ACOUSTIC AND DURABILITY PERFORMANCES OF *ARENGA PINNATA* PANEL

LINDAWATI ISMAIL

A thesis submitted in
fulfillment of the requirements for the award of the
Degree of Master of Mechanical Engineering

Faculty of Mechanical and Manufacturing Engineering
Universiti of Tun Hussein Onn Malaysia

FEBRUARY 2012

ABSTRACT

This study aims to investigate the feasibility of *Arenga Pinnata* fiber to be applied for acoustical material component. There different binders namely polyurethane, urea formaldehyde and latex were employed as binder. The weight percentages of binder used were 10%, 15%, 20%, 25%, and 30%. Hand layup process was used in specimens production. The physical, acoustical and durability properties of the panels were investigated experimentally. The result shows that panel with high percentages of binder tends to have high density and tortuosity, but less porosity. The optimum porosity of 0.94 was obtained from panel that added with 10% Latex. In general, *Arenga Pinnata* panels show good sound absorption from mid to high frequency that is from 2000 Hz to 5000 Hz. The best sound absorption is performed by panel added with 10 % Latex with a maximum absorption coefficient (α) of 0.96 at 3000 Hz. The average Noise Reduction Coefficient (NRC) for all panels is 0.40. The value indicates that *Arenga Pinnata* panels are highly absorptive material. However, *Arenga Pinnata* panel is poor insulator since the optimum sound transmission loss (STL) is only 9.37 dB from panel added with 15% polyurethane at 5000 Hz. Thus, *Arenga Pinnata* panel is applicable to reduce echo caused by reflection effects within a room. Sound absorption increases as porosity increase and decrease as density-tortuosity increase. Hence, *Arenga pinnata* fiber is applicable for acoustical component panel. Moreover, *Arenga Pinnata* panels are durable that resist in water, heat, and fire. It is applicable for heat insulation.

ABSTRAK

Kajian ini bertujuan untuk mengkaji kebolehgunaan serat *Arenga Pinnata* sebagai komponen bahan akustik. Tiga pengikat yang berbeza telah digunakan sebagai pengikat serat iaitu polyurethane, urea formaldehid dan latex. Peratus berat pengikat yang digunakan dalam kajian ini adalah 10%, 15%, 20%, 25%, dan 30%. Spesimen kajian dihasilkan dengan menggunakan proses gelekan tangan. Sifat-sifat fizikal, akustikal dan ketahanan panel spesimen telah dikaji secara ujikaji. Hasil kajian menunjukkan bahawa panel yang mempunyai peratus berat pengikat paling tinggi mempunyai ketumpatan dan ketidaklurusan liang yang tinggi tetapi keliangannya kurang . Keliangan yang optimum, 0.94 diperolehi dari panel yang dicampur dengan 10% Latex. Pada umumnya, *Arenga Pinnata* mempunyai ciri-ciri penyerapan bunyi yang baik dari frekuensi pertengahan ke frequency tinggi, ia itu dari 2000 Hz hingga 5000 Hz. Penyerapan bunyi yang paling baik diperolehi dari panel yang dicampur dengan 10% Latex, di mana pekali penyerapan maksimum (α) adalah 0.96 pada 3000 Hz. Nilai purata pekali pengurangan bunyi (NRC) semua panel spesimen ialah 0.40. Nilai ini menunjukkan bahawa panel-panel *Arenga Pinnata* adalah merupakan bahan penyerap bunyi yang baik. Bagaimana pun, panel *Arenga Pinnata* didapati merupakan penebat yang tidak baik kerana kehilangan hantaran bunyi yang optimum (STL) hanyalah 9.37 dB diperolehi dari panel yang dicampur dengan 15% polyurethane pada 5000 Hz. Oleh kerana itu, panel *Arenga Pinnata* sesuai digunakan untuk mengurangi gema di dalam bilik. Penyerapan bunyi di dapati meningkat dengan meningkatnya keliangan dan berkurang dengan meningkatnya ketumpatan - ketidaklurusan liang. Oleh itu, Serat *Arenga Pinnata* didapati boleh digunakan sebagai panel komponen akustik. Selain dari itu, panel *Arenga Pinnata* juga adalah tahan lasak yang boleh merintangi air, haba dan api. Ianya sesuai digunakan sebagai penebat haba.

CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS AND ABBREVIATIONS

α	-	Sound Absorption Coefficient
α_{∞}	-	Tortuosity
ß	-	Beta Ray
γ	-	Gamma Ray
λ	-	Wavelength
µ	-	Miu
ρ	-	Density
□	-	Porosity
τ	-	Sound Transmission Coefficient
A	-	Cross-sectional Area
c	-	Speed of sound
C	-	Celcius
Co	-	Cobalt
d	-	Diameter
dB	-	Decibel
f	-	Frequency
g	-	Gram
GPa	-	Giga Pascal
Hz	-	Hertz
I_i	-	Sound Incident Wave
I_α	-	Sound Absorbed Wave
Inc.	-	Inch
k	-	Thermal Conductivity
K	-	Kelvin
l	-	Length
L	-	Sound Level
m	-	Meter

mm	-	Millimeter
MPa	-	Mega Pascal
q	-	Heat Conduction
s	-	Second
T_{60}	-	Reverberation Time
V_a	-	Air Voids
V_m	-	Total Volume of The Sample
Sr	-	Strontium
W	-	Watt
ASTM	-	American Society of Testing and Material
ISO	-	International Standard Organization
ITM	-	Impedance Tube Method
NRC	-	Noise Reduction Coefficient
PU	-	Polyurethane
STC	-	Sound Transmission Class
STL	-	Sound Transmission Loss
TF	-	Transfer Function
UL	-	Underwrite Laboratory
UF	-	Urea Formaldehyde
VBT	-	Vertical Burning Test

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Research Background

The increase in population has consequently contributed in increasing the noise problem of the world, recently. Noise as undesirable sound is involved in one of the most dangerous pollution. Expansion of modern industrial operation and transportation such as aircraft, train, cars or buses are the main causes of noise problem in urban areas. In addition, human daily activities have great contribution in generating noise levels that can annoy to other people.

The effect of noise on people have been widely published, whether physiological or psychological effects (Atmaca *et al.*, 2005). The psychological effect is related to emotional annoyance, e.g. eager, insomnia, fear, and stress (Saeki *et al.*, 2004). The physiological effect is related to human body, e.g. hypertension, cardiac disease, colitis, headache, dizziness, and the worst are hearing loss (Blomkvist *et al.*, 2005). Both psychological and physiological effects have been hypothesized caused by high noise level exposure in a long period. Owing to the risk affected on people, noise control is highly required to create acoustically pleasing environment. Noise cannot be destroyed but it can be broken down into acceptable level for human ear.

In any circumstances, noise may be controlled at any of these elements: source, path, and receiver, as listed in Table 1.1. It is essential to treat at least one of these elements. The source is the element that directly responsible for sound generation. The path covers sound propagation media such as air, water or solid material, in where sound wave reacts with as they travel from the source to the receiver (Hansen and Goelzer, 2006). Here, the receiver is where all the sound generated was received.

Table 1.1: Noise Control Approaches at Source-Path-Receiver (Rossing, 2007)

Control at the source	**Control in the path**	**Control at the receiver**
Maintenance	Enclosure	Relocate listener
Avoid Resonance	Barriers	Enclosure listener
Relocate source/space planning	Mufflers	Hearing Protection
Remove noise source	Absorptive treatment	Masking
Use quitter model	Vibration isolation	
Redesign source to be quitter	Active noise control	

The source-path-receiver model of noise control was first recommended by Bolt and Ingard in 1965 (Rossing, 2007). This model has been approved as a very useful way to represent noise problems. The most effective one to control the noise is by treating the noise source directly. It consequently helps to reduce noise level at the receiver. However it is not always feasible to be implemented, in practical. Maintenance factors such as redesign, redevelop, retool and also costs should be taken into consideration. Control noise at the receiver is the least concern since each receiver must be treated individually (Kutthruf, 1991). Noise control option is limited by controlling the transmission path by using acoustic materials, in this case sound absorbing material (Kidner and Hansen, 2008).

