CHAPTER 2
LITERATURE REVIEW

This chapter deals with the review of literature on composites and biocomposites, their properties, advantages and applications. The content for this chapter have been gathered from various research papers, reports and books.

2.1 COMPOSITES

A composite material (or just composite) is a mixture of two or more materials with properties superior to the materials of which it is made (Composite Encyclopedia 2002). A broad definition of a composite is: two or more dissimilar materials which are combined stronger than the individual materials. Whereas a specific definition of composites is: a combination of fibre reinforcement and a matrix. Composites can be both natural and synthetic (man-made). An example of a natural composite is wood and bone. Wood is a combination of cellulose fibre in a lignin matrix. The cellulose fibre provides strength and the lignin is the glue that bonds and stabilizes the fibre. Bone is a combination of a soft form of protein known as collagen and a strong but brittle mineral called apatite (Feldman 1989 & Lou & Chou 1992).

2.1.1 Classification of the Composites

There are two types of fibre reinforcements which are usually used in today’s applications. The first type of fibre reinforcement is thermo plastic/thermoset which has been utilized for long time and includes fibres such as glass, Carbon, Aramid and others. The second type of fibre
reinforcement usage of which has started in recent times is natural fibres, usually based on recycled wastes and agricultural plantation waste such as recycled banana, coir, rice/wheat-straw, jute and many more (Pilato & Michno 1994, TIFAC 2014 & Gupta 1998).

2.1.2 Advantages of Composites

Composite materials offer certain functional conveniences: lightweight, mechanical and chemical resistance, low maintenance and easy to form and flexibility in design. Their mechanical properties (rigidity and fatigue strength) as well as their chemical properties (corrosion resistance) prolong the life of the product (Faruk et al 2012 & Peters 1998). They also bolster safety due to greater shock and fire resistance. Besides that, composite materials provide improved heat or sound insulation and good electric insulation properties (Peters 1998, Agarwal & Broutman 1990 & Pigott 1980).

2.1.3 Applications and Benefits of Composite Materials

The benefits of composite materials have fuelled the growth of new applications in areas such as transportation, construction, corrosion-resistance, marine, infrastructure, consumer products, electrical, aircraft, home appliances and business equipment. The benefits (Bledzki & Gassan 1999, Joshi et al. 2004 & Leão et al. 1998) of using composite materials include:

- **High Strength** – composite materials can be designed to meet the specific strength requirements of an application. A distinct advantage of composites over other conventional materials is the ability to use combinations of resins and reinforcements, and therefore tailor the mechanical and other
physical properties of a composite structure (Bledzki & Gassan 1999).

- **Light Weight** – composites are materials that can be designed for both light weight and high strength. In fact, composites are used to produce the highest strength to weight ratio structures known to man (Joshi et al. 2004).

- **Corrosion Resistance** – composites products provide long-term resistance to severe chemical and temperature environments. Composites are the materials of choice for outdoor exposures, chemical handling applications, and severe environment services (Bledzki & Gassan 1999).

- **Design Flexibility** – Composites have an advantage over other materials because they can be moulded into complex shapes at relatively lower cost. The flexibility of creating complex shapes offers engineers a freedom that hallmarks composites achievement (Leão et al. 1998).

- **Durability** – Coupled with low maintenance requirements, the longevity of composites is a benefit in critical applications. In a half-century of composites development, well-designed composite structures are yet to wear out (Leão et al. 1998).

### 2.2 ADVANTAGEOUS OF NATURAL FIBRE APPLICATIONS IN POLYMER COMPOSITES

Due to the exponential growth of the human population on the Earth, we face more and more environmental problems. Now, in the 21st century, it is clear that we are paying for advanced technology with ecological troubles and even disasters sometimes. And it is in our interests to look for solutions. Therefore, from the material science point of view, there is a

- lower pollution levels during production
- lower energy requirements for fibre production
- CO₂ neutral: amount of CO₂ neutralized during fibre plant growth is comparable with that emitted during processing
- lower cost
- renewable resource
- biodegradable
- recyclable products

Natural fibres in composites can compete with synthetic fibres by

- having lower density compared Kevlar, carbon and glass fibres
- being healthier in use due to their natural origins
- being less abrasive on the processing equipment

Low density is the main point why natural fibre reinforced composites are of interest to the automotive sector.

While the stiffness and strength of fibres are the basis for the reinforcement, the interfacial strength (adhesion) is also important for efficient reinforcement. Therefore these three parameters are to be determined initially and characterized before product development (Leão et al 1998, Kandachar 2002, Geeta et al. 2005, Holdberg & Houston 2006, Shogren 1998,
2.3 COMPOSITES OVERVIEW

Generally, manufacturing composites involves the processing of two main ingredient materials to make a final product. The ingredients involve the matrix and fibre reinforcement. Processing requires the following (Leão et al. 1998, Kandachar 2002, Geeta et al. 2005 & Holdberg & Houston 2006):

- Good bonding between matrix and fibres
- Proper orientation of the fibres
- Good amount of volume fraction of fibres
- Uniform distribution of fibres within the matrix material
- Proper curing or solidification of the resin
- Minimum amount of voids and defects
- Good dimensional control for the final part

There are different forms of reinforcement in composite materials that can be classified as given in Table 2.1 (Pigott 1980, Agarwal & Broutman 1990, Peters 1998 & Faruk et al. 2012).
Table 2.1 Different types of reinforcement in composite materials

<table>
<thead>
<tr>
<th>Sl. No</th>
<th>Types of Reinforcement</th>
<th>Schematic Diagram</th>
</tr>
</thead>
</table>
| 1      | Fibres as the reinforcement (Fibrous Composites):  
                   • Random Fibre (short fibre) reinforced composites  
                   • Continuous Fibre (long fibre) reinforced composites | ![Schematic Diagram](image1) |
| 2      | Particles as the reinforcement (Particulate composites) | ![Schematic Diagram](image2) |
| 3      | Flat flakes as the reinforcement (Flake composites) | ![Schematic Diagram](image3) |
| 4      | Fillers as the reinforcement (Filler composites) | ![Schematic Diagram](image4) |

2.4 BIOCOMPOSITES

Broadly defined, biocomposites are composite materials made from natural/bio fibre and petroleum derived nonbiodegradable polymers (PP, PE) or biodegradable polymers (PLA, PHA). The latter category i.e. biocomposites derived from plant fibre (natural/biofibre) and crop/biobased plastics (biopolymer/bioplastic) are likely to be more eco-friendly and such composites are termed as green composites. As a result of the increasing demand for environmentally friendly materials, and the desire to reduce the
cost of traditional fibre (i.e., Carbon, Glass and Aramid) reinforced composites, new bio based composites have been developed.

Researchers have begun to focus on natural fibre composites (i.e., biocomposites), which are composed of natural or synthetic resins, reinforced with natural fibres. Natural fibres exhibit many advantages; they are low-density materials, yielding relatively lightweight composites with high specific properties. These fibres also significant cost advantages and ease of processing along with being a highly renewable resource, in turn reducing the dependency on foreign and domestic petroleum. Recent advances in the use of natural fibres in composites have been reviewed by several authors, example: cellulose (Morrissey et al. 1985, Krzysik et al. 1993, Okino et al. 2000 & Raghupathy et al. 2002), jute (Do & Lien 1995 & Soumitra et al. 2001, hemp (Do & Lien 1995 & Noura et al. 2014), straw fibres (Krzysik et al. 1993, Han-Seung Yang et al. 2004 & Ismail et al. 2011), switch grass (Sera et al. 1990 & Satyanarayana et al. 1990), kenaf (Satyanarayana et al. 1990 & Thielemans & Wool 2004), coir (Soumitra et al. 2001, Khedari et al 2004 & Asasutjarit et al. 2007 & bamboo (Pakatiprapha et al. 1983).

2.4.1 Bio Based Reinforcement Materials

Bio-based lignocellulosic (LC) materials have been used in the preparation of composites for more than 75 years, with one of their particular applications in aircraft seen as early as the 1940s (Pigott 1980, Sera et al. 1990, Agarwal & Broutman 1990, Leão et al. 1998, Peters 1998, Bruijn 2000, Thielemans & Wool 2004, Holdberg & Houston 2006, Satyanarayana et al. 2007 & Faruk et al. 2010). However, for various reasons, such as superior properties of synthetic fibers and nonavailability of complete data on different lignocellulosic fibers, the use of LCs in composites decreased by the 1980s. However, in the last decade there has been a revival in interest in LCs in
composites, principally for the reasons mentioned earlier, along with those given below:

- The existence of LC sources throughout the world, with some of them being abundant in the tropics (one estimate gives their primary production in 2000 as $2 \times 10^{11}$ metric tons compared to $1.5 \times 10^8$ metric tons of synthetic polymers (Satyanarayana & Wypych 2007), while another estimate puts the fibrous raw materials from agricultural crops to be about $2.5 \times 10^9$ metric tons (Satyanarayana et al. 2008, Asasutjarit et al. 2007, Ismail et al. 2011 & Noura et al. 2014) with the share of natural fibers including cotton at 44.3% of the total 54.2 million metric tons of the world inventory of fibers.

- Increasing ecological concerns, leading to greater focus on plant derived fibers and crop derived plastics as materials for the 21st century, due to their attractive aspects, such as CO$_2$ impounding, reduced dependence on petroleum products and value added opportunities for agricultural industries.

- The availability of complete data concerning their structure and properties, which depends on the source from which they are extracted, the method of extraction, the age of the source, processing, etc (Eichhorn et al. 2001, Iannace et al. 2001, Ismail et al. 2011 & Noura et al. 2014).

Other reasons for their increased use may be seen in Table 2.2 and Table 2.3. The former shows a comparison of specific properties, energy to produce and the cost of these fibers with those of synthetic fibers. The latter lists several merits of these biodegradable fibers in composite technology, highlighting the reasons for the choice of these raw materials often quoted the literature. In addition, these materials have a steadily growing market, with the North American market projected to grow from US$ 155 million in 2000
to US$ 1.38 billion by 2025 (Zhou et al. 2007 & Zulkifli et al. 2009). All these also underline the importance of economic and technological aspects of lingo-cellulosic fibers leading to sustainable development, since these fibers may lead to the production of consumer products with high durability that can be easily recycled as well (Hepworth et al. 2000 & Corbiere et al. 2001).

Table 2.2 Comparison of some specific properties and cost of lignocellulosic fibers and synthetic fibers (Cierpucha et al. 2000 & Pickering et al. 2016)

<table>
<thead>
<tr>
<th>Fibre</th>
<th>Specific gravity</th>
<th>Specific tensile strength (GPa/cm³)</th>
<th>Specific tensile modulus (GPa/cm³)</th>
<th>Cost (US$/ton) as of the year 2010</th>
<th>Energy content (GJ/ton)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plant fibres</td>
<td>1.2-1.5</td>
<td>0.11-1.22</td>
<td>5-85</td>
<td>200-1000</td>
<td>4</td>
</tr>
<tr>
<td>Glass</td>
<td>2.6</td>
<td>1.35</td>
<td>30</td>
<td>1200-1800</td>
<td>30</td>
</tr>
<tr>
<td>Kevlar</td>
<td>1.4</td>
<td>2.71</td>
<td>90</td>
<td>7500</td>
<td>25</td>
</tr>
<tr>
<td>Carbon</td>
<td>1.8</td>
<td>1.71</td>
<td>130</td>
<td>12500</td>
<td>130</td>
</tr>
</tbody>
</table>

Table 2.3 Merit list for the use of lignocellulosic fibers incorporated composites (Satyanarayana et al. 2007, Satyanarayana & Wypych 2007, Satyanarayana et al. 2008 & Satyanarayana et al. 1990)

1. Non-brittle fracture on impact
2. Same performance for lower weight
3. Stronger (25–30%) for the same weight
4. Low cost—less than the base resin
5. Fully and easily recyclable
6. Reduced molding cycle time—up to 30%
7. Non-abrasive to machinery
Table 2.3 (Continued)

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>8.</td>
<td>Natural appearance</td>
</tr>
<tr>
<td>9.</td>
<td>Low thermal expansion coefficient</td>
</tr>
<tr>
<td>10.</td>
<td>Good sound abatement capability</td>
</tr>
<tr>
<td>11.</td>
<td>Better energy management characteristics</td>
</tr>
<tr>
<td>12.</td>
<td>More shatter resistant</td>
</tr>
<tr>
<td>13.</td>
<td>Low mold shrinkage</td>
</tr>
<tr>
<td>14.</td>
<td>Easily colored</td>
</tr>
<tr>
<td>15.</td>
<td>High flex modulus—up to $5 \times$ base resin</td>
</tr>
<tr>
<td>16.</td>
<td>High tensile modulus—up to $5 \times$ base resin</td>
</tr>
<tr>
<td>17.</td>
<td>High notched impact—up to $2 \times$ base resin</td>
</tr>
<tr>
<td>18.</td>
<td>Lower processing energy requirements</td>
</tr>
<tr>
<td>19.</td>
<td>Meets minimum recycle content requirements</td>
</tr>
</tbody>
</table>

Because these fibers are hollow and lignocellulosic in nature, they are better thermal and acoustic insulators. Also, they possess fewer health and environmental hazards compared to synthetic fibers. Figure 2.1 (Junior et al. 2003) shows some of the main fibers used in different forms in biodegradable polymer composites, while Table 2.4 lists their major chemical constituents and typical physical and mechanical properties of various biodegradable fillers/reinforcements. It is clear from Table 2.2 and Table 2.4 that their specific strength properties will certainly be attractive for their use as replacements for synthetic fibers particularly in composites for certain applications. Similar properties as well as the morphology and fracture behavior of most of these lignocellulosic fibers are available elsewhere (Luo & Netravali 1999, Hepworth & Bruce 2000, Mohanty et al. 2001, Kandachar 2002, Wambua et al. 2003, Satyanaryana et al. 2006, Frollini et al. 2007 & Satyanarayana et al. 2008) and accordingly, the properties of individual fibers
are not dealt with here (Satyanarayana et al 1990 & Satyanarayana et al 2008).

