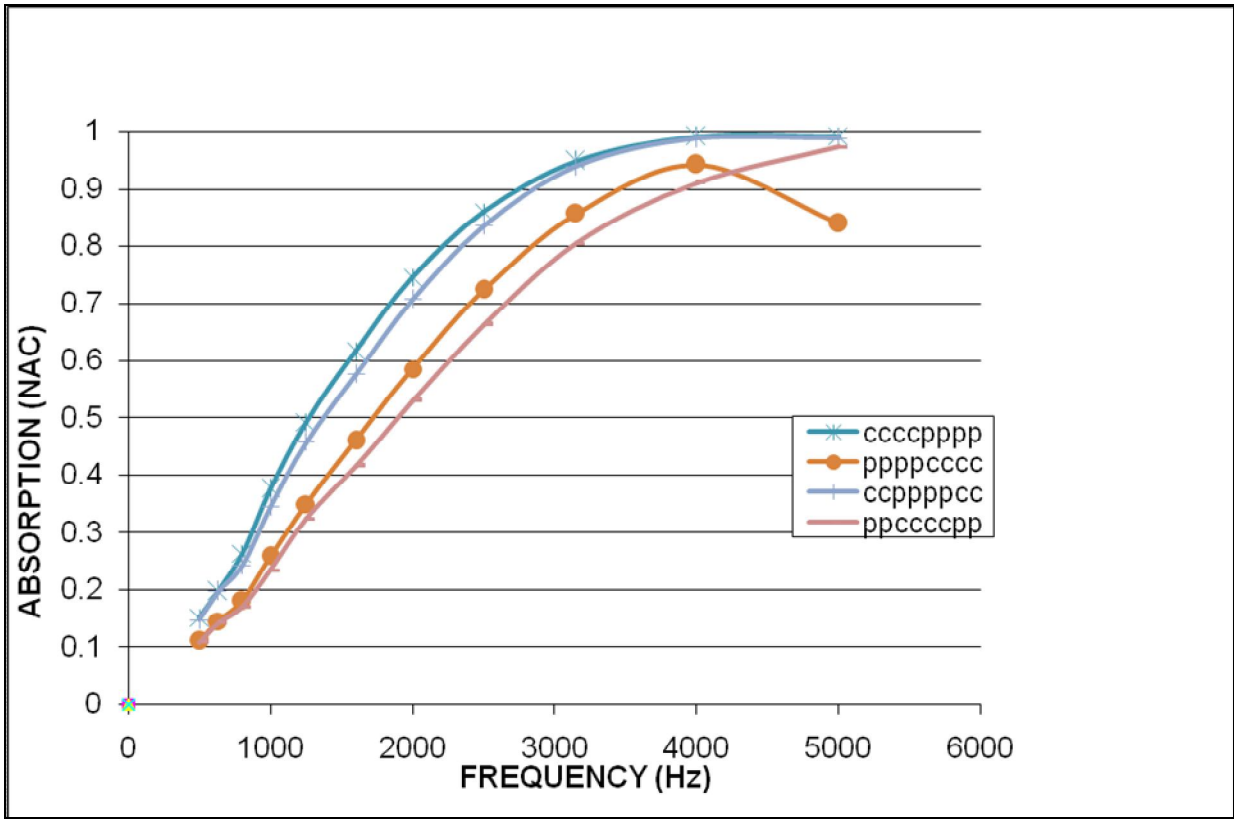


Fig. 4.11: Comparison of 50/50% Cotton and PLA layering arrangements and their flips

In the layering order of samples 1 and 2 presented in Table 4.15 represented graphically in Fig. 4.11; 50% PLA is tacked next to 50% cotton, this sample absorbed to it full capacity at 4000 Hz and maintained a constant flow all through the process when the surface with the cotton fibres is close to the source of sound whereas; when it was flipped over to the surface with PLA fibres was close to the sound source a constant absorption was maintained up to 0.93 at 4000 Hz from where it dropped back to 0.83. On the same curve is sample 2 which is also with 50/50% layering arrangement, in the following order; 25% cotton tacked next to 50% PLA and next to PLA is 25% cotton. Although, there is an interface of a thick PLA layer the absorption flow rate was constant all through and a full absorption was achieved at 4000 Hz because the 25% cotton at the back surface would trap and transduce sound wave instead of allowing it to bounce back.

Table 4.16: Comparing the face and back of Sample 1:

	Frequency (Hz)										
Sample I.D	**500**	**630**	**800**	**1000**	**1250**	**1600**	**2000**	**2500**	**3150**	**4000**	**5000**
MCCCCPPPP	0.153	0.198	0.264	0.376	0.492	0.617	0.746	0.859	0.949	0.991	0.992
MPPPPCCCC	0.111	0.146	0.181	0.258	0.350	0.461	0.586	0.723	0.856	0.942	0.839

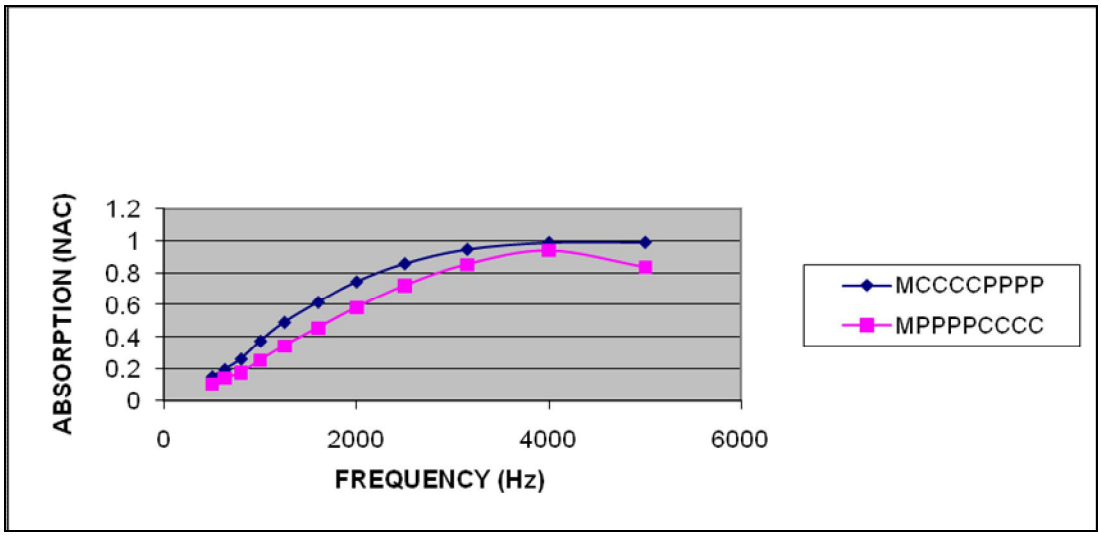


Fig. 4.12: NAC curve for position to the microphone; a flip of the same sample 1.

Note: letter M = microphone.

The result in Table 4.16 which is graphically represented in Fig. 4.12 is a single sample with different fibre types on the front and back surfaces as a result of the layering order. It can be observed in this study that both cotton and polylactic acid fibres are good sound absorbers, but where cotton sample is laid close to PLA sample; cotton dominate the absorption. This is evidence in the sample in Fig. 4.12; a flip of sample 1, the same sample but with different fibre type facing the microphone during acoustical measurement. Whenever cotton surface faces the microphone, the sample exhibits a high value of absorption. This can be attributed to cotton fibre fine linear density which gives higher sound absorption due to the higher number of fibres per volume, more contact area and tortuous channels. Also finer fibres can be vibrated easily by sound wave compared to coarser ones; and cause acoustic energy dissipation.

