ABSTRACT

Kannan Allampalayam Jayaraman, **Acoustical Absorptive Properties of Nonwovens**, under the guidance of (Dr. P. Banks-Lee and Dr. B. Pourdeyhimi).

Today much importance is given to the acoustical environment. Noise control and its principles play an important role in creating an acoustically pleasing environment. This can be achieved when the intensity of sound is brought down to a level that is not harmful to human ears. Achieving a pleasing environment can be obtained by using various techniques that employ different materials. One such technique is by absorbing the sound and converting it to thermal energy. Fibrous, porous and other kinds of materials have been widely accepted as sound absorptive materials. A literature scan [19, 20, 53, 76] showed nonwovens could be considered to be a prospective candidate for sound absorption. The impetus for this study stemmed from the drawbacks associated with the existing sound absorbing materials like felts made from glass, asbestos and rock wool and foams. Some of these drawbacks include the fact that the materials are unsuitable for molding, non-recyclable, difficult to handle and install, dust accumulating and in the case of foams are high in density.

These drawbacks are forcing the acoustical product manufacturers to look into natural, biodegradable raw materials. To assist in that effort, the research presented here studies the feasibility of using kenaf fibers blended with reclaim polyester fibers and other fiber blends as sound absorptive materials. Products from kenaf/reclaim fiber blends will have the benefit of low raw materials and manufacturing cost, at the same time providing a suitable end use for reclaim polyester fibers.

Early work in noise control has shown the importance of understanding micro-structural and other physical parameters in designing high performance acoustic materials. As a final objective, this research describes how the physical elements of nonwoven sound absorbent system like fiber type, fiber size, fiber cross section, material thickness, density, airflow resistance and porosity can change the absorption behavior of nonwovens. Influence of fire retardant treatment, surface impedance, air gap, compression, manufacturing methods and attachment of film on sound absorption behavior of nonwovens were also considered.

Acoustical Absorptive Properties of Nonwovens

by

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To My Family & My Friends

BIOGRAPHY

The author was born in Erode, Tamil Nadu INDIA on October 3, 1980. He received his Bachelors degree in Textile Technology from Kumaraguru College of Technology, Coimbatore, INDIA in April 2002. He has been a Masters student at the North Carolina State University, USA, in the Department of Textile and Apparel Technology and Management, since August 2003. His Masters specialization is in the field of nonwovens. He also has got a Graduate Certificate in Nonwovens Science and Technology.

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TABLE OF CONTENTS

1.0. Introduction

2.0. Literature Review

2.4. Factors Influencing Sound Absorption of Nonwovens

2.6. Measurement of Sound Absorption Coefficient

3.0. Methodology

3.1. Fiber Selection

3.2. Fabric Production

3.3. Parameters for the Study

4.0. Results and Discussions

4.1. Statistical Results

4.2. **Statistical Results: Carded Samples**

4.3. **Statistical Results: Airlaid Samples**

4.4. **Sound Absorption Measurements**

8.0. Appendices

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1: Introduction

The intention of this chapter is to give basic information about acoustics and noise control. The material for this chapter has been gathered from various textbooks and research papers.

1.1. Acoustics

Acoustics is defined as the scientific study of sound which includes the effect of reflection, refraction, absorption, diffraction and interference. Sound can be considered as a wave phenomenon. A sound wave is a longitudinal wave where particles of the medium are temporarily displaced in a direction parallel to energy transport and then return to their original position [68]. The vibration in a medium produces alternating waves of relatively dense and sparse particles – compression and rarefaction respectively (shown in Figure 1.1).

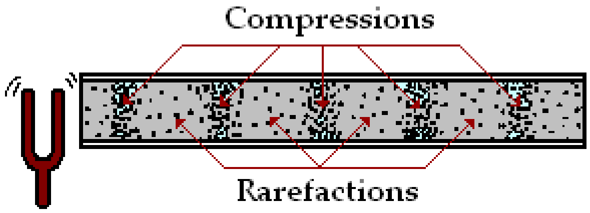


Figure 1.1. Alternative patterns of dense and sparse particles

The resultant variation to normal ambient pressure is translated by the ear and perceived as sound. A simple sound wave is illustrated in Figure 1.2 and may be described in terms of variables like: Amplitude, Frequency, Wavelength, Period and Intensity.

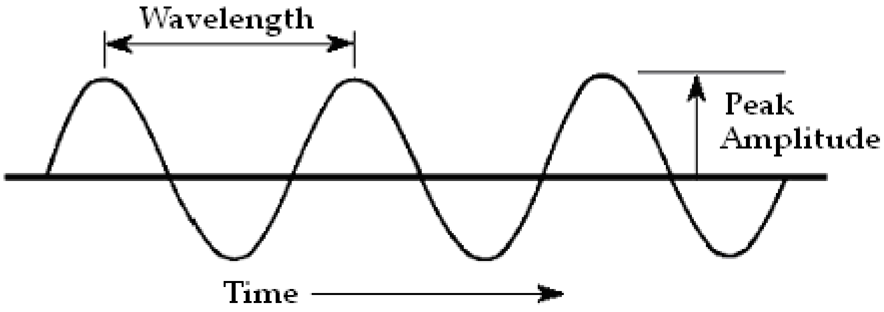


Figure 1.2. Illustration of simple sound wave

Amplitude refers to the difference between maxima and minima pressure [12]. **Frequency** of a wave is measured as the number of complete back-and-forth vibrations of a particle of the medium per unit of time [12]. A commonly used unit for frequency (f) is the Hertz (abbreviated Hz). The **wavelength** (λ) of a wave is the distance which a disturbance travels along the medium in one complete wave cycle [12]. Since a wave repeats its pattern once every wave cycle, the wavelength is sometimes referred to as the length of the repeating patterns. The term '**period**' can be defined as the time required for the completion of one cycle of wave motion [12]. The **intensity** of a sound wave is defined as the average rate at which sound energy is transmitted through a unit area. Frequency and wavelength are related as follows [63]:

$$\text{Wavelength [ft]} = \frac{\text{Speed of sound [ft/sec]}}{\text{Frequency [Hz]}}$$

Like any wave, the speed of sound (v) refers to how fast the disturbance is passed from particle to particle. Under normal condition of pressure and humidity at sea level, sound waves travel at approximately 344 m/s through air [51]. As explained earlier frequency refers to the number of vibrations, which an individual particle makes per unit of time, while speed refers to the distance, which the disturbance travels per unit of time [68].

1.2. Noise Control

“Noise is an unwanted sound and unfortunately most of the machines that have been developed for industrial purposes, for high speed transportation, or to make life more enjoyable are accompanied by noise” [57]. A noise system can be broken down into three elements [3, 27, 57]:

- Noise Source – The element which disturbs the air
- Noise Path – The medium through which the acoustical energy propagates from one point to another

- Noise Receiver – The person who could potentially complain about the quantity or level of noise as perceived at same point

It is necessary to treat at least one element in the noise system if the perceived level of the noise is to be reduced. By reducing the noise level at the source or along the path, the noise level at the receiver is accordingly reduced. Treating the receiver individually in such a way to minimize the sensitivity to high noise levels is another option. But this method is not often followed because of cost of redesign, develop and retool. Treatment of noise receiver is the least desirable approach since each receiver must 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 (generally between the noise source and the noise receiver) so that the level of noise at the receiver is reduced [57]. In general four basic principles are employed to reduce noise [51]: isolation, absorption, vibration isolation and vibration damping. The study here is focused only on the absorption phenomenon of sound, where sound energy is converted into thermal energy.

CHAPTER 2: Literature Review

The following literature review focuses on nonwoven sound absorptive materials and is intended to help orient the reader with respect to the vast body of the knowledge related to porous material. The intent is not to cover all the past literatures but to give necessary and related details about sound absorption and sound absorptive materials.

2.1. Sound Absorptive Materials

Materials that reduce the acoustic energy of a sound wave as the wave passes through it by the phenomenon of absorption are called sound absorptive materials [38]. 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 [7, 38]. Classic examples of resistive material 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 [38].

Porous materials used for noise control are generally categorized as fibrous medium or porous foam. A particular interest of this research is to conduct a systematic study on fibrous sound absorbing materials. Fibrous media usually consists of glass, rock wool or polyester fibers and have high acoustic absorption. Sometimes fire resistant fibers are also used in making acoustical products [10].

Often sound barriers are confused with sound absorbing materials. Generally materials that provide good absorption are poor barriers. Unlike, barriers and damping materials, the mass of the material has no direct effect on the performance of the absorptive materials [57]. The performance of absorptive materials depends on many parameters, which are explained in the latter part of this chapter. Absorptive materials are almost always used in conjunction with barriers of some type since their porous construction permits some noise to pass through relatively unaffected [2]. An absorber, when backed by a barrier, reduces the energy in a sound wave by converting the mechanical motion of the air particles into low-grade heat. This action prevents a buildup of sound in enclosed spaces and reduces the strength of reflected noise [38]. The porous nature of absorptive materials renders them susceptible to contamination, moisture retention and deterioration due to physical abuse. To avoid these problems, facings may be attached to at least one side of the absorber. The addition of a facing to acoustical foam has the effect of increasing the lower frequency absorption at the expense of the higher frequencies [15].

2.2. Mechanism of Sound Absorption in Fibrous Materials

The absorption of sound results from the dissipation of acoustic energy to heat. Many authors have explained this dissipation mechanism in the past [11, 16, 23, 39, 43]. Fridolin et al. [40] 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 undergo periodic compression and relaxation. This results in change of temperature. Because of long time, large surface to volume ratios and high heat conductivity of fibers, 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 fibers 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
- Temperature fluctuations

2.3. Application of Sound Absorptive Materials

Acoustical material plays a number of roles that are important in acoustic engineering such as the control of room acoustics, industrial noise control, studio acoustics and automotive acoustics. Sound absorptive materials are generally used to counteract the undesirable effects of sound reflection by hard, rigid and interior surfaces and thus help to reduce the reverberant noise levels [9, 37]. They are used as interior lining for apartments, automotives, aircrafts, ducts, enclosures for noise equipments and insulations for appliances [33, 73]. Sound absorptive materials may also be used to control the response of artistic performance spaces to steady and transient sound sources, thereby affecting the character of the aural environment, the intelligibility of unreinforced speech and the quality of unreinforced musical sound [25]. Combining absorptive materials with barriers produces composite products that can be used to lag pipe or provide absorptive curtain assemblies.

Note: All noise control problem starts with the spectra of the emitting source. Therefore, sound absorbing materials are chosen in terms of material types and dimension, and also based on the frequency of sound to be controlled [24].

2.4. 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 [31, 47, 48]. A summary of those work are given below.

2.4.1. Fiber Size

Koizumi et al. [58] reported an increase in sound absorption coefficient with a decrease in fiber diameter. This is because, thin fibers can move more easily than thick fibers on sound waves. Moreover, with fine denier fibers more fibers are required to reach an equal more fibers for same volume density which results in a more tortuous path and higher airflow resistance [67, 26]. A study by Youn Eung Lee et al. [74] concluded that the fine fiber content increases 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. [58] also showed that fine denier fibers ranging from 1.5 to 6 denier per filament (dpf) perform better acoustically than coarse denier fibers. Moreover it has been reported by T. Koizumi et al. [58] that, micro denier fibers (less than 1 dpf) provide a dramatic increase in acoustical performance.

2.4.2. Fiber Surface Area

Previous work done by Kyoichi et al. and Narang et al. [36, 52] indicated a direct correlation between sound absorption and fiber surface area. Their study explained the fact that friction between fibers and air increases with fiber surface area resulting in a higher sound absorption. Moreover it has been said that, in the frequency range 1125 Hz – 5000 Hz, fibers with serrated cross sections (e.g., Kenaf) absorb more sound compared to ones with round cross sectional area. Bo-Young Hur et al. [8] 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 fiber with increase of relative density and friction of pore wall.

Man-made fibers are available in various cross-sectional shapes for instance: hollow, trilobal, pentalobal and other novel shapes like 4DG fibers. These cross sectional shapes can add acoustical value by providing more surface area than normal round shaped fibers [67].

2.4.3. 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 [45]. Fibers 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 [12]. 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:

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

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

u = Particle velocity through sample, m/sec

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

ΔT = Incremental thickness, m [37]

Note: The unit that is generally used for the flow resistance is Rayls ($N.S/m^3$ x10). According to Delany et al [43], flow resistance is proportional to the material bulk density and fiber size. Fiber packing density decreases the air permeability with a resultant increase in pressure drop and hence flow resistance [17, 72]. Based upon the airflow test, ASTM D-1564-1971, flow resistance R of the sample is obtained from the following equation (2.2):

$$R = \frac{P}{vl} \tag{2.2}$$

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 fiber diameter [59].

2.4.4. 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 [29]. Equation (2.3) gives the definition for porosity (H).

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

where: V_a = Volume of the air in the voids
V_m = Total volume of the sample of the acoustical material being tested

Shoshani et al. [71] stated that, in designing a nonwoven web to have a high sound absorption coefficient, porosity should increase along the propagation of the sound wave.

2.4.5. 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. [33], tortuosity describes the influence of the internal structure of a material on its acoustical properties. Con Wassilieff [13] describes tortuosity as a measure of how far the pores deviate from the normal, or meander about the material. It was stated that, K. V. Horoshenkov et al. [35] 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 behavior of sound absorbing porous materials.

Along with tortuosity, the inner structure of porous materials has been described by the term 'structure factor' by Zwikker and Kosten [14]. Beranek [37] has given the approximate relation between porosity (*Y*) and structure factor (*K*) for homogenous materials made of fibers or granules with interconnecting pores and is shown in Figure 2.1.

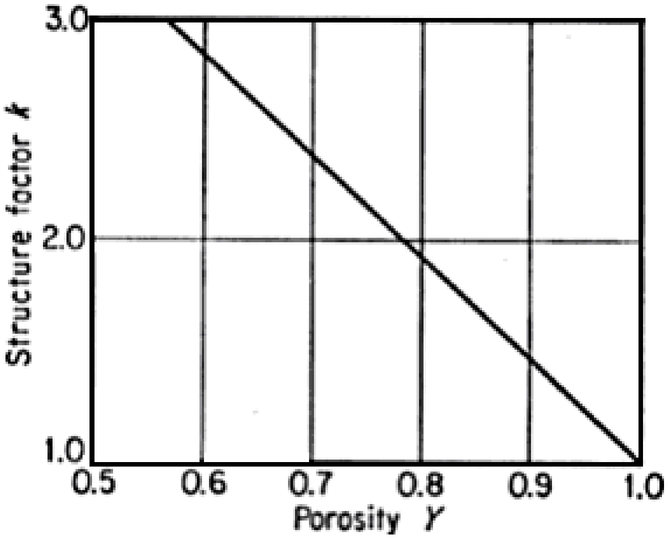


Figure 2.1. Relation between Structure factor and Porosity

2.4.6. Thickness

Numerous studies that dealt with sound absorption in porous materials have concluded that low frequency sound absorption has direct relationship with thickness. 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 [44]. Peak absorption occurs at a resonant frequency of one-quarter wavelength of the incident sound (ignoring compliance effect) [57].

A study by M.A. Ibrahim et al [42] 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 [42]. 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 [58].

2.4.7. Density

Density of a material is often considered to be the important factor that governs the sound absorption behavior of the material. At the same time, cost of an acoustical material is directly related to its density. A study by T. Koizumi et al. [58] showed the increase of sound absorption value in the middle and higher frequency as the density of the sample increased. The number of fibers 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 [67] has showed the following effect of density on sound absorption behavior of nonwoven fibrous materials.

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

2.4.8. Compression

Not much has been published on the influence of compression on sound absorption behavior. A paper by Bernard Castagnede et al. [6] showed that, compression of fibrous mats decreases the sound absorption properties. He explained that, under compression the various fibers in the mat are brought nearer to each other without any deformation (without any change in fiber size). This compression results in a decrease of thickness. More interestingly he also found the other physical variation that occurs during compression. Castagnede et al. [6] found that compression resulted in an increase in tortuosity and airflow resistivity, and a decrease of porosity and thermal characteristic length (shape factor). Despite these physical parameter variations in the compressed material, he stated that the reason for a drop in sound absorption value is mainly due to a decrease in sample thickness. The influence of compression on sound absorption can play an important role in the field of automotive acoustics. The seat padding in the vehicle is subjected to compression / expansion cycles due to the passenger's weight. This results in squeezing down the porous materials (fibrous or cellular) which in turn results in variation of the above physical parameters.

2.4.9. Surface Treatments

As said earlier acoustical materials are used inside buildings and these materials have to satisfy some norms such as: material should have good light reflecting behavior, should have a good appearance and so on. Often when used inside buildings, acoustical materials are coated with paints or some finishes [62]. Therefore, it is necessary to study the effect of these surface coatings on sound absorptive behavior. It was found that, more open-surface type materials suffer most from the application of paint. So, it was suggested by Price [2] that a very thin layer of paint coating should be applied over the material surface. This can be done with the help of spray gun. In the case of materials like felt and polyurethane foam, it would appear that the only way to obtain a desirable surface finish is to cover the surface with perforated paneling of the Helmholtz resonator type. Several authors [29, 62] have studied the effect of such cover screen on sound absorption. The study by Ingard [59] showed the increase of sound absorption at low frequencies at the expense of higher frequencies. Sometimes, fibrous materials are covered with film in order to improve the sound absorption properties at low frequencies by the phenomenon of surface vibration of film [29].

2.4.10. Placement / Position of Sound Absorptive Materials

It is a known fact that sound absorption of a material depends also on the position and placement of that material. It has been reported by Alton [22] that if several types of absorbers are used, it is desirable to place some of each type on ends, sides and ceilings so that all three axial modes (longitudinal, transverse and vertical) will come under their influence. In rectangular rooms it has been demonstrated that absorbing material placed near corners and along edges of room surfaces is most effective. In speech studios, some absorbents that are effective at higher audio frequencies should be applied at head height on the walls. In fact, material applied to the lower portions of high walls can be as much as twice as effective as the same material placed elsewhere [22]. Moreover, it is recommended that untreated surfaces should never face each other.

2.4.11. Surface Impedance

The higher the acoustic resistivity of a material, the higher is its dissipation, for a given layer of thickness. At the same time the surface impedance of the layer also increases with resistivity, resulting in a greater amount of reflections on the surface layer, giving a lower absorptivity capability. Moreover the whole process is frequency dependent, so that for lower frequency bands the necessary layer thickness increases as resistivity decreases [24].

2.4.12. Secondary Factors

Some of the non-acoustical concerns involving acoustical materials are discussed below. Surface of rooms, offices, schools, hospitals, restaurants, industrial plants or any enclosed area in which the occupants are exposed to noise, must satisfy varying degree of structural and architectural requirements. Some of the properties apart from high sound absorptivity that a sound absorbing material should posses are [27]:

- Appearance
- Decorative effect
- Light reflectivity
- Maintainability

- Durability
- Flame resistance

Material selection for acoustical applications may be influenced by the following environmental and regulatory factors as well [51]:

Environmental:

- Exposure
- Solvents
- Vibration
- Dirt
- Oil and grease
- Corrosive materials
- Erosive conditions
- Durability

Regulatory:

- Restrictions on lead-bearing materials in food and drug areas
- Restriction on materials contacting food and drug products
- Requirements for disinfection / cleaning
- Firebreak requirements, ducts, shafts etc

- Restriction on shedding fibers
- Elimination of inspectable areas, where vermin may hide
- Requirements for anchoring equipment
- Guarding equipment

Apart from all the afore-mentioned parameters, sound absorption characteristics of materials are a function of frequency. Performance generally increases with an increase in frequency. Thus in real world applications, sound absorptive materials are chosen according to the spectrum of sound being emitted. For example in automotive noise control, thinner materials that are capable of absorbing high frequencies are used for headliners. At the same time, thicker materials capable of absorbing lower frequencies are used for door panels and carpet backing [80]. Thus, it is essential to know the range of frequencies that need to be controlled in order to have effective use of sound absorptive materials.

Note: Different materials perform differently when they are used for acoustical applications. Generally, porous materials like nonwovens and foams perform well at higher frequencies [55]. To increase low frequency absorption, material thickness should be increased as it gives more surface area for low frequency sound to get absorbed.

2.5. Performance of Sound Absorbing Materials

For porous and fibrous materials, acoustic performance is defined by a set of experimentally determined constants namely: absorption co-efficient, reflection co-efficient, acoustic impedance, propagation constant, normal reduction co-efficient and transmission loss [65]. There are different methods available to determine these acoustical parameters but all of these methods mainly involve exposing materials to known sound fields and measuring the effect of their presence on the sound field.

The performance of sound absorbing materials in particularly is evaluated by the sound absorption co-efficient (α) [35, 38]. Alpha (α) is defined as the measure of the acoustical energy absorbed by the material upon incidence and is usually expressed as a decimal varying between 0 and 1.0. If 55 percent of the incident sound energy is absorbed, the absorption coefficient of that material is said to be 0.55. A material that absorbs all incident sound waves will have a sound absorption coefficient of 1. The sound absorption coefficient (α) depends on the angle at which the sound wave impinges upon the material and the sound frequency. Values are usually provided in the literature at the standard frequencies of 125, 250, 500, 1000 and 2000 Hertz [1, 75]. Other important acoustic parameters that need to be considered while studying the acoustical absorptive properties are:

- Sound Reflection Coefficient: Ratio of the amount of total reflected sound intensity to the total incident sound intensity.
- Acoustic Impedance: Ratio of sound pressure acting on the surface of the specimen to the associated particle velocity normal to the surface.