Figure 2.1 Lignocellulosic reinforcements. (a) banana; (b) sugarcane bagasse (c) curaua (d) flax; (e) hemp; (f) jute; (g) sisal; (h) kenaf; (i) Jute fabric; (j) ramie–cotton fabric; (k) jute–cotton fabric. (Reproduced with the kind permission of the authors (Junior et al 2003)

Table 2.4 Properties of selected natural and glass fibres (TIFAC 2014, Satyanarayana et al 2005)

<table>
<thead>
<tr>
<th>Property</th>
<th>Jute</th>
<th>Banana</th>
<th>Sisal</th>
<th>Pineapple</th>
<th>Coir</th>
<th>Cotton</th>
<th>Glass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Width or Diameter (µm)</td>
<td>25-30</td>
<td>12-30</td>
<td>8-50</td>
<td>20-80</td>
<td>10-50</td>
<td>10-45</td>
<td>7-8</td>
</tr>
<tr>
<td>Density (g/cm³)</td>
<td>1.3</td>
<td>1.35</td>
<td>1.45</td>
<td>1.44</td>
<td>1.15</td>
<td>1.52</td>
<td>2.5</td>
</tr>
<tr>
<td>Volume Resistivity at 100 Volts (W cm x 10⁵)</td>
<td>-</td>
<td>6.5-7</td>
<td>0.4-0.5</td>
<td>0.7-0.8</td>
<td>9-14</td>
<td>-</td>
<td>9-10</td>
</tr>
</tbody>
</table>
Table 2.4 (Continued)

<table>
<thead>
<tr>
<th>Property</th>
<th>Jute</th>
<th>Banana</th>
<th>Sisal</th>
<th>Pineapple</th>
<th>Coir</th>
<th>Cotton</th>
<th>Glass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fibrillar Angle (degree)</td>
<td>8.1</td>
<td>11</td>
<td>10-22</td>
<td>14-18</td>
<td>30-49</td>
<td>20-23</td>
<td>-</td>
</tr>
<tr>
<td>Cellulose/Lignin Content (%)</td>
<td>59-71/11.8-12.9</td>
<td>60-65/5-10</td>
<td>60-67/8-12</td>
<td>80-85/10-12</td>
<td>43-45/45-50</td>
<td>&lt;2</td>
<td>-</td>
</tr>
<tr>
<td>Elastic Modulus (GN/m²)</td>
<td>-</td>
<td>8-20</td>
<td>9-16</td>
<td>34-82</td>
<td>4-6</td>
<td>27</td>
<td>85.5</td>
</tr>
<tr>
<td>Tenacity (MN/m²)</td>
<td>440-533</td>
<td>529-754</td>
<td>568-640</td>
<td>413-1627</td>
<td>131-175</td>
<td>267-345</td>
<td>4585</td>
</tr>
<tr>
<td>Elongation (%)</td>
<td>1-1.2</td>
<td>1.0-3.5</td>
<td>3.7</td>
<td>0.8-1.6</td>
<td>15-40</td>
<td>3-10</td>
<td>5.7</td>
</tr>
<tr>
<td>Moisture regain after 24 hours (%)</td>
<td>6-9</td>
<td>12-14</td>
<td>10-11</td>
<td>11-12</td>
<td>12-13</td>
<td>7-8</td>
<td>0</td>
</tr>
</tbody>
</table>

The microfibrils in lignocellulosic fibers are arranged in the form of a mesh within the cell walls of fibers. The stiffness and tensile strength of these microfibrils have been reported to be 130–140 GPa and 7 GPa, respectively, comparable with 180 and 3–4 GPa for synthetic Kevlar fibers (Kroonbatenburg et al. 1986, Hepworth et al. 2000 & Nakagaito et al. 2005). A recent review presents the details of preparation of cellulosic whiskers, their suspensions, properties and their use in the preparation of polymer nanocomposites along with mathematical modeling to understand the reinforcing effect of cellulose whiskers (Ahmed et al. 2005).

The stiffness and tensile strength for whole phloem fiber cells of flax fibers are reported to be 80 and 2 GPa respectively (Hepworth et al. 2005). Attempts have been made to exploit these microfibrils (or nanofibrils) by
appropriate extraction (Dufresne et al. 1997) for their use in composite technology, where the mechanical properties of nanofibrils exceed the majority of the commonly used reinforcements. For example, composites produced from Swede root (non-fibrous) reinforced polymer composite with PVA resin have exhibited tensile strength of 70 GPa and Young’s modulus of 5–4 GPa (Hepworth et al. 2005).

Preparation methods of fibers for spinning/blending have also been studied, and attempts have been made to weave other fibers, as in the case of cotton. It has been observed that the fiber size (thickness) determines the fiber content in blending (Cierpucha et al. 2000).

2.4.2 Hybrid Biodegradable Composites

For hybrid biodegradable composites, initially plant fibers were used mostly as short fibers and later as woven or non-woven mats/fabrics. The latter were normally obtained based on textile engineering concepts.

Woven fabrics of jute–cotton and wood flour–sisal waste or short fibers have also been used. Blankets/mats of sisal fabric have been produced by compression using glue (Martins et al. 2004), while blankets of luffa cylindrica fibers available in nature have been successfully tried in the preparation of molded composites by compression or resin transfer molding (RTM) (Boynard et al. 2000).

Fabrics of LC fibers are generally produced by hand weaving with one of the fibers in the warp direction (as yarns) and the other in weft direction, observing the specific number of counts in the weft/warp directions to get suitable yarn width and count. Figure 2.1 (i–k) shows a typical pattern of reinforcements used in hybrid LC-based biodegradable composite synthesis. Such reinforcement materials are available readily in nature, as in
the case of luffa cylindrica or materials prepared by textile engineering concepts will go a long way in the preparation of composites. This has led to several researchers to use such renewable and abundantly available lignocellulosic materials to synthesize nanosized materials and their composites similar to the well-known polymer composites containing clays (Orts et al. 2006).

Permeability studies of lignocellulosic reinforcements indicate the amount of reinforcement (volume fraction) that can be used, based on their compactness and permeability values. Thus, recycled paper, having lower permeability \((3.60 \times 10^{-13} \text{ m}^2)\), is found to be more compact and hence a higher volume fraction (42.3\%) can be used compared to cellulose 200, which has the highest permeability value \((6 \times 10^{-10} \text{ m}^2)\) and hence the lowest content (18.3 vol \%) (Wool et al. 2002). Different merits for using lignocellulosic fibers in composites have been given in the Table 2.3. From the foregoing, knowledge is available on various lignocellulosic fibers, their size, chemical composition and tensile properties, available forms and merits for their use in developing composites.

2.4.3 Matrix

It is well known that renewable resources such as plants (e.g., cellulose or chitin, vegetable oils, etc.), bacteria (Woller dorfer & Bader 1998, Gaspar et al. 2005) as well as non-renewable petroleum based polymers (e.g., aliphatic/ aromatic co-polyester) are sources of a variety of polymeric fibre materials (Kurita 2001, Heredia 2003, Deshmukh et al. 2003, Matas et al. 2004, Xu et al. 2003). Accordingly, biodegradable polymeric materials have been classified as natural or synthetic depending on their origin. Also, biodegradable polymers themselves can be classified depending their origin such as agro polymers (starch or cellulose), microbial (poly (hydroxyalkanoate)), chemically synthesized from agro based resource
monomers (poly (lactic acid)) and chemically synthesized from conventionally synthesized monomers. The classification of these polymers and their nomenclature is shown in Fig. 2.2, while Table 2.5 (Scott 2000, Van & Kiekens 2002 & Carvalho et al. 2000) presents some of their properties.

Table 2.5 includes density, glass transition temperature (Tg), melting temperature (Tm) and mechanical properties for bio-polymers. While the density values are important to predict the weight of the composites designed, particularly with lignocellulosic fibers are also important. The low strength properties of these polymers would suggest choosing appropriate fibers to prepare the biocomposite. Finally, the characteristic temperatures give indications of the thermal stability of the resulting composites, which may also have some bearing on the mechanical properties (Van & Kiekens 2002, Carvalho et al. 2000 & Averous 2004).

![Figure 2.2 Classification of biopolymers and their nomenclature (reproduced from Satyanarayana et al 2007 & 2009)]
Table 2.5 Physical properties of the polymers (Iannace et al 2001, Carvalho et al 2000 & Averous 2004)

<table>
<thead>
<tr>
<th>Property</th>
<th>Type of biopolymer</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>PLA</td>
</tr>
<tr>
<td>Density (kg/m$^3$)</td>
<td>1210</td>
</tr>
<tr>
<td>Tensile strength (MPa)</td>
<td>21</td>
</tr>
<tr>
<td>Young’s modulus (GPa)</td>
<td>0.35</td>
</tr>
<tr>
<td>Elongation (%)</td>
<td>2.5</td>
</tr>
<tr>
<td>Tg (°C)</td>
<td>45</td>
</tr>
<tr>
<td>Tm (°C)</td>
<td>150</td>
</tr>
</tbody>
</table>

2.5 FACTORS INFLUENCING THE PERFORMANCE OF BIOCOMPOSITES

Many factors combine to influence the properties of a composite material; however the properties of a composite are dictated by the intrinsic properties of the constituents. How these properties are harnessed to reinforce a composite material is largely governed by the same factors that affect other fibre composite materials, namely the fibre architecture and the fibre–matrix interface.

2.5.1 Fibre Architecture

Fibre architecture, which encompasses fibre geometry, fibre orientation, packing arrangement and fibre volume fraction, controls composite properties, particularly mechanical properties (Hull & Clyne 1996).
Of these, fibre volume fraction ($V_f$) is probably the single most important factor (Matthews & Rawlings 1994), with most mechanical properties increasing with increasing $V_f$ up to a certain critical point. The maximum $V_f$ achievable is, however, largely governed by the orientation and packing arrangement of the fibres and this is, in turn, dictated by the manufacturing process adopted.

The geometry of vegetable fibres is ultimately controlled by the morphology of the fibre tissue. Fibre geometry can to some extent be influenced by the way in which the fibres are extracted and processed. Softwood fibres, known as tracheids, are generally of the order 1.5–5.0 mm in length with transverse dimensions of between 15 µm and 80 µm, giving them an aspect ratio of around 100 (Wilson & White 1986). In certain processes, such as chemical or thermo mechanical pulping, much of this aspect ratio can be maintained; however, hammer milling reduces the fibres to a particulate form, with low aspect ratio. The aspect ratio of individual bast fibre cells is higher and in the region of 1000–1200. Broadly speaking, it is advantageous to retain as much fibre length as possible, since higher aspect ratios give rise to greater reinforcing efficacy. Retaining fibre aspect ratio through processing and in composite manufacture is difficult, to the extent that in compounded and extruded, the fibre frequently serves only as filler and does little to impart true reinforcement to the composite.

At the micro-scale, work is ongoing to separate bast fibres into their elementary units so as to capitalize on the higher aspect ratio of these individual bast fibre cells as well as increase the surface area available for bonding to the matrix (Stuart et al. 2006). This process also serves to eliminate the defects inherent in the fibres, and strength improvements of up to 50% have also been achieved by such methods. An approach that is currently receiving attention from the research community is to break the
fibres themselves down to form ‘cellulose nano fibres’, which can then be used to reinforce composites (Bruce et al. 2003 & Nakagaito & Yano 2004). By breaking up the fibre cell, microscopic defects in the fibre, that can lead to localised stress concentrations within the composite, can be eliminated (Hughes et al. 2000). Another way of manipulating fibre architecture to improve performance is to align the reinforcing fibre within the matrix. In doing this, the packing arrangement is also generally improved, leading to higher \( V_f \) and hence better performance.

### 2.5.2 The Fibre–Matrix Interface

The interface between fibre-matrix interfaces serves to transfer externally applied loads to the reinforcement via shear stresses over the interface. Controlling the ‘strength’ of the interface is imperative and good bonding is essential if stresses are to be adequately transferred among the reinforcements and to maximize true reinforcing function. Another important mechanical property is toughness, or the ability of an engineering material to resist the propagation of cracks. That might occur in the composites by virtue of its heterogeneous structure. It is important that under certain circumstances interfacial adhesion breaks down, so as to allow various toughening mechanisms to become operative. These mechanisms include crack blunting as proposed by Cook & Gordon (1964), energy absorption processes such as the frictional sliding of debonded fibre fragments within the matrix, fibre fracture and the creation of new crack surfaces (Hull & Clyne 1996). Owing to the general incompatibility between natural fibres and most matrix polymers, methods of promoting adhesion are frequently needed. Several approaches have been explored, including chemical modification of the fibres prior to composite manufacture and introducing compatibilising agents to the polymer/fibre mix during processing.
The fibre–matrix interaction may be improved by making chemical or physical modifications to the fibre. All natural fibres are strongly hydrophilic owing to the presence of hydroxyl groups in the cellulose molecules. The hydrophilic nature of biofibres is a potential cause for incompatibility, adhesion and dispersion problems with hydrophobic polymer matrices. Chemical modifications of natural fibres such as acetylation (Cyras et al. 2004 & Tserki et al. 2005), silylation (Pickering et al. 2003 & Weyenberg et al. 2003) and other treatments reduce their moisture sensitivity. Much remains to be done to change/modify and improve the surface characteristics of composite properties (Jacob et al. 2005).

2.6 MANUFACTURING OF BIOCOMPOSITES

The techniques used to manufacture the bio-composites are based largely on existing techniques for processing plastics or composite materials, including press molding, hand lay-up, filament winding, pultrusion, extrusion, injection molding, compression molding, resin transfer molding and sheet molding compounding. It is probably fair to say that the majority of current bio-composite materials based on thermoplastic polymers such as polypropylene and polyethylene are processed by compounding and extrusion.

2.6.1 Compounding and Extrusion of Thermoplastic Polymers and Natural Fibres

During compounding, the thermoplastic polymer is heated to melt and the wood fibres are usually in the form of flour, added along with other additives to improve the characteristics. Once the constituents have been thoroughly mixed, the compound can be either extruded directly in the final product or packed as a precursor to further extrusion or injection moulding processes (Ortmann et al. 2005).
2.6.2 Co-Mingling of Thermoplastic and Natural Fibres

In the automotive industry, longer fibres from flax, hemp, kenaf and cotton are frequently used. These are generally mingled together with fibres of the thermoplastic polymer being used as reinforcement to form a nonwoven structure, which is subsequently hot pressed to melt the thermoplastic fibre thereby forming the composite. The advantage of this approach is that longer fibres (with better reinforcement potential) can be used (Gassan 2003).