Table 4.17: Comparing the two surfaces of sample 2: (A 50/50% layering arrangement)

	Frequency (Hz)										
Sample I.D	**500**	**630**	**800**	**1000**	**1250**	**1600**	**2000**	**2500**	**3150**	**4000**	**5000**
MCCPPCCPP	0.099	0.131	0.160	0.223	0.311	0.404	0.515	0.646	0.801	0.905	0.971
MPPCCPPCC	0.097	0.128	0.163	0.210	0.243	0.379	0.564	0.620	0.766	0.886	0.982

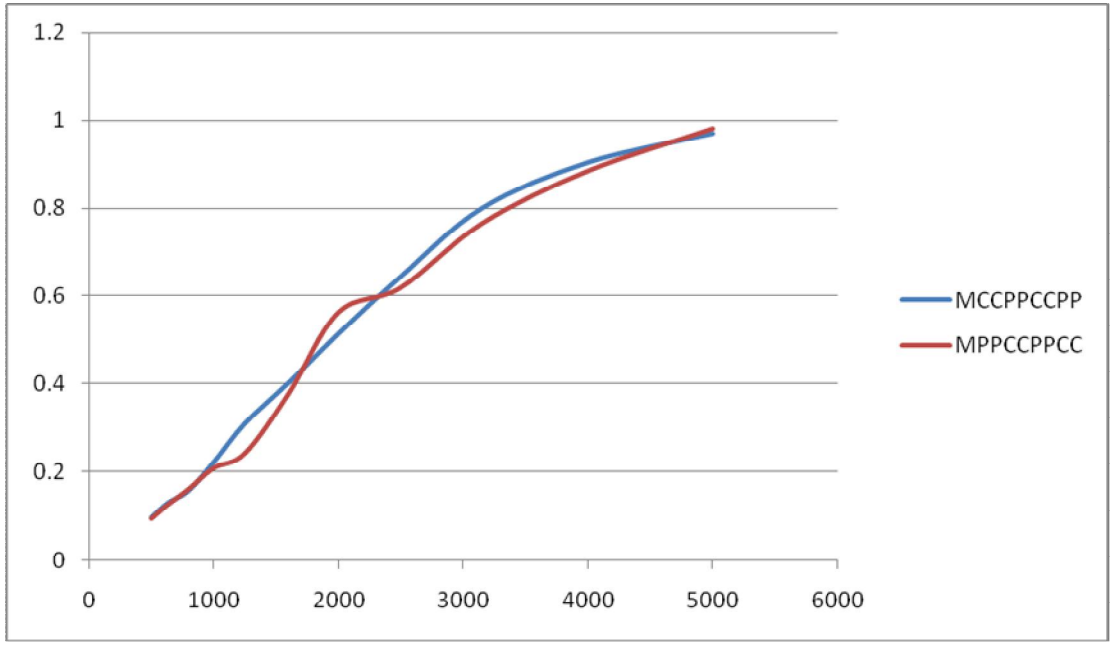


Fig. 4.13: A flip of 50/50% layering arrangement showing positioning to the microphone.

Note: letter M = microphone

The result on Table 4.17 is the presentation of the NAC data for sample 2. The flip of the two sides were measured acoustically because of the layering arrangements which resulted into different fibre type for the front and back surfaces. Although the data on Table 4.17 and the lines on the resultant graph shows that absorption is almost parallel; as can be seen on the NAC curves in Fig. 4.13, there was no constant flow of sound waves on the surface where PLA is facing the microphone especially at the lower frequency level to mid-frequency before the cotton layer interface. This can be explained by the crystalline fibre structure of PLA which also acts like a solid fibre with lower tortuous paths because the fibres are coarser than cotton fibres.

Table 4.18: Front and Back Surface of Sample 3

	Frequency (Hz)										
Sample ID	**500**	**630**	**800**	**1000**	**1250**	**1600**	**2000**	**2500**	**3150**	**4000**	**5000**
CPCPCPCP	0.142	0.188	0.226	0.326	0.436	0.552	0.627	0.810	0.921	0.962	0.995
PCPCPCPC	0.136	0.173	0.231	0.326	0.432	0.550	0.678	0.810	0.920	0.986	0.995

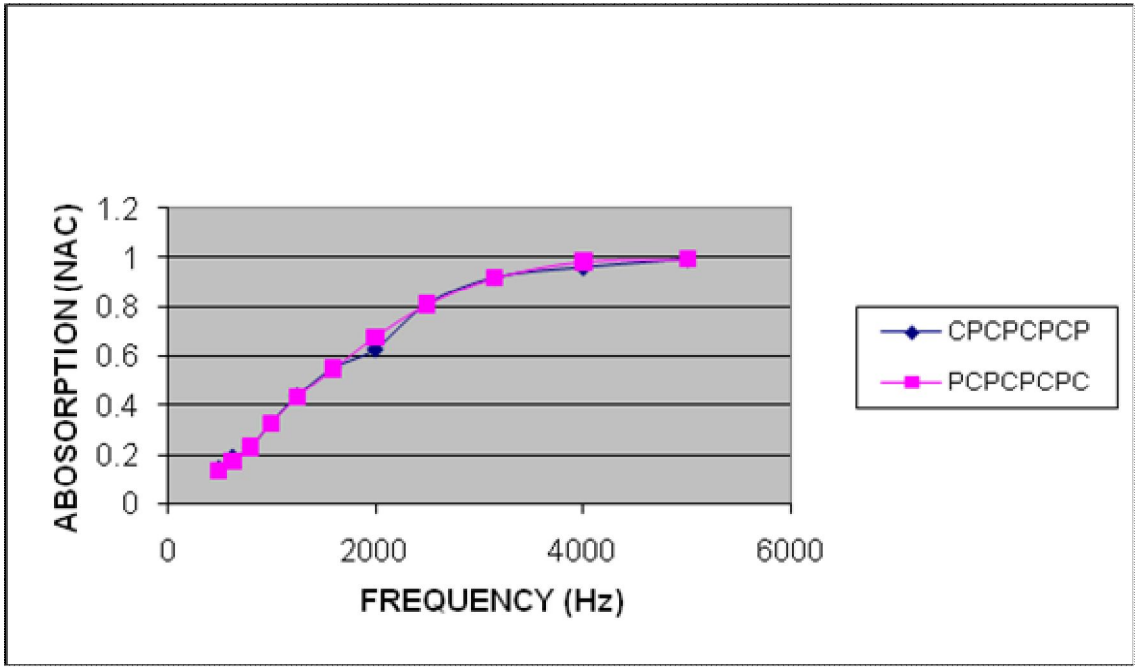


Fig. 4.14: Absorption curve of sample 3 showing layering sequence and the effects of thin interface

Fig. 4.14 is a display of the absorption curve of sample 3 which is a sandwich 50/50% Cotton/PLA. In this layering arrangement, a layer of (200)g/m^2 cotton is tacked next to a layer of (200)g/m^2 PLA x 4, which makes up the (800)g/m^2 of 50/50% layering sequencing that resulted in having a different fibre type on the front and the back surfaces of the sample. Both surfaces were tested acoustically and the result shows that there is no significant difference in sound absorption of the two surfaces. On the NAC curve (Fig. 4.14), both surfaces behaved like an intimate blend. This can be explained by the thin interface of different fibre type which provides for easy propagation of sound wave. It is also of note that full absorption was achieved on both surfaces. Therefore; it can be recommended that where there is a consideration for cotton and PLA composites, this type of layering sequence should be considered. Although PLA is similar to cotton in properties such as appearance, natural fibre hand, wickability/breathability, biodegradability, but does not possess the same sound absorptive abilities as cotton does. This can be seen in Table 4.9 which is a display of sample absorptive level where PLA has a total absorption of 0.489 which placed it on the 12th position, whereas cotton has a total of 0.790 and the 1st position on the level of absorption.