In comparing sound absorbing materials for noise control purposes, the noise reduction co-efficient (NRC) is commonly used. NRC is the average usually stated to the nearest multiple of 0.05, of the co-efficient at four frequencies 250, 500, 1000 and 2000 HZ [27]. It is intended for use as a single number index of the sound absorbing efficiency of a material. This NRC values provides a decent and simple quantification of how well the particular surface will absorb the human voice [64].

The sound absorption for a sample of material or an object is measured sometimes in sabins or metric sabins. One sabin may be thought of as the absorption of unit area (1 m^2 or 1 ft^2) of a surface that has an absorption coefficient of 1.0 (100 per cent). When areas are measured in square meters, the term metric sabin is used. The absorption for a surface can be found by multiplying its area by its absorption coefficient. Thus for a material with absorption coefficient of 0.5, 10 sq. ft has a sound absorption of 5 sabins and 100m^2 is 50 metric sabins [1]. Harris [27] gives four factors that affect the sound absorption co-efficient. They are:

- Nature of the material itself
- Frequency of the sound
- The angle at which the sound wave strikes the surface of the material
- Air gap

More fundamentally, all sound absorptive materials can be characterized by two basic parameters namely: Characteristic Impedance and Complex Propagation Constant [28, 41, 49]. Characteristic impedance is the measure of wave resistance of air. It is the ratio of sound pressure to particle velocity. Attenuation and phase constant which are included in the propagation constant are the measure of how much sound energy is reduced and the speed of propagation of sound respectively. Even other parameters were tried by researchers [46, 54] in order to include various effects like material internal structure, viscous and thermal loss, which are not discussed here.

2.6. Measurement of Sound Absorption Coefficient

A number of measurement techniques can be used to quantify the sound absorbing behavior of porous materials. In general one is interested in one of the following properties: sound absorption coefficient (α), reflection coefficient (R), or surface impedance (Z). Detailed description of the measurement technique used in this research is given below.

2.6.1. Acoustic Measurements

Measurement techniques used to characterize the sound absorptive properties of a material are [75]:

- Reverberant Field Methods
- Impedance Tube Methods
- Steady State Methods

Reverberant Field Method for measuring sound absorption is concerned with the performance of a material exposed to a randomly incident sound wave, which technically occurs when the material is in diffusive field [41]. However creation of a diffusive sound field requires a large and costly reverberation room. A completely diffuse sound field can be achieved only rarely. Moreover, an accurate value of complex impedance cannot be derived from the absorption coefficient alone [75]. Since sound is allowed to strike the material from all directions, the absorption coefficient determined is called random incidence sound absorption coefficient, RAC. This method is clearly explained in ASTM C 423 – 72.

Impedance Tube Method uses plane sound waves that strike the material straight and so the sound absorption coefficient is called normal incidence sound absorption coefficient, NAC [69]. This research uses impedance tube method which is faster and generally reproducible and, in particular, requires relatively small circular samples, either 35 or 100 mm in diameter (according to the type of impedance tube). In the impedance tube method, sound waves are confined within the tube and thus the size of the sample required for test needs only be large enough to fill the cross-section of the tube [32]. Thus this method avoids the need to fabricate large test sample with lateral dimensions several times the acoustical wavelength. The impedance tube method employs two techniques to determine NAC, namely:

1. Movable microphone which is one-third-octave frequencies technique (ASTM C 384) is based on the standing wave ratio principle and uses an audio frequency spectrometer to measure the absorption coefficients at various centre frequencies of the one-third-octave bands.

2. Two-fixed microphone impedance tube or transfer function method (ASTM E 1050), which is relatively recent development. In this technique, a broadband random signal is used as a sound source. The normal incidence absorption coefficients and the impedance ratios of the test materials can be measured much faster and easier compared with the first technique [18].

The final method of measuring the sound absorption coefficient is known as **Steady State Method**. This method is mostly used when the other will not work. This particular method is described in ASTM E336-71. To measure the transmission coefficient of the materials, a third microphone or even a second pair of microphone can be placed behind the test sample in a second impedance tube.

All the nonwoven samples in this work were tested by using the two-microphone impedance tube method (ASTM E 1050), which is described below in section 2.6.2.

2.6.2. Two Microphone Impedance Tube Technique (Transfer Function Method)

The transfer function method (ASTM E 1050) covers the use of an impedance tube, with two microphone locations and a digital frequency analysis system for the determination of normal incidence sound absorption coefficients (NAC) and normal specific acoustic impedance ratios of materials. This test method is similar to Test Method (ASTM C 384) in that it also uses an impedance tube with a sound source connected to one end and the test sample mounted at the other end. The measurement techniques for the two methods are fundamentally different, however. First microphone tube method (standing wave method) is quite cumbersome since a probing of the sound field has to be carried for each frequency.

Theoretical Background:

Rather than probing the sound field to determine sound maxima and minima pressure level as in standing wave tube method, in the two microphone method the ratio between the sound pressure amplitudes at two-fixed microphone positions is measured. Quantities are determined as a function of frequency with a resolution determined by the sampling rate of a digital frequency analysis system [59]. The usable frequency range depends on the diameter of the tube and the spacing between the microphone positions. An extended frequency range may be obtained by using tubes with various diameters and microphones spacing. By this method acoustical parameters like absorption coefficient, reflection coefficient and surface admittance for a small samples exposed to plane waves can be determined [77]. The reflection co-efficient (*R)* of the sample can be obtained from the equation (2.4).

$$R = \frac{H_l - H_i}{H_r - H_l} e^{j2k(l+s)} \tag{2.4}$$

where: H_l = Frequency Response Function (FRF) of the impedance tube

H_i = FRF associated with the incident wave components

H_r = FRF associated with the reflected wave components

k = Wave number

l = Distance between the microphone and the sample

s = Spacing between the microphone [77].

By using equation (2.5), normal sound absorption coefficient, NAC (α) can be determined.

$$\alpha = |1 - R|^2 \tag{2.5}$$

Also normalized surface impedance (*Z*) can be calculated using the equation (2.6):

$$\frac{Z}{\rho c} = \frac{1+R}{1-R} \tag{2.6}$$

where: ρ = Air density (kg/m^3)

c = Sound velocity in air (ms^{-1})

Outline of the theory behind the calculation of sound absorption coefficient by using transfer function method is given by Frank Fahy [25] and many others.

2.6.3. Relation Between Normal Incidence and Random Incidence Co-efficient

Normal incidence sound absorption coefficients can be quite useful in certain situations where the material is placed within a small acoustical cavity close to a sound source, for example a closely fitted machine enclosure. This test method allows one to compare relative values of sound absorption when it is impractical to procure large samples for accurate random-incidence measurements in a reverberation room. Estimates of the random incidence absorption coefficients from NAC values by Faulkner [41] are recorded in Table 2.1.

The results of tests by both methods (reverberation and impedance tube) on sound absorption coefficient of a number of materials have been reported and show that a consistent comparison is not always obtainable [41]. The relation will vary depending on the physical properties, thickness and mounting conditions. However, it may be stated to a rough approximation that random incidence values are twice the normal incidence values in low range, higher by 0.25 to 0.35 in the middle range and approximately equal in the high range [27]. Moreover, paper by Yoshio Imai et al. [72] indicated that, though the results of NAC and RAC are different, the absorption peak positions were the same.

TABLE 2.1. Relation between NAC and RAC

NAC	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
	Random Incidence Sound Absorption Coefficient (RAC)									
0	0	2	4	6	8	10	12	14	16	18
10	20	22	24	26	27	29	31	33	34	36
20	38	39	41	42	44	45	47	48	50	51
30	52	54	55	56	58	59	60	61	63	64
40	65	66	67	68	70	71	72	73	74	75
50	76	77	78	78	79	80	81	82	83	84
60	84	85	86	87	88	88	89	90	90	91
70	92	92	93	94	94	95	95	96	97	97
80	98	98	99	99	100	100	100	100	100	100
90	100	100	100	100	100	100	100	100	100	100

CHAPTER 3: Methodology

Forty-nine samples were produced for use in this research. Samples varied in fabrication method, fiber type used, fiber cross-section and fiber size. As shown in Figure 3.1, samples were either needlepunched, thermal bonded or constructed using a combination of needle punching and thermal bonding. Further more webs for needling were either airlaid or carded. The number of needle passes as well as the layering structure was also varied to create a gradient effect in the mat as seen in Figure 3.2. Shown in Figures 3.3 and 3.4 are profiles of fiber used and their blend ratios. Also an effort was made to study the effect of adding a fire retardant to one of the fiber types. This chapter covers details related to design of experiments, parameters considered for this study and testing procedures. Figure 3 explains the various factors that are considered to study the sound absorptive properties of nonwovens.

3.1. Fiber Selection

Fiber parameters that were varied in this study include fiber size, fiber type and fiber cross-section as seen in Table 3.1.

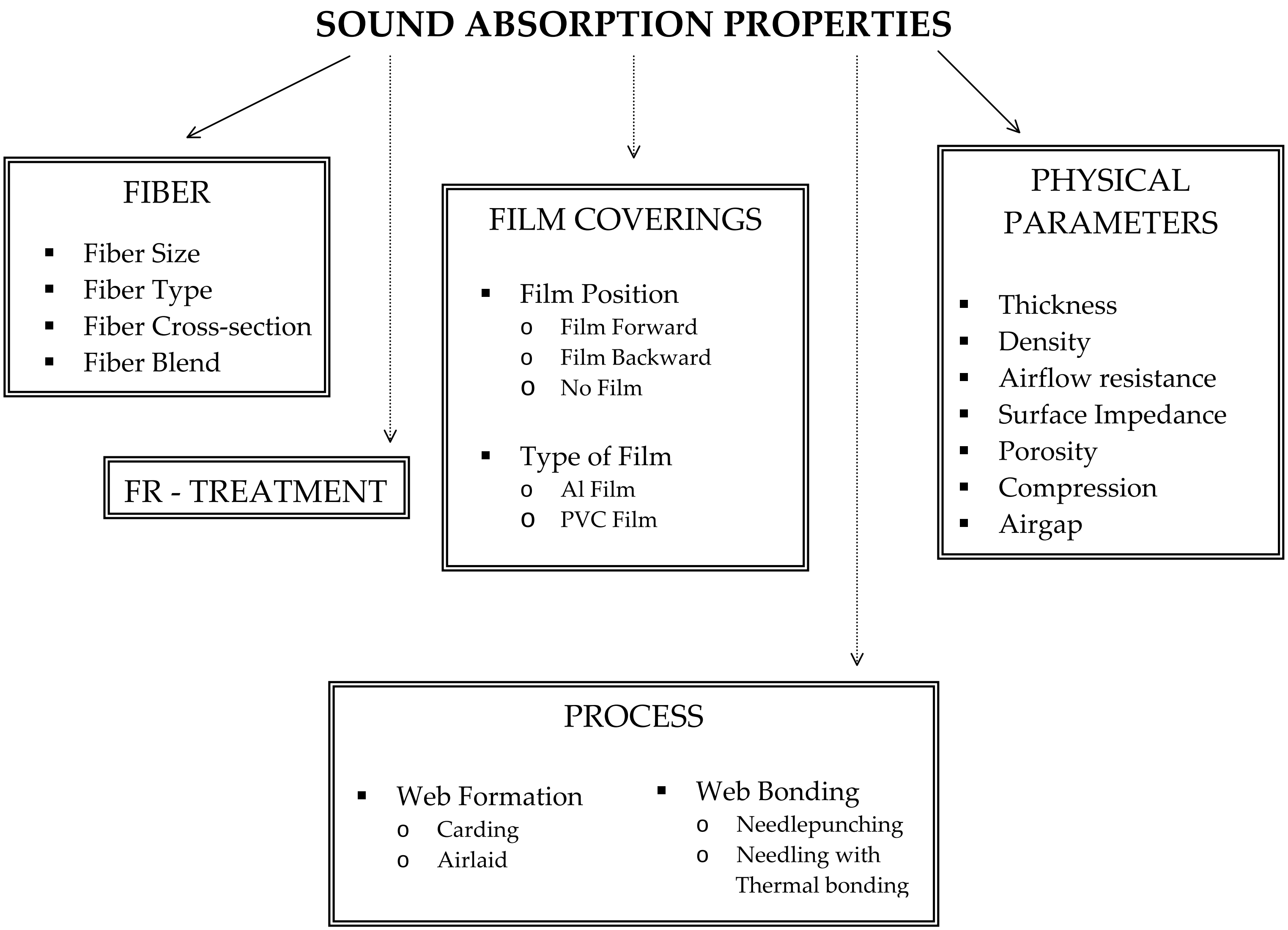


Figure 3. Flow Chart Showing Various Parameters that Controls Sound Absorption of Nonwovens

Note: Apart from above-mentioned parameters, sound absorption depends on frequency and also on the position or placement of the sound absorbing material.

TABLE 3.1. Fibers Used

Fibers	**Source**	**Linear Density** Dtex	**Cut length** cm (in)
Reclaim PET	Rubber mill Inc	4.743	< 8.89 (< 3.5)
Kenaf	Greene Natural Fibers	10.6 – 96.6	6.35 – 8.89 (2.5 – 3.5)
PET Round	Invista International	1.611	7.62 (3)
PET 4DG	Fiber Innovation Technology	6.666	7.62 (3)
PET Low melt	Rubber Mill Inc	6.666	7.62 (3)
PET Hollow	Rubber Mill Inc	6.666	7.62 (3)
PET Round	Rubber Mill Inc	16.665	7.62 (3)

3.1.1. Fiber Flame Retardant Treatment

Kenaf is a natural fiber that has good acoustical properties. At the same time, it catches fire easily. In order to use this fiber in a particular application where flame retardancy is an important factor, it is necessary to improve its flame retardant properties. Flame retardancy can be improved either by treating the fiber or treating the final sample. In this research, kenaf fibers were treated for flame retardancy using a chemical called Glo-Tard FFR-2. Influence of this chemical treatment on sound absorption was also studied. Information about the chemical and its treatment procedure is given below.

3.1.1.1. Chemical Treatment:

Glo-Tard FFR-2 is a flame retardant specially designed for treating fibers. It is a phosphorus-based system, completely free of halogens and metals such as antimony, zinc and magnesium [79]. It has the following features and properties:

- Phosphorus complex
- Rapid wetting, even on reprocessed fibers
- Non-corrosive
- Easy to apply with standard padding or spraying
- Virtually odor free

3.1.1.2. Treatment Procedure:

The steps involved in treating kenaf for flame retardancy are as follows:

1. Conditioning [24 hrs]
2. Treatment with chemical
3. Extraction
4. Drying

Step 1: Conditioning

Kenaf is a naturally grown fiber and has tendency to absorb moisture (10 %). It is necessary to remove all moisture content before treating with chemical. To achieve this, fibers were conditioned in an open space for 24 hrs. Relative humidity of 65 % is maintained through out conditioning process.

Step 2: Chemical Treatment

Washex TDXL dyeing machine (shown in Figure 3.5) is used to mix chemical and the fibers. The concentration of chemical used is 40 % to the weight of total dye bath. Fibers are treated in a cycle of three (1hr). Temperature of the dye bath is kept constant at 66 degree F. Treatment is carried out for one hour.

Figure 3.5. TDXL Dyeing Machine

Step 3: Extraction

To facilitate drying, the treatment solution was extracted using a centrifugal extractor (Figure 3.6). This extraction process is done for two cycles.

Figure 3.6. Centrifugal Extractor

Step 4: Drying

Final drying is achieved by normal drying machine (shown in Figure 3.7). Drying is carried out at a temperature of 155 degree F for 1 hr.

Figure 3.7. Drying Machine

3.1.2. Fiber Blend Ratio

Fibers of different blend ratio were produced in order to study the influence of various fiber types on sound absorption properties. Fiber blend ratio chosen for this research can be seen in Figures 3.3 and 3.4.

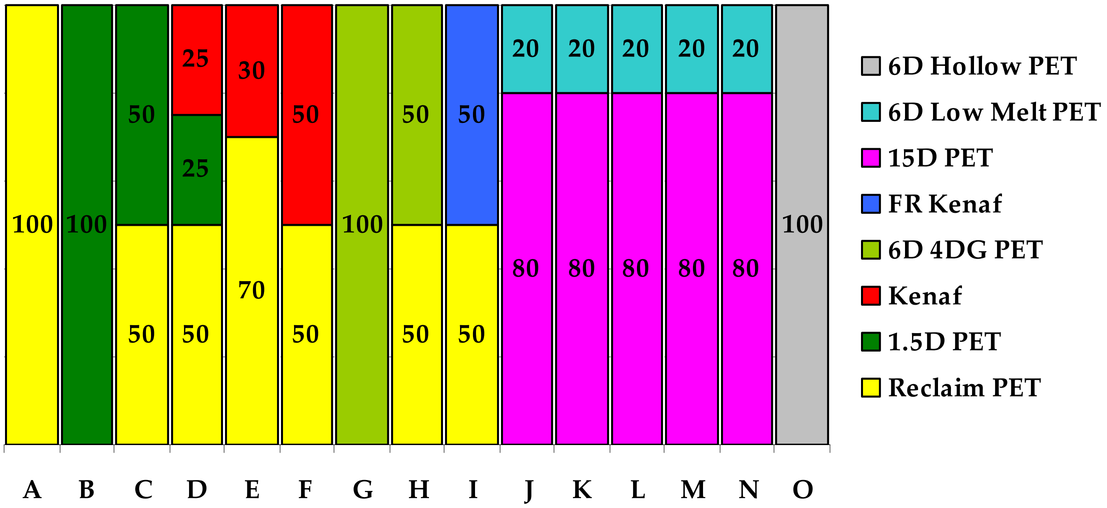


Figure 3.3. Fiber type and blend ratio used in producing samples

GROUP	SAMPLE ID
A	S1, S2, S13 - S15, S31 & S32
B	S3, S4 & S16 - S18
C	S5, S6, S19 - S21, S33 & S34
D	S7, S8, S22 - S24, S35 & S36
E	S9, S10, S25 - S27, S37 & S38
F	S11, S12, S28 - S30, S39 & S40
G	S41
H	S8
I	S42
J	S47
K	S48
L	S49
M	S44
N	S46
O	S45

Figure 3.4. Representation of Nonwoven Samples

3.2. Fabric Production

Fabric production involves fiber opening, fiber blending, formation of webs and bonding of webs. To study the effect of nonwoven processes on sound absorption properties, different processing techniques namely two different web formations and two different web bonding methods were used to produce nonwoven samples.

3.2.1. Web Formation

As the name implies, web formation is the process that arranges the fibers or filaments into a sheet/web form. There are different web formation technologies available today. This research uses two web formation technologies namely: 1. Air laid technology and 2. Carded technology.

1. Air laid Technology:

   Here fibers are fed into an air stream and from there to a moving belt or perforated drum, where they form a randomly oriented web. Compared with carded webs, webs produced through the airlaid process have a lower density and a greater softness. Airlaid webs offer great versatility in terms of the fibers and fiber blends that can be used [66].

2. Carded Technology:

   Producing a carded web starts with opening of bales of fibers. The opened fibers are then combed in to a web by a carding machine, which is a rotating drum or series of drums covered in fine wires or teeth [66]. Here fibers can be parallel laid or random laid (with the help of cross-lapper).

A number of parameters can be varied in airlaid and carded webs to study the influence of these parameters on sound absorption. The parameters varied here are:

- Fabric basis weight [changing the number of layers of web]
- Thickness [changing the number of layers of web]
- Different fiber blend ratios

3.2.2. Web Bonding

Webs produced in carded and airlaid processes have little strength in their unbonded form. Therefore, webs should be bonded by some means. This research uses mechanical (needlepunching) and thermal means of bonding.

1. Needlepunching:

   Here specially designed needles are pushed and pulled through the web to entangle (bond) the fibers. Needlepunching can be used for most fiber types [66].

2. Needlepunching and Thermal Bonding:

   Some needlepunched samples produced in this research suffer from fiber fall out. In order to prevent this fiber fall out, the samples were bonded again thermally. These samples therefore were bonded both by mechanically and thermally means.

Needle penetrations for airlaid webs were varied (higher penetration of top board and lower penetration for bottom board) in order to create a gradient effect in needlepunched mats as shown in Figure 3.2. This gradient effect is used to study the effect of surface impedance on sound absorption properties. The process flow used to make nonwoven needlepunched samples are shown in Figures 3.8 & 3.9.