2.7 LIGNOCELLULOSIC FIBRES: ADVANTAGES AND DISADVANTAGES

The growing interest in lignocellulosic fibres is mainly due to their lower cost with few requirements for equipment and low specific weight, which results in a higher specific strength and stiffness when compared to glass reinforced composites. They also present safer handling and working conditions compared to synthetic reinforcements. Bio-fibres are nonabrasive to mixing and molding equipment, which can contribute to significant cost reductions. The most interesting aspect about natural fibres is their positive environmental impact. The processing atmosphere is friendly with better working conditions and therefore there will be reduced thermal and respiratory irritation. Biofibres possess high electrical resistance. Thermal recycling is also possible. The hollow cellular structure provides good acoustic insulating properties (Yang & Li 2012). The worldwide availability is an additional factor that promotes the use of such fibres (Maya & Sabu 2008). Comparative features of Natural Fibre Composites (NFC) and other materials are given in Table 2.6.
Table 2.6 Comparative features of natural fibre-reinforced composites (NFC) and other materials

<table>
<thead>
<tr>
<th>Properties</th>
<th>NFC</th>
<th>Manmade fibre composites</th>
<th>Particle Board Composites</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (g/cc)</td>
<td>1.72 – 1.76</td>
<td>0.5 – 0.9</td>
<td>0.5 – 0.9</td>
</tr>
<tr>
<td>Moisture Content %</td>
<td>0.2 – 0.38</td>
<td>5 – 8</td>
<td>5 – 15</td>
</tr>
<tr>
<td>Modulus of Bending, N/mm²</td>
<td>85 – 95</td>
<td>12.5 – 15</td>
<td>12.5 – 15</td>
</tr>
<tr>
<td>Tensile Strength, N/mm²</td>
<td>22 – 24</td>
<td>0.6 – 0.7</td>
<td>0.4 – 0.45</td>
</tr>
<tr>
<td>Flexural strength N/mm²</td>
<td>78.5 – 101</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Water Absorption % 24 hours</td>
<td>1.1 – 1.5</td>
<td>10 – 12</td>
<td>17 – 20</td>
</tr>
</tbody>
</table>

2.8 NATURAL FIBRE COMPOSITES IN INDIA

Natural fibres as reinforcing agent in composite matrices (such as cement and polymer) are attracting more attention for various low-cost building products. The natural fibres are abundantly available locally and extracted from renewable resources. Presently, the production of natural fibres in India is more than 6 Million tons as compared to worldwide production of about 25 million tons (Geeta et al. 2005 & Mohanty et al. 2001). Agro-based materials such as plant fibers and natural polymers are some examples. These are abundantly available in nature, but more often than not lead to the generation of “wastes” as shown in Table 2.7 (Pravin & Viveka 2015 & Satyanarayana et al. 2005).
Table 2.7  Availability of natural fibre in India and its applications in building materials (Pravin & Viveka 2015, Satyanarayana et al. 2005)

<table>
<thead>
<tr>
<th>Item</th>
<th>Source</th>
<th>Qty. in MT/year</th>
<th>Application in building material</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rice Husk</td>
<td>Rice mills</td>
<td>25.0</td>
<td>As fuel, for manufacturing building materials and products for production of rice husk binder, fibrous building panels, bricks, acid proof cement</td>
</tr>
<tr>
<td>Bagasse</td>
<td>Sugar mills</td>
<td>5.0</td>
<td>Insulation boards</td>
</tr>
<tr>
<td>Banana leaves/stalk</td>
<td>Banana plants</td>
<td>0.20</td>
<td>In the manufacture of building boards, fire resistance fibre boards</td>
</tr>
<tr>
<td>Coconut husk</td>
<td>Coir fibre industry</td>
<td>3.0</td>
<td>In the manufacture of building boards, roofing sheets, insulation boards, building panels, as a lightweight aggregate, coir fibre reinforced composite, cement board, geo-textile, rubberized coir</td>
</tr>
<tr>
<td>Groundnut shell</td>
<td>Groundnut oil mills</td>
<td>11.00</td>
<td>In the manufacture of buildings panels, building blocks, for making chip boards, roofing sheets, particle boards</td>
</tr>
<tr>
<td>Jute sticks and bark</td>
<td>Jute mills</td>
<td>5.0</td>
<td>For making chip boards, roofing sheets, door shutters</td>
</tr>
</tbody>
</table>
A lot of research has been done on natural fibre reinforced polymer composites but research on banana, coir and sisal fibre reinforced recycled paper pulp biocomposite is very rare. Against this background, the present research work has been undertaken, with an objective to explore the potential of banana, coir and sisal fibre based biocomposites and to study the mechanical, physical and sound absorption characterization of different biocomposites made from them.

### Table 2.7 (Continued)

<table>
<thead>
<tr>
<th>Item</th>
<th>Source</th>
<th>Qty. in MT/year</th>
<th>Application in building material</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rice/wheat straw</td>
<td>Agricultural farm</td>
<td>90/33</td>
<td>Manufacture of roofing units and walls panels/boards</td>
</tr>
<tr>
<td>Saw mill waste</td>
<td>Saw mills/wood</td>
<td>2.00</td>
<td>Manufacture of cement bonded wood chips, blocks, particle boards, insulation boards, briquettes</td>
</tr>
<tr>
<td>Sisal fibres</td>
<td>Sisal plantation (Asia)</td>
<td>0.023</td>
<td>For plastering of walls and for making roofing sheets, composite board with rice husk, cement roofing sheet, roofing tiles, manufacturing of paper and pulp</td>
</tr>
<tr>
<td>Cotton stalk</td>
<td>Cotton plantation</td>
<td>1.10</td>
<td>Fibre boards, panel, door shutters, roofing sheets, autoclaved cement composite, paper, plastering of walls</td>
</tr>
</tbody>
</table>
The study here is focused only on the sound absorption properties of these biocomposites. Biocomposite blocks, made up of lignocellulosic fibres and recycled papers are used to study the acoustic parameters of the panels fitted in the room.

2.9 BIOSCOMPOSITES AS SOUND ABSORBING MATERIALS

This topic contributes to the body of knowledge on the sound absorption properties of bio-based materials, provides a better understanding of the models of some multiporous bio-based materials and multilayered structures, and contributes to the wider adoption of bio-based materials as sound absorbers.

2.9.1 Porous Sound Absorbing Materials

A wide range of sound absorbing materials exist; they provide absorption properties depending upon the frequency, composition, thickness, surface finish and methods of mounting. However, materials that have a high value of sound absorption coefficient are usually porous in nature (Crocker & Arenas 2007). A porous absorbing material is a solid that contains cavities, channels or interstices so that sound waves are able to enter through them and get dissipated. It is possible to classify porous materials according to their availability to an external fluid such as air. The pores that are totally isolated from their neighbors are called closed pores. They have an effect on some macroscopic properties of the material such as its bulk density, mechanical strength and thermal conductivity. However, closed pores are substantially less efficient than open pores in absorbing the sound energy. On the other hand, open pores have a continuous channel of communication with the external surface of the body, and they have great influence on the absorption of sound. Open pores can also be blind (open only at one end) or through (open at two ends) (Rouquerol et al. 1994).
2.9.2 Cellular Absorbance

Porous absorbing materials can be classified as cellular, fibrous or granular; this is based on their microscopic configurations. Porous materials are characterized by the fact that their surfaces allow the sound waves to enter the materials through a multitude of small holes or openings. Materials made from open-celled polyurethane and foams are examples of cellular materials. Fibrous materials consist of a series of tunnel-like openings, formed by interstices in material fibres (Kazragis et al. 2002). Fibrous materials include those made from natural or synthetic fibres such as glass and mineral fibres.

2.9.3 Granular Absorbance

Consolidated granular materials consist of relatively rigid, macroscopic bodies, whose dimensions exceed those of the internal voids by many orders of magnitude (agglomerates). Unconsolidated materials consist of loosely packed assemblages of individual particles (aggregates).

Granular absorbing materials include some kinds of asphalt, porous concrete, granular clays, sands, gravel, and soils (Magrini and Ricciardi 2000 & Asdrubali & Horoshenkov 2002). So the acoustical properties of granular materials are an important factor in controlling outdoor sound propagation (Attenborough & Umnova 2005).

Figure 2.3 shows the three main types of porous sound absorbing materials, their typical microscopic arrangements and some of the physical models used to describe their absorbing mechanisms. When a porous material is exposed to incident sound waves, the air molecules at the surface of the material and within the pores of the material are forced to vibrate and in doing so, lose some of their original energy. This is because part of the energy of the air molecules is converted into heat due to thermal and viscous losses at the
walls of the interior pores and tunnels within the material. At low frequencies, these changes are isothermal, while at high frequencies, it becomes adiabatic. In fibrous materials, much of the energy can also be absorbed by scattering from the fibres and by the vibration caused in the individual fibres (Rouquerol et al. 1994 & Zwikker & Kosten 1949).

![Image of three main types of porous absorbing materials](reproduced from Jorge et al 2010)

**Figure 2.3** The three main types of porous absorbing materials (reproduced from Jorge et al 2010)

The sound absorption mechanism in bulk granular materials is quite similar to that in rigid porous materials where the solid structure can be regarded as ideally rigid and stationary. Then the sound absorption is produced by the viscosity of the air contained inside the interconnecting voids that separate the granules. At low (100-500 Hz) and mid frequencies (500-1000 Hz), the solid structure interacts with the bulk of the gas through an isothermal heat transfer process. In addition, scattering from the granules also influences the absorption of sound energy inside the material. In general, the
basic theoretical approach used to describe the sound absorption of a porous material assumes that the frame of the sound absorber is constrained. Several models (and further improvements) have been developed using this assumption (Delany and Bazley 1970, Allard and Champoux 1992 & Champoux and Stinson 1992). Although the complete poroelastic model developed by Biot (1956a&b) considers the fact that the frame is not constrained (elastic-framed material), simplified models of sound propagation give accurate enough results in the most practical cases. The theoretical details and model comparisons have been discussed by several authors (Umnova et al. 2001, Kidner & Hansen 2008, Allard 1993, Mechel 2002 & Cox & Antonio 2004).

2.9.4 Porous Fibrous Materials

Most of the porous sound-absorbing materials commercially available are fibrous. Fibrous materials are composed of a set of continuous filaments that trap air between them. They are produced in rolls or in slabs with different thermal, acoustical and mechanical properties. Fibres can be classified as natural or synthetic (artificial). Natural fibres can be vegetable (cotton, kenaf, hemp, flax, wood, etc.), animal (wool, fur felt) or mineral (asbestos). Man-Made fibres can be cellulose (bamboo fibre, for example), mineral (fibreglass, mineral wool, glass wool, graphite, ceramic, etc.), or polymer (polyester, polypropylene and Kevlar) (Jorge & Malcolm 2010).

Synthetic fibrous materials made from minerals and polymers are used mostly for sound absorption and thermal isolation. However, since they are made from high-temperature extrusion and industrial processes based on synthetic chemicals, often from petrochemical sources, their carbon footprints are quite significant. Recently, the use of natural fibres in manufacturing sound absorbing materials has received much attention (Ballagh 1996, Zulkifli et al. 2008, Koizumi 2002 & Del Rey et al. 2007). Natural fibres are
essentially completely biodegradable and modern technical developments have made natural fibre processing more economical and eco-friendly. These new methods may result in increased use of high-quality fibre at competitive prices for industrial purposes. The absorption properties of sound-absorbing materials made of these fibres can be similar to those made from minerals and synthetic polymers. These properties can be modified by pre-treatments such as drying, carbonizing, impregnation and mineralization. In addition, natural fibres are also safer for human health compared with most mineral synthetic fibres, since they do not need precautions in handling.

2.10 NATURAL FIBRE REINFORCED COMPOSITES AS SOUND ABSORBERS

Natural fibres are often light and are not harmful for human health and, can therefore be used as sound absorbers in room acoustical products and noise barriers. Furthermore, many of these materials are currently available in the market at competitive prices (Asdrubali et al 2012). Considering bamboo fibre, the sound absorption coefficient increases as the bamboo fibre diameter decreases with the diameters of 90-125 µm, 125-210 µm and 210-425 µm. The energy loss increases as the surface friction increases, because the number of the bamboo fibre increases per the unit area when the bamboo fibre diameter decreases, the sound absorption coefficient becomes high (Koizumi et al 2002). Meanwhile, tests of the sound absorption behavior of natural fibres have shown that their cell-lumens allow them to embrace more diversified modes to attenuate sound wave energy. It is found (Yang & Li 2012) that a single sisal fibre is made up of a bundle of hollow sub fibres that have lumen within them with many connected air cavities, and those air cavities might be the major contributors of sound energy absorption. The cell wall of a sub-fibre is made up of millions of nanofibres (Li et al. 2010). In the presence of nanofibres, fine morphology involving more cells with smaller
size can be achieved. Due to the presence of this fine morphology, more paths for passing sound waves are created and also higher absorption of sound energy, because of higher friction between sound waves and internal cell walls (Bahrambeygi et al. 2013). On the other hand, the nano-sized fibres would also lead to the extra vibrations, which result in more dissipation of sound energy (Koizumi et al. 2002). In contrast, glass fibre has the same regular and solid construction. The sound absorption coefficients of the rice-straw composite boards increases as the frequency increases and, decreases at a frequency of 1000 Hz and then increases again due to their specific characteristic of rice straw reflecting sound in the low frequency range, and absorbing the sound in the middle and high frequency ranges (Asasutjarit et al. 2007 & Jayaraman 2005).

The mechanism by which natural fibre materials absorb sound energy mainly involves three physical processes. First, when the sound waves are incident on the fibres, the viscous effects between the fibre frame and air cavities attenuates part of sound energy and convert it into heat. Second, heat transfer happens due to temperature distinction between different fibres caused by friction, (Sagartzazu et al. 2008) and also this process will further dissipate sound energy. Third, the vibration of air in the bulk materials will also lead to the vibration of fibres (Allard & Daigle 1994, Voronina 1994).

The sound wave could propagate through the air spaces and inside the lumen of natural fibres and a unique lumen structure endows the natural fibres with superior sound absorption ability. Moreover, it can be appreciated that natural fibres possess a multi-scale structure, as shown in Fig. 2.4.

2.10.1 Single Layer Structured Natural Fibre Composites for Sound Insulation

Despite their good acoustical absorption coefficients, natural fibres are not commercially used in their natural form. Generally, they need to be
mixed with additives to keep them in shape and improve characteristics such as fire retardancy and stiffness.

![Multi-scale structure of sisal fibre with glass fibre](reproduced from Yang and Li 2012)

**Figure 2.4** Multi-scale structure of sisal fibre with glass fibre (reproduced from Yang and Li 2012)

In the view of adding value to current natural fibre composites, considerable attention has been paid on the utilization of natural composite materials in sound absorption products. Single layer structured natural fibre composites are defined here as those made through one-step cold/hot compacting of natural fibres and/or natural fibre-bonding agent blends. These composites are divided into two general categories: low-density insulation panels and medium to high-density composite panels (Xiaodong et al. 1965).