Sound absorbing material is effective in reducing noise level within the space by converting sound wave into heat. Various sound absorbing materials with variety of colours, shapes, and sizes are already in the market places. They are not only providing the desired acoustical properties but also thermal conductivity and flammability. Most of available sound absorbing materials are fibrous materials. Conventionally, synthetic fibers such as fiberglass, glass wool or rock wool are chosen as raw material. These materials offer good acoustical performance nevertheless they are quite expensive and are not sustainable (Nick *et al.*, 2002). The environmental concerns over the use of synthetic fiber for acoustical material have enhanced the demand for an alternative material. For that reason, some researchers showed their great interest in developing alternative sound absorber from recycled materials, such as textile, plastics, foam, or rubber (Paulain *et al.*, 2006; Stankevicious *et al.*, 2007 and Zhou *et al.*, 2007). Even products made from recycled material are welcomed, it is not correlated with ecological issue that required low cost and environmentally friendly material. End of life disposal strategies and environmental friendly technologies for their recycling become a great concern of material development. Indeed, as acoustical panel applied for interior finishes, the performance involving durability as exposed to typical environmental condition, water and extreme temperature, are important of considerations.

1.2 Problem Statement

Regarding to environmental concerns, material developer has looking for natural fiber. The low cost, abundance, weightless, and biodegradable makes natural fibers an attractive material considered for sound absorbers (Zulkifli *et al.,* 2010). Several researches and investigations on natural fibers for sound absorbing material development have been reported. It includes the utilization of bamboo (Kai, 2005), kenaf (Tormos, *et al*., 2007), paddy straw (Mediastika, 2007; 2008), jute (Haryanto, 2008), aspen-wheat- barley straw (Saadatnia, *et al*., 2008), coconut coir (Zulkifli *et al.,* 2008-2011), palm oil (Zulkifli *et al.*, 2008), tea-leaf waste(Ersoy and Kucuk, 2009), sugar-cane (Ismail *et al.*, 2010), rami (Chen *et al.*, 2010), and jute felt (Fatima and Mohanty, 2011). The main significant findings with these natural fibers are due to its superior to synthetic fiber with better electrical resistance, mechanical, thermal and acoustical properties. Therefore, natural fibers can be considered as a good potential replacement to substitute commercially synthetic-product based on advanced material manufactures (Joshi *et al.*, 2004). On the other hand, natural fiber panel has poor durability properties when expose to such environmental condition. Therefore, a material with high strength and durability is obviously needed.

Arenga Pinnata fiber, known as ijuk, is a tough-black-fiber that directly obtained from the trunk of sugar palm. Since last decade, ijuk has been extensively used for a number of products such as broom, brushes, mat, water filter, decoration, rope, roof, and many others (Mogea *et al.*, 1991). The attractive features of *Arenga*

Pinnata fibers are low cost, strong and durable in any typical environment condition such as wet, humid, and extreme temperature (Florido and de Mesa, 2003). Regarding to features offered, *Arenga Pinnata* fibers are appropriate for an alternative engineering material.

Previous investigation by Sastra *et al.,* (2005) confirmed that *Arenga Pinnata* fibers are applicable for composite material component. Composite made from woven roving *Arenga Pinnata* fiber demonstrated high flexural strength. Furthermore, a single *Arenga Pinnata* fiber has moderate tensile strength that almost similar to coir, kenaf, bamboo and hemp fibres (in the range of 138.7 – 270 MPa). *Arenga Pinnata* fibre has high strain strength and flexible compared to others (Bachtiar *et al*., 2010). Owing to its mechanical and physical properties, *Arenga Pinnata* fibers are flexible to be used in broadly engineering applications. Very recently, Sarwidi (2011) stated that *Arenga Pinnata* fibers can be used as vibration insulator for vertically earthquake. It is also used for sound proofing in theater and recording studio. Unfortunately, there is lack of information on acoustical properties of *Arenga Pinnata* fibers. Therefore, more research and finding on acoustical properties of *Arenga Pinnata* fiber must be identified.

1.3 Research Questions

Based on explanation above, some important questions are given:

1. Is *Arenga Pinnata* fibers feasible to be applied for acoustical panel component?
2. If so, what is their acoustical property of *Arenga Pinnata* panel?
3. What is their physical property and how is its influence on acoustical properties of *Arenga Pinnata* panel?
4. How durable is *Arenga Pinnata* panel as exposed to typical environmental conditions including water and extreme temperature?

1.4 Research Objectives

The aim of this research is to investigate the feasibility of *Arenga Pinnata* fiber to be employed as acoustical panels component. To achieve this aim, several objectives have been described as follows:

1. To determine the acoustical properties of *Arenga Pinnata* fibers panel.
2. To obtain the physical properties of *Arenga Pinnata* fibers panel and investigate its effect on its acoustical properties of *Arenga Pinnata* fibers panel.
3. To identify the durability of *Arenga Pinnata* fibers panel as exposed to typical environmental conditions including water and extreme temperature.

1.5 Scope of Research

The scope of the study is limited to:

1. The samples are made from *Arenga Pinnata* natural fiber reinforced binders; Polyurethane (PU), Urea Formaldehyde (UF), and Latex.
2. The weight percentages of fiber and binder are 90%:10%, 85%:15%, 80%:20%, 75%:25%, and 70%:30%.
3. The physical properties determined are density, porosity, and tortuosity.
4. The acoustical properties determined are sound absorption coefficient (α), noise reduction index (NRC), sound transmission loss (STL), and sound transmission class (STC).
5. The durability properties determined are hardness, moisture resistant, water resistant, heat and fire resistant.

1.6 Thesis Outline

This section gives a brief summary of the thesis layout. The thesis is organized in five chapters with the following scopes. Chapter one introduces the research topics, which includes background, objective and scope of research.

Chapter two gives a comprehensive literature review about the acoustical properties of material. Definition, theory, and related work outcomes related to the research are elaborated in chapter two. Two common methods, reverberation room and impedance tube method, often used to measure the acoustical properties is also explicated.

Chapter three presents research methodology including material preparation, sample production, and experimental work. Measurement techniques to evaluate acoustical properties of specimens presented in this chapter.

The results of experimental work including physical, acoustical, and durability properties of panel reinforced with *Arenga Pinnata* fiber are presented in chapter four. The influence of density, porosity, and turtuosity on acoustical properties of samples is discussed in this chapter. The performance of panel including durability and resistance is also explained in detailed.

Chapter five pointed out the conclusion of research. Some further works or recommendations are also presented in this chapter.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction to Acoustics

Acoustics is defined as the scientific study of sound, which revolves around the generation, transmission and effect. Sound is generated by a vibrating surface causing pressure variations in an elastic medium that is called a wave (Hansen, 2004). The more elastic a substance, the better it is able to conduct sound waves. The best example is steel, which is highly elastic and an excellent sound conductor.

Sound propagates in the air, water or building material with a certain velocity, normally 344 m/s in the air. Two principal parameters must be aware of when dealing with any acoustics concerns that are frequency and wavelength. Frequency, f, is measured as the number of waves that occur per second and measured in terms of hertz (Hz). Wavelength, λ, is the distance of wave propagation along the medium in one complete wave cycle. These two measures express the nature of pressure variation in a medium that are experienced as sound in the brain. The human ear can detect sounds ranged from approximately 20 to 20,000 Hz but most sensitive in frequency range 500 Hz to 4000 Hz. This upper limit tends to decrease with age. Sound of frequencies below 500 Hz and above 4000 Hz cannot be perceived as sound in the ear but can be felt as vibration in human bodies.

Frequency has inverse relationship to wavelength. They are related to each other through the velocity of sound, v, which points out the direction and time of sound travel to reach listeners. Wavelength is increased as frequency decreased, and conversely as shown in equation 2.1.

$$\lambda = \frac{v}{f} \tag{2.1}$$

where, f = frequency (Hz),
λ = wavelength (m),
v = velocity of sound (m/s).

Besides, sound wave has amplitude properties, which is determine how far wave travel above and below the static pressure of the elastic medium they are traveling through are measured in decibels (dB). The higher the decibel level, the higher the volume produces the loudness of a sound. A jet airplane, for example, has amplitude of 140dB, while a human whisper is approximately 20dB. For typical office environment, the amplitude of sound usually falls in the range of 40 and 60dB. When sound level exceed than 65 dB, the human ears take it as a noise (Crocker, 1998).

Noise as unwanted sound, is one of the most nuisances that decrease the quality of human life. Noise control plays an important role in creating acoustically comfort environment. In order to effort pleasing environment, noise should be broken down into acceptable level to human ears. The simplest way in reducing noise is by treating the noise propagation, by means of putting the acoustical material between source and receiver (Arenas and Crocker, 2010).