Table 4.19: Placement/Distance of Fibre Type to the Microphone in Samples 4 and 5

Frequency (Hz)

Sample ID	500	630	800	1000	1250	1600	2000	2500	3150	4000	5000
Ccpppcc	0.147	0.197	0.243	0.345	0.458	0.577	0.707	0.835	0.939	0.987	0.988
Ppcccpp	0.109	0.143	0.171	0.234	0.325	0.417	0.530	0.663	0.805	0.911	0.973

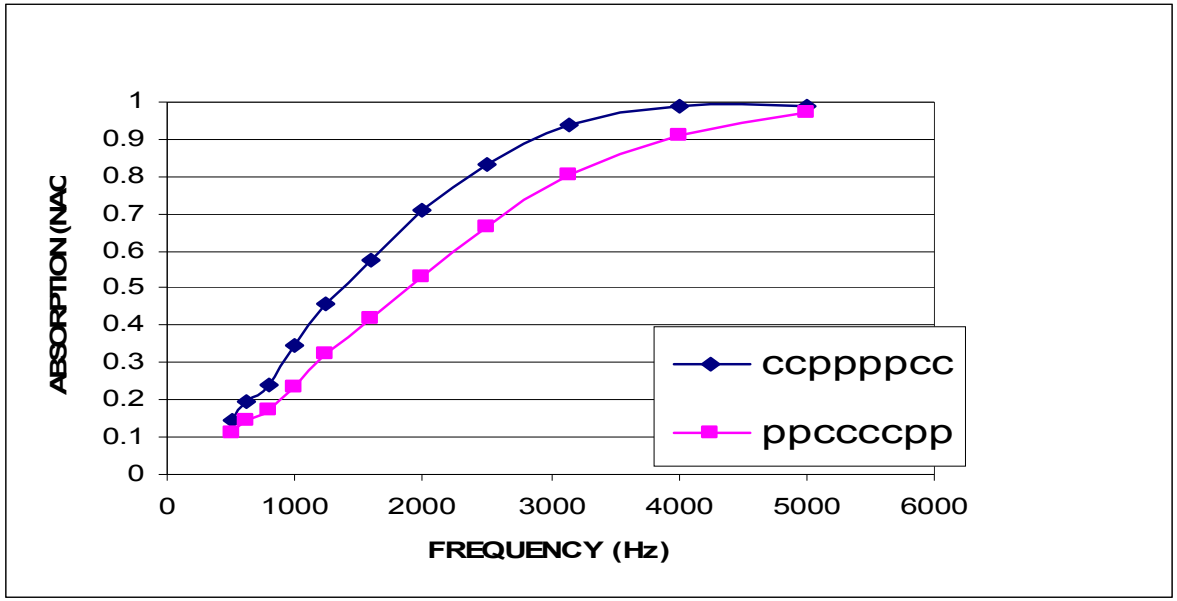


Fig. 4.15: Absorption curve of similar layering arrangement of samples with 50/50 Cotton/PLA.

The absorption curve in Figure 4.15 having its data presented in Table 4.19 is a display the effects of fibre type on absorption with respect to positioning of fibre in alternate layering arrangements as exhibited in samples 4 and 5 respectively. The difference in the results and the unparallel nature of the curve is not strange and can be explained by the differences in structure and characteristics of both fibres used and the surface that is placed next to the microphone. In sample 4; 25% PLA is close to the sound source, another 25% is at the back away from the microphone, while 50% is in-between the PLA layers. Since fibre size does not matter much at lower frequency where the wavelength is long, there was a constant flow of sound wave through the PLA facing the microphone and in-between the mid and high frequency, where there is an interface of 50% cotton. Cotton is fluffy with relatively random fibre placement and thus, higher tortuousity, higher number of small pores, higher number of fibre to fibre contact points, and gradient in porosity due to gravity and it achieved a full absorption at 5000Hz.

In Sample 5, where 25% cotton is tacked to 50%PLA in the middle and next to it is 25% cotton tacked to the back. There is a substantial difference as compared to sample 4; since cotton is facing the microphone at the lower frequency, propagation is controlled by viscosity whereas at high frequency it is controlled by inertia. Therefore inertia force would propel sound wave to hit the cotton fibres and cause it to vibrate, moving through unto the adjacent 50% PLA interface, and as a result, the sample had a constant flow rate and it achieved a full absorption at 4000Hz.

Table 4.20: Comparison of Monolayer to 8 Layers 100% Cotton and PLA Batts

	Frequency Hz										
Sample ID	500	630	800	1000	1250	1600	2000	2500	3100	4000	5000
100% COT^{L}	0.297	0.438	0.588	0.732	0.847	0.934	0.976	0.989	0.976	0.956	0.959
100% PLA^{L}	0.137	0.177	0.22	0.278	0.365	0.449	0.590	0.667	0.768	0.861	0.873
100% COT^{S}	0.059	0.078	0.101	0.132	0.176	0.230	0.292	0.368	0.460	0.578	0.699
100% PLA^{S}	0.062	0.076	0.090	0.110	0.135	0.162	0.195	0.238	0.291	0.380	0.489

- 100% COT^{L} represents cotton batts of eight layers
- 100% PLA^{L} represents PLA batts of eight layers
- 100% COT^{S} represents cotton batts of a single layer

- 100% PLA^{S} represents PLA batts of a single layer

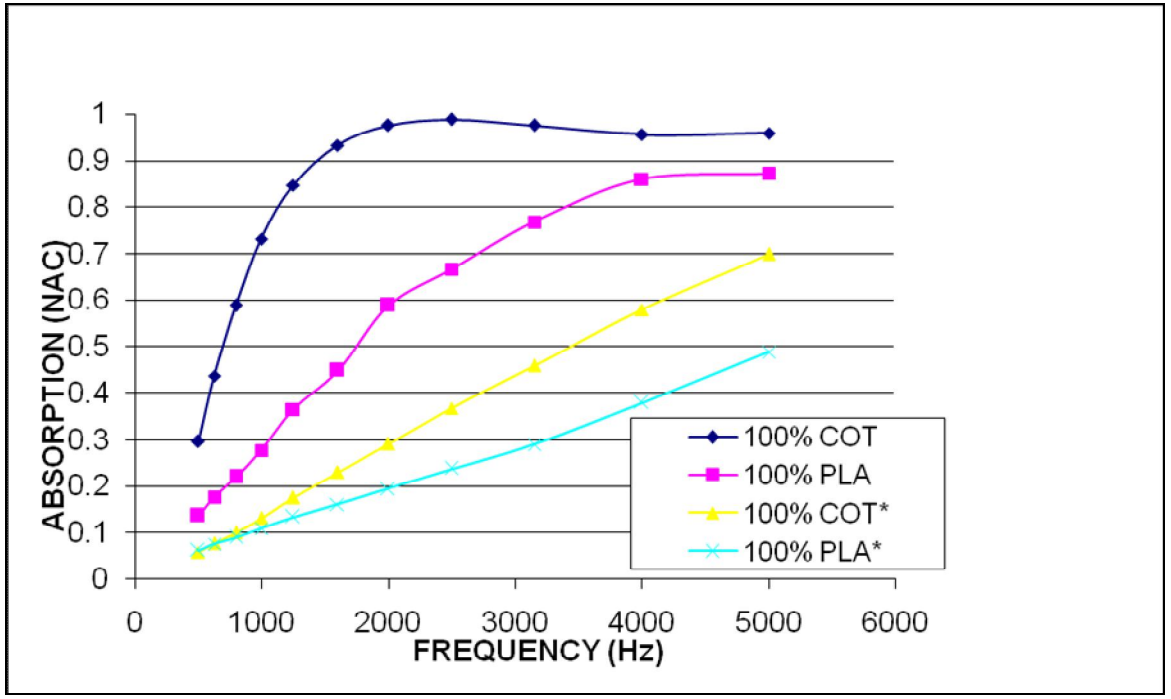


Fig. 4.16: Comparing the NAC curve of both single and eight layers 100% cotton and PLA Batts.