### 2.10.2 Low Density Insulation Panels

The density of insulation panels is an important parameter that noise control engineers often are concerned about. In the low-density insulation panels, natural fibres are compacted together to form highly porous structures. The sound insulation properties of low-density panels are controlled by inter-fibre voids and within-fibre voids (cell-lumen). 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 waves need to enter the porous materials. Thus, there should be enough pores in the materials for the sound to pass through and to 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 (Allard et al. 1989).

The sound absorption coefficients of kapok fibrous assemblies showed that the average noise absorption coefficient of kapok fibrous assemblies increased from 0.627 to 0.646 when the bulk density increased from 8.3 kg/m$^3$ to 25.0 kg/m$^3$ (Xiang et al 2013). The maximum absorption coefficient increases monotonically with the fibre mass density for the cashmere and acrylic fibres, while for the kapok there is an optimal fibre mass density that maximizes the absorption coefficients (Yang et al. 2011). And, compaction increases the chance of friction between sound waves and fibres and when the sound energy loss increases in passing the inter-fibre voids as the surface friction increases, the sound absorption coefficient becomes high. A summary of relevant published data for the acoustic properties of some traditional and natural fibre materials and their composites is given in Table 2.8.

Table 2.8  Sound absorption of various natural fibre reinforced composites

<table>
<thead>
<tr>
<th>Composite type</th>
<th>Specific Gravity</th>
<th>Methods of fabrication</th>
<th>Acoustical Property</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wood-based Material</td>
<td>0.65-0.80</td>
<td>Loose fibres or flakes, with suitable resin binders, compressed into a high-density panel.</td>
<td>Viewed as inherently sound reflecting, rather than sound absorbing.</td>
<td>Wassilieff 1996</td>
</tr>
<tr>
<td>Rice Straw–wood Particle-Composite</td>
<td>0.40 0.60 0.80</td>
<td>Mixing Cut pieces of Rice straw and Wood Particles, was Slowly Sprayed with UF resin adhesive.</td>
<td>It has higher sound absorption coefficient than particle board and plywood in the 500–8000 Hz frequency range.</td>
<td>Yang et al 2003</td>
</tr>
</tbody>
</table>
### Table 2.8 (Continued)

<table>
<thead>
<tr>
<th>Composite type</th>
<th>Specific Gravity</th>
<th>Methods of fabrication</th>
<th>Acoustical Property</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tea-Leaf Fibre Composites</td>
<td>0.02</td>
<td>Composite samples prepared by mixing tea-leaf fibres with a polyurethane formulation.</td>
<td>The 1 cm thick sample is equivalent to that provided by six layers of woven textile fabrics.</td>
<td>Ersoy and Küçük 2009 &amp; Ekici et al 2012</td>
</tr>
<tr>
<td>Coconut Coir Fibre Composite</td>
<td>0.82</td>
<td>Industrial prepared coconut fibres mixed with binder</td>
<td>Fresh coir fibre has a sound absorption coefficient of 0.8. But the samples, mixed with binder have lower sound absorption.</td>
<td>Hosseini et al 2011 &amp; Zulkarnain et al 2011</td>
</tr>
<tr>
<td>Hemp concrete</td>
<td>0.40</td>
<td>Mixing of hemp particles, binder and water.</td>
<td>Has high porosity that combines the microscopic pores of binder and vegetable particles.</td>
<td>Glé et al 2011</td>
</tr>
<tr>
<td>Kapok fibre Composite</td>
<td>0.12</td>
<td>Kapok fibres blended with polypropylene fibres</td>
<td>Special large lumen and thin cell walls structure is beneficial for the sound absorption</td>
<td>Veerakumar and Selvakumar 2012 &amp; Xiang et al 2013</td>
</tr>
<tr>
<td>Corn particle board</td>
<td>0.33</td>
<td>Bind corn cob particles with wood glue</td>
<td>A gain in terms of impact sound insulation capacity</td>
<td>Faustino et al 2012</td>
</tr>
<tr>
<td>Ramie, Flax and Jute Composites</td>
<td></td>
<td>Three kinds of natural fibres reinforced epoxy composites made by hot press.</td>
<td>The multi-scale and hollow lumen structures contribute to the high sound absorption performance</td>
<td>Yang &amp; Li 2012</td>
</tr>
<tr>
<td>Bamboo Fibreboard</td>
<td>0.40-0.60</td>
<td>Bamboo fibreboard formed using 10% binders of material weight by hot press molding.</td>
<td>Sound absorption is higher in high frequency range than plywood.</td>
<td>Koizumi et al 2002</td>
</tr>
</tbody>
</table>
2.10.3 Medium to High Density Composite Panels

Hot-pressed natural fibre composites with medium or high density are made with resin coated fibre, particulate particle strands and surface layer of natural materials such as kenaf, flax, sisal, hemp, cork, sheep wool, bamboo, or coconut fibres, which have shown good sound absorbing performance as given in Table 2.9. Structural arrangement in these composites differs significantly. For example, fibre and particle-type composites are made to form a relatively homogeneous mat through thickness and hot pressing.

Table 2.9 Acoustic properties of some traditional and natural fibre composites

<table>
<thead>
<tr>
<th>Fibre type</th>
<th>Thickness (mm)</th>
<th>Bulk density (g/cm³)</th>
<th>SAC* (at 500 Hz)</th>
<th>NRC*</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cotton</td>
<td></td>
<td>0.04</td>
<td>0.50</td>
<td>0.62</td>
<td>Oldham et al 2011 &amp; Yang and Li 2012</td>
</tr>
<tr>
<td>Flax</td>
<td>50</td>
<td>0.08</td>
<td>0.40</td>
<td>0.55</td>
<td></td>
</tr>
<tr>
<td>Ramie</td>
<td></td>
<td>0.10</td>
<td>0.40</td>
<td>0.55</td>
<td></td>
</tr>
<tr>
<td>Wool</td>
<td></td>
<td>0.10</td>
<td>0.20</td>
<td>0.35</td>
<td></td>
</tr>
<tr>
<td>Jute</td>
<td></td>
<td>0.07</td>
<td>0.20</td>
<td>0.35</td>
<td></td>
</tr>
<tr>
<td>Sisal</td>
<td></td>
<td>0.04</td>
<td>0.10</td>
<td>0.16</td>
<td></td>
</tr>
<tr>
<td>Kapok</td>
<td>60</td>
<td>0.01</td>
<td>0.57</td>
<td>0.63</td>
<td>Xiang et al 2013</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.02</td>
<td>0.54</td>
<td>0.65</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.04</td>
<td>0.64</td>
<td>0.61</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.06</td>
<td>0.30</td>
<td>0.48</td>
<td></td>
</tr>
<tr>
<td>Glass wool</td>
<td>40</td>
<td>0.03</td>
<td>0.40</td>
<td>0.56</td>
<td>Asdrubali 2006</td>
</tr>
<tr>
<td>Mineral wool</td>
<td></td>
<td>0.07</td>
<td>0.70</td>
<td>0.65</td>
<td></td>
</tr>
</tbody>
</table>

*SAC – Sound Absorption Coefficient at 500 Hz; *NRC – Noise Reduction Coefficient
Strand and surface layer composites are made by orienting face/core strands or surface layer to take advantages of strength/expansion properties of wood along the longitudinal direction. Compared to natural fibres, the sound absorption properties of hot-pressed composites generally are reduced. Natural fibres possess excellent sound absorption properties by themselves, whereas the free spaces within and between fibres can be significantly diminished in the case of hot-pressed composites. Meanwhile, the resin would occupy certain effective volume of airflow, as well as cavities between fibres and inside lumens, which tend to become compressed by the pressure applied during the process of composite manufacturing. The sound absorption behavior of the resin system is obviously very low. Additionally, the sound absorption properties largely depend on the frequencies of the sound waves (Yang & Li 2012). The higher the frequency, the shorter the sound waves length and the longer the propagation path of sound wave in the composites. Therefore, more dissipation of sound energy happens in the composites at high frequencies. This explains why natural fibre composites have the best sound absorption performance at high frequencies.

2.10.4 Multilayer Structured Composites

The development of materials, both rigid and light with high damping effect and acoustic insulation, is possible by using a multilayer panel with viscoelastic material. The layered absorbing structure is composed of different sound absorption materials according to certain parameters, making the acoustic attenuation among absorbing layer structure achieve good sound absorption. The object vibrates according to the change of the atmospheric pressure when sound impacts it. This vibration energy dissipates during the transmissible process from inside to outside of the object and increases according to the increase of the weight of the object, generally known as the Mass Law of Sound Insulation (Heckl 1981). Over the years, a great deal of
research has been carried out in identifying the absorption characteristics of different panel constructions.

2.10.5 Sandwich Structure for Sound Insulation

Due to the high stiffness-to-weight and strength-to-weight ratios, sandwich composite materials consisting of two thin and stiff skin sheets (Bahrambeygi et al. 2013) and a lightweight core without adding an excessive mass (Bahrambeygi et al. 2013) are widely employed for sound absorption and vibration damping in various structural applications including aircraft, spacecraft, automotive, wind-turbine blades, and so on. Kurtze and Watters (1959) suggested that a sandwich panel might be a useful way to increase the sound insulation between adjoining spaces over that, which could be obtained using a homogeneous plate. The results are based on an elementary model of sandwich behavior, wherein the core acts as a spacer and transmits shear, while the skins respond as elementary bent plates (Moore & Lyon 1991). Combinations of natural materials have been explored in a sandwich structure configuration. Cotton, bamboo and carbon fibre based composites are chosen as face sheets, while balsa wood, pine wood and synthetic foam are used as core materials in sandwich composite materials. These research works suggest that, if optimized, natural material based sandwich composites could be an environmentally friendly solution to the sandwich structure-noise radiation problem (Sargianis et al. 2013).

2.10.6 Honeycomb Structure for Sound Insulation

A honeycomb panel is a thin lightweight plate with a honeycomb core with hexagonal cells. Flexible, layered laminates are bonded to both sides of the core. When combined into a sandwich panel these elements form a stiff, strong and lightweight structure. The faces of the structure carry the
bending loads and the core carries the shear loads. In general, the honeycomb core is strongly orthotropic, while laminates are not.

A new honeycomb core design has been used to improve the sound absorption. In comparison to a cement panel of the same mass, the honeycomb panels have higher sound absorption at low frequencies between 100 and 200 Hz due to higher stiffness and damping. The honeycomb panels have more significant vibration responses above 500 Hz but these are limited by damping (Ng & Hui 2008).

Thin continuous rolls are produced in conical twin-screw extruders that are thermoformed into half hexagonal or sinusoidal profiles. The corrugated profiles were stacked and then bonded using ultrasonic methods to form cores for sandwich panels. The characteristic sound absorption of these panels at particular frequencies, coupled with good mechanical properties, make them eco-friendly and suitable in automobile, aerospace, packaging and building/construction industries (Rao et al. 2011).

2.11 FACTORS INFLUENCING ACOUSTIC PERFORMANCE IN FIBRE FORM

2.11.1 Fibre Type

Natural fibres have more effective sound proofing properties when compared with synthetic fibres. Natural fibre with reinforced polymer composite has greater capability of sound damping and hence achieving CO₂ balance (Holbery & Houston 2006). Shoshani & Wilding (1991) have shown that the acrylic fibres have generally better sound absorption than wool, the difference (up to 10%) that becomes more significant in the higher frequency range (f > 1000 Hz) (Shoshani & Wilding 1991). Jayaraman (2005) examined the effect of kenaf fibre, which is a natural bast fibre, on the absorption of sound in nonwovens. Untreated kenaf has a negative effect on the noise
reduction performance compared to polyester and reclaimed polyester fibres, however, this effect is less pronounced at high frequencies.

2.11.2 Fibre Size

Porosity, elastic modulus, thickness, flow resistance all of these depends only on the fibre size. Micro fibres have large surface area and hence have greater probability of absorbing more sound than other fibres. They are likely to emerge soon as efficient noise control materials (Jayaraman 2005). A decrease in the fibre diameter increases the sound absorption coefficient. Since, thin fibres can move easily more than thick fibres on sound waves (Hoda 2009).

2.11.3 Fibre Shape

Different fibre shapes result in diverse surface areas, which in turn lead to different viscous and thermal effects (Cox & Antonio 2004). An irregular cross section of fibre also alters the sound absorption behavior (Jayaraman 2005). Greater fibre surface area results in greater sound absorption friction between fibres and air and a direct correlation exists between sound absorption and fibre surface area. In the frequency range 1125 Hz – 5000 Hz, fibres with serrated cross sections absorb more sound compared to the ones with round cross sectional area.

2.12 FACTORS INFLUENCING ACOUSTIC PERFORMANCE OF FABRICS

2.12.1 Woven Structure

Micro-fibre fabrics have great sound absorption potential. Micro-fibre fabrics (except those with a mesh structure) absorbed all sound frequencies better than a conventional fabric because their fibres have a
higher surface area than those of regular fibre fabrics, resulting in higher flow resistance. A thick fabric shows higher absorption at low-frequency than thin fabrics (Young et al. 2007).

2.12.2 Nonwoven Structure

While designing a nonwoven web so as to have a high sound absorption coefficient, the porosity should increase with increasing frequency of the sound wave (Shoshani & Wilding 1991). According to the literature (Young et al. 2007) with increase in frequency, areal density and the distance from the source, the extent of sound reduction increases, while increase in air permeability the extent of sound reduction of the material is decreased (Young et al. 2007). The sound absorption coefficient increases in nonwoven fabrics due to surface friction increases which cause energy loss (Hoda 2009).

2.12.3 Knitted Structure

Fleece fabrics made from normal fibres by knitting technique show less absorption than all micro-fibre based fabrics except mesh structure, proving that micro-fibre fabrics are good sound absorbing materials. Young et al. (2007) found that sound absorption property mainly depends on fabric structure.

2.13 FACTORS INFLUENCING ACOUSTIC PERFORMANCE OF COMPOSITES

The structural factors of the composite materials that mainly influence the acoustic performance are fibre cut-length, fibre volume fraction, material thickness, density and porosity; these can change the sound absorption behavior of the composite materials.
2.13.1 Fibre Cut-length

The composite boards prepared with rice straw which was cut into certain specific sizes and those prepared with random size rice straw showed no difference in strength, but modulus of rupture and internal bonding of composite boards have been considerably improved. This is in line with the found that the use of short fibre length could not lead to any further increase of bending strength (Asasutjarit et al. 2007). The effect of fibre length is directly proportional to sound absorption; the longer is the fibre, the lighter the board and the higher the sound absorption.