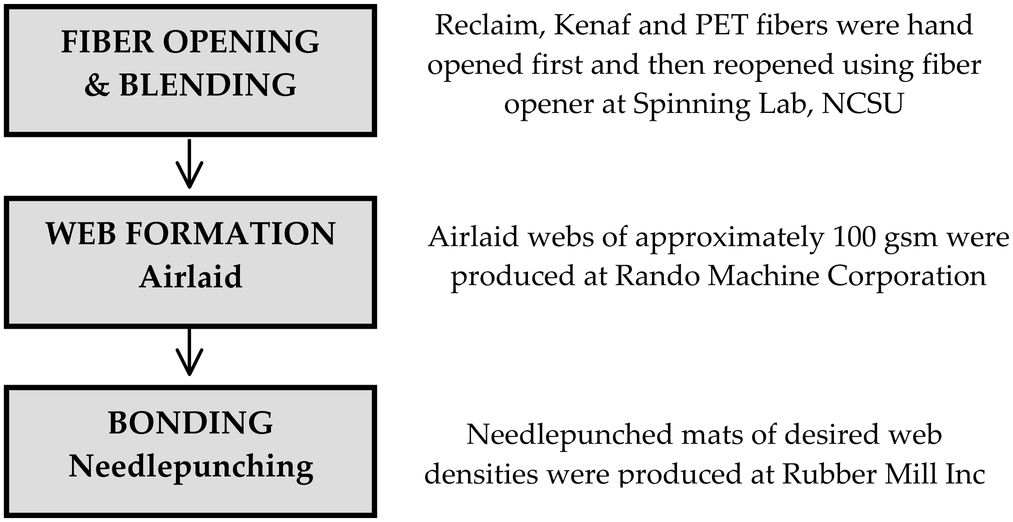


Figure 3.8. Production Flowchart of Needlepunched mats Using Airlaid Webs

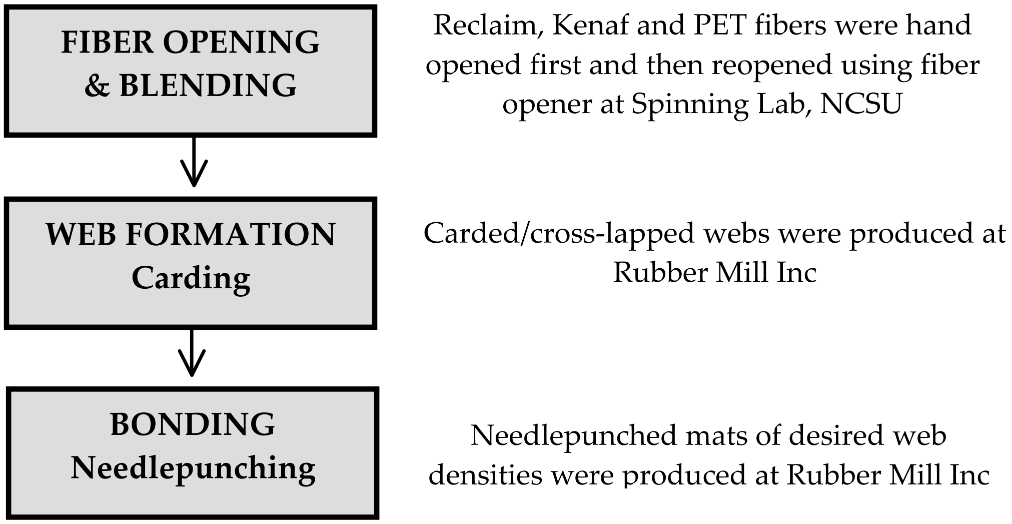


Figure 3.9. Production Flowchart of Needlepunched mats Using Carded Webs

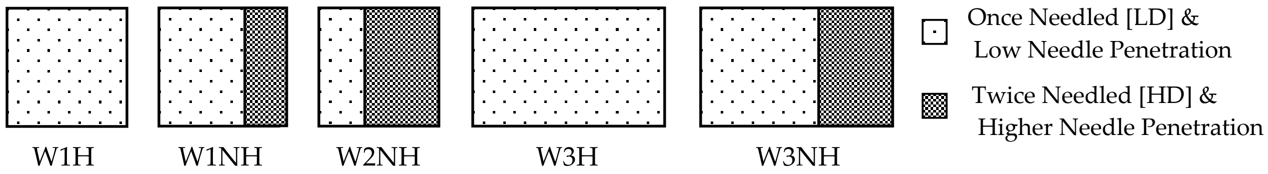


Figure 3.2. Gradient Effect in Nonwoven Samples

All thermal bonded and combinations of needled and thermal bonded mats were obtained from Rubber Mill Inc. These samples include nonwovens laminated with either a polyvinyl chloride (PVC) or an aluminum (Al) film.

FABRICATION

1. **Needle Punching**
2. **Needle Punching & Thermal Bonding**
3. **Thermal Bonding**

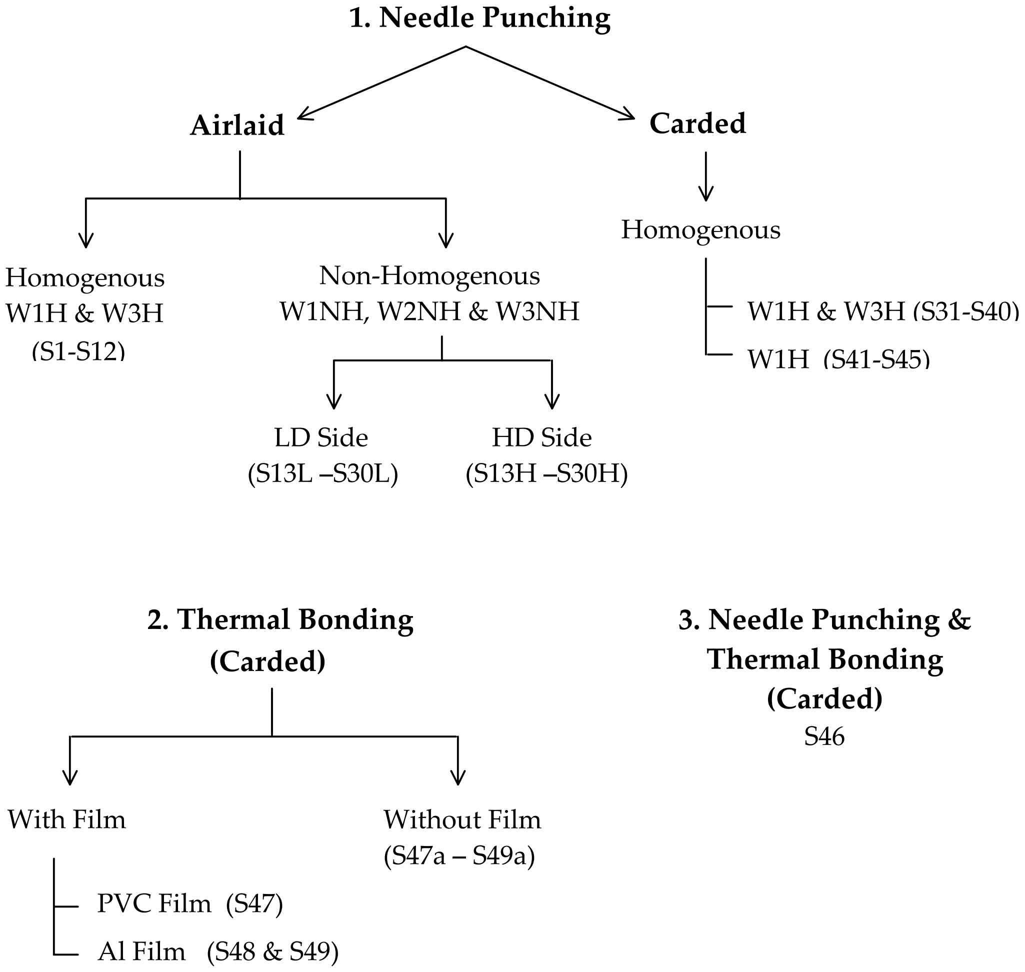


Figure 3.1. Flowchart Showing Fabrication of Nonwoven Samples

3.3. Fabric Characterization

3.3.1. Mass Per Unit Area

Nonwoven samples can be manufactured with different mass/unit area by changing the web basis weight or by changing the number of web layers. This parameter mass/unit area has direct influence on the cost of the product. For this research two levels of mass per unit area were selected, namely: 458 g/m^2 (1.5 oz/ft^2) and 763 g/m^2 (2.5 oz/ft^2). Samples measuring 8.89 cm (3.5″) diameter were cut randomly and were weighed in grams using a Mettler Toledo Precision Weighing (AG 245) balance. All the measurements were performed in accordance with ASTM D 3776 [5], which is the standard test for mass per unit area of a fabric. Due to differences in fiber type, samples produced vary in their mass per unit area in the range 381 – 520 g/m^2 (1.25 – 1.7 oz/ft^2) and 656 - 793 g/m^2 (2.15 – 2.6 oz/ft^2) which can be seen in Table 4.1.

3.3.2. Thickness

Samples measuring 8.89 cm (3.5″) diameter were cut randomly and thickness was measured using a SDL thickness gauge with pressure level 20 gf/cm^2. Just as there is a difference seen in the mass per unit area of samples (because of difficulties in handling natural fibers during web formation) a slight variation is seen in the thickness of all samples produced (see Table 4.1.).

3.3.3. Fiber Orientation Distribution

Sound absorption depends on the porosity of a sample which in turn is governed by many factors. One of the factors that influences porosity of a sample is the orientation of fiber. So, it is important to measure the orientation distribution function (ODF) of all samples. An image analysis technique that uses two-dimensional Fast Fourier Transforms along with Allasso Industries image analysis software was used to obtain the ODF (Orientation Distribution Function) of carded and airlaid samples. The technique was developed by the Nonwoven Cooperative Research Center (NCRC) at North Carolina State University. It is a simple technique, where the optical image of the sample is scanned and Fourier transformations were performed to find the fiber orientation distribution. The results of ODF of both carded and airlaid samples are given in Appendix 7.2.

3.3.4. Airflow Resistance

In all common forms of porous sound absorbing materials, the viscous resistance of air in the porous material has an important influence on the sound absorption mechanism. Knowledge of flow resistance of a material allows the relevant acoustical quantities to be derived. Many past studies have shown the importance of flow resistance on determining the acoustical absorptive properties of a porous material [21, 43, 53]. Theoretical equations by many researchers use flow resistance as an important parameter in their models. It is therefore important to measure the flow resistance of an acoustical sample.

Kawabata KLS Air Resistivity tester (shown in Figure 3.10) was used to determine the airflow resistance of all nonwoven samples. This tester makes precise and speedy measurement of airflow resistance of fabrics. Sample mounting is very simple and moreover one cycle of measurement only requires 10 seconds to complete the test.

Figure 3.10. KLS Airflow Resistivity Tester

This testing machine works on a constant rate of airflow principle. Here airflow is generated by the piston motion of plunger/cylinder mechanism and passed through a specimen from and into atmosphere. The suction and discharge periods of air are 5 seconds respectively and a semiconductor differential-pressure gauge measures the air pressure loss caused by the air resistance of the specimen. The air resistance of the sample is directly indicated on a digital panel meter. The measured values of airflow resistance of all nonwoven samples are given in Table 4.1.

3.3.5. Porosity

Porosity, *H*, of all the nonwoven samples were calculated using equation (3.1):

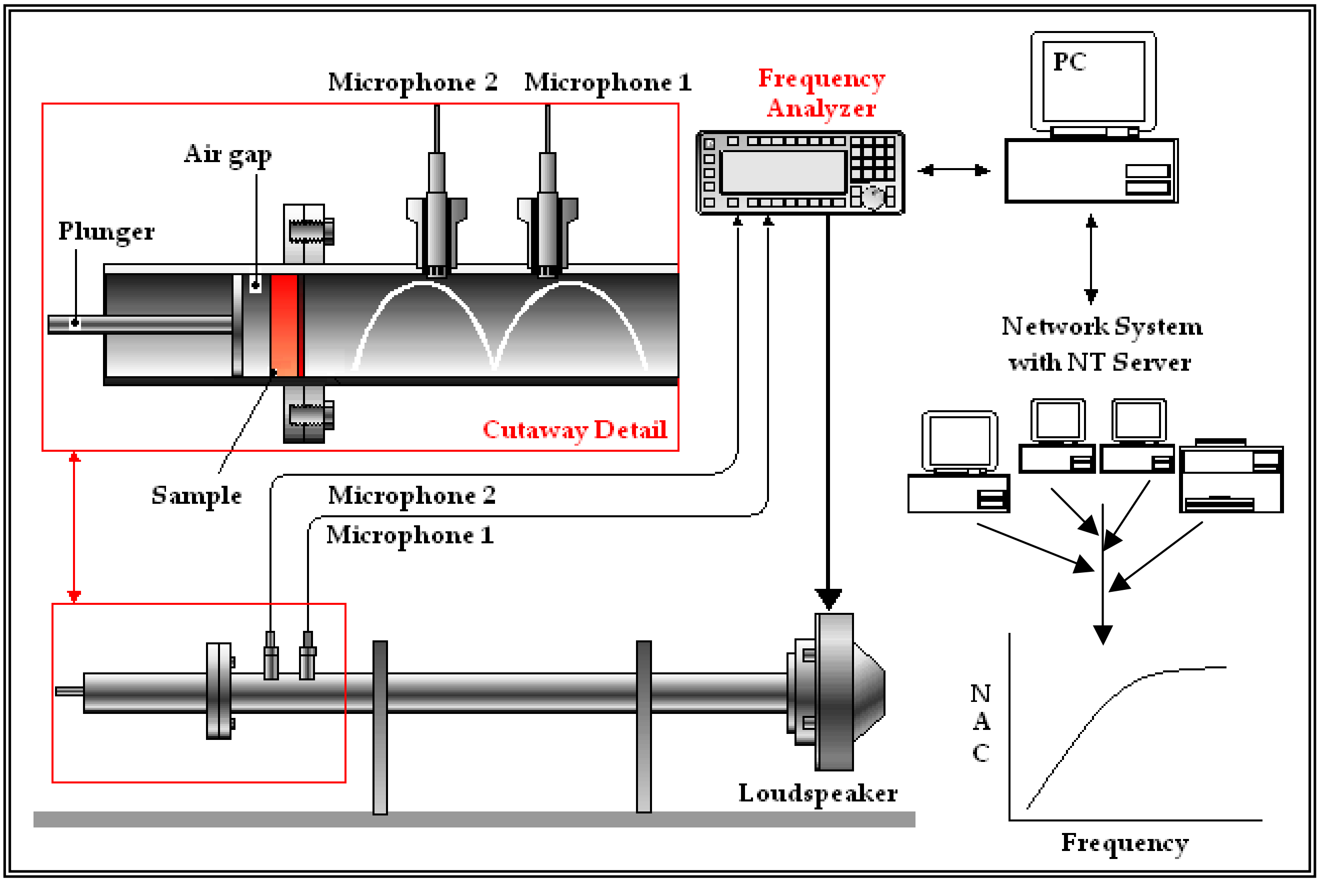
$$H = 1 - \frac{\rho_{fabric}}{\rho_{fiber}} \tag{3.1}$$

where: ρ_{fabric} = Fabric Density, g/cc

ρ_{fiber} = Fiber Density, g/cc

3.3.6. Sound Absorption Coefficient

In this research, the impedance tube method (explained in section 2.6.2) is used to determine the normal incident sound absorption coefficient, NAC of all nonwoven samples. The two-microphone impedance tube method follows ASTM E 1050. The set up used to find NAC of all nonwoven samples is shown in Figure 3.11.



Source: HP Pelzer Automotive System

Figure 3.11. Schematic Sketch of an Impedance Tube Set-Up

This set-up can be used for measurements covering the frequency range from 100 Hz to 5000 Hz. To cover this entire range a single tube and fixed microphone spacing is used [18].

CHAPTER 4: RESULTS AND DISCUSSIONS

Physical properties such as mass per unit area, thickness, airflow resistance, density and porosity of all nonwoven samples were measured using standard test methods and the results are given in Table 4.1. Vertical flame test was carried out to analyze the flame retardancy properties of all nonwoven samples. Fiber orientation distribution function for airlaid and carded samples were determined. The results of vertical flame test and fiber orientation distribution are shown in Appendices 7.1 and 7.2 respectively. The sound absorption measurements were made following ASTM E 1050 to study the acoustical absorptive properties of nonwovens. Effects of fiber, fabric and processing parameters on sound absorption along with statistical results are reported in this chapter.

4.1. Statistical Results: General

Statistical results are presented first considering all samples. Results are then given based on carded web followed by results for airlaid webs.

Table 4.1. Experimental Data on Nonwoven Samples

Sample ID	Mass osf (gsm)	Thickness mm	Density Kg/cubic.m	Airflow Rayls	Porosity	NRC
S1	1.74 (530.96)	6.84	77.63	79.00	0.91	0.11
S2	2.67 (814.75)	10.05	81.07	140.66	0.93	0.13
S3	1.45 (442.47)	7.41	59.71	140.66	0.95	0.20
S4	2.68 (817.80)	15.19	53.84	881.50	0.98	0.35
S5	1.81 (552.32)	7.33	75.35	344.00	0.98	0.16
S6	2.76 (842.21)	12.34	68.25	486.50	0.97	0.22
S7	1.74 (530.96)	6.15	86.34	191.50	0.97	0.11
S8	2.76 (842.21)	9.45	89.12	398.00	0.98	0.19
S9	1.43 (436.36)	5.49	79.48	72.00	0.92	0.08
S10	2.51 (765.93)	7.88	97.20	130.00	0.94	0.11
S11	1.34 (408.90)	5.15	79.40	44.40	0.88	0.08
S12	2.16 (659.12)	7.39	89.19	120.00	0.94	0.10
S13 L	1.55 (472.98)	5.98	79.09	71.50	0.94	0.10
S14 L	1.57 (479.08)	5.78	82.89	86.50	0.94	0.09
S15 L	2.74 (836.11)	10.21	81.89	137.33	0.94	0.15
S16 L	1.56 (476.03)	6.42	74.15	480.66	0.95	0.17
S17 L	1.71 (521.80)	7.52	69.39	494.00	0.95	0.13
S18 L	2.69 (820.85)	13.93	58.93	734.00	0.96	0.35
S19 L	1.88 (573.68)	8.24	69.62	296.00	0.95	0.16
S20 L	1.77 (540.11)	7.11	75.97	319.00	0.94	0.15
S21 L	2.76 (842.21)	11.91	70.72	434.00	0.95	0.22
S22 L	1.54 (469.93)	5.93	79.25	170.00	0.98	0.11
S23 L	1.54 (469.93)	5.05	93.06	176.20	0.98	0.09

Table 4.1. Contd.

Sample ID	**Mass** osf (gsm)	**Thickness** mm	**Density** Kg/cubic.m	**Airflow** Rayls	**Porosity**	**NRC**
S24 L	3.68 (1122.95)	12.26	91.60	524.00	0.98	0.25
S25 L	1.25 (381.43)	4.99	76.44	52.00	0.97	0.08
S26 L	1.21 (369.23)	4.84	76.29	42.00	0.97	0.08
S27 L	2.28 (695.74)	6.42	108.37	120.00	0.96	0.09
S28 L	1.23 (375.33)	4.54	82.67	39.00	0.97	0.08
S29 L	1.26 (384.49)	4.77	80.61	30.00	0.97	0.07
S30 L	2.16 (659.12)	6.51	101.25	94.00	0.96	0.10
S13 H	1.55 (472.98)	5.98	79.09	71.50	0.94	0.11
S14 H	1.57 (479.08)	5.78	82.89	86.50	0.94	0.10
S15 H	2.74 (836.11)	10.21	81.89	137.33	0.94	0.16
S16 H	1.56 (476.03)	6.42	74.15	480.66	0.95	0.20
S17 H	1.71 (521.80)	7.52	69.39	494.00	0.95	0.14
S18 H	2.69 (820.85)	13.93	58.93	734.00	0.96	0.40
S19 H	1.88 (573.68)	8.24	69.62	296.00	0.95	0.16
S20 H	1.77 (540.11)	7.11	75.97	319.00	0.94	0.16
S21 H	2.76 (842.21)	11.91	70.72	434.00	0.95	0.26
S22 H	1.54 (469.93)	5.93	79.25	170.00	0.98	0.12
S23 H	1.54 (469.93)	5.05	93.06	176.20	0.98	0.10
S24 H	3.68 (1122.95)	12.26	91.60	524.00	0.98	0.21
S25 H	1.25 (381.43)	4.99	76.44	52.00	0.97	0.08
S26 H	1.21 (369.23)	4.84	76.29	42.00	0.97	0.08
S27 H	2.28 (695.74)	6.42	108.37	120.00	0.96	0.09
S28 H	1.23 (375.33)	4.54	82.67	39.00	0.97	0.08

Table 4.1. Contd.

Sample ID	Mass osf (gsm)	Thickness mm	Density Kg/cubic.m	Airflow Rayls	Porosity	NRC
S29 H	1.26 (384.49)	4.77	80.61	30.00	0.97	0.07
S30 H	2.16 (659.12)	6.51	101.25	94.00	0.96	0.10
S31	1.53 (469.05)	7.66	61.27	46.50	0.95	0.10
S32	2.60 (795.43)	10.15	78.37	114.00	0.94	0.14
S33	1.87 (571.52)	6.62	86.34	244.00	0.94	0.11
S34	2.54 (775.58)	8.54	90.79	354.00	0.93	0.14
S35	1.74 (531.73)	5.35	99.35	184.00	0.98	0.08
S36	2.86 (874.80)	9.46	92.49	307.33	0.98	0.15
S37	1.36 (416.73)	6.42	64.87	24.00	0.98	0.08
S38	2.42 (738.94)	8.88	83.25	71.50	0.97	0.11
S39	1.50 (459.70)	7.03	65.39	27.30	0.98	0.09
S40	1.82 (557.51)	7.54	73.96	44.00	0.97	0.09
S41	1.61 (492.56)	7.41	66.45	134.00	0.95	0.12
S42	1.41 (431.82)	5.25	82.27	144.00	0.94	0.12
S43	1.65 (504.77)	6.66	75.79	114.00	0.97	0.10
S44	1.02 (311.25)	5.66	54.99	24.00	0.96	0.08
S45	1.52 (463.83)	6.44	72.02	97.33	0.95	0.09
S46	0.81 (247.17)	4.95	49.93	14.00	0.96	0.08
S47	1.03 (314.30)	4.80	65.48	131.50	0.95	0.06
S48	0.51 (155.62)	3.61	43.11	14.00	0.97	0.08
S49	0.96 (292.94)	6.51	45.00	135.50	0.97	0.14
S47 a	0.52 (158.67)	4.83	32.85	15.00	0.98	0.05
S48 a	2.11 (643.87)	13.21	48.74	155.50	0.96	0.07
S49 a	1.47 (448.57)	10.85	41.34	35.00	0.97	0.12

4.1.1. Models to Study the Various Parameters that Influences NAC Values

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. SAS [56] was used to generate general linear models (GLM Procedure), Duncan's Multiple Range Test and t-test (LSD). Statistical test results are included in the Appendix 8.3.1.