In Fig. 4.16 100% monolayer cotton and polylactic batts of 200g/m^2 each are being compared to multilayer cotton and polylactic acid batts of 800g/m^2 (8) layers each. Multilayer cotton obtained a total absorption of (1) at mid-frequency of 2500Hz on the graph in Fig.4.16, whilst that of monolayer cotton batt terminates at 0.7 at a frequency range of 5000Hz in the same Fig. The same thing goes for polylactic acid multilayer which had almost a total absorption of about 0.88dB coefficients at the frequency range 4000Hz, whereas the absorption in monolayer terminated at 0.5 at the frequency range of 5000Hz. This shows the importance of the depth of thickness in creating a resistance, the thicker the material, the greater the sound absorption. It can also be seen that at the lower frequencies monolayer did not absorb much. This can be attributed to the thin layer, since the wave length is longer in this region; thick material is required for good absorption only at low frequencies. However, at higher frequencies thickness has insignificant effect on sound absorption.

Table 4.21: Absorption of Samples with Various Percentage of Cotton/PLA at Various Frequencies

	Frequency (Hz)										
Sample ID	**500**	**630**	**800**	**1000**	**1250**	**1600**	**2000**	**2500**	**3150**	**4000**	**5000**
100%COT	0.297	0.438	0.588	0.732	0.847	0.935	0.976	0.989	0.976	0.956	0.959
75% COT	0.141	0.183	0.230	0.335	0.465	0.580	0.709	0.824	0.917	0.967	0.981
50% COT	0.153	0.198	0.264	0.376	0.499	0.617	0.746	0.859	0.949	0.991	0.992

25% COT	0.141	0.191	0.243	0.324	0.439	0.556	0.687	0.808	0.912	0.963	0.959

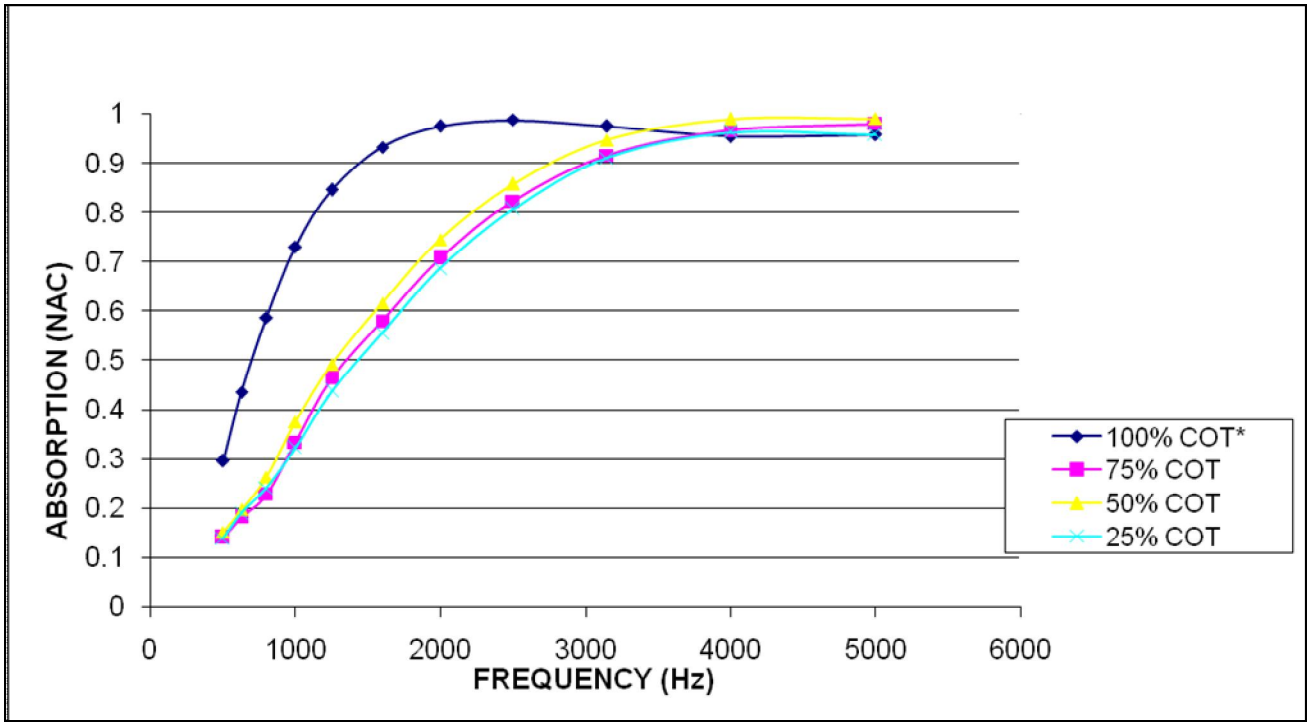


Fig.4.17 NAC curves showing the level of absorption of batt with various blend ratios of PLA/Cotton.

The Table in 4.21 and the resultant curve 4.17 is a comparison of level of absorption for batts of 100%, 75%cotton + 25%PLA, 50% cotton + 50% PLA and 75% cotton + 25%PLA respectively. As it is displayed on the graph, 100% cotton had a very good and constant flow rate of sound wave from the low frequency region, attained a full absorption of one (1) at about 2000 Hz and maintained a constant flow all through. Next to it in performance is the 50/50% sample which performed slightly higher than 75% and 25% blend ratios.

From the analysis of the results in this study, polylactic acid fibre is a good absorber when in composite with cotton. It is interesting to note that cotton always display greater strength once it is placed close to the noise source, its the percentage notwithstanding. In comparison, polylactic acid fibre batts layered with 25%, 50% and 75% cotton all performed better than 100% polylactic acid batts. The fine diameters of cotton, its convolution and spiral shape provide a good surface area and propagation towards sound waves.

Table 4.22: NAC results for 75% PLA and 25% cotton batts.

	Frequency (Hz)										
Sample ID	**500**	**630**	**800**	**1000**	**1250**	**1600**	**2000**	**2500**	**3150**	**4000**	**5000**
PPPCCPPP	0.119	0.154	0.191	0.239	0.334	0.430	0.537	0.669	0.813	0.918	0.978
CPPPPPPC	0.141	0.191	0.243	0.324	0.439	0.556	0.687	0.808	0.912	0.963	0.959
PPCPPCPP	0.131	0.174	0.213	0.282	0.388	0.499	0.616	0.749	0.876	0.957	0.988