Four basic principles can be employed to reduce noise in the propagation path those are noise isolation, noise absorption, vibration isolation and vibration damping. It depends on where the noise generated. If the noise is airborne generated from noisy environment, insulation treatment by means of using barrier is required. If the noise is structure airborne generated from structure vibration, vibration isolation or vibration damping is needed. If the noise is generated within the space, usually reverberations and echoes, absorptive treatment is required. Reverberation is the undesirable effects of sound reflection by hard, rigid and interior surfaces within the room. Echo is repetition of the original sound caused by distinct reflections of long delay. Sound absorption treatment is an effective noise control solution for echo and reverberation in small room, where the intelligibility is important (Long, 2006).

2.2 Sound Absorption

Sound absorption is defined as incident sound that is not reflected back. It occurs when the wavelength of sound waves that strikes on a surface is smaller than dimensions of the materials surface. Sound energy is dissipated into small number of heat as waves bounce around within the material (Cox, and Antonio, 2004).

In large auditorium, the echo in audience areas near to the stage can be optimally reduced by adding sound absorption material at rear wall. Figure 2.1 illustrates room condition with and without sound absorbing treatment. Here, computer acts as sound source while computer operator and worker act as receiver. In the room with no acoustical treatment, the computer operators hear sound from the computer directly (direct sound). On the other hand, office workers hear reflected sound from ceiling, floor, and walls.

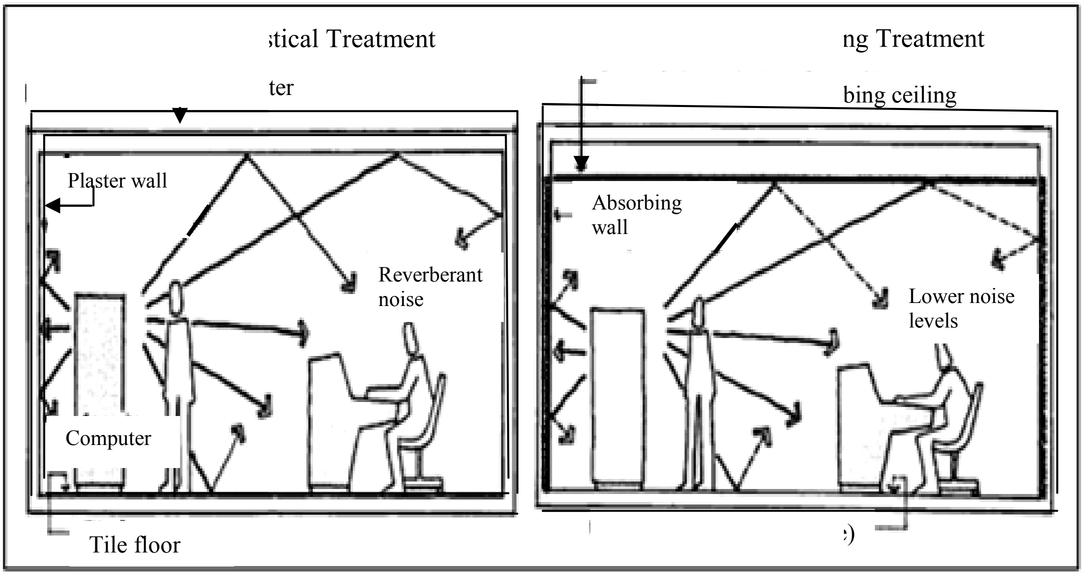

Figure 2.1: Room With and Without Sound Absorptive Treatment (Egan, 1988)

When absorptive treatment are added to the room; the office workers hear less reflected sound because the level of reflected sound is reduced in their part of room. Sound absorption reduce the sound energy in the reverberant field.

In many public places like traffic terminals and department stores, the sound absorption treatment is not only done with the purpose of reducing noise but also to ensure proper intelligibility of speech. Figure 2.2 give another example of effect of sound absorbing material addition within noise spaces.

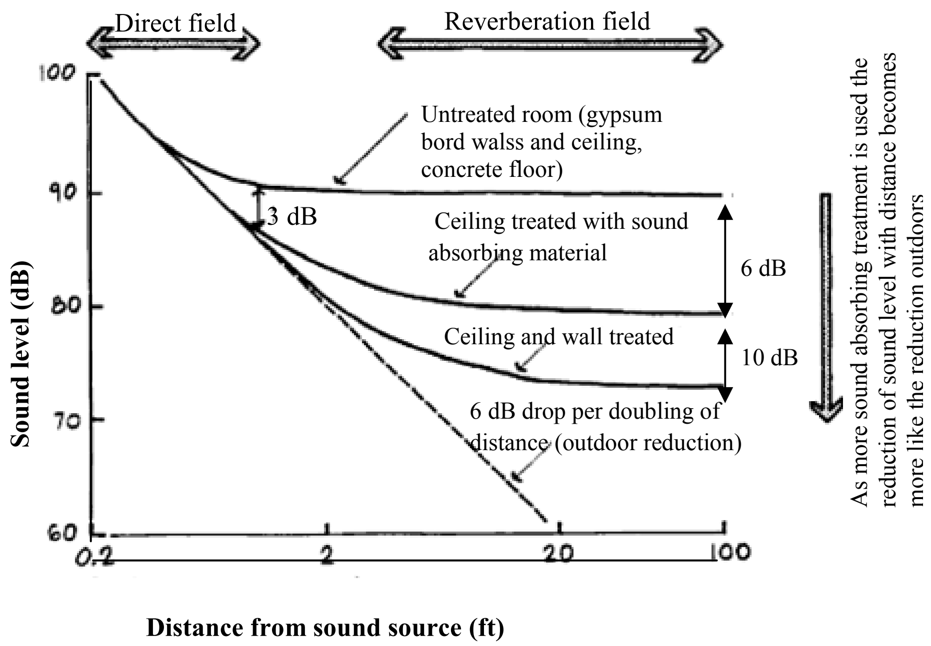

Figure 2.2: Effect of sound absorbers addition (Egan, 1988)

As seen in the Figure 2.2, the addition of sound absorption to the ceiling of a small room (<500 ft^2) can reduce the 10 dB reverberant sound levels of noise source. If all wall and ceiling are treated with sound absorbing material, the sound level in the reverberant field drops an additional 6 dB. Each doubling sound absorbing material within the room reduces one half reverberation times. On the other hand, there is no effect for sound level that close to sound source. Absorption treatment closing to the sound source will only reduce 3 dB of noise source. Walls covered with sound absorbing materials do not have the ability to reduce noise from a source. The maximum effect possible in covering walls with absorbing materials is to avoid reflected noise (Hansen and Goelzer, 2006).

2.3 Sound Absorptive Materials

Sound absorbing materials are a passive medium where incidence sound is converted into heat. It is extensively used to reduce noise level in any industrial operation (Sagartzazu *et al.*, 2008). In general, there are three common types of sound absorbing materials used in reducing noise. They are membrane resonator, Helmholtz resonator and porous absorber.

i. **Membrane Resonators** are usually solid, non-porous, and non-rigid or perforated with cavity behind them. Material like thin wood paneling over framing, lightweight solid ceilings and floors and other large surfaces are experienced of resonating in response to sound. Often, it is used in room designed with special low frequency noise problem such as for music to balance the natural high frequency absorption.

ii. **Helmholtz Resonators** is typically described like a bottle that consists of an enclosed air volume connected to the room by a narrow opening (Xu *et al.,* 2010). Helmholtz resonators are widely used to achieve adequate noise absorption at lower frequencies (Kim and Kim, 2004).

iii. **Porous Absorbers** are extensively used in the noise control engineering (Chao and Jiunn, 2001). Most of available porous absorbers are fibrous media. Fibrous material is considered as a composites medium in which the fibers are suspended in air under certain binding forces (Sides *et al.*, 1971). Foams, fabrics, carpet, and cushions are examples of porous absorbers. These are commonly composed of cellulose or mineral fibers that guaranteed high acoustic absorption and fireproof.

Different absorbers have different sound absorption characteristics for different frequencies. Figure 2.3 demonstrates the sound absorption characteristics of each absorber. Membrane resonators effectively absorb at lower to mid frequency range. Helmholtz resonators are effective at lower frequency but focus in very narrow band of frequencies. Porous absorbers effective absorb at high frequency range (Cox and Antonio, 2004). Thus, when sound absorption treatment is required as solution for noise problem within the room, the material chosen must be proper with the frequency range of interest. Combination of porous materials and resonator can provide the uniform or flat sound absorption with frequency required in recording or radio/ TV studios.