Case 1, shows a linear model developed to determine the various parameters that influence the sound absorption properties of nonwovens. This Case 1 has a R-square value of 0.76. 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 of sound waves. Process, structure and cross-section were found to be insignificant and thus removed to get Case 1a, which has same R-square value that of Case 1. Case 1a shows that the parameters web, lay, blend and frequency all had p-values of < 0.0001 and thus are significant at greater than 99% confidence.

Case 2 was developed to study the influence of interaction between various parameters that control sound absorption. The parameters: web, lay, blend, cross-section, frequency, web/lay, web/blend, web/frequency, lay/blend, lay/frequency and blend/frequency were found to be significant for at least 95% confidence limit. Case 2 had a R-square value of 0.83.

4.1.2. Duncan's Multiple Range Test for NAC

Duncan's Multiple Range test was used to compare all possible pairs of means. This allows one to not only see when there is a significant difference in means but also to see which level of a particular parameter has greater influence on the response variable. In Duncan's test, insignificant differences are represented by the same alphabet. Thus by running this test, parameters that influence sound absorption can be better understood. The results for this test are shown in Appendix 8.3.2.

<u>Web Comparison</u>

Results obtained from Duncan's Multiple Range test shows that there is a significant difference between two types of webs namely: airlaid which is level 2 and carded level 1. The average NAC for all airlaid webs (0.19) was higher than for all carded webs (0.14). This concludes airlaid samples give more NAC values.

Lay Comparison

A significant difference is seen between lay type W3H and W3NH when compared to W1H, W1NH and W2NH. Lay type W3H andW3NH is giving higher NAC values than the other types. This result coincides with the fact that higher thickness leads to more sound absorption.

Cross-section Comparison

There is no significant difference seen between the fiber cross-sections. This insignificant difference was not expected. A presentation by Innotherm solutions [18] stated that an increase in cross-section increases sound absorption. The reason for this contradictory result might be due to large disparities in the number of samples for each cross-section. Number of samples considered for this comparison can be seen in the column that titled 'N'.

4.1.3. t-Tests (LSD) for NAC

The t-test (LSD) allows comparison between parameters having more than 2 levels where as the student t test allows only the comparison between only two means. Here, t-test (LSD) was used to compare means and to study which parameter has more significance.

Web Comparison

There is a significant difference between the airlaid and the carded webs.

Lay Comparison

Based on the t-test (LSD) there is a significant difference between W3H and W3NH when comparing with W1H and W1NH type. Similar difference is observed when W3 types are compared with W2 types. The difference in these means is 0.077 and 0.082 respectively.

Cross-section Comparison

As seen in Duncan's test, there are no significant differences seen between fiber cross-sections.

4.2. Statistical Results: Carded Samples

Since there is a statistical difference between airlaid and carded webs, it was determined that further statistical analysis should be presented based on these two web structures.

4.2.1. Empirical Model To Predict NAC Values

As there is significant difference seen between two different web types, it is necessary to have a separate empirical equation for carded and airlaid samples to predict the sound absorption values. This section explains, the empirical equation for prediction NAC values of the carded samples. Case 3 (shown in Appendix 8.4.1) was developed to study the various factors in carded sample that has influence on sound absorption mechanism. As per this model, the parameter: cross-section, lay and frequency have strong influence over sound absorption of carded samples. This model has R-square value of 0.90. Case 4 eliminates insignificant factors from Case 3.

Case 5 was developed to predict the NAC values for carded samples from measurable physical parameters. In Case 5 it can be seen that airflow, thickness, mass and frequency are all significant at 94% confidence. From Case 5 the following model can be generated and used to predict NAC values for carded webs.

$$\begin{aligned}\text{NAC (alpha)} &= \text{Airflow } (0.00010) + \text{Thickness } (0.00713) + \text{Mass } (0.02223)\\ &\quad + \text{Freq } (0.00011) - 0.112205 \qquad (4.1)\end{aligned}$$

The model has a R-square value of 0.84. 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. The comparison between observed and predicted values is shown in Figure 4.1. Note that at >4100 Hz the observed NAC values are not well predicted by the model. This may be due the fact that a linear model is used and that no interaction effects are included.

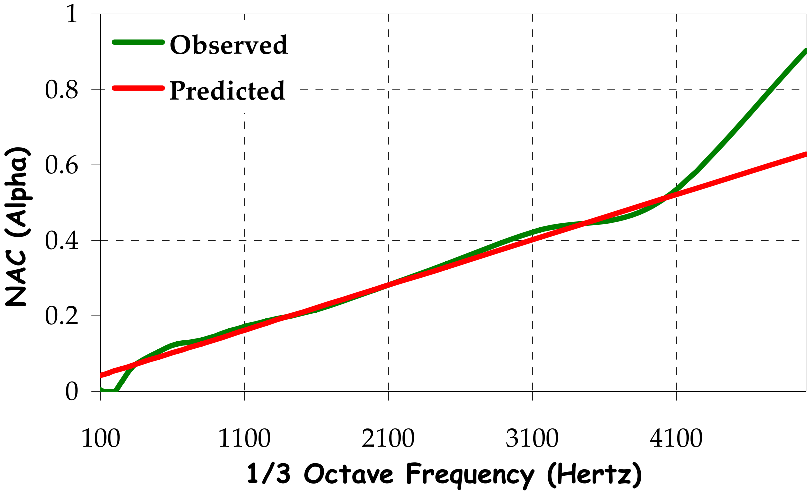


Figure 4.1. Observed values versus predicted values for Case 5

4.2.2. Other Statistical Tests

Duncan's multiple range tests and t-tests were carried out for all carded samples and the results obtained are shown in Appendices 8.4.2. & 8.4.3. respectively. Both tests show the same results as it was explained in earlier sections 4.1.2 and 4.1.3.

4.3. Statistical Results: Airlaid Samples

4.3.1. Models to Study the Various Parameters that Influences NAC Values

Case 6 (shown in Appendix 8.5.1.) was developed to study the various factors in airlaid sample that has influence on sound absorption mechanism. As per this model, the parameter: surface, mass, airflow, thickness and frequency have strong influence over sound absorption of airlaid samples. This model has R-square value of 0.79. As the parameter "surface" has got significant influence over sound absorption values, separate model for each surface types namely high density (HD), low density (LD) and normal density were developed. A generalized model to predict NAC values of all airlaid samples was also developed.

4.3.2. Empirical Model To Predict NAC Values: High Density Samples

Case 7 was developed to predict the NAC values for high-density airlaid samples from measurable physical parameters. In Case 7 it can be seen that airflow, thickness, mass and frequency are all significant at 99% confidence. From Case 7 the following model can be generated and used to predict NAC values for high-density airlaid webs.

$$\text{NAC (alpha)} = \text{Airflow } (0.0002) + \text{Thickness } (0.0418) - \text{Mass } (0.0894) \qquad (4.2)$$

+ Frequency (0.00013) – 0.16431

The model has a R-square value of 0.74. 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. The comparison between observed and predicted values is shown in Figure 4.2.

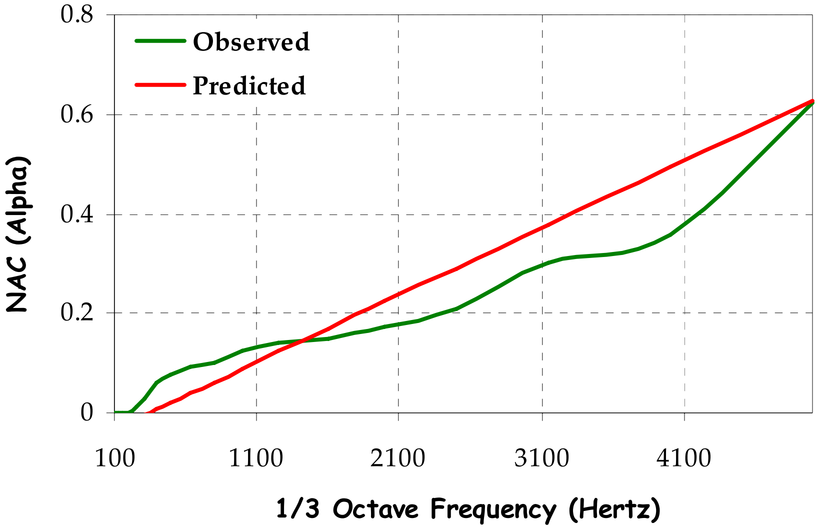


Figure 4.2. Observed values versus predicted values for Case 7

4.3.3. Empirical Model To Predict NAC Values: Low Density Samples

Case 8 was developed to predict the NAC values for low-density airlaid samples from measurable physical parameters. In Case 8 it can be seen that airflow, thickness and frequency are all significant at 99% confidence. From Case 8 the following model can be generated and used to predict NAC values for low-density airlaid webs.

$$\text{NAC (alpha)} = \text{Airflow}\ (0.0001) + \text{Thickness}\ (0.0150) + \text{Frequency}\ (0.00013) - 0.1519 \qquad (4.3)$$

The model has R-square value of 0.83. 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. The comparison between observed and predicted values is shown in Figure 4.3.

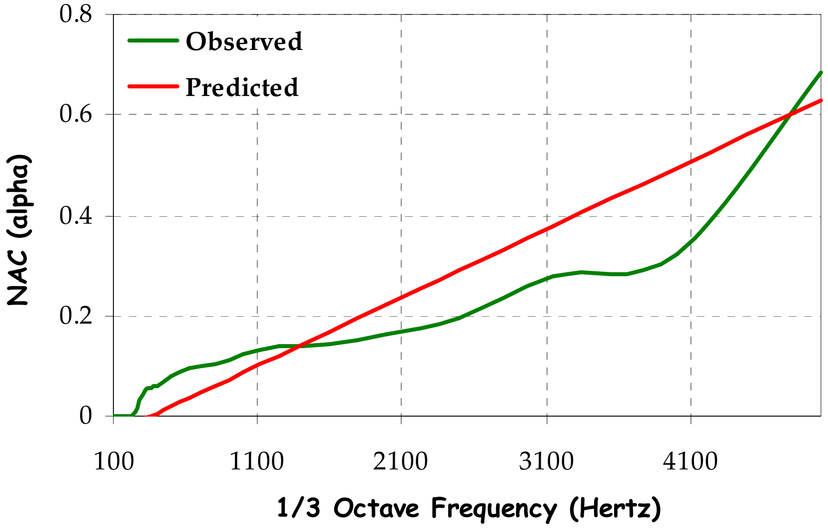


Figure 4.3. Observed values versus predicted values for Case 8

4.3.4. Empirical Model To Predict NAC Values: Normal Samples

Case 9 was developed to predict the NAC values for normal airlaid samples from measurable physical parameters. In Case 9 it can be seen that airflow and frequency are all significant at 99% confidence. From Case 9 the following model can be generated and used to predict NAC values for normal airlaid webs.

$$\text{NAC (alpha)} = \text{Airflow}\ (0.0003) + \text{Frequency}\ (0.00015) - 0.0836 \qquad (4.4)$$

The model has R-square value of 0.85. 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. The comparison between observed and predicted values is shown in Figure 4.4.

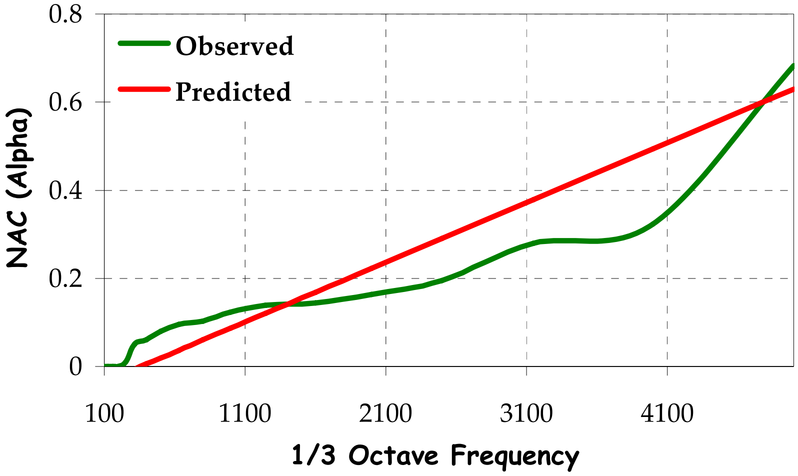


Figure 4.4. Observed values versus predicted values for Case 9

4.3.5. Empirical Model To Predict NAC Values: Airlaid Samples (altogether)

Case 10 was developed to predict the NAC values for airlaid samples in general from measurable physical parameters. In Case 10 it can be seen that airflow, thickness, mass and frequency are all significant at 99% confidence. From Case 10 the following model can be generated and used to predict NAC values for airlaid webs.

$$\text{NAC (Alpha)} = \text{Thickness}\ (0.02143) + \text{Airflow}\ (0.00020) + \text{Freq}\ (0.00013)$$

$$- \text{Mass}\ (0.02768) - 0.14769 \qquad (4.5)$$

The model has R-square value of 0.79. The comparison between observed and predicted values is shown in Figure 4.5.

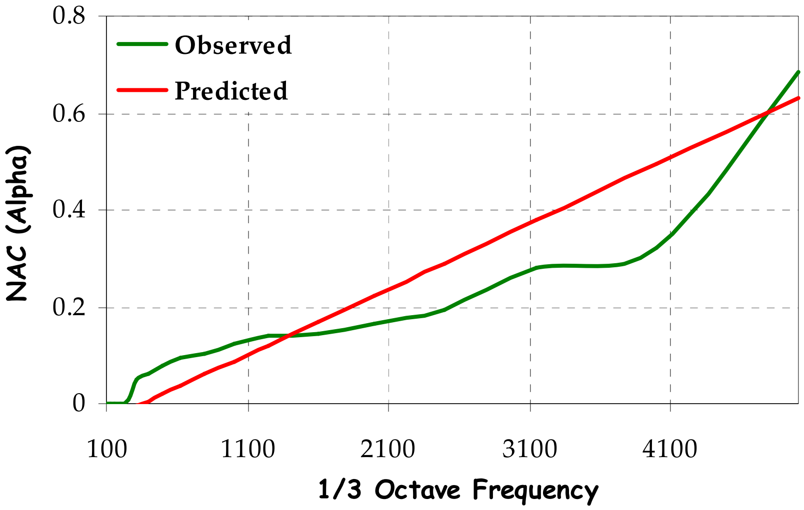


Figure 4.5. Observed values versus predicted values for Case 10

4.3.6. Other Statistical Tests

Duncan's multiple range tests and t-test was carried out for all airlaid samples and the results obtained are shown in Appendices 8.5.2 & 8.5.3 respectively. Both tests show the same results as it was explained in earlier sections 4.1.2 and 4.1.3 respectively.

4.4. Sound Absorption Measurements

The measured sound absorption coefficient of each sample is a continuous curve in the frequency range from 100 Hz to 5000 Hz. In order to obtain statistical models NAC values for 1/3 octave frequency bands which include 100, 125, 160, 200, 250, 315, 400, 500, 630, 800, 1000, 1250, 1600, 2000, 2500, 3150, 4000 and 5000 Hz were plotted.

The average absorption is usually described in terms of the NRC (Noise Reduction Coefficient) factor, defined as the arithmetic average of the NAC at the frequencies 250, 500, 1000 and 2000 Hz, to which the human ear is mostly sensitive [26, 67]. NRC of all nonwoven fabrics is shown in Table 4.1. The influence of the various nonwoven fabric parameters on NAC, at various 1/3-octave frequencies is given in Figure 4.6 to Figure 4.25.

4.4.1. Influence of Fiber Type, Fiber Size and Fiber Cross-section

The emphasis in this research was to investigate the uses of polyester reclaim fibers and reclaim/virgin blends as sound absorbing materials. It was difficult to find virgin fibers with non-round cross-sections having linear densities similar to that of the reclaim fiber that had a round cross section. However, several inferences can be made from Figures 4.6 and 4.7 relating to the influence of fiber type on sound absorption coefficient. As seen in Figures 4.6 and 4.7, fiber type has significant influence on sound absorption capacity of nonwovens. By comparing the hollow and 4DG PET, which have the same linear density and length, the effect of fiber cross-section can be seen. Figure 4.6 shows that 4DG fibers have higher NAC values than hollow fibers. This result is related to an increase in scattering with an increase in fiber surface area and surface deformation. Also from Figure 4.6, since the reclaim fiber, which has round cross-section, has a lower linear density (4.74 Dtex) than the 4DG fiber (6.66 Dtex) one would expect the reclaim fiber to have a higher NAC value. This however is not the case which implies that the irregular cross-section of the 4DG fiber is a dominating factor.

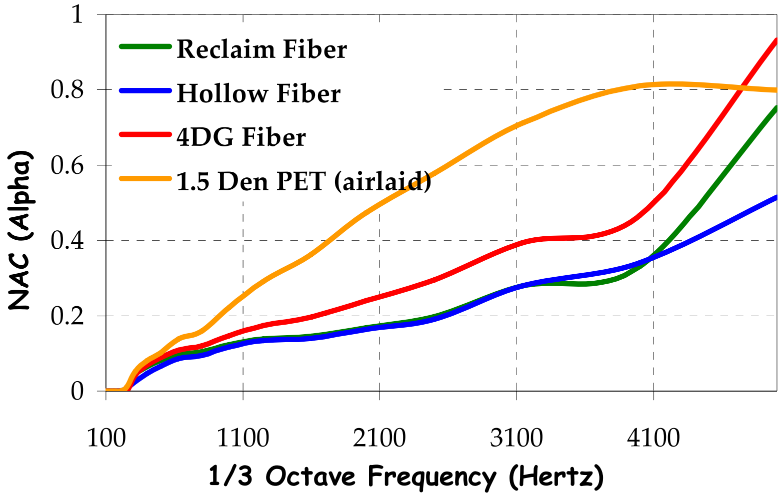


Figure 4.6. Sound absorption of fabric made from100% fibers of varying cross-sections

As expected the finer size PET absorbs more sound than other fibers (Figure 4.6). This is because finer linear density allows more fibers per volume, more contact area and more tortuous channels allowing more absorption. Moreover fine fibers move relatively more easily than coarser fibers which causes finer fibers to convert acoustic energy into heat more easily than coarser fibers. Moreover 1.5 Denier PET samples do not show much increase in sound absorption after 4100 Hz. This is due to increase of flow resistance where it is difficult for high frequency sound waves to enter into the material to get dampened. Also as seen in Figure 4.6, below 4000 Hz there is not much difference in NAC values of reclaim and hollow fibers. However, above 4000Hz the reclaim performs better. This may be due to the lower fiber size of the reclaim fiber.

As shown in Figure 4.7, a similar trend can be observed when all fibers as well as kenaf fibers are blended with reclaim fibers. However, note that there is a slight decrease in NAC when reclaim fibers are blended with untreated kenaf and a slight increase in an NAC when reclaim is blended with FR kenaf. The changes, though slight, are seen in all frequencies greater than 1100 Hz.

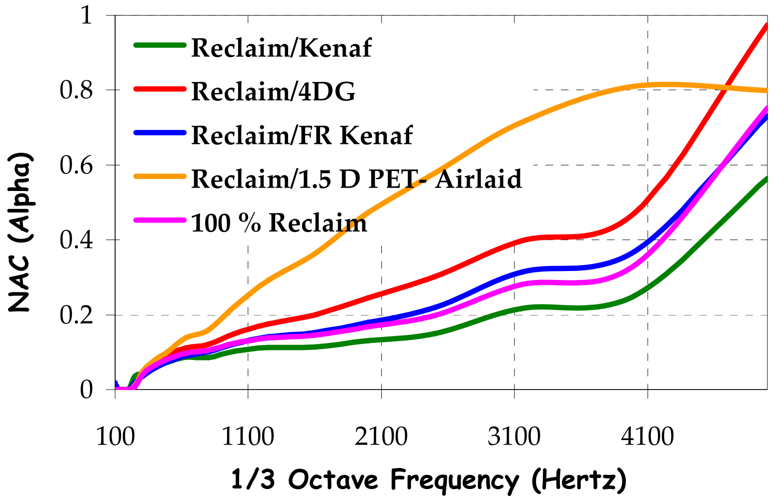


Figure 4.7. Sound absorption of reclaim PET blended with other fibers (50/50 blend ratio)

4.4.2. Influence of Kenaf

To study the influence of kenaf content on sound absorption properties, samples of 70/30 – reclaim/kenaf and 50/50 – reclaim/kenaf were compared. Figure 4.8 shows that an increase in kenaf content has negative effect on sound absorption.

However, above 4100 Hz the trend is reversed (i.e., an increase in kenaf increases NAC).