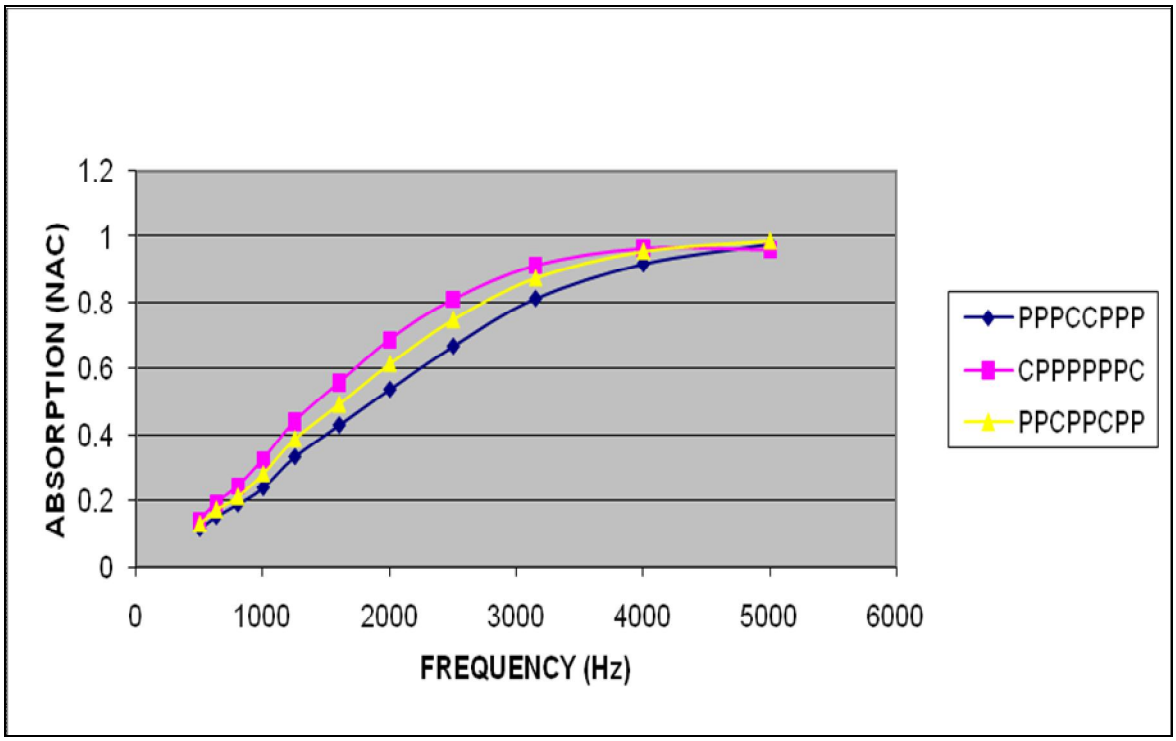


Fig. 4.18.: NAC curves of 25% Cotton and 75% PLA (sandwich) layering order.

In the layering arrangements in Fig. 4.18; cotton of 25 percentages are sandwiched unto 75 percentage PLA, which are samples 6, 7 and 8 respectively in Table 3.1 (Layering Arrangement of Batts in Chapter 3). The samples which had cotton tacked to the front and back exhibited the best result; with good absorption from the low frequency region which was maintained all through to the end. Next to it in performance is the sample with 2 layers of PLA (25) % in the front and also at the back. It is interesting to note that with the addition of 25% cotton to 75% PLA; there was a constant flow in sound wave all through and a full absorption was achieved. Whereas, 100% PLA when tested, as presented in Table 4.20 and in Fig. 4.16 did not have a constant flow rate and the highest level of absorption; at mid-frequency range of 2000 -2500 Hz, was 0.590 dB while cotton attained 0.976 dB. And at 4000Hz PLA attained it fullest capacity of 0.83dB at 4000Hz as compare to cotton which attained it full capacity of 1dB at 2500Hz. Although this level of absorption is good; but cotton performed excellently. It also reiterates that fine cotton fibre has finer linear density which gives higher sound absorption due to the higher number of fibres per volume, more contact area, and more tortuous channels.

Table 4.23: Absorption at Various Frequencies in Samples with 75% cotton /25%PLA

	Frequency (Hz)										
Sample ID	**500**	**630**	**800**	**1000**	**1250**	**1600**	**2000**	**2500**	**3150**	**4000**	**5000**
PCCCCCCP	0.141	0.183	0.230	0.335	0.465	0.580	0.709	0.824	0.917	0.967	0.981
CCPCCPCC	0.129	0.173	0.230	0.334	0.454	0.581	0.706	0.826	0.924	0.979	0.992
CCCPPCCC	0.123	0.165	0.208	0.309	0.424	0.545	0.690	0.805	0.916	0.979	0.999

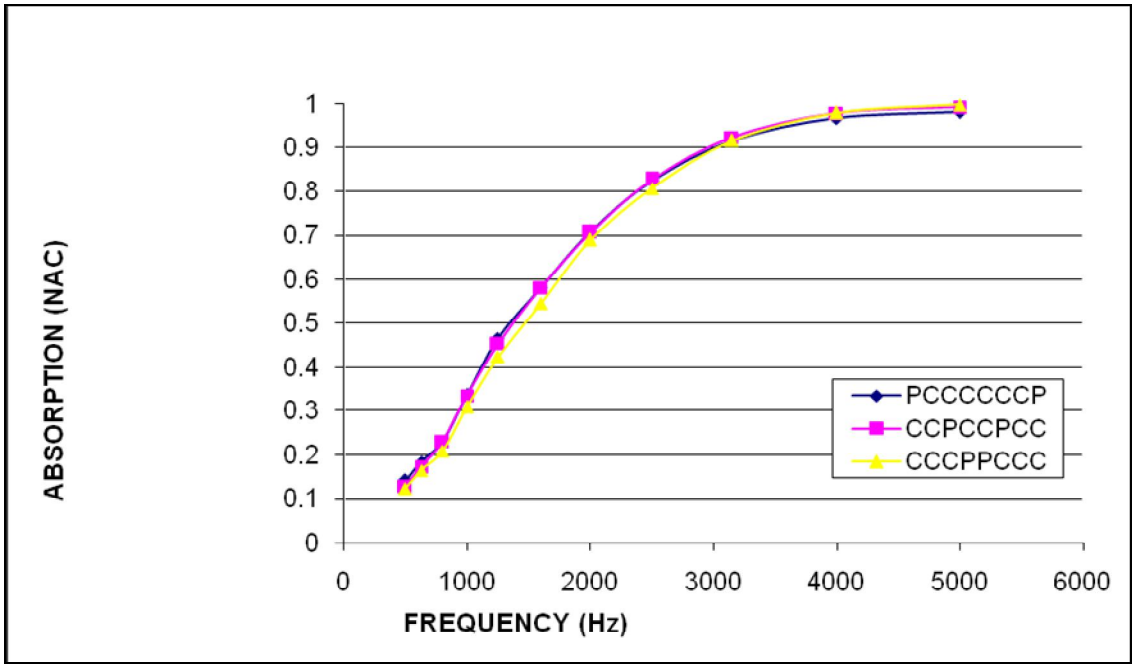


Fig. 4.19: NAC curve showing the effects of layering arrangement of 25% PLA and 75% cotton.

The results in Table 4.23 which is graphically represented in Fig. 4.19, shows the absorption level when batts 25% PLA is layered with 75% cotton batts. As expected the cotton overshadows the PLA in the absorption in this layering sequence because of its high percentage. There was a constant flow of sound wave and the samples behaved like 100% cotton, absorption here is total, whereby cotton overshadowed and dominated in the absorption where placed at the front and the back of the polylactic acid fibre in a sample. Positioning to the sound source and layering sequence does not have any influence on these sets of sample which are displayed as intimate blend on the NAC curve in Fig. 4.19.

The fibre shape and morphology of polylactic acid fibre is hollow and crystalline whereas; cotton is elliptical, amorphous and to some degree crystalline. Therefore, when cotton is layered with polylactic acid fibre, it does not allow sound to bounce back or resonance rather, it enhances the performance of PLA. In the absorption data in Table 4.23 and the resultant graph in Fig. 4.19, the presence of 25% PLA does not exhibit any significance.