2.13.2 Fibre Content

Han-Seung Yang et al. (2004) proved that test samples prepared from composite board containing 30 wt. % of random cut rice straws, without size screening have good acoustic insulating properties over a wide frequency range, because of the larger pores. The bending strength and sound absorption is increased when the rice straw particle length and content were increased. Lower fibre content leads to lower void space, moisture content, water absorption, thickness of swelling and sound absorption.

2.13.3 Thickness

Mohammad Hosseini Fouladi (2010) stated that adding polypropylene to coir fibre air gap combination helped to greatly reduce the thickness of air gap while the acoustical performance remained intact. Hence it is an efficient tool to reduce the thickness of acoustic isolators in practical use (Mohammad 2010).

The thicker the material, the higher is the sound absorption (Fig. 2.5). Generally, when the thickness of the material matches one tenth of the
wavelength of the incidence sound, effective sound absorption is achieved. At a resonance frequency of one-quarter wavelength of the incidence sound, peak sound absorption occurs. The necessity for the significant thickness to wavelength ratio renders porous materials inefficient as sound absorbers at low frequency. This ratio is extremely small at low frequencies as the wavelength may reach values that are in the order of 10 meters (Cox & D’Antonio 2004).

![Figure 2.5 Effect of thickness on sound absorption](image)

2.13.4 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 (Fig. 2.6). A previous study showed that increase in the density of the sample increased the sound absorption value in the middle and high frequency levels. The number of fibres per unit area increases when the apparent density is high (Hoda 2009, Young et al. 2007 & Teli et al. 2007).
2.13.5 Porosity

In order for a material to absorb sound, it must be porous, so that the sound waves can move into the material. Porosity is the ratio of open space volume to the total volume of the porous material. Only connected pores, which are accessible to air flow, should be included in porosity (Cox & D’Antonio 2004). The gravimetric measurement of the porosity requires the knowledge of the volume of the porous material and the density of the fibres. The porous material is weighed and fabric density is calculated.

The effects highlighted in the graphs increasing porosity airflow will result in increased levels of absorption performance (Fig. 2.7 and 2.8) and with that the potential to improve the acoustic comfort of any space that these materials are used within.
2.13.6 Tortuosity

The ratio between the passage way through the pores and the thickness of the porous material is called tortuosity (Jayaraman 2005). Tortuosity gives the extent of the deviation of the pores from the normal of material thickness. The sound absorption performance of porous materials is generally affected by tortuosity which does not allow the sound waves to follow straight paths. The air that is forced to follow a tortuous path suffers accelerations which cause momentum transfer from air to the material. The value of tortuosity determines the high frequency behavior of sound absorbing porous materials (Jayaraman 2005).

2.13.7 Air Gap

Air gap behind the material increases NAC (normal incidence sound absorption coefficient) substantially in the low frequency range with the cost of high frequencies Jayaraman (2005) found that the air gap caused an increase in the absorption in the frequency range from 500 to 4500 Hz. He did not find a significant difference in NAC values for nonwovens with 5 mm air gap compared to those with 10 mm air gap, whereas the maxima peak is at a lower frequency for the greater depth of the air gap (Jayaraman 2005).
Summarizing the effects highlighted in the graphs, increasing density /thickness/ porosity and airflow will result in increased levels of absorption performance and with that the potential to improve the acoustic comfort of any space that these materials are used (Fig 2.5 – 2.8).

2.14 APPLICATIONS OF MODELING METHODS

To predict the acoustic behavior of bio-based materials and structures, models with the power of predicting the noise absorption coefficient have been investigated (Shoshani & Yakubov 1999). One of the first fundamental works on the bending of sandwich plates was published by Hoff (1950). Hamilton's principle was used to derive the differential equations governing the bending of rectangular sandwich panels. Another classic paper develops a simple model to predict the sound transmission through sandwich panels (Nilsson 1990). The laminates are described as thin plates. The thick core is isotropic and only shear effects are included. A more general description of the bending of sandwich beams is given by Nilsson (1990). The general wave equation is used to describe the displacement in the core. Most of the models that have been found to be useful for predicting acoustical properties fall in one of two categories: theoretical micro-structural and empirical phenomenological models (Cox & Antonio 2004). These modeling categories are explained in the following sections.

2.14.1 Finite Element Method

Generally the transfer matrix methods of modeling are not adapted to predict the vibro-acoustic behavior of finite skew plates. The finite element method (FEM) used by Panneton & Atalla (1996) to predict the sound transmission through finite multilayer systems with poroelastic materials is well adapted to model complex finite geometries. These models, while accurate, lead to large frequency-dependent matrices for three-dimensional
problems, necessitating important setup time, computer storage and solution
time. Various finite element methods are often proposed for describing the
vibration of sandwich panels. For example, Liew et al. (1995) used a finite
element model for the numerical evaluation of frequency response functions
of honeycomb panels. Structures with and without delaminating were
considered. A finite element vibration analysis of composite beams based on
Hamilton's principle is presented by Shi & Lam (1999). A standard finite
element method code is used by Cummingham et al. (2000), to determine the
Eigen frequencies of curved sandwich panels. The agreement between
predicted and measured Eigen frequencies is found to be very good.

2.14.2 Patch-mobility Approach

Nevertheless, the main drawback of finite element models comes
from the significant computational time required. The patch-mobility method
(PMM), which is used to couple acoustic linear problems, is presented by
Ouisse et al. (2005). It allows one to consider several acoustic subsystems,
coupled through surfaces divided into elementary areas called patches. These
subsystems have to be studied independently with any available method, in
order to build a database of transfer functions called patch transfer functions,
which are defined using mean values on patches, and rigid boundary
conditions on the coupling area. Indeed, the use of a mobility technique
makes it possible to characterize each component of the vibro-acoustic
problem separately, either analytically or numerically, and then to calculate
the global response, by solving the interaction equation. If one element is
modified, then only its own characterization has to be calculated before
solving interaction equations (Chazot & Guyader 2007).
2.14.3 Empirical Models

Due to structural and geometrical complexities, it is extremely hard to define the acoustical behavior of most sound absorbers based on theoretical models (Chazot & Guyader 2007). Thus, a number of empirical models have been developed for sound absorption behavior (Cox and Antonio 2004 & Asdrubali and Horoshenkov 2002). One of the most used empirical models for absorbent materials has been proposed by Delany and Bazley (1970). They obtained simple power-law relations by best fitting a large amount of experimental data for a range of fibrous porous absorbers. The empirical model is a good and fast approximation to the theoretical calculations because the model needs only one input parameter, which is the airflow resistivity. Bies & Hansen (1980) extended the lower and upper frequency ranges of validity of this model. Further updates and improvements were recommended by Miki (1990 a & b). The model of Allard & Champoux (1992) is derived purely from a more rigorous theoretical basis. The range of validity extends further than that of Delany & Bazley (1970), but it is also limited to fibrous materials. The main reason for these models being restricted to fibrous material only, is due to the two other important material parameters, porosity and tortuosity, being significantly different from unity.

Unlike models developed particularly for absorbing materials and frequency ranges, the Champoux-Allard model is a generalized model for sound propagation over a wide range of frequencies. The model of Champoux-Allard is based on five intrinsic properties of the porous medium: the flow resistivity, porosity, tortuosity, viscous characteristic and thermal characteristic. While the open porosity and airflow resistivity can be directly measured, the measurements of the three remaining properties are usually complex. To solve the problem, an inverse characterization method based on impedance tube measurements is proposed. It is shown that this method can yield reliable evaluations of the tortuosity, viscous and thermal characteristic (Atalla et al. 1998).
In addition, Garai & Pompoli (2005) developed an empirical model based on a number of measurements upon polyester fibres. Due to the differences of fibre diameters and the densities of the matrix materials, they corrected some parameters in order to apply the calculations of polyester fibres effectively (Garai & Pompoli 2005). The model proposed by Delany & Bazely (1970) was found to predict values of absorption coefficients for fibres with a large range of diameters, which were in better agreement with measured values than predicted by the model of Garai & Pompoli (2005). However, the latter model gave more accurate predictions for the case of wool, for which the fibre diameters were similar to those of the polymer fibres on which the Garai & Pompoli (2005) model was based. Both models were not effective when dealing with large diameter fibres. This failure may be due to the differences in the diameters of the fibres involved in their derivation from those of the coarser natural fibres. This could be resolved by a systematic study similar to that carried out by Delany & Bazely (1970), Garai & Pompoli (2005). It should be pointed out that the diameter and density of polyester are similar to natural fibre. Thus, using the Garai and Pompoli model to predict the sound absorption parameter of natural fibre might give an accurate result (Yang & Li 2012). Table 2.10 indicates summary of the various selected models.

**Table 2.10 Summary of the various selected models**

<table>
<thead>
<tr>
<th>Sl. No</th>
<th>Finite Element Method (FEM)</th>
<th>Patch-mobility approach</th>
<th>Empirical models</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>It is one of the numerical methods</td>
<td>Either analytical or numerical methods</td>
<td>It is found to be an efficient statistical technique that can be used for various experimental investigations</td>
</tr>
<tr>
<td>2</td>
<td>Many time-consuming experiments can be replaced by computer simulations</td>
<td>It is a time-consuming experimental process</td>
<td>It is a time-consuming experimental process</td>
</tr>
</tbody>
</table>
Table 2.10 (Continued)

<table>
<thead>
<tr>
<th>Sl. No</th>
<th>Finite Element Method (FEM)</th>
<th>Patch-mobility approach</th>
<th>Empirical models</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>It is an efficient and cost-effective way to model and analyze the relationships that describe process Variations</td>
<td>The use of a mobility technique makes it possible to characterize each component of the problem separately, either analytically or numerically, and then to calculate the global response, solving the interaction equation</td>
<td>It is an efficient and cost-effective way to model and analyze the relationships that describe process variations</td>
</tr>
<tr>
<td>4</td>
<td>FEM code for simulating is not commercially available</td>
<td>It is not a commercially available model</td>
<td>It is a commercially available model</td>
</tr>
<tr>
<td>5</td>
<td>It is proposed to result in a reduction of the necessary experimental cost and effort in addition for receiving a higher level of verification</td>
<td>It is proposed to result in a reduction of the necessary experimental cost and effort in addition for receiving a higher level of verification</td>
<td>It is proposed to result in a reduction of the necessary experimental cost and effort in addition for receiving a higher level of verification</td>
</tr>
<tr>
<td>6</td>
<td>It represents the existing process in order to evaluate the quality of the inputs</td>
<td>It provides the guidance in the selection of the proper combination of the process parameters at their specified levels</td>
<td>It provides the guidance in the selection of the proper combination of the process parameters at their specified levels</td>
</tr>
</tbody>
</table>

### 2.15 STRUCTURE OPTIMIZATION FOR SOUND ABSORPTION

The sound transmission/absorption performance of materials is of the utmost importance for noise control in automobiles, aircrafts, buildings, highway infrastructures and several other engineering applications. There is a growing interest in optimizing and developing layered absorbing composites,
which will meet the high stiffness-to-weight ratio and offer improved acoustic performance. In order to design noise absorbers comprising of several layers with different properties, a theoretical generalization of the Zwikker & Kosten model was suggested (Shoshani & Yakubov 2000, 2001). The material and geometric properties of the structure are treated as the design variables with the objective to maximize the sound transmission loss across the beam. Appropriate constraints are imposed to maintain material and structural integrity (Thamburaj & Sun 2002). An optimization study of cylindrical sandwich shells to minimize the transmitted sound into the interior is presented. From the promising optimization results it is seen that the reinforcement angles in the composite sandwich layers are effective structural design parameters to minimize the sound transmission into the interior without giving up the structural rigidity, particularly at low frequencies where the structural damping is not effective (Denli & Sun 2008). The novel Discrete Material Optimization (DMO) formulation has been applied to achieve the design optimization of fibre angles, stacking sequence and selection of material for laminated composite plates. Several numerical examples are presented in order to illustrate this approach (Niu et al. 2010).

The influence of morphologically altered cellulose fibres on the acoustic and mechanical properties was described by Neithalath et al. (2004). Three fibre morphologies for macro-nodules, discrete fibres, and petite nodules were considered. The acoustic absorption coefficient was found to increase with an increase in fibre volume for three fibre types investigated, though “macro-nodule” fibres were found to be the most effective. This suggests that there is an optimum fibre volume, which maximizes the loss modulus for saturated composites while the loss modulus is practically independent of fibre volume for dry composites (Neithalath et al. 2004). The acoustic absorption properties of various common fibre assemblies including cashmere, goose down and kapok fibre materials were studied (Yang et al.
There generally exists a sound frequency maximizing the absorption capability of fibre assembly at a given fibre mass. In addition, the characteristic diameter of effective pores, instead of the porosity or the fibre volume fraction is the dominant factor on the sound absorption of the fibre assemblies. The results suggest that a fibre assembly with a lower fibre density and a smaller fibre average diameter leads to a better sound absorption performance (Yang et al. 2011).

Recent development in wood/natural fibre filled plastic composite co-extrusion technology allows creating multi-layer composites with different complementary layer characteristics, and in making properties of final products highly “tunable”. For example, target composite properties such as oxygen, sound and moisture barrier, shading and insulation and mechanical properties can be achieved by incorporating one or more layers with target properties. In addition, co-extrusion can significantly reduce material and production costs, and help recycle used material (Kim et al. 2012 & Yao & Wu 2010). Sound insulation application of co-extruded wood/natural fibre plastic composites can help develop new market opportunities for the materials in both exterior and interior uses.

However while the acoustical properties of many natural fibres have been investigated, the comparative acoustical characteristic of various lignocellulosic fibres is rarely studied. It is found that the scientific data on acoustical properties of banana, coir and sisal fibre reinforced recycled paper pulp composites is not available. In the present study, our attention has been focused on physical, mechanical and acoustic characteristics of these fibres reinforced recycled paper pulp composites with fifteen different combinations for each fibre. Apart from this, a comparison between the physical and acoustic properties of three different fibre reinforced composites has been also presented with respect to different fibre cut length, fibre volume fractions and thickness of the biocomposites.
2.16 FUNDAMENTALS OF ACOUSTICS

The objective of this topic is to give basic information about acoustics and its control. The content of this chapter has been gathered from various textbooks, research papers and website publications.

2.16.1 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 (Lewis 1994 & Hong 2005). The vibration in a medium produces alternating waves of relatively dense and sparse particles, compression and rarefaction, respectively as shown in the Figure 2.9.