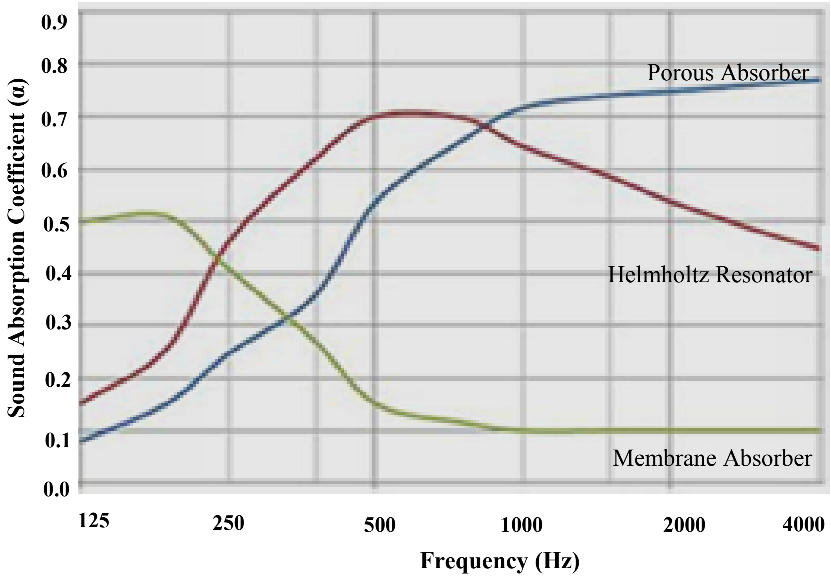

Figure 2.3: Sound Absorption Characteristics of Absorbers (Jacobsen *et al.,* 2010)

Among those, the most encountered sound absorbers are porous material. Most of the porous sound absorbers commercially available are foam and fibrous materials (Chao and Jiunn, 2001). They are composed of a set of continuous fibre that traps air between them (Sides *et al*., 1971). Synthetic fibers are mostly used for sound absorption materials. They are processed in high temperature extrusion from synthetic chemicals and often from petrochemical sources. Eventhough these commercial product provide adequate sound absorption performance, they are relatively expensive and unbiodegradable. In addition, their carbon residues pose hazard to human health and environment (Arenas and Crockers, 2010). These drawbacks have forced researchers shift to recycled material such as textile, rubber, and plastics (Nick *et al*., 2002; Paulain *et al.,* 2006; Stankevicius *et al*., 2007; Zhou *et al*., 2007). Although recycled acoustics products can work as well as commercial acoustics product, energy efficiency in production process must be taken into account for sustainable design. Environmental awareness on sustainable material development has led manufacturers look for natural fibers.

2.4 Natural Fibrous Absorbers

Natural fiber is fiber that directly obtained from an animal, mineral, or vegetable source. The fibers are usually freed from the stalk by a retting process (Frankovich, 2008). Numerous studies to investigate natural fibers for sound absorbing material have been done. Xu *et al.,* (2004) investigated sound absorption properties of kenaf core fiber using impedance tube method. Allesandro and Pispola (2005) did the evaluation of the sound absorption performances of kenaf as innovative sustainable fibrous materials using reverberation method. Additionally, Tormos *et al.,* (2007) proposed an empirical model to determine absorption behaviour of absorbent materials based on kenaf. Likewise, Ramis *et al.,* (2010) investigate the sound absorption of material based kenaf using the same method, empirical model. Their results demonstrated that materials based on kenaf have good sound absorption and suitable for thermal insulation and sound absorbing material. They are good sound absorber at higher frequency band. According to Arenas and Crockers (2010), acoustical materials made of a mix of natural kenaf fibers and polyester are currently available commercially.

Composite panel made from jute and ramie fiber, were found demonstrated good sound absorption at high frequencies. The maximum sound absorption coefficient reached out at 4000 Hz from jute fiber and at 5000 Hz from ramie fiber (Sabri, 2007). Single layer panel from paddy husk sodium silicate performed good sound absorption in high frequency range (Fahmi, 2006). Moreover, paddy straw is viable for acoustical panel (Mediatika, 2007). It has large hollow space (porosity) allows sound to propagate inside it (Mediastika, 2008). In addition, the acoustic board made of aspen particles with different percentage of wheat and barley straw notified that no significant difference on sound absorption coefficient of wheat and barley straw. Both straws demonstrated optimum sound absorption at 2000 Hz. Increasing in straw percentage has increased sound absorption coefficient values (Saadatnia *et al.,* 2008).

Several studies reported that coir fiber is suitable for sound absorbing material (Nor *et al*., 2004). Multi-layer coir fiber panel contributed to increase the sound absorption coefficient in a wide range of frequency (Zulkifli *et al*., 2008). The coir fiber with the perforated panel gives higher sound absorption coefficient (α) for the lower frequencies range from 800 Hz until 1800 Hz but lower at higher frequency. The sound absorption coefficient (α) for coir fiber with perforated panel is around 0.70-0.80 for the frequency range of 1000 to 1800 Hz (Zulkifli *et al*., 2009a). Later on, Zulkifli *et al.,* (2009b) compared the acoustical properties of composite based coir fibers and oil palm treated with Polyvinyl Acrylic (PVA). Composite with oil palm fiber showed higher sound absorption than coir fiber, but in average both composite panels have a high potential to be used as a sound absorber materials. As a natural material, tea-leaf fiber-waste was tested and demonstrated good absorption properties than polyester and polypropylene based non-woven fiber material (Ersoy and Kucuk, 2009). Acoustic board made from *Bagasse* also show good sound absorption properties at high frequency (Ismail *et al*., 2010). At lower frequency, sound absorption of material can be improved by giving some air gap, air back and perforated layer with cavity behind them, (Zulkifli *et al*., 2010; Ayoub *et al*., 2009; Fouladi *et al.,* 2010).

Very recently studied by Fatima and Mohanty (2011) concluded that composite from jute felts has higher sound absorption than fiber felts. The absorption properties of sound-absorbing materials made of these fibers can be similar to those made from minerals (Chen *et al*., 2010). Those results show that natural fiber composites are likely to be advanced to glass fiber composites in most cases for the following reasons:

i. Natural fiber production has lower environmental impacts compared to glass fiber production.
ii. Natural fiber composites have higher fiber content for equivalent performance, reducing more polluting base polymer content.
iii. In auto application, the lightweight natural fiber composites improve fuel efficiency and reduce emissions in the use phase of the component.
iv. Natural fiber reported provides good thermal and noise insulator (Badri and Amin, 2006).

Though many advantages of using natural fibers for composites, they also have some disadvantages. Frequently, natural composites have lower durability when exposed to certain environmental condition. They have lower strength properties, high moisture absorption that causes fiber swelling. *Arenga Pinnata* fiber is one of natural fiber that has high naturally strength and durability.

2.4.1 *Arenga Pinnata* Fiber

Arenga Pinnata fiber, known as Ijuk, is the fibers produced from sugar palm. Sugar palm is one of the oldest cultivated plants in Asia. Geographically, it distributed in all of tropical South and Southeast Asia countries, from India to Guam and from Myanmar to Nusa Tenggara Timur in Indonesia. Typically, it grows close to human settlements where anthropochoric breeding plays a major role. It is a fast growing palm that reaches maturity within 10 years. It has become an enduring match throughout the world and a most economically important plant in Asia. Sugar palm is one of the most diverse multipurpose tree species in culture. Almost of all parts of the tree is daily utilized, since the last decade (Mogea *et al*., 1991). Table 2.1 lists the utilization of sugar palm.

Table 2.1: The utilization of *Arenga Pinnata* (Mogea *et al*., 1991)

Part of Sugar Palm	**Utilization**
Root	Tea to bladder stones, insect repellent, post for pepper, boards, tool handles, water pipes, musical instruments like drums, and, Erosion control
Stem core	Sago, fibers
Pitch of leaf's rachis	Drinking cup
Young leaves	Cigarette paper, salads
Leaflet midrid	Brooms, baskets, meat skewers
Fruit	Sap tapped for fresh drink, wine, vinegar, and palm sugar
Endosperm of unripe	Kolang kaling (cocktail)
Flower	Source of nectar for honey production
Old woody leaf bases	Biofuel
Timber	The very hard outer part of the trunk is used for barrels, flooring and furniture.
Hair of base of the leaf Sheaths	Fire ignition

The most important product of sugar palm is sugar. Sugar palm is more productive four to eight times than sugar cane. Another important product of sugar palm is ijuk (*Arenga Pinnata* fiber).