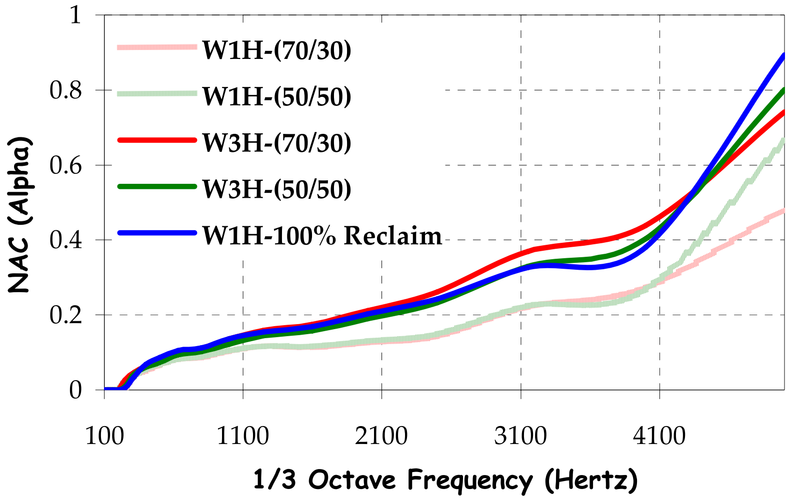


Figure 4.8. Sound absorption of fabric made of kenaf and reclaim fibers

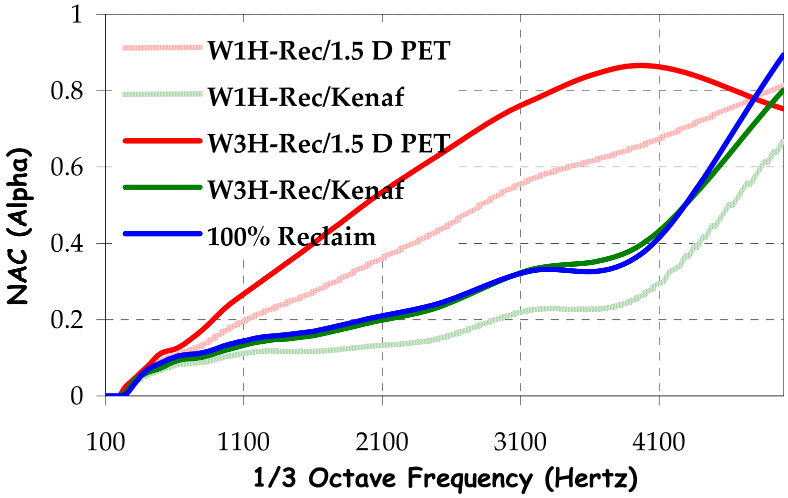


Figure 4.9. Comparison of kenaf and 1.5 D PET blends with reclaim

Moreover, Figure 4.9 clearly shows that the blends containing kenaf and reclaim fibers are less suitable as sound absorbing materials than blends of reclaim and PET fibers. This is true in all frequencies between 1100 and 4100 Hz.

4.4.3. Influence of Surface Impedance

Influence of surface impedance on sound absorption has been investigated by using airlaid samples (S1 – S30) of different configuration namely W1H, W1NH, W2NH, W3H and W3NH (see Figure 3.8). Samples with "H" stands for homogenous type that means there is no difference in the density along its thickness. On other hand, samples with "NH" stands for non-homogenous type where there is a density gradient seen along its thickness. This density gradient is created by varying the needling conditions namely depth of needle penetration and number of needle passes. As explained in Figure 3.8, samples labeled W1 and W2 have the same range of thickness while those labeled W3 were produced with higher density and thickness.

All airlaid non-homogenous samples (shown in Figure 3.9) were tested by having sound waves incident to low density (LD) and high density (HD) sides. Test results (seen in Figure 4.10 & 4.11) on comparing these different configured samples are as follows:

1. All samples irrespective of type, show better sound absorption values when sound faces higher density side. This might be due to the number and size of holes formed in HD side due to higher needling. These pores allow more sound to penetrate the fabric and to be trapped their by the tortuous nature of nonwovens. This should be verified by pore size measurements.
2. As expected, all W3 samples performs better than W1 and W2 samples because of W3 had greater thickness than W1 and W2 samples.

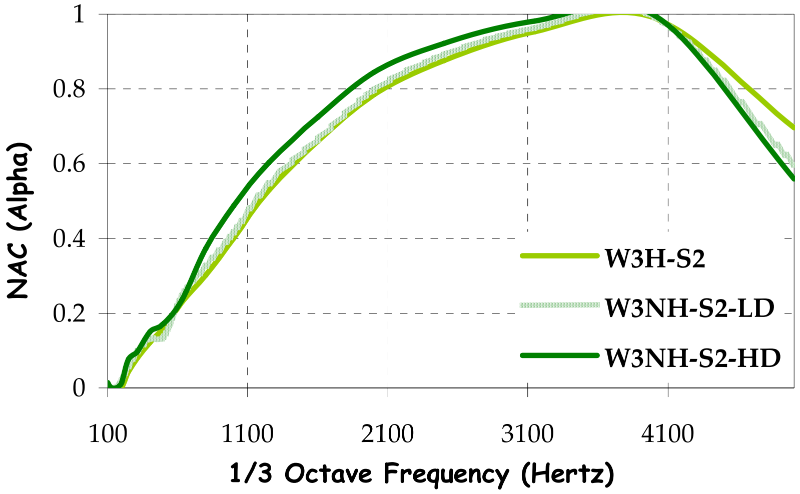


Figure 4.10. Influence of surface impedance on sound absorption

3. Out of six different fiber blend ratio (A - F, shown in Figure 3.5), four samples show better values for W3NH configuration than W3H type. Interestingly higher values of NAC for W3NH type are not because of airflow resistance (as airflow resistance of all those four samples are less than W3H type). Thus,

it is understood that, surface impedance can significantly influence sound absorption capacity of nonwovens by altering porosity and tortuous path of the sample.

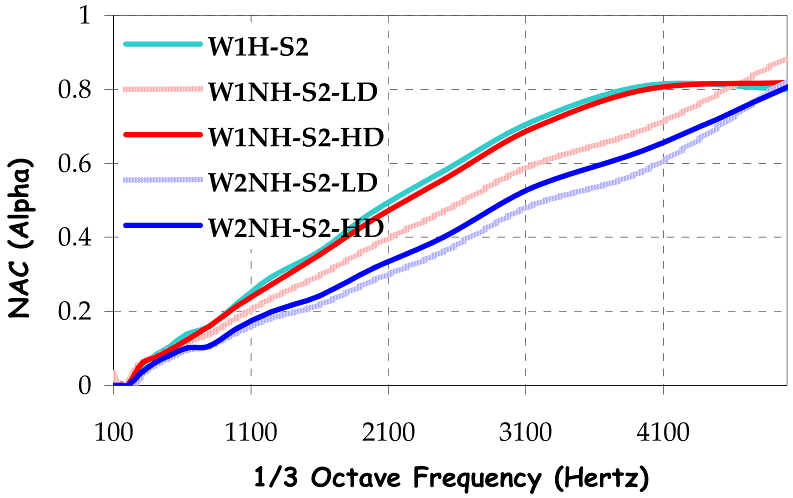


Figure 4.11. Influence of surface impedance on sound absorption

4. Similar type of trend can be seen when comparing W1NH and W2NH type, where, W1NH performs most of the time (5 out of 6 samples) better than W2NH. Thus, to get better sound absorption in multilayered acoustical materials, the sound impinging side should have higher density for only few mm of thickness and then density should decrease as sound proceeds through the material.

5. Comparison of W1NH and W1H is hard as the test results show half the time samples with W1NH configuration is performing better than W1H type.

However, comparison of "NH" and "H" type in the W3 samples clearly shows, "NH" types are always better than "H" types. But at the same time the "NH" configuration works better only when an optimum thickness and density gradients are choosed. The surface impedance results for all other samples are shown in Appendix 7.6.

4.4.4. Influence of Fire Retardant (FR) Treatment

Effect of FR treatment on sound absorption is investigated by comparing nonwoven samples of treated and untreated kenaf fibers blended with reclaim fibers. Results shown in Figure 4.12 indicate the positive influence of FR treatment on sound absorption properties.

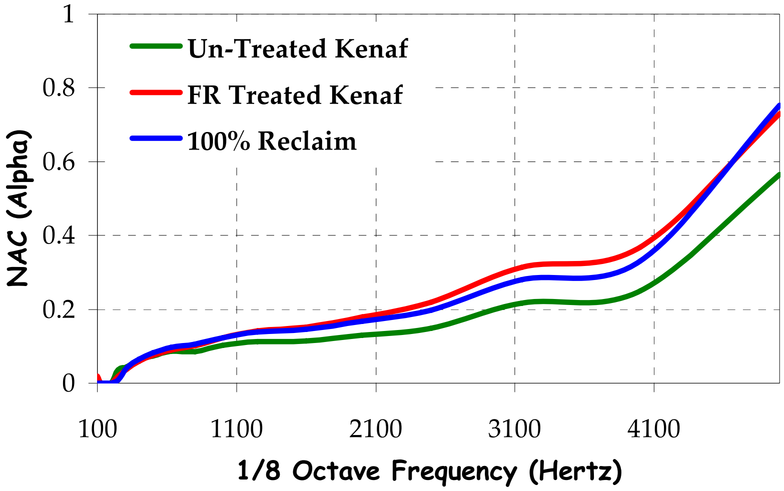


Figure 4.12. Influence of flame retardancy treatment on sound absorption

The reason being, the treatment of kenaf fibers for fire retardant might change its fiber structure in such a way that it absorbs sound better than untreated kenaf fibers. It is possible that treatment increases surface voids on the fibers which might later entrap more sound. This must be verified by taking SEM scans of the treated and untreated fibers.

4.4.5. Influence of Nonwoven Processes

As it is well-known, final properties of the sample depends on the process that is used for making it. So, it is imperative to study the influence of processes (i.e. nonwoven processes) on sound capacity of nonwovens. Two factors namely web formation (carding and airlaid) and bonding technologies (needlepunching and thermal bonded mat with needlepunching) were analyzed for its sound absorption properties. The influence of both web formation and bonding techniques on the impact sound absorption properties can be observed by studying the results presented in Figures 4.13 and 4.14 respectively.

Samples labeled S1 to S30 are needlepunched using airlaid webs. Carded webs are needled to get samples S31 to S45. Unfortunately, due to limitations in the processibility, S3 samples (100% 1.5 D PET) were not produced using carded technique. Comparative study results of carded and airlaid samples are shown in Figure 4.13. Higher sound absorption values for all airlaid samples irrespective of fiber blend ratio can be seen. The reason for better performance of airlaid samples might be due to the following effects:

1. Higher values of airflow resistance for all airlaid samples, which is due to the orientation of fiber. Airlaid samples have fibers in random fashion where as fibers in carded samples are aligned mostly in machine direction. A random lay of fibers will create more tortuous channels which increases sound absorption.
2. Differences in pore structure due to different fiber orientation. Random arrangement fibers produce samples with small pores and a higher number of fiber to fiber contact points which ends in better sound absorption properties.
3. As it is known that, airlaid process deposits the fiber with the help of air stream (aerodynamics). This type of deposition creates a porosity gradient along the thickness of the sample when fibers with different densities are used. That is: when fibers with different densities for e.g. in this case, kenaf (1.55 g/cm^3) and PET (1.3 g/cm^3) are used to form a web in airlaid machine, fibers having high densities fall first and settles down allowing lower density fiber at the top. This creates a gradient in porosity. This porosity gradient has a positive effect on sound absorption properties which makes airlaid samples to perform better than carded samples.

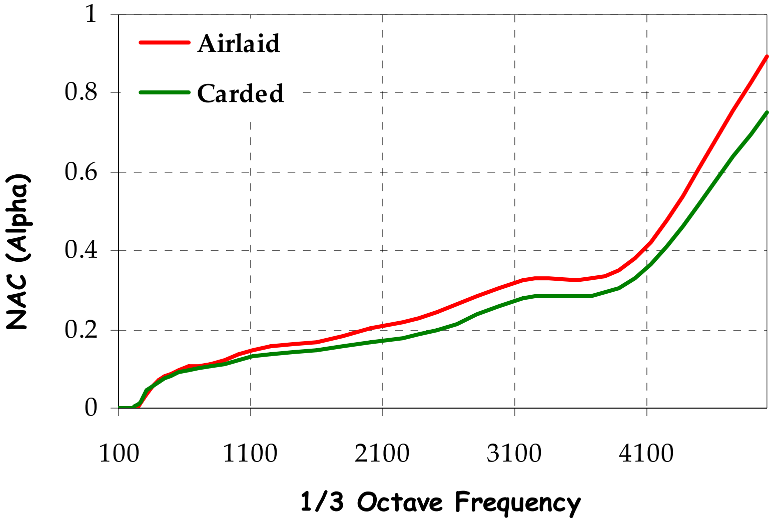


Figure 4.13. Influence of nonwoven processes (Web Formation)

When comparing samples of two different bonding techniques, there is not much difference seen (Figure 4.14) between needled and needled with thermally bonded samples.

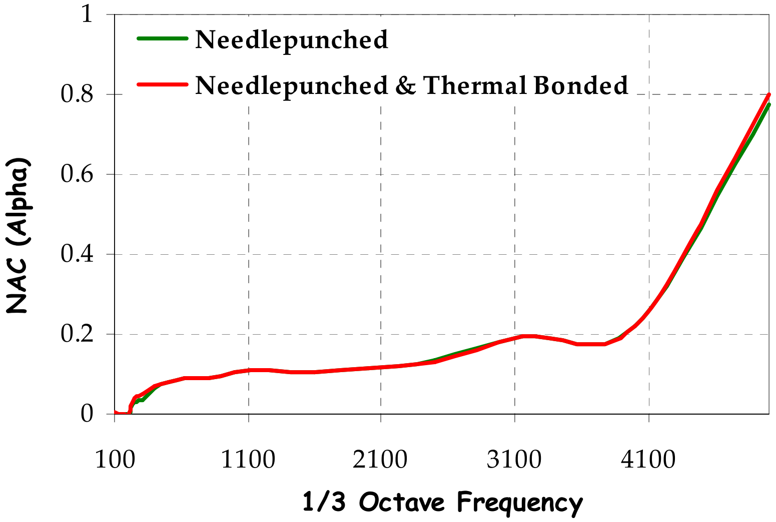


Figure 4.14. Influence of nonwoven processes (Bonding Technology)

Note: Results of fiber orientation distribution function (ODF) shown in Appendix 7.2 indicates same ODF for carded and airlaid samples. It should be understood that the ODF obtained from optical means reflects the surface ODF and not the entire ODF of the sample.

4.4.6. Influence of Airgap

Sound absorption measurement calculations were performed with and without an airgap of 5 mm and 10 mm between the rear of sample and the backing of the movable plunger of the impedance tube. The results for the Figure 4.15, states that, for the same amount of material, it is much better to have an airgap behind the layer, which coincides with the results of I. P. Dunn et al. [32]. The creation airgap increases NAC values in mid and higher frequencies, in spite of showing minima at certain frequencies. There is not much difference seen between 5 mm airgap sample and 10 mm airgap sample. Moreover, maxima peak for different airgap is different (higher the airgap distance, maxima peak shift towards lower frequency). This indicates that there is an optimum value for an airgap beyond which there is not much influence seen in sound absorption properties.

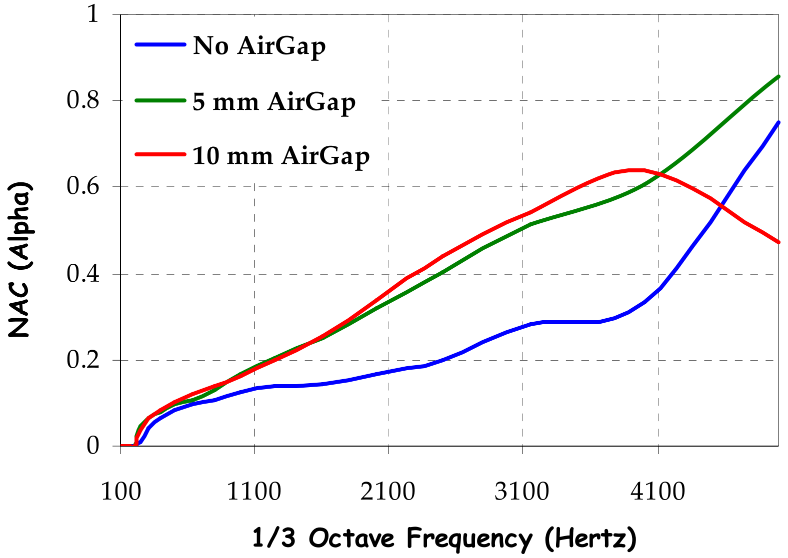


Figure 4.15. Influence of airgap on sound absorption

4.4.7. Influence of Compression

The effect of compression on acoustical properties of samples was studied by compressing a particular sample (S18 -L). From the result shown in Figure 4.16, it can be understood that compression has negative influence on sound absorption capacity of nonwovens. The reason for reduced sound absorption for compressed samples might be due to the decrease in thickness of nonwoven sample. As it was explained earlier in section 2.4.8, under compression the various fibers in the mat are brought nearer from each other's without any deformation (without any change in fiber size). This compression results in decrease of thickness (from 22.70 mm to 17.20 mm) which is responsible for the decrease of sound absorptive capacity.

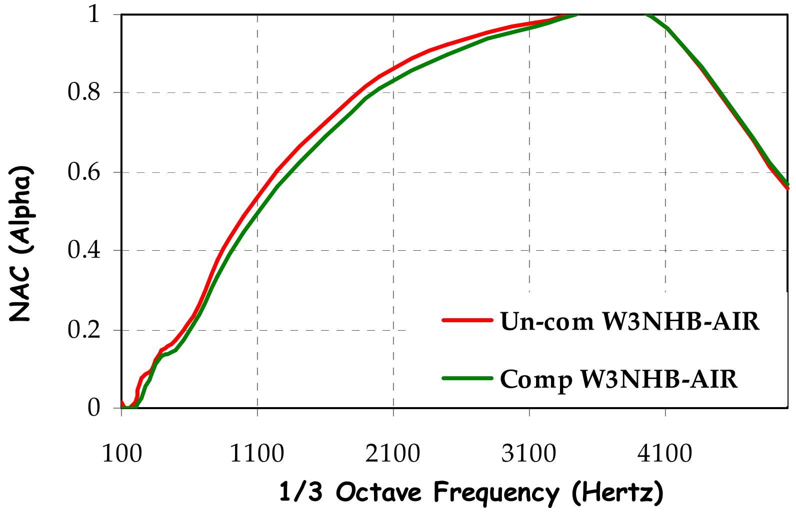


Figure 4.16. Influence of compression on sound absorption

4.4.8. Influence of Film

Perforated screens, woven fabrics and films are used to cover the porous and fibrous sound absorbing materials in order to prevent the material from detrimental environments or to meet the aesthetic performances [30, 50, 60]. Sometimes these coverings are used to prevent the fall of fibers from product. Films are highly reflective to the sound waves and thus have a dramatic influence on absorptive properties of porous or fibrous materials. Therefore it is necessary to study the effect of film on sound absorption, when it is attached to fibrous or porous sound absorbing materials. In this study, two kinds of films namely, PVC and Al film were used to analyze its influence on acoustical absorptive properties. The results of sound absorption of film (PVC & Al) attached samples are given in Figure 4.17 – 4.20.

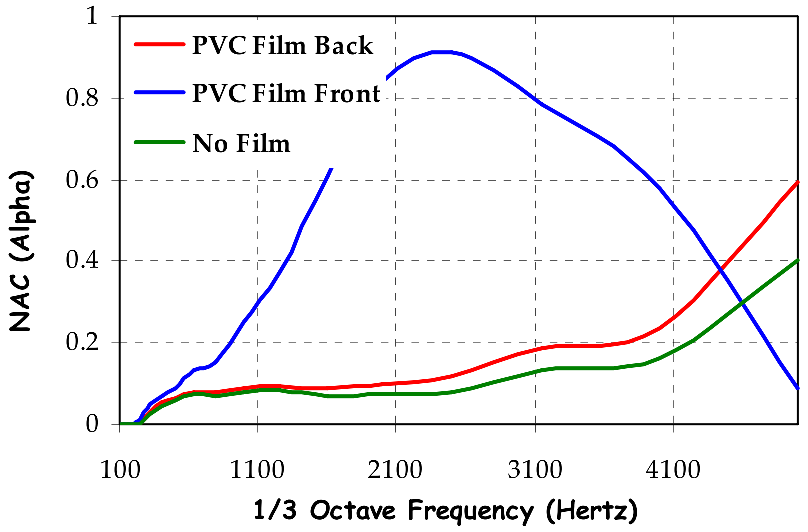


Figure 4.17. Influence of PVC film – S47

Good difference in absorption trends seen in Figures 4.17, 4.18 & 4.19 shows that the film attached samples when placed in such a way that film is at the rear side of sound always performs better at all frequencies than sample with out film. This is due to the reflective phenomenon of sound waves by the film which makes the sound waves to pass through the material twice. Thus, attachment of film helps the absorbing material in absorbing more sound. At the same time, the influence of film when attached to the rear end of thicker absorbing material is less (seen in Figure 4.19), which might be due to the larger amount of sound absorption by porous part before the sound hits the film of the porous material.