![Figure 2.9 Alternative patterns of dense and sparse particles](image)

The resultant variation to normal ambient pressure is translated by the ear and perceived as sound. A simple sound wave is illustrated in Figure 2.10 and may be described in terms of variables like: amplitude, frequency, wavelength, period and intensity. To control sound in today’s world environment, we need to know a little about these fundamental properties. Once these fundamental properties of sound or sound waves are understood,
we can proceed to implement effective noise control measures (Robert 2011 & Filippi 1998).

2.16.2 Frequency (pitch)

Sound is a form of mechanical energy transmitted by vibration of the molecules of whatever medium the sound is passing through. The speed of sound in air is approximately 344 m/s. In steel it is approximately 4987 m/s, and in water 1494 m/s. The denser the medium, the faster sound travels in that medium. A pure sound wave of a single frequency takes the shape of a sine wave (Figure 2.10). The number of cycles per second made by a sound wave is termed its frequency, expressed in hertz (Hz). The sound we hear is usually radiated in all directions from a vibrating medium (Robert 2011 & Filippi 1998).

![Figure 2.10 Wavelength in air versus frequency under normal conditions](image)

Most of the sounds we hear, however, are a combination of many different frequencies (Figure 2.11). Healthy young human beings normally hear frequencies as low as about 20 Hz and as high as 20,000 Hz. At middle age this range decreases to about 70 to 14,000 Hz. By comparison, the frequency range of a piano keyboard is from 31.5 Hz to 8,000 Hz (Filippi 1998). Because human hearing is most acute to frequencies in the region of 4000 Hz, we hear a 4000 Hz tone as being louder than a tone at some other
frequency, even though the acoustical energy or sound power may be the same. For purposes of noise control, acousticians divide the audible sound spectrum into octaves, just as the piano keyboard does. These divisions are expressed as octave bands and are referred to by their center frequencies. Each center frequency is twice that of the one before it. When a more detailed sound spectrum is required, octave bands are further divided into thirds as shown in Table 2.11.

![Figure 2.11 Complex sound wave patterns](image)

**Table 2.11 Octave band and band limits**

<table>
<thead>
<tr>
<th>Octave band center</th>
<th>frequencies, Hz Band Limits</th>
</tr>
</thead>
<tbody>
<tr>
<td>32-22</td>
<td>45</td>
</tr>
<tr>
<td>63-45</td>
<td>89</td>
</tr>
<tr>
<td>125-89</td>
<td>178</td>
</tr>
<tr>
<td>250 -178</td>
<td>355</td>
</tr>
<tr>
<td>500-354</td>
<td>709</td>
</tr>
<tr>
<td>1000-707</td>
<td>1414</td>
</tr>
<tr>
<td>2000-1411</td>
<td>2822</td>
</tr>
<tr>
<td>4000-2815</td>
<td>5630</td>
</tr>
<tr>
<td>8000-5617</td>
<td>11234</td>
</tr>
</tbody>
</table>
2.16.3 Wavelength

The wavelength of a sound wave is the distance between the start and end of a sound wave cycle or the distance between two successive sound wave pressure peaks (Figure 2.12). Numerically, it is equal to the speed of sound in the material such as air divided by the frequency of the sound wave (Robert 2011, Filippi 1998 & Smith et al 1996). For example: The wavelength of a 100 Hz tone at room temperature is 344 m/s divided by 100 Hz which is equal to 3.4 m.

![Figure 2.12 Two sounds of equal frequency and differing amplitude](image_url)

2.16.4 Amplitude (loudness)

The amplitude or loudness of a sound wave is expressed by its sound pressure level. Sounds having the same wavelength (equal frequency) may have differing loudness (Figure 2.12). Because the sound pressure of a sound wave may vary over a wide range of change in magnitude of ten million to one, it is expressed using a logarithmic scale. This is the basis of the decibel scale, which compresses the range of sound pressure into a scale from 0 to 150. The decibel (dB) is not an actual measure of amplitude or loudness, but expresses the ratio between a given sound pressure and a reference sound pressure (Robert 2011, Filippi 1998 & Smith et al. 1996).
This relationship is expressed by the following equation:

\[
\text{Sound pressure level (L}_p\text{)} = 10 \log \left( \frac{P}{P_{re}} \right)^2
\]  

(2.1)

where, \(L_p\) is the Sound Pressure Level; \(P\) is the Sound Pressure (Pa); \(P_{re}\) is the sound pressure at the threshold of hearing (0.00006 Pa).

Table 2.12 gives sound pressure levels in dB and sound pressure in Pascal’s (Pa) for various sounds within the human hearing range. Note that, because the decibel scale is logarithmic, a sound pressure level of 80 dB is 1,000 times that of the sound pressure level at 40 dB (Robert 2011 & Filippi 1998).

**Table 2.12 Sound pressure levels for various sounds**

<table>
<thead>
<tr>
<th>Source of noise</th>
<th>Sound pressure level, dB</th>
<th>Sound pressure, Pa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Threshold of pain</td>
<td>120</td>
<td>20</td>
</tr>
<tr>
<td>Loud rock music</td>
<td>110</td>
<td>6.3</td>
</tr>
<tr>
<td>Metalworking plant</td>
<td>100</td>
<td>2</td>
</tr>
<tr>
<td>Average street noise</td>
<td>70</td>
<td>0.06</td>
</tr>
<tr>
<td>Average office noise</td>
<td>60</td>
<td>0.02</td>
</tr>
<tr>
<td>Quiet residential street</td>
<td>50</td>
<td>0.006</td>
</tr>
<tr>
<td>Very quiet home radio</td>
<td>40</td>
<td>0.002</td>
</tr>
<tr>
<td>Inside a country home</td>
<td>30</td>
<td>0.0006</td>
</tr>
<tr>
<td>Threshold of hearing</td>
<td>10</td>
<td>0.00006</td>
</tr>
</tbody>
</table>
2.16.5 Period

The term ‘period’ can be defined as the time required for the completion of one cycle of wave motion (Hong 2005).

2.16.6 Intensity

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 (Smith et al 1996):

\[
\text{Wavelength} = \left( \frac{\text{Velocity of sound (m/s)}}{\text{Frequency (Hz)}} \right)
\] (2.2)

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 (Robert 2011 & Filippi 1998). 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 time (Hong 2005).

2.17 NOISE POLLUTION

Noise pollution is an important issue when the sonic level exceeds the limit 65 dB, i.e. noise or sound hazarders. Higher levels of noise, further, affects human health and can lead to hypertension, depression, dizziness and most commonly, loss of hearing ability (Cho-nan and Jiunn-Hwan 2001). The consequences of excessive noise, range from the merely annoying, unpleasant psychological effects to harmful physiological effects (Lewis 1994, Hong 2005, Robert 2011, Filippi 1998, Smith et al. 1996 & Cho-nan & Jiunn-Hwan 2001).
2.18 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 pleasant are accompanied by noise. A noise system can be broken down into three elements as shown in figure 2.13 (Filippi 1998 & Cho-nan & Jiunn-Hwan 2001):

- 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

Figure 2.13 A common noisy situation in many populated cities

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, development and retooling. 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 a 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 (Filippi 1998 & Cho-nan & Jiunn-Hwan 2001). In general four basic principles are employed to reduce noise (Filippi 1998 & Cho-nan & Jiunn-Hwan 2001): isolation, absorption, vibration isolation and vibration damping.

2.18.1 Materials for Sound Control

Sound control materials are classified into three types such as barrier (to resist absorption), absorption and damping materials as shown in Table 2.13 (Lewis 1994).

Table 2.13 Sound control materials and classification

<table>
<thead>
<tr>
<th>Barrier Material</th>
<th>Absorbent material</th>
<th>Damping Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glass</td>
<td>Non woven</td>
<td></td>
</tr>
<tr>
<td>Wood</td>
<td>Woven</td>
<td>Barrier and absorbent material including any type of fluids</td>
</tr>
<tr>
<td>Composite</td>
<td>Knitted</td>
<td></td>
</tr>
<tr>
<td>Brick wall</td>
<td>Porous materials</td>
<td></td>
</tr>
</tbody>
</table>

2.18.2 Sound Absorption

The sound absorption using textile materials lead to following reactions: sound energy dissipates into heat energy, change in the flow direction of sound wave and friction with the fibres and air molecules. Absorption is categorized into Porous absorption and resonant absorption phenomena (Smith 1996).
2.18.3 Porous Absorption

Porous absorptive materials include open air-filled pores such as mineral wools, textiles, upholstered furniture, porous fibreboards, certain coating materials, etc. This kind of absorbents are the most important when it comes to general noise control. The transformation of the kinetic energy of sound wave into thermal energy is due to the friction among the moving air particles and the material itself. This is why materials with open air-filled pores are preferred for noise reduction. If the pores are closed, the sound wave will not penetrate the material and there will be no loss due to friction (Filippi 1998).

2.18.4 Resonant Absorption or Resonance

Resonant absorption does not depend on the properties of the material in the same way as for porous absorption, where the absorption is obtained by energy losses in an oscillating system. The absorption coefficient does not increase with the frequency, as for porous absorbers, but has its maximum around a determined frequency, known as the resonance frequency (Filippi 1998).

2.19 SOUND ABSORPTION BY FIBROUS MATERIALS

Sound absorbing substances absorb the sound energy and convert this to thermal energy when the sound wave strikes the fibres or fibrous assemblies, a phenomenon of energy conversion process. When a sound wave hits the surface of a material, part of it will be absorbed and part of it will be reflected (figure 2.14), depending upon the properties of the material (Smith et al. 1996). Reverberation time will be long in a room without sound absorbent materials and long reverberation times reduce the clarity of speech with noise and echoes (Filippi 1998). Sound and noise control is required

Natural sound absorbing materials such as air, water vapour and many impurities are present in the environmental. However, such natural sound absorptions are almost never sufficient. There are several kinds of commercial absorbers available in the market such as porous and resonant absorbers (Filippi 1998 & Yakir & Yakov 1999).

![Figure 2.14 Sound absorption mechanisms](image)

Many research papers quote that textile materials having a porous structure (foam and nonwovens) have good sound absorption properties. Nonwoven fibre webs can be considered as noise control elements for a wide range of applications, such as acoustic ceilings and barriers, carpets and wall claddings (Robert 2011). Rock wool, glass, polyester, cotton and acrylic fibres also have high acoustic absorption coefficients. Sometimes fire resistant fibres are also used in making acoustical products (Brüel & Kjær 2012). In comparison with other sound absorbents in the market, textile materials have several advantages like low production costs, low specific gravity and can also function as decoration and thermal control substances (Ballagh 1996). However, noise absorption coefficient of porous materials generally depends
on the thickness, flow resistance, porosity and morphology of pores (Ballagh 1996 & Young et al. 2007). A graph (Figure 2.15) plotted between frequency / absorption of different materials shows that different elements can change the absorption qualities of some materials. For example with fibreboard, painting the surface of the board decreases its absorption potential, especially at frequencies above 500 Hz (Hoda 2009 & Robert 2011).

Figure 2.15  Absorption characteristics of some materials (Hoda 2009 & Lewis 1994)

Building materials are generally rated by their Noise Reduction Coefficient (NRC). This single number rating is the average of the sound absorption coefficients of a material at 250, 500, 1000, and 2000 Hz, rounded to the nearest 0.05 (Robert B 2011 & Filippi 1998). Sound absorption
coefficients and single number rating values are determined using ASTM Standard C423, Standard Test Method for Sound Absorption and Sound Absorption Coefficients by the Reverberation Room Method. A material is usually considered to be a sound absorber if it has an NRC value greater than 0.35 (Robert 2011 & Filippi 1998).

The sound absorption performance of a material is commonly published as a Table (2.14) of sound absorption coefficients at octave band center frequencies from 125 to 4000 Hz. For example, Table 2.14 gives sound absorption data for Certain Teed CertaPro™ Commercial Board, Type CB 300 (Filippi 1998).

<table>
<thead>
<tr>
<th>Type</th>
<th>Thickness</th>
<th>Octave Band Center Frequencies, Hz</th>
<th>NRC</th>
</tr>
</thead>
<tbody>
<tr>
<td>CB 300</td>
<td>Inches</td>
<td>125</td>
<td>250</td>
</tr>
<tr>
<td>(unfaced)</td>
<td>mm</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>0.08</td>
<td>0.25</td>
</tr>
<tr>
<td></td>
<td>1 ½</td>
<td>0.10</td>
<td>0.51</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>0.21</td>
<td>0.73</td>
</tr>
<tr>
<td></td>
<td>2 ½</td>
<td>0.31</td>
<td>0.81</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>0.41</td>
<td>0.96</td>
</tr>
<tr>
<td></td>
<td>3 ½</td>
<td>0.72</td>
<td>1.14</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>0.75</td>
<td>1.18</td>
</tr>
</tbody>
</table>

2.20 PERFORATED ACOUSTICAL UNITS

Various types of perforated, imperforated, fissured or textured cellulose and mineral fibre tiles, lay in panels and perforated metal pans with

2.20.1 Acoustical Plasters and Sprayed-on Materials

These acoustical finishes are used mostly for noise reduction purposes and sometimes in auditoriums where any other acoustical treatment would be impractical because of the curved or irregular shape of the surface. These are applied in semi-plastic consistency, either by spray gun or by hand trowelling (Robert 2011).

2.20.2 Acoustical Blankets

Acoustical blankets are manufactured from rock wool, glass fibres, wood fibres, hair felt, etc. Generally installed on a wood or metal framing system, these blankets are used for acoustical purposes for varying thicknesses between 1-5 inches. Their absorption increases with thickness, particularly at low frequencies (Jorge et al. 2010, Hoda 2009, Yakir & Yakov 1999 & Brüel & Kjær 2012).

2.20.3 Carpets and Fabrics

These absorb airborne sounds and noises within the room, also reduce and in some cases almost completely eliminate impact noises above from it and also eliminate surface (surrounded) noises (Smith et al. 1996).

2.20.4 Panel Absorbers

Any impervious materials installed on a solid backing but separated from it by an air space, will act as a panel absorber and vibrate when struck by sound waves. The flexural vibration of the panels then absorbs certain
amount of incident sound energy by converting into heat energy (Jorge et al 2010, Hoda 2009 & Cho-nan and Jiunn-Hwan 2001). Among the auditorium finishes and constructions the following panel absorbers contribute to low-frequency absorption: wood and hard board panels, gypsum boards, rigid plastic boards, windows, doors, glazing, etc (Robert 2001 & Filippi 1998). Wall structures like porous wall partitions, double wall partitions, cavity walls are often used as the sound absorbers in various constructions (Robert 2011, Cho-nan & Jiunn-Hwan 2001 & Filippi 1998).