(i) The Utilization of *Arenga Pinnata* Fiber

Ijuk is black fiber spanned over the sugar palm trunk, as portrayed in Figure 2.4. In general, Ijuk fiber is strong, rigid, tough, waterproof, and durable (Sitepu *et al.,* 2006). Ijuk is natural fibers of plant origin that consists of 51.54 % celluloses, 15.88 % Hemicelluloses, 43.09 % lignin, 8.9% water, and 2.54 % ash (Wahyuni, 2010).

Figure 2.4: *Arenga Pinnata* fibers (Kusmanto, 2009)

According to Mogea *et al.,* (1991) *Arenga Pinnata* fiber has conventionally used for filters, component in road construction, basement of sport course and as shelters for fish breeding. It is known for its durability and fire resistant. The fibers are also known to be seawater-resistant. It can stand long as expose to either fresh or salt water (Florido and de Mesa, 2003). Ropes made from Ijuk are usually used in marine work because it can hold bamboo tightly compared to other ropes made from coir, ramie, wood or synthetics fibers. Furthermore, *Arenga Pinnata* fibers are conventionally used for roofing material, as can be seen at some Indonesian traditional houses, e.g. Batak, Toraja, Minahasa, Minangkabau, and Bali temples (Ticoalu *et al.,* 2011). These facts proved that *Arenga Pinnata* has great naturally strength and durability when are exposed to certain environmental condition.

(ii) Previous Study on *Arenga Pinnata* Fiber

Several investigations have been done to investigate the potentiality of *Arenga Pinnata* fibers. Sastra *et al.,* (2005) investigated the viability of *Arenga Pinnata* fibers to be applied for composite material. The composites were produced from woven roving, long, and chop random fibers reinforced with epoxy resin. The 10 wt. % woven roving fiber content demonstrated the highest flexural strength (108.15MPa) and Young's modulus (4421.8MPa) compared to chop and long fiber. It means that *Arenga Pinnata* fibers are applicable for composite material component overall.

Furthermore, Leman *et al.* (in Ticoalu *et al.,* 2011) investigated the tensile strength of *Arenga Pinnata* fiber reinforced composite. The fibers (chop fiber) were treated in both fresh and seawater for 30 days. It found that both freshwater and seawater treatment contribute to the improvement of the tensile strength of the specimens up to more than 50%. Otherwise, Bachtiar *et al*., (2008) did alkali treatment on the fiber. The alkali treatment was also demostrated significant tensile strength. Furthermore, Bachtiar *et al*., (2010) identified the physical-mechanical properties of single *Arenga Pinnata* fiber. The results obtained were compared with other fiber, as shown in Table 2.2.

Table 2.2: Physical-Mechanical of *Arenga Pinnata* (Bachtiar *et al*., 2010)

Natural Fibers	**Density, g/cm^3**	**Tensile Stregth, MPa**	**Young modulus, GPa**	**Strain, %**	**Diameter, µm**
Bamboo	0.6-0.8	200.5(7.08)		10.2	
Caurana	1.33	665-1404	20-36	2-3	49-100
Coir	1.25	138.7	6	10.5	396.98
E-Glass	2.55	1800-3000	72-83	3	8-14
Hemp	1.48	550-900	73	1.6	
Kenaf	1.4	215.4	13-17	1.18-1.31	
Jute	1.18	393-773	26.5	1.8	200
Arenga Pinnata	1.29	190.29(46.77)	3.69 (0.54)	19.6(6.7)	99-311

As seen in Table 2.2, single *Arenga Pinnata* fiber showed the moderate tensile strength that almost similar to coir, kenaf, bamboo and hemp fibres (in the range of 138.7 – 270 MPa). The strain of *Arenga Pinnata* fibre gave the highest value compared to others. *Arenga Pinnata* fibre is more flexible than the other natural fibers. Those results showed that *Arenga Pinnata* fibre are applicable for polymer composites component.

Recently, Ticoulu *et al.,* (2011) investigated the mechanical properties of *Arenga Pinnata* panel reinforced polyester resin. The study reported that unidirectional *Arenga Pinnata* fibers/polyester composites have the highest tensile strength, whereas, the woven roving fibers/polyester composites have the highest flexural strength. Owing to chemical, mechanical and physical properties, *Arenga Pinnata* fibers are flexible to be used in wide applications.

Sitepu *et al.,* (2006) investigated the feasibility of using *Arenga Pinnata* fiber based composite for nuclear radiation shielding. The panel was radiated by Gamma (γ) and Beta (β) ray. Gamma (γ) ray was generated from Co-60 whereas Beta (β) ray was generated from Sr-90. The results found that composite with optimum *Arenga Pinnata* fibers content established higher radiation absorption coefficient than aluminum. Thus, *Arenga Pinnata* based composite has the potential to replace the aluminum that recently used as radiation shielding. In this research, the feasibility of using *Arenga Pinnata* fibers for acoustical panel is investigated.

2.5 Mechanism of Sound Absorption in Fibrous Absorbers

The sound absorption of fibrous material has been studied for several decades. According to Kinsler (1980), sound absorption is a result of dissipating incident sound into thermal energy. Fibrous absorber is a dissipative media, which acts as a transducer, converting sound incident wave into thermal energy as the results of particular process related to viscosity, thermal conductivity, and molecular relaxation (Crockers, 1998).

When a sound wave impinges the surface of the absorber, some sound wave would be in motion within absorber. The motion of sound wave sets the fibers into vibration. The fibers vibrations allow air to flow in the interstices between fiber and particles. The air motions through narrow constrictions cause some energy loss (Long, 2006). The losses of sound energy indicate some sound energy is absorbed within material through dissipation process. Dissipation is accounted for by friction due to the relative velocity between air and fibers as results of viscous boundary layer effects. This effect takes account to the high frequency losses. The velocity of sound in porous absorber is lower than in the air. A lower sound velocity within porous material also contributes to absorption.

As well as viscosity, energy is absorbed through thermal losses as sound propagates through these small orifices within fibrous material. Since thermal equilibrium is restored fast, fluctuation in pressure and density are isothermal. Increasing temperature in the gas has transported heat away from interaction site to dissipate. In air-filled sound absorbing materials, the frequency dependence of the compressibility varies from isothermal at low frequencies to adiabatic in the high-frequency regime (Cortis, 2001). At lower frequency, absorption effect caused by fibers that relatively efficient conductor of heat. In addition, dissipation can be a result of scattering and vibration of the fibers. The fibers of the material wipe together up under the influence of the sound waves (Arenas and Crocker, 2010). However, dissipation due to scattering is neglected; therefore, it must be assumed that the wavelength is large relative to the pore size (Biot, 1962).

2.6 Physical Properties Influencing Sound Absorption of Fibrous Material

Typically, fibrous materials are excellent in absorbing noise at high frequency range. The effectiveness of *Arenga Pinnata* depends upon its physical and microstructure properties such as density, porosity, and tortuosity. Different methods have been developed in order to characterize these parameters. All of these parameters are potentially measurable or can be calculated by non-acoustic means (Ballagh, 1996). Some of them are based on the physical and mathematical definition of the parameters.

2.6.1 Density (ρ)

Density of a material is often considered as one of the important factor when dealing with the sound absorption behavior of the material. Materials with different densities tend to have different sound absorption properties. A study by Xu *et al.,* (2004) reported that density of porous material would considerably influence the sound absorption coefficient of the acoustic materials. It was figured out in Figure 2.5.

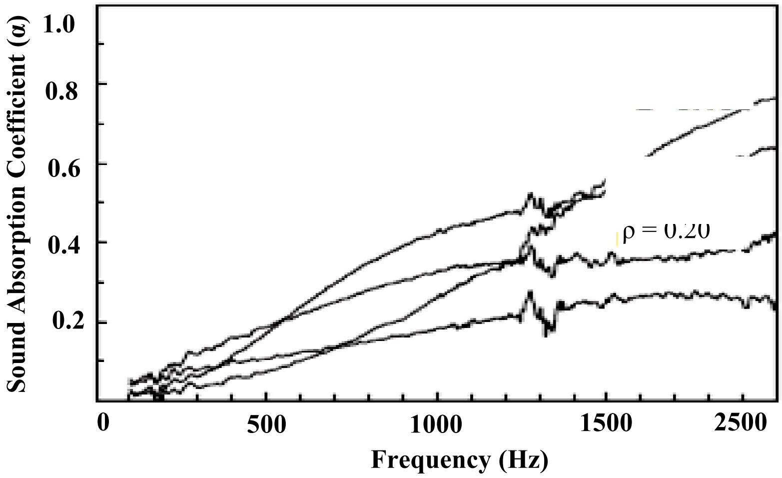

Figure 2.5: Influence of Density on Sound Absorption Coefficient (Xu *et al.*, 2004)

At lower frequency (<500 Hz) sound absorption coefficients of materials effectively increases with increasing in density but tend to decrease at higher frequency (>2000 Hz) for denser samples. Less dense samples provide higher sound absorption coefficient than denser samples. It is because of large porosity within them. The similar statement declared by other author, e.g. Ballagh (1996), Sheddeq (2009), and Saadatnia *et al.*, (2008).