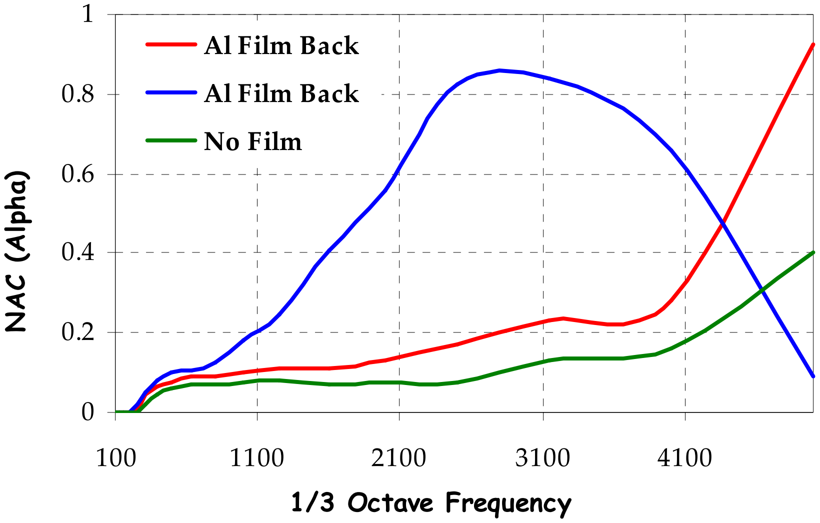


Figure 4.18. Influence of Al film – S48

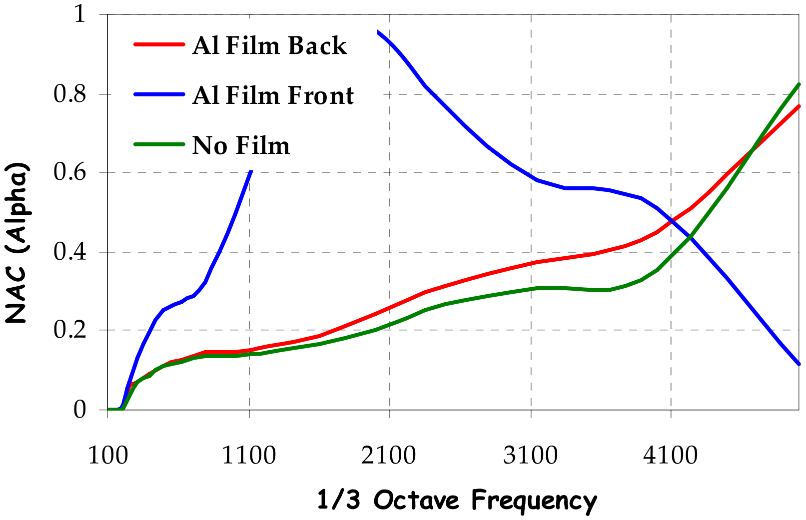


Figure 4.19. Influence of Al Film

When film side of the sample is facing sound, absorption peak reaches its maximum till certain frequency and then drops down. Reason for this type of sound absorption might be due to the resonance effect of film.

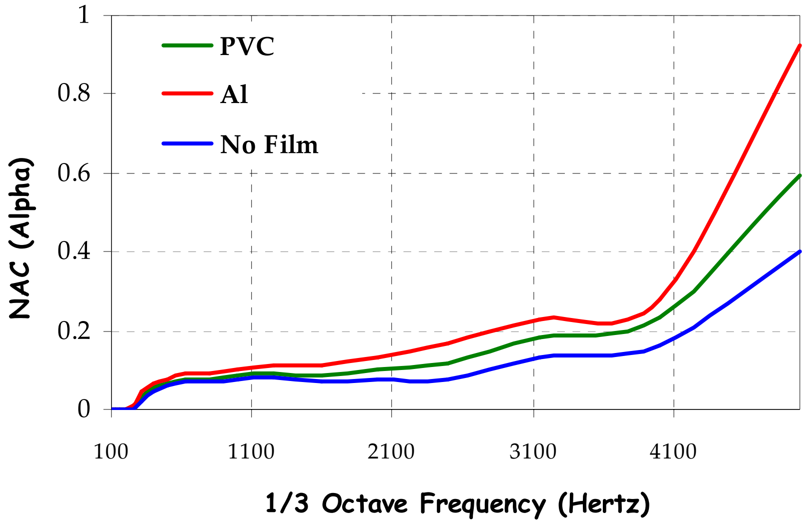


Figure 4.20. Influence of film type on sound absorption

When comparing two films (shown in Figure 4.20): PVC and Al for sound absorption properties, samples attached with Al film shows better results which might be due to the effect of physical properties of film like: thickness, stiffness and bonding of film to the material.

4.4.9. Influence of Mass per Unit Area and Thickness

Past literature scan on sound absorption of nonwoven materials have shown that the sound absorption coefficient strongly dependent on material mass/unit area and thickness. Correlation between NRC and mass/unit area and NRC and thickness are shown in Figures 4.21 and 4.22 respectively.

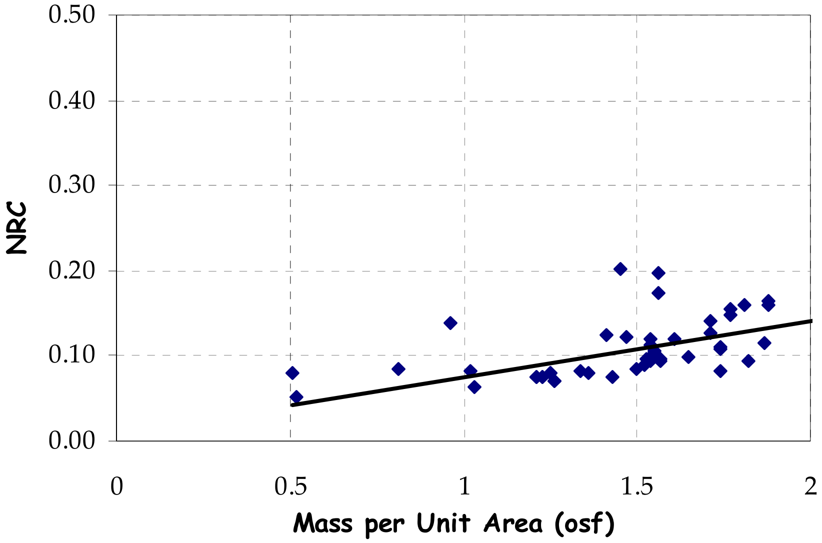


Figure 4.21. Influence of mass/unit area on sound absorption

Figure 4.21 indicates, NRC values increases as mass/unit area increases. This might be due to change of properties like: increase of airflow resistance, more tortuous path, small pore size and more contact area for sound to get dampened. However, after certain level (after 1.5 osf (457.72 gsm)), NRC values starts decreasing and this might be due to reflection of sound due to high flow resistivity of the material. Influence of felt thickness is demonstrated in Figure 4.22, which shows that thicker the material better the NRC values. Moreover, literatures in the past [3, 31] have indicated the importance of thickness on low frequency sound absorption. This behavior is based on the physics – low frequency means higher wavelength and higher wavelength sound can be absorbed if the material is thicker.

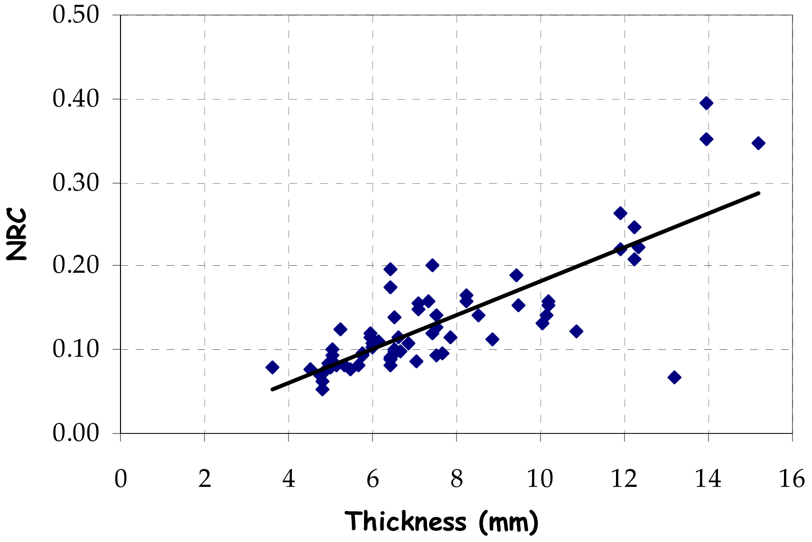


Figure 4.22. Influence of thickness on sound absorption

Note: The thickness and mass/unit area should be chosen from the point of view of cost of performance.

4.4.10. Influence of Airflow Resistance

It is known that the resistance to which the fibrous materials offer to the flow of sound has got a great influence on sound absorption. The measured airflow resistivity of the nonwoven samples were scattered in a wider range. Figure 4.23, states the relationship between Normal Reduction Coefficient, NRC and the airflow resistance. From the Figure 4.23, it can be inferred that, higher airflow resistance always gives better sound absorption values. However, there is an optimum value for an airflow resistance, beyond which sound starts reflecting from the material, there by decreasing sound absorption. That is, if Rayls value is too small, the sound wave flows through the sample without friction against the walls of the pores of the sound absorbing material, whilst if Rayls value is too large, sound waves cannot flow easily through the sample, because of large friction.

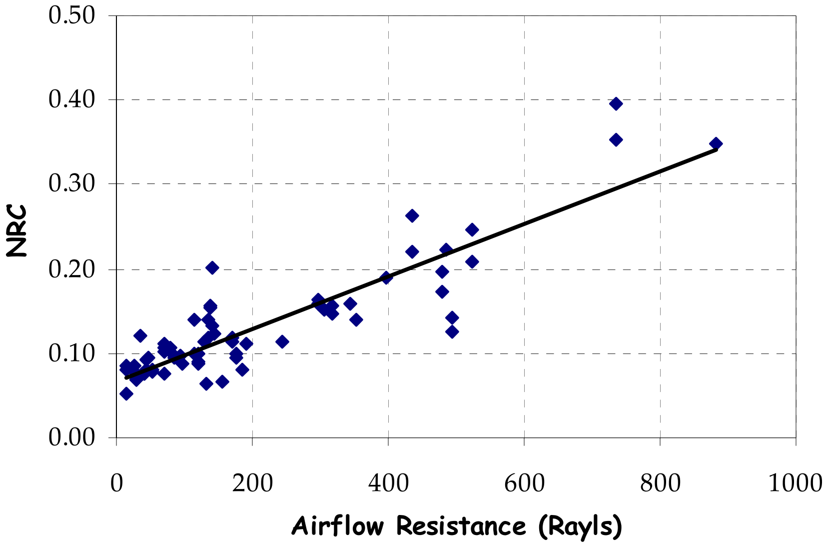


Figure 4.23. Influence of airflow resistance on sound absorption

Airflow resistance of a nonwoven sample depends on the sample bulk density and the diameter of the fiber. Figure 4.24 show the flow resistivity as a function of density for various fibrous sound absorbing materials. The results from the graph show that flow resistivity increases very strongly with increasing bulk density.

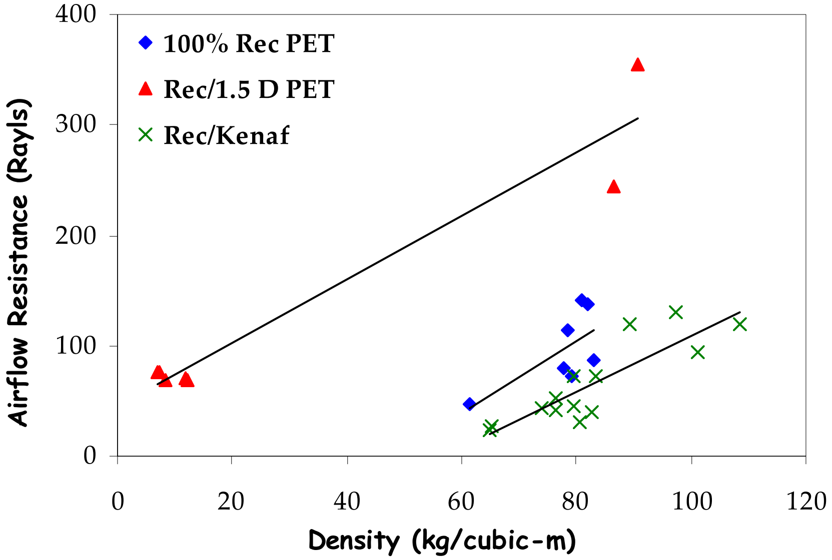


Figure 4.24. Airflow resistance as a function of density

4.4.11. Influence of Porosity

Many researchers have cited the importance of porosity in evaluating acoustical absorptive properties [51, 71]. Pores formed in nonwoven samples are very complex. There are open pores, closed pores and isolated pores. Among them, the pores, which form channels through the sample, along which sound waves can propagate for effective sound absorption, are important. Details about pore size and shape of relatively thick nonwoven samples are difficult to determine. Porosity of all nonwoven samples was calculated using equation 2.3 and are plotted versus NRC values (see Figure 4.25). Theoretically determined porosities were in the range of 0.89 - 0.98. A broad range of values is needed in order to see the true effect of porosity on sound absorption.

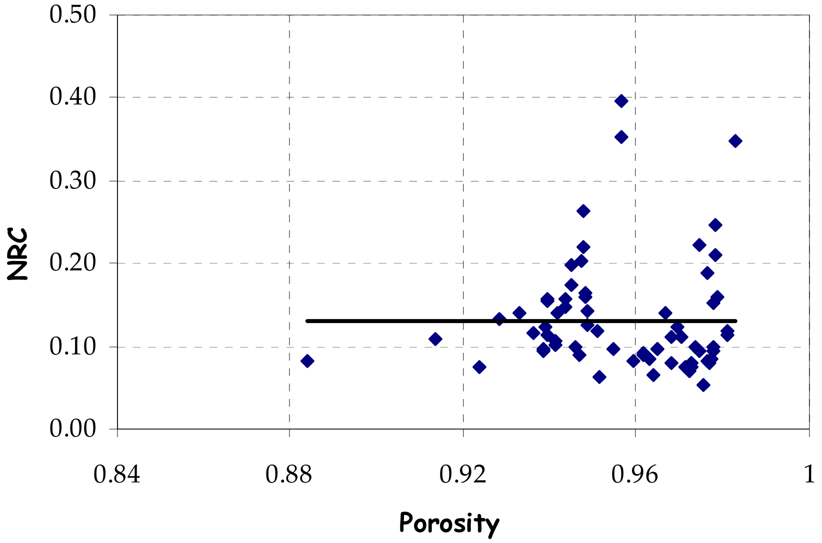


Figure 4.25. Influence of porosity on sound absorption

CHAPTER 5: Conclusion

The influence of changing various components of a nonwoven material on sound absorption capacity is presented in this research. The results presented here encourage more awareness of the application of nonwoven fabrics in acoustics. Some of the important conclusions of this research are:

- An appreciable increase in Normal Absorption Coefficient, NAC, values can be obtained by altering surface impedance of the material.
- Films such as aluminum and PVC attached to nonwovens increase sound absorption at low and mid frequencies at the expense of higher frequencies.
- Fiber surface area and fiber size have strong influence on sound absorption properties of nonwovens. Higher surface area and lower fiber size increases sound absorption.
- Use of reclaim and kenaf fibers in acoustics is feasible if the proper parameters (mass per unit area and thickness) are chosen to make the product.
- Positive effect was seen when kenaf fibers are treated with FR treatment.
- Reclaim fibers blended with 1.5 denier PET or 4DG PET yielded fabrics with better NAC values than fabrics with 100% reclaim PET fibers.

- To increase the NAC values, an airgap can be created between the acoustical material and surface being treated. At the same time, creation of airgap will have minima at various frequencies for various airgap distances.

CHAPTER 6: Recommendations For Further Research

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

- Choosing various levels of thickness and densities for the sample
- Experimental measurement of tortuosity and porosity
- Comparing the experimental work with some already existing theoretical models
- Making samples using spunbond and melt blown technologies
- Making samples using 100% natural fibers like kenaf, flax or hemp
- Fabricating multilayered composite structure using different materials and technologies
- Fibers with same size and different cross-section to produce nonwoven fabric

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CHAPTER 8: Appendices

8.1. Vertical Flame Test Measurements

As acoustical materials are used as interior surface finishes, their flame resistance characteristics are of extreme importance. The flame resistances of airlaid samples of W1H airlaid structure were measured. The flame resistances of treated and un-treated kenaf were also compared. The test method used to determine the flame resistance of acoustical sample is ASTM D 64123. This test method uses 3″ x 12″ sample. This test is used to determine if a fabric is "flame-resistant" or whether a fabric will ignite and continue to burn after exposure to an ignition source. Vertical flame test is the most commonly used test in the FR industry. The test method sets criteria on how the test should be conducted (sample size, number of trials, type of flame, etc.), but does not establish performance requirements. Reported values (shown in Table 8.1) are:

- The time the fabric continues to burn after the flame source is removed (after flame in seconds)
- The length of fabric that was damaged (char length in inches)

- The length of time the fabric continues to glow after the flames extinguish (after glow in sec). This value is often reported, but rarely used in performance standards.

After-glow time is defined as the time the specimen continues to glow after it has ceased to flame. Details about apparatus (shown in Figure 8.1) used for this test can be seen in ASTM standard D 6413. The procedure and the results of vertical flame test are as follows:

1. Clamp the test specimen between the two halves of the holder, with bottom of the specimen even with the bottom of the holder.
2. Insert the specimen holder containing the specimen into the test cabinet and position the burner with the middle of the lower edge of the test specimen centered 19 mm above the burner and leveled with the bottom metal prong.
3. Start the flame impingement timer and expose the specimen for 12 seconds. Immediately flame is removed, start a stopwatch for measurement of the after-flame and after-glow time.
4. Remove the specimen holder from the test cabinet. Turn on the hood ventilation to clear the test cabinet of fumes and smoke. Allow the specimen to cool.

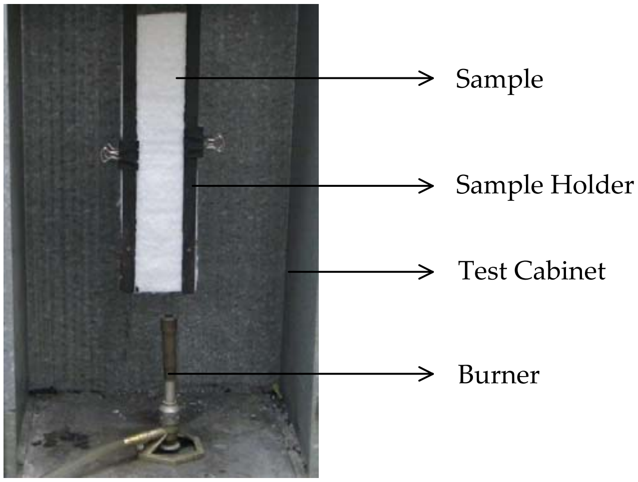

Figure 8.1. Vertical Flame Test Setup

Figure 8.2. Un-Treated Kenaf

Figure 8.3. FR Treated Kenaf

TABLE 8.1. Flame Resistance of Acoustical Samples

Sample ID	After Flame Time	After Glow Time
S1	23.84	-
S3	35.66	-
S5	29.63	-
S7	1Min36 Sec	4 Min 10 Sec
S9	1Min11 Sec	4 Min 12 Sec
S11	1Min06 Sec	4 Min 20 Sec
S39	1 Min 42 Sec	4 Min 5 Sec
S43	15 Sec	-

From Table 8.1, it is understood that, FR treated kenaf has good flame retardancy properties than all other samples. Sample S39 made of reclaim and untreated kenaf (50/50) has very low flammability properties compare to sample S43, which is made of reclaim and FR treated kenaf (50/50). This shows FR treatment for kenaf fibers resulted in formation of flameproof acoustical sample. Moreover, all kenaf samples except S43 has after glow time which can be seen in Table 8.1.