- Rigid and massive homogeneous walls consist of stone, brick or concrete masonry, well plastered on one or both sides. Their sound insulation depends on their weight per unit area (Robert 2011).

- Partition wall of porous material can be of rigid or non-rigid type. In the rigid partitions, insulation is 10% higher (Jorge et al 2010, Robert 2001 & Filippi 1998).

- Double wall partition consists of plasterboards or fibreboards or plaster on laths on both the faces, with sound absorbing blankets in between (Robert 2001 & Filippi 1998).

- Cavity wall construction is an ideal construction from the point of view of sound insulation. The gap between two walls can be filled by air or some resilient material (Robert 2001 & Filippi 1998).

2.21 ACOUSTICS MEASUREMENTS

This topic deals with the basic measurements of acoustics and detailed description of the various methods that facilitate the determination of sound absorbers’ parameters. The first part deals with the description of sound absorbing materials’ acoustical parameters. The second part introduces different methods for determination of these parameters, impedance tube methods and reverberant field method with the comparisons highlighted.
2.21.1 Basics of Sound Level Measurements

A sound level meter is used to measure the sound pressure levels. Since the human ear is not equally sensitive to all sound levels, most sound level meters have internal frequency weighting systems to give readings equivalent to how one hears the sound levels. These weighting systems are designated as A, B & C. The ‘A’ weighting is used most frequently because it yields sound measurements that most closely reflect how we actually hear a sound. These response curves, which plot the relative response in dB against frequency in Hz, are shown in Figure 2.16. Continuous exposure to weighted sound levels above 85 dB can cause permanent hearing loss. It is possible, under perfect listening conditions, for the human ear to detect changes in sound level as little as 1 dB. However, a change of at least 3 dB is normally required in order to be detectable (Filippi 1998, Robert 2011). A 10 dB change in sound level is commonly heard as twice as loud or one-half as loud. Sound is measured in decibels (dB), using sound level meters.

![Figure 2.16 A, B and C frequency weighting curves (Robert 2011)](image)

Figure 2.16 A, B and C frequency weighting curves (Robert 2011)

Sound level meters measure the pressure of the sound waves. The higher the decibel, the higher is the sound pressure and louder the levels. However, it’s very important to understand that decibels are measured on a logarithmic scale and not a linear scale. This means that every increase of 1 dB equates to a ten-fold increase in sound intensity (roughly equivalent to loudness) so a 20 dB sound is not twice as loud as a 10 dB sound, but ten
times as loud. That’s why an increase of a single decibel can make a significant difference, particularly at higher decibel levels. Each extra decibel means more energy, which at a certain energy level can cause damage to the ear drum. For the same reason, when you have several sources of sound, measuring the total sound level is not just a case of adding decibels together. For example, if you have two machines each generating 80 dB of sound, the total sound level is not 160 dB but 83 dB. This is because decibels need to be first converted to their sound pressures, then added and converted back to decibels (Hong 2005 & Robert 2011).

As an example, if a running motor is emitting sound at 65 dB, and a second similar motor is also operated, the total sound pressure level will be 65 + 3 = 68 dB. If one motor is emitting 65 dB and the other 70 dB, when both motors are operating the total sound pressure level will be 70 + 1 = 71 dB. If one motor is emitting 65 dB and the other 75 dB, when both motors are operating the total sound pressure level will remain at 75 dB, the sound level of the noisier motor. In this example, the effect of the logarithms in the calculation means that doubling the amount of decibels only results in a 3 dB increase in the total sound level. It calls for a precise measurement. Imprecise sound level meters often have a margin of error of up to 3 dB, which can make a significant difference in terms of observations (Table 2.15).

Table 2.15  Adding dB to sound levels for second source (Hong 2005 and Robert 2011)

<table>
<thead>
<tr>
<th>If the difference between the two sound levels is:</th>
<th>Add to the higher sound level:</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 dB or less</td>
<td>3 dB</td>
</tr>
<tr>
<td>2 or 3 dB</td>
<td>2 dB</td>
</tr>
<tr>
<td>4 to 9 dB</td>
<td>1 dB</td>
</tr>
<tr>
<td>10 dB or greater</td>
<td>0 dB</td>
</tr>
</tbody>
</table>
2.22 HOW DO WE SENSE LOUDNESS?

As noted, sounds at some frequencies are perceived as louder to the human ear than sounds at certain other frequencies, even though they may actually have the same dB level. This demonstrates two interesting facts about how we hear (Robert 2011, Filippi 1998 & Smith et al 1996):

- The lower the frequency, the less sensitive the human ear is to it, especially sounds below 100 Hz.
- The human ear is most sensitive to sounds around 4000 Hz.

2.22.1 Sound Propagation

Sound waves radiate directly and spherically outward from the source (Figure 2.17), decreasing in amplitude with the square of the distance from the source and sound pressure level decreasing 6 dB for each doubling of distance. However, if the sound source is indoor, the reflected or reverberant sound will add to the overall sound level within the room to make up for the decreasing direct sound energy (Robert 2011).

Figure 2.17 Direct sound energy decreases with the square of the distance from the source (Robert 2011)
2.22.2 Acceptable Background Sound

We have defined noise as unwanted sound. Whether we are in our homes, workplaces, or outdoors, we will almost certainly be exposed to a certain level of background or ambient sound. Before we can begin to solve a noise control problem, we must determine how much background sound is acceptable. We can never create, nor do we really want, a completely sound-free environment. We do not wish to live in a world without sound. The question becomes: at what level does background sound become too loud for a particular situation? A moderate level of background sound can be helpful when it prevents private conversation in the home or office from being overheard by nearby listeners, yet doesn’t make it difficult for those conversing, to be heard by each other. Very low level background sound can even contribute to sleep or rest when not interrupted by intermittent or sudden loud noises. In some public places, a somewhat higher level of background sound may be acceptable (Table 2.16) (Robert 2011).

Table 2.16 Acceptable indoor noise levels (Robert 2011)

<table>
<thead>
<tr>
<th>Type of building noise level range</th>
<th>Sound level, dB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radio &amp; T.V. station</td>
<td>25-30</td>
</tr>
<tr>
<td>Music room</td>
<td>30-35</td>
</tr>
<tr>
<td>Hospital &amp; Auditorium</td>
<td>35-40</td>
</tr>
<tr>
<td>Apartments, hospitals &amp; homes</td>
<td>35-40</td>
</tr>
<tr>
<td>Conference room, offices &amp; library</td>
<td>35-40</td>
</tr>
<tr>
<td>Court room &amp; class room</td>
<td>40-45</td>
</tr>
<tr>
<td>Public offices, banks &amp; stores</td>
<td>45-50</td>
</tr>
<tr>
<td>Restaurants</td>
<td>50-55</td>
</tr>
</tbody>
</table>
2.23 SOURCES OF NOISE

Sources of noise can be classified as those originating outside and those originating inside a building (Robert 2011, Filippi 1998 & Smith et al 1996).

2.24 SOUND PATHS

Sound waves can travel through any media such as air, water, wood, masonry, or metal, depending on the media through which it travels, sound is either airborne or structure borne (Hong 2005, Robert 2011& Filippi 1998).

Airborne sound radiates from a source directly into and travels through the air. The sound of traffic passing our homes, the sound of music or voices from the next room or office and the noise from low flying aircraft all travel to our ears as airborne sound.

The structure borne sound is travelling through solid materials usually in direct mechanical contact with the sound source or from an impact on that material. Examples are footsteps or objects falling on the floor upstairs, a knock at the door, or vibration from loud speakers on the floor. All structure borne sound must eventually become airborne sound in order for us to hear it. We can only feel structure borne sound as vibrations in a material. In most noise control situations, both airborne and structure borne sound must be considered. The difference between the airborne and structure borne noise is related to the origin of noise in relation to the receiver room only.

2.25 ACOUSTIC PROBLEMS IN ROOMS

2.25.1 Echo

Sound wave after originating in an enclosed space spreads out and strikes the surfaces of ceiling, walls, floors and objects like furniture. Some of
them are reflected back. These reflected waves get reunited and give rise to echo. In other words, echo is an indirect or reflected voice heard just after the direct hearing of the voice coming from the same sound source. The formation of echoes normally happens when the time lag between the two voices is about $1/17$ of a second and the reflecting surfaces are situated at a distance greater than 15 m (Robert 2011 & Filippi 1998). This defect usually occurs when the shape of reflected surface is smooth in texture. Echoes cause disturbance and unpleasant hearing. These can be avoided by planning the shape and size of the room based on the simple law of reflection, which states that the direction of travel of reflected sound should make the same angle with the wall as that of the incident sound (Hong 2005, Robert 2011 & Filippi 1998).

2.25.2 Dead Spots

Due to high concentration of the sound rays at some points, spots of low sound intensity are sometimes formed, causing unsatisfactory hearing for the audience situated in these spots known as 'dead spots'. This defect can be eliminated by providing suitable diffusers, enabling uniform distribution of sound in the hall (Robert 2011 & Filippi 1998).

2.25.3 Long Delayed Reflection

This defect is similar to echo except that the time delay between the perception of direct and reflected sound is a little less (Robert 2011 & Filippi 1998).

2.25.4 Reverberation

Reverberant sound is the reflected sound, as a result of improper absorption. Excessive reverberation is one of the most common defects, with
the result that sound once created prolongs for a longer duration resulting in confusion with the sound created next. However, some reverberation is necessary for good hearing. Thus, optimum clarity depends on correct reverberation time, which can be controlled by suitably installing the absorbent materials (Smith et al. 1996 & Cho-nan & Jiunn-Hwan 2001).

2.25.5 Insufficient Loudness

This defect is caused due to lack of sound reflecting flat surfaces near the sound source and excessive sound absorption treatment in the hall. The defect can be removed by providing hard reflecting surface near the source, and by adjusting the absorption of the hall so as to get optimum time of reverberation (Robert 2011 & Filippi 1998).

2.25.6 External Noise

External noise from vehicles, traffic engines, factories, cooling plants, etc. may enter the hall either through the openings or through even walls and other structural members having improper sound insulation. This defect can be removed by proper planning of the hall with respect of its surroundings and by proper sound insulation of exterior walls (Smith et al 1996 & Cho-nan & Jiunn-Hwan 2001).

2.26 Acoustical Properties Measurements

As mentioned earlier, there are many problems caused due to noise which include malfunctioning of machines and instruments, mental tension, deafness, headache, etc. To overcome these problems, absorbing materials are used. Several types of sound absorbing materials are currently available for noise control applications and plenty of examples can be found in the area of building construction and transportation industry (Hong 2005, Robert 2011&

Acoustic material testing is the process by which acoustic characteristics of materials are determined in terms of absorption, reflection, impedance, admittance and transmission loss. Different methods can be used to determine the acoustic properties of materials and these methods mainly involve exposure to known sound fields and measuring the effect of the material’s presence on the sound field, and in order to ensure accuracy and repeatability, there is a range of standards covering material testing that prescribes well-defined acoustical conditions and special instrumentation. Yakir & Yakov (1999) used methods devised by Roush to test acoustic materials for measuring acoustic absorption, transmission loss and insertion loss.

2.27 ACOUSTIC ABSORPTION TESTING

Sound absorption is an important property of automotive interior components because it measures how effectively sound is dissipated once it enters the interior, which affects the overall sound levels. When a sound wave strikes a surface, a fraction of the acoustic energy is absorbed and the remainder is reflected. The ratio of absorbed energy to incident energy averaged over all possible angles of incidence is the Sabine Absorption Coefficient (or simply the absorption coefficient) of the surface. The Sabine area is the absorption coefficient multiplied by the actual surface area. The absorption coefficient is measured by placing a sample in a reverberant room, introducing a sound source, terminating the sound source, and measuring the
resulting sound field decay. To minimize laboratory-to-laboratory variation, standardized reverberation rooms are used to during the measurements (Yakir & Yakov 1999).

### 2.27.1 Alpha Cabin Testing

The Alpha Cabin (Fig. 2.18) is a one-third scale (8.6 ms) reverberation room that is used to measure the random incidence sound absorption of materials and parts. The test is similar to ASTM C-423 but carried out in a smaller room than that specified in the ASTM C-423. The Alpha Cabin has approximate dimensions of 1.2 m x 1.6 m x 1.8 m with nonparallel walls. Nonparallel walls force the reflecting sound waves that produce the modes (standing waves) to reflect from all the walls in the room. Thus, a sample placed on the floor will affect the decay time of all of the modes. The Alpha Cabin equipment tests the sample, one third-octave band at a time. The sound field decay rate is measured and recorded at each of five microphone positions. This process is repeated for each third octave band from 400 Hz to 10,000 Hz. The absorption coefficient is calculated from the average of five measured decay rates for each third octave band (Roush 2013).

![Figure 2.18 Alpha Cabin for the random incidence sound absorption of materials](image-url)
2.27.2  Impedance Tube Testing (Two-microphone Transfer-function Method)

An impedance tube (Fig. 2.19) is used to test material samples for normal incidence sound absorption according to ASTM E1050 and ISO 10534-I and ISO 10534-II, “Standard Test Method for Impedance and Absorption of Acoustical Materials Using a Tube, Two Microphones and a Digital Frequency Analysis System.” In an impedance tube, a loudspeaker is mounted at one end and a material sample is placed at the other end. The loudspeaker generates random sound waves which propagate as plane waves in the tube and are reflected from the sample surface. This leads to a standing-wave interference pattern resulting from forward- and backward-travelling waves inside the tube. The sound pressure is measured at two microphone locations and the transfer function between the two measurements is calculated (Roush 2013). From this information, it is possible to determine the complex reflection coefficient, the sound absorption coefficient and the normal acoustic impedance of the material. The usable frequency range depends on the diameter of the tube and the spacing between the microphone positions. Roush method can provide measurements from 100 Hz to 1,600 Hz, as well as from 400 Hz to 6,300 Hz.

Figure 2.19  Schematic diagram of the impedance tube for the two-microphone transfer-function method (Roush 2013)
An Impedance tube can be used to measure the acoustic properties of small test samples, including composite materials (for example, ceiling tiles) and irregular materials (for example, fissured acoustic tiling). The piston back plate, onto which test samples are mounted inside the adjustable sample holders, can be withdrawn in order to produce an air gap behind the test sample. This can be used to simulate measurements on hanging ceilings (Roush 2013).