2.6.2 Porosity (*ø*)

Porosity is one of the important factors that should be considered while studying sound absorption mechanism in porous material. Porosity of absorbers consist frictional drag; thereby the sound energy propagated is converted to heat. Porous materials are excellent in sound absorption and good heat insulator. Its open pores allow restricted airflow through the material thus absorbing sound and also preventing efficient heat exchange.

For typical absorbers such as rock wool or mineral wool, the porosity is close to unity, and so the value is often assumed rather than measured (Rossing, 2002). The influence of porosity on sound absorption coefficient of material is illustrated in Figure 2.6.

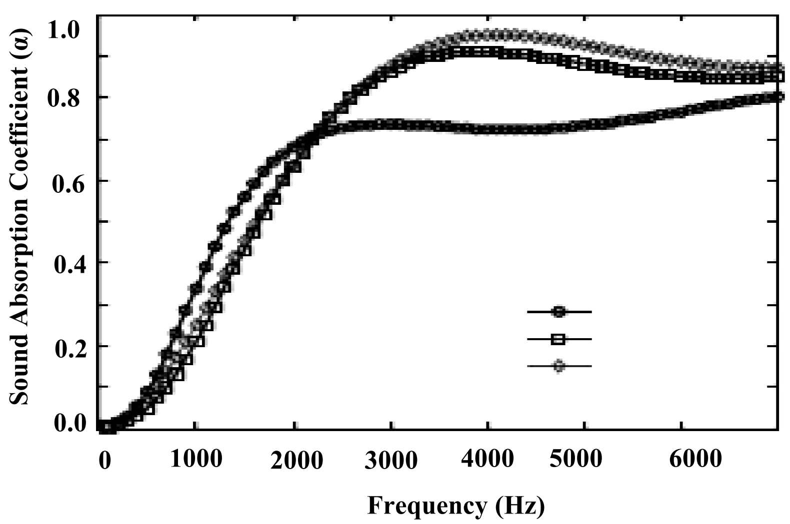

Figure 2.6: Influence of Porosity on Sound Absorption Coefficient (Sun *et al.,* 2010)

Figure 2.6 shows sound absorption coefficient of material with different porosity number. It shows that sound absorption is significantly increased by increasing in porosity (Stankevicius *et al*., 2007). Good absorbers tend to have high porosity. Small pores resulting in no sound wave can propagate within the space because there is no sufficient volume for pressure to change and the material can be classified as closed cell (Sheddeq, 2009). The orientation of pores relative to the incident sound field has an effect on the sound propagation. This effect is represented by the parameter tortuosity (α_∞) (Cox and Antonio, 2004).

2.6.3 Tortuosity (α_∞)

Tortuosity is a measure of the "non-straightness" of the pore structure of the porous material. For fibrous materials, tortuosity (α_∞) is approximately unity while for granular materials, such as soil, α_∞=2.0 (Cox and Antonio, 2004). Sakagami, *et al*. (1999) plotted the influence of tortuosity on sound absorption coefficient in Figure 2.7.

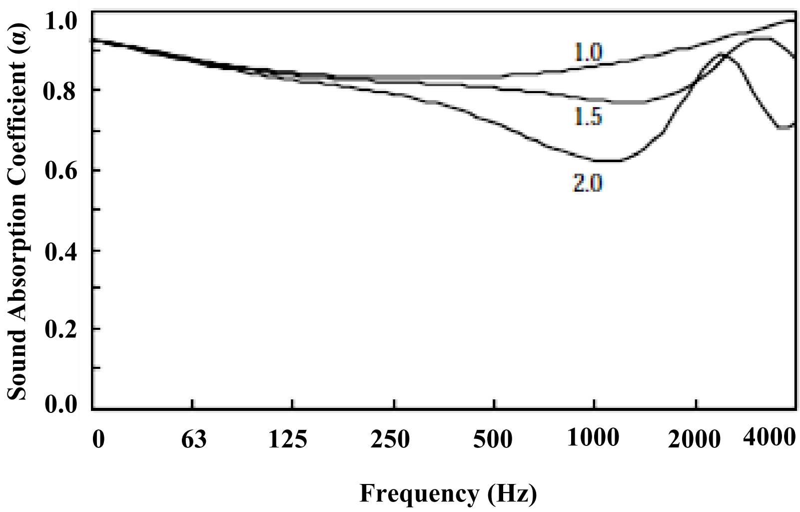

Figure 2.7: The Effect of the Tortuosity on Sound Absorption Coefficient (Sakagami *et al*., 1996)

The Figure shows that the effect of tortuosity on sound absorption coefficient is limited at mid to high frequency range; from 500 Hz to 4000 Hz. It appears that the optimum sound absorption performed by the less tortuous material, 1.0. At 1000 Hz, the sound absorption coefficients tend to decrease as tortuosity value was increased to 1.5 and 2.0. The more tortuous material is the lower absorption coefficient (Knapen *et al.,* 2003). At frequency above 1000 Hz, the fluctuation of absorption performed by sample with tortuosity 1.5 and 2.0. Higher tortuosity causes larger fluctuations in sound absorption coefficient. The fluctuation starts to manifest itself from lower frequencies as the tortuosity increased. On the other hand, tortuosity has only a small effect on noise transmission coefficient (Sakagami *et al*., 1996)

2.7 Acoustical Properties of Fibrous Absorber

In principle, all building materials have some acoustical properties that will reflect, absorb, or transmit the sound striking them (Bilova and Lumnitzer, 2010). When sound wave interacts with surface of a wall or ceiling, a part of energy is reflected, another part is absorbed by the wall and the other part is transmitted through the wall. Figure 2.8 shows the interaction of incident sound wave on material surface. The amounts of energy going to reflection, absorption, or transmission are depending on the acoustical performance of the material surface.

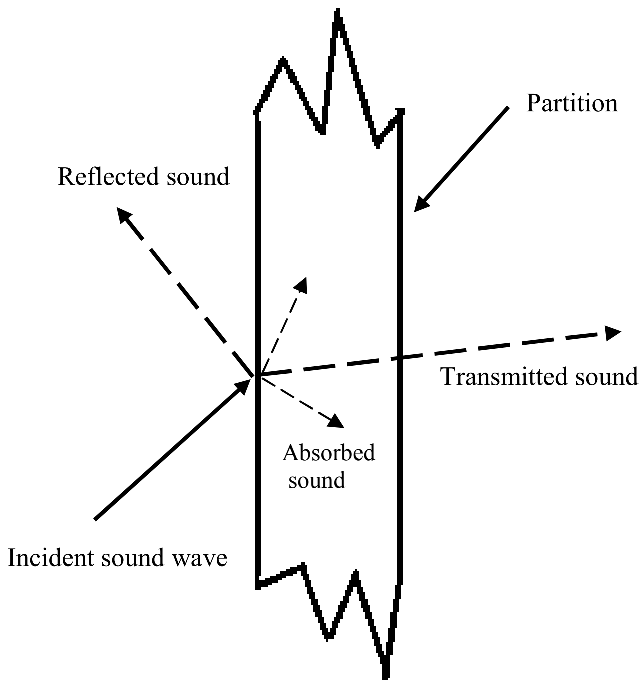

Figure 2.8: Interaction of Sound Wave on Material (Cowan, 1994)

For fibrous materials, acoustic performance is defined by a set of experimental investigation, namely: Sound absorption coefficient (α), noise reduction coefficient (NRC), sound transmission loss (STL), and sound transmission class (STC).

2.7.1 Sound Absorption Coefficient (α)

Sound absorption coefficient (α) is a key feature when determine the performance of sound absorbing by a material. It is defined as the ratio of sound energy absorbed by a material to incident sound energy striking them, as expressed in equation 2.5.

$$\alpha = \frac{I_\alpha}{I_i} \qquad 2.5$$

Where, α = sound absorption coefficient,

I_i = incident sound energy, and

I_a= sound absorbed.