8.2. Fiber Orientation Distribution

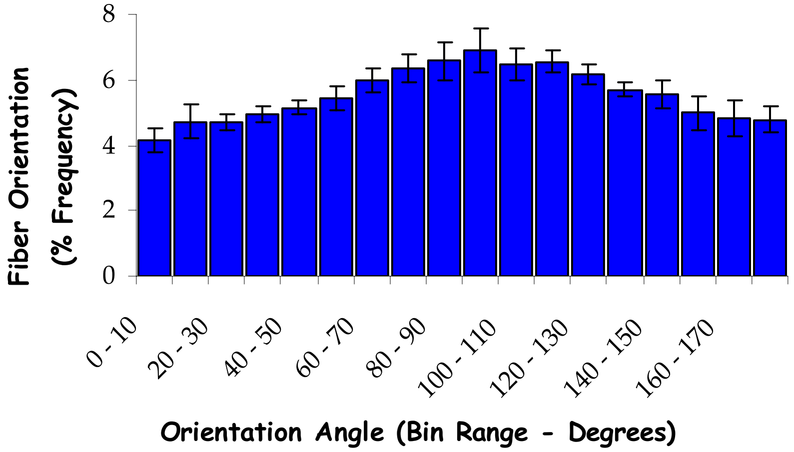

Figure 8.4. Fiber Orientation Distribution Function – Airlaid Sample (S1)

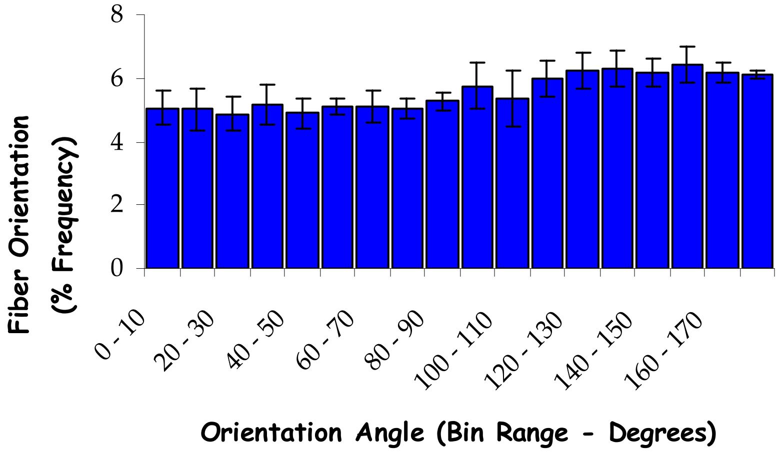

Figure 8.5. Fiber Orientation Distribution Function – Carded Sample (S31)

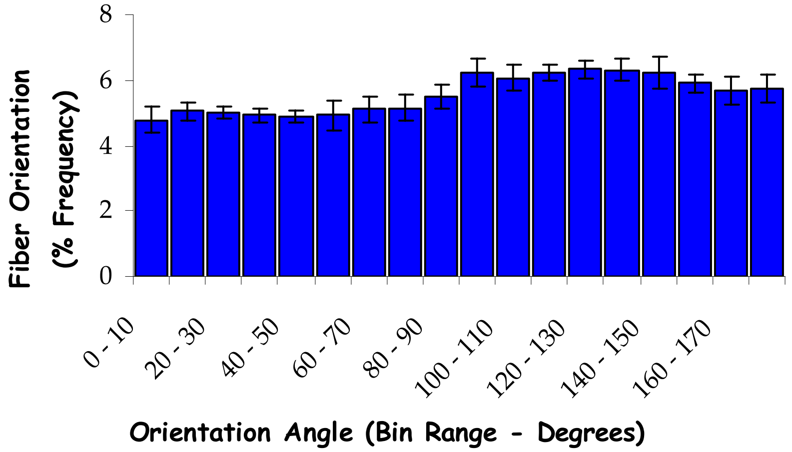

Figure 8.6. Fiber Orientation Distribution Function – Airlaid Sample (S5)

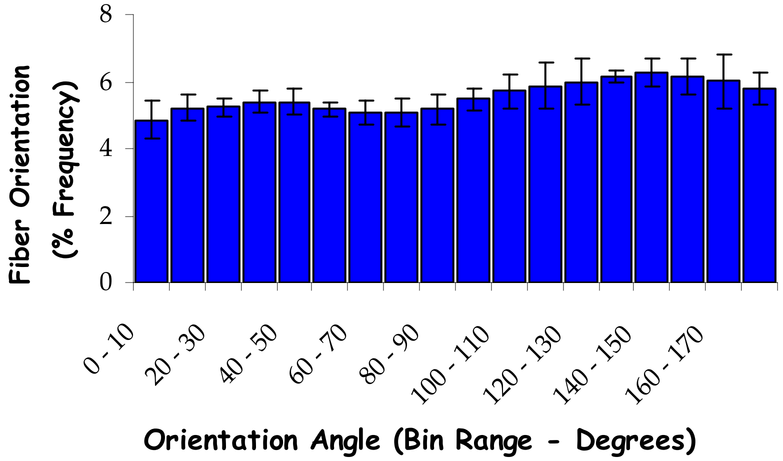

Figure 8.7. Fiber Orientation Distribution Function – Carded Sample (S33)

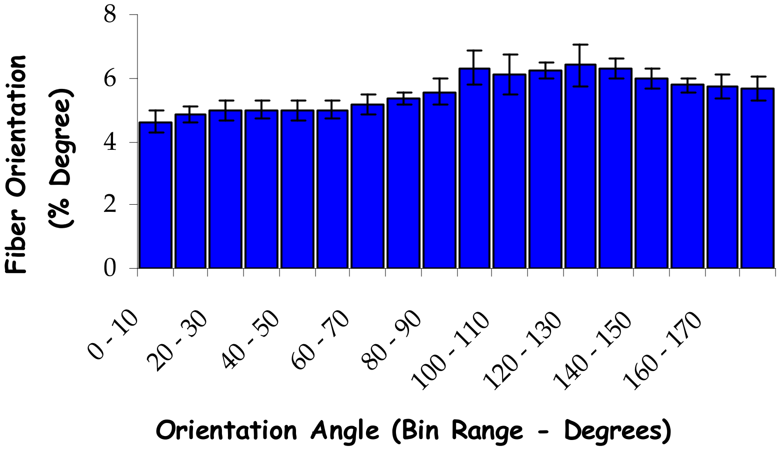

Figure 8.8. Fiber Orientation Distribution Function – Airlaid Sample (S7)

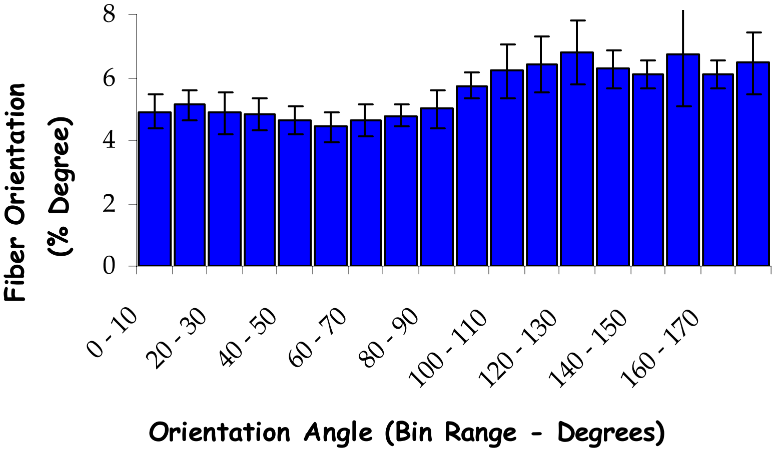

Figure 8.9. Fiber Orientation Distribution Function – Carded Sample (S35)

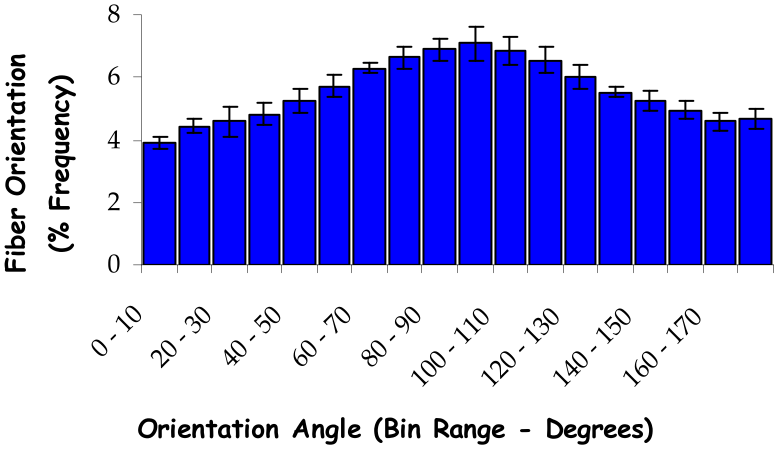

Figure 8.10. Fiber Orientation Distribution Function – Airlaid Sample (S9)

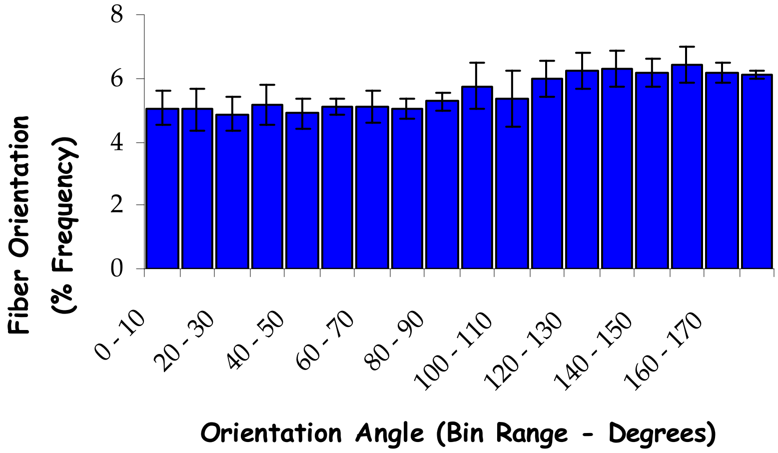

Figure 8.11. Fiber Orientation Distribution Function – Carded Sample (37)

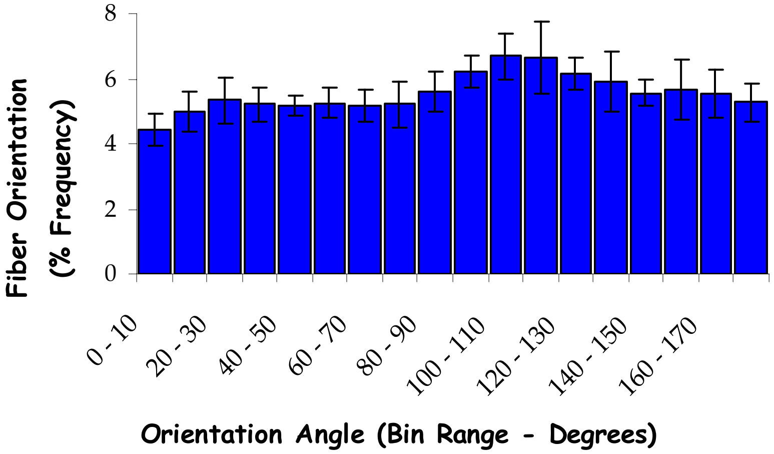

Figure 8.12. Fiber Orientation Distribution Function – Airlaid Sample (S11)

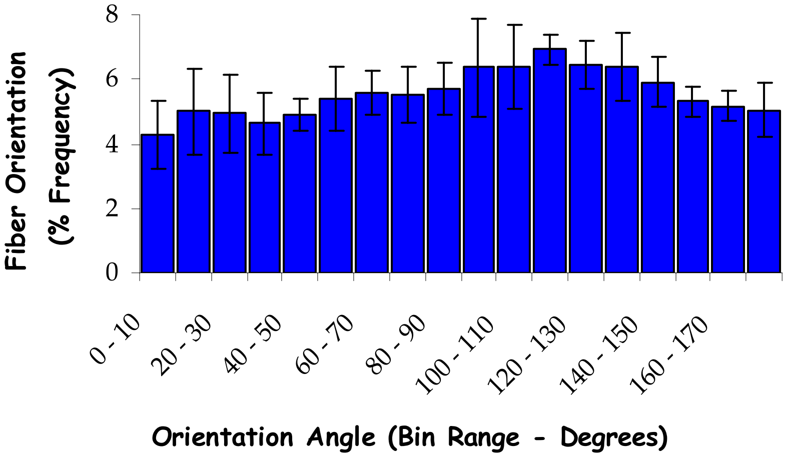

Figure 8.13. Fiber Orientation Distribution Function – Carded Sample (S39)

8.3. STATISTICAL RESULTS: GENERAL

Table showing different variables and their levels used for statistics

VARIABLES	LEVELS				
	1	2	3	4	5
Process	Needlepunching	Thermal Bonding	Needling + Thermal Bonding		
Web	Carded	Airlaid			
Struct	Homogenous	Nonhomogenous			
Lay	W1H & W1NH	W2NH	W3H & W3NH		
Blend	100%	50 / 50 %	70 / 30 %	80 / 20 %	50 / 25 / 25 %
Cross	Round	4DG Fiber	Hollow Fiber		
Surface	High Density Side	Low Density Side	Normal Sample		

8.3.1. The GLM Procedure: Class Level Information

```
Class          Levels Values

Process          3     1 2 3
Web              2     1 2
Struct           2     1 2
Lay              3     1 2 3
Blend            5     1 2 3 4 5
Cross            3     1 2 3
Freq            19     0 100 125 160 200 250 315 400 500 630 800 1000 1250 1600 2000 2500
                       3150 4000 5000
                       Number of observations = 1296
```

CASE 1:

```
Dependent Variable: NAC

                                         Sum of
      Source                  DF        Squares     Mean Square    F Value    Pr > F

      Model                   29    48.75804582      1.68131192     143.31    <.0001

      Error                 1266    14.85235246      0.01173172

      Corrected Total       1295    63.61039828


                          R-Square     Coeff Var      Root MSE      NAC Mean

                          0.766511      61.07788      0.108313      0.177336
```

```
Source                      DF      Type I SS    Mean Square   F Value   Pr > F
Process                      2     0.49050595     0.24525297     20.91   <.0001
Web                          1     0.18511257     0.18511257     15.78   <.0001
Struct                       1     0.04735675     0.04735675      4.04   0.0447
Lay                          2     1.39158618     0.69579309     59.31   <.0001
Blend                        4     1.13570235     0.28392559     24.20   <.0001
Cross                        1     0.00470733     0.00470733      0.40   0.5266
Freq                        18    45.50307470     2.52794859    215.48   <.0001

Source                      DF    Type III SS    Mean Square   F Value   Pr > F
Process                      1     0.00034080     0.00034080      0.03   0.8647
Web                          1     0.13534669     0.13534669     11.54   0.0007
Struct                       1     0.00727669     0.00727669      0.62   0.4311
Lay                          2     1.71712059     0.85856030     73.18   <.0001
Blend                        3     1.23573706     0.41191235     35.11   <.0001
Cross                        1     0.00361287     0.00361287      0.31   0.5790
Freq                        18    45.50307470     2.52794859    215.48   <.0001
```

CASE 1a:

```
Dependent Variable: NAC

                                       Sum of
      Source                      DF      Squares    Mean Square   F Value   Pr > F
      Model                       25  48.71255558     1.94850222    166.10   <.0001
      Error                     1270  14.89784269     0.01173058
      Corrected Total           1295  63.61039828

                    R-Square     Coeff Var      Root MSE      NAC Mean
                    0.765795      61.07494      0.108308      0.177336

      Source                      DF    Type I SS    Mean Square   F Value   Pr > F
      Web                          1   0.54446643     0.54446643     46.41   <.0001
      Lay                          2   1.54788540     0.77394270     65.98   <.0001
      Blend                        4   1.12513294     0.28128324     23.98   <.0001
      Freq                        18  45.49507081     2.52750393    215.46   <.0001

      Source                      DF  Type III SS    Mean Square   F Value   Pr > F
      Web                          1   0.31589807     0.31589807     26.93   <.0001
      Lay                          2   1.78430760     0.89215380     76.05   <.0001
      Blend                        4   1.24969479     0.31242370     26.63   <.0001
      Freq                        18  45.49507081     2.52750393    215.46   <.0001
```

CASE 2:

```
Dependent Variable: NAC

                                              Sum of
      Source                      DF         Squares     Mean Square    F Value    Pr > F

      Model                      159     52.59150086      0.33076416      34.10    <.0001

      Error                     1136     11.01889741      0.00969973

      Corrected Total           1295     63.61039828


                          R-Square     Coeff Var      Root MSE      NAC Mean

                          0.826775      55.53709      0.098487      0.177336


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

      Web                          1      0.54446643      0.54446643      56.13    <.0001
      Lay                          2      1.54788540      0.77394270      79.79    <.0001
      Blend                        4      1.12513294      0.28128324      29.00    <.0001
      Cross                        2      0.03626850      0.01813425       1.87    0.1547
      Freq                        18     45.49667505      2.52759306     260.58    <.0001
      Web*Lay                      1      0.03798374      0.03798374       3.92    0.0481
      Web*Blend                    3      0.18612879      0.06204293       6.40    0.0003
      Web*Freq                    17      0.83760692      0.04927100       5.08    <.0001
      Lay*Blend                    6      0.33343603      0.05557267       5.73    <.0001
      Lay*Freq                    35      1.19114256      0.03403264       3.51    <.0001
      Blend*Freq                  70      1.25477450      0.01792535       1.85    <.0001


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

      Web                          1      0.12280053      0.12280053      12.66    0.0004
      Lay                          2      0.80060075      0.40030038      41.27    <.0001

      Blend                        4      0.12838439      0.03209610       3.31    0.0105
      Cross                        2      0.04584081      0.02292040       2.36    0.0946
      Freq                        18     22.72747414      1.26263745     130.17    <.0001
      Web*Lay                      1      0.03281841      0.03281841       3.38    0.0661
      Web*Blend                    3      0.18530061      0.06176687       6.37    0.0003
      Web*Freq                    17      0.38025037      0.02236767       2.31    0.0019
      Lay*Blend                    6      0.26668533      0.04444756       4.58    0.0001
      Lay*Freq                    35      1.15213767      0.03291822       3.39    <.0001
      Blend*Freq                  70      1.25477450      0.01792535       1.85    <.0001
```

8.3.2. Duncan's Multiple Range Test for NAC

Web Comparison

```
Alpha                           0.05
Error Degrees of Freedom        1286
Error Mean Square           0.046934
Harmonic Mean of Cell Sizes      576

NOTE: Cell sizes are not equal.

                                     Number of Means          2
                                     Critical Range       .02504

                      Means with the same letter are not significantly different.

                      Duncan Grouping          Mean      N    Web

                                   A        0.19183    864    2

                                   B        0.14835    432    1
```

Lay Comparison

```
Alpha                           0.05
Error Degrees of Freedom        1286
Error Mean Square           0.046934
Harmonic Mean of Cell Sizes 351.0172

NOTE: Cell sizes are not equal.

                               Number of Means          2          3
                               Critical Range       .03208      .03378

                      Means with the same letter are not significantly different.

                      Duncan Grouping          Mean      N    Lay

                                   A        0.23069    414    3

                                   B        0.15355    666    1
                                   B
                                   B        0.14842    216    2
```

Cross-section Comparison

```
Alpha                           0.05
Error Degrees of Freedom        1286
Error Mean Square           0.046934
Harmonic Mean of Cell Sizes 26.80851

NOTE: Cell sizes are not equal.
```

```
                    Number of Means          2          3
                    Critical Range       .1161      .1222


         Means with the same letter are not significantly different.


         Duncan Grouping          Mean      N    cross

                       A       0.18216     18    2
                       A
                       A       0.17805   1260    1
                       A
                       A       0.12271     18    3
```

8.3.3. T Tests (LSD) for NAC

Web Comparison

```
Alpha                          0.05
Error Degrees of Freedom       1286
Error Mean Square          0.046934
Critical Value of t         1.96181


                   Comparisons significant at the 0.05 levels are indicated by ***.


                                  Difference
                         Web         Between      95% Confidence
                     Comparison        Means          Limits

                     2    - 1        0.04348     0.01844  0.06852   ***
```

Lay Comparison

```
Alpha                          0.05
Error Degrees of Freedom       1286
Error Mean Square          0.046934
Critical Value of t         1.96181


                   Comparisons significant at the 0.05 levels are indicated by ***.


                                  Difference
                         Lay         Between      95% Confidence
                     Comparison        Means          Limits

                     3    - 1        0.07714     0.05054  0.10374   ***
                     3    - 2        0.08226     0.04659  0.11794   ***
                     1    - 2        0.00512    -0.02815  0.03840
```

Cross-section Comparison

```
  Alpha                          0.05
  Error Degrees of Freedom       1286
  Error Mean Square          0.046934
  Critical Value of t         1.96181
```

```
                       Comparisons significant at the 0.05 levels are indicated by ***.


                                         Difference
                            Cross          Between       95% Confidence
                          Comparison         Means           Limits

                             2    - 1        0.004114    -0.096775  0.105003
                             2    - 3        0.059450    -0.082220  0.201119
                             1    - 3        0.055336    -0.045553  0.156224
```

8.4. STATISTICAL RESULTS: Carded Samples

8.4.1. The GLM Procedure: Class Level Information

CASE 3:

```
Class         Levels    Values
Process          3       1 2 3
Blend            5       1 2 3 4 5
Cross            3       1 2 3
Lay              2       1 3
Freq            19       0 100 125 160 200 250 315 400 500 630 800 1000 1250 1600 2000
                        2500 3150 4000 5000
                              (Number of observations = 432)
Dependent Variable: NAC
                                              Sum of
      Source                      DF         Squares     Mean Square    F Value    Pr > F
      Model                       26     13.97597671      0.53753757     152.38    <.0001
      Error                      405      1.42872644      0.00352772
      Corrected Total            431     15.40470315

                          R-Square     Coeff Var      Root MSE      NAC Mean
                          0.907254      40.03700      0.059395      0.148349

      Source                      DF       Type I SS     Mean Square    F Value    Pr > F
      Process                      2      0.13115209      0.06557604      18.59    <.0001
      Blend                        4      0.00400558      0.00100139       0.28    0.8884
      cross                        1      0.01390000      0.01390000       3.94    0.0478
      Lay                          1      0.09319216      0.09319216      26.42    <.0001
      Freq                        18     13.73372689      0.76298483     216.28    <.0001

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

      Process                      1      0.00034080      0.00034080       0.10    0.7561
      Blend                        3      0.02066361      0.00688787       1.95    0.1206
      cross                        1      0.02754344      0.02754344       7.81    0.0054
      Lay                          1      0.09485814      0.09485814      26.89    <.0001
      Freq                        18     13.73372689      0.76298483     216.28    <.0001
```

CASE 4:

```
Dependent Variable: NAC
                                              Sum of
      Source                      DF         Squares     Mean Square    F Value    Pr > F
```

```
     Model                      21     13.92130415      0.66291925     183.23    <.0001

     Error                     410      1.48339900      0.00361805

     Corrected Total           431     15.40470315

                        R-Square     Coeff Var      Root MSE      NAC Mean

                        0.903705      40.54633      0.060150      0.148349

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

     Cross                       2      0.03246425      0.01623212       4.49    0.0118

     Lay                         1      0.15675388      0.15675388      43.33    <.0001

     Freq                       18     13.73208602      0.76289367     210.86    <.0001

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

     Cross                       2      0.03911743      0.01955871       5.41    0.0048

     Lay                         1      0.15824611      0.15824611      43.74    <.0001

     Freq                       18     13.73208602      0.76289367     210.86    <.0001
```