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Table 4. 24: Results for 100% cotton and 100% PLA fabrics.

	Frequency (Hz)										
Sample ID	**500**	**630**	**800**	**1000**	**1250**	**1600**	**2000**	**2500**	**3150**	**4000**	**5000**
COT FABRIC	0.03	0.036	0.041	0.049	0.064	0.086	0.112	0.139	0.187	0.273	0.385
PLA FABRIC	0.0410	0.051	0.061	0.075	0.087	0.102	0.119	0.146	0.191	0.247	0.299

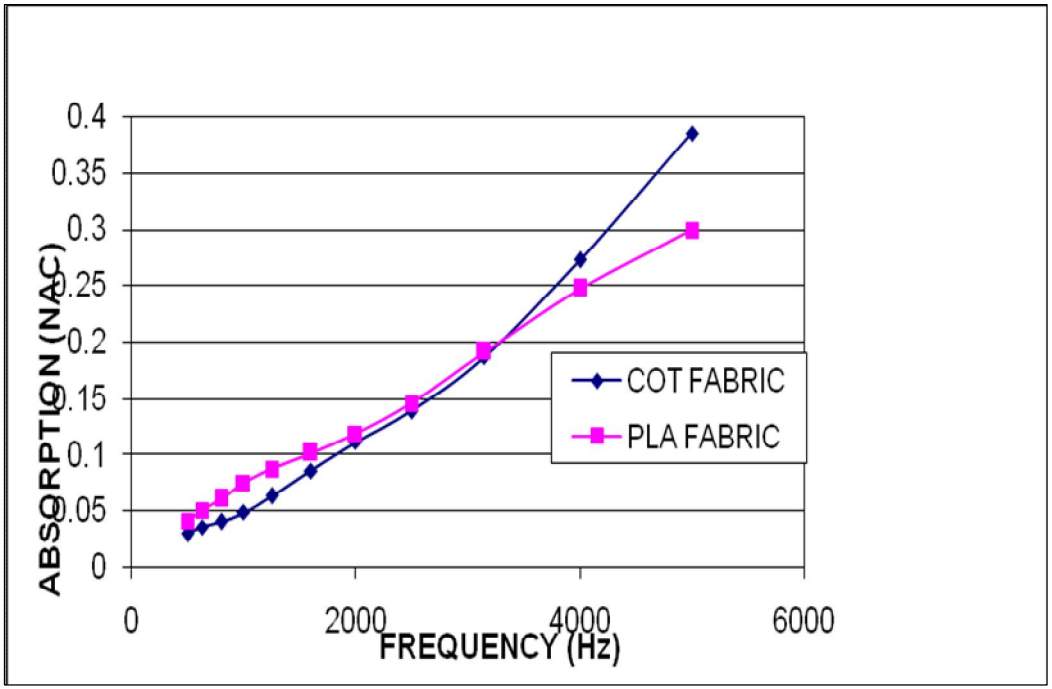

0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
ABSORPTION (NAC)
0
2000
4000
6000
FREQUENCY (Hz)
COT FABRIC
PLA FABRIC

Fig. 4.20: Comparing 100% Needle-punch Cotton fabric versus 100% PLA needle-punch fabric.

Fig. 4.20 is a presentation of the NAC curve of needle-punched fabric of 100% cotton compared to needle-punched fabric of 100% PLA. In this result the needle-punched sample fabrics did not exhibit good sound absorption properties. The reason for poor absorption in needle-punch fabric can be attributed to the pore size.

This is because the porosity in needle-punched fabric is not as good as that of batts. Porosity determines the ratio between the average particle velocity in the channels and on the cross-sectional average particle velocity of the absorber material. The sound absorption performance of porous materials is largely affected by tortuosity that does not allow the sound waves to follow straight paths. The value of tortuosity determines the high frequency behavior of sound absorbing porous materials.

It is interesting to note in the results in Table 4.24 graph in Fig. 20 that PLA fabric is a better sound absorber at low frequencies, but the reverse is the case at higher frequencies because the wave length are longer in the region. In Table 4.24 PLA absorption stopped at 0.299dB whereas, cotton stopped at 0.385dB all at 5000 Hz. With this result, it can deduced that batts are best form of nonwoven for sound absorber, since any sound absorbing material that does not attain 0.450dB cannot be term good absorber.

Table 4.25: NAC results for 100% monolayer PLA and Cotton batts and fabrics

	Frequency (Hz)										
Sample ID	**500**	**630**	**800**	**1000**	**1250**	**1600**	**2000**	**2500**	**3150**	**4000**	**5000**
100% COT*	0.059	0.078	0.101	0.132	0.176	0.230	0.292	0.368	0.460	0.580	0.699
100% PLA*	0.062	0.076	0.091	0.110	0.135	0.162	0.195	0.238	0.291	0.380	0.489
COT FABRIC	0.03	0.036	0.041	0.049	0.064	0.086	0.112	0.139	0.187	0.273	0.385
PLA FABRIC	0.050	0.051	0.061	0.075	0.087	0.112	0.119	0.146	0.191	0.247	0.299

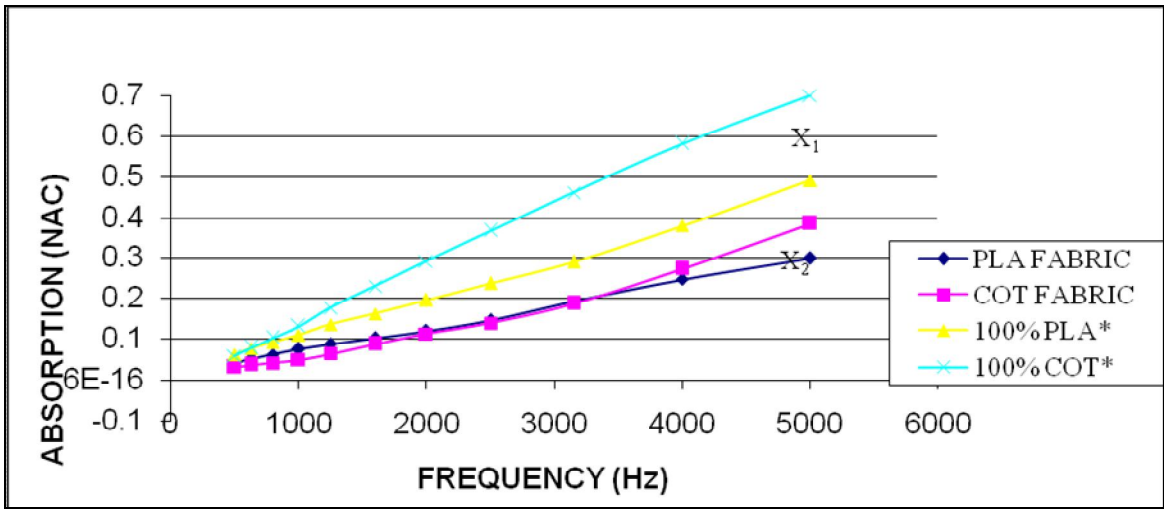


Fig. 4.21: A comparison of monolayer cotton and PLA batts with cotton and PLA fabrics

Table 4.25 and the resultant graph in Fig. 4.21 are a comparison of monolayer 100% cotton and 100% PLA batts versus needle-punch cotton and PLA fabrics of normalised weights. As expected of nonwoven materials, absorption is very low at lower frequency-range since maximum energy is dissipated in the region where maximum particle velocity takes place, and particle velocity is far from the material at low frequencies especially, when the absorber is thin. The result is as expected of nonwoven materials with differing pore sizes.