Typically, sound absorption coefficient is a unitless quantity, ranging between 0 and 1.0. Value of 0 means all of incidence sound energy is reflected or transmitted, whereas, value of 1.0 means all of incidence sound energy is absorbed. In facts, value of 0 and 1.0 are ideal values that do not exist since all material will reflect, absorb, or transmit some sound striking those (Cox and Antonio, 2004). For an example, an acoustical material that suspended on wall has a sound absorption coefficient (α) of 0.45 at 500 Hz. It shows that this material absorbs of 45 % incident sound striking it and the rest of 55% incident sound energy is reflected back into the space or transmitted through the wall.

Sometimes, certain materials quote sound absorption coefficient greater than 1.0. This is commonly resulted from reverberation room method measurement that attribute to edge effects or diffraction effects caused by lack of diffuse field in the measuring room. If any sound absorption coefficient value is greater than 1.0, it should be taken as 1.0 in any consideration or calculation (Long, 2006; Rossing, 2007).

Table 2.3 presents sound absorption coefficient of common commercial absorbers in human speech frequency. For typical cases, it is convenient to use a single number to describe sound absorption of material denoted as noise reduction coefficient (NRC).

REFERENCES

Alessandro, D. F. and Pispola, G. (2005). Sound Absorption Properties of Sustainable Fibrous Materials in an Enhanced Reverberation Room. *The Congress and Exposition on Noise Control Engineering.* Brazil.

Arenas, P. J and Crocker, M.J. (2010). Recent Trends in Porous Sound Absorbing Material. *Material References Issue, 13*. 12-17.

Atmaca, E., Peker, I, and Altin, A. (2005). Industrial Noise and Its Effects on Humans. *Polish Journal of Environmental Studies, 14(6).* 721-726.

Ayoub, M., Nor, M.J.M., Amin, N., Zulkifli, R., Fouladi, M.H., and Ismail, A.R.I. (2009). Analysis on Sound Absorption of Natural Coir Fiber Using Delany-Bazley Model. *Proceedings of the Conference on Mechanical Engineering (ICME2009).* Bangladesh: December 26-28.

Bachtiar,D., Sapuan, S.M. and Hamdan, M.M. (2008). The Effect of Alkaline Treatment on Tensile Properties of Sugar Palm Fibre Reinforced Epoxy Composites. *Materials & Design 29,* 1285–1290.

Bachtiar, D., Sapuan, S.M., Zainudin, E.S., Khalina, A. and Dahlan, K.Z.M. (2010). The TensileProperties of Single Sugar Palm (*Arenga Pinnata*). *Materials Science and Engineering 11 (2)*.

Badri, K and Amin, K.A.M. (2006). Biocomposites from Oil Palm Resources. *Journal of Oil Palm Resources*, 103-113.

Ballagh, K. O. (1996). Acoustical Properties Of Wool. *Applied Acoustics, 48 (2),* 101-120.

Bilova, M. and Lumnitzer, E. (2010). Evaluation of the Acoustic and Non-Acoustic Properties of Sound Absorbing Materials Using a Three-Microphone Impedance Tube. *Applied Acoustics, 71,* 506–509.

Biot, M.A. (1962). Generalized Theory of Acoustic Propagation in Porous Dissipative Media. *Journal of The Acoustical Society of America, 34(5) I*, 1254-1264.

Blomkvist,V., Eriksen, C. A., Theorell, T., Ulrich, R., and Rasmanis, G.(2005). Acoustics and Psychosocial Environment in Intensive Coronary Care. *Occupation Environment Medical, 62*, 1-8.

Castagneade, B., Aknine, A., Brouard, B., and Tarnow, V. (2000). Effects of Compression on The Sound Absorption of Fibrous Materials. *Applied Acoustics, 61*, 173-182

Chao, N. W. and Jiunn, H. T. (2001**).** Experimental Study of The Absorption Characteristics Of Some Porous Fibrous Materials. *Applied Acoustics, 62,* 447-459.

Chen, D., Li, J., and Ren, J. (2010). Study on Sound Absorption Property of Rami Fibre Reinforced Poly(L-Lactic Acid) Composites: Morphology and Properties. *Composites: Part A 41*, 1012-1018.

Cortis, Smeulders, D.M.J., Lafarge, D., Firdaouss, M., and Guer, J.L. (2001). Geometry Effects on Sound in Porous Media. *IUTAM Symposium on Theoretical and Numerical Methods in Continuum Mechanics of Porous Materials.* Netherlands: Kluwer Academic Publishers.

Cowan, J. P. (1994). *Handbook of Environmental Acoustics.* New York : ITP Van Nostrand Reinhold.

Cox, T.J. and Antonio, J. D. (2004). *Acoustics Absorbers and Diffusors.* London: Spon Press Taylor & Francis Group.

Crocker, M. J. (1998). *Handbook of Acoustics.* Canada: A Wiley-Interscience.

Egan, M. D. (1988). *Architectural Acoustics.* New York: McGraw-Hill.

Ersoy, S. and Kucuk, H.(2009). Investigation of Industrial Tea Leaf Fibre Waste Material for Its Sound Absorption Properties. *Applied Acoustics*, *70*, 215-220.

Fatima, S. and Mohanty, A.R. (2011). Acoustical and Fire Retardant Properties of Jute Composite Materials. *Applied Acoustics,* 72, 108-114.

Florido, H.B. and de Mesa, P.B. (2003). Sugar Palm [Arenga pinnata (Wurmb.)]. *Research Information Series on Ecosystems, 15(2).*

Fouladi , M.H., Nor, M.J.M., Ayub, M.D., Leman, Z.A. (2010). Utilization of Coir Fiber in Multilayer Acoustic Absorption Panel. *Applied Acoustics,7,* 241–249.

Hansen, C. H. (2004). *Fundamentals of Acoustics*. Adelaide University: Lecture Note, 23-53.

Hansen, C. H. and Goelzer, B.I.F. (2006). *Engineering Noise Control.* Adelaide University: Lecture Note, 10.

Haryanto, T. (2007*). Effect of Fibre Ratio on Acoustic Properties and Compressive Strength of Polyester - Ramie (Jute) Fibre Composite*. Institute of Sepuluh November: Undergraduate Theses.

Ismail, L., Ghazali, M.I., Mahzan, S., Zaidi, A.M.A (2010). Sound Absorption of *Arenga Pinnata* Natural Fiber.*World Academy of Science, Engineering and Technology*, 67. 804-806.

Jacobsen, F., Poulsen, T., Rindel, J.H., Gade, A.C., and Ohlrich, M. (2010). *Fundamentals of Acoustics and Noise Control.* Technical University of Denmark: Note no 31200.

Joshi, S.V., Drzal, L.T., and Mohanty, S.A. (2003).Are Natural Fiber Composites Environmentally Superior to Glass Fiber Reinforced Composites?. *Composites: Applied Science and Manufacturing, 35*. 371-376.

Kidner, M. R.F. and Hansen, C. H. (2008). A Comparison and Review of Theories of The Acoustics of Porous Materials. *International Journal of Acoustics and Vibration, 13(3)*, 111-119.

Kim, S.R. and Kim, Y.N. (2004). Broadband Sound Absorption by Helmholtz Array Panel; Its Physical Phenomena and Theory. *The 33rd International Congress and Exposition on Noise Control Engineering.* Prague: August 22-25.

Kinsler, L.A. (1980). *Fundamentals of Acoustics 3rd Edition.* California: John Wiley & Son.

Knapen. E, Lanoye. R, Vermeir. G and Van G. D. (2003). Sound Absorption By Polymer-Modified Porous Cement Mortars. *6th International Conference on Materials Science and Restoration*. MSR-VI Aedificatio Publishers, 347–358.

Kruger, J.and Quickert, M. (1997). Determination of Acoustic Absorber Parameter in Impedance Tubes. *Applied Acoustics, 50,* 79-89.

Kuttruff, H. (1991). *Room Acoustics.* England: Elsevier Science Publishing.

Long, M. (2006). *Architectural Acoustics.* California: Elsevier Academic Press.

Mediastika, C. E. (2007). Potential of Paddy Straw as Material Raw of Acoustic Panel. *Architectural Dimension*, 35(2). 183-189.

Mediastika, C. E. (2008). Paddy Straw as Walling Panel*, Architecture Dimension, 36(1),* 20-27.

Mogea, J., Seibert J. B., Smiths W.(1991) Multipurpose Palms: The Sugar Palm (*Arenga pinnata* (Wurmb) Merr.) *Agrof Sys, 13,* 111-129.

Nick, A., Becker, U. and Thoma, W. (2002). Improved Acoustic Behavior of Interior Part of Renewable Resources in the Automotive Industry. *Journal of Polymers and The Environment, 10 (3),* 115-118.