CASE 5:

```
Dependent Variable: NAC

                                            Sum of
    Source                      DF         Squares     Mean Square    F Value    Pr > F

    Model                        4     12.97036295      3.24259074     568.77    <.0001

    Error                      427      2.43434020      0.00570103

    Corrected Total            431     15.40470315

                        R-Square     Coeff Var      Root MSE      NAC Mean

                        0.841974      50.89688      0.075505      0.148349

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

     Airflow                     1      0.25367999      0.25367999      44.50    <.0001

     Thickness                   1      0.23506410      0.23506410      41.23    <.0001

     Mass                        1      0.02308739      0.02308739       4.05    0.0448

     Freq                        1     12.45853147     12.45853147    2185.31    <.0001

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

     Airflow                     1      0.02100475      0.02100475       3.68    0.0556

     Thickness                   1      0.04854495      0.04854495       8.52    0.0037

     Mass                        1      0.02269379      0.02269379       3.98    0.0467

     Freq                        1     12.45853147     12.45853147    2185.31    <.0001

                                                    Standard
                 Parameter         Estimate            Error    t Value    Pr > |t|

                 Intercept      -.1122056078      0.01282386      -8.75      <.0001
                 Airflow        0.0001098092      0.00005721       1.92      0.0556
                 Thickness      0.0071367958      0.00244573       2.92      0.0037
                 Mass           0.0222323590      0.01114317       2.00      0.0467
                 Freq           0.0001196831      0.00000256      46.75      <.0001
```

8.4.2. Duncan's Multiple Range Test for NAC

Process Comparison

```
Alpha                            0.05
Error Degrees of Freedom          405
Error Mean Square            0.003528
Harmonic Mean of Cell Sizes 45.31469

NOTE: Cell sizes are not equal.

                               Number of Means          2          3
                               Critical Range       .02453     .02582

                     Means with the same letter are not significantly different.

                    Duncan Grouping          Mean      N    Process

                                  A       0.16183    270    1

                                  B       0.12634    144    2
                                  B
                                  B       0.12220     18    3
```

Cross-section Comparison

```
Alpha                            0.05
Error Degrees of Freedom          405
Error Mean Square            0.003528
Harmonic Mean of Cell Sizes     26.4

NOTE: Cell sizes are not equal.

                               Number of Means          2          3
                               Critical Range       .03214     .03383

                     Means with the same letter are not significantly different.

                     Duncan Grouping          Mean      N    cross

                                   A       0.18216     18    2

                                   B       0.14798    396    1
                                   B
                                   B       0.12271     18    3
```

8.4.3. T Tests (LSD) for NAC

Process Comparison

```
Alpha                          0.05
Error Degrees of Freedom        405
Error Mean Square          0.003528
Critical Value of t         1.96584

                   Comparisons significant at the 0.05 level are indicated by ***.

                                  Difference
                        Process      Between       95% Confidence
                     Comparison        Means            Limits

                     1    - 2       0.035494     0.023445  0.047542  ***
                     1    - 3       0.039628     0.011204  0.068051  ***
                     2    - 3       0.004134    -0.025056  0.033324
```

Cross-section Comparison

```
Alpha                          0.05
Error Degrees of Freedom        405
Error Mean Square          0.003528
Critical Value of t         1.96584

                   Comparisons significant at the 0.05 level are indicated by ***.

                                  Difference
                          Cross      Between       95% Confidence
                     Comparison        Means            Limits

                     2    - 1       0.034184     0.006044  0.062323  ***
                     2    - 3       0.059450     0.020529  0.098370  ***
                     1    - 2      -0.034184    -0.062323 -0.006044  ***
                     1    - 3       0.025266    -0.002873  0.053405
                     3    - 2      -0.059450    -0.098370 -0.020529  ***
                     3    - 1      -0.025266    -0.053405  0.002873
```

8.5. STATISTICAL RESULTS: Airlaid Samples

8.5.1. The GLM Procedure: Class Level Information

CASE 6:

```
Dependent Variable: NAC

                                              Sum of
      Source                      DF         Squares     Mean Square    F Value    Pr > F

      Model                        5     37.89495441      7.57899088     665.84    <.0001

      Error                      858      9.76627429      0.01138260

      Corrected Total            863     47.66122870

                          R-Square     Coeff Var      Root MSE      NAC Mean

                          0.795090      55.61679      0.106689      0.191829

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

      surface                      1      0.01874053      0.01874053       1.65    0.1998

      Airflow                      1      4.66513747      4.66513747     409.85    <.0001

      Thickness                    1      0.38731738      0.38731738      34.03    <.0001

      Mass                         1      0.00943336      0.00943336       0.83    0.3629

      Freq                         1     32.81432567     32.81432567    2882.85    <.0001


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

      surface                      1      0.05713871      0.05713871       5.02    0.0253

      Airflow                      1      0.40486572      0.40486572      35.57    <.0001

      Thickness                    1      0.35451910      0.35451910      31.15    <.0001

      Mass                         1      0.06207631      0.06207631       5.45    0.0198

      Freq                         1     32.81432567     32.81432567    2882.85    <.0001
```

CASE 7: For High Density Webs

```
Dependent Variable: NAC

                                              Sum of
      Source                      DF         Squares     Mean Square    F Value    Pr > F

      Model                        4     13.37563272      3.34390818     227.59    <.0001

      Error                      319      4.68698012      0.01469273

      Corrected Total            323     18.06261283
```

```
                    R-Square     Coeff Var      Root MSE      NAC Mean

                    0.740515      63.56806      0.121214      0.190683

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

      Airflow                      1      1.85602015      1.85602015     126.32    <.0001

      Thickness                    1      0.17582838      0.17582838      11.97    0.0006

      Mass                         1      0.02597658      0.02597658       1.77    0.1846

      Freq                         1     11.31780761     11.31780761     770.30    <.0001

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

      Airflow                      1      0.17524210      0.17524210      11.93    0.0006

      Thickness                    1      0.45523689      0.45523689      30.98    <.0001

      Mass                         1      0.20720076      0.20720076      14.10    0.0002

      Freq                         1     11.31780761     11.31780761     770.30    <.0001

                                                      Standard
                Parameter         Estimate               Error    t Value    Pr > |t|

                Intercept     -.1643151454          0.02332352      -7.05      <.0001
                Airflow       0.0002004125          0.00005803       3.45      0.0006
                Thickness     0.0418483812          0.00751815       5.57      <.0001
                Mass          -.0894802977          0.02382775      -3.76      0.0002
                Freq          0.0001346657          0.00000485      27.75      <.0001
```

CASE 8: For Low Density Webs

```
Dependent Variable: NAC

                                                Sum of
      Source                      DF           Squares     Mean Square    F Value    Pr > F

      Model                        3     13.78808546      4.59602849     544.34    <.0001

      Error                      320      2.70183551      0.00844324

      Corrected Total            323     16.48992097

                    R-Square     Coeff Var      Root MSE      NAC Mean

                    0.836152      49.82309      0.091887      0.184427

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

      Airflow                      1      1.65916009      1.65916009     196.51    <.0001

      Thickness                    1      0.21243344      0.21243344      25.16    <.0001

      Freq                         1     11.91649193     11.91649193    1411.37    <.0001

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

      Airflow                      1      0.18106158      0.18106158      21.44    <.0001

      Thickness                    1      0.21243344      0.21243344      25.16    <.0001

      Freq                         1     11.91649193     11.91649193    1411.37    <.0001
```

```
                                           Standard
Parameter         Estimate                    Error    t Value    Pr > |t|

Intercept     -.1519983281           0.01715985      -8.86      <.0001
Airflow       0.0001876203           0.00004052       4.63      <.0001
Thickness     0.0150980305           0.00300998       5.02      <.000
Freq          0.0001355178           0.00000361      37.57      <.0001
```

CASE 9: Normal Webs

```
Dependent Variable: NAC

                                         Sum of
      Source                      DF          Squares     Mean Square    F Value    Pr > F

      Model                        2      11.16130660      5.58065330     627.71    <.0001

      Error                      213       1.89369042      0.00889057

      Corrected Total            215      13.05499702


                    R-Square     Coeff Var      Root MSE      NAC Mean

                    0.854945      46.07314      0.094290      0.204652


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

      Airflow                      1       1.14506683      1.14506683     128.80    <.0001

      Freq                         1      10.01623976     10.01623976    1126.61    <.0001


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

      Airflow                      1       1.14506683      1.14506683     128.80    <.0001

      Freq                         1      10.01623976     10.01623976    1126.61    <.0001


                                                   Standard
            Parameter         Estimate                Error    t Value    Pr > |t|

            Intercept     -.0836005209           0.01159479      -7.21      <.0001
            Airflow       0.0003132535           0.00002760      11.35      <.0001
            Freq          0.0001521669           0.00000453      33.57      <.0001
```

CASE 10:

```
Dependent Variable: NAC

                                         Sum of
      Source                      DF          Squares     Mean Square    F Value    Pr > F

      Model                        4      37.83781570      9.45945392     827.17    <.0001

      Error                      859       9.82341300      0.01143587

      Corrected Total            863      47.66122870


                    R-Square     Coeff Var      Root MSE      NAC Mean
```

```
                  0.793891      55.74677      0.106939      0.191829

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

     Airflow                      1       4.68373488      4.68373488     409.57    <.0001

     Thickness                    1       0.38130553      0.38130553      33.34    <.0001

     Mass                         1       0.00828501      0.00828501       0.72    0.3949

     Freq                         1      32.76449027     32.76449027    2865.06    <.0001

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

     Airflow                      1       0.44354871      0.44354871      38.79    <.0001

     Thickness                    1       0.32181548      0.32181548      28.14    <.0001

     Mass                         1       0.05376387      0.05376387       4.70    0.0304

     Freq                         1      32.76449027     32.76449027    2865.06    <.0001

                                                     Standard
                 Parameter         Estimate             Error    t Value    Pr > |t|

                 Intercept     -.1476964781        0.01303432     -11.33      <.0001
                 Airflow       0.0002017685        0.00003240       6.23      <.0001
                 Thickness     0.0214346973        0.00404062       5.30      <.0001
                 Mass          -.0276864062        0.01276897      -2.17      0.0304
                 Freq          0.0001381490        0.00000258      53.53      <.0001
```

8.5.2. Duncan's Multiple Range Test for NAC

Lay Comparison

```
Alpha                                0.05
Error Degrees of Freedom              839
Error Mean Square                0.014705
Harmonic Mean of Cell Sizes      277.7143
                                 NOTE: Cell sizes are not equal.

                             Number of Means           2           3
                             Critical Range       .02020      .02127

                    Means with the same letter are not significantly different.

                    Duncan Grouping          Mean       N    Lay

                                 A        0.24347         324     3

                                 B        0.16912         324     1

                                 C        0.14842         216     2
```

Surface Comparison

```
Alpha                            0.05
Error Degrees of Freedom         839
```

```
Error Mean Square                 0.014705
Harmonic Mean of Cell Sizes     277.7143
                                   NOTE: Cell sizes are not equal.

                               Number of Means           2           3
                               Critical Range       .02020      .02127

                     Means with the same letter are not significantly different.

                    Duncan Grouping          Mean      N    surface

                                  A          0.20465     216     3
                                  A
                                  A          0.19068     324     1
                                  A
                                  A          0.18443     324     2
```

8.5.3. t-Test (LSD) for NAC

Lay Comparison

```
Alpha                         0.05
Error Degrees of Freedom      839
Error Mean Square             0.014705
Critical Value of t           1.96280

                   Comparisons significant at the 0.05 level are indicated by ***.

                                            Difference
                            Lay             Between      95% Confidence
                        Comparison          Means          Limits

                        3    - 1             0.074349     0.055649  0.093050  ***
                        3    - 2             0.095048     0.074140  0.115956  ***
                        1    - 3            -0.074349    -0.093050 -0.055649  ***
                        1    - 2             0.020699    -0.000209  0.041607
                        2    - 3            -0.095048    -0.115956 -0.074140  ***
                        2    - 1            -0.020699    -0.041607  0.000209
```

Surface Comparison

```
Alpha                         0.05
Error Degrees of Freedom      839
Error Mean Square             0.014705
Critical Value of t           1.96280

                   Comparisons significant at the 0.05 level are indicated by ***.

                                          Difference
                          Surface            Between       95% Confidence
                        Comparison             Means           Limits

                        3    - 1            0.013969    -0.006938  0.034877
                        3    - 2            0.020226    -0.000682  0.041134
                        1    - 2            0.006256    -0.012444  0.024957
```

8.6. Surface Impedance Results

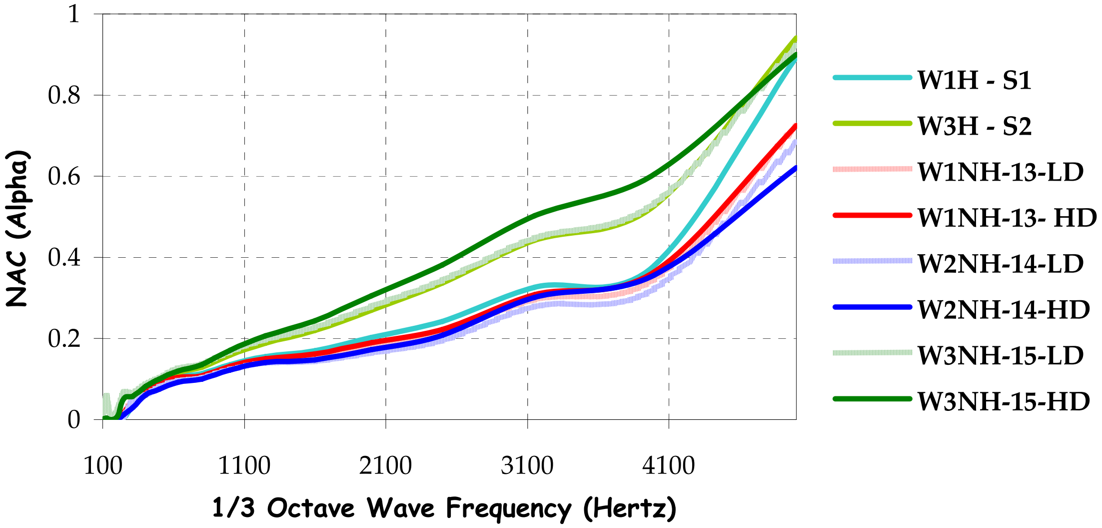

Figure 8.14. Influence of Surface Impedance – Sample Group A

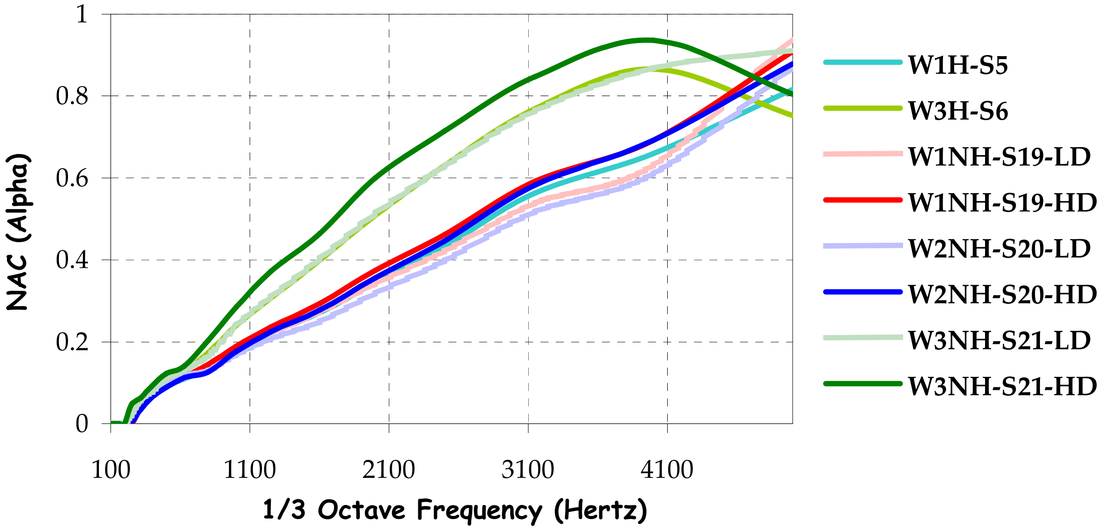

Figure 8.15. Influence of Surface Impedance – Sample Group C

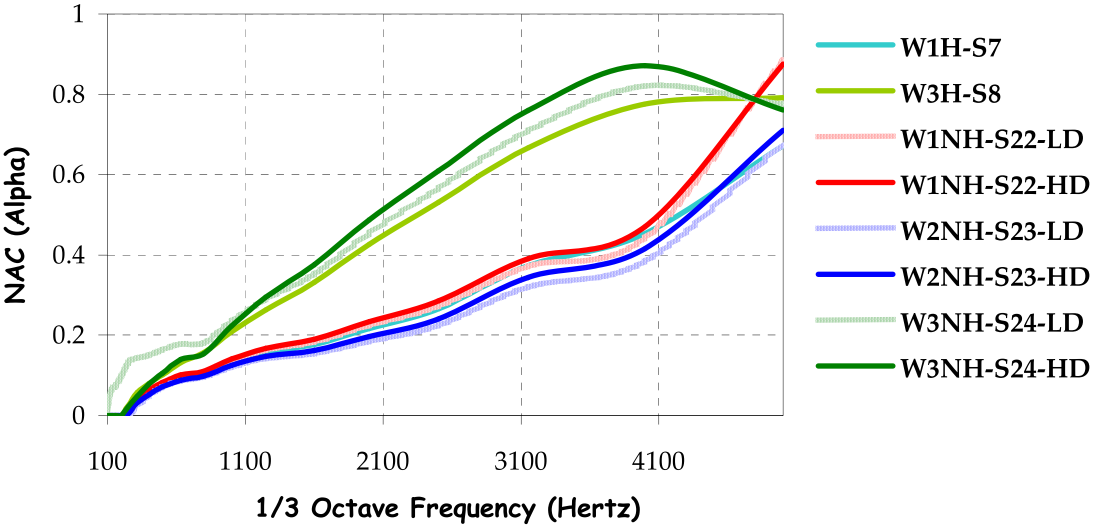

Figure 8.16. Influence of Surface Impedance – Sample Group D

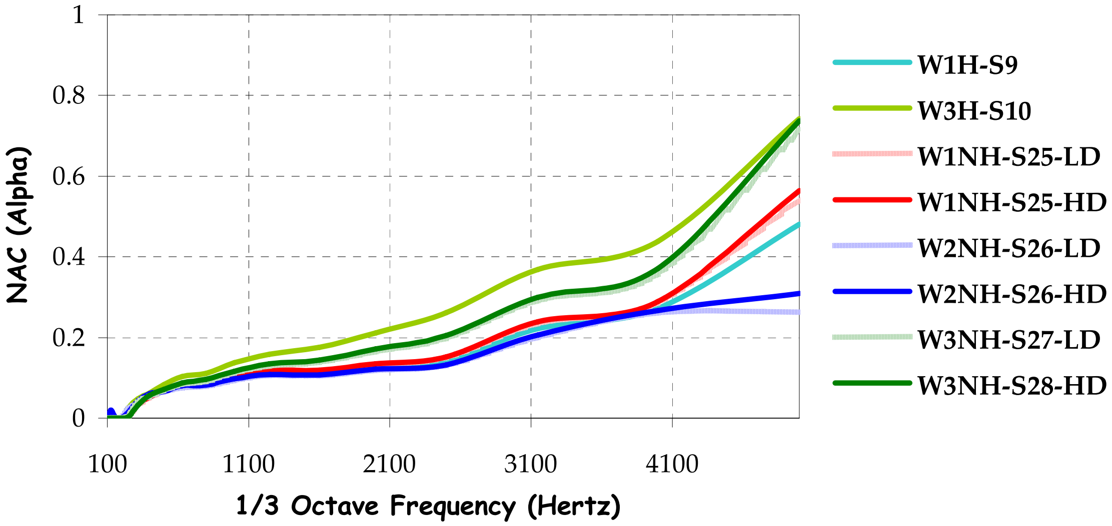

Figure 8.17. Influence of Surface Impedance – Sample Group E

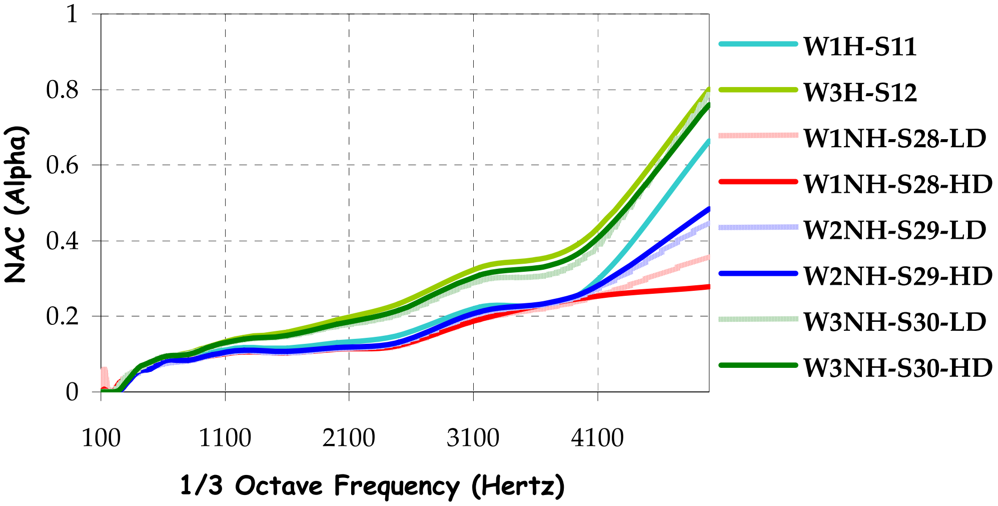

Figure 8.18. Influence of Surface Impedance – Sample Group F