The sizes of pores and their arrangements in needle-punch materials are not as comparable to that in batts therefore; the poor performance is not unexpected since a unit decrease in a significant variable result to a decrease in sound absorption coefficient. This is because porosity determines the ratio between the average particle velocity in the channels and on the cross-sectional average particle velocity of the absorber material. The sound absorption performance of porous materials is largely affected by tortuosity; which does not allow the sound waves to follow in straight paths since the value of tortuosity determines the response of sound absorbing materials to high frequency sound.

Table 4.26: NAC results for monolayer 100% cotton and 100% PLA

	Frequency Hz										
SAMPLE ID	**500**	**630**	**800**	**1000**	**1250**	**1600**	**2000**	**2500**	**3150**	**4000**	**5000**
100% Cot	0.059	0.078	0.101	0.131	0.176	0.230	0.292	0.368	0.460	0.580	0.699
100%PLA	0.062	0.076	0.090	0.109	0.135	0.162	0.195	0.238	0.291	0.380	0.489

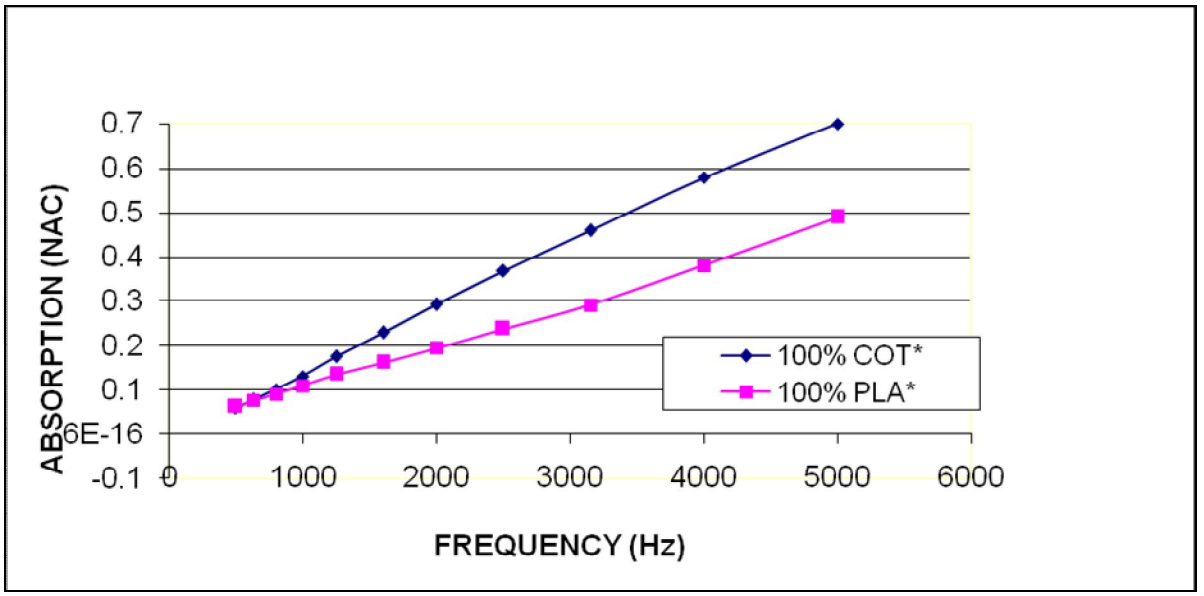

ABSORPTION (NAC)
0.7
0.6
0.5
0.4
0.3
0.2
0.1
6E-16
-0.1
0
1000
2000
3000
4000
5000
6000
FREQUENCY (Hz)
100% COT*
100% PLA*

Fig. 4.22: comparing monolayer of 100% Cotton and single layer 100% PLA.

Fig. 4.22 is the NAC curve of a 200g/m^2 PLA batts and 200g/m^2 cotton batts. As expected of nonwoven materials absorption is low at lower frequency-range since maximum energy is dissipated in the region where maximum particle velocity takes place, and particle velocity is far from the material at low frequencies especially, when the absorber is thin. As can be seen in the Fig.4.22 absorption flow rate became constant and normal between the mid and high frequency ranges. In this result, cotton exhibited higher absorption as usual. Nevertheless, because the layer is thin cotton recorded 0.7 absorption coefficient of 0.7 at 5000 Hz while PLA recorded absorption coefficient of 0.5 at 5000 Hz. With this absorption rate, batts are excellent in absorbing sound wave in comparison to fabrics.

Table 4.27: Model Summary for Comparing the Variable that gives better Absorption.

Model	R	R Square	Adjusted R Square	R Square Change	F Change	Sig. F Change
1	.779[a]	.607	0.607	.607	1697.316	.0001
2	.915[b]	.838	0.837	.230	1556.005	.0001
3	.919[c]	.845	0.845	.008	53.415	.0001
4	.921[d]	.849	0.849	.004	28.538	.0001
5	.923[e]	.852	0.852	.003	24.672	.0001
6	.923[f]	.852	0.852	.000	1.114	.2911
7	.925[g]	.855	0.854	.003	21.227	.0001
8	.925[h]	.856	0.855	.001	5.256	.0221

1. Predictors: (Constant), Freq

2. Predictors: (Constant), Freq, Thickness

3. Predictors: (Constant), Freq, Thickness, Resist

4. Predictors: (Constant), Freq, Thickness, Resist, Porosity

5. Predictors: (Constant), Freq, Thickness, Resist, Porosity, Weight

6. Predictors: (Constant), Freq, Resist, Porosity, Weight

7. Predictors: (Constant), Freq, Resist, Porosity, Weight, Airflow

8. Predictors: (Constant), Freq, Resist, Porosity, Weight, Airflow, Thickness

Regression analysis was used to evaluate the variables used in this study and their contribution to absorption as presented in Table 4.7, model eight (8) where all the variables were present was found to yield the best R-Square value.

Table 4.28: Total Model for Absorption Coefficient showing all the Variables

Model	Variables	Absorbent Coefficient[a]	t - Value	Signi. Level
1	(Constant)	.114	10.619	.0001
	Freq	.000	41.198	.0001
2	(Constant)	-.365	-26.152	.0001
	Freq	.000	64.040	.0001
	Thickness	40.478	39.446	.0001
3	(Constant)	-.389	-27.738	.0001
	Freq	.000	65.552	.0001
	Thickness	35.559	29.451	.0001
	Resist	1.631	7.309	.0001
4	(Constant)	-3.292	-6.057	.0001

	Freq	.000	66.370	.0001
	Thickness	33.994	27.682	.0001
	Resist	1.922	8.464	.0001
	Porosity	3.051	5.342	.0001
5	(Constant)	-8.327	-7.257	.0001
	Freq	.000	67.084	.0001
	Thickness	-9.288	-1.056	.2911
	Resist	1.680	7.309	.0001
	Porosity	8.344	6.918	.0001
	Weight	.001	4.967	.0001
6	(Constant)	-7.250	-13.824	.0001
	Freq	.000	67.080	.0001
	Resist	1.712	7.512	.0001
	Porosity	7.210	13.137	.0001
	Weight	.001	28.396	.0001
7	(Constant)	-9.580	-13.210	.0001
	Freq	.000	67.682	.0001
	Resist	.823	2.771	.0061
	Porosity	9.827	12.498	.0001
	Weight	.0001	19.130	.0001
	Airflow	.0001	-4.607	.0001
8	(Constant)	-12.269	-8.903	.0001
	Freq	.0001	67.811	.0001
	Thickness	-20.602	-2.293	.0221
	Resist	.638	2.079	.0381

Porosity	12.677	8.623	.0001
Weight	.001	5.661	.0001
Airflow	-.001	-5.043	.0001

Table 4.28 can be described as one output with many explanatory facets due to the input variables which are linear. In this analysis, the adequacy of the model for data was evaluated.