Nor, M.J.M., Jamaludin, N., Tamiri, F.M. (2004). A Preliminary Study of Sound Absorption Using Multi-Layer Coconut Coir Fibers. *Electronic Journal Technical Acoustics,* 3, 1-8.

Oldfield, R. (2006). *Improved Membrane Absorber*. Salford University: Master Theses.

Paulain, N., Legeais, V., Roualt, E., Parmentier, D., Boccaccio, G., Dorget, M., and Roux, J.C.L. (2006). Development of an Acoustic absorbent Material Using Scrap Tires. *CTTM-IRC.*

Rahman, M.R., Islam, M.N., Huque, M.M., Hamdam, S., Ahmed, A.S. (2010). Effect of Chemical Treatment on Rice Husk (RH) Reinforced Polyethylene (PE) Composites. *BioResources 5(2)*, 854-869.

Ramis, J. Alba, J., Rey, L.D., Escuder, E., and Sanchís V.J. (2010). New Absorbent Material Acoustic Based on Kenaf Fibre. *Materiales de Construcción, 60 (299),* 133-143.

Rashdi, A.A.A., Sapuan, S.M., Ahmad, M.M.H.M., and Khalina, A. (2009). Water Absorption and Tensile Properties of Soil Buried Kenaf Fiber Reinforced Unsaturated Polyester Composites (KFRUPC). *Journal of Food, Agriculture & Environment*, *7 (3&4),* 908-911.

Rossing, T.D. (2002). *The Science of Sound.* USA: Addison Wesley.

Rossing, T. D. (2007). *Handbook of Acoustics.* New York: Springer.

Saadatnia, M., Ebrahimi, G., and Tajvidi, M. (2008). Comparing Sound Absorption Characteristic of Acoustic Boards Made of Aspen Particles and Different Percentage of Wheat and Barley straws. *17th World Conference on Nondestructive Testing*. Shanghai: October 25-28.

Sabri. (2007). *Evaluation of the Acoustical Performance of Natural Fiber as Alternative Material to Control Noise.* Institute of Technology Bandung: Masters Theses.

Saeki, T., Fujii, T., Yamaguchi, S., and Harima, S. (2004). Effects of Acoustical Noise on Annoyance and Performance Fatigue During Mental Memory Task. *Applied Acoustics 65,* 913–921.

Sagartzazu, X., Nieto, L.H., and Pagalday, J.M. (2008). Review in Sound Absorbing Materials. *Architectural Computational Methods Engineering*, *15,* 311-342.

Sakagami, K., Kiyama, M., Marimoto, M., and Takahashi, D. (1996). Sound Absorption of a Cavity-Backed Membrane: A Step Towards Design Method for Membrane-Type Absorbers. *Applied Acoustics, 49(3),* 231-241.

Sarwidi (2011). *Tentang Ijuk: Lagi-Lagi Ijuk Bisa Jadi Bahan Untuk Bangunan Rumah Anti Gempa*. Http://arengabroom.blogspot.com.

Sastra, H.Y., Siregar, J.P., Sapuan, S.M., Leman, Z. and Hamdan, M.M. (2005). Flexural Properties of *Arenga Pinnata* Fibre Reinforced Epoxy Composites. *American Journal of Applied Sciences*, *21-24,* ISSN 1546-9239.

Sheddeq, H. S. (2009). Factors Influencing Acoustic Performance of Sound Absorptive Materials. *Australian Journal of Basic and Applied Sciences*, *3(4)*, 4610-4617.

Sides, DJ, Attenborough, K, Mulholland, K.A. (1971). Application of a Generalized Acoustic Properties Theory to Fibrous Absorbers. *Journal of Sound and Vibration (1),* 49-64.

Siegesmund, S. and Snethlage, R. (2011). *Stone in Architecture*: *Properties, Durability*. Springer.

Sitepu, M., Christiani, E.S., Sembiring, M., Barus, D., and Sudiati (2006). Modifikasi Serat Ijuk dengan Radiasi Sinar – γ Suatu Studi untuk Perisai Radiasi Nuklir. *Jurnal Sains Kimia, 10(1),* 4–9.

Stankevicius, V., Skripkiunas, G., Grinys, A., and Miskinis, K. (2007). Acoustical Characteristics and Physical – Mechanical Properties of Plaster with Rubber Waste Additives. *Material Science*, *13 (4).*

Strong, A.B. (1999*). Flammability Testing*. Brigham Young University.

Sun, F., Chen, H., Wu, J., and Feng, K. (2010). Sound Absorbing Characteristics of Fibrous Metal Materials at High Temperatures. *Applied Acoustics, 71*, 221–235.

Taib, R. M., Ramarad, S., Ishak, Z.A.M., and Todo, M. (2008). Water Absorption and Tensile Properties of Kenaf Bast Fiber-Plastisized Poly(Lactic Acid) Biocomposites. *Proc. of The Polymer Processing Society 24th Annual Meeting.* Italy.

Thompson, D.J., Gardonio, P. and Rohlfing, J. (2009). Can a Transmission Coefficient be Greater Than Unity?. *Applied Acoustics, 70,* 681-688.

Ticoalu, A., Aravinthan, T., and Cardona, F. (2011). Experimental Investigation into Gomuti Fibres/Polyester Composites. *Incorporating Sustainable Practice in*

Mechanics of Structures and Materials – Fragomeni, Venkatesan, Lam & Setunge (eds). London: Taylor & Francis Group. ISBN 978-0-415-61657-7.

Tormos, D. R., Romina, Fernandez, A., Jesus, and Vicente, S. (2007). Proposal an Empirical Model for Absorbent Acoustical Materials Based in Kenaf. *19th International Congress on Acoustics.* Madrid. (1-6).

Umnova, O., Attenborough, K., Ho, C.S., and Cummings, A.(2005).Deduction of Tortuosity and Porosity from Acoustic Reflection and Transmission Measurements on Thick Samples of Rigid-Porous Materials. *Applied acoustics 66*, 607–624.

Vissamraju, K. (2005). *Measurement of Absorption Coefficient of Road Surfaces Using Impedance Tube Method* . Auburn University, Alabama: Masters Thesis.

Wahyuni, N. (2010). *Pemanfaatan Serat Ijuk Pendek Dalam Pembuatan Beton Ringan dan Karakteristiknya.* University of North Sumatera: Undergraduate Thesis.

Wassilieff, C. (1996). Sound Absorption of Wood-Based Materials. *Applied Acoustics, 48(4),* 339-356.

Xu, J.,Sugawara, R., Widyorini, R., Han, G., and Kawai, S. (2004). Manufacture and Properties of Low-Density Binderless Particleboard from Kenaf Core. *The Japan Wood Research Society, 50*, 62-67.

Xu, M.B, Selamet A., and Kim, H.(2010). Dual Helmholtz Resonator. *Applied Acoustics,*71, 822–829.

Yousefi, H. (2009). Canola Straw as a Bio-Waste Resource For Medium Density Fiberboard (MDF) Manufacture. *Waste Management*, *29*, 2644-2648.

Zhou, H., Bo, L., Guangsu, H., and Jia, H. (2007). A Novel Composite Sound Absorber with Recycled Rubber Particles. *Journal of Sound and Vibration, 304,* 400-406.

Zulkifli, R., Nor, M.J.M., Tahir, M.F.M., Ismail, A.R., and Nuawi, M.Z. (2008). Acoustic Properties of Multi-Layer Coir Fibres Sound Absorption Panel. *Journal of Applied Sciences*, *8(20)*, 3709-3714.

Zulkifli, R., Nor, M.J.M., Ismail, A.R., Nuawi, M.Z., and Thahir, M.F.M. (2009a). Effect of Perforated Size and Air Gap Thickness on Acoustic Properties of Coir Fibre Sound Absorption Panels. *European Journal of Scientific Research, 28(2)*, 242-252. *ISSN 1450-216X.*

Zulkifli, R., Nor, M.J.M., Ismail, A.R., Nuawi, M.Z., Abdullah, S., Thahir, M.F.M., and Rahman, M. N.A. (2009b). Comparison of Acoustic Properties between Coir Fibre and Oil Plam Fibre. *European Journal of Scientific Research, 33*, 144-152. *ISSN 1450-216 X.*

Zulkifli, R., Zulkarnain and Nor, M.J.M. (2010). Noise Control Using Coconut Coir Fiber Sound Absorber with Porous Layer Backing and Perforated Panel. *American Journal of Applied Sciences, 7(2),* 260-264. *ISSN 1546-9239.*