### 2.27.3 Impedance Tube Testing (Four-microphone Transfer-function Method)

A sound source (loudspeaker) is mounted at one end of the impedance tube, and a sample of the material is placed in a holder (Fig. 2.20). The loudspeaker generates broadband, stationary random sound waves that propagate as plane waves. The plane waves hit the sample in the holder with part of the waves reflected back into the source tube, part absorbed by the material and part passing through the material to the receiving tube. The portion of the plane waves that pass through the material then encounter the end of the receiving tube where some of the waves are reflected and some exit the tube. By measuring the sound pressure at four fixed locations (two in the source tube and two in the receiving tube) and calculating the complex transfer function using a four-channel digital frequency analyzer, it is possible to determine the transmission loss of the material. The usable frequency range depends on the diameter of the tube and the spacing between the microphones positions (Roush 2013).

The measurement of a material’s transmission loss is of interest for noise control using a barrier. This is important where a noise source can be separated from the listener by an obstruction, for example, in an automobile, where the dashboard acts as a barrier between the engine and passenger.
compartments, or in buildings, where a wall or door separates a noise source from a listener.

**Figure 2.20 Schematic diagram of the impedance tube for the four-microphone transfer-function method** (Roush 2013)

Techniques exist for measuring the performance of a complete component (dashboard, door, etc.) using a source and a receiving room or using a reverberation room, but the procedures take a long time to set up and produce results. Also, measurements of a complete component are a function of the component’s materials, the geometry of the component and its boundary conditions and would be very sensitive to the fixing method.

It is desirable to measure the transmission loss of components’ materials for directly use in (Roush 2013):

- Comparison of different materials for specific applications
- Analytical models used in the design of materials and components
- Performance verification of materials before they are manufactured into component
2.27.4 Overview of Sound Absorption Measurements

There are two basic approaches to determine the acoustic characteristics of sound absorbing materials and structures: one by using a reverberation chamber and the other by using a tube as an acoustic interferometer (Miki 1990 a&b, Atalla et al. 1998, Garai & Pompoli 2005 & Shoshani & Yakubov 2000). A transfer function is set up in the interferometer tube and it is possible to measure not only the absorption coefficient but also to estimate the corresponding reflection coefficient (Garai & Pompoli 2005). In an impedance tube method, there are five basic measurement methods: standing wave, transfer function, least-squares, three point and nonlinear regression. The advantages of the impedance tube method being that normal incidence parameters are determined; it gives fast and accurate measurements. It is easy to assemble and disassemble the instrument. In the existing impedance tube design, large frequency range can be achieved by using different interferometer tube and microphone spacing (Garai & Pompoli 2005). The reverberation method measures the reverberation time in an empty reverberant room and then repeats the process after introducing a sample of the test material. From the two reverberation times, the total absorptions in the two cases are determined, the difference being attributed to the absorption added by the sample. Dividing the sample absorption by sample area gives the absorption per square feet, which is taken to be the absorption coefficient (Atalla et al. 1998).

The three standardized measurement methods best known are: reverberation chamber method described in the standards ISO 354 and ASTM C-423 and two different impedance tube methods that are described in standards ISO 10534-1 and ISO 10534-2. The acoustic characteristics of a sound-absorbing material are frequently estimated by the use of an interferometer. This is due to the relative simplicity and the reliability of the
results. Most publications deal with this method and describe experiments on various materials (Miki 1990 a & b, Shoshani & Yakubov 2000).

### 2.28 ACOUSTIC CHARACTERISTICS AND SURFACE IMPEDANCE

The acoustic impedance at a particular frequency indicates how much sound pressure is generated by the vibration of molecules of a particular acoustic medium at a given frequency. The ratio of acoustic pressure in a medium to the associated particle velocity is defined as specific impedance (or surface impedance if referred to an interface between two fluids or fluid-solid) (Jaatinen 2011):

\[ z = \frac{P(x, t)}{v(x, t)} \]  

(2.3)

### 2.29 REFLECTION AND ABSORPTION COEFFICIENT AT NORMAL INCIDENCE

#### 2.29.1 Reflection Coefficient

The reflection coefficient \( R \) at the surface of a layer is the ratio of the pressures \( p^* \) and \( p \) created by the outgoing and the ingoing waves at the surface of the layer (Jaatinen 2011). For instance, at \( x_1 \), the reflection coefficient \( R(x_1) \) is equal to

\[ R(x_1) = \frac{p^*(x_1, t)}{p(x_1, t)} \]  

(2.4)

This coefficient does not depend on 't' because the numerator and the denominator have the same dependence on 't'. Using previous equations, the reflection coefficient \( R(x_1) \) can be written as
\[ R(x_i) = \frac{z(x_i) - z_{c1}}{z(x_i) + z_{c1}} \] (2.5)

where, \( Z_{c1} \) is the characteristic impedance in fluid 1. The in-going and outgoing waves at \( x_1 \) have the same amplitude if \( |R(x_1)| = 1 \). This occurs if \( |Z(x_1)| \) is infinite or equal to zero. If \( |Z(x_1)| \) is greater than 1, the amplitude of the outgoing wave is larger than the amplitude of the ingoing wave. More generally, the coefficient \( R \) can be defined everywhere in a fluid where an ingoing and an outgoing wave propagate in opposite directions (Jaatinen 2011).

### 2.29.2 Absorption Coefficient

The absorption coefficient \( \alpha(x_1) \) is related to the reflection coefficient \( R(x_1) \) as follows

\[ \alpha(x_1) = 1 - |R(x_1)|^2 \] (2.6)

The phase of \( R(x_1) \) is removed, and the absorption coefficient does not carry as much information as the impedance or the reflection coefficient. The absorption coefficient is often used in architectural acoustics, where this simplification can be advantageous. It can be rewritten as (Jaatinen 2011):

\[ \alpha(x_i) = 1 - \frac{E^*(x_i)}{E(x_i)} \] (2.7)

where \( E(x_i) \) and \( E^*(x_i) \) are the average energy flux through the plane \( x = x_i \) of the incident and the reflected waves, respectively.
2.30 DEFINITION AND SYMBOLS

2.30.1 Sound Absorption Coefficient at Normal Incidence - $\alpha (\omega)$

It is the ratio of sound power entering the surface of the test object (without return) to the incident sound power for a plane wave at normal incidence (Jaatinen 2011).

2.30.2 Sound Pressure Reflection Coefficient at Normal Incidence - $R (\omega)$

It is the complex ratio of the amplitude of the reflected wave to that of the incident wave in the reference plane for a plane wave at normal incidence (Jaatinen 2011).

2.30.3 Normal Surface Impedance - $Z_s (\omega)$

It is the ratio of the complex sound pressure $P(\omega)\big|_{x=0}$ to the normal component of the complex sound particle velocity $V(\omega)\big|_{x=0}$ at an individual frequency in the reference plane ($x = 0$) (Jaatinen 2011).

2.30.4 Wave Number

It is the variable defined by (Jaatinen 2011):

$$K_0 = \frac{\omega}{c_0} = \frac{2\pi f}{c_0} = \frac{2\pi}{\lambda_0}$$  \hspace{1cm} (2.8)

where,

$\omega$ is the angular frequency;

$f$ is the frequency;

$c_0$ is the speed of sound;

$\lambda_0$ is the wavelength.
2.30.5 Complex Sound Pressure $P(\omega)$

It is the Fourier transform of the temporal acoustic pressure $p(t)$ (Jaatinen 2011):

2.30.6 Cross Spectrum $S_{12}(\omega)$

It is the product $P_2(\omega)P_1(\omega)^*$, determined from the complex sound pressures $P_1(\omega)$ and $P_2(\omega)$ at two microphone positions (Jaatinen 2011).

Note: * means the complex conjugate

2.30.7 Auto Spectrum $S_{11}(\omega)$

It is the product $P_1(\omega)P_1(\omega)^*$, determined from the complex sound pressure $P_1(\omega)$ at microphone position one (Jaatinen 2011).

Note: * means the complex conjugate

2.30.8 TRANSFER FUNCTION $H_{12}(\omega)$

It is the transfer function from microphone position one to two, defined by the complex ratio (Jaatinen 2011):

$$
\frac{P_2(\omega)}{P_1(\omega)} = \frac{S_{12}(\omega)}{S_{11}(\omega)} \text{ or } \frac{S_{22}(\omega)}{S_{21}(\omega)} \text{ or } \sqrt{\frac{S_{12}(\omega)S_{22}(\omega)}{S_{11}(\omega)S_{21}(\omega)}}
$$

(2.9)

2.31 MEASUREMENTS PERFORMED WITH AN IMPEDANCE TUBE

An impedance tube is a straight, rigid, smooth cylindrical pipe composed by two main sections or tubes: transmitting and receiving tube. The
test sample is mounted at one end of the impedance tube (receiving tube). Plane waves are generated in the transmitted tube by a sound source (random, pseudo-random sequence, or chirp), and the sound pressures are measured at two locations near to the sample (preferably less than 3 times the diameter of the tube). The complex acoustic transfer function of the two microphone signals is determined and used to compute the normal-incidence complex reflection coefficient $R(\omega)$, the normal-incidence absorption coefficient $a(\omega)$, and the surface impedance of the test material $Z_s(\omega)$ (Jaatinen 2011).

The quantities are determined as functions of the frequency with a frequency resolution which is determined from the sampling frequency and the record length of the digital frequency analysis system used for the measurements. The usable frequency range depends on the width of the tube and the spacing between the microphone positions. The measurements may be performed by employing one of two following techniques:

1. Two-microphone method (using two microphones in fixed locations)
2. One-microphone method (using one microphone successively in two locations)

The first technique requires a pre-test or in-test correction procedure to minimize the amplitude and phase difference characteristics between the microphones; however, it combines speed, high accuracy and ease of implementation. This technique is recommended for general test purposes.

The second technique has particular signal generation and processing requirements and may require more time; however, it eliminates phase mismatch between microphones and allows the selection of optimal microphone locations for any frequency. It is recommended for precision.
2.32 LIMITATIONS OF THE IMPEDANCE TUBE MEASUREMENTS

As all instruments, the impedance tube presents some limitations about which acoustic properties can be measured and in which range of frequency (Jaatinen 2011).

1. Measurements performed in an impedance tube are at normal incidence. It is important to keep in mind that in real life this condition is often not satisfied. However, characteristic impedance and wave number of a porous media can be measured with this instrument and used to predict acoustic behavior of the material at oblique incidence.

2. Plane wave can be generated in a tube only if the excitation frequency is below the smallest acoustic mode of the tube. This condition defines the upper working frequency limit of this instrument.

3. Microphones spacing defines both upper and lower working frequencies of the tube. Microphone spacing is 5% of the longest measurable wavelength and 95% of the shortest one (keep in mind that the length of the tube has to be long enough so that at least half of the longest wavelength can fit in it).

2.33 DETERMINATION OF THE REFLECTION COEFFICIENT (R)

All materials have certain sound absorbing properties. Incident sound energy which is not absorbed must be reflected, transmitted or dissipated. The normal incidence reflection factor can be calculated using the formula (Mohammad et al. 2011 & Jaatinen 2011):
\[ R = \frac{e^{-jk_0 s} - H_{12} e^{jko x_1}}{H_{12} - e^{jko s}} \]  \hspace{1cm} (2.10)

where,

- \( H_{12} \) is Transfer function measured between two microphones,
- \( K_0 \) is wave number in air,
- \( x_1 \) is the distance between sample and the farther microphone location,
- \( S \) between microphone distances,
- \( j \) is \(-1\)

### 2.34 DETERMINATION OF THE SOUND ABSORPTION COEFFICIENT (\(\alpha\))

The coefficient can be viewed as a percentage of sound being absorbed, where 1.00 is complete absorption (100%) and 0.01 is minimal (1%). For convenience in analyses, the absorption coefficient is defined in terms of sound pressure reflection factor \( R \) of the absorber interface (Mohammad et al. 2011 & Diego et al. 2012):

\[ \alpha = 1 - |R^2| \] \hspace{1cm} (2.11)

### 2.35 COMPARISON OF DIFFERENT METHODS FOR ACOUSTIC MEASUREMENTS

If a comparison is made about the three methods cited above, advantages and disadvantages of each one can be listed. The reverberation chamber measurement described by ISO 354 is an accurate method for estimating the acoustic absorption for all sounds incident angles while the impedance tube only considers normal incident angles. So the reverberation
chamber requires a special installation and a considerable space to locate it, once the related standard regulates it as a room with a volume of 200 m³, at least (Beranek & Ver 1992). In order to guarantee a uniform distribution of natural frequencies, especially in low frequencies bands, the microphone should not have two dimensions equal or multiple to each other. The method is performed as a comparison measurement between the reverberation times of an empty chamber and with absorptive material arranged on the floor. The sample area has from 10 m² to 12 m² (Beranek & Ver 1992, Vissamraju 2005).

Unlike the reverberation chamber, the acoustic absorbing measurements using the impedance tube method are accurate for normal incident sounds waves only (Chung & Blaser). So with the methods described by ISO- 10534-1 or ISO- 10534-2 is possible to determine the normal incidence absorption coefficient and the specific acoustic surface impedance. Although for low frequencies the impedance tube method may not give accurate results because an airtight fit of the sample is needed given that at the same time the sample has to be able to vibrate freely (Massarane 2008). The advantage of the impedance tube is its portability. The apparatus consists of a rigid walled tube with a sound source at one end and the sample of absorbing material to be tested at the other end. All the experimental system can be placed at a laboratory stand.

As cited above there are two methods which are employed for acoustical impedance measurements using an impedance tube: the method using standing wave ratio (ISO 10534-1) and the transfer-function method (ISO 10534-2). The first one uses transient sound excitation to excite a single microphone that can be move lengthwise inside the tube and the second uses continuous white noise to excite one or two-microphones. The classical acoustics theory can be used to derive the equations for the two methods. The transfer function (TF) method was presented by Chung & Blazer (Champoux
& Stinson 1992) which consists of two fixed microphones located at two different positions in the tube wall. The incident and reflected waves can be recovered mathematically in an easily understood form. From these the reflection coefficient of the sample can be calculated for the same frequency band as the broadband exciting signal. The impedance and absorption coefficient can be calculated as well. The transfer function method has proven to be reliable and it is widely used in researches and practical applications (Biot 1956 a & b).

Over the years the impedance tube has been proved to be viable when compared to others methods cited above, due to relatively easy construction, low cost, portability and quick results. Although the reverberation chamber requires tests specimens which are rather large, it is not convenient for research and development work where only samples of specimen’s smaller size are available. Due to these advantages, this equipment and methodology has been extensively used in the acoustic characterization of many kinds of materials (Massarane 2008).

A new approach is developed in this project on an impedance tube setup for measuring the sound absorption coefficient. The goal was to obtain a low cost experimental setup which is capable of determining the sound absorption coefficients of different materials in a precise manner using the two microphone impedance tube technique.