The F-Statistic rejects Ho since the P-value < 0.01 is significant in the model.

Goodness of fit:

Ho = my model is not adequate for the data (or not fit) is rejected.

Hi = my model is fit for the data is accepted at 85.8% degree confidence with an R-Square of R^2 =0.856.

As can be seen in Table 4.28 where the dependent variable is absorption and the contributions of other variables are expressed in equation (4.3), which is model 8 where all the input variables contributed significantly.

NAC = -12.269 + 0.001(freq) -20.602 (t) +638 (rst) – 12.677 (po) + 0.001 (wt) -0.001(af)

F – Value = < 0.01 . . . . . (4.3)

R-Square value = 0.856.

From the analysis and findings in this study it has been established that the dependent variables in this research are absorption and airflow. Absorption is constant without the contributions of other variables at -12.269; one (1) unit increase or decrease in frequency results to an increase or a decrease of the value of frequency in the analysis which is + 0.001 in absorption . The same explanation goes for other variables used in the model.

Other factors such as the fibre size, fibre density and fibre diameter did not make significant contribution in the model since they are structural properties of the materials being investigated.

Table 4.29: R-Square Values and Level of Significant for Airflow.

Model Summary Airflow

Model	R	R Square	Sig. F Change
1	.738[a]	.544	.0001
2	.853[b]	.728	.0001
3	.920[c]	.846	.0001
4	.921[d]	.848	.0001

a. Predictors: (Constant), Resistivity

b. Predictors: (Constant), Resistivity, Porosity

c. Predictors: (Constant), Resistivity, Porosity, Thickness

d. Predictors: (Constant), Resistivity, Porosity, Thickness, Weight

The model summary for airflow in Table 4.29 presents the level of significant of airflow in sound absorption coefficient of the materials tested.

The Table presents the summary of results for each of the four (4) models used to analyse the correlation between airflow and the other variables. As can be seen on the Table, the first model which has only resistivity is significant at 1% level. Although the model with four (4) variables (resistivity, porosity, thickness and weight) is also significant at 1% level, but gave the best R-Square value of 0.848.

CHAPTER 5

5.0 Conclusion, Summary and Recommendations

5.1 Conclusion

From the analysis and findings of this study, which are based on the set objectives of the study it can be concluded that the fibres used are good in absorbing sound. Also the R-square value obtained from the model used which is (0.856) is a level considered to be good values for experimental textile data, where there is relatively large variability in the raw materials.

In conclusion results from the evaluations carried out on the acoustical properties of cotton and polylactic acid fibre webs and fabrics have established that the materials are effective and could be used as alternative to glass-fibre mats and other fibres synthesised from petrochemicals. Therefore, this research has contributed to knowledge by discovering that naturally available fibres which are biodegradable are excellent material in absorbing sound energy.

Interestingly, it was discovered that an appreciable increase in normal absorption coefficient, NAC, values were obtained by using the impedance material in web form instead of bonding. Therefore; it can be concluded that this research has succeeded not only in introducing new acoustic materials, but in establishing that webs could be used behind panels or in places where finishing is not required. Needle-punched samples absorbed sound energy, nevertheless; webs performed 2.5 times better as presented on Table 4.9. Moreover, the innovative aspect of these materials from the natural source is their light

weight coupled with low cost which is a great asset to the automotive and aircraft industry, since automobile production is now focused on a drastic weight reduction to cut down on energy consumption.

Multi-layer absorbers achieve higher sound absorption than the mono-layer absorbers with the same thickness. Layers of nonwoven made from the two fibre types used were varied in order of arrangements and the effect of positioning to the microphone was evaluated. In the findings, structural parameters such as fibre fineness, material thickness, porosity, linear density and air-flow resistance were discovered to have great influence on sound absorption coefficient in the frequency range of 200Hz to 5000Hz.

It is of interest note that below 500Hz, materials made from cotton fibres have a lower sound absorption capacity whereas, they give higher absorption values at higher frequency range.

It can be concluded that it is better to use finer fibres and make fabrics or batts thicker but looser, as could be seen with the results of cotton material; fluffier materials possess better sound absorptive capability than the compact ones. Materials made from coarser fibres does not have as much value of sound absorption coefficients as the finer ones, which accord negligible effects to weight per unit area of samples.

In all the layering arrangements, cotton samples performed excellently when placed next to the microphone and where the percentage of the PLA interface is not high, its presence is overshadow by cotton.

In the literature scan of the use of natural fibrous material in acoustics; both cotton and PLA have been used only as composites with other synthetic fibres and a homogenous material or in layers as this research has done. In the light of this, this research has added to knowledge in advancing natural materials.

In the areas of cost; it is also discovered that the most innovative aspect of materials from the natural source is their light weight coupled with low cost which is a great asset to the automotive industry, since automobile production is now focused on a drastic weight reduction to cut down on energy consumption.

In application, cotton and PLA are excellent acoustical materials based on renewable resources that can lead to viable alternatives to conventional materials for current and future applications.

Automotive interiors with a reinforcement of natural fibres are considered to be physiologically safer than glass fibre parts. Further advantages result from their cooling effect, and particularly their high absorbency. With respect to industrial safety, natural fibres do not cause allergic reactions or skin irritations renewable resources that can lead to viable alternatives to conventional materials.

Areas of application could include buildings: (which may include ceilings and wall cladding curtains/drapes); partitioning: where space is a problem; studios, workshops, lecture halls, hospitals and high star hotels); automobile interior: (which may include: headliner, trunks, hood, the door panels and carpets); appliances, machineries', ear-muffs, plugs and some power tools.

Sound absorbing materials such as felts made from glass, asbestos, rock wool, polyurethane foams and other synthetic fibres are the traditional materials broadly in the market. Some of the drawbacks associated with these existing materials include; stability in moulding, difficulty to handle, non-recyclable, high density, the possibility of health hazard and high cost of production.

In order to address some environmental problems, governments of most advanced countries have thought it logical to put a number of regulations in place. These include regulations requiring the manufacturing industry to select materials and process technologies with less impact on the ecological environment. Considering the end-of-life of materials as relating to issue of deposition of fractions of worn-out materials and environmental safety, industry and consumer society has now led to an emphasis on eco-friendly materials.

Cotton is a cellulosic fibre which is from the hair of cotton seed; while PLA fibre is extracted from starch in plant matter and converted to a fermentable sugar (e.g. glucose) by enzymatic hydrolysis. Therefore, they are both obtained from annually renewable crops; whereas, the conventional synthetic polymers rely on reserves of oil and gas for their monomer source and energy to manufacture.

5.2 Summary

In general, porous sound-absorbing materials have evolved from the initial material at its inception into more advanced materials over the years. Moreover, the concepts of environmentally friendly, sustainable, recycled, and green building materials is now driving the manufacturers to seek for safer, lighter and more technologically optimized sound-absorbing materials, a purpose which cotton and PLA used in this research readily accomplished. This research has succeeded not only in developing good

sound absorbing materials, but it has also identified environmentally friendly materials which inflict the least amount of harm on the environment without compromising the performance characteristics.

5.3 Recommendations for further studies

The results of this investigation have paved the way for several possibilities for future research. Some of the important ones are described below:

1. Various levels of thickness and densities of sample should be used.
2. Experimental measurement of tortuosity and porosity.
3. Make samples using spunbond and melt blown technologies.
4. Make intimate samples using 50% cotton and 50% PLA and compare it effectiveness to same percentage in layering.
5. Fibres with same size and different cross-section should be used to produce nonwoven samples for analysis.

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